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GEOLOGIC CONTROLS OF HYDRAULIC CONDUCTIVITY IN THE SNAKE RIVER PLAIN AQUIFER AT AND NEAR THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY, IDAHO

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4033

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY

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Geologic Controls of Hydraulic Conductivity in the Snake River Plain Aquifer at and near the Idaho National Engineering and Environmental Laboratory, Idaho

By S.R. Anderson, Mel A. Kuntz, *and* Linda C. Davis

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Idaho Falls, Idaho
February 1999

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND ABBREVIATED UNITS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/y)	1,233	cubic meter per year

For temperature, degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F=(1.8)(°C) + 32.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Geologic Controls of Hydraulic Conductivity in the Snake River Plain Aquifer at and near the Idaho National Engineering and Environmental Laboratory, Idaho

By S.R. Anderson, Mel A. Kuntz, *and* Linda C. Davis

Abstract

The effective hydraulic conductivity of basalt and interbedded sediment that compose the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory (INEEL) ranges from about 1.0×10^{-2} to 3.2×10^{4} feet per day (ft/d). This six-order-of-magnitude range of hydraulic conductivity was estimated from single-well aquifer tests in 114 wells, and is attributed mainly to the physical characteristics and distribution of basalt flows and dikes. Hydraulic conductivity is greatest in thin pahoehoe flows and near-vent volcanic deposits. Hydraulic conductivity is least in flows and deposits cut by dikes. Estimates of hydraulic conductivity at and near the INEEL are similar to those measured in similar volcanic settings in Hawaii.

The largest variety of rock types and the greatest range of hydraulic conductivity are in volcanic rift zones, which are characterized by numerous aligned volcanic vents and fissures related to underlying dikes. Volcanic features related to individual dike systems within these rift zones are approximated in the subsurface by narrow zones referred to as vent corridors. Vent corridors at and near the INEEL are generally perpendicular to ground-water flow and average about 1 to 2 miles in width and 5 to 15 miles in length. Forty-five vent corridors are inferred to be beneath the INEEL and adjacent areas. Vent corridors are characterized locally by anoxic water and altered basalt. In many of the vent corridors, water from the uppermost 200 feet of the aquifer is 1 to 7 degrees Celsius warmer than the median temperature of water (13 degrees Celsius) throughout the aquifer.

Three broad categories of hydraulic conductivity corresponding to six general types of geologic controls can be inferred from the distribution of wells and vent corridors. Hydraulic conductivity of category 1 includes 73 estimates, ranges from 1.0×10^{2} to 3.2×10^{4} ft/d, and corresponds to (1) the contacts, rubble zones, and cooling fractures of thin, tube-fed pahoehoe flows; and (2) the numerous voids present in shelly pahoehoe and slab pahoehoe flows; and bedded scoria, spatter, and ash near volcanic vents. Hydraulic conductivity of category 2 includes 28 estimates, ranges from 1.0×10^{0} to 1.0×10^{2} ft/d, and corresponds to (3) relatively thick, tube-fed pahoehoe flows that may be ponded in topographic depressions; and (4) thin, tube-fed pahoehoe flows cut by discontinuous dikes. Hydraulic conductivity of category 3 includes 13 estimates, ranges from 1.0×10^{-2} to 1.0×10^{0} ft/d, and corresponds to (5) localized dike swarms; and (6) thick, tube-fed pahoehoe flows cut by discontinuous dikes. Some overlap between these categories and controls is likely because of the small number of hydraulic conductivity estimates and the complex geologic environment.

Hydraulic conductivity of basalt flows probably is increased by localized fissures and coarse mixtures of interbedded sediment, scoria, and basalt rubble. Hydraulic conductivity of basalt flows is decreased locally by abundant alteration minerals of probable hydrothermal origin. Hydraulic conductivity varies as much as six orders of magnitude in a single vent corridor and varies from three to five orders of magnitude within distances of 500 to 1,000 feet. Abrupt changes in hydraulic conductivity over short distances suggest the presence of preferential pathways and local barriers that may greatly affect the movement of ground water and the dispersion of radioactive and chemical wastes downgradient from points of waste disposal.

INTRODUCTION

The Idaho National Engineering and Environment Laboratory (INEEL), operated by the U.S. Department of Energy (DOE) and formerly known as the Idaho National Engineering Laboratory, covers about 890 mi^2 of the eastern Snake River Plain in eastern Idaho (fig. 1). Facilities at the INEEL are used in the development of peacetime atomic-energy applications, nuclear-safety research, defense programs, and advanced energy concepts. Liquid radionuclide and chemical wastes generated at these facilities have been discharged to onsite infiltration ponds and disposal wells since 1952; use of disposal wells was discontinued in 1984. Liquid-waste disposal has resulted in detectable concentrations of several waste constituents in water from the Snake River Plain aquifer underlying the INEEL (Bartholomay and others, 1997).

Concern about the potential for migration of radioactive and chemical wastes in the unsaturated zone and the aquifer has resulted in numerous geologic, hydrologic, and geochemical studies of the subsurface at and near the INEEL. From 1988 to 1997, the U.S. Geological Survey (USGS), in cooperation with the DOE, conducted a sitewide study of the stratigraphy of basalt and sediment underlying the INEEL and adjacent areas to determine stratigraphic relations that might affect the movement of wastes (Anderson and Lewis, 1989; Anderson, 1991; Lanphere and others, 1993, 1994; Anderson and Bowers, 1995; Anderson and others, 1996a; Reed and others, 1997; Anderson and Liszewski, 1997). Stratigraphic relations were determined from selected core data and natural-gamma logs (Anderson and Bartholomay, 1995). During this time, many single-well aquifer tests also were performed to estimate the range and distribution of transmissivity and hydraulic conductivity of the basalt and sediment (Ackerman, 1991; Bartholomay and others, 1997). Estimates of transmissivity and hydraulic conductivity vary almost six orders of magnitude over distances of a few hundreds to a few thousands of feet. This six-order-of-magnitude range and its distribution have been attributed, in part, to local variations in basalt stratigraphy that affect the number of basalt-flow contacts at any one place in the aquifer (Morin and others, 1993; Welhan and others, 1997; Welhan and Reed, 1997; Welhan and Wylie, 1997). These contacts, which form the main conduits for ground-water flow, typically have zones of irregular fractures and voids that are characterized by hydraulic conductivities greater than those of massive flow interiors. Other factors that probably affect the range and distribution of transmissivity and hydraulic conductivity include the presence of sedimentary interbeds (Geslin and others, 1997), rock alteration (Mann, 1986; Morse and McCurry, 1997), and vents, dikes, and fissures in volcanic rift zones (Kuntz, 1992; Kuntz and others, 1992; Smith and others, 1996; Hughes and others, 1997).

Purpose and Scope

This report describes numerous geologic controls of hydraulic conductivity in the Snake River Plain aquifer at and near the INEEL. Specifically, this report proposes and describes a relation, not previously documented, between hydraulic conductivity, basalt stratigraphy, and the distribution of vents, dikes, and fissures in volcanic rift zones at and near the INEEL. This relation is based on the assumption that hydraulic conductivity of basalt contacts, rubble zones, and cooling fractures is increased or decreased by localized near-vent volcanic deposits, dikes, and fissures. Areas near volcanic vents are composed mostly of highly permeable flows and scoria-ash deposits. Dikes are dense, vertical sheets of basalt that impede the movement of ground water. Fissures are highly permeable, vertical openings in basalt. Many vents and most dikes and fissures are concealed by surficial basalt flows and sediment; therefore, the probable locations of these volcanic features and their effects on hydraulic conductivity were inferred from indirect data, including data from similar volcanic settings in Hawaii (Meyer and Souza, 1995). The effects of sediment and rock alteration on hydraulic conductivity also were considered, although the amount of sediment and rock alteration is not significant in most parts of the Snake River Plain aquifer at and near the INEEL.

The relation between hydraulic conductivity, basalt stratigraphy, and volcanic features at and near the INEEL was evaluated using transmissivity estimates from 114 wells (Ackerman, 1991; Bartholomay and others, 1997), stratigraphic data from 333 wells (Anderson and others, 1996a), and

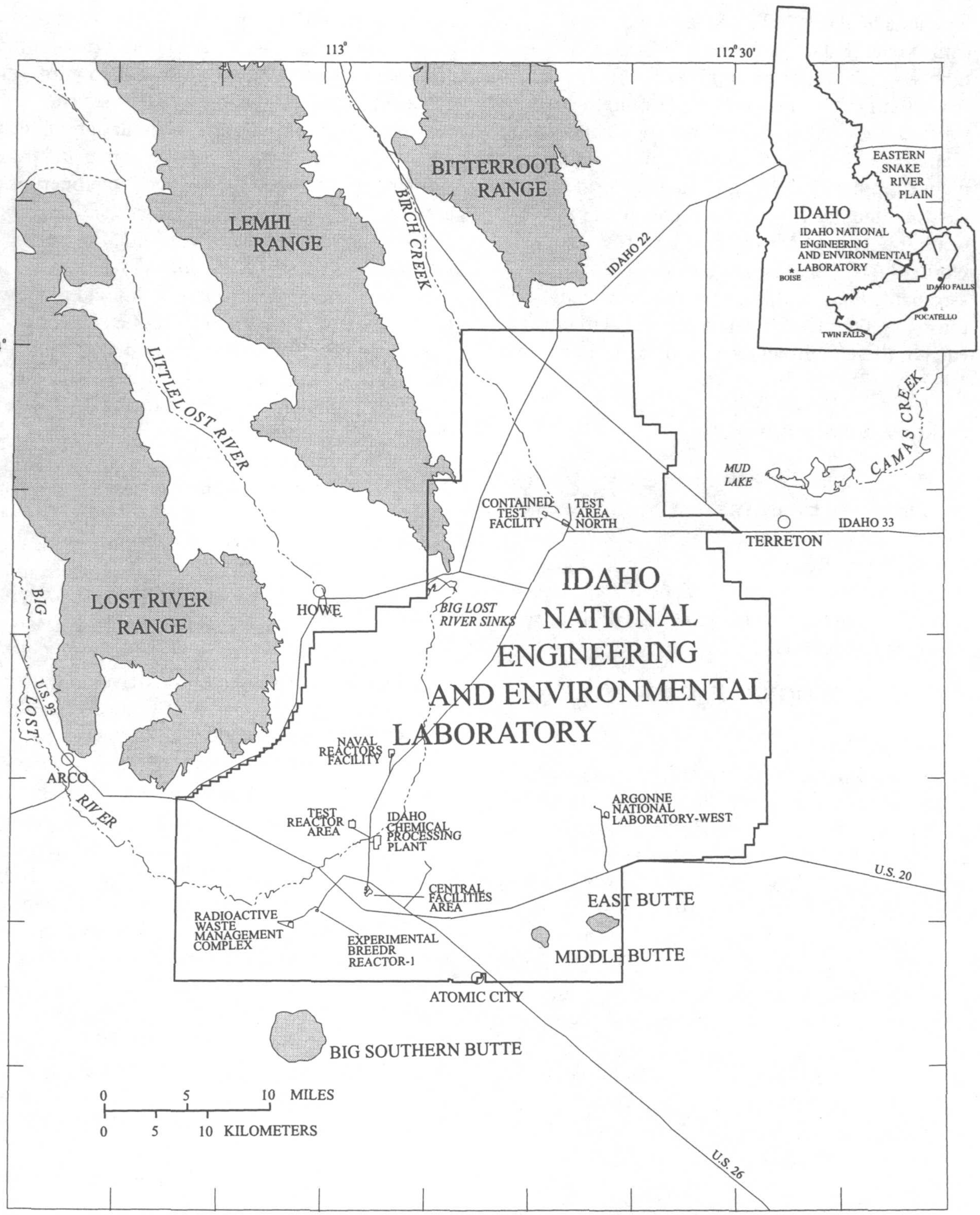

Figure 1. Location of the Idaho National Engineering and Environmental Laboratory and selected facilities.

locations of about 200 surficial and concealed volcanic vents (Kuntz and others, 1994; Hughes and others, 1997; Anderson and Liszewski, 1997). About half of the transmissivity estimates and two-thirds of the stratigraphic data were obtained from wells at and near the Radioactive Waste Management Complex (RWMC), Idaho Chemical Processing Plant (ICPP), Test Reactor Area (TRA), Central Facilities Area (CFA), and Test Area North (TAN) (figs. 1-3). Volcanic vents and their associated dikes and fissures are distributed throughout the INEEL and are inferred to underlie each of these facilities (Anderson and Liszewski, 1997, fig. 7).

Acknowledgments

The clarity and technical content of this report were improved by reviews from Scott S. Hughes, Idaho State University, and Stephen B. Gingerich, USGS, Water Resources Division. The authors also thank Angela Schmidt, Idaho State University, for her assistance in preparing GIS illustrations for this report.

GEOHYDROLOGIC SETTING

The INEEL is located on the west-central part of the eastern Snake River Plain, a northeast-trending structural basin about 200 mi long and 50 to 70 mi wide (fig. 1). The INEEL is underlain by a sequence of Tertiary and Quaternary volcanic rocks and sedimentary interbeds that is more than 10,000 ft thick (Whitehead, 1992). The volcanic rocks consist mainly of basalt flows in the upper part of the sequence and rhyolitic ash-flow tuffs in the lower part. Basalt and sediment generally range in age from about 200 thousand to 4 million years before present (Anderson and others, 1997) and underlie the plain to depths ranging from about 2,200 to 3,800 ft below land surface in the southwestern part of the INEEL near wells INEL #1 and NPR WO-2 (fig. 2).

The INEEL is underlain by hundreds of basalt flows, basalt-flow groups, and sedimentary interbeds. Basalt makes up about 85 percent of the volume of deposits in most areas. A basalt flow is a solidified body of rock formed by a lateral, surficial outpouring of molten lava from a vent or fissure (Bates and Jackson, 1980). A basalt-flow group consists of one or more distinct basalt flows deposited during a single, brief eruptive event (Kuntz and others, 1980). All basalt flows of a group erupted from the same vent or several nearby vents; represent the accumulation of one or more lava fields from the same magma; and have similar geologic ages, paleomagnetic properties, potassium contents, and natural-gamma emissions (Anderson and Bartholomay, 1995). The basalt flows consist mainly of medium- to dark-gray vesicular to dense olivine basalt. Individual flows generally range from 10 to 50 ft thick and are locally interbedded with scoria and thin layers of sediment. Sedimentary interbeds are as thick as 50 ft and consist of well sorted to poorly sorted deposits of clay, silt, sand, and gravel. In places, the interbeds contain or consist mainly of scoria and basalt rubble. Sedimentary interbeds accumulated on the ancestral land surface for hundreds to hundreds of thousands of years during periods of volcanic quiescence, and are thickest between basalt-flow groups.

The basalt and sediment underlying the INEEL, where saturated, form the Snake River Plain aquifer. Depth to water at the INEEL ranges from about 200 ft below land surface in the northern part to about 900 ft in the southern part (Ott and others, 1992). The general direction of groundwater flow is northeast to southwest at an average hydraulic gradient of about 4 ft/mi. The effective base of the aquifer at the INEEL dips towards the southwest and the center of the plain, and generally coincides with the top of a thick and widespread layer of clay, silt, sand, and altered basalt that is equivalent in age to the Glenns Ferry Formation of southern Idaho (Mann, 1986; Whitehead, 1992; Repenning and others, 1995; Anderson and Liszewski, 1997). The top of this layer ranges in depth from 815 to 1,710 ft below land surface in the western half of the INEEL (Anderson and Liszewski, 1997, table 3). The effective saturated thickness of the aquifer ranges from about 450 ft near the TRA to about 1,200 ft near the ICPP and RWMC (fig. 1). Saturated thickness in the eastern half of the INEEL may be greater than 1,200 ft.

Hydraulic properties of the aquifer differ considerably from place to place depending on the

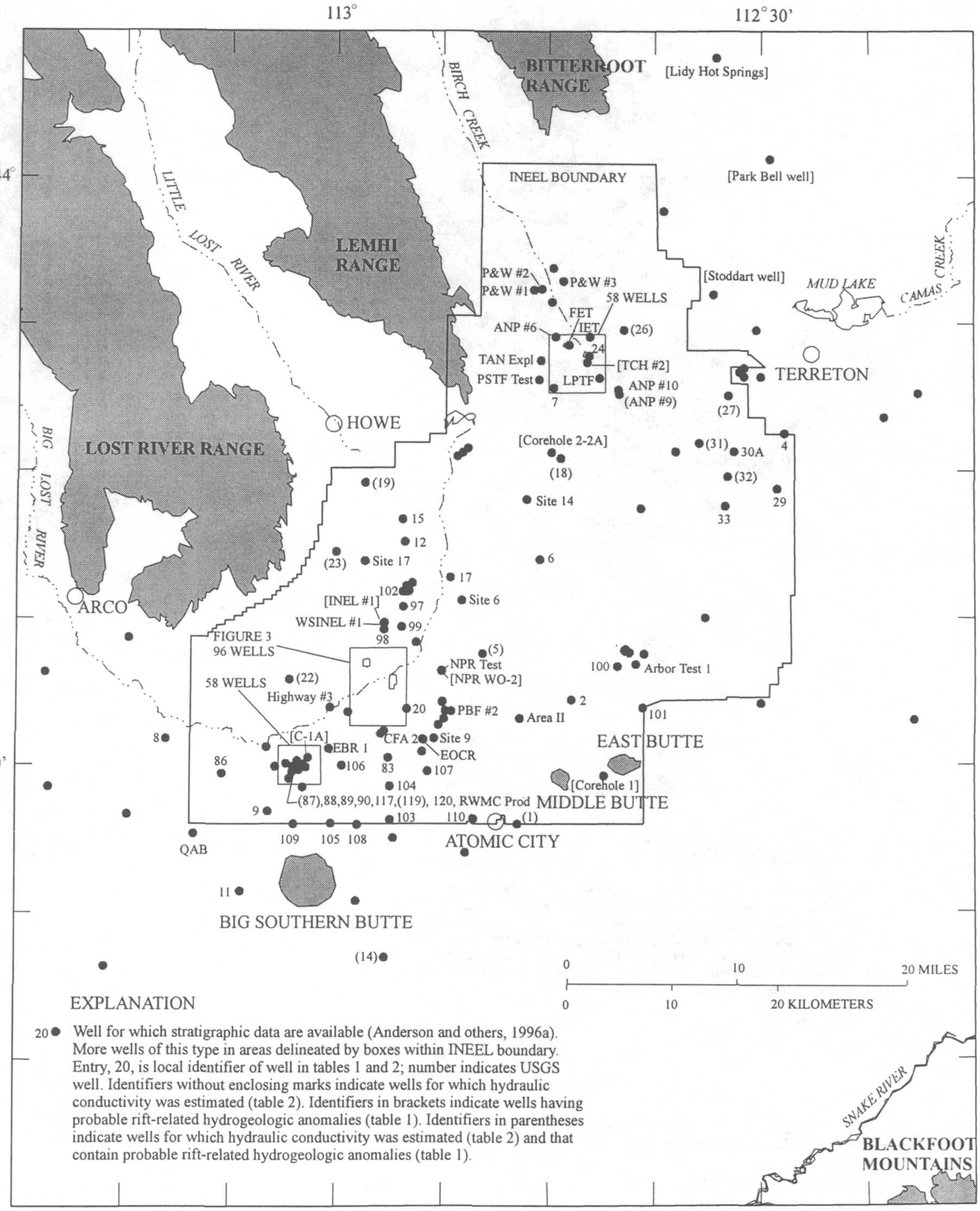

Figure 2. Location of wells at and near the Idaho National Engineering and Environmental Laboratory for which stratigraphic data and estimates of hydraulic conductivity are available.

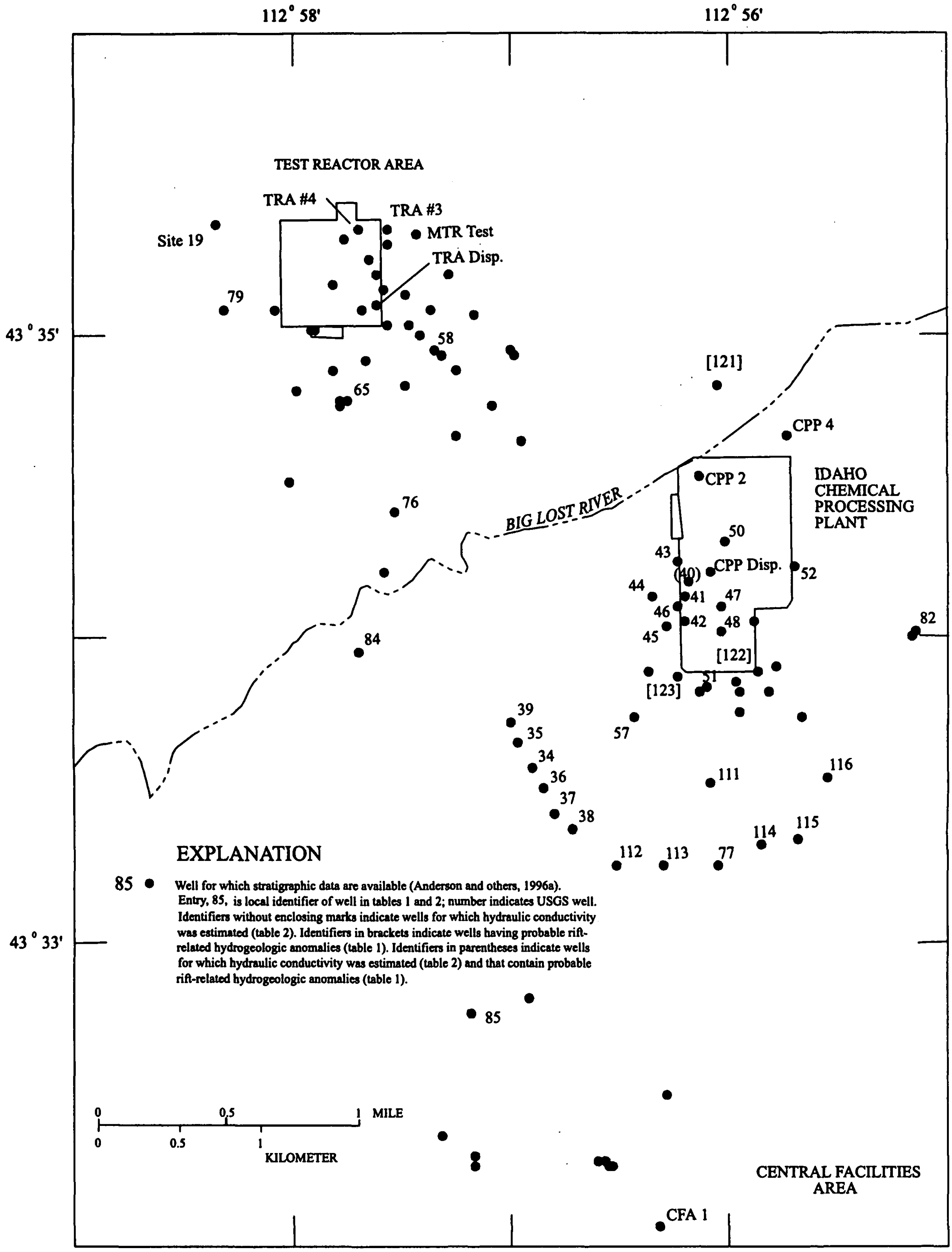

Figure 3. Locations of wells at and near the Idaho Chemical Processing Plant, Test Reactor Area, and Central Facilities Area for which stratigraphic data and estimates of hydraulic conductivity are available.

layering and physical characteristics of the basalt and sediment. In places, the basalt and sediment in the uppermost part of the aquifer yield thousands of gpm of water to wells, with negligible drawdown (Ackerman, 1991). Hydraulic data for altered basalt, sediment, and rhyolitic ash-flow tuffs underlying the aquifer are sparse, but data from well INEL #1 (fig. 2) indicate that these rocks are much less transmissive than those in the aquifer (Mann, 1986). Localized zones of perched ground water, which are attributed mainly to infiltration of water from unlined percolation ponds and recharge from the Big Lost River, are present in basalt and sediment overlying the regional aquifer (Cecil and others, 1991). In places, geothermal water likely circulates upward from deep, underlying rocks into the Snake River Plain aquifer (Mann, 1986; McLing and Smith, 1997; Morse and McCurry, 1997). Upward circulation of this water is suggested by increased hydraulic head with depth in wells INEL #1 and Corehole 2-2A (fig. 2), open fissures in volcanic rift zones that cross the INEEL, and numerous geothermal springs along the edges of the eastern Snake River Plain. Geothermal water probably is greatly diluted by the much larger volume of cold water that recharges the aquifer.

Stratigraphy

At least 178 basalt-flow groups and 103 sedimentary interbeds underlie the INEEL above the effective base of the aquifer (Anderson and others, 1996a; Anderson and Liszewski, 1997). Basalt-flow groups and sedimentary interbeds are informally referred to as A through S5. Basalt-flow groups AB through L and related sediment range in age from about 200 to 800 thousand years and make up the unsaturated zone and uppermost part of the aquifer in most areas of the INEEL. Basalt-flow groups LM through S5 and related sediment range in age from about 800 thousand to 1.8 million years and make up the unsaturated zone and aquifer at and near TAN (fig. 1) and the lowermost part of the aquifer elsewhere at the INEEL. Most wells in the southern and eastern parts of the INEEL are completed in basalt-flow groups AB through I and related sediment (Anderson, 1991). Flow groups AB through I and related sediment range in age from about 200 to 640 thousand years and make up a stratigraphic section characterized by horizontal to slightly inclined layers (fig. 4). Estimates of transmissivity and hydraulic conductivity are mainly of basalt flows of this age in the uppermost 300 ft of the aquifer. The stratigraphy of the aquifer at and near the ICPP is dominated by thick, massive-basalt flows of flow group I and thin, overlying flows of flow groups E through G (fig. 4).

Basalt Flows

Basalt flows in the Snake River Plain aquifer consist mainly of pahoehoe lava that issued from numerous eruptive fissures and small shield volcanoes (fig. 5) (Kuntz, 1992; Kuntz and others, 1992). High effusion rates and low lava viscosities, both of which characterize shield-type eruptions, favor numerous flow units and the formation of compound lava flows (Walker, 1970). Greater hydraulic conductivity is favored by the large number of rubble-covered surfaces between flow units in compound lava flows. Large-volume, tube-fed, shield-type lava fields are composed of numerous flow units of large areal extent, whereas surface-fed, fissure-type lava fields are smaller in volume and are composed of fewer flow units. Near-vent flows in shield-forming eruptions are composed mainly of shelly pahoehoe and slab pahoehoe (fig. 5). Greater hydraulic conductivity is favored in these types of near-vent deposits by their relatively large volumes of void spaces, which can be as much as 75 percent of the total volume.

The relative hydraulic conductivity associated with different types of volcanic rocks in the Snake River Plain aquifer can be inferred from outcrop exposures (Kuntz and others, 1994). The inferred relative hydraulic conductivity distribution through a typical buried shield volcano in the Snake River Plain aquifer (fig. 5) suggests that conductivity of a single lava field is greatest in near-vent volcanic deposits composed of shelly pahoehoe and slab pahoehoe flows and bedded scoria, spatter, and ash. These near-vent deposits typically cover about 10 to 20 percent of a lava field. Hydraulic conductivity of basalt flows is least for thick, tube-fed pahoehoe flows and ponded flows inside of vent craters and topographic depressions. Hydraulic conductivity of strati-

EXPLANATION

B — BASALT — Basalt–flow group composed of one or more related flows. Letter, B, indicates sequence of group from top to bottom of section. Locally includes cinders and thin layers of sediment

CLAY, SILT, SAND, AND GRAVEL — Major sedimentary interbed between basalt–flow groups. Locally includes cinders and basalt rubble

GEOLOGIC CONTACT — Queried where uncertain

38 / 729 — WELL — Entry, 38, is local well identifier. Dashed line indicates measured or estimated water level in aquifer in 1990. Lower arrow indicates measured water level in aquifer in 1989 or 1990. Upper arrow indicates measured water level of perched ground water in 1989 or 1990. Number 729, at bottom of well is total depth of well in feet below land surface

Location of Section

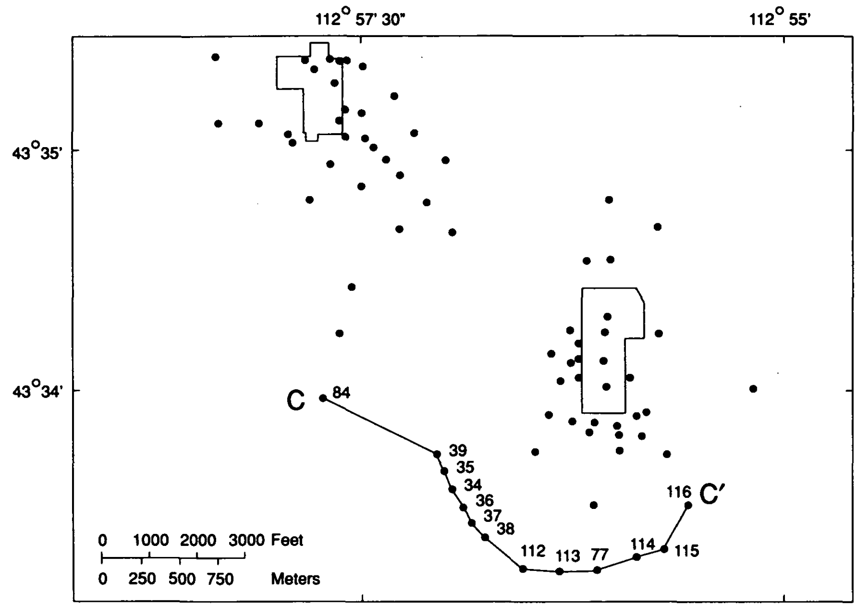

Figure 4. Geologic section C-C' at the Idaho Chemical Processing Plant (from Anderson, 1991).

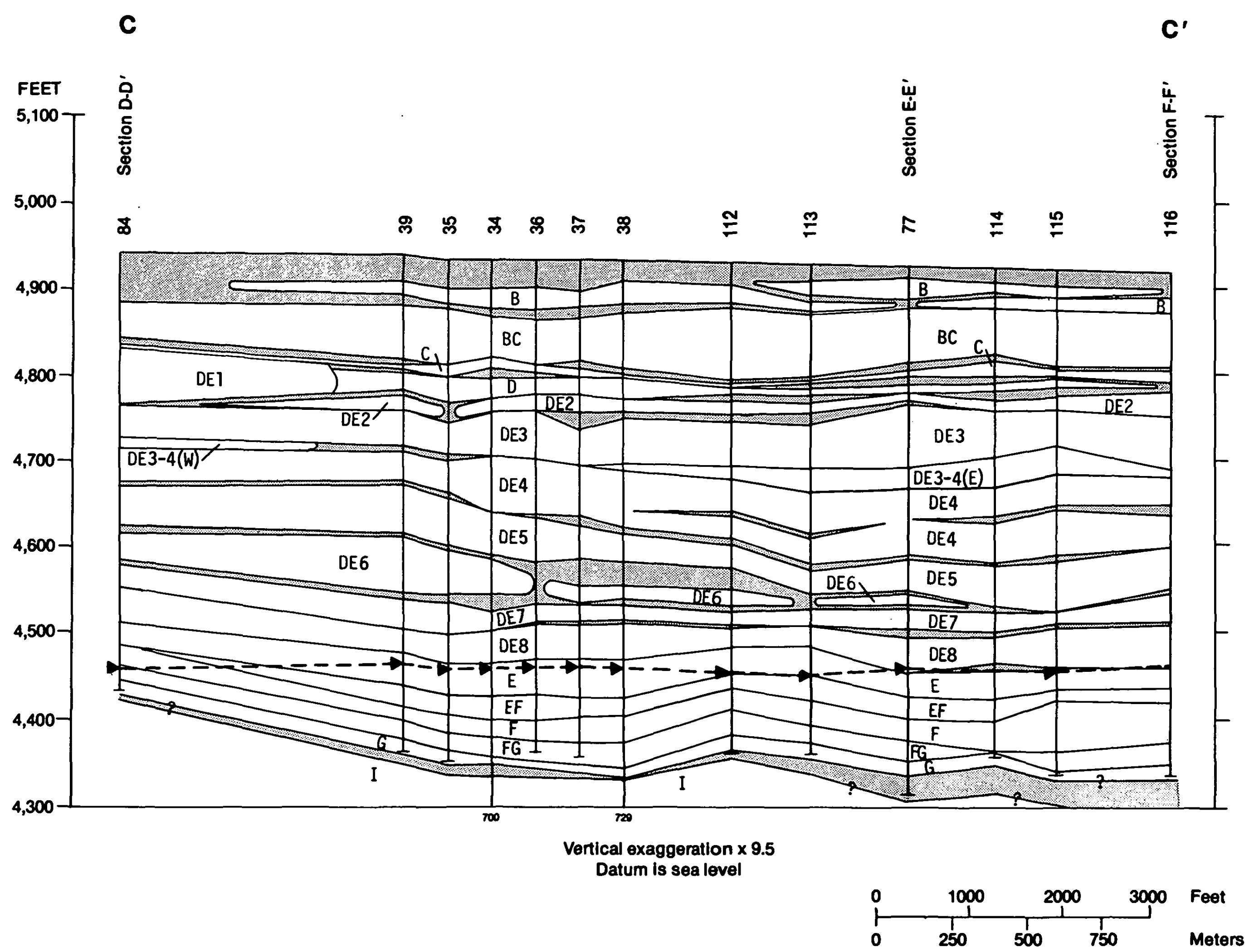

Figure 4. Geologic section C-C' at the Idaho Chemical Processing Plant (from Anderson, 1991)—Continued.

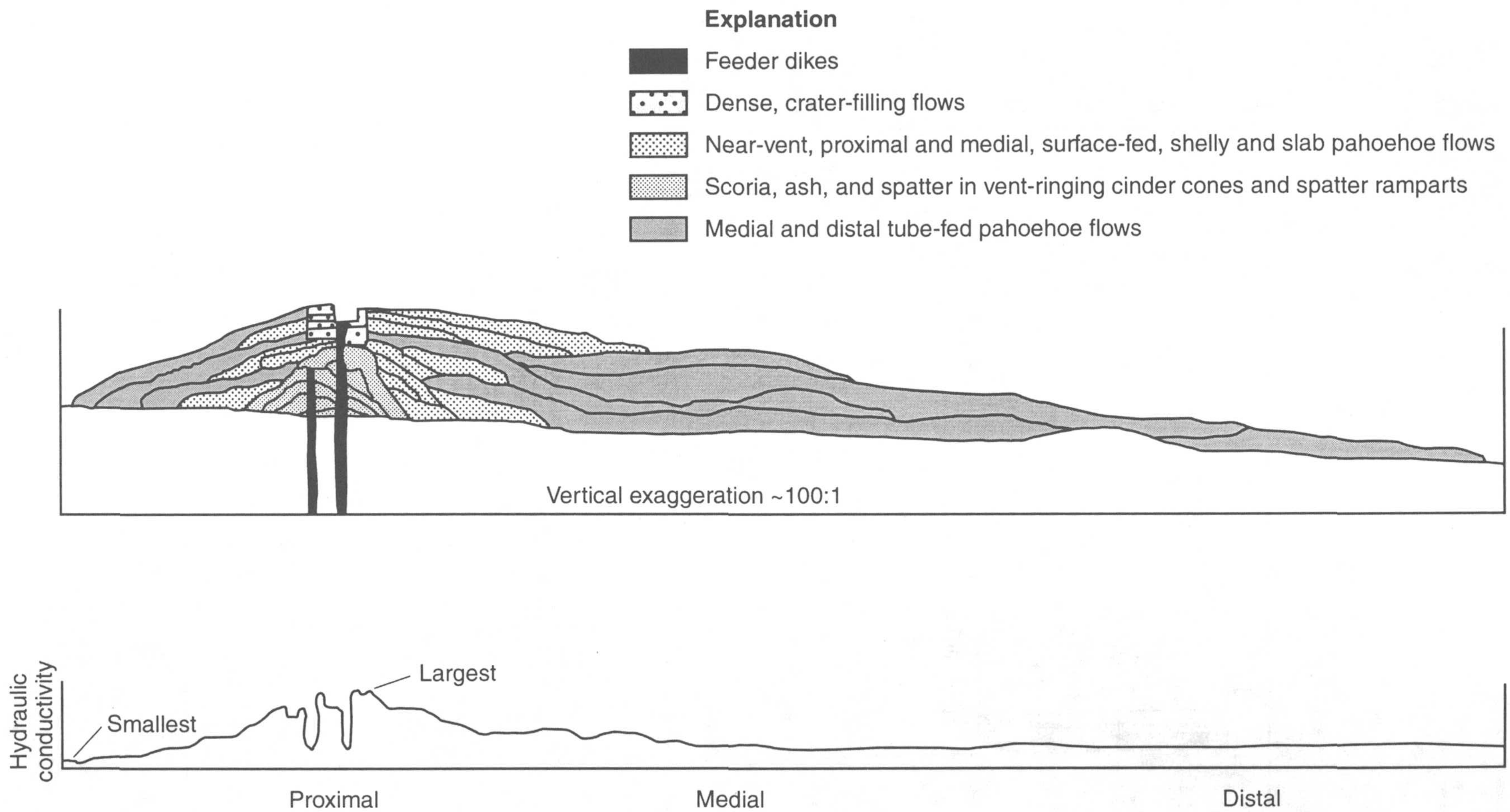

Figure 5. Basalt-flow morphology and inferred relative hydraulic conductivity through a typical shield volcano in the Snake River Plain aquifer.

graphic intervals composed of thin, tube-fed flows from many different lava fields, such as flow groups E through G at and near the ICPP (fig. 4), can be as great as that of stratigraphic intervals near a single vent. Hydraulic conductivity of tube-fed flows locally is increased by open lava tubes. Dikes generally have the least hydraulic conductivity of volcanic rocks in the aquifer because they represent vertical fissures that were filled by basaltic magma. Dikes that reached the surface to form lava flows are referred to as feeder dikes (fig. 5).

Geologic controls of hydraulic conductivity at and near the INEEL were evaluated using the stratigraphic data described by Anderson and others (1996a, table 6). These data include detailed estimates of the distribution of individual basalt flows and basalt-flow groups in the aquifer. A basalt flow, defined on the basis of physical and petrographic characteristics, is a collection of related flow units within a basalt-flow group (fig. 4) (Kuntz and others, 1980; Lanphere and others, 1993, 1994; Anderson and Bartholomay, 1995). In general, basalt flows less than 30 ft thick occupy the medial and distal parts of lava fields (fig. 5) and are characterized mainly by thin, tube-fed flows having large hydraulic conductivity. Basalt flows more than 30 ft thick are generally of two types. Some of these flows are proximal to the vents of shield volcanoes and are characterized mainly by near-vent volcanic deposits having large hydraulic conductivity. Other flows occupy the medial and distal parts of lava fields and represent thick, ponded, tube-fed flows having small hydraulic conductivity. Most basalt flows penetrated by wells at and near the INEEL are less than 30 ft thick and are composed, on average, of two flow units.

Sedimentary Interbeds

Sediment is distributed throughout the INEEL and adjacent areas and consists mainly of loess and deposits of fluvial, lacustrine, and playa origin (Kuntz and others, 1994; Spinazola, 1994; Anderson and others, 1996b; Geslin and others, 1997; Gianniny and others, 1997). Because loess blankets much of the present land surface, it may be the dominant sediment type in the subsurface. Fluvial deposits are distributed along and near Big Lost River, Little Lost River, Birch Creek, and Camas Creek (fig. 1). Lacustrine and playa deposits occur mainly in the area between Big Lost River Sinks and Mud Lake (fig. 1).

In the subsurface, sediment is interbedded with basalt and also occurs in many basalt fractures. The thickness and distribution of sedimentary interbeds in most areas have been described (Anderson and others, 1996a), but the lithology and hydraulic characteristics of this sediment generally are not well known. Hydraulic conductivity of sedimentary interbeds may be greatest near rivers and creeks, where coarse mixtures of sand and gravel commonly occur. Hydraulic conductivity of sedimentary interbeds may be least in the area between Big Lost River Sinks and Mud Lake, where thick, fine-grained lacustrine and playa deposits commonly occur (Spinazola, 1994). Basalt rubble and scoria are present between basalt flows in many areas. Hydraulic conductivity of rubble and scoria may be greater than that of coarse-grained fluvial deposits in some areas. Hydraulic conductivity of loess, which consists mainly of silt and fine sand, is probably intermediate between that of fluvial and playa deposits.

Volcanic Rift Zones and Vent Corridors

Source vents for most basalt flows at and near the INEEL are concentrated in volcanic rift zones that trend perpendicular to the axis of the eastern Snake River Plain and parallel to the adjacent mountain ranges (Kuntz and others, 1992, Kuntz and others, 1994). Volcanic rift zones (fig. 6) are characterized by eruptive and noneruptive fissures, dikes, monoclines, faults, graben, and volcanoes having elongated slot-shaped vents (Rodgers and others, 1990; Kuntz, 1992; Kuntz and others, 1992; Smith and others, 1996). The distribution of volcanoes, dikes, and fissures is of hydrologic importance at and near the INEEL because these features are numerous and may greatly affect the range and distribution of hydraulic conductivity and the movement of ground water and wastes. Areas proximal to volcanic vents may provide localized, preferential pathways for ground-water flow. Dikes may impede the movement of ground water and diminish the hydraulic conductivity measured in nearby wells (Meyer and Souza, 1995; Hughes and others, 1997). Noneruptive fissures that parallel dikes may locally provide addi-

Vent Corridor in a Volcanic Rift Zone

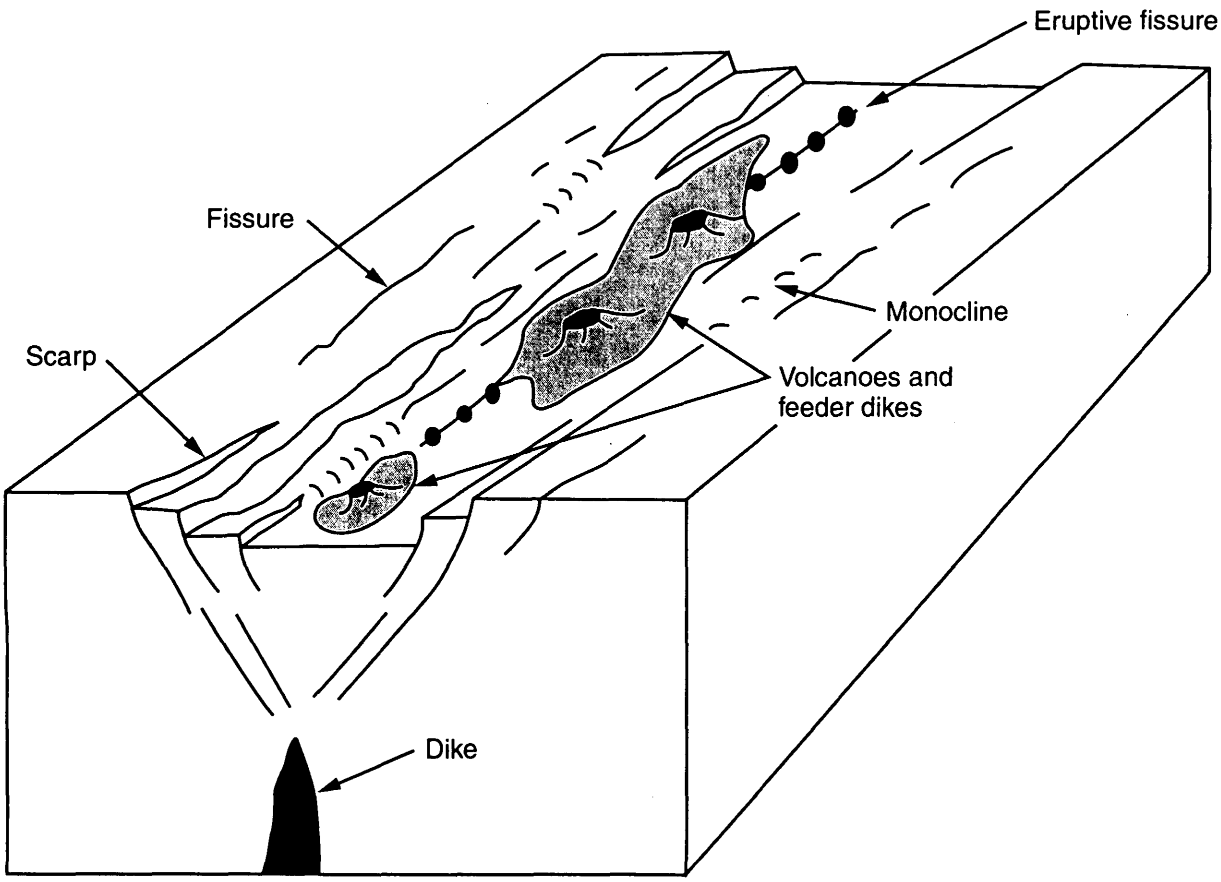

Figure 6. Geologic features of a vent corridor in a volcanic rift zone at and near the Idaho National Engineering and Environmental Laboratory (modified from Smith and others, 1996).

tional conduits for ground-water flow. Hydraulic conductivity of these fissures may be large because they cut across many highly-permeable zones in and between individual basalt layers (Hughes and others, 1997; Welhan and Wylie, 1997).

Because fissures possibly extend upward into the aquifer from depths of several thousands of feet, some may provide local conduits for upward circulation of geothermal water from deep, underlying rocks into the Snake River Plain aquifer. This mechanism was suggested by Morse and McCurry (1997) to explain the abundance of alteration minerals observed in many drill cores. These alteration minerals locally diminish the hydraulic conductivity of basalt flows as shown by aquifer-test data (Mann, 1986) and water-temperature gradients in many deep wells that indicate conductive rather than convective heat flow within zones of pervasive alteration (Morse and McCurry, 1997). Conductive heat flow indicates poor ground-water circulation, whereas convective heat flow indicates active circulation. Zones of alteration generally occur below the effective base of the aquifer as defined by Anderson and Liszewski (1997). However, some zones extend into the aquifer and probably represent localized alteration in and near relatively young fissures.

The locations of vents, dikes, and fissures must be known or approximated to evaluate the relation between these features and hydraulic conductivity in wells at and near the INEEL. The locations of surficial vents are known from outcrop exposures (Kuntz and others, 1994; Hughes and others, 1997), and the locations of concealed vents were approximated by Anderson and Liszewski (1997, fig. 7) on the basis of interpreted stratigraphic relations at and near the INEEL. Most dikes and fissures are concealed and have not been identified in vertical cores; therefore, their distribution is uncertain. Dikes and open fissures are most likely to occur along and parallel to the trace of eruptive fissures marked by one or more vents (fig. 6). On the basis of this likelihood, 45 zones of aligned vents, dikes, and fissures were approximated from the known and inferred locations of volcanic vents described by Kuntz and others (1994), Hughes and others (1997), and Anderson and Liszewski (1997). *These zones are herein referred to as vent corridors (fig. 7) to distinguish them from previously described volcanic rift zones.* Vent corridors 7 through 15 (fig. 7) roughly coincide with the Circular Butte-Kettle Butte and the Lava Ridge-Hells Half Acre volcanic rift zones mapped by Kuntz and others (1992). Vent corridors 19 through 24 and 33 through 39 roughly coincide with the Howe-East Butte and the Arco-Big Southern Butte volcanic rift zones, respectively. Vent corridors along the eastern and southern boundaries of the INEEL between corridors 5 and 42 roughly coincide with the area commonly referred to as the axial volcanic zone (Welhan and others, 1997).

Vent corridors (fig. 7) average about 1 to 2 mi in width and 5 to 15 mi in length, dimensions that are consistent with those predicted from geologic models of a string of dikes (fig. 6) in the subsurface (Smith and others, 1996). The average orientation of vent corridors is about N. 45° W., approximately parallel to the adjacent mountain ranges and perpendicular to the axis of the eastern Snake River Plain. Vent corridors contain vents of different ages, including many that are younger than the basalt flows in the aquifer (Anderson and Liszewski, 1997). Vent corridors 8, 23, 25, and 33 (fig. 7), which cover the TAN, TRA, ICPP, and RWMC may contain a large number of dikes and fissures. This assumption is based on the number and ages of concealed vents inferred in these areas (Anderson and Liszewski, 1997). In all areas, the number of dikes and fissures likely increases with depth. Individual dikes and fissures probably are no more than a few feet wide in most places (Smith and others, 1996).

Very few feeder dikes for the various types of volcanoes in the eastern Snake River Plain have been exposed because erosion is almost nonexistent. Therefore, the number and dimensions of feeder dikes in volcanic rift zones and vent corridors at and near the INEEL (figs. 6 and 7) is somewhat conjectural and must be estimated using what is known or can be reasonably inferred about basaltic dikes elsewhere on the eastern Snake River Plain. These estimates can be made from geologic maps of the Great Rift volcanic rift zone southwest of the INEEL (Kuntz and others, 1989a,

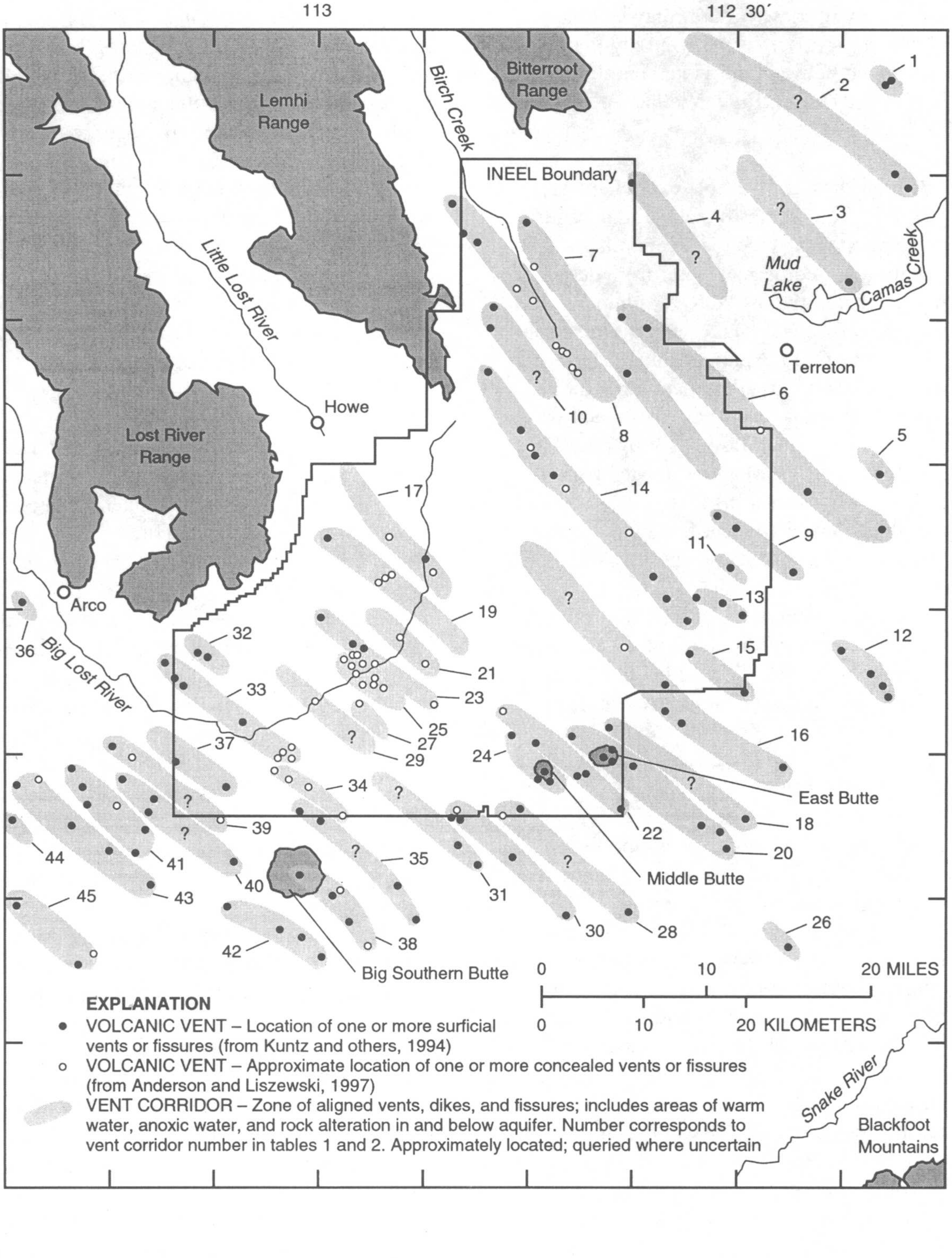

Figure 7. Locations of volcanic vents and vent corridors at and near the Idaho National Engineering and Environmental Laboratory.

1989b, 1989c, 1992). Dikes are typically 1 to 4 ft wide, a few hundred feet to a few miles long, and of unknown vertical extent. In general, dikes on the eastern Snake River Plain are widely spaced geographically and are not concentrated within sheeted dike zones such as are common in Hawaii or in mid-oceanic ridges.

Dikes in volcanic rift zones in Hawaii and Iceland occur in swarms forming what is known as sheeted dikes. In such localities, parallel dikes are intruded so closely to one another that there is little, if any, country rock lying between the dikes. Because the dikes fill tensional fissures, sheeted dikes demonstrate that the fissuring is concentrated within a relatively narrow zone.

The exception to the generalization of widely-spaced dikes in the eastern Snake River Plain is along the Great Rift volcanic rift zone, where several to a few tens of dikes may be in close contact over horizontal distances of 100 ft to several miles. That there may be other exceptions to this generalization is suggested also by the number and proximity of inferred vents concealed beneath some areas at the INEEL, such as in vent corridors 23 and 25 at and near the ICPP and TRA (fig. 7). In these areas, the number and spacing of dikes may be similar to those of the least concentrated dike swarms in Hawaii and Iceland.

Hydrogeologic Anomalies

Data from wells indicating the presence of anoxic water, rock alteration, and the highest water temperatures in the uppermost 200 ft of the aquifer, 1 to 7°C higher than the median water temperature throughout the aquifer, were used to refine estimates of the areal extent of some vent corridors (fig. 7). These data, which describe conditions referred to as probable rift-related hydrogeologic anomalies because of their suspected relation to vent corridors, provide possible evidence of dikes and fissures in the Snake River Plain aquifer (table 1, located at the end of this report). All anomalies are consistent with possible upward circulation of geothermal water along open fissures into the colder water of the aquifer; however, higher water temperatures alternatively may indicate areas of localized water stagnation near dikes or upward circulation of shallow ground water near dikes and fissures.

Temperatures of water samples collected from 129 monitoring wells in 1995 ranged from 9.5 to 20°C; the median temperature was 13°C (Bartholomay and others, 1997). These temperatures are considered accurate to ±0.5°C. By comparison, the temperature of Lidy Hot Springs, located north of the INEEL along the edge of the plain, is 47°C (fig. 2, table 1). Temperature logs of water in deep wells completed in altered basalt and rhyolite below the effective base of the Snake River Plain aquifer indicate conductive heat flow and water temperatures that increase with depth, an increase consistent with regional geothermal gradients (Brott and others, 1981; Smith and others, 1994; Morse and McCurry, 1997). In one of these wells, Corehole 2-2A (fig. 2), water temperatures at and below the effective base of the aquifer, between a depth of 1,340 and 2,600 ft below land surface, range from 22 to 45°C (Morse and McCurry, 1997). The temperature at the bottom of this well is nearly identical to that of Lidy Hot Springs. Corehole 2-2A is located near well USGS 18 (fig. 2) in vent corridor 14 (fig. 7) along the trace of the Lava Ridge-Hells Half Acre volcanic rift zone (Kuntz and others, 1994). Well USGS 18 is completed in the uppermost 200 ft of the aquifer. The temperature of water in this well, 15°C (table 1), may be influenced by nearby dikes or fissures.

Anoxic water is present in Lidy Hot Springs, Park Bell well, and Stoddart well, located in vent corridors 2, 3, and 4, respectively (figs. 2 and 7; table 1). Abundant authigenic and alteration minerals consisting of calcite, clays, and zeolites are present in wells C-1A, Corehole 1, Corehole 2-2A, INEL #1, and NPR WO-2, located in vent corridors 33, 22, 14, 21, and 21, respectively (figs. 2 and 7). The highest water temperatures in the uppermost 200 ft of the aquifer, 14 to 20°C, are in well ANP #9 and wells USGS 1, 5, 14, 18, 19, 22, 23, 26, 27, 31, 32, 40, 87, 119, 122, and 123, located in vent corridors 8, 28, 19, 38, 14, 17, 29, 19, 7, 6, 7, 7, 25, 33, 33, 25, and 25, respectively (table 1; fig. 7). Although other interpretations of these hydrogeologic data are possible, the collective data strongly suggest the presence of dikes, fissures, and areas of geothermal water within vent corridors. The interpretation of geothermal water within vent corridors assumes that its associated high water temperatures and anoxic water are greatly diluted by the large volume of cold water that recharges the Snake River Plain aquifer. Mann (1986) estimated that the volume of upward flow into the aquifer could be on the order of 15,000 acre-ft/yr, a volume equal to about 12 percent of the average annual recharge to the aquifer from Big Lost River.

HYDRAULIC CONDUCTIVITY

Hydraulic conductivity was estimated from single-well aquifer tests in 114 wells at and near the INEEL to evaluate its range and distribution with respect to geologic characteristics of the aquifer (table 2, located at the end of this report). The relation between hydraulic conductivity and geologic characteristics was evaluated by comparing estimates of hydraulic conductivity to the average thickness of basalt and sediment layers coinciding with perforated or open intervals in each well. This approach was based on the assumption that any given stratigraphic interval composed of thin basalt layers has more contacts, rubble zones, and cooling fractures, and, hence, greater hydraulic conductivity than an interval of equal thickness composed of thick layers (Morin and others, 1993; Welhan and Wylie, 1997). Hydraulic conductivity associated with contacts, rubble zones, and cooling fractures of basalt layers also is assumed to be locally increased or decreased by near-vent volcanic deposits, dikes, fissures, zones of alteration, and sediment.

Hydraulic conductivity was estimated only for wells having transmissivity estimates and stratigraphic data (Ackerman, 1991; Anderson and others, 1996a; Bartholomay and others, 1997). Hydraulic conductivity was estimated by dividing each transmissivity estimate by the total length of all perforated or open intervals in a given well (table 2). The resulting values mainly represent the effective hydraulic conductivity of basalt flows, and are referred to as values of bulk hydraulic conductivity by Welhan and Reed (1997). Qualifying assumptions used to estimate transmissivity (Ackerman, 1991, p. 6) also are applicable to estimates of hydraulic conductivity. Relative uncertainties of transmissivity estimates are reported as orders of magnitude (Ackerman, 1991). Because estimates of hydraulic conductivity are derived from transmissivity, their relative uncertainties are assumed to be equal in magnitude to those of each corresponding transmissivity estimate (table 2). Relative uncertainties range from ± 0.1 to greater than ± 0.5 orders of magnitude, and are equal to or greater than ± 0.4 orders of magnitude in 94 of the 114 wells (table 2).

The total length of perforated or open intervals used to estimate hydraulic conductivity in each of the 114 wells ranges from 15 to 475 ft and averages 109 ft (table 2). Perforated or open intervals coinciding with basalt-flow group I (fig. 4) and with areas below the effective base of the aquifer were subtracted from total lengths in 23 wells located mainly at and near the ICPP and CFA (fig. 3; table 2). This was done because the hydraulic conductivity of these thick, massive rocks ranges from 1 to 5 orders of magnitude less than that of overlying stratigraphic layers (Mann, 1986; Morin and others, 1993; Frederick and Johnson, 1996). Adjusted estimates of hydraulic conductivity in these wells are as much as three times greater than unadjusted estimates, and are similar to those obtained in other wells.

The relation between hydraulic conductivity and average layer thickness for 114 wells indicates that hydraulic conductivity ranges from 1.0×10^{-2} to 2.4×10^{4} ft/d (0.01 to 24,000 ft/d) for an average layer thickness of about 10 to 50 ft (fig. 8; table 2). Hydraulic conductivity ranges from 1.0×10^{2} to 2.4×10^{4} ft/d (100 to 24,000 ft/d) in 73 of the 114 wells, from 1.0×10^{0} to 1.0×10^{2} ft/d (1 to 100 ft/d) in 28 wells, and from 1.0×10^{-2} to 1.0×10^{0} ft/d (0.01 to 1 ft/d) in 13 wells. This range of hydraulic conductivity, which includes only two estimates greater than 8.8×10^{3} ft/d, is nearly identical to that of similarly derived ranges reported by Wylie and others (1995) and Welhan and Reed (1997), 1.0×10^{-2} to 7.4×10^{3} ft/d. Average layer thickness ranges from about 10 to 30 ft in 98 wells and from about 30 to 50 ft in 16 wells.

Estimates of hydraulic conductivity in figure 8 are based on 114 of the 136 values of transmissivity from Ackerman (1991) and Bartholomay and others (1997), which were estimated from single-well aquifer tests. Estimates reported by Wylie and

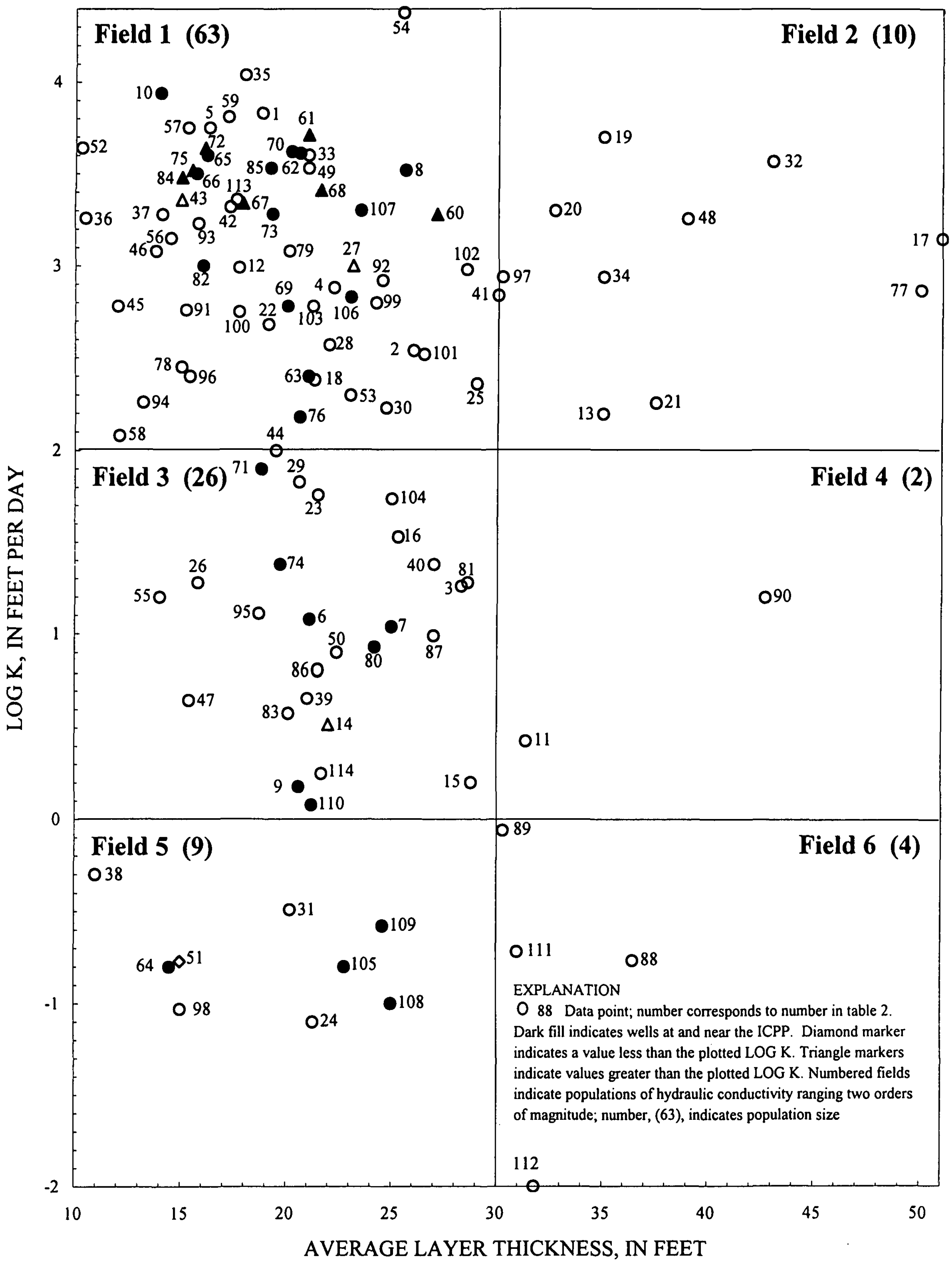

Figure 8. Relation between hydraulic conductivity (K) and average layer thickness of basalt and sediment in selected wells completed in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory.

others (1995) are based on the 94 values of transmissivity from Ackerman (1991) and about 50 additional values estimated from slug tests, single-well tests, and multiple-well tests in some of these and additional wells. Estimates reported by Welhan and Reed (1997) are based on 79 of the 94 values of transmissivity from Ackerman (1991). Estimates of transmissivity reported by Ackerman (1991) and Bartholomay and others (1997) are negatively skewed on a log scale, have measures of central tendency close to 6.0×10^4 ft^2/d, and vary nearly six orders of magnitude. Estimates of transmissivity reported by Wylie and others (1995) have an apparent log-normal distribution centered about 6.0×10^3 ft^2/d, and vary nearly seven orders of magnitude. These differences in transmissivity may be the result of differences in some test locations, test methods, and well discharges. For example, 30 of the 42 estimates of transmissivity reported by Bartholomay and others (1997), which represent locations not considered in earlier studies, are greater than 6.0×10^3 ft^2/d, the center of the log-normal distribution reported by Wylie and others (1995). Likewise, Wylie and others (1995) reported 10 values of transmissivity from 4 wells that are equal to or greater than the largest value estimated by Ackerman (1991) and Bartholomay and others (1997), 1.2×10^6 ft^2/d. These values were estimated from a multiple-well test near well USGS 120 (fig. 2) that was conducted for 36 days using an average well discharge of about 2,800 gpm. These values include two estimates of transmissivity for well USGS 120 that are about one order of magnitude greater than that estimated by Ackerman (1991) from a single-well test using a well discharge of about 21 gpm (table 2).

The similar estimates of hydraulic conductivity obtained by Wylie and others (1995), Welhan and Reed (1997), and this study (fig. 8; table 2) suggest that conductivity generally is not biased by reported differences in transmissivity distributions. However, transmissivity and hydraulic conductivity of basalt and sediment in some wells may be underestimated, such as in well USGS 120 (table 2), for which discharge rates were low. Values of hydraulic conductivity shown in figure 8 and table 2 were estimated from the transmissivity data published by Ackerman (1991) and Bartholomay and others (1997) because these data were assembled and analyzed in the same manner. Despite some inherent limitations (Ackerman, 1991), these data represent the largest set of internally consistent hydraulic conductivity estimates available for the Snake River Plain aquifer.

The range, frequency distribution, and central tendencies of hydraulic conductivity estimates are shown in figure 9 and table 3 (located at the end of this report). Estimates of hydraulic conductivity span about six orders of magnitude; the distribution of estimates is negatively skewed in a manner similar to that of transmissivity (Ackerman, 1991, p. 31). Most measures of central tendency are close to 1,500 ft/d. Measures of central tendency do not consider associated uncertainties of estimates, greater than and less than values, and possible sampling bias of hydraulic conductivity classes. Associated uncertainties range from ±0.1 to greater than ±0.5 orders of magnitude for 102 estimates, 11 greater than values, and 1 less than value of hydraulic conductivity (table 2). Wells from which estimates were obtained are located throughout the INEEL, but are concentrated at and near the RWMC, ICPP, TRA, and TAN (figs. 2 and 3); 99 of the 114 wells are located within vent corridors (table 2), which have the largest variety of rock types in the aquifer.

Three broad categories of hydraulic conductivity are suggested by the number of estimates assigned to conductivity classes 1 through 13 in figure 9. Hydraulic conductivity of category 1 ranges from 1.0×10^2 to 3.2×10^4 ft/d and includes 73 estimates that range from 1.0×10^2 to 2.4×10^4 ft/d. Hydraulic conductivity of category 2 ranges from 1.0×10^0 to 1.0×10^2 ft/d and includes 28 estimates that range from 1.2×10^0 to 7.9×10^1 ft/d. Hydraulic conductivity of category 3 ranges from 1.0×10^{-2} to 1.0×10^0 ft/d and includes 13 estimates that range from 1.0×10^{-2} to 8.8×10^{-1} ft/d. One less than value is in hydraulic conductivity class 3 (fig. 8 and table 2, data point 51). One greater than value is in class 6 (fig. 8 and table 2, data point 14). Ten greater than values are greater than 1.0×10^2 ft/d and are in classes 11, 12, and 13 (fig. 8 and table 2, data points 27, 35, 43, 60, 61, 62, 68, 72, 75, and 84). These greater than values suggest that upper limits of hydraulic conductivity could be greater than 3.2×10^4 ft/d. However, this is

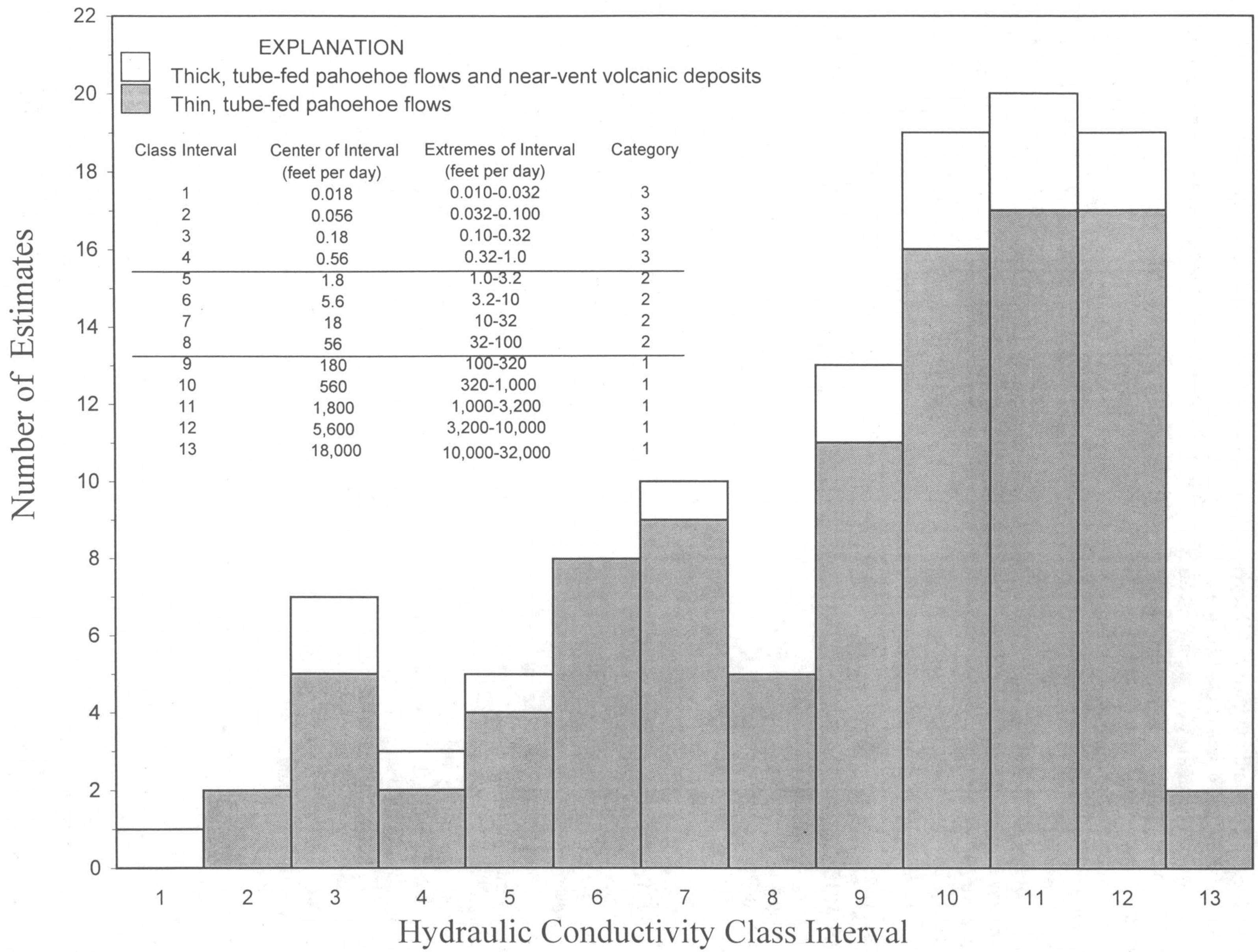

Figure 9. Frequency distribution of hydraulic conductivity estimates at and near the Idaho National Engineering and Environmental Laboratory (units are feet per day; range of intervals is 0.5 order of magnitude).

not likely because estimates of hydraulic conductivity obtained from comparable basalt flows on the Columbia Plateau and in Hawaii are all less than this value (Hansen and others, 1994; Meyer and Souza, 1995). The frequency distribution of hydraulic conductivity on the Columbia Plateau is log normal and centered about 5.0×10^{0} ft/d (Hansen and others, 1994, p. 16), indicating that basalt flows on the Columbia Plateau are generally less transmissive and more uniform than those in the Snake River Plain aquifer. The frequency distribution of hydraulic conductivity in Hawaii is unknown; however, its range and corresponding rock types are remarkably similar to those in the Snake River Plain aquifer (Meyer and Souza, 1995).

GEOLOGIC CONTROLS OF HYDRAULIC CONDUCTIVITY

The range and frequency distribution of hydraulic conductivity (figs. 8 and 9; table 2) are controlled by three main rock types at and near the INEEL. These rock types are: (1) thin, tube-fed pahoehoe flows; (2) thick, tube-fed pahoehoe flows; and (3) near-vent volcanic deposits composed of shelly pahoehoe and slab pahoehoe flows and bedded scoria, spatter, and ash. Thin, tube-fed flows, represented in figure 8 by fields 1, 3, and 5, are the most abundant flows in the subsurface and generally average less than 30 ft thick. Thick, tube-fed flows and near-vent volcanic deposits, represented in figure 8 by fields 2, 4, and 6, are much less abundant than thin, tube-fed flows and generally average more than 30 ft thick. Hydraulic conductivity of thin, tube-fed flows ranges from 7.9×10^{-2} to 2.4×10^{4} ft/d based on estimates from 98 wells. Hydraulic conductivity of thick, tube-fed flows and near-vent volcanic deposits ranges from 1.0×10^{-2} to 5.0×10^{3} ft/d based on estimates from 16 wells and straddle-packer tests from two additional wells (Morin and others, 1993). Of the 114 wells evaluated for hydraulic conductivity (table 2), 99 are located within vent corridors and 15 are located outside of vent corridors (fig. 7). Hydraulic conductivity ranges from about 1.0×10^{-2} to 2.4×10^{4} ft/d within vent corridors and from about 1.3×10^{1} to 5.6×10^{3} ft/d outside of vent corridors. These ranges suggest that hydraulic conductivity is also greatly affected by dikes, fissures, and zones of alteration within vent corridors. Sediment is distributed throughout many parts of the INEEL and may locally increase or decrease hydraulic conductivity in the wells where it is present.

Thin, Tube-Fed Pahoehoe Flows and Dikes

Hydraulic conductivity associated with thin, tube-fed pahoehoe flows is equal to or greater than 1.0×10^{2} ft/d in 63 wells, less than 1.0×10^{0} ft/d in 9 wells, and between these values in 26 wells (figs. 8 and 9). This skewed distribution strongly suggests that upper limits of hydraulic conductivity are controlled by voids associated with the contacts, rubble zones, and cooling fractures of thin, tube-fed flows. Lower limits of hydraulic conductivity probably are related primarily to dikes that locally impede the flow of ground water through these voids. Because dikes occupy narrow zones (figs. 5, 6, and 7), they probably are penetrated by the fewest number of wells in any given area. This assumption is consistent with the smaller number of hydraulic conductivity estimates attributed to their effects. The smallest values of hydraulic conductivity associated with thin, tube-fed flows probably occur in wells that penetrate localized dike zones ranging in width from a few hundred to a few thousand feet within vent corridors.

The relation between hydraulic conductivity and thin, tube-fed pahoehoe flows and dikes can be evaluated on the basis of data from the 32 wells indicated by dark fill in figure 8 (fields 1, 3, and 5). These wells are completed in the thin, tube-fed flows of basalt-flow groups E through G at and near the ICPP (fig. 4) mainly in vent corridor 25 (fig. 7). Vent corridor 25 contains a string of eruptive fissures marked by seven concealed vents near the southern boundaries of the ICPP and TRA that are younger than flow groups E through G (Anderson and Liszewski, 1997). This string of eruptive fissures and concealed vents is approximately centered along a northwest-trending strike between wells USGS 79 and 115 (fig. 3). Similar eruptive fissures and vents are also present in adjacent vent corridors 23 and 27 (fig. 7). Hydraulic conductivity of the 32 wells ranges from 1.0×10^{-1} to 8.8×10^{3} ft/d (fig. 8, table 2). Smallest and largest values are from wells USGS 114 and CPP Disp, located in and near a zone of probable dikes about 3,000 ft wide, immediately south of ICPP wells USGS 42 and 122 (fig. 3). Estimates of hydraulic conductivity for eight wells in this zone, USGS 38, 45, 51, 77, 111, 114, 115, and 116 (fig. 8, data points 64, 71, 74, 80, 105, 108, 109, and 110), two wells in vent corridor 27, CFA 1 and CFA 2 (fig. 8, data points 6 and 7), and one well in vent corridor 23, CPP 4 (fig. 8, data point 9) range from 1.0×10^{-1} to 7.9×10^{1} ft/d and are within the range of categories 2 and 3 in figure 9. The proximity of these wells to concealed eruptive fissures and vents strongly suggests that this range of hydraulic conductivity is affected by dikes.

Estimates of hydraulic conductivity for the remaining 21 wells of this population range from 1.5×10^{2} to 8.8×10^{3} ft/d (fig. 8, field 1) and are within the range of category 1 in figure 9. This range of hydraulic conductivity probably is affected by the contacts, rubble zones, and cooling fractures of thin, tube-fed flows in areas where dikes are not present. Changes in hydraulic conductivity of three to five orders of magnitude occur within distances of 500 to 1,000 ft in and near the zone of probable dikes south of the ICPP. These changes can be shown by the distribution of hydraulic conductivity estimated for basalt-flow groups E through G in geologic section C-C' (fig. 4). Values of hydraulic conductivity across this section are greater than 3.0×10^{3}, 4.0×10^{3}, greater than 3.7×10^{3}, greater than 1.9×10^{3}, 4.1×10^{3}, 2.5×10^{2}, 1.6×10^{-1}, 6.7×10^{2}, 2.0×10^{3}, 8.6×10^{0}, 1.0×10^{-1}, 2.6×10^{-1}, and 1.2×10^{0} ft/d for wells USGS 84, 39, 35, 34, 36, 37, 38, 112, 113, 77, 114, 115, and 116, respectively (table 2). Although dikes likely occur in other parts of vent corridor 25, their probable effects are most apparent near the southern boundary of the ICPP, where there are many wells for which hydraulic conductivities have been estimated. The actual locations and spacing of individual dikes in vent corridor 25 and other vent corridors are unknown.

The frequency distribution of hydraulic conductivity for the 32 wells at and near the ICPP is roughly proportional to that for all 98 wells completed in thin, tube-fed flows (figs. 8 and 9). Hydraulic conductivity of each of these populations is greater than 1.0×10^{2} ft/d for almost two-thirds of samples and less than this value for the rest. These proportional distributions strongly suggest that estimates of hydraulic conductivity and their corresponding geologic controls in the 32 wells at and near the ICPP are representative of those in the other 66 wells completed in thin, tube-fed flows at and near the INEEL.

Geologic interpretations and the three categories of hydraulic conductivity shown in figure 9 suggest three general types of geologic controls associated with thin, tube-fed flows and dikes. Category 1 ranges from 1.0×10^{2} to 3.2×10^{4} ft/d and probably includes the effects of thin, tube-fed flows. Category 2 ranges from 1.0×10^{0} to 1.0×10^{2} ft/d and probably includes the effects of thin, tube-fed flows cut by discontinuous dikes. Category 3 ranges from 1.0×10^{-2} to 1.0×10^{0} ft/d and probably includes the effects of localized dike swarms. Some overlap between these categories and controls is likely because of the small number of hydraulic conductivity estimates and the complex geologic environment. Although somewhat conjectural, these categories and controls are consistent with those reported for similar volcanic settings in Hawaii (Meyer and Souza, 1995).

Thick, Tube-Fed Pahoehoe Flows, Near-Vent Volcanic Deposits, and Dikes

The hydraulic conductivity of thick, tube-fed pahoehoe flows and near-vent volcanic deposits is difficult to evaluate because few estimates for these flows and deposits are available. Hydraulic conductivity associated with thick, tube-fed flows and near-vent deposits is greater than 1.0×10^{2} ft/d in 10 wells, less than 1.0×10^{0} ft/d in 4 wells, and between these values in 2 wells (fig. 8, table 2). Available estimates suggest that upper limits of hydraulic conductivity are controlled by the numerous voids in near-vent volcanic deposits. Lower limits of hydraulic conductivity are most likely controlled by thick, tube-fed flows and dikes. Thick, tube-fed flows are characterized by fewer contacts, rubble zones, and cooling fractures and lower hydraulic conductivity than thin, tube-fed flows. Where they have ponded in topographic depressions, thick, tube-fed flows are so massive that their hydraulic conductivity may not be much greater than that of a dike.

The relation between hydraulic conductivity and thick, tube-fed pahoehoe flows, near-vent volcanic deposits, and dikes can be evaluated on the basis of data from selected wells that penetrate basalt-flow group I at and near the ICPP and TRA. Basalt-flow group I (fig. 4) is one of the thickest and most extensive flow groups at and near the INEEL (Wetmore and others, 1997), and is composed of tube-fed flows and near-vent deposits having an average thickness of about 30 to 50 ft (Anderson and others, 1996a). Hydraulic conductivity of flow group I is greatest in wells near its vent, which is north of the TRA (Anderson and Liszewski, 1997, fig. 7). Hydraulic conductivity of flow group I is least in wells at and near the ICPP (Morin and others, 1993; Frederick and Johnson, 1996), where the flows likely ponded in a topographic depression and were subsequently cut by dikes associated with younger eruptions.

These relations can be illustrated by data from wells MTR Test and USGS 44, 45, and 58. Wells USGS 58 and MTR Test, located near the TRA (fig. 3), are perforated or open only in flow group I less than 1 mi from its vent and associated near-vent deposits. Wells USGS 44 and 45, located near the ICPP (fig. 3), are open in thick, tube-fed flows of flow group I that likely ponded in a topographic depression more than 1 mi from its vent. Hydraulic conductivity of flow group I ranges from 7.4×10^2 to 1.4×10^3 ft/d in wells USGS 58 and MRT Test, respectively (table 2), and probably is affected by the numerous void spaces in near-vent volcanic deposits. Hydraulic conductivity of flow group I, estimated from straddle-packer tests (Morin and others, 1993), is 3.0×10^2 ft/d or less in well USGS 44 and 1.0×10^1 ft/d or less in well USGS 45. These values of hydraulic conductivity are likely affected by the sparse void spaces present in thick, ponded, tube-fed flows. Because these values are maximum estimates and the corresponding basalt flows have few void spaces, hydraulic conductivity of flow group I in wells USGS 44 and 45 and many other nearby wells may be similar to that of thick, massive basalt flows on the Columbia Plateau. Typical values of hydraulic conductivity of basalt flows on the Columbia Plateau range from about 1.0×10^0 to 2.6×10^1 ft/d (Hansen and others, 1994). Estimates of hydraulic conductivity in wells USGS 38, 111, 114, and 115 (table 2), suggest that hydraulic conductivity of basalt-flow group I may be less than 1.0×10^0 ft/d where it probably is cut by dikes south of the ICPP.

Near-vent volcanic deposits represent only about 10 to 20 percent of most lava fields, and thick, ponded, tube-fed flows are rare (Wetmore and others, 1997). Therefore, fewer estimates of hydraulic conductivity are available for these rock types than for other rock types at and near the INEEL. The largest estimates of hydraulic conductivity associated with these rock types range from 1.6×10^2 to 5.0×10^3 ft/d (fig. 8, field 2) and are similar to those of the most permeable, thin, tube-fed flows. These estimates, which include those from wells USGS 58 and MTR Test, are most likely controlled by near-vent volcanic deposits, because 9 of the 10 wells in this category are located near known or inferred volcanic vents within vent corridors, where the potential for these deposits is high. The smallest estimates of hydraulic conductivity associated with these rock types, 1.0×10^{-2} to 8.8×10^{-1} ft/d (fig. 8, field 6), are similar to those of thin, tube-fed flows cut by dikes. These estimates are from wells USGS 88, 89, 117, and 119, located in a zone of probable dikes at the RWMC (fig. 2) within vent corridor 33 (fig. 7). This area contains a northwest-trending string of eruptive fissures marked by four concealed vents that are younger than the basalt flows in the aquifer (Anderson and Liszewski, 1997, fig. 7).

Geologic interpretations and the three categories of hydraulic conductivity shown in figure 9 suggest three general types of geologic controls associated with near-vent volcanic deposits, thick, tube-fed pahoehoe flows, and dikes. Category 1 ranges from 1.0×10^2 to 3.2×10^4 ft/d and probably includes the effects of shelly pahoehoe and slab pahoehoe flows and bedded scoria, spatter, and ash near volcanic vents. Category 2 ranges from 1.0×10^0 to 1.0×10^2 ft/d and probably includes the effects of thick, tube-fed flows. Category 3 ranges from 1.0×10^{-2} to 1.0×10^0 ft/d and probably includes the effects of thick, tube-fed flows cut by discontinuous dikes or dike swarms. Some overlap between these categories and controls is likely because of the small number of hydraulic conductivity estimates and the complex geologic environment. Although somewhat conjectural, categories 2 and 3 and their respective controls are consistent with those reported for thick basalt flows on the Columbia Plateau (Hansen and others, 1994). Category 1 is consistent with the known physical characteristics of volcanic vents on the surface of the eastern Snake River Plain (fig. 5).

Fissures, Alteration, and Dikes

Hydraulic conductivity of basalt flows cut by fissures or altered by secondary mineralization is difficult to distinguish from that of other geologic features in wells at and near the INEEL. Hydraulic conductivity of fissures may be similar in magnitude to that of thin, tube-fed pahoehoe flows and near-vent volcanic deposits having considerable primary voids. Conversely, hydraulic conductivity of altered basalt in which the alteration is pervasive and seals most voids may be similar to that of a dike swarm. For example, the reported hydraulic conductivity of altered basalt below the effective base of the aquifer in well INEL #1 (fig. 2) is 3.0×10^{-2} ft/d (Mann, 1986). This value is similar to the smallest values attributed to the zone of probable dikes south of the ICPP in vent corridor 25 (fig. 7). If alteration occurs in and near fissures, those that are partly to completely filled by secondary minerals may have the same hydraulic effect as a dike. Hydraulic conductivity in wells located near fissures and dikes may range from small to large depending on the distribution of wells, fissures, alteration, and dikes. Some wells near deep, open fissures may contain anoxic water and higher water temperatures.

The relation between hydraulic conductivity and fissures, alteration, and dikes was evaluated on the basis of estimates from 15 shallow wells characterized by water temperatures of 14°C or higher in or near potential fissures and dikes within many vent corridors at and near the INEEL (fig. 7, table 1). These wells were selected because the water temperatures may have resulted from upward circulation of water or water stagnation in or near open fissures, zones of alteration, and dikes within vent corridors. Thirteen of these wells are perforated or open in thin, tube-fed pahoehoe flows. Well USGS 18 (fig. 8, data point 48) is perforated or open in near-vent volcanic deposits, and well 119 (fig. 8, data point 112) in thick, tube-fed pahoehoe flows. Estimates of hydraulic conductivity for these 15 wells range from 1.0×10^{-2} to 2.4×10^{4} ft/d and include the smallest and largest known values at and near the INEEL.

Hydraulic conductivity for 10 of these wells (fig. 8, data points 2, 35, 45, 48, 49, 52, 54, 58, 59, and 66) ranges from 1.2×10^{2} to 2.4×10^{4} ft/d and corresponds to the range of conductivity of category 1 in figure 9. The median value of hydraulic conductivity for the 10 wells is 3.3×10^{3} ft/d compared with a median of 1.3×10^{3} ft/d for the entire population of 73 wells in this category. Hydraulic conductivity of the other 5 wells (fig. 8, data points 38, 51, 55, 87, and 112) ranges from 1.0×10^{-2} to 1.6×10^{1} ft/d and corresponds to the range of conductivity of categories 2 and 3 in figure 9. The higher median value of hydraulic conductivity for the 10 wells in category 1 suggests that open fissures may be present and may increase the conductivity of basalt flows in some vent corridors. The lower values of hydraulic conductivity for the 5 wells in categories 2 and 3 are probably related to dikes and dike swarms, because zones of alteration have not been identified in shallow cores.

Sedimentary Interbeds

Hydraulic conductivity of sedimentary interbeds is difficult to distinguish from that of volcanic rocks in wells at and near the INEEL. Estimates of hydraulic conductivity in most wells are dominated by the void spaces in basalt because sediment generally makes up less than 15 percent of most perforated or open intervals (table 2). At and near Mud Lake (fig. 1), median values of hydraulic conductivity for wells completed in basalt and sediment are slightly larger than those for wells completed only in basalt or only in sediment (Spinazola, 1994). This observation suggests that sediment increases the hydraulic conductivity of basalt in some wells. Sediment may increase the hydraulic conductivity of basalt where it consists of coarse mixtures of sand, gravel, scoria, and basalt rubble. Reported median values of hydraulic conductivity in wells at and near Mud Lake are 7.8×10^{2} ft/d for those completed in sediment, 1.2×10^{3} ft/d for those completed in basalt, and 1.5×10^{3} ft/d for those completed in basalt and sediment (Spinazola, 1994). The median values reported for basalt and sediment at Mud Lake are similar to the median value attributed to thin, tube-fed pahoehoe flows, near-vent volcanic deposits, and their associated sedimentary interbeds in wells at and near the INEEL, 1.3×10^3 ft/d (fig. 8, fields 1 and 2).

Eleven wells having abundant sediment were used to evaluate the relative effect of sediment on hydraulic conductivity in wells at and near the INEEL. Estimates of hydraulic conductivity for these wells (fig. 8, data points, 8, 27, 33, 43, 45, 52, 56, 59, 78, 85, and 92) range from 2.8×10^2 to 6.5×10^3 ft/d, correspond to the range of conductivity of category 1 in figure 9, and are similar to those for wells at and near Mud Lake. Perforated or open intervals in these wells coincide with areas of 20 to 50 percent sediment. Average thickness of sediment layers in the 11 wells ranges from 5 to 29 ft; median average thickness is 12 ft (Anderson and others, 1996a, table 6). The median value of hydraulic conductivity for these wells is 2.3×10^3 ft/d compared with that of 1.3×10^3 ft/d for the entire population of 73 wells in category 1 (fig. 9). This higher median value suggests that sediment may increase the hydraulic conductivity of basalt in some wells. Of these 11 wells, 5 are located near Big Lost River at and near the ICPP and TRA where sand and gravel is abundant, 5 are located considerably east or southeast of the river in areas where loess, scoria, and basalt rubble probably are abundant, and 1 is located near alluvial fans adjacent to the Lost River Range (figs. 2 and 3). Estimates of hydraulic conductivity at and near the INEEL generally do not reflect the small values associated with thick layers of clay and silt because few wells are perforated or open in these deposits (Spinazola, 1994).

Comparison with Hawaii

The range and distribution of hydraulic conductivity at and near the INEEL can be compared with those in Hawaii because of similarities in the geohydrologic settings of these areas (Whitehead, 1992; Meyer and Souza, 1995; Smith and others, 1996). According to Meyer and Souza (1995), "the general movement of ground water in the islands of Hawaii is from the mountainous interior toward the sea. This movement is largely through thin-bedded basaltic lavas originating from one or more elongate rift zones along the topographic crest of volcanoes." Basaltic aquifers in these settings are referred to as high-level and basal aquifers (fig. 10).

Hydraulic conductivity of high-level aquifers in Hawaii is greatly affected by the distribution of zones of closely-spaced, nearly vertical and nearly parallel dikes, referred to as dike complexes. According to Meyer and Souza (1995), "intersecting dikes are common with the result that ground water is impounded and compartmentalized between dikes. Water levels within dike complexes are typically several hundred to 1,000 ft or more above sea level." The number of dikes in a dike complex ranges from about 10 to 1,000 per mile of horizontal distance across the zone, probably averages between 100 and 200 per mile, and declines abruptly near its edge (Meyer and Souza, 1995). The average reported width of dikes is about 2 ft. Basal aquifers are generally free of dikes and are dominated by tube-fed pahoehoe flows generally less than 10 ft thick (William Meyer, USGS, oral commun., 1997). Thus, although hydraulic conductivity is controlled by the void spaces of the basalt flows in each aquifer, conductivity is also controlled by the distribution of dikes and their boundary effects in high-level aquifers.

Categories of hydraulic conductivity at and near the INEEL (fig. 9) are similar to those reported for basal aquifers, high-level aquifers, and dike complexes in Hawaii (fig. 10). The median hydraulic conductivity of category 1, 1.3×10^3 ft/d, is within the reported range of measured values for basal aquifers in Hawaii, 5.0×10^2 to 5.0×10^3 ft/d (Meyer and Souza, 1995). The range of category 1, 1.0×10^2 to 3.2×10^4 ft/d, is identical to the reported range of plausible values for basal aquifers in Hawaii. The median hydraulic conductivity of category 2, 1.1×10^1 ft/d, is within the reported range of measured values for high-level aquifers in Hawaii, 6.6×10^0 to 2.0×10^1 ft/d. The range of category 2, 1.0×10^0 to 1.0×10^2 ft/d, is identical to the reported range of plausible values for high-level aquifers in Hawaii. The median hydraulic conductivity of category 3, 1.7×10^{-1} ft/d, is about one order of magnitude greater than the reported model-simulated value for dike complexes in Hawaii, 2.5×10^{-2} ft/d. The range of category 3, 1.0×10^{-2} to 1.0×10^0 ft/d, is

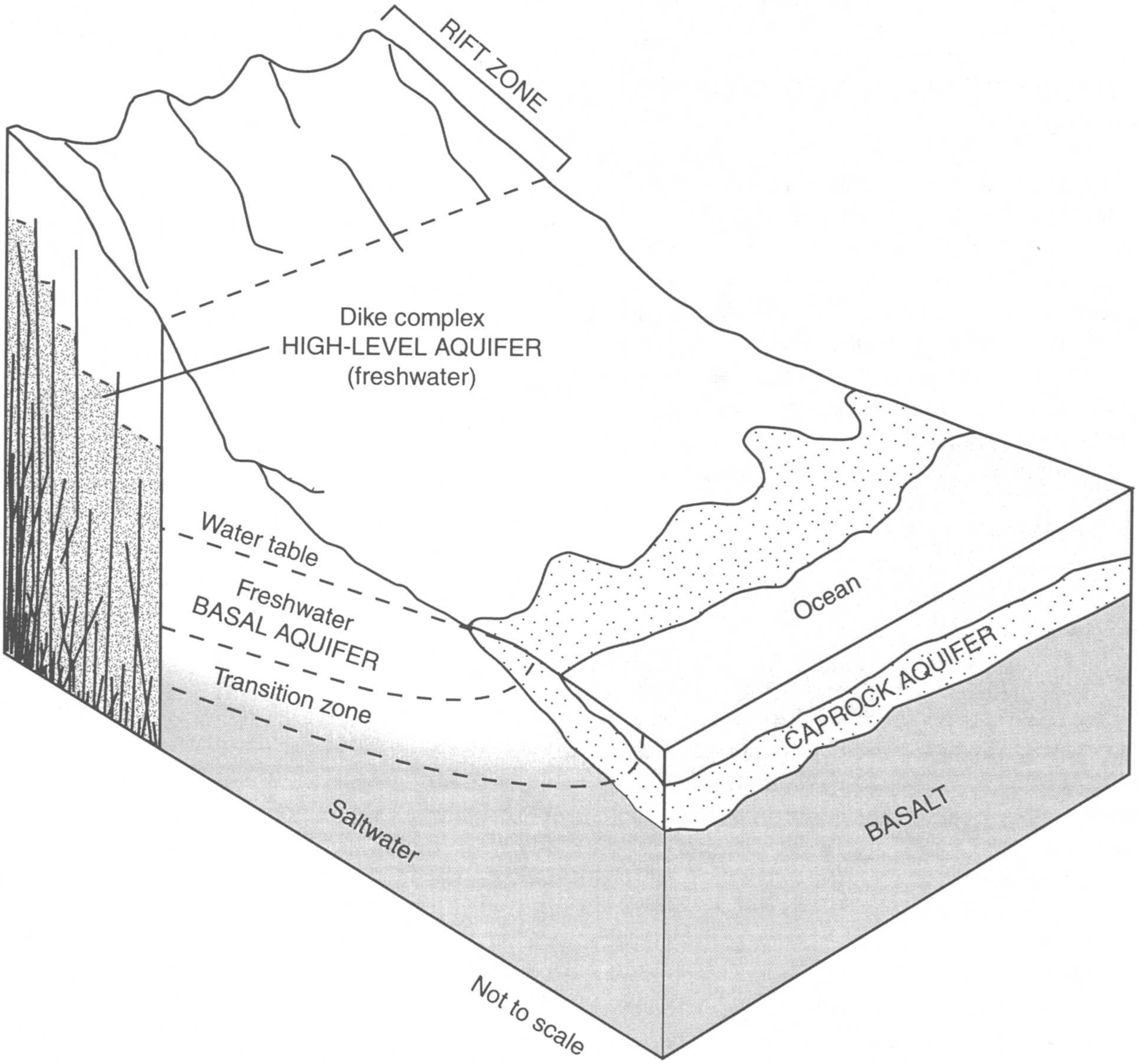

Figure 10. Geohydrologic setting of Hawaii (from Meyer and Souza, 1995).

one order of magnitude less than to one order of magnitude greater than the largest reported plausible value for dike complexes in Hawaii. These similarities suggest that geologic controls of hydraulic conductivity in the Snake River Plain aquifer at and near the INEEL are similar to those of basal aquifers, high-level aquifers, and dike complexes in Hawaii.

HYDROLOGIC IMPLICATIONS OF VENT CORRIDORS

The potential for migration of radioactive and chemical wastes at and near the INEEL is dependent on many complex factors including the distribution of vent corridors (fig. 7). Because vent corridors have the largest variety of rock types and the greatest range of hydraulic conductivity in the Snake River Plain aquifer, these areas may have a significant effect on the movement of ground water and wastes. The potential for rapid movement of ground water and wastes is greatest in thin, tube-fed pahoehoe flows, near-vent volcanic deposits, and open fissures. The movement of ground water and wastes may be greatly impeded by dikes, thick, tube-fed pahoehoe flows, and zones of alteration.

The main direction of ground-water flow at and near the INEEL generally is southwestward, perpendicular to the orientation of vent corridors and their associated volcanoes, dikes, and fissures. Because of this orientation and the large variation of hydraulic conductivity within vent corridors (table 2), these areas probably are characterized by complex pathways for localized ground-water flow. Preferential pathways and local barriers associated with volcanoes, dikes, and fissures within vent corridors may affect the dispersion of wastes in complex ways, as suggested by Hughes and others (1997) and as shown by Bartholomay (1997). These pathways and barriers may greatly increase the overall widths of waste plumes that extend across one or more vent corridors.

Hydraulic conductivity of dikes is sufficiently low to restrict the movement of ground water and increase hydraulic head in the aquifer where dikes are numerous and closely spaced. Dikes are so numerous and closely spaced in Hawaii (fig. 10) that water levels within dike complexes are typically several hundred to 1,000 ft or more above sea level (Meyer and Souza, 1995). Dikes in the uppermost part of the Snake River Plain aquifer at and near the INEEL generally do not restrict the movement of ground water to this degree and must be less numerous and (or) more permeable than dikes in Hawaii. This conclusion is consistent with geologic interpretations suggesting that dikes are generally widely spaced geographically and not concentrated in sheeted dike zones such as are common in Hawaii.

Gradients of hydraulic head in the uppermost part of the aquifer at and near the INEEL range from about 1 to 15 ft/mi and average about 4 ft/mi (Bartholomay and others, 1997). Abrupt changes in hydraulic gradients within this range occur in the northeastern and southwestern parts of the INEEL between vent corridors 6 and 14 and between vent corridors 29 and 33, respectively (fig. 7), and are attributed to dikes, increased fine-grained sediment, and (or) changes in dip of stratigraphic layers (Anderson and Liszewski, 1997). Hydraulic gradients are about 25 to 30 ft/mi between vent corridor 40 (fig. 7) and the Great Rift volcanic rift zone southwest of the INEEL (Lindholm and others, 1987). These gradients are consistent with the potential effects of numerous and closely spaced dikes along and near the Great Rift volcanic rift zone, where the spacing of dikes may be similar to that of the least concentrated dike complexes in Hawaii.

The number of dikes at and near the INEEL probably increases with depth as in Hawaii (fig. 10). Therefore, hydraulic head probably increases with depth where dikes are present and more numerous than in the uppermost few hundred feet of the aquifer. Hydraulic head increases with depth in two deep wells, INEL #1 (10,365 ft) and Corehole 2-2A (3,000 ft) (fig. 2), located in vent corridors 14 and 21 (fig. 7), respectively. Hydraulic head in intervals deeper than about 3,500 ft below land surface in well INEL #1 is about 100 ft higher than the head in adjacent well WS INEL #1 (fig. 2), which is completed in the uppermost 200 ft of the aquifer (Mann, 1986). Hydraulic head in intervals deeper than about 1,900 ft below land surface in well Corehole 2-2A is about 35 ft higher than the head in adjacent well USGS 18 (fig. 2), which is also completed in the uppermost 200 ft of the aquifer (Ott and others, 1992). Although these hydraulic heads may be the result of other factors, they are also consistent with the potential effects of numerous and closely spaced dikes at depth in and below the aquifer in vent corridors 14 and 21.

Gradients of hydraulic head suggest that dikes in the uppermost few hundred feet of the aquifer at and near the INEEL are generally not as numerous and closely spaced as in Hawaii. However, the distribution of hydraulic conductivity and concealed volcanic vents suggest that dikes may be more numerous in some areas, such as in vent corridors 23 and 25 (fig. 7) at and near the ICPP and TRA, than might be predicted from the known locations of volcanic vents at the land surface (Kuntz and others, 1994). The range and distribution of hydraulic conductivity of thin, tube-fed pahoehoe flows at and near the ICPP (figs. 4 and 8) suggest that numerous dikes are present in this area, but that these dikes are laterally discontinuous. Laterally discontinuous dikes in this area and other parts of the INEEL may contribute more to the complexity of ground-water flow paths and the dispersion of radioactive and chemical wastes than to increased hydraulic head in the uppermost part of the aquifer.

SUMMARY AND CONCLUSIONS

The effective hydraulic conductivity of basalt and interbedded sediment that compose the Snake River Plain aquifer at and near the INEEL ranges from about 1.0×10^{-2} to 3.2×10^{4} ft/d. This six-order-of-magnitude range of hydraulic conductivity was estimated from single-well aquifer tests in 114 wells, and is attributed mainly to the physical characteristics and distribution of basalt flows and dikes. Hydraulic conductivity is greatest in thin pahoehoe flows and near-vent volcanic deposits. Hydraulic conductivity is least in flows and deposits cut by dikes. Estimates of hydraulic conductivity at and near the INEEL are similar to those measured in similar volcanic settings in Hawaii.

The largest variety of rock types and the greatest range of hydraulic conductivity are in volcanic rift zones, which are characterized by numerous aligned volcanic vents and fissures related to underlying dikes. Volcanic features related to individual dike systems within these rift zones are approximated in the subsurface by narrow zones referred to as vent corridors. Vent corridors at and near the INEEL are generally perpendicular to ground-water flow and average about 1 to 2 miles in width and 5 to 15 miles in length. Forty-five vent corridors are inferred to be beneath the INEEL and adjacent areas. Vent corridors are characterized locally by anoxic water and altered basalt. In many of the vent corridors, water from the uppermost 200 feet of the aquifer is 1 to 7°C warmer than the median temperature of water (13°C) measured throughout the aquifer.

Three broad categories of hydraulic conductivity corresponding to six general types of geologic controls can be inferred from the distribution of wells and vent corridors. Hydraulic conductivity of category 1 includes 73 estimates, ranges from 1.0×10^{2} to 3.2×10^{4} ft/d, and corresponds to (1) the contacts, rubble zones, and cooling fractures of thin, tube-fed pahoehoe flows; and (2) the numerous voids present in shelly pahoehoe and slab pahoehoe flows and bedded scoria, spatter, and ash near volcanic vents. Hydraulic conductivity of category 2 includes 28 estimates, ranges from 1.0×10^{0} to 1.0×10^{2} ft/d, and corresponds to (3) relatively thick, tube-fed pahoehoe flows that may be ponded in topographic depressions; and (4) thin, tube-fed pahoehoe flows cut by discontinuous dikes. Hydraulic conductivity of category 3 includes 13 estimates, ranges from 1.0×10^{-2} to 1.0×10^{0} ft/d, and corresponds to (5) localized dike swarms; and (6) thick, tube-fed pahoehoe flows cut by discontinuous dikes. Some overlap between these categories and controls is likely because of the small number of hydraulic conductivity estimates and the complex geologic environment.

Hydraulic conductivity of basalt flows probably is increased by localized fissures and coarse mixtures of interbedded sediment, scoria, and basalt rubble. Hydraulic conductivity of basalt flows is decreased locally by abundant alteration minerals of probable hydrothermal origin. Hydraulic conductivity varies as much as six orders of magnitude in a single vent corridor and varies from three to five orders of magnitude within distances of 500 to 1,000 ft. Abrupt changes in hydraulic conductivity over short distances suggest the presence of preferential pathways and local barriers that may greatly affect the movement of ground water and the dispersion of radioactive and chemical wastes downgradient from points of waste disposal.

Of all the geologic factors that control hydraulic conductivity and the movement of ground water and wastes at and near the INEEL, dikes may be the most important and, also, the most difficult to quantify. Dikes can be inferred from geologic models and indirect data, such as hydraulic conductivity, but have not yet been identified in vertical cores. Horizontal cores or selected geophysical techniques, such as borehole tomography or detailed gravity and magnetic surveys, might provide stronger evidence of dikes in the subsurface. These methods, combined with additional aquifer tests, detailed measurements of vertical flow and water temperatures in selected wells, detailed evaluations of radioactive and chemical constituents in water, and simulations of ground-water flow likely would improve present interpretations of dikes and their effects on the movement of ground water and wastes in the Snake River Plain aquifer at and near the INEEL.

REFERENCES CITED

Ackerman, D.J., 1991, Transmissivity of the Snake River Plain aquifer at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4058 (DOE/ID-22097), 35 p.

Anderson, S.R., 1991, Stratigraphy of the unsaturated zone and uppermost part of the Snake River Plain aquifer at the Idaho Chemical Processing Plant and Test Reactors Area, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4010 (DOE/ID-22095), 71 p.

Anderson, S.R., Ackerman, D.J., Liszewski, M.J., and Freiburger, R.M., 1996a, Stratigraphic data for wells at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 96-248 (DOE/ID-22127), 27 p. and 1 diskette.

Anderson, S.R., and Bartholomay, R.C., 1995, Use of natural-gamma logs and cores for determining stratigraphic relations of basalt and sediment at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho: Journal of the Idaho Academy of Science, v. 31, no. 1, p. 1-10.

Anderson, S.R., and Bowers, Beverly, 1995, Stratigraphy of the unsaturated zone and uppermost part of the Snake River Plain aquifer at Test Area North, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 95-4130 (DOE/ID-22122), 47 p.

Anderson, S.R., and Lewis, B.D., 1989, Stratigraphy of the unsaturated zone at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 89-4065 (DOE/ID-22080), 54 p.

Anderson, S.R. and Liszewski, M.J., 1997, Stratigraphy of the unsaturated zone and the Snake River Plain aquifer at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 97-4183 (DOE/ID-22142), 65 p.

Anderson, S.R., Liszewski, M.J., and Ackerman, D.J., 1996b, Thickness of surficial sediment at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 96-330 (DOE/ID-22128), 16 p.

Anderson, S.R., Liszewski, M.J., and Cecil, L.D., 1997, Geologic ages and accumulation rates of basalt-flow groups and sedimentary interbeds in selected wells at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 97-4010 (DOE/ID-22134), 39 p.

Bartholomay, R.C., Tucker, B.J., Ackerman, D.J., and Liszewski, M.J., 1997, Hydrologic conditions and distribution of selected radiochemical and chemical constituents in water, Snake River Plain aquifer, Idaho National Engineering Laboratory, Idaho, 1992 through 1995: U.S. Geological Survey Water-Resources Investigations Report 97-4086 (DOE/ID-22137), 57 p.

Bates, R.L., and Jackson, J.A., eds., 1980, Glossary of geology (2d ed.): Falls Church Va., American Geological Institute, 749 p.

Brott, C.A., Blackwell, D.D., and Ziagos, J.P., 1981, Thermal and tectonic implications of heat flow in the eastern Snake River Plain, Idaho: Journal of Geophysical Research, v. 86, no. B12, p. 11,709-11,734.

Cecil, L.D., Orr, B.R., Norton, Teddy, and Anderson, S.R., 1991, Formation of perched groundwater zones and concentrations of selected chemical constituents in water, Idaho National Engineering Laboratory, Idaho 1986-88: U.S. Geological Survey Water-Resources Investigations Report 91-4166 (DOE/ID-22100), 53 p.

Davis, L.C., Hannula, S.R., and Bowers, Beverly, 1997, Procedures for use of, and drill cores and cuttings available for study at, the Lithologic Core Storage Library, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 97-124 (DOE/ID-22135), 31 p.

Frederick, D.B., and Johnson, G.S., 1996, Estimation of hydraulic properties and development of a layered conceptual model for the Snake River Plain at the Idaho National Engineering Laboratory, Idaho: State of Idaho INEL Oversight Program and Idaho Water Resources Research Institute, Technical Completion Report, 67 p. and 2 appendices.

Geslin, J.K., Gianniny, G.L., Link, P.K., and Riesterer, J.W., 1997, Subsurface sedimentary facies and Pleistocene stratigraphy of the northern Idaho National Engineering Laboratory—controls on hydrogeology: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 15-28.

Gianniny, G.L., Geslin, J.K., Link, P.K., and Thackray, G.D., 1997, Quaternary surficial sediments near Test Area North (TAN), northeastern Snake River Plain—an actualistic guide to aquifer characterization: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 29-44.

Hansen, A.J., Vaccaro, J.J., and Bauer, H.H., 1994, Ground-water flow simulation of the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4187, 81 p., 15 pls. in pocket.

Hughes, S.S., Casper, J.L., and Geist, Dennis, 1997, Potential influence of volcanic constructs on hydrogeology beneath Test Area North, Idaho National Engineering Laboratory, Idaho: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 59-74.

Kuntz, M.A., 1992, A model-based perspective of basaltic volcanism, eastern Snake River Plain, Idaho, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 289-304.

Kuntz, M.A., Champion, D.E., and Lefebvre, R.H., 1989a, Geologic map of the Fissure Butte quadrangle, Blaine and Butte Counties, Idaho: U.S. Geological Survey Geologic Quadrangle Map GQ-1635, scale 1:24,000.

Kuntz, M.A., Covington, H.R., and Schorr, L.J., 1992, An overview of basaltic volcanism of the eastern Snake River Plain, Idaho, in Link, P.K., Kuntz, M.A., and Platt, L.B., eds, Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 227-267.

Kuntz, M.A., Dalrymple, G.B., Champion, D.E., and Doherty, D.J., 1980, Petrography and paleomagnetism of volcanic rocks at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho, with an evaluation of potential volcanic hazards: U.S. Geological Survey Open-File Report 80-388, 63 p.

Kuntz, M.A., Lefebvre, R.H., and Champion, D.E., 1989b, Geologic map of the Watchman quadrangle, Butte County, Idaho: U.S. Geological Survey Geologic Quadrangle map GQ-1633, scale 1:24,000.

Kuntz, M.A., Lefebvre, R.H., Champion, D.E., and Skipp, Betty, 1989c, Geologic map of the Inferno Cone quadrangle, Butte County, Idaho: U.S. Geological Survey Geologic Quadrangle Map GQ-1632, scale 1:24,000.

Kuntz, M.A., Skipp, Betty, Lanphere, M.A., Scott, W.E., Pierce, K.L., Dalrymple, G.B., Champion, D.E., Embree, G.F., Page, W.R., Morgan, L.A., Smith, R.P., Hackett, W.R., and Rodgers, D.W., 1994, Geologic map of the Idaho National Engineering Laboratory and adjoining areas, eastern Idaho: U.S. Geological Survey Miscellaneous Investigations Map I-2330, scale 1:100,000.

Lanphere, M.A., Champion, D.E., and Kuntz, M.A., 1993, Petrography, age, and paleomagnetism of basalt lava flows in coreholes Well 80, NRF 89-04, NRF 89-05, and ICPP 123, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 93-327, 40 p.

Lanphere, M.A., Kuntz, M.A., and Champion, D.E., 1994, Petrography, age, and paleomagnetism of basalt lava flows in coreholes at Test Area North (TAN), Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 94-686, 49 p.

Lindholom, G.F., Garabedian, S.P., Newton, G.D., and Whitethead, R.L., 1987, Configuration of the water table and depth to water, spring 1980, water-level fluctuations, and water movement in the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Hydrologic Investigations Report HA-703, 1 sheet.

Mann, L.J., 1986, Hydraulic properties of rock units and chemical quality of water for INEL-1—a 10,365-foot deep test hole drilled at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 86-4020 (IDO-22070), 23 p.

McLing, T.L., and Smith, R.W., 1997, The effect of hydrothermal water on the Snake River Plain aquifer [abs.]: Geological Society of America Abstracts with Programs: v. 29, no. 6, p. A-323.

Meyer, William, and Souza, W.R., 1995, Factors that control the amount of water that can be diverted to wells in a high-level aquifer, *in* Water resources and environmental hazards—emphasis on hydrologic and cultural insight in the Pacific Rim: American Water Resources Association, June 1995, p. 207-216.

Morin, R.H., Barrash, Warren, Paillet, F.L., and Taylor, T.A., 1993, Geophysical logging studies in the Snake River Plain aquifer at the Idaho National Engineering Laboratory—wells 44, 45, and 46: U.S. Geological Survey Water-Resources Investigations Report 92-4184, 44 p.

Morse, L.H., and McCurry, Michael, 1997, Possible correlations between basalt alteration and the effective base of the Snake River Plain aquifer at the INEEL: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 1-13.

Ott, D.S., Edwards, D.D., and Bartholomay, R.C., 1992, Water-level data for selected wells on or near the Idaho National Engineering Laboratory, Idaho, 1983 through 1990: U.S. Geological Survey Open-File Report 92-643 (DOE/ID-22105), 307 p.

Reed, M.F., Bartholomay, R.C., and Hughes, S.S., 1997, Geochemistry and stratigraphic correlation of basalt lavas beneath the Idaho Chemical Processing Plant, Idaho National Engineering Laboratory: Environmental Geology, v. 30, p. 108-118.

Repenning, C.A., Weasma, T.R., and Scott, G.R., 1995, The early Pleistocene (latest Blancan-earliest Irvingtonian) Froman Ferry Fauna and history of the Glenns Ferry Formation, southwestern Idaho: U.S. Geological Survey Bulletin 2105, 86 p.

Rodgers, D.R., Hackett, W.R., and Ore, H.T., 1990, Extension of the Yellowstone Plateau, eastern Snake River Plain, and Owyhee plateau: Geology, v. 18, p. 1,138-1,141.

Smith, R.P., Hackett, W.R., Josten, N.E., Knutson, C.F., Jackson, S.M., Barton, C.A., Moos, D., Blackwell, D.D., and Kelley, S., 1994, Synthesis of deep drill hole information at the Idaho National Engineering Laboratory (INEL)—upper crustal environment in the continental track of a mantle hotspot: International Symposium on the Observation of the Continental Crust Through Drilling, 7th, Santa Fe, N. Mex., April 25-30, 1994, Proceedings, p. 89-92.

Smith, R.P., Jackson, S.M., and Hackett, W.R., 1996, Paleoseismology and seismic hazards evaluations in extensional volcanic terrains: Journal of Geophysical Research, v. 101, no. B3, p. 6,277-6,292.

Spinazola, J.J., 1994, Geohydrology and simulation of flow and water levels in the aquifer system in the Mud Lake area of the eastern Snake River Plain, eastern Idaho: U.S. Geological Survey Water-Resources Investigations Report 93-4227, 78 p.

Walker, G.P.L., 1970, Compound and simple lava flows and flood basalts. Bulletin of Volcanology 35, p. 579-590.

Welhan, J.A., Funderberg, T., and Smith, R.P., 1997, Stochastic modeling of hydraulic conductivity in the Snake River Plain aquifer—1. hydrological constraints and conceptual approach: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 75-91.

Welhan, J.A., and Reed, M.F., 1997, Geostatistical analysis of regional hydraulic conductivity variations in the Snake River Plain aquifer, eastern Idaho: Geological Society of America Bulletin, v. 109, no. 7, p. 855-868.

Welhan, J.A., and Wylie, A., 1997, Stochastic modeling of hydraulic conductivity in the Snake River Plain aquifer—2. evaluation of lithologic controls at the core and borehole scales: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 93-107.

Wetmore, P.H., Hughes, S.S., and Anderson, S.R., 1997, Model morphologies of subsurface Quaternary basalts as evidence for a decrease in the magnitude of basaltic magmatism at and near the Idaho National Engineering and Environmental Laboratory, Idaho: Symposium on engineering geology and geotechnical engineering, 32d, Boise, Idaho, March 26-28, 1997, Proceedings, p. 45-48.

Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-B, 32 p., 6 pls. in pocket.

Wylie, A.H., McCarthy, J.M., Neher, E., and Higgs, B.D., 1995, Large-scale aquifer pumping test results: LMITCO, Engineering Design File Report ER-WAG7-56, p. [Available from U.S. Department of Energy, Idaho Operations Office, 785 DOE Place, Idaho Falls, ID 83401-1562].

Table 1. ***Probable rift-related hydrogeologic anomalies in selected wells completed in and below the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory***

[Locations of wells shown in figures 2 and 3. Vent corridor numbers correspond to those in figure 7. Cores listed in Davis and others (1997). Hydrologic anomalies include water temperatures (WT) ranging from 14.0 to 20.0 degrees Celsius in the uppermost 200 ft of the aquifer (shallow aquifer), abrupt downward increases in water-temperature gradients (WTG) in deep wells, abrupt downward decreases in laboratory-derived values of porosity and permeability (PL), and anoxic water (AW) of geothermal origin. Geologic anomalies include abundant authigenic and alteration minerals identified by visual (AV) or laboratory (AL) methods; minerals include calcite, clays, and zeolites. Laboratory data from Morse and McCurry (1997) and Welhan and Wylie (1997). NA, indicates not applicable; --, indicates no data.]

Well identifier	Vent corridor	Core	Hydrogeologic anomaly		Depth of well
			Hydrologic	Geologic	
ANP #9	8	No	WT (14.0)	--	Shallow aquifer
Corehole 1	22	Yes	WTG	AV	Deep aquifer
Corehole 2-2A	14	Yes	WTG	AL	Below aquifer
C-1A	33	Yes	WTG, PL	AV	Deep aquifer
INEL #1	21	No	WTG	AV	Deep aquifer
Lidy Hot Springs	2	NA	WT (47.0), AW	NA	Limestone outcrop
NPR WO-2	21	Yes	WTG	AV	Below aquifer
Park Bell well	3	No	AW	--	Unknown
Stoddart well	4	No	AW	--	Unknown
TCH #2	8	Yes	NA	AV (?)	Deep aquifer
USGS 1	28	No	WT (14.5)	--	Shallow aquifer
USGS 5	19	No	WT (15.0)	--	Shallow aquifer
USGS 14	38	No	WT (15.0)	--	Shallow aquifer
USGS 18	14	No	WT (15.0)	--	Shallow aquifer
USGS 19	17	No	WT (17.0)	--	Shallow aquifer
USGS 22	29	No	WT (20.0)	--	Shallow aquifer
USGS 23	19	No	WT (15.5)	--	Shallow aquifer
USGS 26	7	No	WT (15.0)	--	Shallow aquifer
USGS 27	6	No	WT (15.5)	--	Shallow aquifer
USGS 31	7	No	WT (15.5)	--	Shallow aquifer
USGS 32	7	No	WT (14.5)	--	Shallow aquifer
USGS 40	25	No	WT (14.0)	--	Shallow aquifer
USGS 87	33	No	WT (14.0)	--	Shallow aquifer
USGS 119	33	No	WT (14.0)	--	Shallow aquifer
USGS 121	23	Yes	NA	AV (?)	Shallow aquifer
USGS 122	25	No	WT (17.0)	--	Shallow aquifer
USGS 123	25	Yes	WT (14.5)	NA	Shallow aquifer

Table 2. ***Estimates of average layer thickness, transmissivity, and hydraulic conductivity of basalt and sediment in selected wells completed in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory***

[Numbers correspond to data points in figure 8. Locations of wells shown in figures 2 and 3. Total perforated or open interval(s): parentheses indicate basalt and sediment below effective base of aquifer deleted; brackets indicate basalt-flow group I(2) deleted (Anderson and others, 1996a). Number and average thickness of complete basalt and sediment layers in and near perforated or open interval(s) modified from Anderson and others (1996a). Transmissivity from Ackerman (1991) and Bartholomay and others (1997); estimate for well ANP #9 is a corrected value (Ackerman, written commun., 1998). Relative uncertainty in orders of magnitude. Hydraulic conductivity (K) estimated from transmissivity and total length of perforated or open interval(s); values are bulk conductivity as defined by Welhan and Reed (1997). Field numbers correspond to those in figure 8. Vent corridor numbers correspond to those in figure 7. ft^2/d, feet squared per day; ft/d, feet per day; NA, indicates not applicable; <, indicates less than; >, indicates greater than]

Number	Well identifier	Penetration (feet)	Total perforated or open interval(s) (feet)	Number of layers (percent sediment)	Average layer thickness (feet)	Transmissivity (ft^2/d)	Relative uncertainty	Hydraulic conductivity (K) (ft/d)		Field	Vent corridor
								K	Log K		
1	ANP #6	91	75	4 (0.0)	18.8	5.0×10^5	0.4	6.7×10^3	3.83	1	8
2	ANP #9	322	77	3 (0.0)	26.0	2.7×10^4	0.4	3.5×10^2	2.54	1	8
3	ANP #10	457	100	3 (5.0)	28.3	1.8×10^3	0.4	1.8×10^1	1.26	3	8
4	AREA II	215	159	9 (9.4)	22.2	1.2×10^5	0.4	7.5×10^2	2.88	1	22
5	Arbor Test 1	117	100	7 (0.0)	16.3	5.6×10^5	0.4	5.6×10^3	3.75	1	16
6	CFA 1	171	171	9 (9.4)	21.1	2.1×10^3	0.4	1.2×10^1	1.08	3	27
7	CFA 2	209	150	8 (0.0)	25.0	1.7×10^2	0.1	1.1×10^1	1.04	3	27
8	CPP 2	148	[49]	3 (22.4)	25.6	1.6×10^5	0.4	3.3×10^3	3.52	1	23
9	CPP 4	255	[165]	8 (0.0)	20.6	2.5×10^2	0.4	1.5×10^0	0.18	3	23
10	CPP Disp	147	[86]	6 (8.1)	14.0	7.6×10^5	0.4	8.8×10^3	3.94	1	25
11	EBR I	479	475	15 (1.5)	31.4	1.3×10^3	0.1	2.7×10^0	0.43	4	NA
12	EOCR	753	186	11 (10.2)	17.7	1.8×10^5	0.4	9.7×10^2	2.99	1	NA
13	FET-Disp-1	101	96	4 (0.0)	35.0	1.5×10^4	0.4	1.6×10^2	2.20	2	8
14	Highway #3	212	100	5 (0.0)	22.0	$>3.3\times10^2$	>0.5	$>3.3\times10^0$	>0.52	3	29
15	IET Disp	117	100	4 (0.0)	28.8	1.6×10^2	0.1	1.6×10^0	0.20	3	8
16	LPTF Disp	109	103	5 (0.0)	25.3	3.5×10^3	0.1	3.4×10^1	1.53	3	8
17	MTR Test	137	137	3 (0.0)	51.0	2.0×10^5	0.4	1.4×10^3	3.15	2	23
18	NPR Test	144	35	3 (14.3)	21.3	8.6×10^3	0.4	2.4×10^2	2.38	1	8

Table 2. ***Estimates of average layer thickness, transmissivity, and hydraulic conductivity of basalt and sediment in selected wells completed in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory***--Continued

Number	Well identifier	Penetration (feet)	Total perforated or open interval(s) (feet)	Number of layers (percent sediment)	Average layer thickness (feet)	Transmissivity (ft^2/d)	Relative uncertainty	Hydraulic conductivity (K) (ft/d)		Field	Vent corridor
								K	Log K		
19	P&W #1	117	50	2 (0.0)	35.0	2.5×10^5	0.4	5.0×10^3	3.70	2	8
20	P&W #2	77	68	3 (0.0)	32.7	1.4×10^5	0.4	2.0×10^3	3.30	2	8
21	P&W #3	102	79	2 (0.0)	37.5	1.4×10^4	0.4	1.8×10^2	2.26	2	8
22	PBF #2	752	267	14 (4.1)	19.1	8.0×10^4	0.4	4.8×10^2	2.68	1	23
23	PSTF Test	114	103	6 (0.0)	21.5	5.9×10^3	0.4	5.7×10^1	1.76	3	10
24	QAB	348	38	3 (0.0)	21.3	3.0×10^0	0.1	7.9×10^{-2}	-1.10	5	39
25	RWMC Prod	112	30	2 (0.0)	29.0	6.8×10^3	0.4	2.3×10^2	2.36	1	33
26	Site 6	172	95	6 (0.0)	15.8	1.8×10^3	0.4	1.9×10^1	1.28	3	17
27	Site 9	584	373	16 (36.7)	23.1	$>3.9\times10^5$	>0.5	$>1.0\times10^3$	>3.00	1	NA
28	Site 14	454	182	8 (0.0)	22.0	6.7×10^4	0.4	3.7×10^2	2.57	1	NA
29	Site 17	206	206	10 (17.0)	20.6	1.4×10^4	0.5	6.8×10^1	1.83	3	19
30	Site 19	398	[179]	9 (0.0)	24.7	3.1×10^4	0.4	1.7×10^2	2.23	1	25
31	TAN Expl	346	283	14 (13.8)	20.2	9.0×10^1	0.1	3.2×10^{-1}	-0.49	5	10
32	TRA #3	141	[27]	1 (0.0)	43.0	1.0×10^5	0.1	3.7×10^3	3.57	2	23
33	TRA #4	517	(22)	2 (36.4)	21.0	8.7×10^4	0.4	4.0×10^3	3.60	1	23
34	TRA Disp	815	(70)	2 (0.0)	35.0	6.2×10^4	0.4	8.8×10^2	2.94	2	23
35	USGS 1	46	30	2 (0.0)	18.0	$>3.3\times10^5$	>0.5	$>1.1\times10^4$	>4.04	1	28
36	USGS 2	47	21	2 (0.0)	10.5	3.7×10^4	0.4	1.8×10^3	3.26	1	NA
37	USGS 4	291	268	19 (0.0)	14.1	5.0×10^5	0.5	1.9×10^3	3.28	1	6
38	USGS 5	34	22	2 (18.2)	11.0	1.1×10^1	0.4	5.0×10^{-1}	-0.30	5	19
39	USGS 6	207	88	5 (11.4)	21.0	4.1×10^2	0.4	4.6×10^0	0.66	3	16
40	USGS 7	991	(135)	5 (3.7)	27.0	3.3×10^3	0.4	2.4×10^1	1.38	3	10
41	USGS 8	46	30	1 (0.0)	30.0	2.1×10^4	0.4	7.0×10^2	2.84	1	36
42	USGS 9	28	28	3 (0.0)	17.3	5.9×10^4	0.4	2.1×10^3	3.32	1	NA
43	USGS 11	100	30	2 (33.3)	15.0	$>7.0\times10^4$	>0.5	$>2.3\times10^3$	>3.36	1	NA

Table 2. ***Estimates of average layer thickness, transmissivity, and hydraulic conductivity of basalt and sediment in selected wells completed in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory***--Continued

Number	Well identifier	Penetration (feet)	Total perforated or open interval(s) (feet)	Number of layers (percent sediment)	Average layer thickness (feet)	Transmissivity (ft^2/d)	Relative uncertainty	Hydraulic conductivity (K) (ft/d)		Field	Vent corridor
								K	Log K		
44	USGS 12	367	105	6 (19.0)	19.5	1.1×10^{4}	0.4	1.0×10^{2}	2.00	1	17
45	USGS 14	36	36	3 (33.3)	12.0	2.2×10^{4}	0.4	6.1×10^{2}	2.78	1	37
46	USGS 15	294	70	5 (10.0)	13.8	8.5×10^{4}	0.4	1.2×10^{3}	3.08	1	17
47	USGS 17	145	98	7 (10.2)	15.4	4.4×10^{2}	0.1	4.5×10^{0}	0.65	3	17
48	USGS 18	60	24	1 (0.0)	39.0	4.3×10^{4}	0.5	1.8×10^{3}	3.26	2	14
49	USGS 19	127	21	1 (0.0)	21.0	7.2×10^{4}	0.4	3.4×10^{3}	3.53	1	17
50	USGS 20	215	48	4 (0.0)	22.4	3.8×10^{2}	0.4	7.9×10^{0}	0.90	3	25
51	USGS 22	46	15	3 (0.0)	15.0	$<2.6\times10^{0}$	>0.5	$<1.7\times10^{-1}$	<-0.77	5	29
52	USGS 23	66	20	3 (25.0)	10.3	8.8×10^{4}	0.5	4.4×10^{3}	3.64	1	19
53	USGS 24	108	70	3 (0.0)	23.0	1.4×10^{4}	0.4	2.0×10^{2}	2.30	1	8
54	USGS 26	60	34	2 (0.0)	25.5	8.2×10^{5}	0.5	2.4×10^{4}	4.38	1	7
55	USGS 27	86	20	2 (50.0)	14.0	3.3×10^{2}	0.4	1.6×10^{1}	1.20	3	6
56	USGS 29	71	62	4 (24.2)	14.5	8.7×10^{4}	0.4	1.4×10^{3}	3.15	1	NA
57	USGS 30A	140	76	5 (6.6)	15.3	4.3×10^{5}	0.4	5.6×10^{3}	3.75	1	NA
58	USGS 31	177	143	12 (7.0)	12.1	1.7×10^{4}	0.4	1.2×10^{2}	2.08	1	7
59	USGS 32	102	86	5 (26.7)	17.2	5.6×10^{5}	0.5	6.5×10^{3}	3.81	1	7
60	USGS 34	227	[201]	7 (2.0)	27.1	$>3.9\times10^{5}$	>0.5	$>1.9\times10^{3}$	>3.28	1	25
61	USGS 35	105	105	5 (0.0)	21.0	$>3.9\times10^{5}$	>0.5	$>3.7\times10^{3}$	>3.71	1	25
62	USGS 36	94	94	5 (0.0)	20.6	3.9×10^{5}	0.5	4.1×10^{3}	3.61	1	25
63	USGS 37	106	65	3 (0.0)	21.0	1.6×10^{4}	0.4	2.5×10^{2}	2.40	1	25
64	USGS 38	257	[29]	2 (17.2)	14.5	4.6×10^{0}	0.4	1.6×10^{-1}	-0.80	5	25
65	USGS 39	97	97	6 (10.3)	16.2	3.9×10^{5}	0.4	4.0×10^{3}	3.60	1	25
66	USGS 40	32	27	3 (0.0)	15.7	8.7×10^{4}	0.4	3.2×10^{3}	3.50	1	25
67	USGS 41	215	[176]	10 (2.3)	17.9	$>3.9\times10^{5}$	>0.5	$>2.2\times10^{3}$	>3.34	1	25
68	USGS 42	218	[149]	7 (0.0)	21.6	$>3.9\times10^{5}$	>0.5	$>2.6\times10^{3}$	>3.41	1	25

Table 2. ***Estimates of average layer thickness, transmissivity, and hydraulic conductivity of basalt and sediment in selected wells completed in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory***--Continued

Number	Well identifier	Penetration (feet)	Total perforated or open interval(s) (feet)	Number of layers (percent sediment)	Average layer thickness (feet)	Transmissivity (ft^2/d)	Relative uncertainty	Hydraulic conductivity (K) (ft/d)		Field	Vent corridor
								K	Log K		
69	USGS 43	225	[133]	7 (3.0)	20.0	8.0×10^{4}	0.4	6.0×10^{2}	2.78	1	25
70	USGS 44	191	[98]	5 (0.0)	20.2	4.1×10^{5}	0.4	4.2×10^{3}	3.62	1	25
71	USGS 45	191	[117]	6 (7.7)	18.8	9.3×10^{3}	0.4	7.9×10^{1}	1.90	3	25
72	USGS 46	193	[113]	7 (5.3)	16.1	$>5.0\times10^{5}$	>0.5	$>4.4\times10^{3}$	>3.64	1	25
73	USGS 48	291	[212]	11 (6.6)	19.3	4.1×10^{5}	0.4	1.9×10^{3}	3.28	1	25
74	USGS 51	204	[123]	6 (3.2)	19.7	2.9×10^{3}	0.4	2.4×10^{1}	1.38	3	25
75	USGS 52	198	[124]	8 (4.0)	15.5	$>4.1\times10^{5}$	>0.5	$>3.3\times10^{3}$	>3.52	1	23
76	USGS 57	273	[185]	9 (2.7)	20.6	2.8×10^{4}	0.4	1.5×10^{2}	2.18	1	25
77	USGS 58	50	50	1 (0.0)	50.0	3.7×10^{4}	0.4	7.4×10^{2}	2.87	2	25
78	USGS 65	34	34	2 (23.5)	15.0	9.5×10^{3}	0.4	2.8×10^{2}	2.45	1	25
79	USGS 76	252	[161]	8 (2.5)	20.1	1.9×10^{5}	0.4	1.2×10^{3}	3.08	1	25
80	USGS 77	144	140	6 (0.0)	24.2	1.2×10^{3}	0.4	8.6×10^{0}	0.93	3	25
81	USGS 79	229	[136]	5 (2.9)	28.6	2.6×10^{3}	0.4	1.9×10^{1}	1.28	3	25
82	USGS 82	247	[117]	8 (6.0)	16.0	1.2×10^{5}	0.4	1.0×10^{3}	3.00	1	23
83	USGS 83	257	236	12 (15.2)	20.1	9.0×10^{2}	0.1	3.8×10^{0}	0.58	3	29
84	USGS 84	21	21	2 (0.0)	15.0	$>6.4\times10^{4}$	>0.5	$>3.0\times10^{3}$	>3.48	1	25
85	USGS 85	155	115	6 (22.6)	19.2	3.9×10^{5}	0.4	3.4×10^{3}	3.53	1	27
86	USGS 86	46	46	4 (19.6)	21.5	3.0×10^{3}	0.1	6.5×10^{0}	0.81	3	36
87	USGS 87	87	87	4 (17.2)	27.0	8.5×10^{2}	0.1	9.8×10^{0}	0.99	1	33
88	USGS 88	87	75	2 (0.0)	36.5	1.3×10^{1}	0.1	1.7×10^{-1}	-0.77	6	33
89	USGS 89	56	56	3 (0.0)	30.3	4.9×10^{1}	0.1	8.8×10^{-1}	-0.06	6	33
90	USGS 90	31	31	3 (67.7)	42.7	4.9×10^{2}	0.4	1.6×10^{1}	1.20	4	33
91	USGS 97	131	122	8 (0.0)	15.2	7.1×10^{4}	0.4	5.8×10^{2}	2.76	1	NA
92	USGS 98	107	98	4 (29.6)	24.5	8.1×10^{4}	0.4	8.3×10^{2}	2.92	1	21
93	USGS 99	63	63	4 (0.0)	15.8	1.1×10^{5}	0.4	1.7×10^{3}	3.23	1	21

Table 2. ***Estimates of average layer thickness, transmissivity, and hydraulic conductivity of basalt and sediment in selected wells completed in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory***--Continued

Number	Well identifier	Penetration (feet)	Total perforated or open interval(s) (feet)	Number of layers (percent sediment)	Average layer thickness (feet)	Transmissivity (ft^2/d)	Relative uncertainty	Hydraulic conductivity (K) (ft/d)		Field	Vent corridor
								K	Log K		
94	USGS 100	79	79	6 (5.1)	13.2	1.4×10^{4}	0.4	1.8×10^{2}	2.26	1	16
95	USGS 101	95	95	6 (11.6)	18.7	1.2×10^{3}	0.4	1.3×10^{1}	1.11	3	NA
96	USGS 102	77	77	5 (9.1)	15.4	1.9×10^{4}	0.4	2.5×10^{2}	2.40	1	19
97	USGS 103	181	181	6 (0.0)	30.2	1.6×10^{5}	0.4	8.8×10^{2}	2.94	2	NA
98	USGS 104	148	148	10 (12.2)	15.0	1.4×10^{1}	0.1	9.4×10^{-2}	-1.03	5	31
99	USGS 105	134	134	6 (0.0)	24.2	8.5×10^{4}	0.4	6.3×10^{2}	2.80	1	35
100	USGS 106	177	177	10 (9.0)	17.7	1.0×10^{5}	0.4	5.6×10^{2}	2.75	1	NA
101	USGS 107	214	214	8 (0.0)	26.5	7.0×10^{4}	0.4	3.3×10^{2}	2.52	1	NA
102	USGS 108	156	156	6 (0.0)	28.5	1.5×10^{5}	0.4	9.6×10^{2}	2.98	1	34
103	USGS 109	182	182	8 (4.9)	21.2	1.1×10^{5}	0.4	6.0×10^{2}	2.78	1	NA
104	USGS 110	214	200	8 (0.0)	25.0	1.1×10^{4}	0.4	5.5×10^{1}	1.74	3	30
105	USGS 111	137	137	6 (0.0)	22.8	2.2×10^{1}	0.1	1.6×10^{-1}	-0.80	5	25
106	USGS 112	96	96	4 (0.0)	23.0	6.4×10^{4}	0.4	6.7×10^{2}	2.83	1	25
107	USGS 113	97	97	4 (0.0)	23.5	1.9×10^{5}	0.4	2.0×10^{3}	3.30	1	25
108	USGS 114	100	100	4 (0.0)	25.0	1.0×10^{1}	0.1	1.0×10^{-1}	-1.00	5	25
109	USGS 115	123	123	5 (0.0)	24.6	3.2×10^{1}	0.1	2.6×10^{-1}	-0.58	5	25
110	USGS 116	127	127	6 (0.0)	21.2	1.5×10^{2}	0.1	1.2×10^{0}	0.08	3	25
111	USGS 117	74	74	3 (16.2)	31.0	1.4×10^{1}	0.1	1.9×10^{-1}	-0.72	6	33
112	USGS 119	105	105	5 (5.8)	31.8	1.1×10^{0}	0.4	1.0×10^{-2}	-2.00	6	33
113	USGS 120	94	94	5 (8.5)	17.6	2.2×10^{5}	0.4	2.3×10^{3}	3.36	1	34
114	WS INEL #1	210	210	10 (0.0)	21.7	3.7×10^{2}	0.1	1.8×10^{0}	0.25	3	21

Table 3. ***Central tendencies of hydraulic conductivity estimates***
[ft/d, feet per day]

Number of observations	**114**
Range of values	**[1]0.01-24,000 ft/d**
Measures of central tendancy	
Arithmetic mean	1,500 ft/d
Root mean square	3,300 ft/d
Geometric mean	140 ft/d
Median	520 ft/d
[2]Mode	1,800 ft/d

[1]Includes 11 observations with greater than and less than values.

[2]Mode is center of hydraulic conductivity class interval 11 (fig. 9).