Research Technical Completion Report

STRADDLE-PACKER AQUIFER TEST ANALYSES OF THE SNAKE RIVER PLAIN AQUIFER AT THE IDAHO NATIONAL ENGINEERING LABORATORY

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ABSTRACT

The State of Idaho INEL Oversight Program, with the University of Idaho, Idaho State University, Boise State University, and the Idaho Geologic Survey, used a straddle-packer system to investigate vertical variations in characteristics of the Snake River Plain aquifer at the Idaho National Engineering Laboratory in southeast Idaho.

Sixteen single-well aquifer tests were conducted on isolated intervals in three observation wells. Each of these wells has approximately 200 feet of open borehole below the water table, penetrating the E through G and I basalt flow groups and interbedded sediments of the Snake River Plain aquifer. The success of the aquifer tests was limited by the inability to induce measurable drawdown in several zones. Time-drawdown data from aquifer tests were matched to type curves for 8 of the 16 zones tested.

A single aquifer test at the water table exhibited greater curvature than those at depth. The increased degree of curvature suggests an unconfined response and resulted in an estimate of specific yield of 0.03.

Aquifer tests below the water table generally yielded time-drawdown graphs with a rapid initial response followed by constant drawdown throughout the duration of the tests; up to several hours in length. The rapid initial response implies that the aquifer responds as a confined system during brief pumping periods. The nearly constant drawdown suggests a secondary source of water, probably vertical flow from overlying and underlying aquifer layers.

Three analytical models were applied for comparison to the conceptual model and to provide estimates of aquifer properties. Theis, Hantush-Jacob leaky aquifer, and the Moench double-porosity fractured rock models were fit to time-drawdown data. The leaky aquifer type curves of Hantush and Jacob (1955) generally provided the best match to observed drawdown. A specific capacity regression equation was also used to estimate hydraulic conductivity.

Estimated values of horizontal hydraulic conductivity of tested intervals ranged from $1.5\text{x}10^{-5}$ to 18 ft/min depending upon the interval and analytical technique employed. Hydraulic conductivity estimates resulting from the different analytical techniques varied by less than one order of magnitude for a given interval. In general, hydraulic conductivity estimates by the Theis method were largest, followed by Moench double porosity estimates. The Hantush and Jacob method with the maximum expected leakage factor (r/B=0.3), generally yielded the smallest values of hydraulic conductivity. Conceptually, the leaky model

is probably most consistent with test conditions, but vertical leakage rates are not well constrained.

The large variation in estimated hydraulic conductivity among the tested intervals, more than four orders of magnitude, demonstrates the extreme vertical heterogeneity of the fractured basalts and interbedded sediments of the Snake River Plain aquifer. Lateral hydraulic conductivities estimated from the single-well aquifer tests have a high degree of variability and are less than values estimated from the two-well tests. The two-well tests are more representative of large-scale properties than the single-well tests, which are probably influenced by local heterogeneities.

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CHAPTER 1:
INTRODUCTION

Background

The Idaho National Engineering Laboratory (INEL) is located in southeast Idaho and is operated by the U.S. Department of Energy (DOE). The INEL encompasses 890 square miles of the Snake River Plain about 40 miles west of Idaho Falls (Figure 1). Since it was established in 1949 as the National Reactor Testing Station, 52 nuclear reactors have been constructed and tested at the INEL.

There are several major facilities at the INEL which have served a range of uses associated with DOE operations, including nuclear-reactor research, waste disposal, and reprocessing of spent nuclear fuel. One of these facilities, the Idaho Chemical Processing Plant (ICPP), was constructed in the early 1950s to recover fissionable materials from spent nuclear fuel (Figure 2). Reprocessing of nuclear fuel began at the ICPP in 1952, and continued intermittently until 1994.

From 1953 to 1984, low-level radioactive, chemical, and sanitary waste water from the ICPP was discharged directly to the Snake River Plain aquifer (SRPA) via an injection well (CPP-03). At present, process waste water is discharged to two unlined infiltration ponds located south of the ICPP, and sewage effluent is routed to a infiltration pond east of the facility.

Disposal of waste water at the ICPP has resulted in the formation of contaminant plumes which extend several miles downgradient (Barraclough and Jensen, 1976; Barraclough and others, 1982; Mann and Cecil, 1990). Contaminants detected in the aquifer include tritium, strontium-90, iodine-129, nitrate, and chloride.

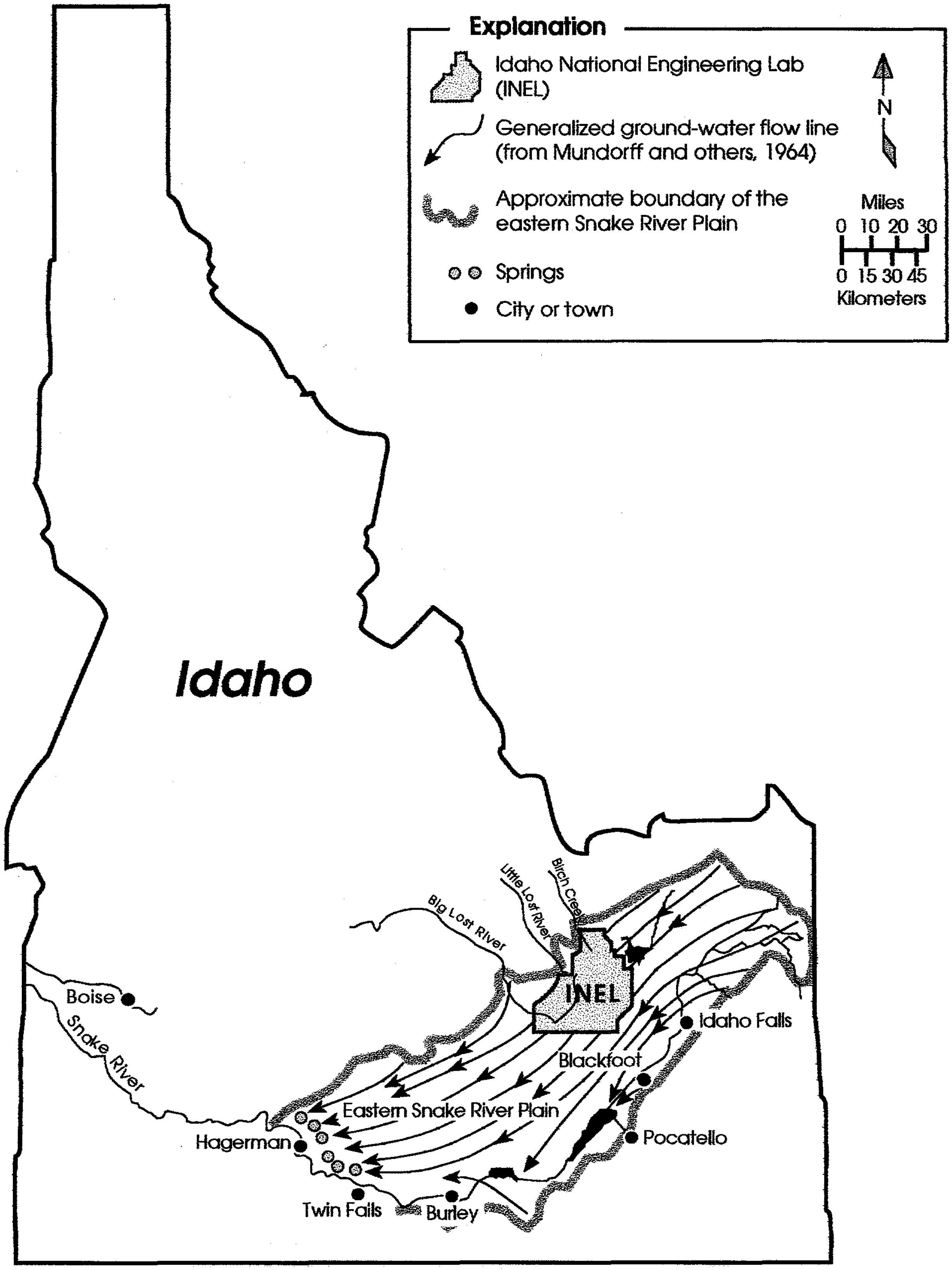


Figure 1. Map of Idaho showing the locations of the INEL, eastern Snake River Plain, and generalized ground-water flow lines of the Snake River Plain aquifer.

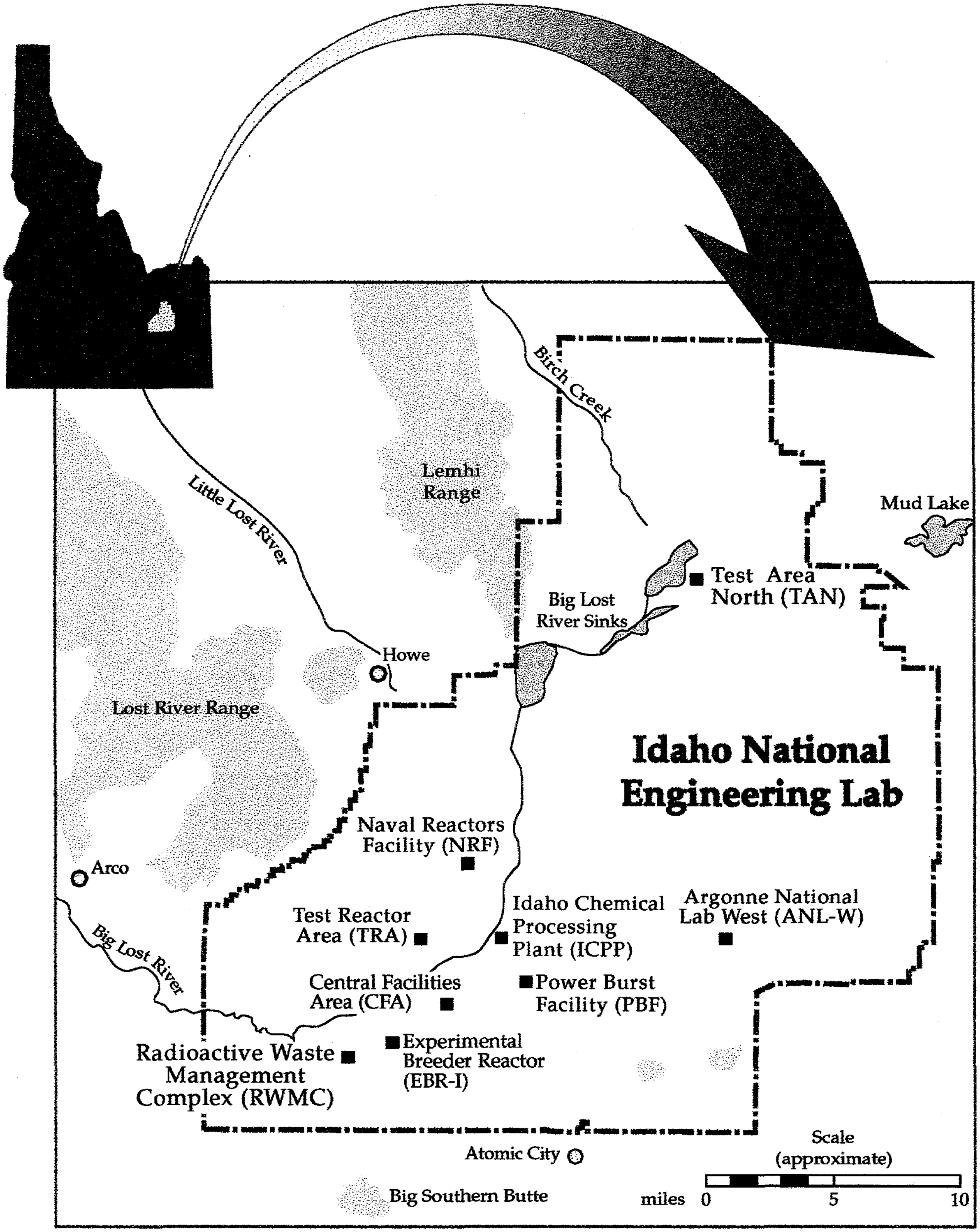


Figure 2. Location of the Idaho Chemical Processing Plant at the Idaho National Engineering Laboratory.

In 1989, the INEL Oversight Program was established by the legislature of the State of Idaho to provide an unbiased and independent source of information on the INEL's impact on the environment. In an effort to characterize the three-dimensional nature of the ICPP contaminant plumes, the INEL Oversight Program, in cooperation with the University of Idaho, Idaho State University, Boise State University, and the Idaho Geological Survey, conducted a series of straddle-packer tests in four observation wells (USGS-44, USGS-45, USGS-46, and USGS-59) located west and south of the ICPP (Figure 3). These wells were installed by the U.S. Geological Survey in the 1950s and 1960s to monitor the water quality of the aquifer.

A straddle-packer system was used to isolate specific intervals of the Snake River Plain aquifer and monitor water quality, vertical gradients, and the aquifer response to an applied hydraulic stress. Three types of aquifer tests were performed with the straddle-packer system:

1) **Single-well tests.** Water was pumped from a specific interval of the aquifer using a pump located between two packers.
2) **Slug tests.** The riser pipe on the straddle-packer system was filled with water, which was instantaneously released into the interval of the aquifer between the two packers.
3) **Multiple-well tests.** The straddle-packer system was used in observation wells to measure the response of specific zones in the aquifer to pumping of the ICPP production wells.

This report discusses the results and interpretation of the single well tests.

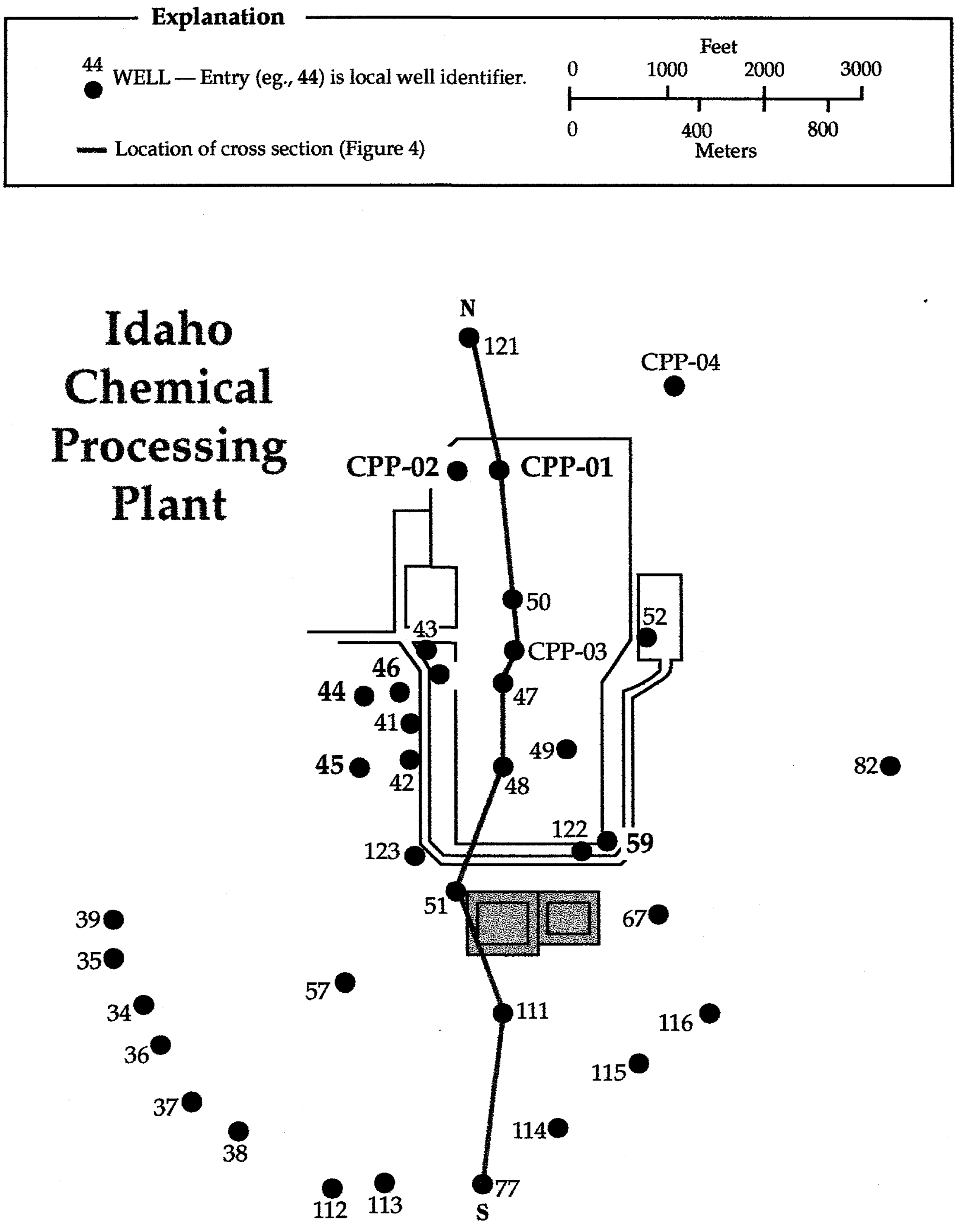


Figure 3. Locations of selected observation wells at the Idaho Chemical Processing Plant.

Geology

The INEL is located in the central part of the eastern Snake River Plain, a large northeast-trending basin covering approximately 12,000 square miles (Figure 1). The basin has been filled by several thousand feet of Tertiary and Quaternary basalt and sediment. A more detailed discussion of the geology and geologic history of the Snake River Plain can be found in Robertson and others (1974), Bonnichsen and Breckenridge (1984), Hackett and others (1986), Whitehead (1986), and Lindholm (1993).

Anderson (1991) studied the stratigraphy of the vadose zone and upper portion of the Snake River Plain aquifer in the vicinity of the ICPP using geophysical logs coupled with paleomagnetic data and radiometric-age determinations from the basalt. Twenty three basalt-flow groups were identified and categorized into seven stratigraphic units based on source and age relations. Composite stratigraphic units generally consist of multiple basalt flows and sedimentary interbeds (Figure 4). The location of the cross section in Figure 4 is shown on Figure 3.

The USGS wells tested by the INEL Oversight Program were ideally suited for performing packer testing in the Snake River Plain aquifer because they were drilled to a depth of about 650 feet below land surface (bls) and are open to the aquifer over an interval of approximately 200 feet. The wells, which were cased throughout the vadose zone, are completed in Flow Groups E-G and Flow Group I, as identified by Anderson (1991) and shown in Figure 4. The flow units dip to the southeast. Individual flows in Flow Groups E-G are 10-26 feet thick in wells USGS-44, -45, -46, and -59 (Steve Anderson, 1995, personal communication). The two basalt flows in Flow Group I which were identified in these wells are typically thicker, ranging from 19 ft to >90 ft. A

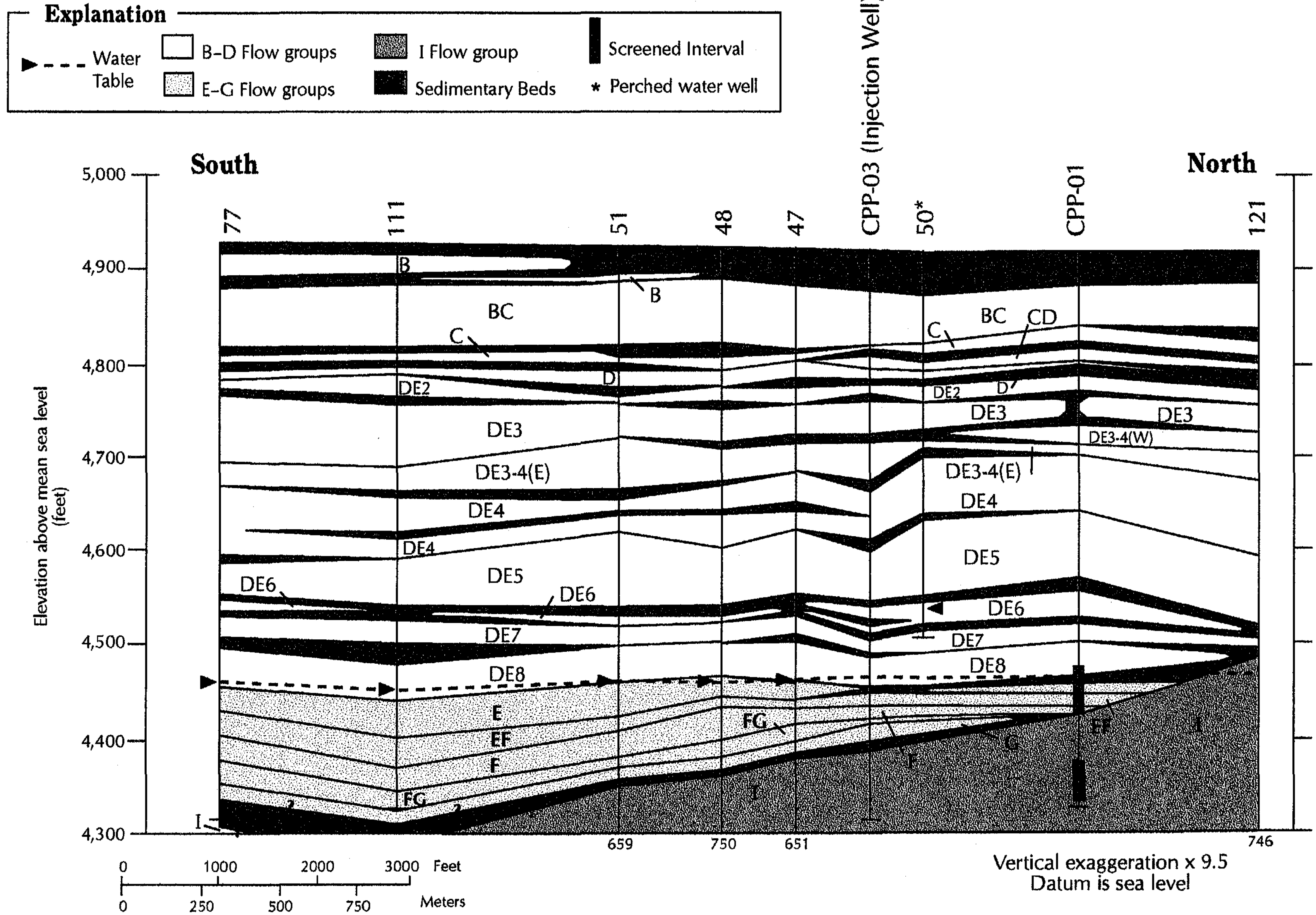


Figure 4. Geologic cross section at the Idaho Chemical Processing Plant (after Anderson, 1991). See figure 3 for location of cross section.

sedimentary interbed, four to nine feet thick, is present at the top of Flow Group I in USGS-45, -46, and -59.

Hydrogeology

The Snake River Plain aquifer is present beneath nearly all of the eastern Snake River Plain. The aquifer primarily consists of a layered sequence of basaltic lava flows intercalated with sedimentary interbeds. Recharge to the aquifer is primarily from irrigation, underflow from basins north and northwest of the INEL, and precipitation on the plain. The primary discharge areas for the aquifer is the Thousand Springs region near Hagerman (Figure 1), and springs near American Falls Reservoir. At the INEL, depth from land surface to the aquifer ranges from about 200 feet at the north end of the INEL to more than 600 feet at the south end.

Considerable debate exists over the thickness of the Snake River Plain aquifer. Robertson (1974) states that "Although the real aquifer system is probably more than 1,000 feet (300 meters) thick, a thickness of 250 feet (76 meters) is used in this study based on apparent layering effects in the aquifer." Based on the presence of low permeability sedimentary layers encountered in a well drilled approximately three miles north of the ICPP, Mann (1986) suggested that the Snake River Plain aquifer is 450-800 feet thick. Modeling studies performed by the U.S. Geological Survey represented the eastern Snake River Plain aquifer as a four-layer system, with the total thickness of the aquifer at the INEL ranging from 500 ft to over 3000 ft in thickness (Garabedian, 1989).

Most, if not all, of the aquifer tests at the INEL have been conducted in partially penetrating wells in an aquifer of unknown thickness. The thickness of the tested interval is a function of the construction characteristics of a given pumping well. Estimates of transmissivity from these tests do not represent the entire thickness of the aquifer.

Transmissivity estimates for the Snake River Plain aquifer range over several orders of magnitude. Walton (1958) analyzed aquifer test data for nineteen wells at the INEL, and determined that the transmissivity of the aquifer ranged from 2.8 to 1670 ft^2/min. Ackerman (1991) evaluated aquifer-test data from 94 wells at the INEL, and reported transmissivity estimates of the Snake River Plain aquifer ranging from 0.0008 to 530 ft^2/min. Table 1 summarizes the transmissivity determined for the ICPP production wells.

Table 1. Transmissivity estimates for the Snake River Plain aquifer determined from aquifer tests of the ICPP production wells (Ackerman, 1991).

Well	Transmissivity (ft^2/min)
CPP-01	51
CPP-02	111

Wylie and others (1994) estimated the transmissivity of the aquifer to be about 695 ft^2/min based on a multiple-well aquifer test conducted near the Radioactive Waste Management Complex (RWMC). Haskett and Hampton (1979) and Mundorff and others (1964) reported transmissivity values of 14 to 3472 ft^2/min from aquifer tests in the eastern Snake River Plain aquifer.

Previous studies have evaluated the Snake River Plain aquifer as a water-table aquifer (Garabedian, 1989; Wylie and others, 1994). Estimates of specific yield from aquifer tests in the eastern Snake River Plain aquifer range from 0.01 to 0.22 (Haskett and Hampton, 1979; Mundorff and others, 1964).

Purpose and Objectives

Straddle-packer testing of the Snake River Plain aquifer was conducted with the overall purpose of improving the level of understanding of variations in aquifer characteristics in the vertical dimension. This improved understanding will subsequently lead to improved qualitative and quantitative models of contaminant movement in the aquifer.

Aquifer tests on straddle-packer isolated intervals were performed to assess local variability of hydraulic conductivity in the aquifer profile. In contrast, the parallel analysis of two-well tests, utilizing the ICPP production wells as pumping wells, provided a larger-scale perspective of the system (Frederick and Johnson, 1996). The objectives of the aquifer test analysis included:

1) Evaluation of aquifer response to pumping to assess validity of alternative conceptual models.
2) Estimation of local aquifer properties in 15 to 20 foot intervals in each of the four tested wells.
3) Comparison of hydraulic conductivity estimates from single-well aquifer tests to the larger-scale estimates from the two-well ICPP aquifer tests.
4) Relating test results to aquifer conceptual models.

CHAPTER 2:
METHODOLOGY

The State of Idaho, INEL Oversight Program began work on vertical characterization of the Snake River Plain aquifer in 1991. The project, "Hydrologic Investigations of Boreholes Open Over Large Intervals" was funded by the DOE and involved researchers from the University of Idaho, Idaho State University, Boise State University, Idaho Geologic Survey, and the U.S. Geologic Survey. In 1992, a straddle-packer system was purchased from Baski Water Instruments, Inc. of Denver, Colorado for the study. The straddle-packer system was used to estimate hydraulic properties of discrete aquifer intervals and collect ground-water samples.

The straddle-packer assembly is shown in Figure 5. When the system is deployed in the aquifer, the packers are inflated with nitrogen gas. Hydraulic head is measured by three Paroscientific, Inc. "Digiquartz" depth sensors (transducers) at frequencies as high as one measurement per second. The upper and lower transducers monitor pressure above and below the packer isolated interval. The middle transducer measures pressure in the 15 to 20 foot long isolated zone. A five-horsepower submersible pump capable of about 20 gpm discharge (with 460 feet of static lift) is utilized to pump from the isolated interval. Water is pumped through a two-inch diameter stainless steel riser pipe to the surface. Flow rate is controlled through manaual adjustment of a ball valve. At flow rates less than about 6 gpm, discharge fluctuated and created uncertainty in interpretaion of the test data. Additional information on the straddle-packer can be found in Olsen (1994).

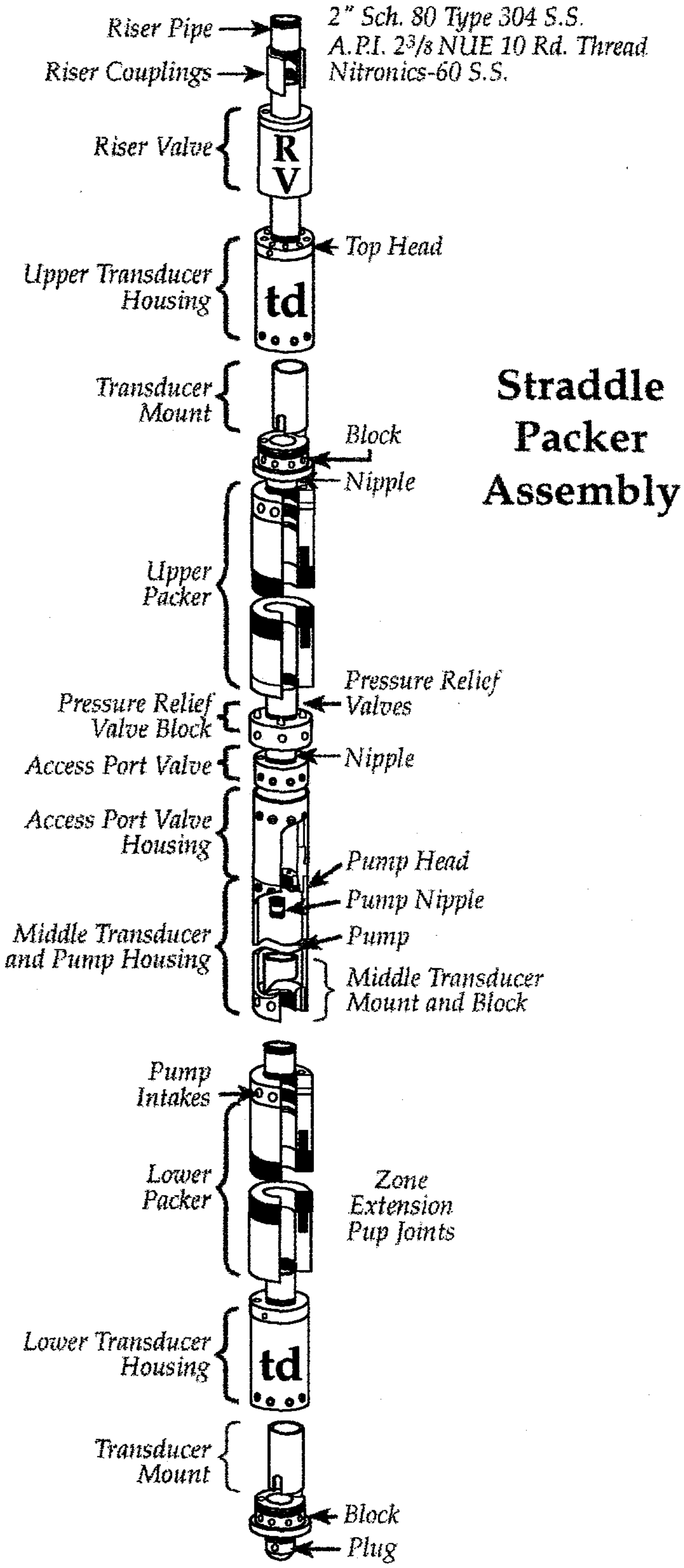


Figure 5. Schematic of the straddle packer system. (from Olsen, 1994; not to scale).

From 1992 to 1994, four wells near the Idaho Chemical Processing Plant were investigated with the straddle-packer. Monks (1994) reported estimates of hydraulic conductivity from tested intervals in well USGS-44. A total of sixteen aquifer tests were conducted in wells USGS-45, -46, and -59. Aquifer tests of eight of these intervals could not be used for type curve matching due to 1) inability to measure extremely small drawdowns or 2) excessive drawdowns resulting in early termination of aquifer tests. A maximum or minimum specific capacity was estimated for these intervals and a corresponding maximum or minimum hydraulic conductivity was calculated from a regression equation (Ackerman, 1991).

Intervals for packer testing were selected primarily by viewing video logs of the well to identify intervals of the borehole where the borehole wall would provide a suitable seal for the straddle-packers located on both ends of the packer assembly. Ideally, these zones would have a smooth borehole wall, absence of fractures, and a minimal number of vesicles.

CHAPTER 3

EVALUATION OF ANALYTICAL TECHNIQUES FOR APPLICATION TO STRADDLE-PACKER AQUIFER TESTS

Aquifer tests conducted with the straddle-packer system involved conditions that deviated from the ideal "Theis" situation of a fully penetrating well in a homogeneous, isotropic, confined aquifer of infinite extent. The departures from ideal conditions were as follows:

1) The tests were conducted in the fractured basalts and interbedded sediments of the Snake River Plain aquifer. It is uncertain whether the aquifer responds as a porous or fractured (double porosity) medium at the scale of the tests.

2) The tests were single well tests. No observation wells were used. Uncertainty exists regarding the effective radius of the well and well efficiency. Results are also heavily biased by hydraulic conditions immediately surrounding the borehole which may have been affected by cable-tool drilling.

3) The straddle-packer isolates 15 to 20 foot segments of boreholes in an aquifer which is at least two-hundred feet thick. The actual thickness of the aquifer is unknown. The test methodology may result in vertical flow in the aquifer.

4) The Snake River Plain aquifer is probably unconfined in long-term pumping situations, but may be locally confined. Straddle-packer aquifer tests may respond as confined,

leaky, or as a delayed water table response (e.g. delayed yield). A delayed water-table response was observed in these wells during the two-well aquifer tests interpreted by Frederick and Johnson (1996).

Analytical techniques are available that individually address some of the departures from ideal conditions. A comparison of observed data to theoretical solutions from alternative models provides insight into the validity of those models for application to straddle-packer tests. Although no analytical technique is perfectly suited to analysis of straddle-packer aquifer test data, three methods are applied to qualitatively evaluate conformity of data to theoretical curves and gain a subjective understanding of the sensitivity of property estimates to the assumptions accompanying each method.

Three analytical techniques are applied to a total of eight intervals in wells USGS 45, 46, and 59. Additional tests in well USGS 44 are described in Monks, (1994). Aquifer test information is limited to these intervals primarily because of immeasurably small, or excessively large, drawdown in other intervals (within the operable pump discharge range). Therefore, the reported aquifer test data do not represent the full range of permeabilities in the profile, but are limited to zones of intermediate permeability.

Most analytical techniques are applied to pumping wells penetrating the full thickness of an aquifer. Consequently, these techniques are used to estimate aquifer transmissivity. By definition, transmissivity relates to the entire thickness of an aquifer; however, intervals isolated by the straddle-packer system varied in length between 18 and 20 feet, substantially less than the several hundred feet of aquifer thickness.

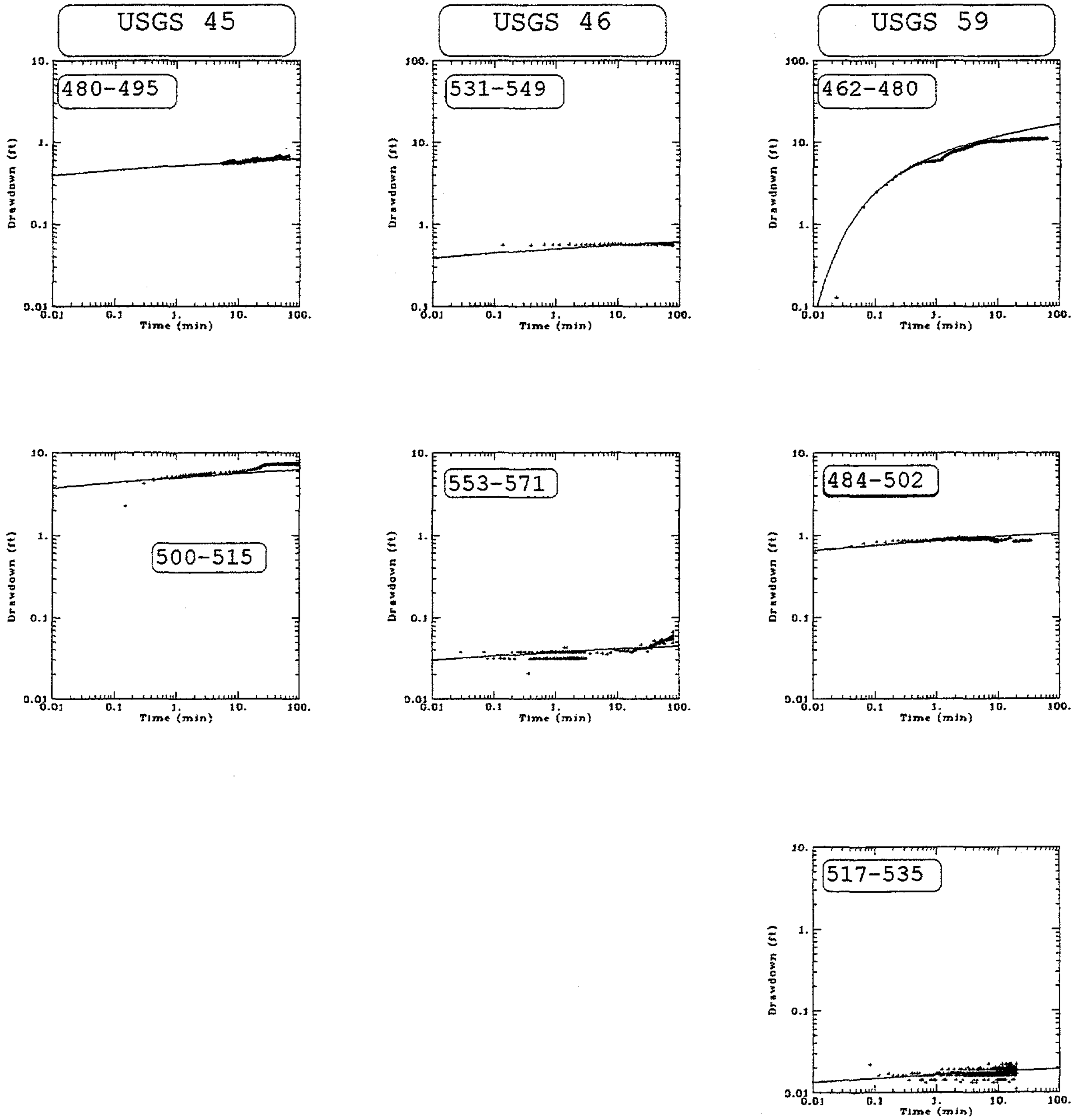
Therefore, transmissivity values estimated from the aquifer tests were divided by the length of the tested interval to estimate an average hydraulic conductivity for the interval. The hydraulic conductivity calculated by this procedure would tend to overestimate actual hydraulic conductivity when the methods applied do not account for vertical flow into the interval.

Non-linear well loss is also of concern with single-well aquifer tests. Discharge rates were less than 20 gpm and the boreholes are uncased. Therefore, well losses are assumed to be negligible.

Theis Model

Theis (1935) developed type curves for unsteady-state flow to a fully-penetrating pumping well in a confined aquifer. The assumptions of confined aquifer conditions, homogenous porous media, and a pumping well which fully penetrates the aquifer may not be consistent with conditions of straddle-packer testing. The validity of the Theis assumptions can be partially assessed from the conformity of the time-drawdown data to the Theis type curve.

Comparisons of observed time-drawdown data to Theis type curves are provided in Figure 6 for eight tested intervals in wells USGS 45, USGS 46, and USGS 59. The observed time-drawdown data exhibits little curvature relative to theoretical Theis response, except in the water-table interval of well USGS 59. The minimal curvature at early time in most intervals implies that either storativity is very small, or the Theis model is inappropriate for this application. Results from the Theis type curve matching are provided to demonstrate the insensitivity of hydraulic conductivity estimates to the choice of model.



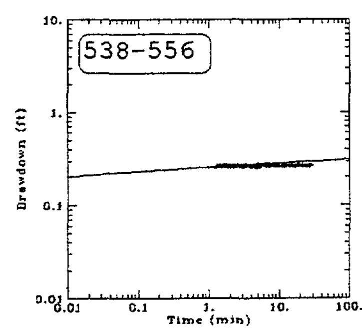


Figure 6. Theis type curve matches for tested intervals in wells USGS 45,46, and 59.

In general, the near constant drawdown observed in most of the aquifer tests does not permit unique estimation of aquifer storativity or specific storage. Specific storage was therefore assumed to be equal to 1.4×10^{-8} ft^{-1} for all intervals below the water table. This value reflects only aquifer storage resulting from the compressibility of water in a matrix of one percent porosity matrix, assuming no elasticity of the aquifer skeleton. This value is supported by the two-well aquifer tests described by Frederick and Johnson (1996). Fortunately, estimates of hydraulic conductivity are relatively insensitive to uncertainty in estimates of storativity. For example, in the 480-495 foot interval of well USGS 45, a specific storage of 1.4×10^{-8} ft^{-1} results in a best match to the Theis curve when combined with an interval hydraulic conductivity of 0.33 ft/min. A specific storage value of 2.7×10^{-4} ft^{-1} (maximum possible while maintaining a match with observed data) results in a type curve fit with an interval hydraulic conductivity of 0.22 ft/min. Hydraulic conductivity estimates listed in Table 2 are based on an assumed specific storage of 1.4×10^{-8} (1/ft) except for the uppermost interval of well 59.

Curvature of the time-drawdown plot for the water-table interval of well USGS 59 (462-480 ft bls in Figure 6) is likely associated with contributions from dewatering of voids at the water table (e.g. specific yield). A type curve match (violating the assumption of a confined aquifer) in this interval results in estimate of 0.03 for aquifer specific yield. This estimate, however, is considered inaccurate due to violations of Theis assumptions and uncertainties associated with well efficiency and effective radius.

The lack of time-drawdown curvature in the later time data in Figure 6 and in aquifer tests described by Monks (1994) is likely the result of vertical flow into the packer-isolated interval, however, this condition may also be due to double porosity effects. The reason for the late-time upward curvature occurring in the 553 to 571 foot bls interval in well USGS 46 is unknown, but may be associated with caving of sediment interbeds suggested by increased particulate concentrations observed during pumping.

Hydraulic conductivity estimates resulting from matching the Theis type curve range from 0.0011 to 18 ft/min (Table 1). These values may overestimate actual transmissivity of the isolated intervals (with the loose interpretation of transmissivity being the product of the hydraulic conductivity and the thickness of the interval) due to effects of vertical leakage. These estimates do not reflect the full range of hydraulic conductivity in the profile, as they do not include the most permeable and least permeable intervals, where aquifer tests were ineffective. Hydraulic conductivity estimates from the Theis model are compared to other methods of estimation and the two-well analyses in chapter five.

Vertical Leakage Methods

The leaky aquifer method of Hantush and Jacob (1955) takes into account vertical leakage into the pumped zone through an overlying aquitard. The supporting assumptions of the method appear to match test conditions more closely than those of the "leaky with storage" approach of Hantush (1960). The "leaky without storage" model of Hantush and Jacob (1955) assumes vertical flow into the pumped aquifer from an overlying constant-head aquifer, through an aquitard with no storativity. The concept is analogous to an infinitely thin membrane of reduced permeability separating the pumped aquifer from an overlying constant head source. These assumptions resemble actual conditions in that the high hydraulic conductivity of overlying or underlying aquifer layers results in near constant head in these units, and the storativity of the formation is small ($7x10^{-6}$; Frederick and Johnson, 1996). Due to the lack of definable aquitards above or below tested intervals, the leakage parameter (r/B) of Hantush and Jacob (1955) has little physical meaning in this application.

Table 2. Hydraulic conductivity estimated from Theis type curve matches.

Well	Interval (ft bls)	Hydraulic Conductivity (ft/min)
USGS 45	480-495	0.33
USGS 45	500-515	0.047
USGS 46	531-549	0.44
USGS 46	553-571	6.7
USGS 59	462-480	0.0011
USGS 59	484-502	0.061
USGS 59	517-535	18.
USGS 59	538-556	1.0

* Specific yield is estimated at water table intervals.

The Hantush and Jacob (1955) method assumes that flow in the aquitard is vertical and flow in the pumped aquifer is horizontal. Lack of significant contrast between hydraulic conductivity in the pumped interval and overlying or underlying layers may result in violation of this assumption and produce errors in hydraulic conductivity estimates in excess of five percent (Neuman and Witherspoon, 1969a).

The method of Hantush and Jacob (1955) uses two independent dimensionless parameters (u and r/B). Unique estimation of these parameters is often difficult based exclusively on time-drawdown data, especially when the plots lack curvature. Additional constraints are needed for unique and correct property estimates. A range of reasonable values of the leakage parameter (r/B) can be determined from estimates of hydraulic conductivity and aquitard thickness, even though the aquitard may be similar in character to the pumped interval. A minimum value of r/B is calculated from the formula for r/B:

$r/B = r(K'/Kbb')$ where

r = radius of the well,

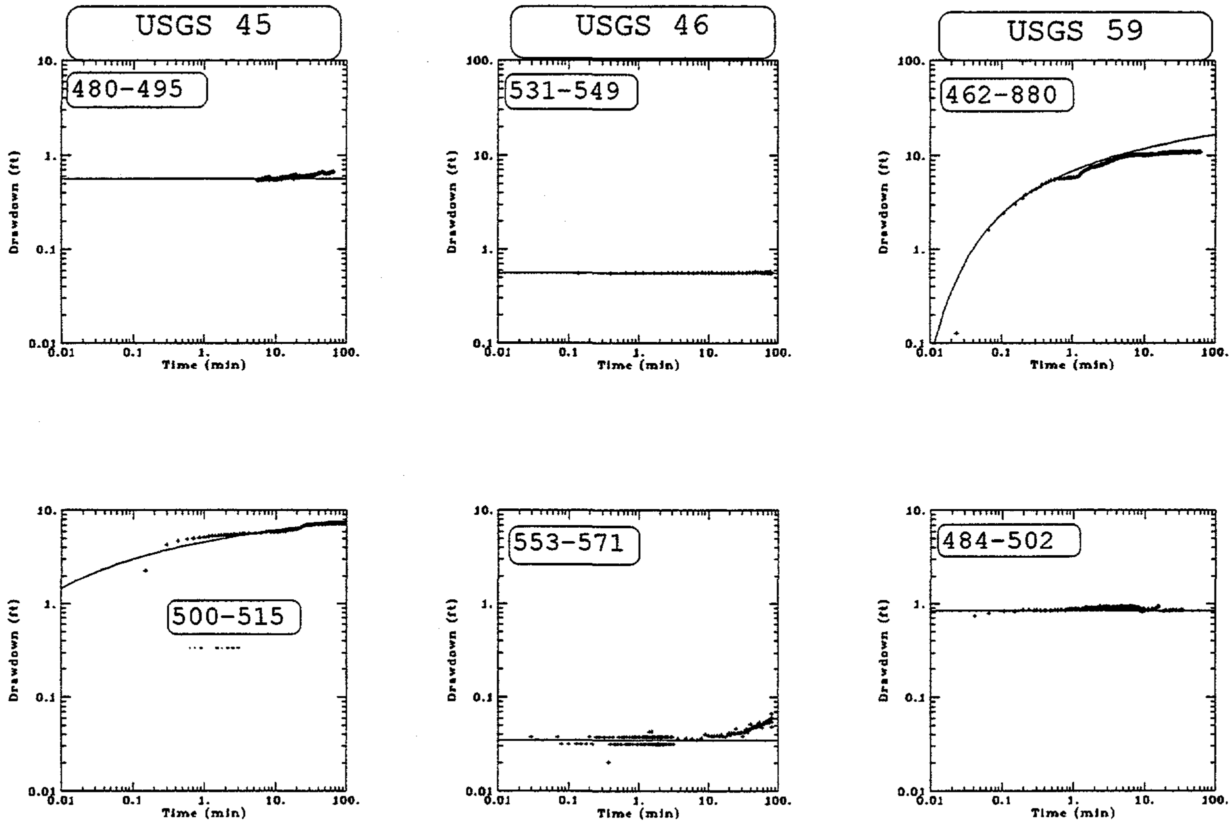
K' = vertical hydraulic conductivity of the aquitard,

K = horizontal hydraulic conductivity of the aquifer,

b = thicknesss of the aquifer, and

b' = thickness of the aquitard.

A minimum value of 0.003 is expected assuming an aquitard thickness three times greater than the thickness of the pumped interval (18 ft) and a vertical hydraulic conductivity of the aquitard that is two orders of magnitude less than the horizontal hydraulic conductivity of the pumped interval. The expected maximum value of r/B is 0.3, which corresponds to isotropic media and an approximate aquitard thickness of one foot. The two-order of magnitude variation in r/B results in a range of possible hydraulic conductivity and storativity values that produce a match between type curves and observed time-drawdown data. Type curve matches for an r/B of 0.003 are presented in Figure 7. The corresponding matches for the maximum expected r/B of 0.3 are shown in Figure 8. The estimated hydraulic conductivity and storativity values for each interval are summarized in Table 2.



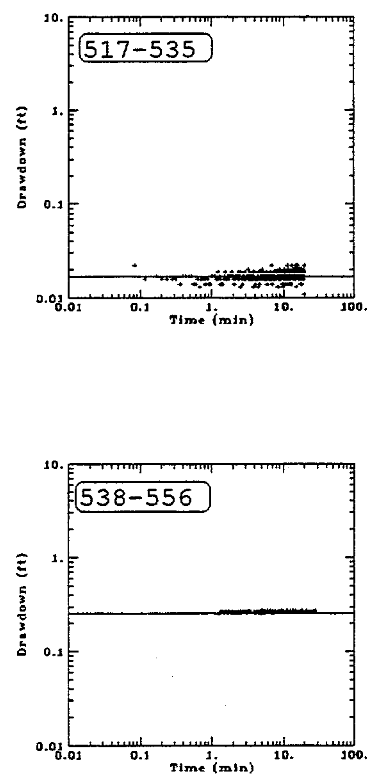
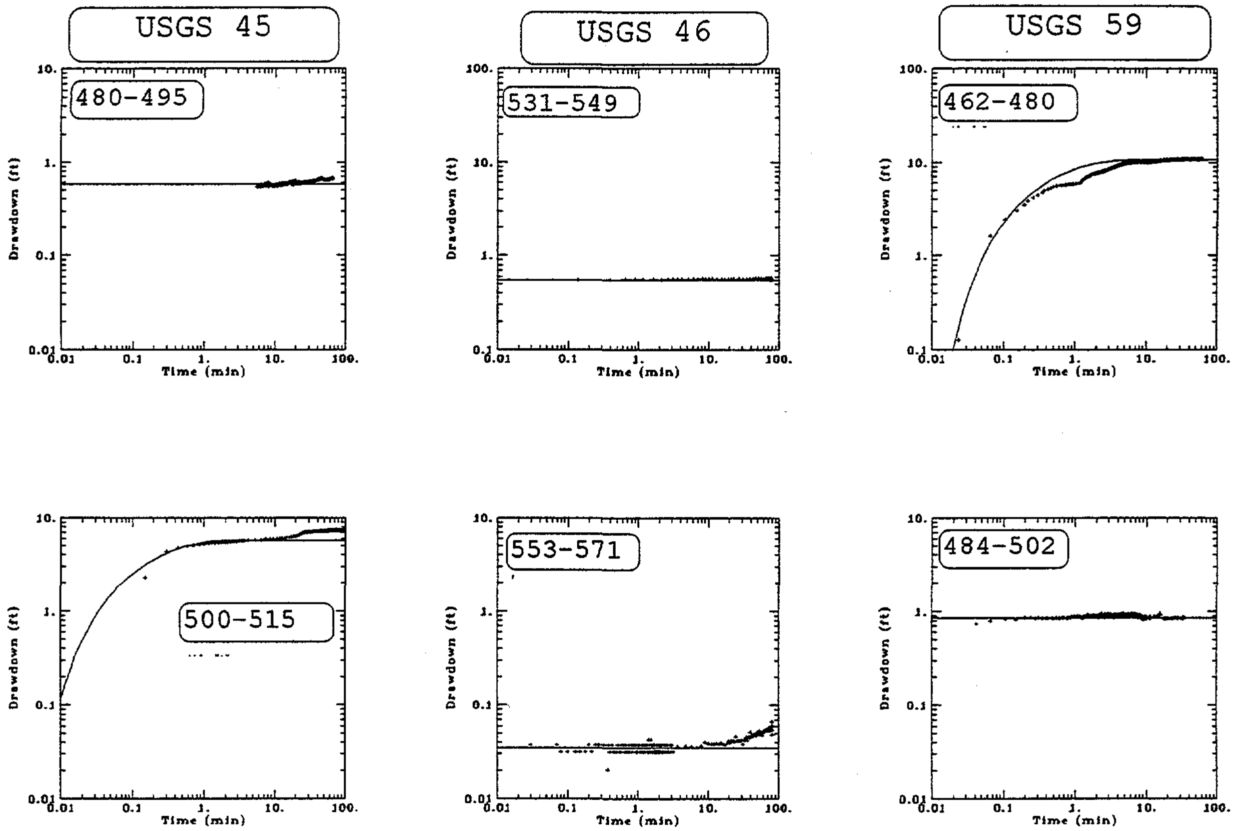


Figure 7. Hantush and Jacob type curve matches for a leakance factor (r/B) of 0.0003.



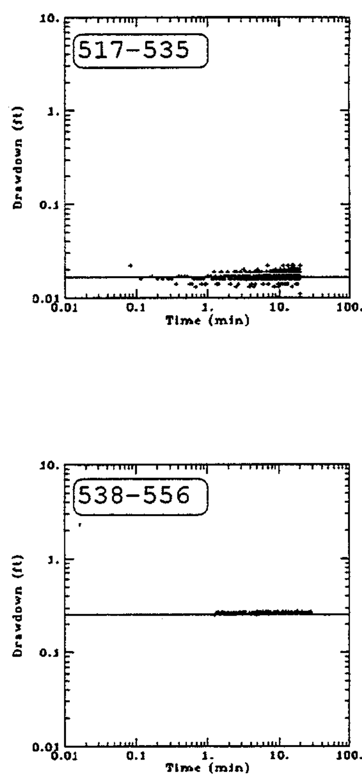


Figure 8. Hantush and Jacob type curves for a leakance factor (r/B) of 0.3.

Table 3. Hantush and Jacob (leaky aquifer) estimates of hydraulic conductivity and storativity.

Well	Interval (ft bls)	Minimum Leakage r/B=0.003		Maximum Leakage r/B=0.3	
		Hydraulic Conductivity (ft/min)	Specific Storage* (ft^{-1})	Hydraulic Conductivity (ft/min)	Specific Storage* (ft^{-1})
USGS45	480-495	0.17	$1.4x10^{-8}$	0.039	$1.4x10^{-8}$
USGS45	500-515	0.018	$8.7x10^{-4}$	0.0060	0.007
USGS46	531-549	0.23	$1.4x10^{-8}$	0.053	$1.4x10^{-8}$
USGS46	553-571	3.6	$1.4x10^{-8}$	0.83	$1.4x10^{-8}$
USGS59	462-480	0.0011	0.03**	0.00061	0.03**
USGS59	484-502	0.039	$1.4x10^{-8}$	0.0089	$1.4x10^{-8}$
USGS59	517-535	8.3	$1.4x10^{-8}$	1.9	$1.4x10^{-8}$
USGS59	538-556	0.55	$1.4x10^{-8}$	0.13	$1.4x10^{-8}$

* Specific storage estimates are non-unique.
** Specific yield is estimated for water table intervals.

Type curve matching using the minimum expected leakage factor (r/B=0.003) results in larger values of estimated hydraulic conductivity compared to those resulting from the maximum anticipated leakage factor (r/B=0.3). The difference results from the need for higher values of lateral hydraulic conductivity to compensate for the lesser vertical leakage in the case where r/B is small. The difference in hydraulic conductivity is consistently less than one order of magnitude, which reflects a likely range of error in estimated hydraulic conductivity. In contrast, the range of estimated hydraulic conductivity among intervals spans nearly four orders of magnitude.

In most intervals, the Hantush and Jacob leaky type curve match was highly non-unique with respect to specific storage. Consequently, specific storage values equivalent to the compressibility of water in a one percent porosity aquifer were assumed in most of the type curve matches (1.4×10^{-8}). Variations of several orders in magnitude of specific storage generally have little or no effect on estimates of hydraulic conductivity.

In the water table interval of well USGS 59 (462-480 feet bls) and in one deeper interval in well USGS 45, larger storativities were used. The relatively large storativity in water table interval likely represents a contribution of aquifer specific yield. In the 500 to 515 foot interval of well USGS 45, a larger estimate of specific storage was generated to attempt to match a single data point at 12 seconds (0.2 minutes) of pumping. The reason for the apparent curvature in the time-drawdown graph at this interval is unknown.

Double-Porosity Model

Numerous authors have developed models for ground-water flow in a double-porosity medium (e.g. Warren and Root, 1963; Moench, 1984). These models assume flow occurs in a series of parallel fractures, with an additional contribution of water from storage in the matrix blocks which separate the fractures. Warren and Root (1963) assumed that block to fissure flow occurred under pseudo-steady state conditions. Kazemi (1969) assumed flow to the fissures occurred under transient conditions. Moench (1984) introduced the concept of a "fracture skin" which delays the flow contributions from the blocks and thus results in a pressure response similar to that of pseudo-steady state flow. Moench's model assumes the fracture skin has negligible storage capacity and that the flow from the blocks is perpendicular to the block-fracture interface. Flow to the well only occurs in the fractures, which receive water from the matrix blocks.

The double-porosity model may effectively represent flow in the SRPA in massive basalts where flow is dominated by a few fractures. In addition, ground-water flow in rubble zones may approximate a double-porosity model, where the rubble zone essentially behaves as a large fracture, with additional water coming from secondary fractures and vesicles. A double-porosity response may be difficult to distinguish from vertical leakage effects, which are not included in the double-porosity analytical methods.

Double-porosity type curves (Moench, 1984) were matched to observed drawdown for 8 pumped intervals using curve matching AQTESOLV (Duffield and Rumbough, 1991). The method allows adjustment of six variables representing:

1) hydraulic conductivity of fractures (K),
2) specific storage of the fractures (S_s),
3) hydraulic conductivity of the rock matrix (K'),
4) specific storage of the rock matrix (S_s'),
5) dimensionless permeability of a fracture skin (S_f), and
6) dimensionless wellbore skin (S_w).

In addition, the Moench model allows the choice of either a slab or sphere representation of the matrix blocks. The large number of variables results in a high degree of non-uniqueness in the solutions, which was partially relieved by assuming fracture and well bore skin conditions did not exist in the tested wells (S_w=0 and S_f=0). The layered basalts of the Snake River Plain aquifer were considered to be best represented as slab-shaped blocks with thickness varying according to qualitative estimates of fracturing in each interval apparent from video logs. Specific storage was assumed equal to a value representing the compressibility of water (1.4×10^{-8}) when solutions were highly non-unique with respect to storage.

Table 4. Estimated aquifer properties from double-porosity type curves.

Well	Interval	Fracture Hydraulic Conductivity (ft/min)	Fracture S_s (ft^{-1})	Matrix Hydraulic Conductivity (ft/min)	Matrix S_s (ft^{-1})
USGS45	480-495	0.31	1.4×10^{-8}	0.02	1.4×10^{-8}
USGS45	500-515	0.043	1.4×10^{-8}	0.001	1.4×10^{-8}
USGS46	531-549	0.4	1.4×10^{-8}	1×10^{-7}	0.0001
USGS46	553-571	7.0	1.4×10^{-8}	0.02	1.4×10^{-8}
USGS59	462-480	0.0014	0.002*	0.0014	0.002
USGS59	484-502	0.04	1.4×10^{-8}	2×10^{-8}	0.001
USGS59	517-535	15	1.4×10^{-8}	1×10^{-7}	1×10^{-5}
USGS59	538-556	1.0	1.4×10^{-8}	1.0	1.4×10^{-8}

* Actually representative of S_Y divided by interval thickness.

Type curves matches to time drawdown data are shown in Figure 9. The resulting property estimates, although recognized as non-unique, are listed in Table 4 for each tested interval. Fracture hydraulic conductivity estimates for the eight intervals ranged from 0.0014 to 15 ft/min and are comparable to values estimated from porous media models. Matrix hydraulic conductivities control the rate of release of water from the rock matrix and ranged from $2x10^{-8}$ to 1.0 ft/min. An equally good fit of measured data to the theoretical curves can be obtained by other combinations of matrix and fracture hydraulic conductivities.

Specific Capacity Regression

Transmissivity can be approximated from specific capacity (discharge divided by drawdown) of a well due to the near proportionality of specific capacity and transmissivity at any given time. According to the Theis relationship (and accompanying assumptions), specific capacity gradually decreases with increasing time, but remains nearly constant at long pumping times. Ackerman (1991) developed a non-linear relationship between transmissivity and specific capacity at the INEL:

$$T = 40.62(Q/s)^{1.1853} \quad ,$$

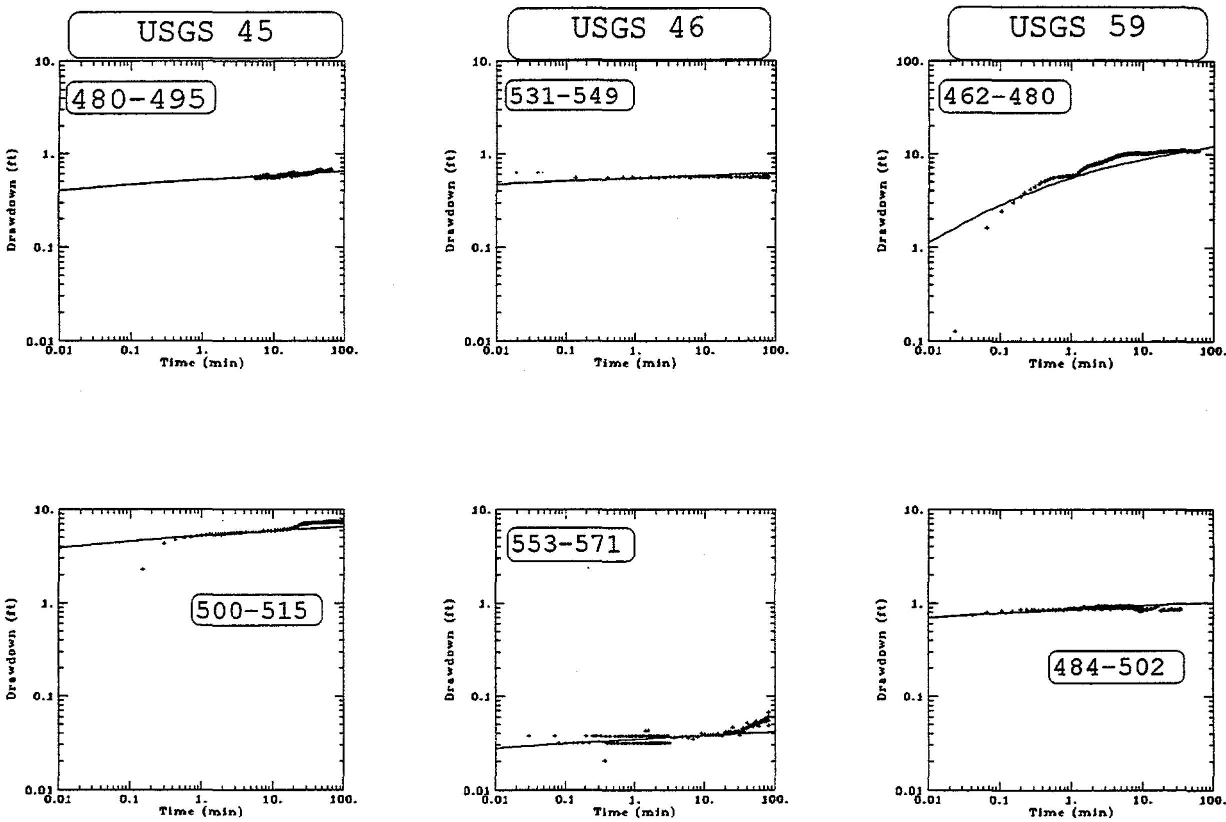
where

T = transmissivity (ft^2/day),

Q = discharge rate (gpm), and

s = drawdown (ft).

The transmissivity is converted to average interval hydraulic conductivity by dividing by the thickness of the tested interval. This technique was applied to all tested intervals and was



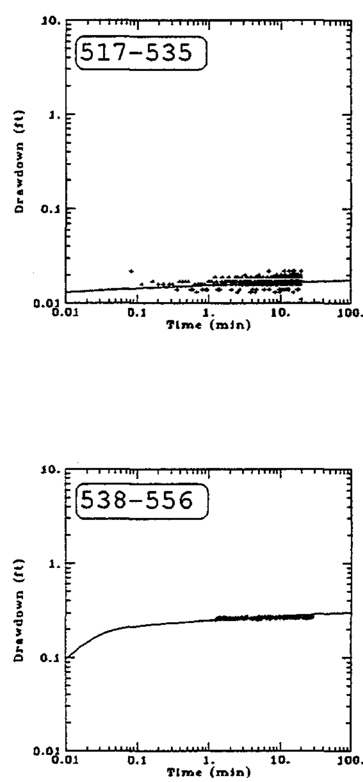


Figure 9. Moench type curves for tested intervals in wells USGS 45, 46, and 59.

Table 5. Specific capacity and corresponding hydraulic conductivity estimates.

Well	Interval	Specific Capacity (gpm/ft)	Hydraulic Conductivity (ft/min)
USGS 45	462-477	<1.3*	0.003
USGS 45	480-495	19	0.06
USGS 45	500-515	2.3	0.005
USGS 45	519-534	0.2	0.0003
USGS 46	461-483	>850	>3.8
USGS 46	488-506	>320	>1.5
USGS 46	507-525	>850	>1.8
USGS 46	531-549	32	1.7
USGS 46	553-571	600	6.0
USGS 46	575-593	>300	>1.3
USGS 46	594-612	<.1*	<0.0001
USGS 46	611-629	<.02*	$<1.5\times10^{-5}$
USGS 59	462-480	0.4	0.008
USGS 59	484-502	5.7	0.01
USGS 59	517-535	870	5.0
USGS 59	538-556	80	0.2

* Pumping time less than 15 minutes.

particularly useful for zones where drawdown was rapid and constant.

The regression equation of Ackerman (1991) was applied to straddle-packer aquifer test data with the knowledge that vertical leakage may result in overestimation of aquifer hydraulic conductivity. Specific capacity values at pumping times greater than 15 minutes, and the corresponding regression estimate of hydraulic conductivity for each packer-tested interval in wells USGS 45, 46, and 59 are presented in Table 5. In three intervals, maximum values of hydraulic conductivity were estimated by using drawdowns measured after brief pumping periods. In four intervals, drawdown was too small to be reliably measured and a minimum measurable drawdown of 0.02 feet was used to estimate a minimum value for specific capacity. Specific capacity values and the corresponding estimates of hydraulic conductivity range over more than five orders of magnitude. The range of hydraulic conductivity is greater than that produced by the other analytical methods due to the inclusion of higher and lower permeability intervals.

CHAPTER 4:

COMPARISON OF RESULTS

Hydraulic Conductivity

Hydraulic conductivity estimates vary with tested interval and with analytical technique. Estimated values for each interval and method are presented in Table 6. Type curve matches in several intervals were not possible due to limited data. In those intervals a regression between aquifer transmissivity and well specific capacity (Ackerman, 1991) was applied to obtain a maximum or minimum estimate of hydraulic conductivity.

The Theis and double-porosity models resulted in approximately the same estimates of hydraulic conductivity (fracture hydraulic conductivity in the double-porosity model) for all intervals. These values were consistently greater than or equal to estimates from the leaky models. The higher estimates of hydraulic conductivity are expected since leaky methods allow for a secondary source of water associated with vertical flow. The Theis type curve normally did not match the observed data as well as the Hantush and Jacob (1955) leaky aquifer model.

The Hantush and Jacob leaky method was applied at two pre-specified values of the leakage factor, r/B, representing the expected extremes. The Hantush and Jacob (1955) type curves provided the best general match to observed data compared to the Theis or Moench double porosity methods. The better conformity of observations to theoretical curves implies that the leaky aquifer model is most appropriate for the straddle-packer aquifer tests in this environment. Hydraulic conductivities determined from the Hantush and Jacob leaky aquifer method were generally less than those estimated by either the Theis method or Moench double-porosity method. The larger leakage factor (r/B=0.3) consistently

Table 6. Comparison of hydraulic conductivity estimates from different analytical methods in ft/min.

Well	Interval	Theis	Leaky (r/B= .003)	Leaky (r/B= 0.3)	Double Porosity Fracture K	Specific Capacity
45	480-495	0.33	0.17	0.039	0.31	0.06
45	500-515	0.047	0.018	0.006	0.043	0.005
45	519-534	NA	NA	NA	NA	0.0003
46	461-483	NA	NA	NA	NA	>3.8
46	488-506	NA	NA	NA	NA	>1.5
46	507-525	NA	NA	NA	NA	>1.8
46	531-549	0.44	0.23	0.053	0.4	1.7
46	553-571	6.7	3.6	0.83	7.0	6.0
46	575-593	NA	NA	NA	NA	>1.3
46	594-612	NA	NA	NA	NA	<0.0001
46	611-629	NA	NA	NA	NA	<.000015
59	462-480	.0011	0.0011	0.00061	0.0014	0.008
59	484-502	0.061	0.039	0.0089	0.04	0.01
59	517-535	18.	8.3	1.9	15	5.0
59	538-556	1.0	0.55	.13	1.0	0.2

resulted in smaller estimates of hydraulic conductivity than the smaller value (r/B=0.003), due to the greater potential for vertical flow from overlying and underlying intervals.

The double-porosity model (Moench, 1984) typically resulted in a reasonable, but non-unique, match with observed drawdown due to the large number of variables.

Hydraulic conductivity values determined with the various methods (i.e. type curves and specific capacity) are consistently within an order of magnitude (Table 6). As such, the error associated with the selection of the model is probably less than an order of magnitude. This is an acceptable error range, considering that the heterogeneity of the system results in vertical variations of hydraulic conductivity greater than four orders of magnitude. Estimates of hydraulic conductivity are insensitive to uncertainties of as much as two orders of magnitude in specific storage.

No consistent pattern of increasing or decreasing hydraulic conductivity with depth was apparent (Figure 10). This result is attributed to control of hydraulic conductivity largely by basalt-flow structure. Excessive drawdown in aquifer tests in the deeper zones of wells USGS 44 (see Monks, 1994) and USGS 46 (Table 6), however, indicate low values of hydraulic conductivity (less than 0.001) for the tested interior of the I-basalt flow at depths between 590 and 650 feet below land surface. Vertical variations of hydraulic conductivity show little consistency among wells, except again for observations of low permeability in the deeper zones of wells USGS 44 and USGS 46.

Storativity

Aquifer storativity or specific storage cannot be reliably estimated from the straddle-packer aquifer tests. Lack of

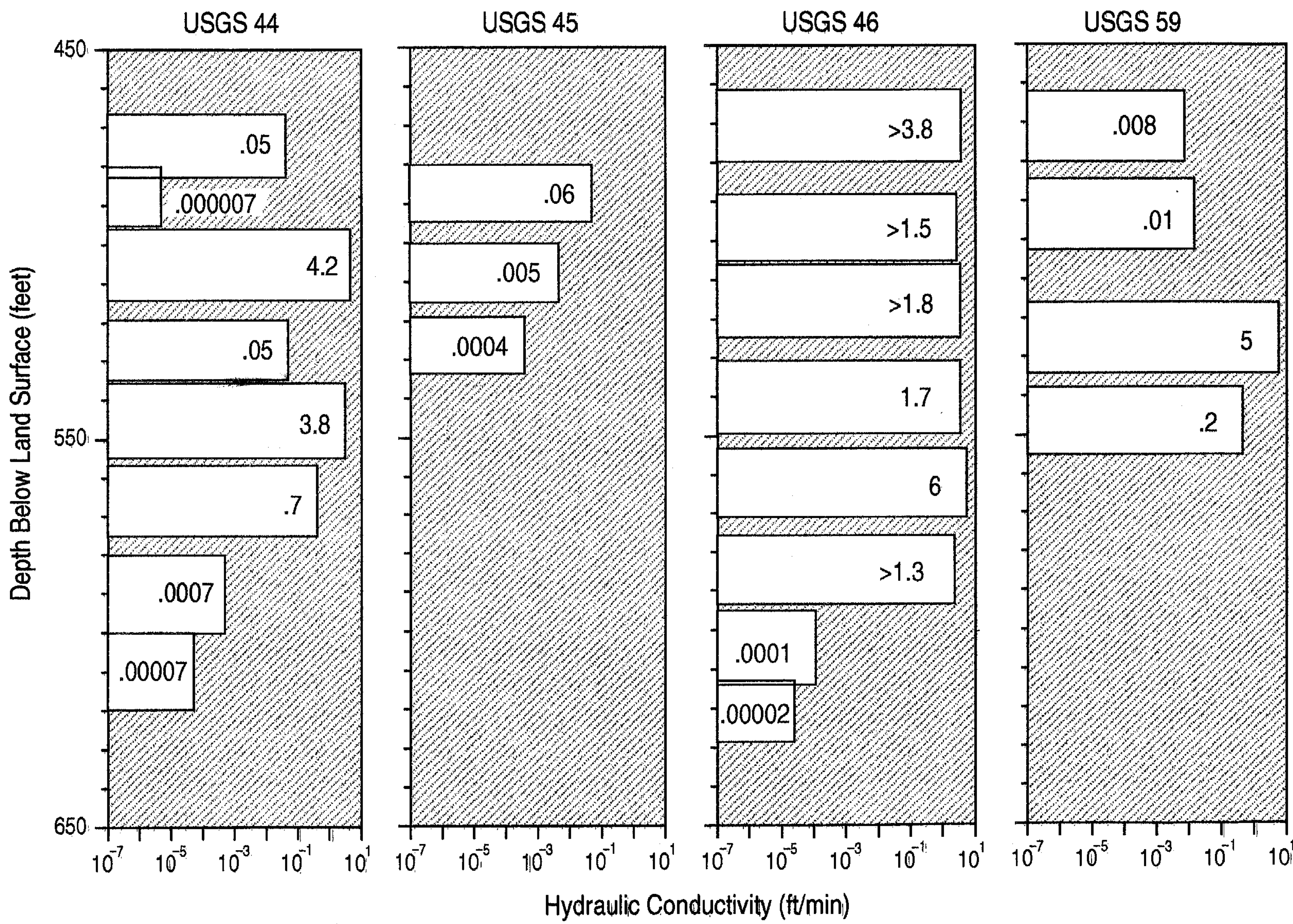


Figure 10. Hydraulic conductivity profiles in wells USGS 44, 45, 46, and 59.

curvature in the data plot prevents a unique determination of specific storage, especially when vertical leakage conditions exist. In addition, property estimation is complicated by uncertainties regarding well radius and well efficiency.

CHAPTER 5:

IMPLICATIONS FOR CONCEPTUAL MODELS

Horizontal Hydraulic Conductivity

Horizontal hydraulic conductivity estimates from the single-well aquifer tests reflect aquifer conditions in the vicinity of tested boreholes. Hydraulic conductivity estimates from single well tests vary greatly among wells (Figure 10). Consequently, single-well estimates of hydraulic conductivity are considered more representative of local than regional aquifer characteristics.

An average horizontal hydraulic conductivity of multiple straddle-packer intervals can be calculated as the arithmetic average of estimated hydraulic conductivities of the corresponding test intervals, weighted by the length of the intervals. Hydraulic conductivities averaged for the E-H and I basalt flow groups of Anderson (1991) can then be compared to the two-well estimates of hydraulic conductivity (Frederick and Johnson, 1996). Table 7 presents average hydraulic conductivity estimates from the single-well and two-well aquifer tests. The single-well estimates for the E-H basalt flow group vary over two orders of magnitude and are consistently less than the two-well test estimates. The differences are thought to be a result of local variations in aquifer properties.

Table 7. Average hydraulic conductivity estimates of basalt flow groups.

Basalt Flow Group	Single-Well Test Average Hydraulic Conductivity (ft./min.)				Two-Well Test Hydraulic Conductivity (ft./min.)
	USGS 44	USGS 45	USGS 46	USGS 59	
E-H	1.7	0.02	2.5	1.3	3.0
I	0.95	NA	1.7	NA	1.8

Vertical Hydraulic Conductivity

Alternating layers of high and low horizontal hydraulic conductivity result in an overall effective vertical hydraulic conductivity that is less than the arithmetic average hydraulic conductivity of the individual layers. Effective vertical hydraulic conductivity of a multiple layer system is calculated by the following equation:

$$Ke' = d_T \,/\, \Sigma_{i=1,n}(d_i/K'_i)$$

where

Ke' = composite vertical hydraulic conductivity,

d_T = composite thickness of sequence of layers,

d_i = thickness of layer i, and

K'_i = horizontal hydraulic conductivity of layer i.

The above equation can be applied to calculate composite vertical hydraulic conductivity of the E through H and I basalt flow groups. This application, however, requires the simplifying assumption that individual layers are internally isotropic and laterally continuous. Although this assumption may be in error, the calculation provides a useful comparison to the larger scale estimates from the two-well tests.

A broad range of vertical hydraulic conductivity of the E-H and I flow groups results from application of the above equation to the interval hydraulic conductivities in the four tested wells. Calculated vertical hydraulic conductivity of the E through H basalt flow group ranges between $2x10^{-5}$ and $2x10^{0}$ ft/min. The values range from $3x10^{-4}$ to $2x10^{0}$ ft/min for the deeper I basalt flow group. The two-well tests (Frederick and Johnson, 1996) produced vertical hydraulic conductivity estimates of the two flow groups as 0.03 and 0.008 ft./min., respectively. The vertical hydraulic conductivities estimated from the two-well aquifer tests fall within the broad range of those calculated for the basalt flow groups using the single-well test data.

Flow Pathways

The aquifer test results support a conceptual model of an aquifer locally characterized by highly heterogeneous hydraulic properties that appears homogeneous when examined on a sufficiently large scale. Both single-well and two-well tests imply that vertical hydraulic conductivity of the aquifer, as a whole, is substantially less than horizontal.

CHAPTER 6:

SUMMARY

The State of Idaho INEL Oversight Program, with the University of Idaho, Idaho State University, Boise State University, and the Idaho Geologic Survey, used a straddle-packer system to investigate vertical variations in characteristics of the Snake River Plain aquifer at the Idaho National Engineering Laboratory in southeast Idaho.

Sixteen single-well aquifer tests were conducted on isolated intervals in three observation wells. Each of these wells has approximately 200 feet of open borehole below the water table, penetrating the E through G and I basalt flow groups and interbedded sediments of the Snake River Plain aquifer. The success of the aquifer tests was limited by the inability to induce measurable drawdown in several zones. Time-drawdown data from aquifer tests were matched to type curves for 8 of the 16 zones tested.

A single aquifer test at the water table exhibited greater curvature than those at depth. The increased degree of curvature suggests an unconfined response and resulted in an estimate of specific yield of 0.03.

Aquifer tests below the water table generally yielded time-drawdown graphs with a rapid initial response followed by constant drawdown throughout the duration of the tests; up to several hours in length. The rapid initial response implies that the aquifer responds as a confined system during brief pumping periods. The nearly constant drawdown suggests a secondary source of water, probably vertical flow from overlying and underlying aquifer layers.

Three analytical models were applied for comparison to the conceptual model and to provide estimates of aquifer properties.

The Theis, Hantush and Jacob leaky aquifer, and Moench double-porosity fractured rock models were fit to time-drawdown data. The leaky aquifer type curves of Hantush and Jacob (1955) generally provided the best match to observed drawdown. A specific capacity regression equation was also used to estimate hydraulic conductivity.

Estimated values of horizontal hydraulic conductivity of tested intervals ranged from 1.5×10^{-5} to 18 ft/min depending upon the interval and analytical technique employed. Hydraulic conductivity estimates resulting from the different analytical techniques varied by less than one order of magnitude for a given interval. In general, hydraulic conductivity estimates by the Theis method were largest, followed by Moench double porosity estimates. The Hantush and Jacob method with the maximum expected leakage factor ($r/B=0.3$), generally yielded the smallest values of hydraulic conductivity. The leaky conceptual model is probably most consistent with test conditions, but vertical leakage rates are not well constrained.

The large variation in estimated hydraulic conductivity among the tested intervals, more than four orders of magnitude, demonstrates the extreme vertical heterogeneity of the fractured basalts and interbedded sediments of the Snake River Plain aquifer. Lateral hydraulic conductivities estimated from the single-well aquifer tests have a high degree of variability and are less than values estimated from the two-well tests. The two-well tests are more representative of large-scale properties than the single-well tests, which are probably influenced by local heterogeneities.

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APPENDIX A

DETAILED DESCRIPTION OF AQUIFER TESTS

Well 45

Aquifer tests were performed in four intervals in USGS 45 in August, 1993:

1) 462-477 ft bls (interval was pumped dry),
2) 480-495 ft bls,
3) 500-515 ft bls, and
4) 519-534 ft bls (variable discharge).

The well casing extends to a depth of 462 ft bls, and the water table is at 461 ft bls. The stratigraphic units identified in this well are shown in Figure A1 (Anderson, 1991; Anderson, pers. comm). Depths greater than 534 ft bls were not tested due to borehole deviation incompatible with packer dimensions.

462-477 ft bls

This interval consists of a massive basalt from 462-470 ft bls. Video logs show that the basalt has sparse vesicles and isolated vertical fractures from 467-470 ft. Vesicles are more common, but decrease with depth, over the interval from 472-481 ft bls. The reddish basalt at a depth of 470-471 ft may be a rubble zone.

An aquifer test for this interval was initiated on August 19, 1993; however, the test was terminated after less than one half minute of pumping because the drawdown was greater than five feet. The relatively large drawdown raised concerns that the interval would be pumped dry and damage the pump. Because of the short duration of this test it was not possible to measure the discharge rate. Discharge rates for the aquifer tests typically ranged from

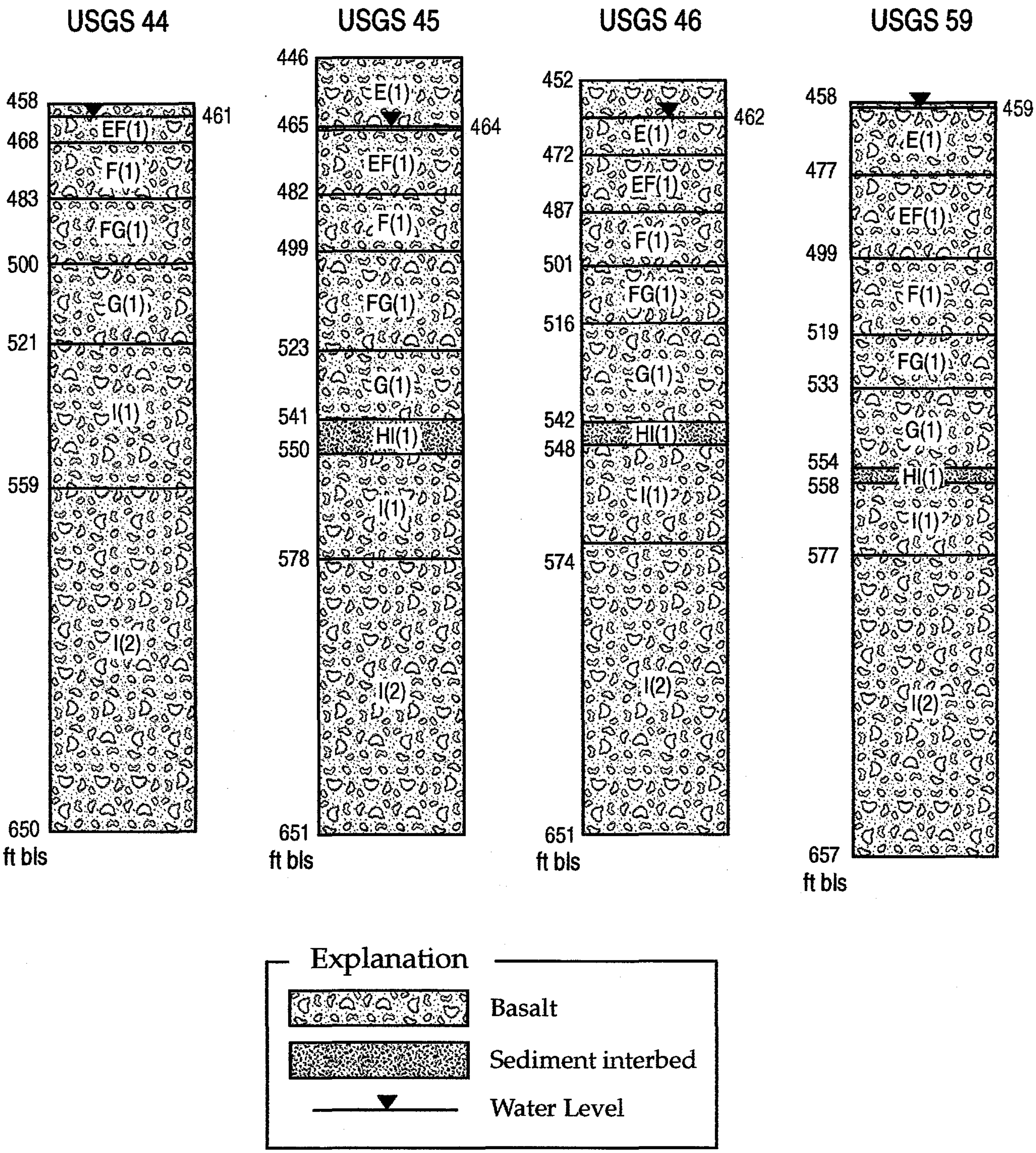


Figure A1 Stratigraphic units identified in wells USGS 44, 45, 46, and 59 (after Anderson, 1996).

1.5 to 2.5 ft^3/min, so it was assumed that the discharge rate was 2.0 ft^3/min. The estimated aquifer properties should be interpreted with caution as only three data points were used. The data were not evaluated using the Moench curve for double-porosity because the number of variables in the Moench solution exceeded the number of data points.

An estimate of hydraulic conductivity was obtained from the specific capacity determined from drawdown data collected while the interval was being pumped for geochemical sampling. During sampling, the discharge rate of approximately six gpm resulted in a drawdown of 4 to 4.5 ft, yielding a specific capacity of approximately 1.3 gpm/ft.

480-495 ft bls

From 480-485 ft, there is a vesicular basalt with isolated fractures which appear to have sediment infilling or secondary mineralization. A large breakout zone with red coloration occurs from 485-487 ft. It could not be determined from the TV log whether this zone is a rubble zone and/or a sedimentary interbed. The lower eight feet of this interval is a vesicular basalt with sparse vertical fractures. Because of the large breakout, a slab thickness of 13 ft was used for the Moench type curve analysis.

A 65-minute aquifer test was performed on this interval at an average discharge rate of 1.54 ft^3/min. The riser pipe was empty when the test was initiated, and took approximately five minutes to fill. As a result, the drawdown data collected while the riser pipe was filling were not considered in the evaluation of aquifer properties because of the variable discharge rate.

500-515 ft bls

The upper one foot of this interval is vesicular basalt with local vertical fractures. From 501-503 ft, there is a breakout zone. The remainder of the interval is a vesicular basalt which becomes massive over the lower three feet. A slab thickness of seven feet was assumed in the development of the Moench type curve.

An aquifer test lasting over 130 minutes at a discharge rate of 2.46 ft^3/min was performed on this interval on August 12, 1993. An anomalous increase in drawdown was observed after approximately 100 minutes of pumping so the test was repeated on August 13. However, the generator failed after 100 minutes of pumping at a discharge rate of 2.36 ft^3/min. The data collected on August 13 was compared to type curves to obtain estimates of hydraulic conductivity for this interval.

519-534 ft bls

The interval from 512-524 ft bls is a massive basalt which is vesicular over the lower two feet. TV logs suggest a large vertical fracture from 524-530, below which is 10 ft (530-540) of massive basalt. The massive basalt above and below this interval should provide an excellent seal with the straddle-packer.

An aquifer test was performed on this interval on August 5, 1993; however, as drawdown exceeded 20 ft it was necessary to adjust the discharge rate to prevent the interval from being pumped dry and damaging the pump. Consequently, the discharge rate was reduced to about six gpm, but was highly variable, resulting in unstable drawdowns that could not be matched to type curves.

An attempt was made to provide some information on the hydraulic conductivity of this zone by using the equation developed by Ackerman (1991). The drawdown after 30-minutes of pumping was

24.5 ft. Assuming a discharge rate of six gpm, this yields a specific capacity of 0.2 gpm/ft, and an estimated hydraulic conductivity of 0.0003 ft/min (0.4 ft/day). However, there is considerable uncertainty in this estimate due to variable discharge.

Well 46

Aquifer tests were performed at the following intervals in USGS 46:

1) Water table to 483 ft bls
2) 488-506 ft bls
3) 507-525 ft bls
4) 531-549 ft bls
5) 553-571 ft bls
6) 575-593 ft bls

Discharge rates ranged from six to eighteen gallons per minute, and in several of the intervals no measurable drawdown occurred during the aquifer test. The stratigraphic sequence penetrated by this well is shown in Figure A1.

Water Table-483 ft bls

The depth to water in USGS 46 is about 458 ft bls, and the well is cased to a depth of 460 feet. This interval is a vesicular basalt with vertical fractures from 460-484 ft bls, consequently the lower packer may not have formed an effective seal.

On Sept. 14, an aquifer test was performed on this interval for approximately 27 minutes at an average discharge rate of 17.7 gpm. Hydraulic head measured by the middle transducer increased during pumping, indicating some extraneous effect was sufficient to mask the response to pumping. An increasing discharge rate could be responsible for the decrease in drawdown; however, static head after completion of the test was 0.01 ft greater than static conditions before the test began, suggesting an impact from barometric pressure changes or cessation of pumping in the ICPP production well.

<u>488-506 ft bls</u>

From 484-489 ft bls, the basalt is vesicular, and locally massive. Vertical fractures and small breakout zones are visible in the vesicular basalt from 489-502 ft bls. The basalt is more massive, with sparse vesicles, from a depth of 502-511 ft.

Drawdown was monitored during the USGS ground-water sampling on Sept. 15 to determine if a more complete aquifer test should be performed on this interval. These data indicated that less than 0.02 ft of drawdown occurred at a pumping rate of approximately 6.5 gpm, therefore, an aquifer test was not performed on this interval.

<u>507-525 ft bls</u>

The upper five feet of this interval is a massive basalt. Small breakouts and vertical fractures are present in the basalt from 511-519 ft. At depths of 519-535 ft bls, the basalt is primarily massive, with some vesicles and vertical fractures.

On Sept. 27, 1993, this interval was pumped at a rate of 2.41 ft^3/min. There was no measurable drawdown, so the pump was shut off after only 2.9 minutes of pumping.

<u>531-549 ft bls</u>

The upper ten feet of this interval is a massive basalt, with a vertical fracture at about 540 ft. A small breakout is present in the basalt from 541-546 ft, and it appears that there may be some secondary mineralization in this zone. The basalt is vesicular and shows evidence of vertical fractures from 546-549 ft bls, and grades into a massive basalt from 549-553 ft bls. The Moench type curve analysis assumed a slab thickness of 17-ft.

This interval was pumped at a rate of 18 gpm for 78 minutes on September 29, 1993. The maximum drawdown measured during the test was 0.57 ft.

<u>553-571 ft bls</u>

A massive basalt is present from 549-553 ft bls, below which is a small breakout zone two feet thick. The basalt is vesicular and contains vertical fractures from 555-561 ft, and massive from 561-568 ft. From 568 to 575 ft is a vesicular basalt which is locally massive from 570-575. A slab thickness of 17-ft was used for the Moench type curve.

An 81-minute aquifer test at about 18 gpm was performed on this interval on October 1, 1993. Maximum drawdown was about 0.06 ft; however, the hydraulic head did not recover to pre-test levels after completion of the test. The increase in drawdown after approximately 30 minutes of pumping is probably due to pumping at the ICPP production well. Therefore, the maximum drawdown due to pumping with the straddle-packer pump is probably closer to 0.03 ft.

<u>575-593 ft bls</u>

There is a small breakout in the basalt from 575-577 ft bls. From 577 to 649 ft bls the basalt is vesicular to massive.

This interval was pumped for USGS water-sampling from 07:40 to 15:26 on Sept. 21 at a discharge rate of approximately six gpm. The drawdown from pumping was masked by effects of the ICPP production well and up to 0.1 ft of variation in head readings, probably due to a variable discharge rate.

Well 59

Aquifer tests were performed at the following intervals in Well 59:

1) 462 to 480 feet below land surface (bls)
2) 484-502 ft bls
3) 517-535 ft bls
4) 538-556 ft bls

Discharge rates ranged from 4 to 20 gallons per minute, and specific intervals were pumped from 30 to 68 minutes. The drawdown in the pumped interval ranged from 0.03 ft to 10.8 ft. The water level in the aquifer was about 459 feet below land surface, and the well is cased to a depth of 459 ft. Drawdown stabilized almost immediately after pumping began in the tests conducted in the three lower intervals. This is probably the result of vertical leakage into the pumped interval. Stratigraphic units identified in USGS 59 are shown in Figure A1.

462 to 480 feet bls

The basalt from 460-465 ft bls is massive, and small breakouts and fractures are present from 465-474 ft. The TV log shows a vesicular basalt from 477-482 ft. A slab thickness of 10-ft was used to generate the Moench type curve.

A 62-minute aquifer test was performed on this interval at an average discharge rate of 0.54 ft^3/minute. Maximum drawdown during the test was 10.8 feet.

484 to 502 ft bls

Vertical fractures are present in the basalt from 484-490 ft bls. A large breakout from 490-503 ft bls may be a interflow zone. From 503-507 ft the basalt is vesicular. Due to the large breakout, a slab thickness of two feet was assumed for the Moench type curve.

This interval was pumped at a rate of 0.63 ft^3/minute for 36 minutes. The maximum drawdown during the aquifer test was approximately 0.9 ft.

517 to 535 ft bls

A vesicular basalt is present from 509-517 ft bls. There is a small breakout from 517-519 ft, and vesicular basalt from 519-522 ft. The large breakout from 522-528 ft may be a interflow zone. Horizontal fractures are present in the basalt from 528-532 ft, and the interval from 532-535 ft contains a large vertical fracture. A slab thickness of two feet was used to generate the Moench type curve.

This interval was pumped for approximately 68 minutes at a rate of 2.68 ft^3/min. One early-time measurement was deleted as it corresponded to filling the riser pipe, and thus was measured at a higher discharge rate. The hydraulic head didn't return to the static level measured prior to the test, therefore the apparent increase in drawdown about five minutes into the test is probably due to pumping of the ICPP production well.

538 to 556 ft bls

Horizontal fractures are present in the basalt from 535-540 ft bls, and there is a small breakout from 540-545 ft. A massive basalt is present from 545-551 ft, with a sedimentary interbed at 551-553 ft and a small breakout from 553-557 ft. This probably corresponds to sedimentary interbed HI(1), which is shown at a depth of 554-558 ft bls in Figure A1. Below the interval, from 557-560 ft, is a vesicular basalt which overlies a broken basalt zone that is fifteen feet thick. A slab thickness of three feet was used for the Moench type curve.

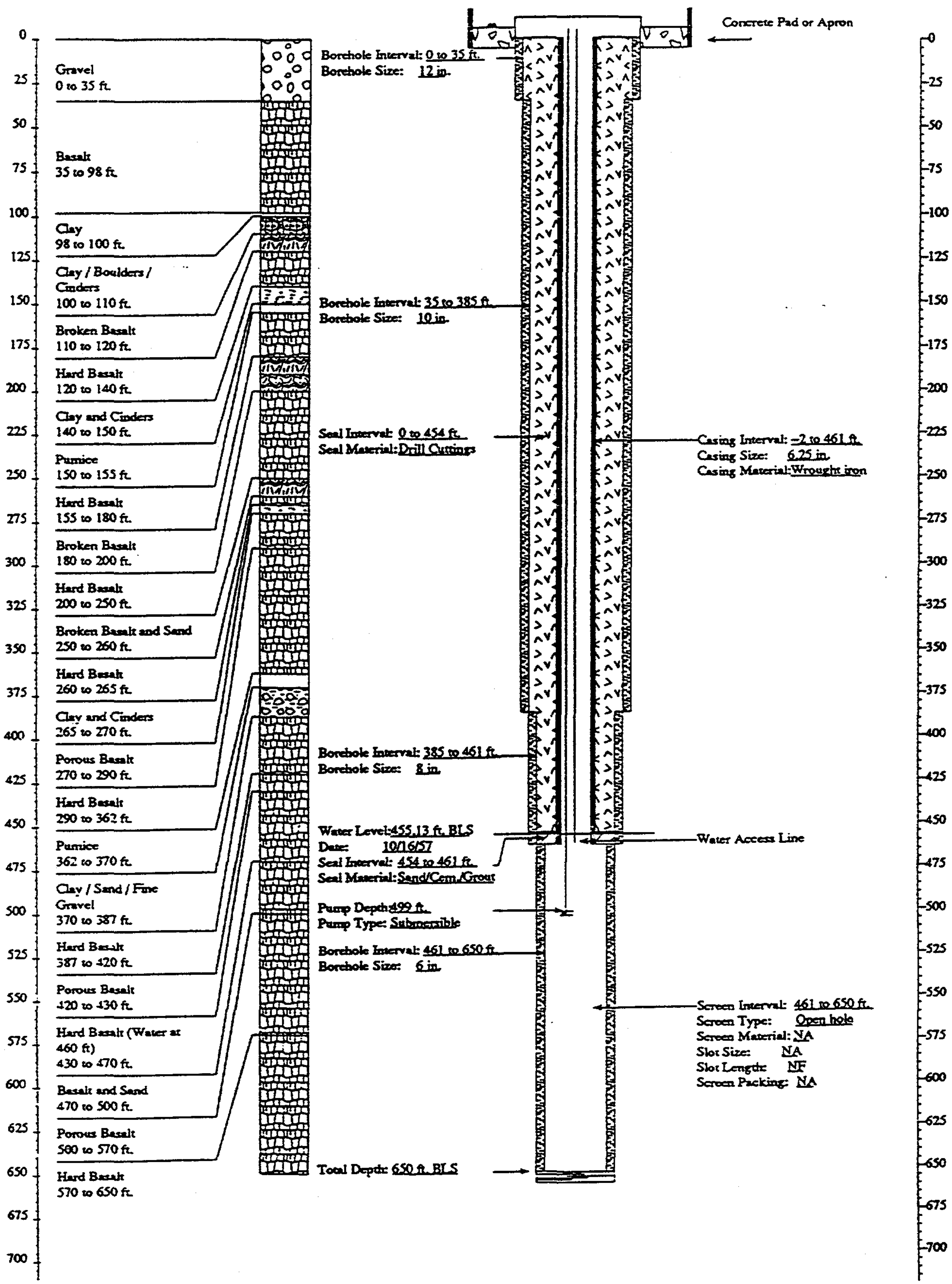
A 30 minute aquifer test was performed on this interval at a discharge rate of 2.68 ft^3/min. The drawdown data suggest that the discharge rate decreased during the first one minute of pumping, so those data were ignored in the interpretation of the results.

APPENDIX B

LITHOLOGIC DESCRIPTION FROM DRILLERS' LOGS OF TESTED WELLS

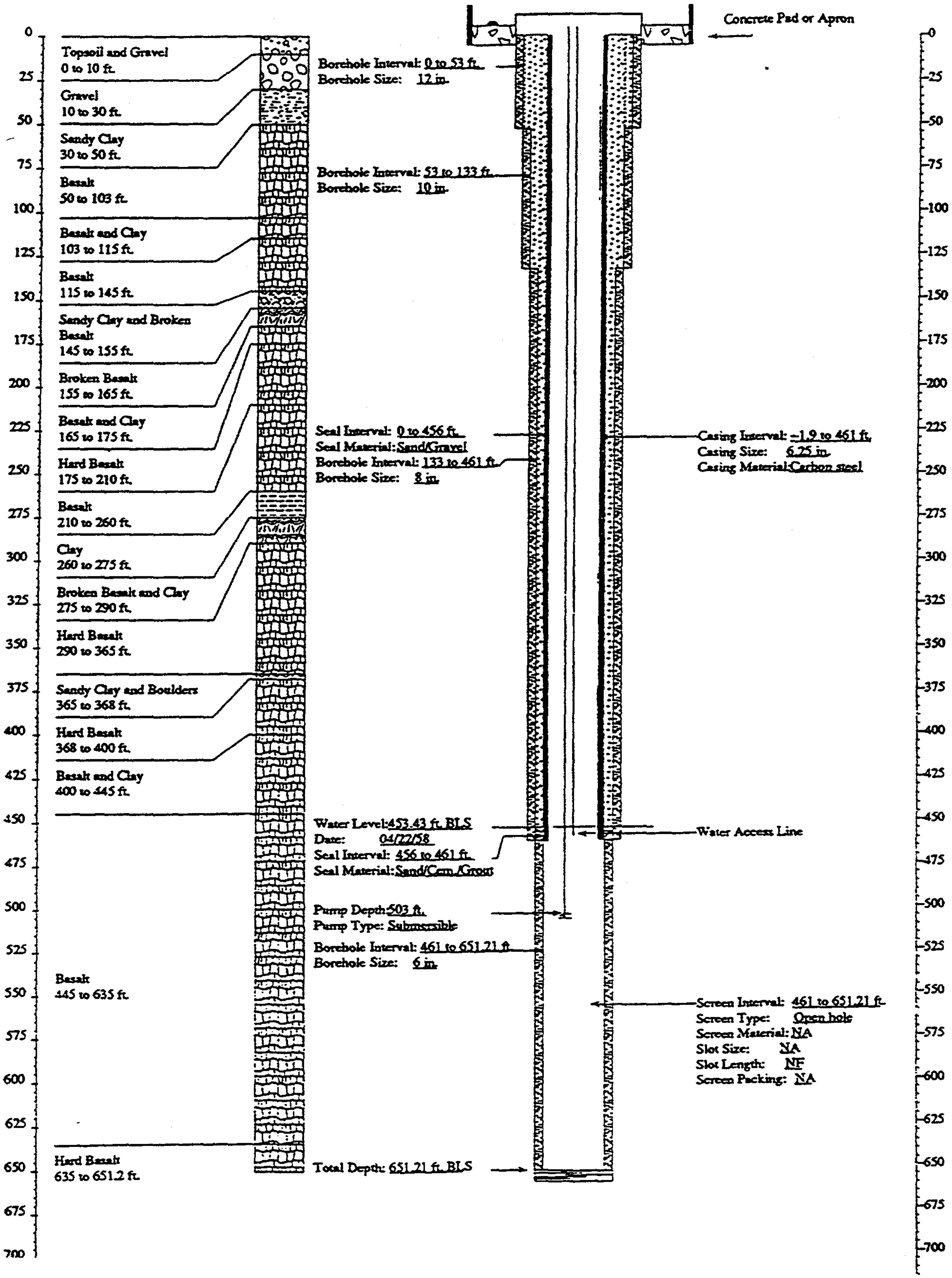
(from Sehlke, G., D.E. Davis, W.W. Tullock, and J.A. Williams, 1993, Well fitness evaluation for the Idaho National Engineering Laboratory, U.S. Department of Energy Idaho Field Office, DOE/ID-10392, 7 volumes)

USGS-44

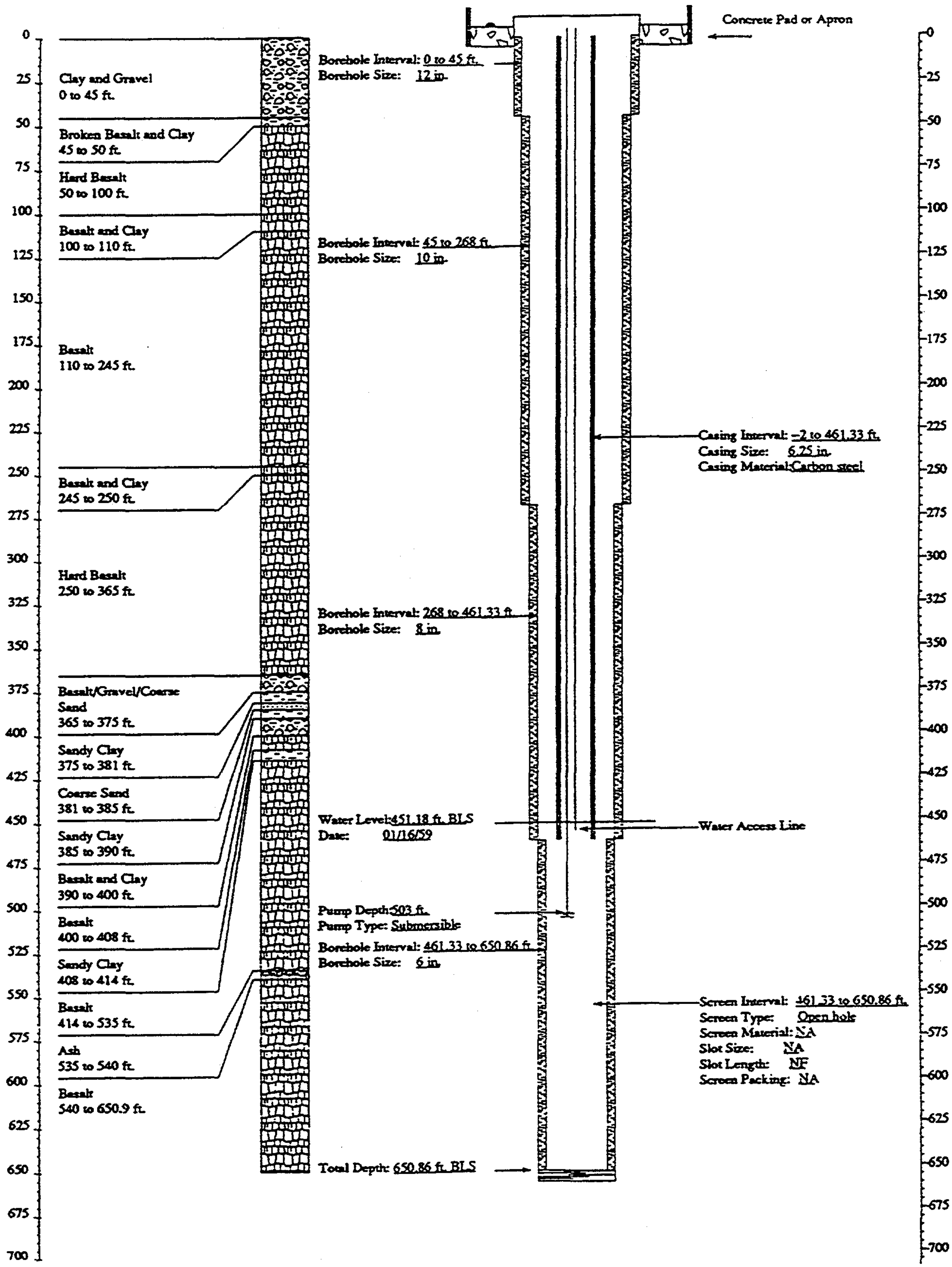


Concrete Pad or Apron
Gravel 0 to 35 ft.
Basalt 35 to 98 ft.
Clay 98 to 100 ft.
Clay / Boulders / Cinders 100 to 110 ft.
Broken Basalt 110 to 120 ft.
Hard Basalt 120 to 140 ft.
Clay and Cinders 140 to 150 ft.
Pumice 150 to 155 ft.
Hard Basalt 155 to 180 ft.
Broken Basalt 180 to 200 ft.
Hard Basalt 200 to 250 ft.
Broken Basalt and Sand 250 to 260 ft.
Hard Basalt 260 to 265 ft.
Clay and Cinders 265 to 270 ft.
Porous Basalt 270 to 290 ft.
Hard Basalt 290 to 362 ft.
Pumice 362 to 370 ft.
Clay / Sand / Fine Gravel 370 to 387 ft.
Hard Basalt 387 to 420 ft.
Porous Basalt 420 to 430 ft.
Hard Basalt (Water at 460 ft) 430 to 470 ft.
Basalt and Sand 470 to 500 ft.
Porous Basalt 500 to 570 ft.
Hard Basalt 570 to 650 ft.
Borehole Interval: 0 to 35 ft.
Borehole Size: 12 in.
Borehole Interval: 35 to 385 ft.
Borehole Size: 10 in.
Seal Interval: 0 to 454 ft.
Seal Material: Drill Cuttings
Casing Interval: -2 to 461 ft.
Casing Size: 6.25 in.
Casing Material: Wrought iron
Borehole Interval: 385 to 461 ft.
Borehole Size: 8 in.
Water Level: 455.13 ft. BLS
Date: 10/16/57
Seal Interval: 454 to 461 ft.
Seal Material: Sand/Cem./Grout
Water Access Line
Pump Depth: 499 ft.
Pump Type: Submersible
Borehole Interval: 461 to 650 ft.
Borehole Size: 6 in.
Screen Interval: 461 to 650 ft.
Screen Type: Open hole
Screen Material: NA
Slot Size: NA
Slot Length: NF
Screen Packing: NA
Total Depth: 650 ft. BLS
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
575
600
625
650
675
700

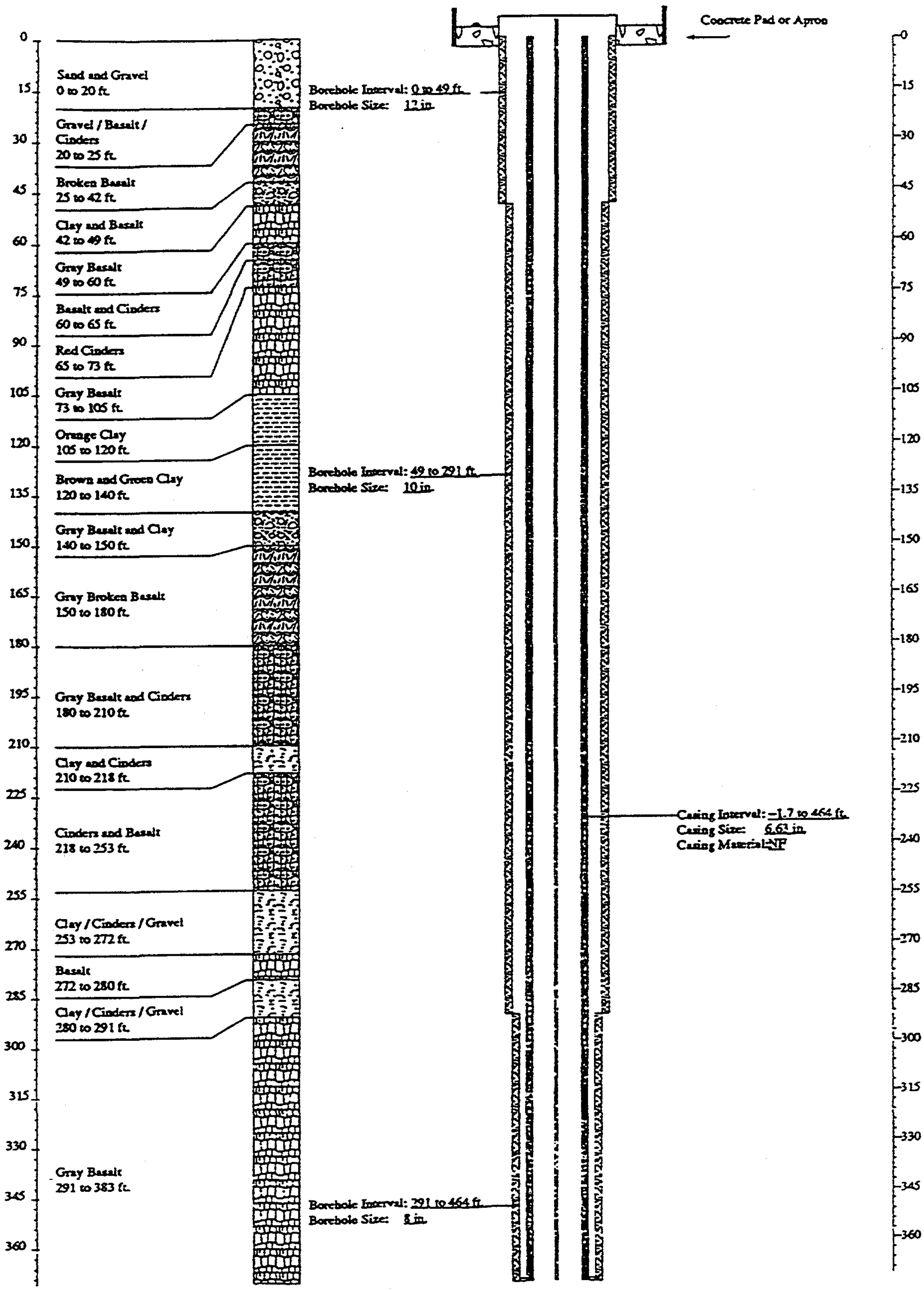
USGS-45


Concrete Pad or Apron
Topsoil and Gravel
0 to 10 ft.
Gravel
10 to 30 ft.
Sandy Clay
30 to 50 ft.
Basalt
50 to 103 ft.
Basalt and Clay
103 to 115 ft.
Basalt
115 to 145 ft.
Sandy Clay and Broken
Basalt
145 to 155 ft.
Broken Basalt
155 to 165 ft.
Basalt and Clay
165 to 175 ft.
Hard Basalt
175 to 210 ft.
Basalt
210 to 260 ft.
Clay
260 to 275 ft.
Broken Basalt and Clay
275 to 290 ft.
Hard Basalt
290 to 365 ft.
Sandy Clay and Boulders
365 to 368 ft.
Hard Basalt
368 to 400 ft.
Basalt and Clay
400 to 445 ft.
Basalt
445 to 635 ft.
Hard Basalt
635 to 651.2 ft.
Borehole Interval: 0 to 53 ft.
Borehole Size: 12 in.
Borehole Interval: 53 to 133 ft.
Borehole Size: 10 in.
Seal Interval: 0 to 456 ft.
Seal Material: Sand/Gravel
Borehole Interval: 133 to 461 ft.
Borehole Size: 8 in.
Casing Interval: -1.9 to 461 ft.
Casing Size: 6.25 in.
Casing Material: Carbon steel
Water Level: 453.43 ft. BLS
Date: 04/22/58
Seal Interval: 456 to 461 ft.
Seal Material: Sand/Cem./Grout
Water Access Line
Pump Depth: 503 ft.
Pump Type: Submersible
Borehole Interval: 461 to 651.21 ft.
Borehole Size: 6 in.
Screen Interval: 461 to 651.21 ft.
Screen Type: Open hole
Screen Material: NA
Slot Size: NA
Slot Length: NF
Screen Packing: NA
Total Depth: 651.21 ft. BLS
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
575
600
625
650
675
700

USGS-46


Concrete Pad or Apron
Clay and Gravel
0 to 45 ft.
Broken Basalt and Clay
45 to 50 ft.
Hard Basalt
50 to 100 ft.
Basalt and Clay
100 to 110 ft.
Basalt
110 to 245 ft.
Basalt and Clay
245 to 250 ft.
Hard Basalt
250 to 365 ft.
Basalt/Gravel/Coarse Sand
365 to 375 ft.
Sandy Clay
375 to 381 ft.
Coarse Sand
381 to 385 ft.
Sandy Clay
385 to 390 ft.
Basalt and Clay
390 to 400 ft.
Basalt
400 to 408 ft.
Sandy Clay
408 to 414 ft.
Basalt
414 to 535 ft.
Ash
535 to 540 ft.
Basalt
540 to 650.9 ft.
Borehole Interval: 0 to 45 ft.
Borehole Size: 12 in.
Borehole Interval: 45 to 268 ft.
Borehole Size: 10 in.
Borehole Interval: 268 to 461.33 ft.
Borehole Size: 8 in.
Water Level: 451.18 ft. BLS
Date: 01/16/59
Pump Depth: 503 ft.
Pump Type: Submersible
Borehole Interval: 461.33 to 650.86 ft.
Borehole Size: 6 in.
Total Depth: 650.86 ft. BLS
Casing Interval: -2 to 461.33 ft.
Casing Size: 6.25 in.
Casing Material: Carbon steel
Water Access Line
Screen Interval: 461.33 to 650.86 ft.
Screen Type: Open hole
Screen Material: NA
Slot Size: NA
Slot Length: NF
Screen Packing: NA
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
575
600
625
650
675
700

USGS-59


Concrete Pad or Apron
Sand and Gravel
0 to 20 ft.
Gravel / Basalt / Cinders
20 to 25 ft.
Broken Basalt
25 to 42 ft.
Clay and Basalt
42 to 49 ft.
Gray Basalt
49 to 60 ft.
Basalt and Cinders
60 to 65 ft.
Red Cinders
65 to 73 ft.
Gray Basalt
73 to 105 ft.
Orange Clay
105 to 120 ft.
Brown and Green Clay
120 to 140 ft.
Gray Basalt and Clay
140 to 150 ft.
Gray Broken Basalt
150 to 180 ft.
Gray Basalt and Cinders
180 to 210 ft.
Clay and Cinders
210 to 218 ft.
Cinders and Basalt
218 to 253 ft.
Clay / Cinders / Gravel
253 to 272 ft.
Basalt
272 to 280 ft.
Clay / Cinders / Gravel
280 to 291 ft.
Gray Basalt
291 to 383 ft.
Borehole Interval: 0 to 49 ft.
Borehole Size: 12 in.
Borehole Interval: 49 to 291 ft.
Borehole Size: 10 in.
Borehole Interval: 291 to 464 ft.
Borehole Size: 8 in.
Casing Interval: -1.7 to 464 ft.
Casing Size: 6.63 in.
Casing Material: NF
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
360