Attn: M. K. Knapp   Knapp

Evaluation of Hydraulic Head Measurements in DC-1

To: M. R. Knapp, Chief, WMGT
From: F. R. Cook, Onsite BWIP Rep., NRC

Prepared by

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for

Rockwell Hanford Operations
Energy Systems Group

Buyer: W.R. Terry
Technical Representative: Dr. L.S. Leonhart

Submitted in fullfillment of Task A of Rockwell Purchase Order M30-SBB-267950, 06/13/83.

FINAL REPORT
NOVEMBER, 1983

NOT SAME AS ATTACHED

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from F.R. Cook
See Pocket 2 for the rest of the Report

Evaluation of Hydraulic Head Measurements in DC-1

WM Record File 101

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FINAL REPORT
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Attn: Neil Coleman MS 623 SS
from F.R. Cook

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FINAL REPORT

NOVEMBER, 1983

FOREWORD

This report was prepared by G.E. Grisak on the basis of reports and information kindly provided by the Rockwell Technical Representative Dr. L.S. Leonhart. However, the interpretations provided as well as any errors or omissions are solely the responsibility of the writer. Numerical calculations were conducted by D.W. Lafleur (GTC) utilizing the HCTM (developed by INTERA Environmental Consultants) three-dimensional finite difference ground water simulation code.

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GTC

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1.0 INTRODUCTION

The purpose of this report is to evaluate the hydraulic head data obtained from the multiple piezometer installation ARH-DC-1 (DC-1) on the Hanford Reservation and to determine its suitability for inclusion in the Basalt Waste Isolation Project (BWIP) baseline data set. The BWIP project is conducted by Rockwell Hanford Operations, a division of Rockwell International, under contract to the U.S. Department of Energy's Office of Waste Isolation. The BWIP project is in support of the National Waste Terminal Storage Program to identify candidate sites for storage of nuclear waste in geologic media and to provide the technology and the facilities for such storage. The fundamental performance objective of a nuclear waste storage site is to maintain separation of the waste materials from the accessible environment during their hazardous lifetime (Leonhart, 1983). The hydrogeologic system, as the principal potential mode of waste transport to the accessible environment, is implicitly integral to the performance assessment requirements of any site.

A reliable baseline data set must clearly be the first step in the performance assessment of any potential repository site. From a hydrogeologic viewpoint, the baseline data set consists of both descriptive and quantitative data. The descriptive data include the geographic and geologic settings, while the quantitative data start with meteoric, topographic and major hydrologic controls and continue to the details of hydraulic head, permeability characteristics of the geologic media, and hydrogeochemistry. The spatial and temporal variation of these hydrogeologic characteristics form an important part of the baseline data set. Only after these data have been obtained, assimilated and assessed, including an analysis of the uncertainty associated with data collection and assessment methods, can an initial site characterization be deemed completed. On completion and

acceptance of a site characterization data set, performance assessment activities can proceed to provide an evaluation of the site suitability as a terminal waste storage site.

The baseline data set required for site characterization of the Hanford area is being developed in the context of a Reference Repository Location (RRL) located within the Hanford Reservation (Figure 1). The RRL is located approximately 15 to 20 kilometers west of the Colombia River (Figure 2) and encompasses the 200 West area, an existing waste treatment facility. Boreholes DC-1 and DC-2 (Figure 2) are located near the northeastern corner of the 200 East area, a second existing waste treatment facility, approximately 2 kilometers east of the RRL boundary.

Borehole DC-1 was drilled for the purpose of obtaining hydrogeologic information at multiple levels in the Hanford hydrostratigraphic sequence. DC-1 is a single borehole, multiple piezometer installation completed in 1972. Since its completion there have been various opinions and reports concerning the reliability and comparability of the hydraulic head data obtained from the packer tests conducted during the drilling of DC-1 (and the adjacent borehole DC-2), and the subsequent water levels measured in the DC-1 piezometers over the decade since the piezometers were installed. The packer tests suggested a decreasing hydraulic head below about 3000 feet depth, while the piezometer data indicated a slight upward gradient. Since the interpretation and relevance of vertical gradient data is crucial, not only to site characterization but also to performance assessment activities, the discrepancy between these two data sets concerning the hydraulic head in DC-1 requires reconciliation. This report addresses the drilling, installation and monitoring at the DC-1 and DC-2 locations and attempts to provide an evaluation of the head measurements on the basis of hydraulic principles and measurement practices. Recommendations for a testing

program which would evaluate the intraborehole integrity of the cement seals are provided, as are calculations and recommendations concerning the effect, on the water levels measured in DC-1, of the drilling and completion of DC-2.

2.0 DRILLING AND COMPLETION OF DC-1 and DC-2

2.1 DC-1

Borehole DC-1 was an exploratory hole drilled in 1969 by Fenix and Scisson, Inc. under the technical direction of the Atlantic Richfield Hanford Company as prime support contractor for the U.S. Atomic Energy Commission's Richland Operations Office. Hydrological (packer) tests were performed during the drilling for the purpose of permeability testing, geochemical sampling and for obtaining hydraulic head measurements at various depths in the sediments and basalt underlying the Hanford reservation. Considerable difficulties, related to the initial attempts to cement off the Mabton and Vantage interbeds, were encountered during the drilling (Completion Report, ARH-DC-1, 1969). The final completed borehole DC-1, although advanced to a total depth of 5661 feet, was cemented back to 824 feet from a Lynes packer set at 1224 feet. The reason for cementing back was that it was thought the original hole had not been re-entered after cementing off the Mabton interbed and the hole to 5661 feet was considered to be a sidetrack from the original hole. The borehole which was considered the original borehole and which had been cemented during the Mabton cementing job, had been advanced to a depth of 2848 feet. In the final analysis, the hole to 2848 feet turned out to be a sidetracked hole and the hole to 5661 feet was in fact the "original" hole.

The complete drilling history of DC-1 is somewhat complicated due to a number of attempts to re-enter the "original" borehole; however, the final "as-built" drawing (Figure 3) as of 10/10/69

shows a cemented sidetracked hole to a depth of 2848 feet and an original hole to a depth of 5661 feet with a cement plug between 824 feet and a Lynes packer at 1224 feet (Completion Report, ARH-DC-1, 1969).

The original hole was re-entered in 1972 under a borehole recovery drilling program conducted by Fenix and Scisson, Inc. under the technical direction of Atlantic Richfield Hanford Company. The original borehole (TD 5661 feet) was re-entered after locating it with downhole whipstock directional drilling techniques. The cement plug was drilled, the Lynes packer milled out (after it had moved downhole to 2041 feet) and the hole cleaned to 5582 feet. Cleaning stopped at that depth due to high circulation losses, junk and solid debris in the bottom of the hole, and torquing problems with the tools.

On completion of hole cleaning, geophysical logs were run and the hole was cemented back to 4849 feet with neat cement (ASTM Type 2; API Type B) at 15.6 pounds per gallon. The piezometers, with sand/pea gravel packs and cement seals, were then successively installed as illustrated in the Recovery and Completion Report, Hole ARH-DC-1 (1972) "as-built" drawings (Figure 4, Figure 5) and the photograph of the surface installation (Figure 6).

2.2 DC-2

DC-2 is a single borehole with two deviated core intervals drilled and completed between 1977 and 1978. The hole was drilled for the purposes of obtaining hydrologic and structural information on the basalts between 2300 and 3300 feet depth. The original vertical hole DC-2 was located about 60 feet to the southwest of DC-1 and drilled to a vertical depth of 3300 feet. DC-2 was completed in September 1977 as an open hole (3.032 inches) between 2253 and 3300 feet depth, with a NX casing

cemented to a depth of 2253 feet (Figure 7). The hole was left open for 11 months and then cemented in mid-August, 1978 immediately prior to the commencement of drilling of DC-2-A1.

DC-2-A1 is an angle core hole (2.98 inches) kicked off from the original hole in a westerly direction at a depth of 2370 feet. The hole was gyro surveyed and showed a horizontal displacement on the surface projection of 248.7 feet with a final trend of N88.2°W (Figure 8). The total measured length of borehole DC-2-A1 is 3348 feet whereas the true vertical depth is 3298.8 feet. There were no hydrologic tests conducted in DC-2-A1 and the hole was cemented back, on completion of drilling in October 1978, from total depth to 2238 feet.

Drilling commenced on DC-2-A2, a second angle core hole kicked off from DC-2, in October 1978 (immediately after the cementing of DC-2-A1). The cement plug in DC-2-A1 was drilled out to a depth of 2307 feet and DC-2-A2 was kicked off, after a couple of false starts, at 2280 feet, again away from DC-1 in a southwest direction. DC-2-A2 was completed in December 1978 and has remained open since. The gyro survey of DC-2-A2 showed a horizontal displacement, on the surface projection, of 290.9 feet with a final trend of S33.9°W (Figure 8). The total measured length of DC-2-A2 is 3374 feet, whereas the true vertical depth is 3313.8 feet (Figure 7). There were packer tests conducted in DC-2 and DC-2-A2 on completion of drilling (Science Applications Inc., 1978 and Apps and others, 1979; as reported in Gephart and others, 1979).

3.0 HYDRAULIC HEAD MEASUREMENTS

3.1 Packer Tests in DC-1 and DC-2

The hydraulic head data obtained from packer tests in DC-1 are shown in Figure 9. The packer straddle interval varied from about 30 to 200 feet, normally straddling more than one interflow. The heads in the DC-1 packer tests were measured with downhole mechanical pressure gauges in association with testing sequences which included permeability testing and ground water sampling (Gephart and others, 1979). The accuracy of the DC-1 heads is reported (op. cit.) as ± 20 feet. With this accuracy the trends observed are probably more relevant than the absolute values of the measurements. Although there are some unreconciled discrepancies between the DC-1 packer test measurements reported in NRC (1983) and Gephart and others, 1979 (see Figure 9) the apparent trend observed in the packer test results is a decrease in hydraulic head below the Umtanum flow of the Grande Ronde Formation; suggesting downward movement of ground water below a depth of about 3000 feet.

The hydraulic heads measured in borehole DC-2 after coring (as reported in Gephart and others, 1979) are also shown on Figure 9. There are two information sources for packer tests in DC-2 as referenced in Gephart and others (1979). The data shown from Apps and others (1979) show a distinct decrease in head with depth, while the data shown from Science Applications Inc. (1978) have less trend to them.

Although it is clear from Figure 9 why a decreasing hydraulic head with depth is interpreted from the packer tests in DC-1 and DC-2, it is also clear that considerable uncertainty is inherent in the head data. For instance, the 'reported' hydraulic heads for the Grande Ronde between 2100 and 2500 feet depth range from 403 to 470 feet above sea level. A similar range of values for head measurements exists in the lower portion of the Umtanum flow.

Although the possibility of head differences across various units certainly exists, it is not likely that the hydraulic head pattern at depth is as complicated as the compilation of measurements on Figure 9 might suggest.

3.1.1 Sources of Uncertainty in Packer Tests

The measurement of representative formation hydraulic heads using packer isolated intervals in open boreholes is a reasonably difficult task, particularly in relatively impermeable media. There are two main sources of uncertainty in pressure measurement; equipment-related uncertainty and formation-related uncertainty. Equipment-related uncertainty is usually reflected in the accuracy reported for a particular measurement. For instance, the accuracy of ±20 feet reported in Gephart and others (1979) for the head measurements from La Sala and Doty (1971) are most likely associated with the downhole mechanical pressure gauges normally utilized at that time. The accuracy of ± 2.5 feet reported (op. cit.) for the DC-2 measurements is probably part of the specification data related to quartz or high resolution strain gauge transducers which have been in use for the last few years. Equipment-related accuracy can be expressed quite confidently based on 'before' and 'after' test calibrations, etc. However, formation-related uncertainty is quite a different matter. The following discussion attempts to address some of the formation related uncertainties associated with downhole pressure or hydraulic head measurements.

<u>Formation Related Uncertainty</u>

It is most instructive to approach the problem of pressure measurement and formation responses to drilling and testing by considering the sequential occurrence of events from the time a geologic interval is intersected to the completion of

a packer test. An arbitrary selection of initial pressure and temperature conditions are employed for illustrative purposes. The conditions are:

- in-situ pressure > annulus pressure and,
- in-situ temperature > drill fluid temperature.

Annulus pressure refers to the downhole absolute pressure corresponding to the elevation of the overflow of drilling fluid (during drilling) at the wellhead.

Prior to drilling into an interval the pressure and temperature of the interval are considered to be at in-situ or formation conditions (P_f and T_f). As the interval is drilled, the rock is subjected to annulus pressure (P_a) and drilling fluid temperature (T_d). Pressure and temperature profiles are developed into the formation in response to the differential pressures and temperatures between the borehole fluid and the rock (Figure 10). The P and T profiles into the rock averaged over the entire interval are schematically illustrated in Figure 10. In reality, the P and T profiles will be different between the top and the bottom of the interval, since the upper portion has been open to drilling conditions for a longer period of time than the lower portion. The longer the interval is open and under annulus P_a and T_d conditions the further into the formation the P and T profiles develop. For instance, if drilling continues for another day or two before testing, the P and T in the immediate borehole vicinity will decrease even further, and the gradients between the formation and the borehole will decrease (profile 2 on Figure 10).

If single or double packer equipment is then installed in the borehole and attempts are made to measure the in-situ pressure, the pressure response is dependent on a number of factors, including rock hydraulic conductivity, fluid compressibility, fluid density, fluid thermal expansion coefficient, fluid vicosity, fluid heat capacity, rock thermal conductivity, rock

heat capacity, and the interrelationships between these parameters at various pressures and temperatures. The relative importance of the pressure and temperature dependence of the fluid parameters (Figure 11) are summarized below.

Relative Dependence of Borehole and Formation Fluid Parameters on Pressure and Temperature

	Density	Compress-ibility	Coefficient of thermal expansion	Viscosity
Temperature	high	high	very high	very high
Pressure	moderate	high	low	low

The above table and dependencies are most relevant to the case of a 'shut-in' interval, that is, when the pressure measurement does not rely on an equilibrated column of water (i.e., piezometer standpipe) for hydraulic head measurement, but rather the pressure of the interval is measured directly with a downhole transducer. In this instance the rate of recovery of the interval from drilling P_a and T_d to formation P_f and T_f is dependent primarily on the fluid and medium properties related to compressibility and thermal expansivity. In other words, pressure recovery is faster because it is not necessary for the column of water to come to equilibrium with the formation. (In relatively impermeable formations, as discussed in Section 3.2, it simply may not be possible to representatively measure in-situ hydraulic heads with a standpipe piezometer). Shut-in pressure measurements are the most common type of packer test pressure measurements, unless the formation is extremely permeable.

It can be shown that under most hydrogeologic conditions, and in particular in fractured rock environments, thermal transport (or the development of temperature profiles into the rock from the borehole) is relatively independent of water flow or pressure conditions. The rock is a significant heat source/sink, the thermal properties of which tend to overcome any significant heat movement via advection with the water. Therefore, under the conditions illustrated in Figure 10, there is no heat transported from the rock to the borehole by water movement, rather the heat transport is virtually all by heat conduction. Heat transport by conduction is governed by the thermal conductivity and heat capacity of the formations. Although flow (advection) or pressure have little influence on heat transport in fractured rock, the converse is not true. Heat transport and thermal conditions have a substantial effect on pressure profiles and shut-in interval pressure conditions, as illustrated by the temperature dependence of the fluid properties presented in Figure 11.

There are a number of possible pressure responses, after an interval is 'shut-in'. In many cases the 'shut-in' results in a slight pressure increase in the interval due to a 'squeeze' pressure on the fluid between the packers. Although this is not the case with some equipment configurations, a shut-in squeeze serves a useful illustrative purpose. In order to describe the possible presure responses which could occur after an interval is shut-in, the cases of a low permeability, medium permeability and a high permeability interval are considered (Figure 12). The case of an increasing temperature after shut-in is used for illustrative purposes.

Low Permeability Response

In a low permeability interval the pressure decay in response to the shut-in squeeze is limited initially by the formation permeability. However, if a significant temperature rise

(i.e., 1° or 2°C) occurs over the test period in response to the temperature differential between the rock and the borehole, the pressure in the interval will actually continue to increase due to the temperature rise. The pressure increase is moderated slightly by pressure dissipation into the formation. For the purpose of comparison, the response of the interval without a temperature increase is also shown. Conversely, if T_d had been higher than T_f, the pressure in the shut-in interval would decrease due to not only a formation permeability-related pressure dissipation but also due to a decreasing temperature. With sufficient temperature decrease it is not difficult to visualize pressure dropping below the in-situ pressure, due solely to temperature changes.

The thermal expansion coefficient of water varies significantly over the potential range of subsurface temperatures. Figure 13 illustrates the change in pressure due to a temperature change in an interval with zero permeability. The graphs are calculated using the thermal expansion coefficient of water at the temperatures 20, 40, 60, and 80°C. Figure 13 simply serves to illustrate possible magnitudes of pressure change. For instance, at a temperature around 40°C, a 2°C change in temperature in a zero permeability shut-in interval will result in a pressure change (expressed as hydraulic head) of about 180 meters.

The pressure response history of a shut-in interval is also related to the length of time the borehole has been open to annulus pressure. If the borehole has been open for an extremely long period, the pressure around the borehole will be at approximately P_a, and the resultant pressure history will be more in response to the P_a "pressure-skin" than to P_f, resulting in possible misinterpretations of the actual formation pressure.

Medium Permeability Response

In a medium permeability interval, again with a temperature increase, the pressure decay is moderated somewhat by the temperature increase (see Figure 12). The result is a pressure response curve which on first inspection could be misinterpreted as a low permeability response. However, the actual permeability is greater than the pressure response curve indicates if temperature is included in the analysis.

High Permeability Response

The pressure response in a high permeability zone is relatively insensitive to temperature changes. The insensitivity is due to the relative ease with which a high permeability zone dissipates any pressure change, providing the zone has sufficient lateral extent to accommodate the pressure changes. If the permeability is very high the initial pressure response may be more related to the annulus pressure than to the formation pressure (see Figure 12). If the high permeability zone has been open for a lengthy period, it may be an extremely long time before the influence of the P_a "pressure-skin" is removed from the measurement of P_f.

A detailed analysis of isothermal and nonisothermal borehole pressure history effects has recently been conducted by GTC (1983). Borehole pressure history simply refers to the 'pressure-skin' which develops in the borehole vicinity as a consequence of drilling activities. In addition NRC (1983, Appendix G) also addressed the pressure profiles in a simplified layered system with various boundary conditions, relating the calculations to packer measurements obtained during drilling and testing programs. Sokol (1963) addresses the composite water levels which result from perforation of more than one aquifer, with different hydaulic heads in each

aquifer. He demonstrates that, for instance, the water level in the open hole DC-2-A2 or in DC-1 between 1969 and 1972 will fluctuate in response primarily to the most permeable zone (eg. the ratio of the water level fluctuation in DC-2-A2 to the hydraulic head fluctuation in any zone perforated by DC-2-A2 is equal to the ratio of the transmissivity of the zone of interest to the total transmissivity of the open hole).

Without going into great detail, it can be stated that the length of time a borehole is open to drilling conditions and the length of time the borehole provides a 'short-circuit' of the in-situ formation pressure profile, are both strongly related to the time required to measure representative in-situ pressures. In some instances it may be virtually impossible to recover the in-situ head profile with open hole packer tests.

There are a number of different borehole conditions which could be illustrated with schematic diagrams such as Figure 12. However, the main purpose of this discussion is simply to address the nature and cause of some of the borehole history and temperature-related uncertainties associated with pressure measurement at depth in geologic formations. It is clear that detailed analysis of downhole pressure, temperature and actual or inferred borehole history conditions must be conducted before a substantial reduction in the uncertainty associated with packer test hydraulic head measurements can be accomplished. This is not to infer that pressures or hydraulic heads were incorrectly measured in previous packer testing programs in DC-1 and DC-2, but rather to suggest that pressure measurement at depth in low permeability formations is a difficult and developing technology, still in the research phases.

3.2 Piezometer Measurements in DC-1

Following installation of the DC-1 piezometers the U.S. Geologic Survey undertook the measurement of water levels until the Survey's Richland office closed in 1973. At that time, an interim summary of water level data along with comments was submitted by the Geological Survey (La Sala, 1973). The letter report states that the water level measurements were required "to compare with data obtained during the drilling and testing at well ARH-DC-1 to evaluate the effects of drilling and pumping on short term packer tests." The following comments and recommendations were also submitted:

"(1) Piezometer 4 in ARH-DC-1 shows a consistent decline in head for the period of measurement indicating that the effects of drilling are very long-lived or that the piezometer is poorly connected, hydraulically, with the aquifer (partially plugged screen or sand pack).

. . .

(3) Water level trends in ARH-DC-1 piezometers (except number 4) and piezometer DDH-3 have been generally similar since January 1973.

(4) Head in ARH-DC-1 piezometers apparently increases with depth. The opposite trend was obtained for water-level measurements made during drilling.

. . . the following recommendations are therefore made:

(1) Water-level measurements should be continued in these piezometers at not longer than monthly intervals for the next two years to verify that natural conditions obtain and to observe the trends at water levels at depth in the basalt on and near the Hanford Reservation.

(2) Well development procedures (swabbing, pumping) be instituted as quickly as possible in piezometer DH-4 and in ARH-DC-1 piezometer 4 in one year, if the historical trend in water-level change continues.

(3) At intervals of approximately 5 years, suitable testing be done to ascertain that piezometers are open only to the zones in which they have been completed."

Water level measurements in DC-1 were apparently discontinued until 1975. The water levels measured in the DC-1 piezometers since their installation are shown in Figure 14. Except for DC-1-4, all the water levels appeared to have equilibrated relatively rapidly. DC-1-4, with a screened interval centre at 2956 feet and with a cement seal above and below of thickness' 808 and 190 feet respectively, appeared to require an exceptionally long time to equilibrate. The DC-1-4 water level in 1972 (immediately after installation) was approximately 432 feet above sea level. The water level slowly declined over the next few years until it reached an apparent equilibrium level of about 405 feet above sea level. It remained at 405 feet above sea level until the end of 1978, when it rapidly rose approximately 5 feet to 410 feet above sea level, which was almost identical to the level in DC-1-5, the standpipe in the 1219 feet to 2105 feet open zone. The drilling of DC-2-A2 in October 1978 may have resulted in the establishment of interconnectivity between DC-1-4 and DC-1-5 and caused the sudden water level change. The relative elevations and distances of the DC-1 piezometers and DC-2 boreholes are shown in Figure 15, while the DC-2 drilling programs are schematically shown on the water levels diagram in Figure 14.

During the testing of DC-2-A2, a water level response was noted in piezometers DC-1-1, 2 and 3 (RHO-BW1-ST-5). These responses are not shown on Figure 14 as they were not quantitatively recorded. The responses were apparently due to swabbing of the DC-2-A2 interval at 3243 to 3273 feet below ground surface. During swabbing of this interval in DC-2-A2, the water level declined several feet in piezometer DC-1-3 and a few inches in piezometers DC-1-1 and DC-1-2.

An obvious change in water levels in virtually all the DC-1 piezometers is reasonably coincident with the drilling of DC-2, DC-2-A1 and DC-2-A2 (see Figure 14). The change is most noticeable on completion of DC-2-A2, when there was a drop of 2 or 3 feet in piezometers DC-1-1, -2 and -3, a rise of 5 feet in DC-1-4 and then a drop of approximately 3 or 4 feet in DC-1-4 and DC-1-5 between the end of 1978 and 1979. Water level measurements were discontinued between the end of 1979 and the latter part of 1981, and then continued on a monthly basis for about a year.

3.2.1 Sources of Uncertainty in DC-1 Piezometer Measurements

There are several possible sources of uncertainty involved in determination of the representativeness of the hydraulic head measurements provided by the peizometers installed in DC-1. Some of these uncertainties are relatively generic to piezometers, while others are more directly related to site conditions.

In order for any piezometer to provide meaningful hydraulic head data, the following criteria must be satisfied:

- the piezometer must be hydraulically connected to the zone of interest, installed so as to minimize the time lag (Hvorslev, 1951) for representative measurements;
- the piezometer intake zone (screen) must be hydraulically isolated from other zones with potentially different hydraulic heads;
- the standpipe (tubing) portion of the piezometer must be free from leaks.

Water level data for the DC-1 piezometer suggests that, at least initially, piezometers 1, 2, 3 and 5 were reasonably well hydraulically connected to the zones of interest (although

there is no available information on any development procedures which may have been employed). Piezometer DC-1-4 was the slowest responding piezometer, either because it was situated in a relatively impermeable section of rock or because it was plugged with fines from the sand/gravel mixture placed around the screen. Discussion with personnel familiar with the installation (C.T. Webster, personal communication, 1975) indicated that there were no irregularities in the piezometer installation procedures and that cement invasion into the piezometer DC-1-4 gravel pack was not likely. It is possible that cement may have entered fracture zones locally around the cemented portions of the borehole and reduced the overall vertical hydraulic communication of the basalts in the borehole vicinity; perhaps even serving to isolate piezometer DC-1-4. In any event, the slow response of DC-1-4 for the first few years indicates that it may either 1) not have been well connected hydraulically to the basalt or 2) it was well connected but the formation is relatively impermeable. A subsequent rapid water level change appears related to the drilling of DC-2-A2.

The time lag referred to above is simply the time difference between a change in head in the formation and the manifestation of that change in the water level measured in the piezometer. The "Basic Time Lag" T_o (Hvorslev, 1951) is defined as the time that would be required for complete equalization of the head difference between the formation and the piezometer if the original rate of inflow (or outflow) to the piezometer caused by that head difference were maintained. In very impermeable formations it can be seen that T_o is of the order of several months. The Basic Time Lag for a DC-1 piezometer, had it been installed in a section of basalt with a hydraulic conductivity of 10^{-12} m/s, is about 80 days.

In order to hydraulically isolate the DC-1 piezometers, each from the other, cement seals (neat cement, ASTM Type II; API

Type B) were used between the gravel packed zones. As noted above, there were apparently no major difficulties with the cementing of the piezometers and a reasonable seal should have been achieved, at least initially. Coring activities during the first DC-1 drilling and cementing program in 1969 apparently yielded a solid core which was longitudinally divided into parts composed of cement and basalt (Completion Report, ARH-DC-1, 1969), suggesting a fairly good bond was achieved between the cement and the formation. There have been suggestions that the cement bond may not have been adequate or may have deteriorated (Gephart and others, 1979). However there is no obvious evidence from the water level data that the cement was not providing isolation immediately after the piezometers were installed. There is some evidence of a hydraulic connection established between DC-1-4 and DC-1-5 around the end of 1978, however this could be as much a consequence of DC-2-A2 drilling activities as of direct cement deterioration. The drilling of DC-2, DC-2-A1 and DC-2-A2 may have enhanced any cement deterioration underway by adding undersaturated water (fresh-water muds were used for drilling DC-2-A2 (RHO-BWI-C-39) and probably for DC-2 and DC-2-A1) to the immediate DC-1 environment. Cement deterioration is difficult to quantify, although alteration to geochemical stability via circulating ground water and remineralization are considered to be inevitable (Roy and others, 1982).

3.2.1.1 DC-1 Intraborehole Integrity

The permeability of the cement seals is the most relevant concern to the hydraulic isolation of the individual piezometers in DC-1. Most common downhole cement mixtures (such as those utilized in DC-1) are generally considered to have a hydraulic conductivity of the order of 10^{-8} to

10^{-9} m/s or less after a set period of about 10 days (Smith 1976; Roy and others, 1979).

Provided an adequate bond with the basalt has been achieved and maintained, it is instructive to consider quantitatively the effectiveness of such a cement seal in isolating the DC-1 piezometers. The example case of DC-1-3 and DC-1-4 is selected for illustration, since these are separated by the smallest cement thickness of 190 feet. A numerical model was constructed to evaluate the simplified system illustrated in Figure 16. Approximately half the sandpacked interval of DC-1-3 was incorporated and assigned a constant head of 412 ft asl. Physically the constant head simply means that DC-1-3 would be in a much more permeable zone compared to DC-1-4. The full sandpacked interval of DC-1-4 was included, assigned an initial head of 417 ft asl, and the grid (i.e. cement) extended in the vertical direction to eliminate any boundary effects. The gravel packs were assigned an arbitrary hydraulic conductivity of 10^{-6} m/s. The cemented length of 190 ft between DC-1-3 and DC-1-4 (as well as the extended grid above DC-1-4) were assigned different hydraulic conductivities, and the head in the formation to which DC-1-4 is open was assumed to not affect the head measurement of the DC-1-4 piezometer. This in fact represents the case where the formation open to DC-1-4 is relatively less permeable than the assigned cement seal. (The case of variable formation permeabilities is addressed in the following section).

The calculations were performed in order to obtain some idea of the limiting cement hydraulic conductivities. However, the modeled system is very much an approximation and has inherent limitations which must be recalled when the results are interpreted. The limitations include the fact that the hydraulic head measured by the piezometer DC-1-4 in the model

is assumed to respond only to the head in DC-1-3. In fact the response in DC-1-4 will strongly depend on the hydraulic regime to which DC-1-4 is actually open. For instance, if the formation to which DC-1-4 is open is relatively permeable and if the actual boundaries of the DC-1-4 formation are at a sufficiently large distance, the response in DC-1-4 may not be measurable due to the moderating effect that the formation would have.

The hydraulic head profile between DC-1-3 and DC-1-4 after 10 years is plotted on Figure 16. It can be seen that, after 10 years, with a cement hydraulic conductivity of 10^{-11} m/s or greater, the hydraulic head in DC-1-4 would be the same as that in DC-1-3 (recalling that the DC-1-4 formation hydraulic head is assumed to have no influence). In actual fact the head in the DC-1-4 formation will moderate the response in DC-1-4 to some extent, providing the DC-1-4 formation is somewhat more permeable than the cement seal. These calculations simply serve to illustrate that the cement seal provided in a single borehole, multiple piezometer installation must at least be lower in permeability than the formation between the isolated intervals; otherwise a certain amount of "short circuiting" is inevitable. In addition, it can be seen that a cement hydraulic conductivity of less than 10^{-11} m/s would be required to totally isolate DC-1-4 from DC-1-3 for a ten year period. A hydraulic conductivity for cement this low is not likely; in fact the cement hydraulic conductivity would more likely be of the order of 10^{-8} to 10^{-9} m/s (Smith 1976; Roy and others 1979), suggesting that unless the hydraulic conductivities of the formations to which both DC-1-3 and DC-1-4 are open are at least 10^{-8} m/s or greater, the cement would not provide sufficient isolation for adequate hydraulic head measurements. Data on the hydraulic conductivities of these intervals are not presently available, however hydraulic

testing procedures recommended later should serve to clarify the situation to some extent.

3.2.1.2 Analysis of DC-1 and DC-2 Hydraulic Interference

Further sources of uncertainty in the hydraulic heads measured by DC-1 piezometers are the drilling and testing activities in DC-2. As discussed earlier, there are noticeable changes in DC-1 water levels which appear to be relatively coincident with DC-2, DC-2-A1 and DC-2-A2 activities (see Figure 14). For the purposes of illustration and to assess the possible hydraulic interference, a simplified two-dimensional system was analyzed numerically. The two-dimensional modelled system is illustrated in Figure 17. A layered system was approximated, based on available estimates of the transmissivities of the various subsurface units (Bruce, 1983; internal letter). The initial condition in all DC-1 piezometers was assumed to be a hydraulic head of 417 feet asl and a constant head of 417 feet was assigned to the elevation corresponding to the Mabton interbed. The drilling of DC-2-A2 was considered as a starting point for transient simulations and a constant composite head of 412 ft asl (see Figure 14) was assigned to the DC-2-A2 open hole between 2253 feet and 3314 feet at a distance of 150 feet from DC-1 (in actuality the distance varies between about 60 feet and 300 feet; however, 150 feet was selected for convenience and illustrative purposes). Transient simulations, representing 1979 to 1984, were then conducted using various transmissivities for the Grande Ronde Formation and various horizontal to vertical (Kh:Kv) hydraulic conductivity ratios. It is obvious that these calculations are more generic in nature than they are specific to the

DC-1/DC-2 area. However they are provided simply to quantitatively illustrate the potential hydraulic interference between boreholes located as close as DC-2-A2 and DC-1.

Figure 18 illustrates the response of DC-1 piezometers to the open hole DC-2-A2 using an intermediate Grande Ronde transmissivity of 10^{-2} ft^2/day and Kh:Kv values between 1 and 1000. Several points could be made regarding the calculated DC-1 piezometer response data shown in Figure 18; however, each of these would need to be qualified with all the above assumptions and approximations. In effect the calculations should be regarded simply as illustrative of the possible effect which DC-2-A2 has on the water levels in DC-1. Figure 19 illustrates the calculated response in DC-1 piezometers using a constant Kh:Kv = 1 and various transmissivities for the Grande Ronde. The conclusion which should be drawn from these calculations is not that any individual piezometer responded in a particular manner, but rather that an effect from the DC-2-A2 open hole is seen in all the piezometers except DC-1-5 in all the modeled cases. This is reasonable since in the model DC-1-5 is the uppermost piezometer in one of the highest transmissivity units (T = 10^2 ft^2/day) and is closest to the assigned constant head of 417 ft asl at the Mabton elevation. The main point of the calculations shown on Figures 18 and 19 is that it is virtually impossible to isolate the DC-1 piezometers from the hydraulic influence of the open borehole DC-2-A2.

3.3 Residual Uncertainties

The previous discussions have addressed the general sources of uncertainty in head measurements in the DC-1/DC-2 area. There are also several other potential sources of uncertainty which are

relevant to the DC-1 piezometer measurements but have not been addressed directly since the possible magnitude of the effects on the hydraulic head measurements is unknown. Some of the other possible sources of uncertainty are listed below.

- The ARH-DC-1 initial drilling program was a reasonably complicated sequence of events. Several pilot holes and exploratory runs were made and numerous cement jobs, ranging from small to large, were conducted. The precise elevations and lengths of the various drilled and cemented intervals, plus the success of each individual cement job may have some impact on the hydraulic heads in the formations intersected. The possibility exists for short circuiting through some of these drilled and cemented intervals.

- ARH-DC-1 was open from 1224 feet to 5661 feet for a period of 3 years prior to recovery and piezometer completion in 1972. Obviously a "pressure-skin" representing the composite pressure in the open interval will have developed in all the formations between 1224 feet and 5661 feet. In-situ formation pressure recovery, as measured by the DC-1 piezometers, would probably require at least several years.

- Piezometer DC-1-5 now measures the composite water level of a completely open interval between 1219 feet and 2015 feet. This open interval is a relatively constant head line pressure source to the formations in the DC-1 area. Although the effect of this source may be more prevalent laterally (due to possibily high Kh:Kv values) the magnitude of the effect on the nearest deeper piezometers (DC-1-4 and DC-1-3) is not known. Calculations conducted in section 3.2.1.2 did not treat this area as a line

source; however, further calculations could be done to evaluate the possible effects.

- DC-2 remained open between 2253 feet and 3300 feet for a period of 11 months prior to cementing. The residual effect of this "short-circuiting" is unknown, as are the relative effectiveness' of the cement seals in DC-2 and DC-2-A1. Further transient calculations, similar to those in 3.2.1.2, could be conducted to investigate the possible residual effects.

4.0 SUMMARY AND CONCLUSIONS

This report has addressed the hydraulic head measurements in boreholes DC-1 and DC-2 in the context of the uncertainties associated with head measurements and the factors that must be considered in evaluation of the DC-1 and DC-2 measured heads. It has not been concluded that either the packer tests or the DC-1 piezometers are more correct in their representation of the hydraulic head profile in the DC-1 vicinity. Rather, the required data needs for determination of representative hydraulic head measurements have been identified. The following conclusions are presented in that context.

1. DC-1 piezometers will provide representative hydraulic head measurements only if the following criteria are met:

   - the piezometers are hydraulically well connected to the formations and the Basic Time Lag, T_O, is minimal;

   - the piezometer intake zones are hydraulically isolated from other zones with potentially different hydraulic heads.

   Methods to establish if the DC-1 piezometers meet these criteria are addressed in the recommendations.

2. The cement used to seal the piezometers, each from the other, suggests that in order for meaningful head measurements to be obtained, the piezometer intake zones must be adjacent to formations with hydraulic conductivities of greater than 10^{-8} to 10^{-7} m/s.

3. The drilling and recovery history of DC-1 (open hole for 3 years between 1224 feet and 5661 feet) dictates that at least several years stabilization would be required after piezometer installation before it could be assumed that representative hydraulic heads were being measured by the piezometers.

4. Borehole DC-2 has a direct influence on the piezometer measurements in DC-1. In particular, the presently open interval of DC-2-A2 between 2253 feet and 3314 feet is probably a significant determinant of all the DC-1 piezometer water levels except those in piezometer DC-1-5. DC-1-5 is open to a large relatively permeable interval between 1219 feet and 2105 feet.

5. The uncertainties associated with packer test hydraulic head measurements are relatively large and are related to equipment specifications as well as to borehole pressure and temperature history and formation characteristics. The uncertainties become greater as the formation permeability becomes lower. It is not clear to what extent the relevant conditions have been assessed in the packer test hydraulic head measurements in DC-1 and DC-2.

5.0 RECOMMENDATIONS

1. DC-1 piezometers should be developed and hydraulic tests conducted on each piezometer. The tests could be designed as constant head injection tests. A reservoir and constant head injection system could be set up in the field which could be used to fill each of the DC-1 piezometers in turn and maintain the head at the top of the piezometers for extended periods of time. (DC-1-5 may, in fact, be too permeable to allow such testing without a relatively large reservoir. If, however, the adequacy of the cement seals between the other piezometers is determined, then inferences may need to be drawn regarding the cement seal below DC-1-5.) Water level responses in all other piezometers and DC-2 should be measured during the injection tests. The purpose of these tests are twofold; a) to evaluate the adequacy of the cement seals between the piezometers and b) to evaluate the hydraulic conductivity of the formations to which the piezometer intake zones are open. These tests should be conducted over an extended period of time in each piezometer in order to determine the effectiveness of the cement seal between piezometers. The following table of testing periods is based on radius of influence calculations to the nearest adjacent piezometers using the Theis equation. The times indicated correspond to about a 5% response, in the nearest monitoring piezometer, to the change in head in the injection piezometer. The test period for each of the DC-1 piezometers has been derived using a minimum acceptable cement hydraulic conductivity of 10^{-7} m/s and a specific storage of the cement of 3×10^{-5} m^{-1}.

	DC-1-1	DC-1-2	DC-1-3	DC-1-4	DC-1-5
Injection Period (days)	45	40	5	5	55

If the cement seals prove to be adequate and the hydraulic conductivity of the formations to which the DC-1 piezometers are open is of the order of 10^{-6} to 10^{-7} m/s or higher, consideration should be given to including the hydraulic head measurements, from the period 1975-1978, in the ground water monitoring data base. If the cement seals are found to be inadequate, consideration should be given to removing DC-1 from the monitoring network data base.

Provided the cement seals between the DC-1 piezometers are adequate it is suggested to proceed to recommendation 2.

2. DC-2-A2 should be permeability profiled in detail using straddle packer testing methods and the Lynes or Tam hydrologic testing tools. Response measurements should also be made in each of the DC-1 piezometers to each tested interval in DC-2. The purpose of the detailed profiling in DC-2 and response measurements in DC-1 is to provide quantitative interconnectivity data on which to base calculations of the possible post-1978 DC-2 influences on DC-1.

3. Providing a) the cement seals between the DC-1 piezometers are adequate and b) there is a demonstrated interconnectivity between DC-2 and DC-1, quantitative methods should be employed to evaluate the effect of the open hole DC-2-A2 on DC-1 water levels between 1978 and

the present. With the data acquired from 1) and 2) above, these calculations should provide a meaningful analysis of small-scale interconnectivity and perhaps vertical permeability. The DC-1 piezometer responses to the open hole DC-2-A2 actually represent a five year hydraulic test. Attempts should also be made to recover any DC-2 water level data from the files.

4. If the DC-1 cement seals are inadequate, the alternatives are i) drilling out the installation and replacing the piezometers, which would then require an extremely long stabilization period, since the length of time the cement seals have been inoperative could extend as far back as 1972, or ii) abandoning the site and relying on new multiple piezometer installations for the baseline data.

5. If the DC-1 cement seals are adequate, then the dispositon of DC-2 becomes relevant (otherwise DC-2 should be simply cemented and abandoned with DC-1). It is not recommended that DC-2-A2 remain open if DC-1 remains in the monitoring network. DC-2 should be completed by either i) a multiple packer/piezometer port installation such as those manufactured by Westbay or Baski, or ii) cementing the open interval and abandoning the borehole. The former provides the opportunity for post-completion verification of the DC-1 water levels, while the latter substantially reduces any uncertainty in packer seal integrity.

6. Original data files from all the packer test measurements should be examined in detail to determine if there is sufficient data to reduce the presently large range of uncertainty. Considering that pressure measurement at depth in low permeability geologic formations is a

developing technology, and still partially in the research phases, it is not likely that the uncertainty associated with the DC-1 and DC-2 packer test hydraulic head measurements will be substantially reduced. However, these data do warrant examination and analysis.

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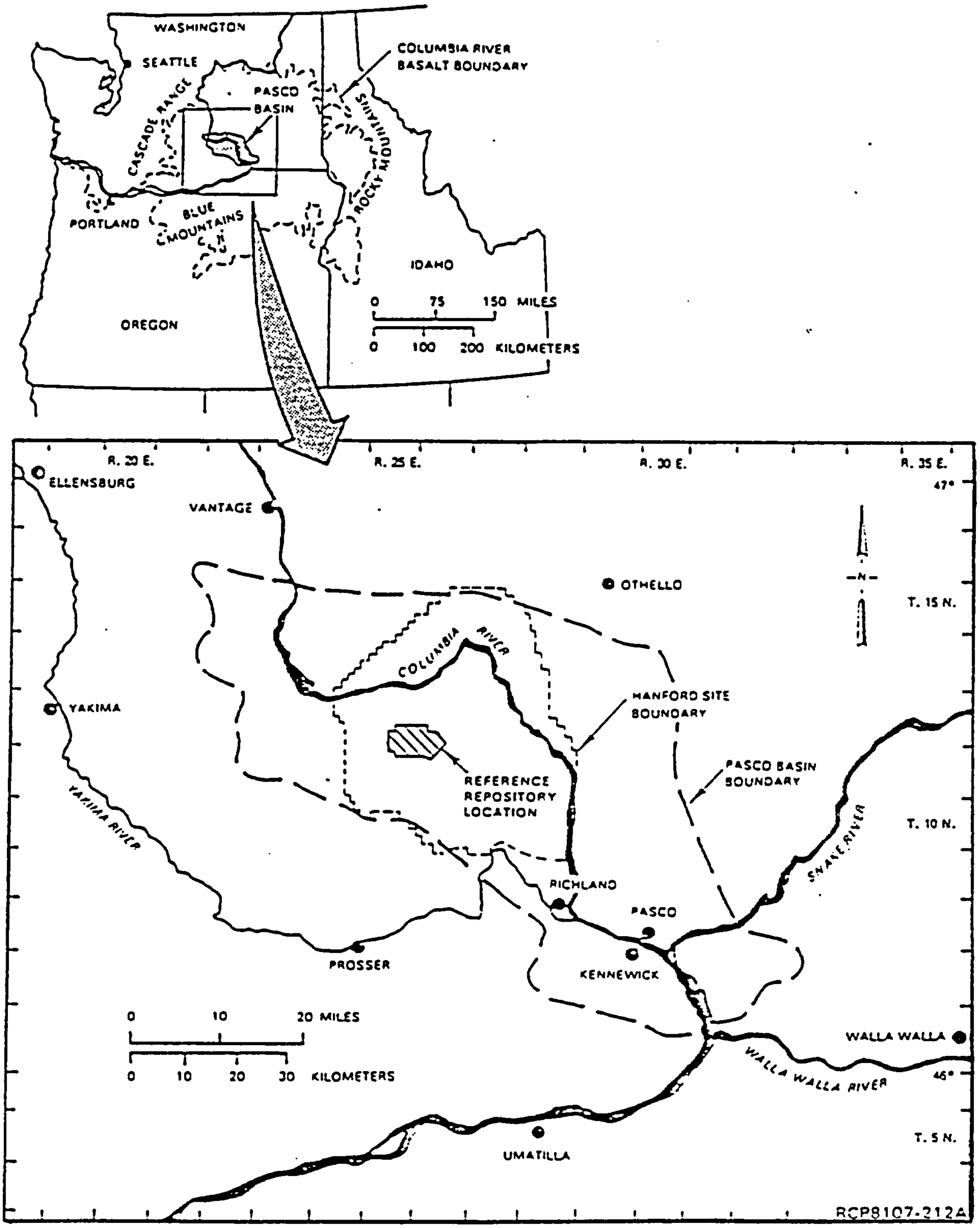

Figure 1. Map of the Reference Repository Location within the Hanford Reservation (from SD-BWI-TP-020)

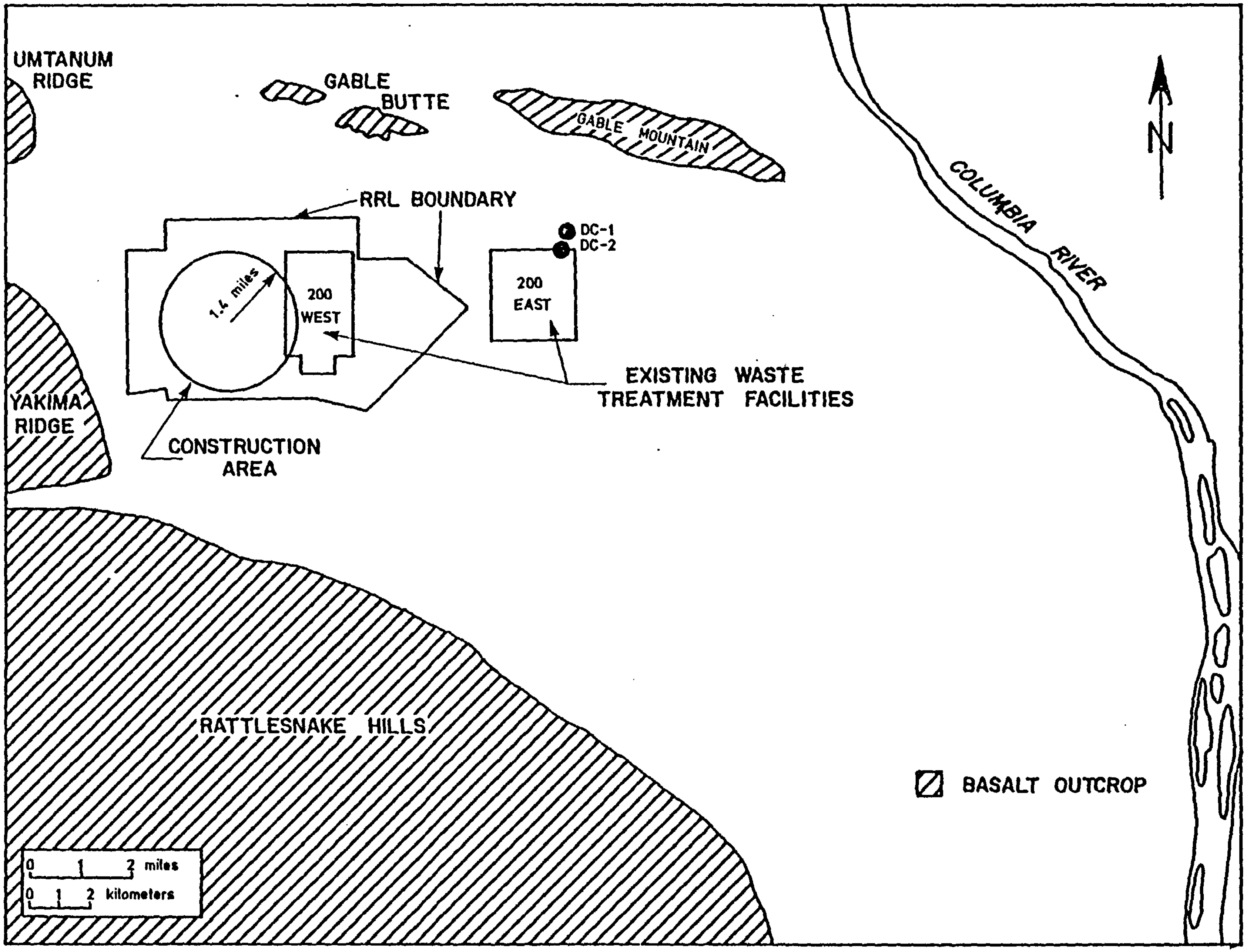

Figure 2. Location map showing location of boreholes DC-1 and DC-2 (from SD-BWI-TP-020) Hole ARH-DC-1, 1972)

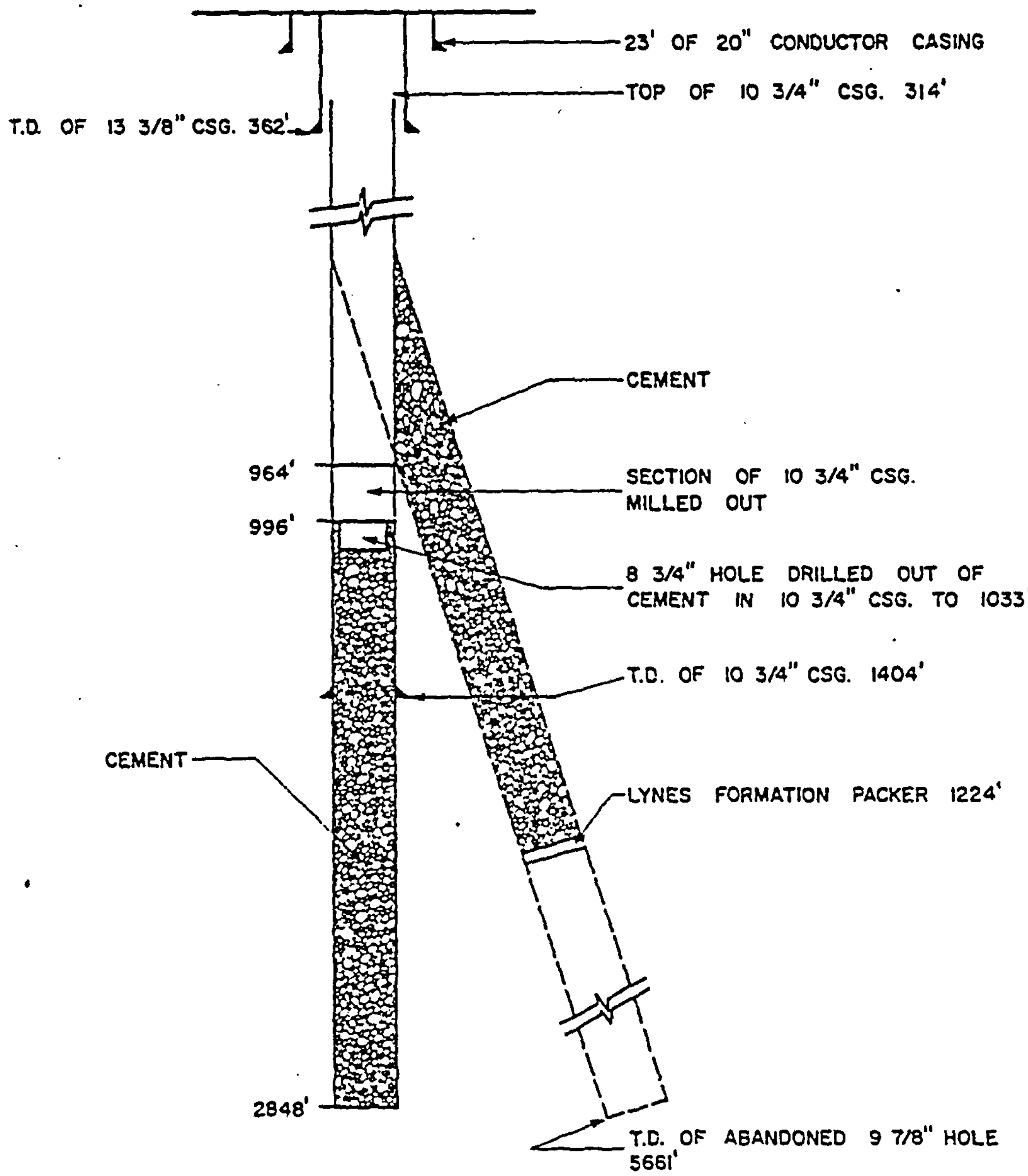

Figure 3. "As-built" drawing of DC-1 as of 10/10/69 (from Completion Report Exploration Hole ARH-DC-1, 1969)

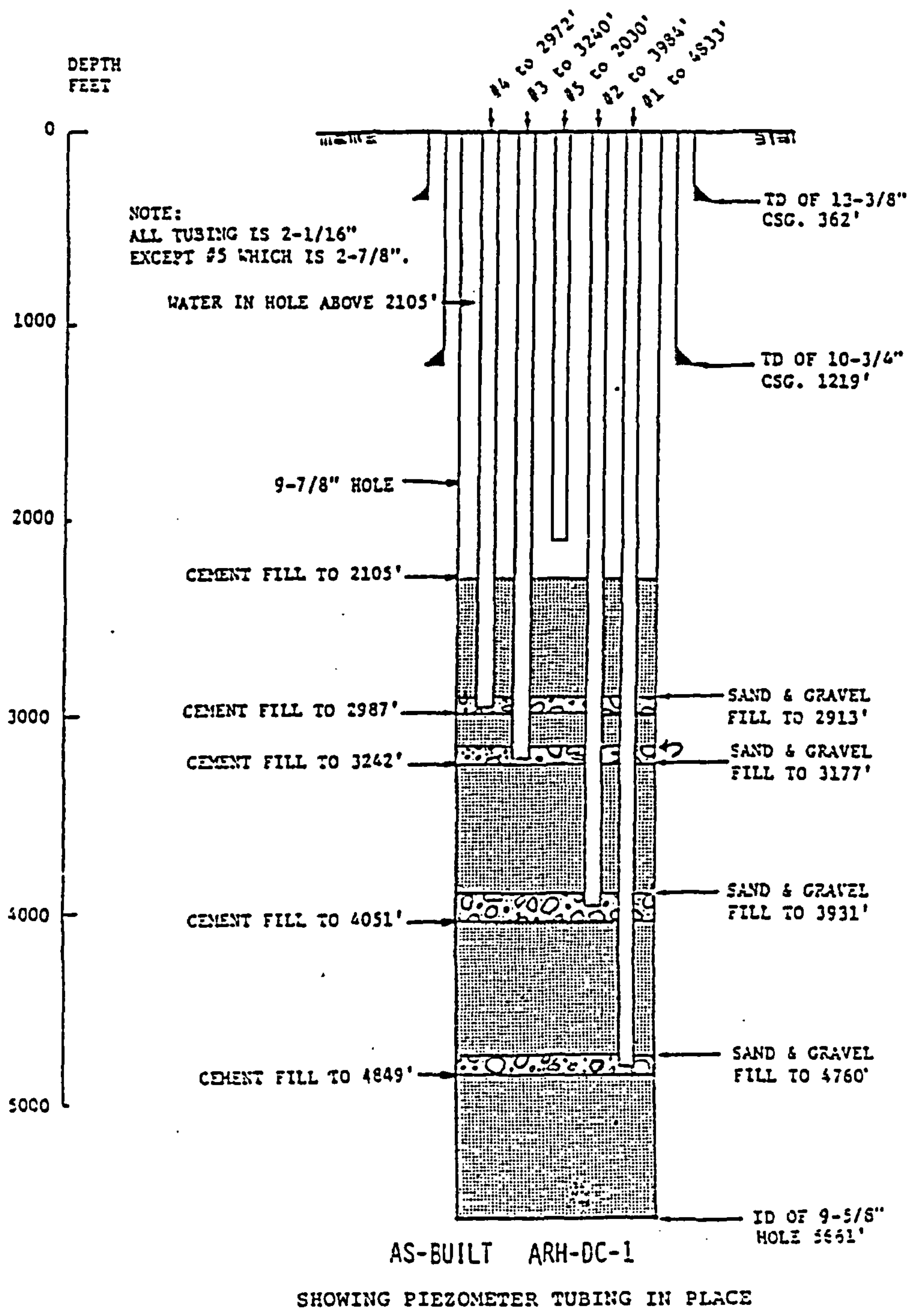

Figure 4. DC-1 "as-built" piezometer tubing details (from Recovery and Completion Report, Hole ARH-DC-1, 1972)

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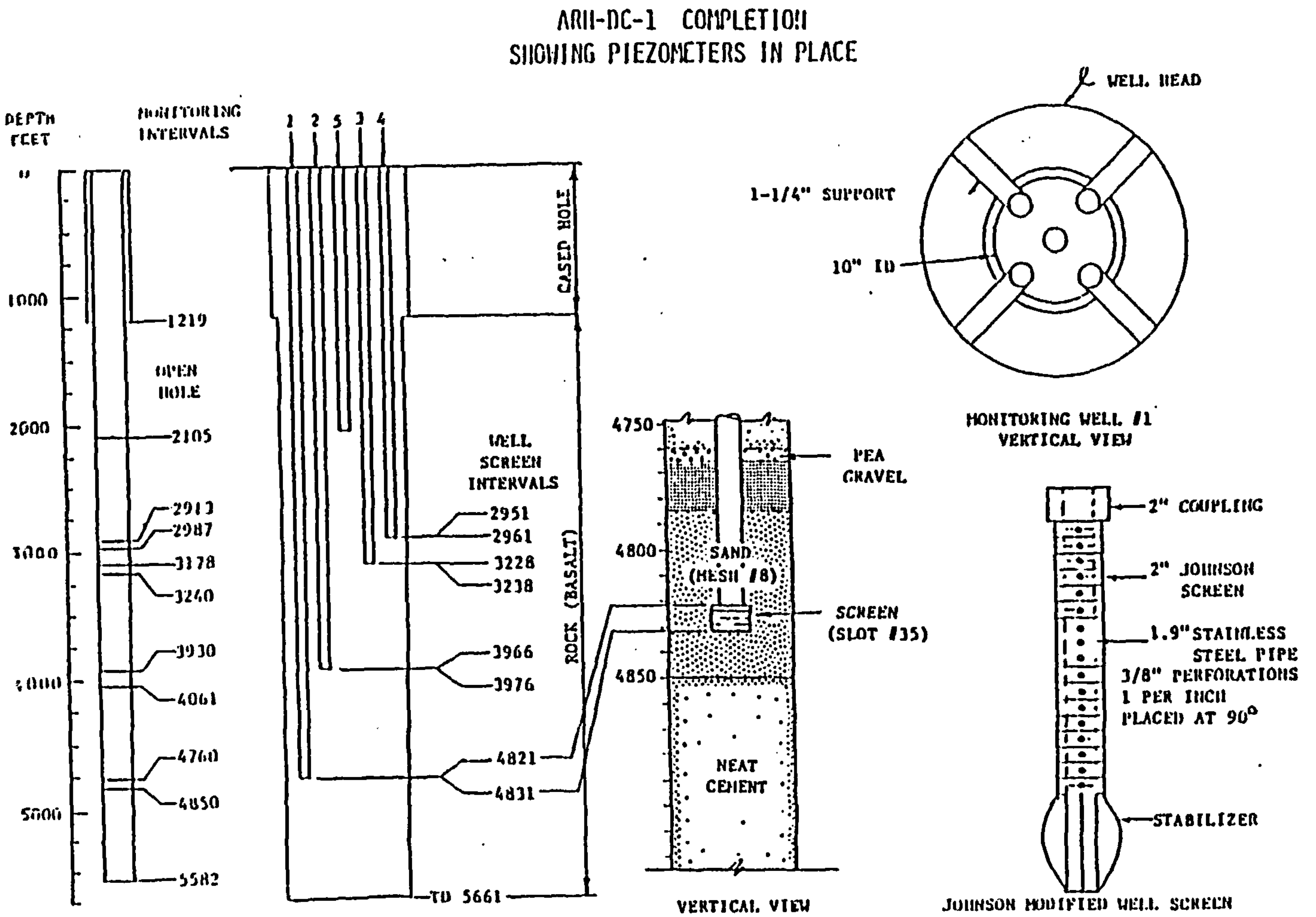

Figure 5. DC-1 "as-built" piezometer completion details (from Recovery and Completion Report, Hole ARH-DC-1, 1972)

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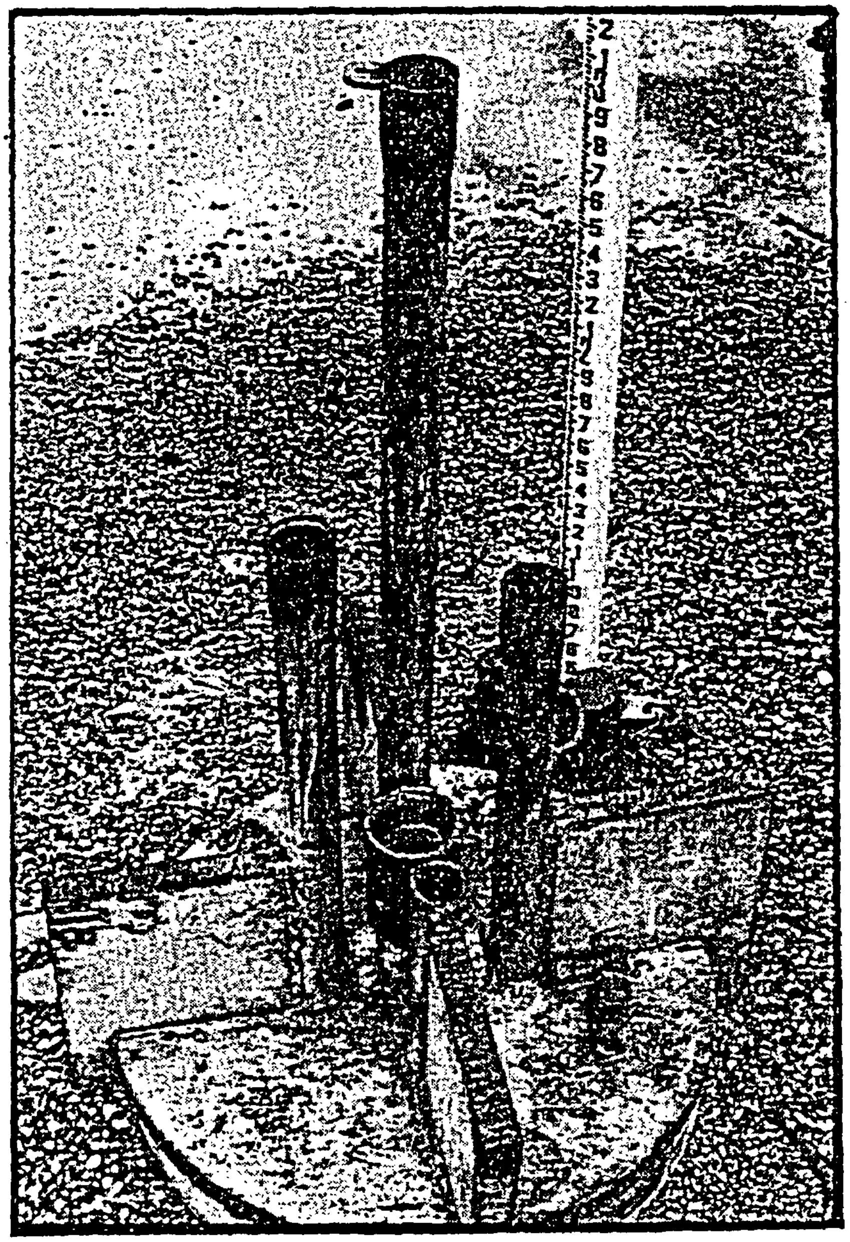

Figure 6. DC-1 surface completion photograph

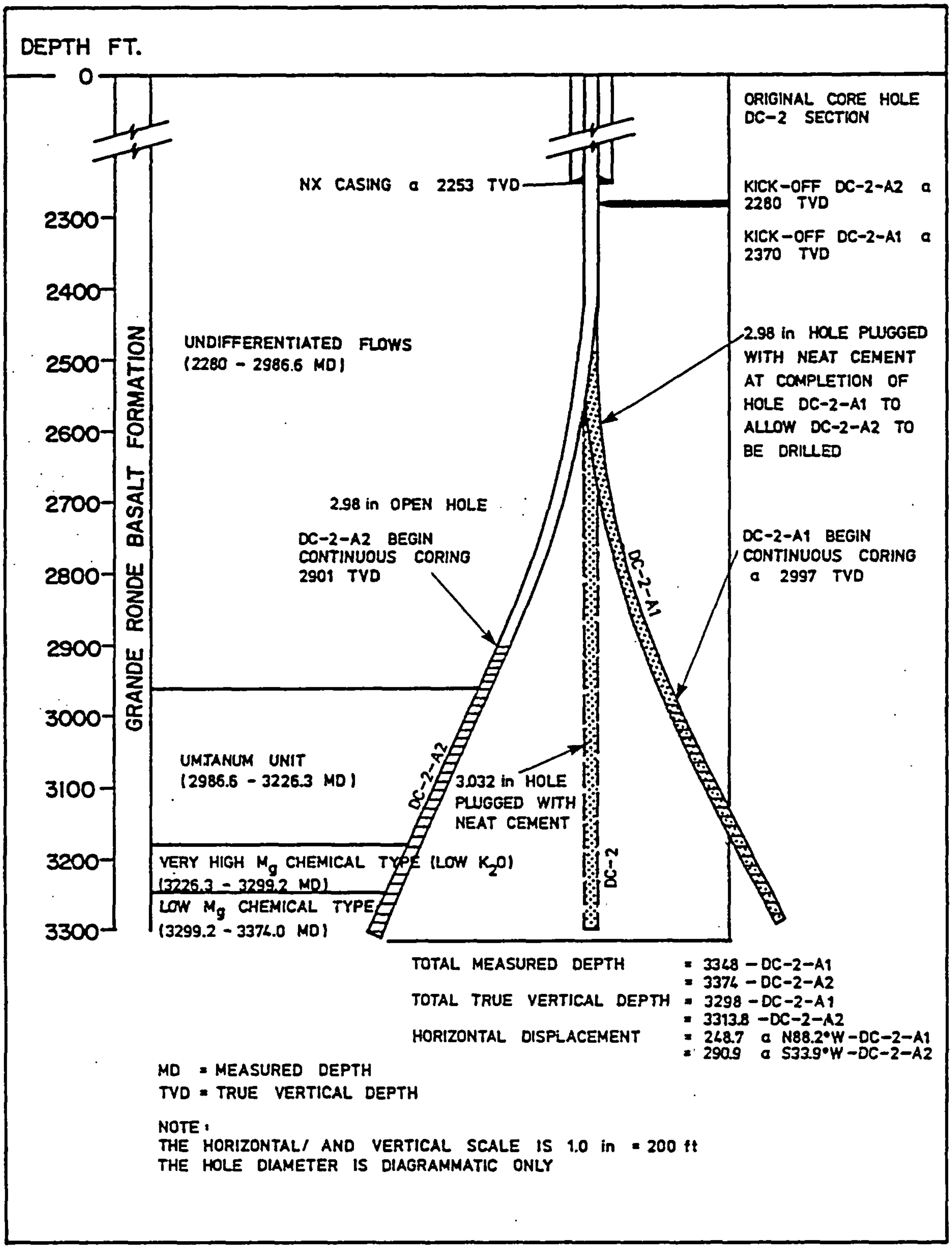

Figure 7. DC-2, DC-2-A1 and DC-2-A2 drilling, completion and "as-built" details (from RHO-BWI-C-39)

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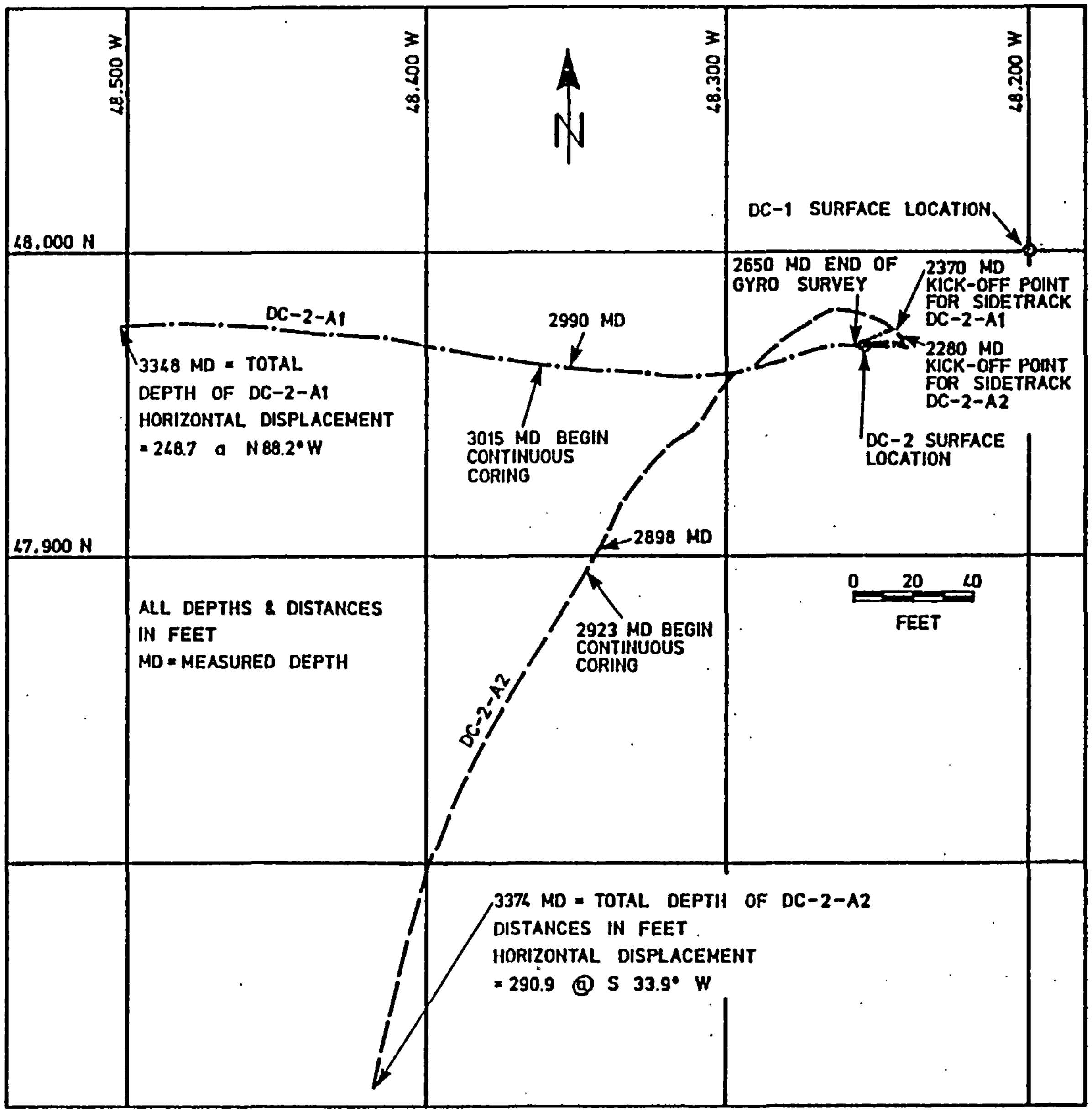

Figure 8. Plan view of surface projections of DC-2-A1 and DC-2-A2 (from RHO-BWI-C-31 and RHO-BWI-C-39)

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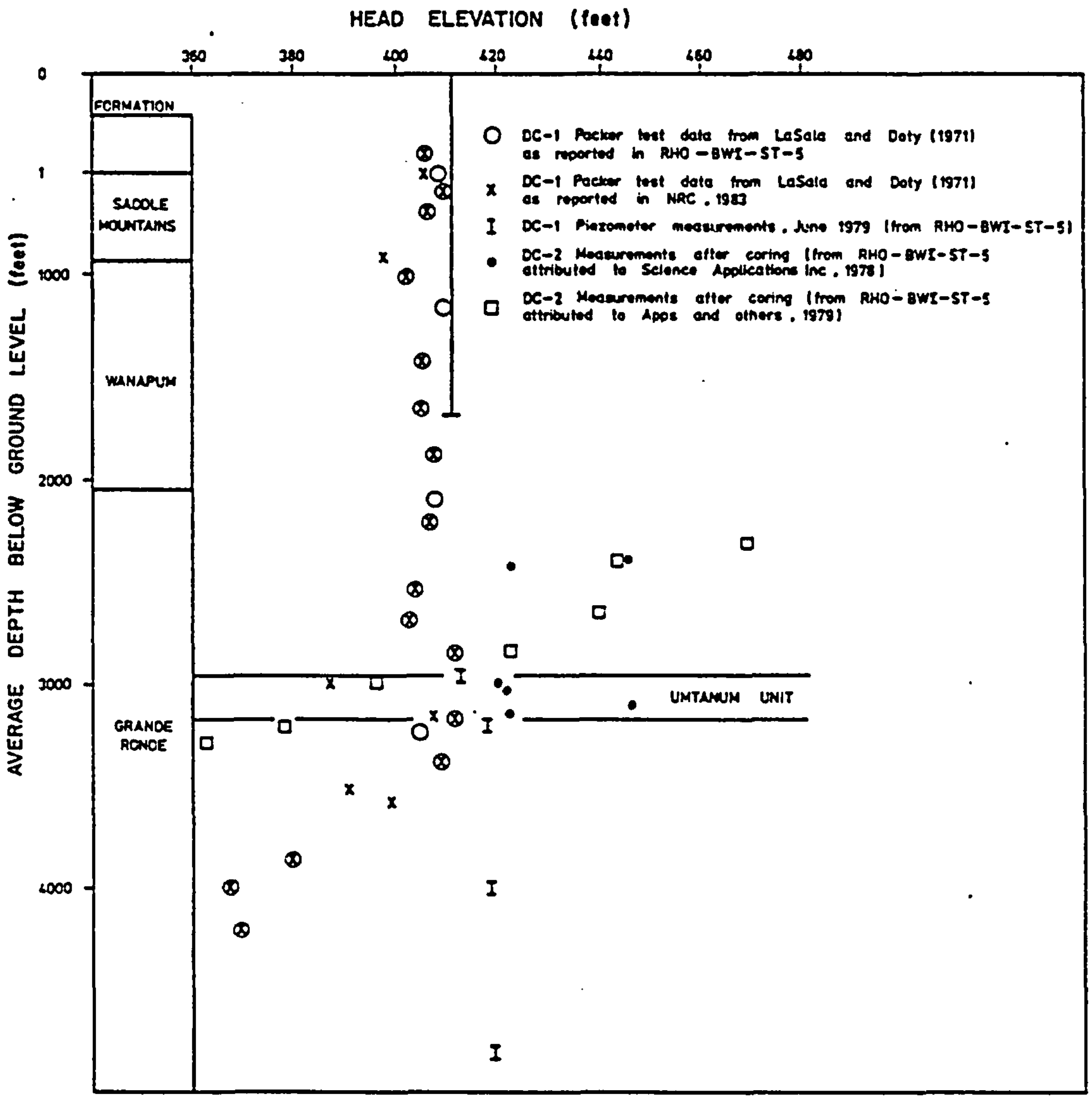
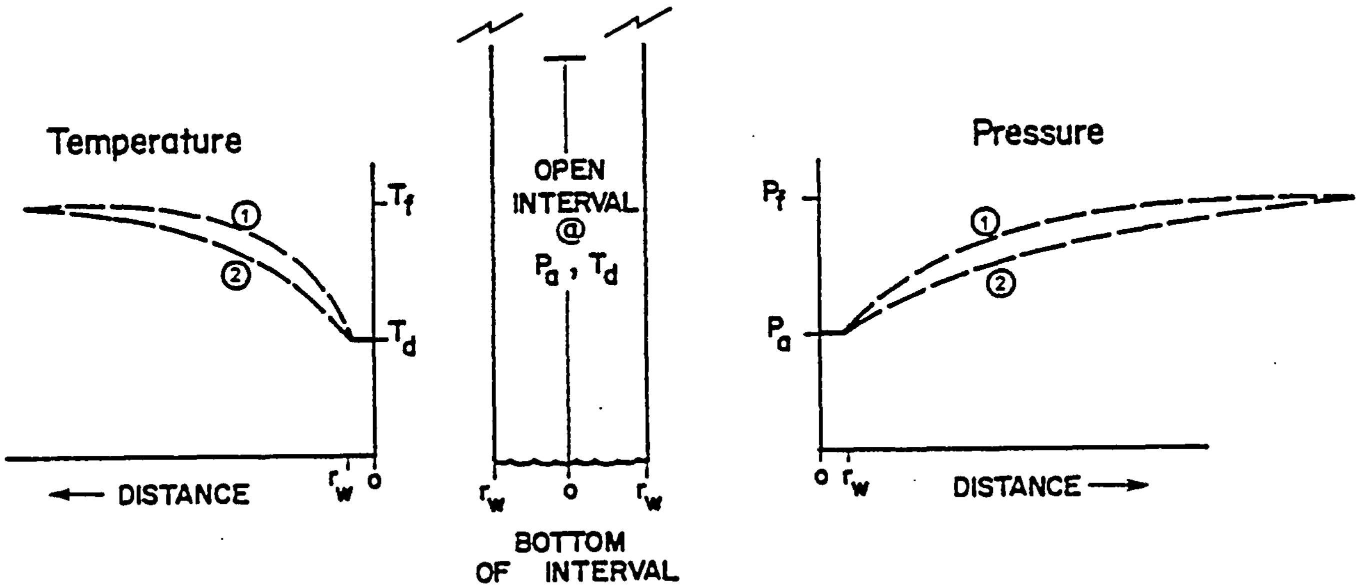


Figure 9. Hydraulic heads for boreholes DC-1 and DC-2 as reported in RHO-BWI-ST-5 and NRC, 1983 (after RHO-BWI-ST-5)



P_a	annulus pressure
P_f	formation (in-situ) pressure
T_f	formation (in-situ) temperature
T_d	drill fluid temperature
①	profile on completion of drilling
②	profile after some period of continual drilling
r_w	radius of borehole

Figure 10. Schematic pressure and temperature profiles in a recently drilled interval

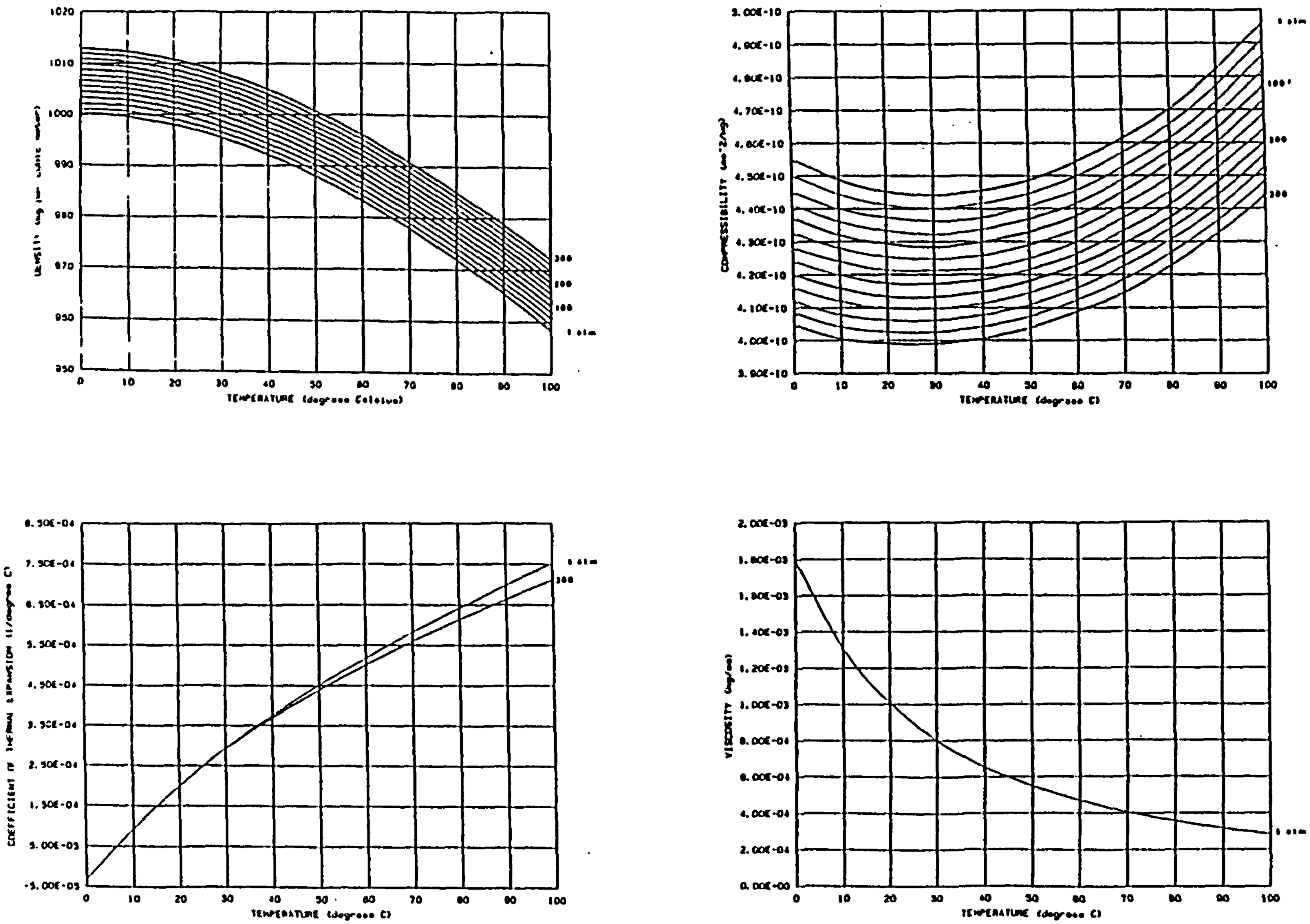


Figure 11. Fluid properties relevant to pressure measurement at depth in geologic formations

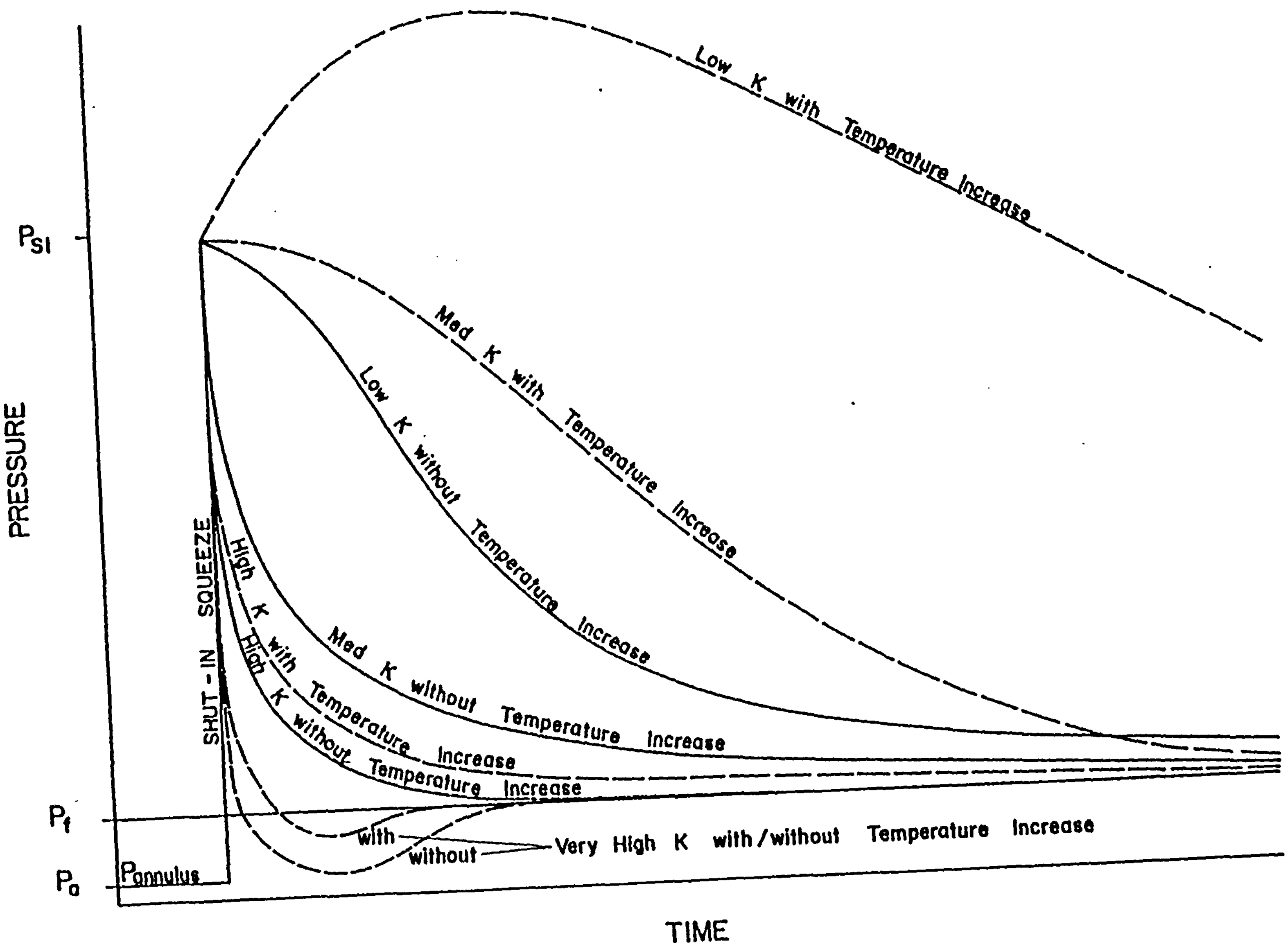


Figure 12. Schematic pressure response in a packer test with a shut-in squeeze pressure, with and without temperature increases in the shut-in interval

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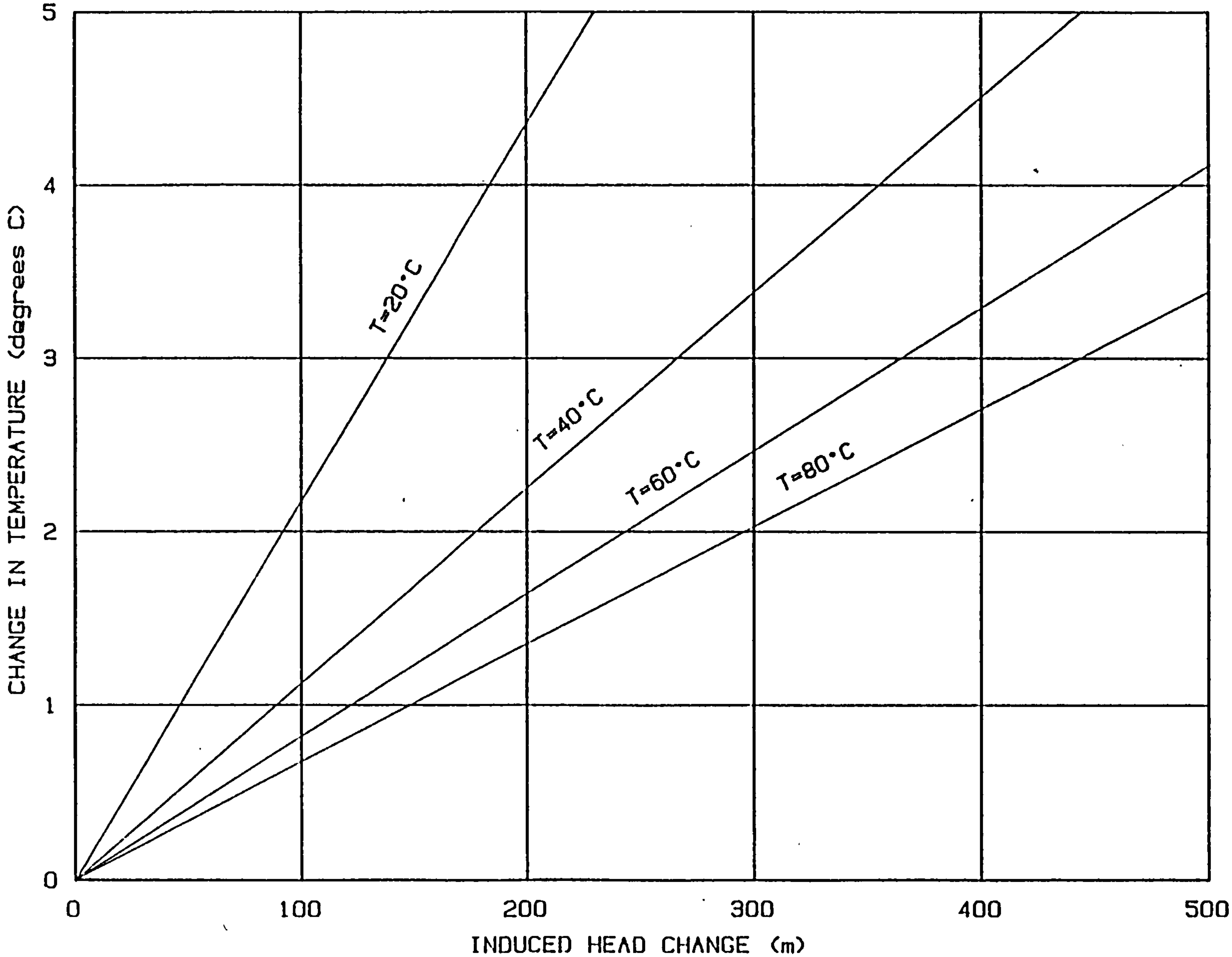

Figure 13. Induced pressure change (expressed as hydraulic head change) from a temperature change in a test interval (any length) at initial temperatures of 20, 40, 60 and 80°C (assuming no fluid loss to the rock)

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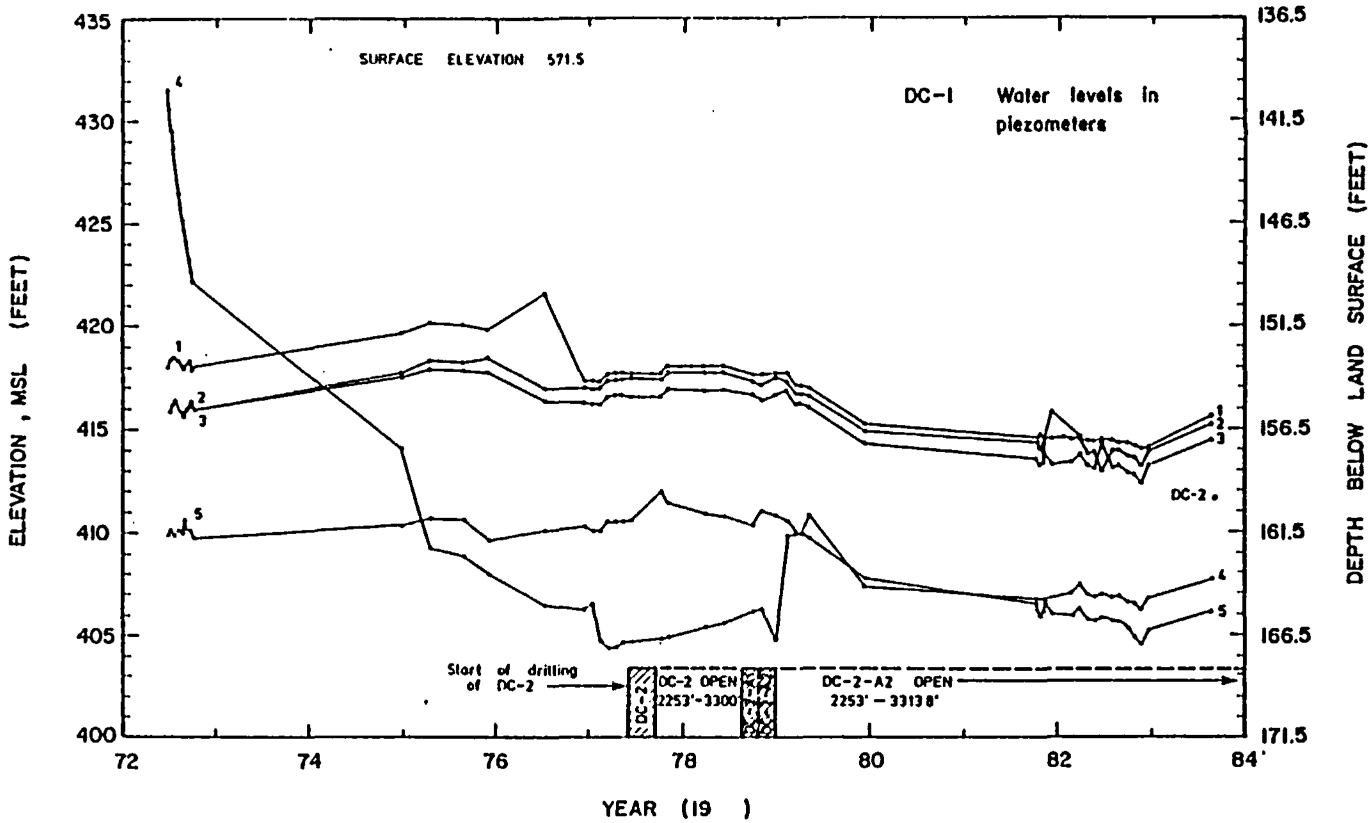
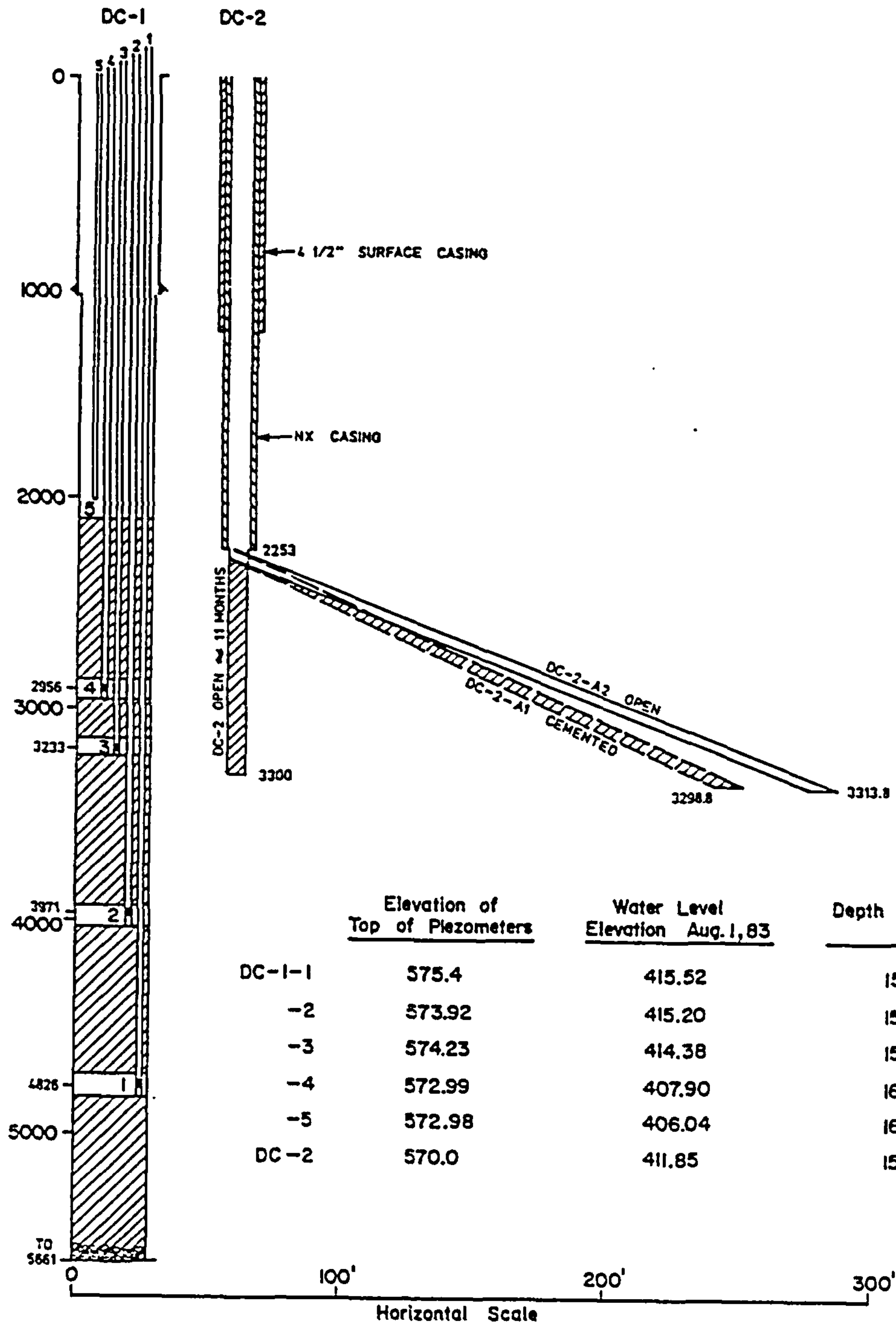


Figure 14. Water level data from DC-1 piezometers, 1972 to 1983 (from file hydrograph data)



	Elevation of Top of Piezometers	Water Level Elevation Aug. 1, 83	Depth to Water
DC-1-1	575.4	415.52	159.88
-2	573.92	415.20	158.72
-3	574.23	414.38	159.85
-4	572.99	407.90	165.05
-5	572.98	406.04	166.94
DC-2	570.0	411.85	158.15

Figure 15. Relative elevations and distances of DC-1 piezometers and DC-2 boreholes

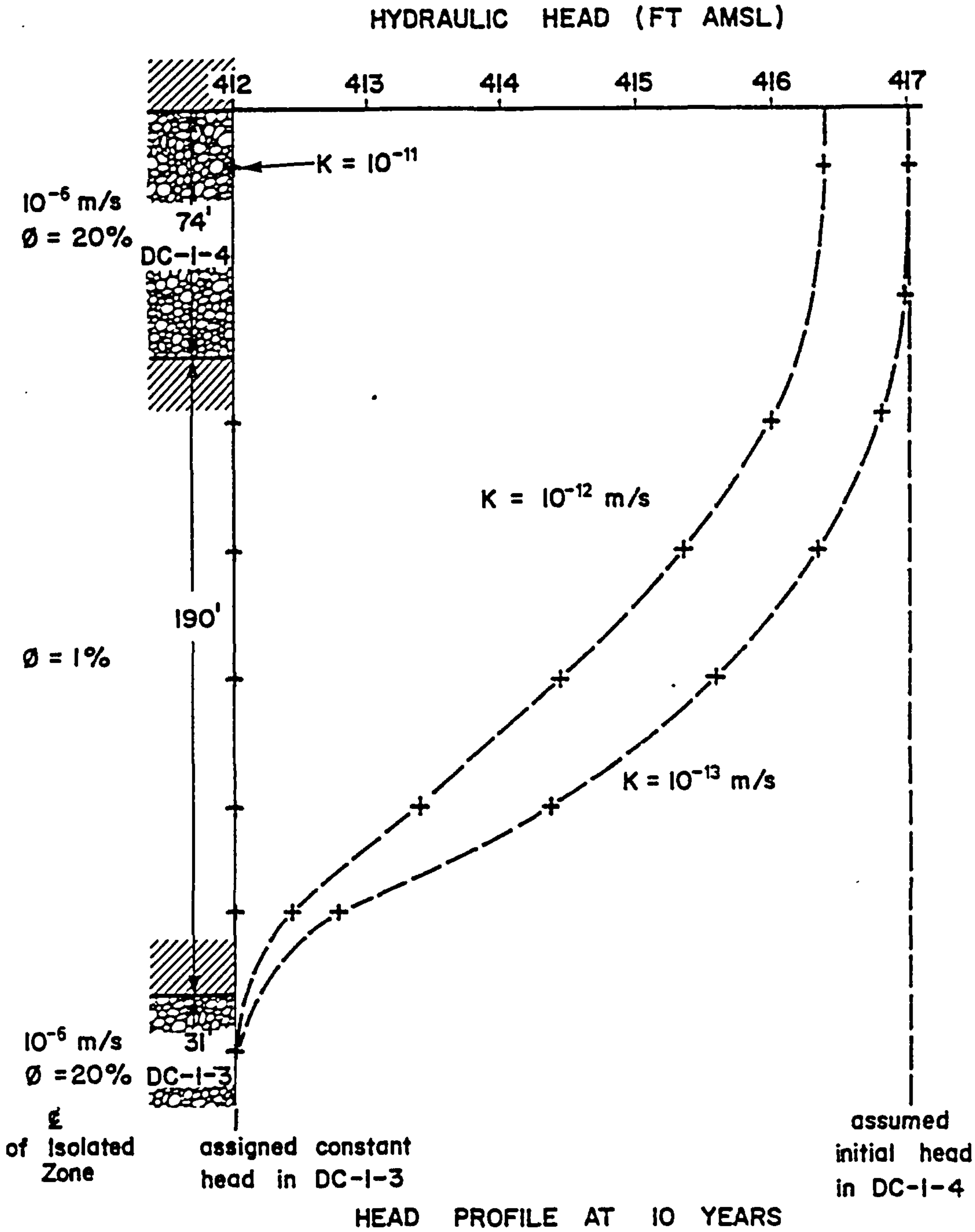


Figure 16. Results of one-dimensional numerical model calculations showing the effect of the permeability of the cement in isolating piezometers DC-1-3 and DC-1-4. DC-1-3 is considered to be connected to a relatively permeable, constant head (412 fasl) formation and the hydraulic head profile is plotted after 10 years

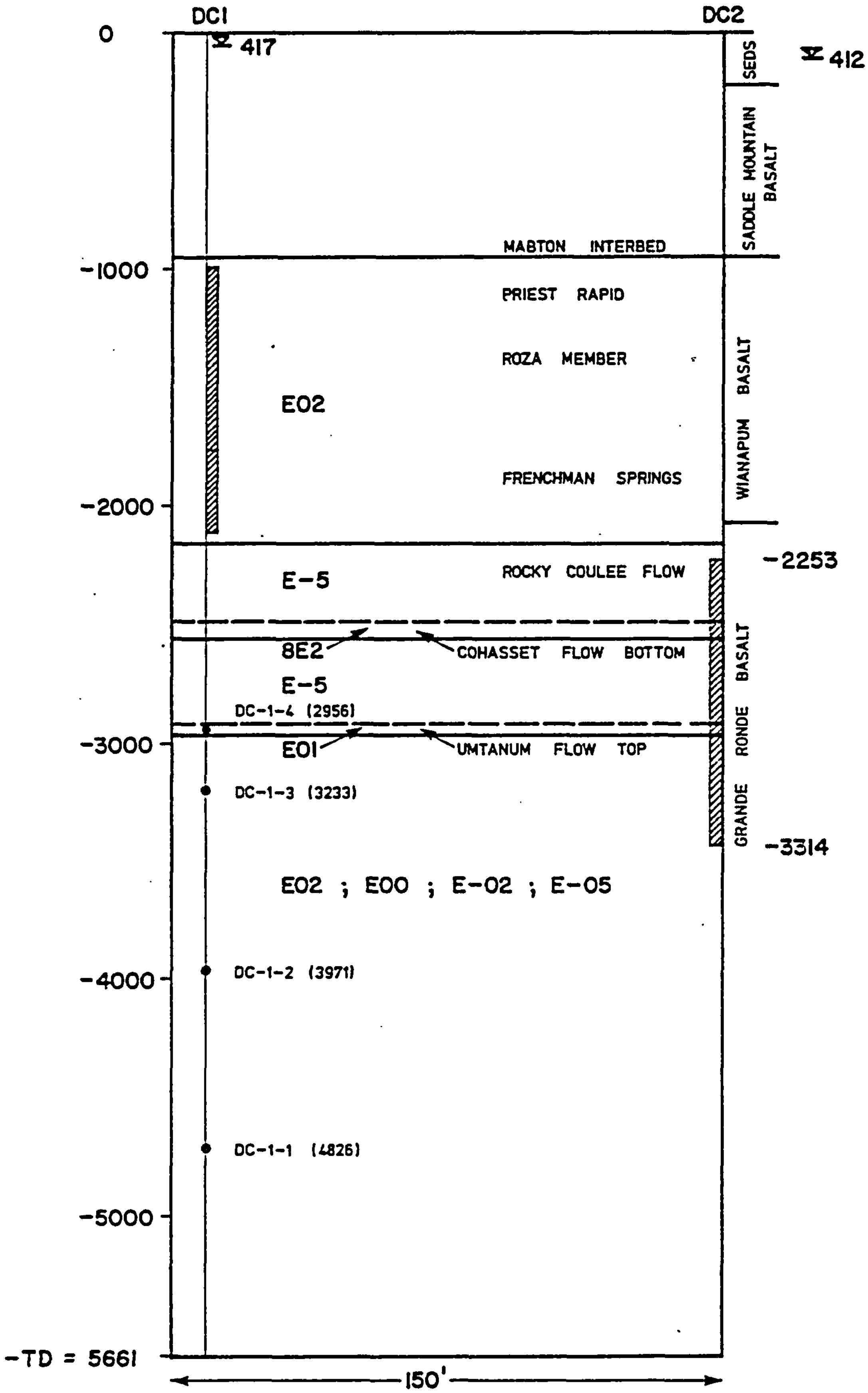


Figure 17. Hydrostratigraphic system modeled to evaluate the hydraulic interference between DC-2-A2 open hole and DC-1 piezometers. Transmissivities are in ft^2/day

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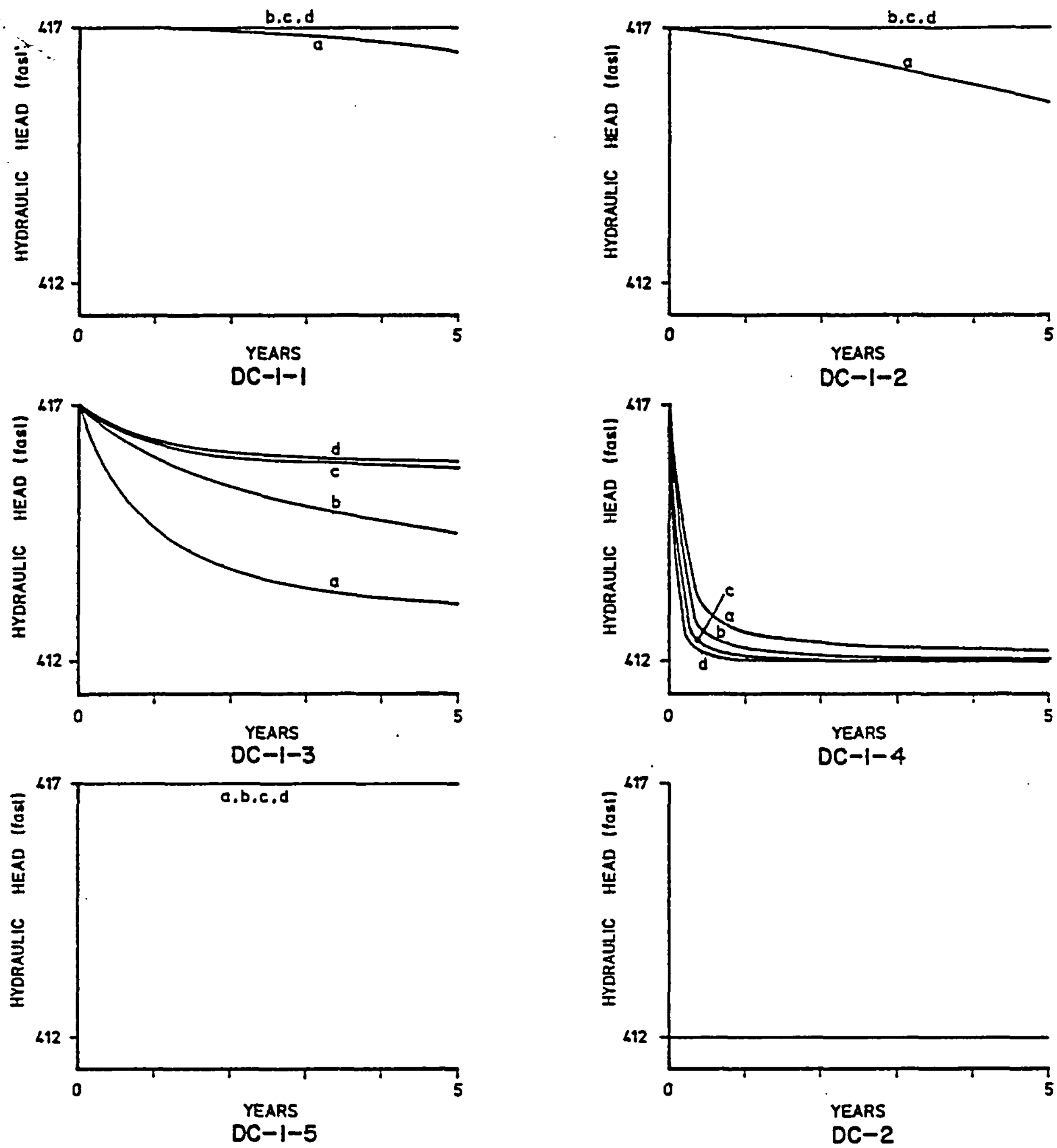

LEGEND

	G.R. TRANSMISSIVITY	KH : KV
a	E-02	1 : 1
b	E-02	10 : 1
c	E-02	100 : 1
d	E-02	1000 : 1

Figure 18. DC-1 piezometer responses to DC-2-A2 calculated by numerically modeling the two-dimensional system depicted in Figure 17 and varying the Kh:Kv ratio (G.R. = GRANDE RONDE formation)

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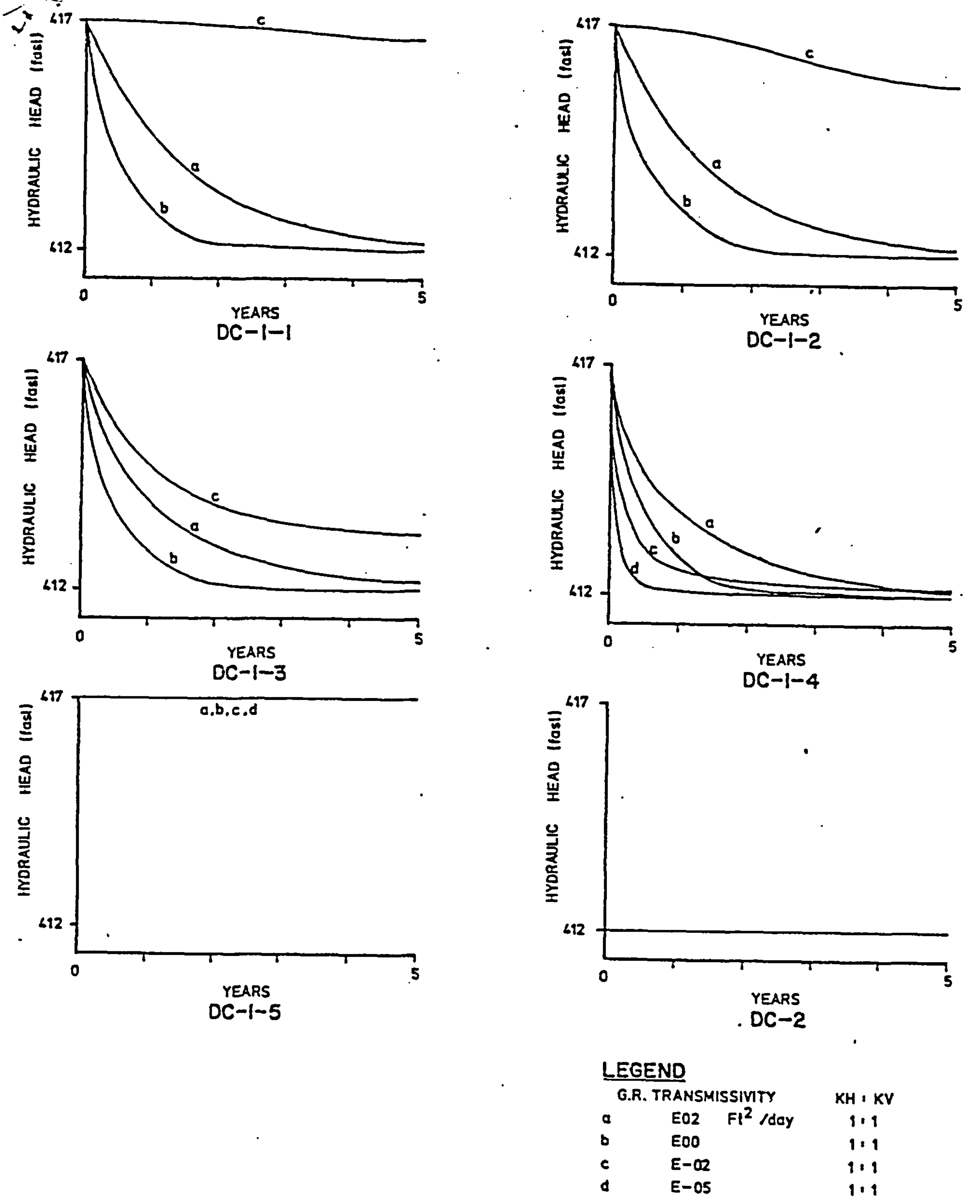

Figure 19. DC-1 piezometer responses to DC-2-A2 calculated by numerically modeling the two-dimensional system depicted in Figure 17, holding Kh:Kv at 1 and vary the transmissivity of the Grande Ronde (G.R) formation

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