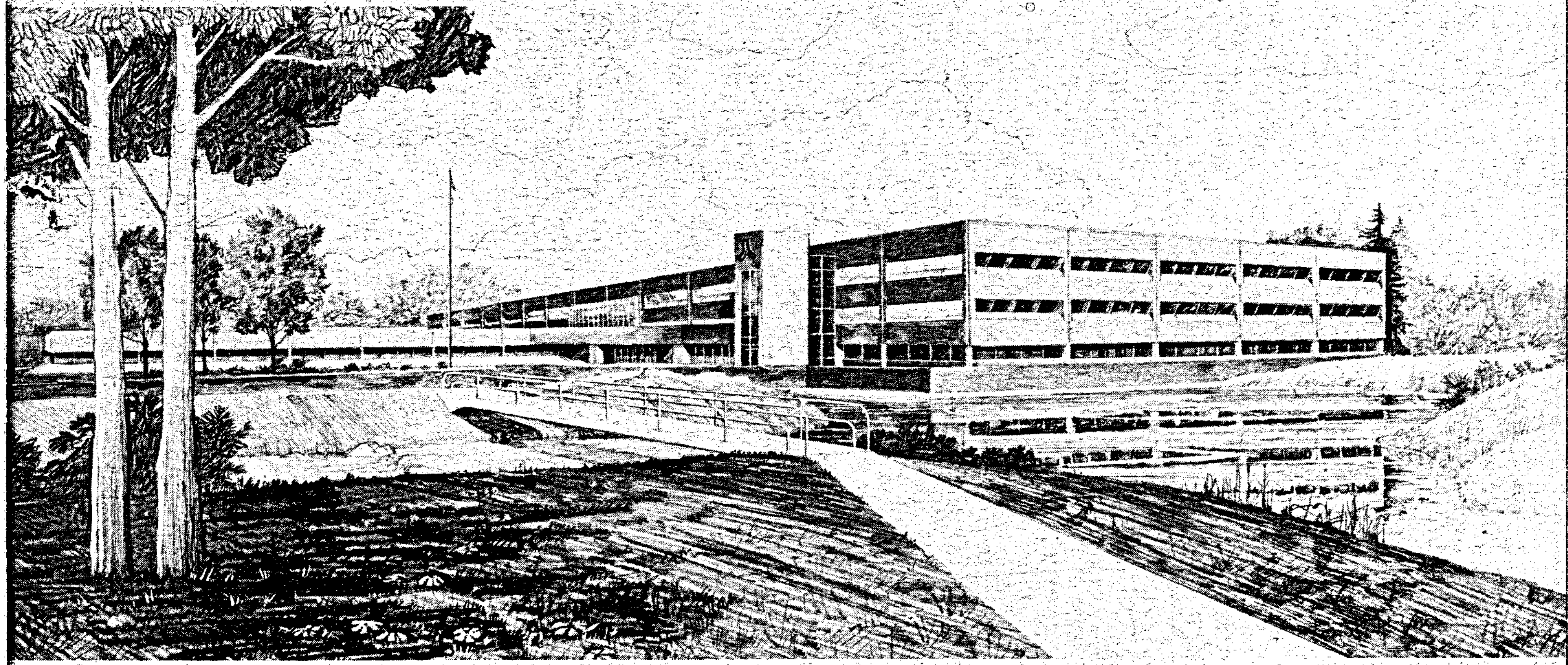
756
3-14-80

DR. 858

EGG-2011
(Supersedes TREE-1161)



U.S. Department of Energy
Idaho Operations Office • Idaho National Engineering Laboratory

MASTER

Geothermal Resource Exploration in Boise, Idaho

Lynn B. Nelson
Warren L. Niemi
Roger C. Stoker

February 1980

Prepared for the
U.S. Department of Energy
Under DOE Contract No. DE-AC07-76IDO1570

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EG&G Idaho

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
NTIS Price Codes: Printed Copy A03
Microfiche A01

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

EGG-2011
(Supersedes TREE-1161)
Distribution Categories: UC66a,b

GEOTHERMAL RESOURCE EXPLORATION IN BOISE, IDAHO

Lynn B. Nelson
Warren L. Niemi
Roger C. Stoker

Published February 1980

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Idaho Operations Office
Under Contract No. DE-AC07-76IDO1570

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

Exploratory drilling in Boise, Idaho, in the vicinity of the Boise Front Fault has confirmed the presence of a 170°F (77°C) geothermal resource below about 800 ft (244 m) near the Veterans Hospital of the Military Reserve Park. The Idaho National Engineering Laboratory (INEL), sponsored by the Department of Energy, drilled three exploratory slim holes and two deep exploratory test wells. This report presents study results based on tests of the two exploratory-test wells.

Faulting related to the Boise Front Fault defines a major physiographic break in the area that acts as a subsurface conduit through which geothermal water circulates. Hydrologic tests indicate that rocks disturbed by the Boise Front Fault may be as much as ten times more permeable than those removed from the major structural lineament.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the many people involved in this project. This includes those from the Department of Energy, U.S. Geological Survey, City of Boise, Bureau of Land Management, Boise State University, Idaho Bureau of Mines and Geology, the drillers, and co-workers from EG&G Idaho, Inc. The report preparation involved the technical consultation and assistance of Dr. D. W. Allman, Dr. J. F. Kunze, and Dennis Goldman of EG&G Idaho, Inc. Their assistance and cooperation was extremely helpful and is very much appreciated.

CONTENTS

FIGURES

SUMMARY

The geothermal resource at Boise, Idaho, has been in use for 85 years, but major production has been restricted to only two wells. Several other wells were drilled before 1976, but none were as productive or as hot as the original two located on the old Idaho Penitentiary site. The two penitentiary (Warm Springs) wells produce water at 168°F (76°C), while the others produce water at an average temperature of only 108°F (42°C) from about the same depth of 425 ft (130 m).

The Idaho National Engineering Laboratory (INEL) began a project in 1975 to investigate the nature of the resource and the economic feasibility of using geothermal water for space heating in several homes and large buildings. The project led, in 1976, to the siting and drilling of three slim (2-7/8-in. or 73-mm-diam) exploratory holes and two deep exploratory test wells. The two test wells were tested during 1976, 1977, and 1978 to determine the nature and size of the geothermal resource. The drilling and engineering test results have confirmed the presence of a fracture- controlled aquifer in the vicinity of the Veterans Hospital of the Military Reserve Park.

GEOTHERMAL RESOURCE EXPLORATION IN BOISE, IDAHO

INTRODUCTION

The Department of Energy (DOE)-sponsored Boise Geothermal Space Heating project was initiated on January 1, 1975 to investigate the feasibility of heating part of the State Capitol complex and related public buildings with geothermal energy.

The major objective of the project was to detect, delineate, and evaluate the geothermal resource along the Boise Front in the vicinity of the State Capitol Building with the intent of converting the heating sytem in this and related buildings to use this resource. To accomplish the objective, geological, geophysical, and hydrologic resource studies were conducted in the area. Finally, several exploratory wells were drilled to various depths to confirm the presence of geothermal water while providing information for all phases of the project.

Between August 1977 and February 1978, personnel from the Idaho National Engineering Laboratory (INEL) conducted several pump and flow tests on two of the exploratory wells: BHW-1 (Beard) and BEH-1 (BLM). In addition, one flow test was conducted at the BHW-1 well after its completion in October 1976.

The purpose of this report is to present the findings of these tests and conclusions that may be drawn from them.

PHYSIOGRAPHY, CLIMATE, GEOLOGY, AND GEOHYDROLOGY[1]

Physiography

Boise, Idaho is located along the contact of two physiographic provinces: the Northern Rocky Mountain province (the Idaho Batholith) and the Columbian Intermountain Province (the Snake River Plain). Boise is situated on a broad alluvial plain of the Snake River Plain, while the foothills and mountains (Boise Ridge) of the Idaho Batholith lie to the northeast, rising to an elevation of 6025 ft (1836 m) at Boise Peak. To the southwest, the Boise Valley is characterized by several flat alluvial terraces composed of material shed from the Boise Foothills region.

Climate

The project area is characterized by arid to semi-arid climatic conditions. Weather conditions are quite diverse due to the extreme variation in relief. Temperature records show a yearly mean of 51°F (10.5°C). Summer days tend to be warm and dry. The average daily maximum temperature in the summer is 84°F (28.9°C), with temperatures well over 100°F (37.8°C) having been recorded. Temperatures dip considerably in the winter months. The mean temperature for January ranges from -22 to 37°F (-5.6 to 2.8°C).[2]

Most of the precipitation is received during the winter months. The yearly mean values for precipitation, as measured at the U.S. Weather Station at the Boise Airport (elevation 2838 ft, 865.0 m), is 11.9 in. (304 cm). Records for the Boise 7n station (elevation 3885 ft, 1184 m), over a 3-year period, show an average of approximately 20 in. (508 cm). The high relief and orographic effect of the Boise Ridge is the main reason for this extreme difference in precipitation.

Geology

The major rock types in the Boise area range from Cretaceous to Pleistocene in age. The older rocks, those of the Idaho Batholith, have been uplifted, faulted, and eroded due to many years of crustal unrest. These crystalline granitic rocks are unconformably overlain by the much younger Glenns Ferry Formation of the Idaho Group.

The Idaho Group is composed of clastic beds and interrelated basalt flows. It has been divided into seven major formations. The distribution of the Idaho Group suggests that the deposition of these formations took place in a subsiding basin.

These formations range in age from early Pliocene to middle Pleistocene.[3] Figure 1 shows the rock types in the Boise area.

Structurally, Boise appears to be on the downthrown block of a major fault known as the Foothills Fault.[4] The Boise Foothills are located on the upthrown block of this same fault (Figure 2). The fault extends approximately 9 miles (14.5 km) along the base of the Foothills. The Foothills Fault is not a single structure,[4] but is, instead, part of a system of northwest-southeast trending faults that define a regional zone of weakness along the northern margin of the Snake River Plain.

Several strong northeast-southwest trending linear patterns, likely a result of faulting, have been noted by photogeologic methods.[5] These linears correspond to major drainages flowing southwest from the Boise Ridge and have been named the Freestone Trend.[5] The intersection of the Foothills Fault with the Freestone Trend appears connected to the flow of the geothermal fluids in the area.

Geohydrology

In the Boise area there are three separate aquifer systems: (a) the shallow, or water table aquifer, (b) the deep artesian aquifer, which occurs under an artesian head, and (c) the geothermal aquifer, which contains waters apparently heated at depth in the fractures of the Idaho Batholith. There is some interaction between all three systems; however, each has its own distinct water-bearing characteristics.

Shallow Aquifer (Water Table Aquifer)

The shallow aquifer lies within the recent alluvium of the Boise River floodplain and derives most of its recharge from surface sources, such as rainfall, streams, canals, and irrigation. The water table configuration within the shallow system generally follows the ground surface topography, while the depth to the water table fluctuates seasonally.

The water table along the Boise Ridge is within the Glenns Ferry Formation. This shallow system is independent of the floodplain shallow system mentioned above. Although probably interconnected, they are both separate systems and should not be confused. The water table in the Boise flood plain is found in river alluvium, whereas the water table along the ridge is located mainly in the Glenns Ferry formation.

Throughout the shallow groundwater system in the Boise floodplain, water levels fluctuate seasonally, but antithetic to anticipated natural groundwater fluctuations. Due to storage and diversion of Boise River water and pumping from local irrigation wells, water table highs occur in early fall, near the end of the irrigation season; lows occur in early spring, when the irrigation season begins. In most of the valley, fluctuation is less than 10 ft (3.05 m), although some areas southwest of Boise have repeated fluctuations of up to 60 ft (68.3 m). The water table fluctuates more normally along the ridge with water level highs and lows occurring in the spring and fall, respectively.

Deep Artesian Aquifer System

The deep artesian aquifer system of the Boise area occurs at depths in excess of 500 ft (152 m) and is found in lower strata of the Glenns Ferry Formation. The deep system is a confined aquifer occurring under considerable artesian head.

The Glenns Ferry Formation, composed of sand layers with a relatively high hydraulic conductivity, is interbedded with silt and clay of lower hydraulic conductivity. The contrast in hydraulic conductivity results in greater transmission of groundwater in the sands, with discharge concentrated toward the downstream end of the sand. This increases the vertical gradient in the layers having lower hydraulic conductivity, as well as the overall vertical gradient of the aquifer formation, and creates favorable conditions for artesian flow.[6] The flow direction of the artesian system is approximately the same as that of the water table system.

The Boise Ridge is the main recharge area for the deep artesian aquifer system. Most of the water available for recharge is the result of precipitation falling along the ridge, where many potential channels are available for surface water infiltration and aquifer recharge. Some of these

Quaternary	Recent	Recent alluvium and surficial deposits	Unconsolidated clay, silt sand, and fine to coarse gravel of fluviatile origin. Overlies older deposits of the Glenns Ferry Formation in the Boise Region.
Tertiary and Quaternary	Pleistocene	Snake River Basalt	Light to dark gray, vesicular, olivine basalt. Columnar jointing.
	Pliocene	Glenns Ferry Formation	Layered sediments of varied composition with interlayered basalts.
Tertiary	Miocene	Late Columbia River Basalt	Light to dark gray, dense glassy basalt.
Cretaceous	Late to Mid Cretaceous	Idaho Batholith	Light to medium gray quartz monzonite and granodiorite.

Source: L.L. Mink and D.L. Graham, Geothermal Potential in the West Boise Area, TREE-1162, October 1977.

INEL-A-14 360

Figure 1. Major rock units of the Boise Front area and their physical characteristics[1].

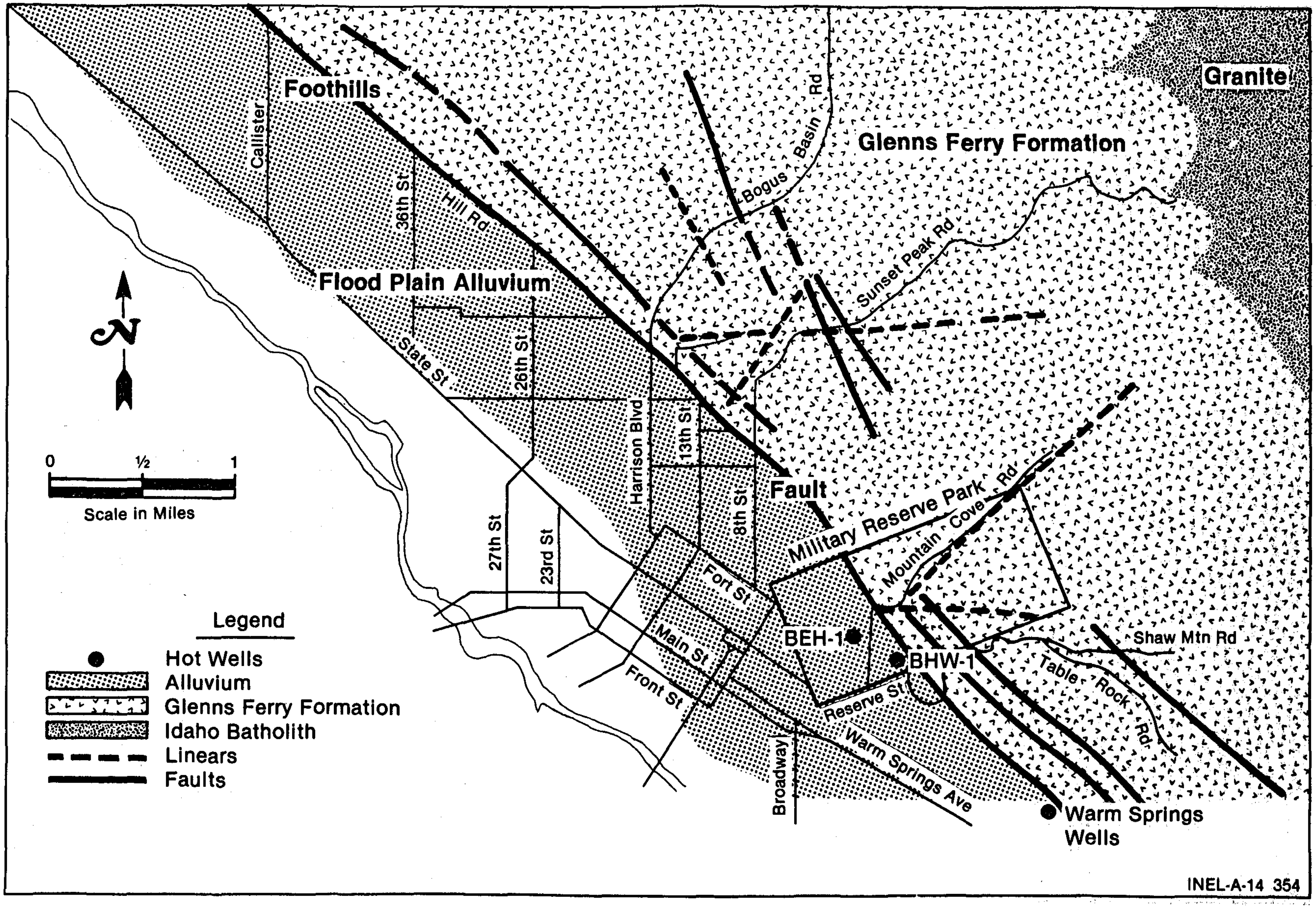


Figure 2. Boise area generalized geologic map.

channels are the permeable sediments, the contact between the Glenns Ferry sediments and the batholith, and the many shears and fractures present in the granitic rocks of the batholith.

Geothermal Aquifer System

The warm waters of the geothermal system are associated with major structural features. These structures include major faults in the area as well as numerous linear trending features that have been mapped by photogeologic methods.

Heat for the geothermal water is believed to originate from deep circulation within the fracture systems of the Idaho batholith. Water is heated at depth and moves along fault and fracture zones and upward, mixing with and heating the water in the Glenns Ferry Formation. The Boise Front Fault, running northwest-southeast along the mountains near the northeast boundary of the city, appears to be a hydrologic boundary beyond which considerable mixing occurs with the cooler groundwaters of the near surface extension of the Deep Artesian or Water Table Aquifer Systems.

EXPLORATORY SLIM HOLE AND TEST WELL DRILLING

Exploratory Slim Hole Drilling

Three exploratory slim holes were sited (Figure 3) and drilled, based on the area structural geology. These holes were drilled and cored to a depth of 259 ft (79 m), 655 ft (200 m), and 550 ft (168 m), respectively. They confirmed the presence of extensive hydrothermal rock alteration in the area and the presence of hot water within the fractured zones associated with major faulting. Lithologic columns, revealed by cores and cuttings from the wells, are described in Figure 4, and temperature profiles are shown in Figure 5.

During slim-hole drilling, core recovery was difficult because of the unconsolidated nature of the Glenns Ferry Formation. The gravel beds in the formation proved almost impossible to core, and the basalt layers caused mechanical failure of the light drill string and wireline corebarrels.

Based on thermal gradient information gained from the first two slim holes, sites were selected for two exploratory wells (Figure 3). BHW-1 (Boise Hot Well, or Beard Well) was sited along the Boise Front Fault, just southeast of the intersection of the Freestone Creek and Cottonwood Creek linears. BEH-1 (Boise Exploratory Hole, or BLM Well) was sited in the same general linear intersection area, but away from the Boise Front Fault and in the same location as the second exploratory slim hole, BSH-2. BSH-3 was intended to provide lithologic data, and was also intended to be a monitor well to observe the effect of pumping the Boise Warm Springs water district wells and the INEL wells. Before water was encountered, however, drilling on BSH-3 was terminated because of mechanical failure.

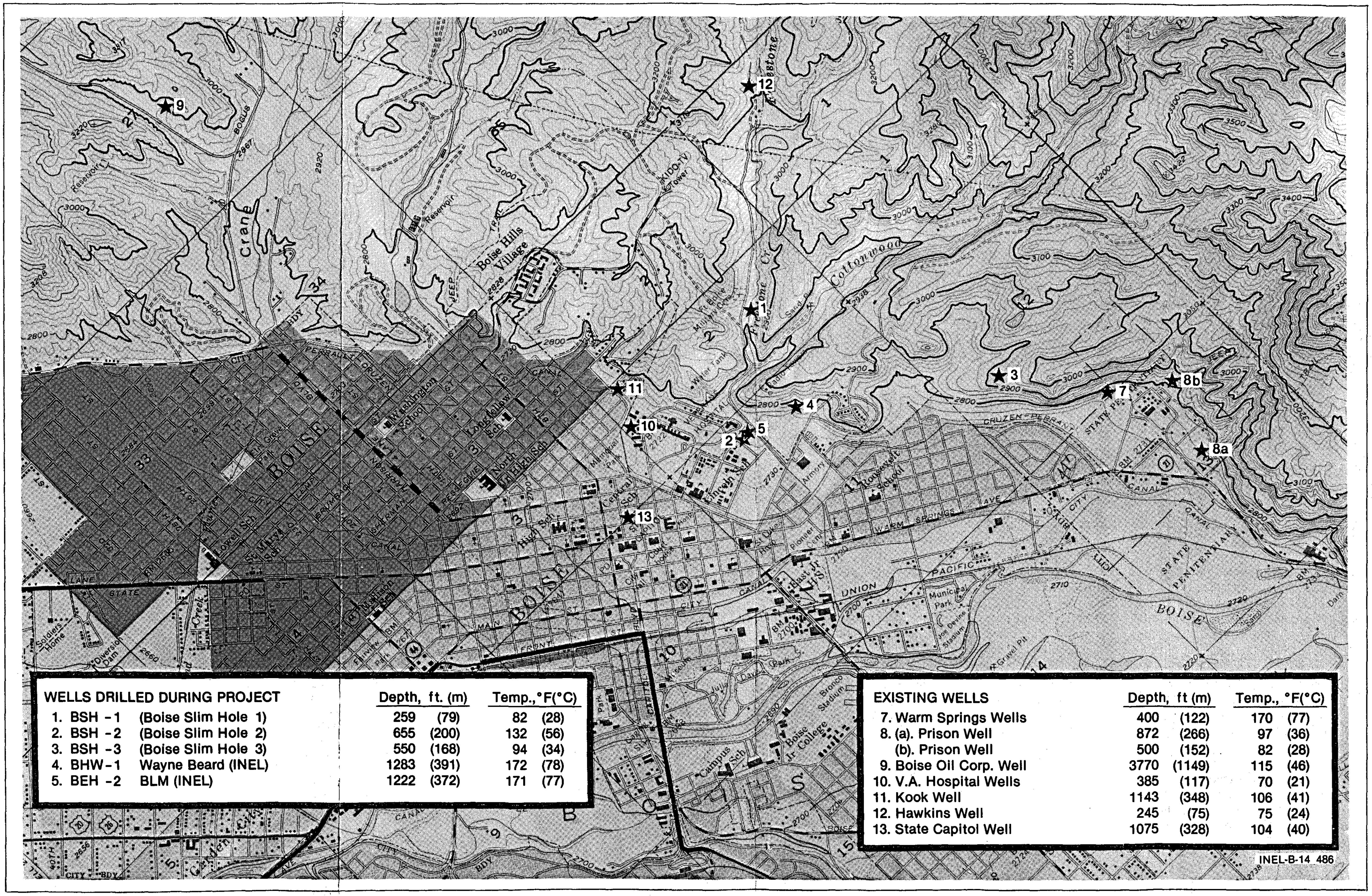
Test Well Drilling

BHW-1 (Beard) Well

BHW-1 was drilled with a rotary drill rig during January, February, and March 1976 (see Figure 6 for the lithologic log and pertinent construction specifications). Eight-in. casing was set and cemented at 202 ft (61.6 m), and an open 6-1/4-in. (158.8-mm) hole was completed to 967 ft (295 m). Hot water flow and lost circulation zones were encountered below 850 ft (259 m). Several beds of clay (montmorillonite) were encountered, necessitating drilling fluid dilution to maintain a water and light mud fluid. Three caving sand layers were also encountered that caused drilling difficulties.

Several temperature profiles were run in the well during drilling to determine the potential geothermal aquifers. The maximum temperature was 175°F (78°C), depth of 900 ft (274 m) (see Figure 7). During preliminary flow testing in June, the well caved in and ceased to flow. The sand beds encountered at approximately 450 ft (137 m) matched the quartz grains that were flushed out just before the flow stopped.

During July and August 1976, the driller cleaned out the well and deepened it to 1283 ft (351 m). After the well was deepened, slotted casing and screen were hung from the production string to prevent any further caving and flow blockage.



WELLS DRILLED DURING PROJECT		Depth, ft. (m)		Temp.,°F(°C)	
1. BSH - 1	(Boise Slim Hole 1)	259	(79)	82	(28)
2. BSH - 2	(Boise Slim Hole 2)	655	(200)	132	(56)
3. BSH - 3	(Boise Slim Hole 3)	550	(168)	94	(34)
4. BHW - 1	Wayne Beard (INEL)	1283	(391)	172	(78)
5. BEH - 2	BLM (INEL)	1222	(372)	171	(77)

EXISTING WELLS	Depth, ft (m)		Temp., °F(°C)	
7. Warm Springs Wells	400	(122)	170	(77)
8. (a). Prison Well	872	(266)	97	(36)
(b). Prison Well	500	(152)	82	(28)
9. Boise Oil Corp. Well	3770	(1149)	115	(46)
10. V.A. Hospital Wells	385	(117)	70	(21)
11. Kook Well	1143	(348)	106	(41)
12. Hawkins Well	245	(75)	75	(24)
13. State Capitol Well	1075	(328)	104	(40)

Figure 3. Exploratory slim hole, test hole, and existing geothermal well locations, depths, and temperatures.

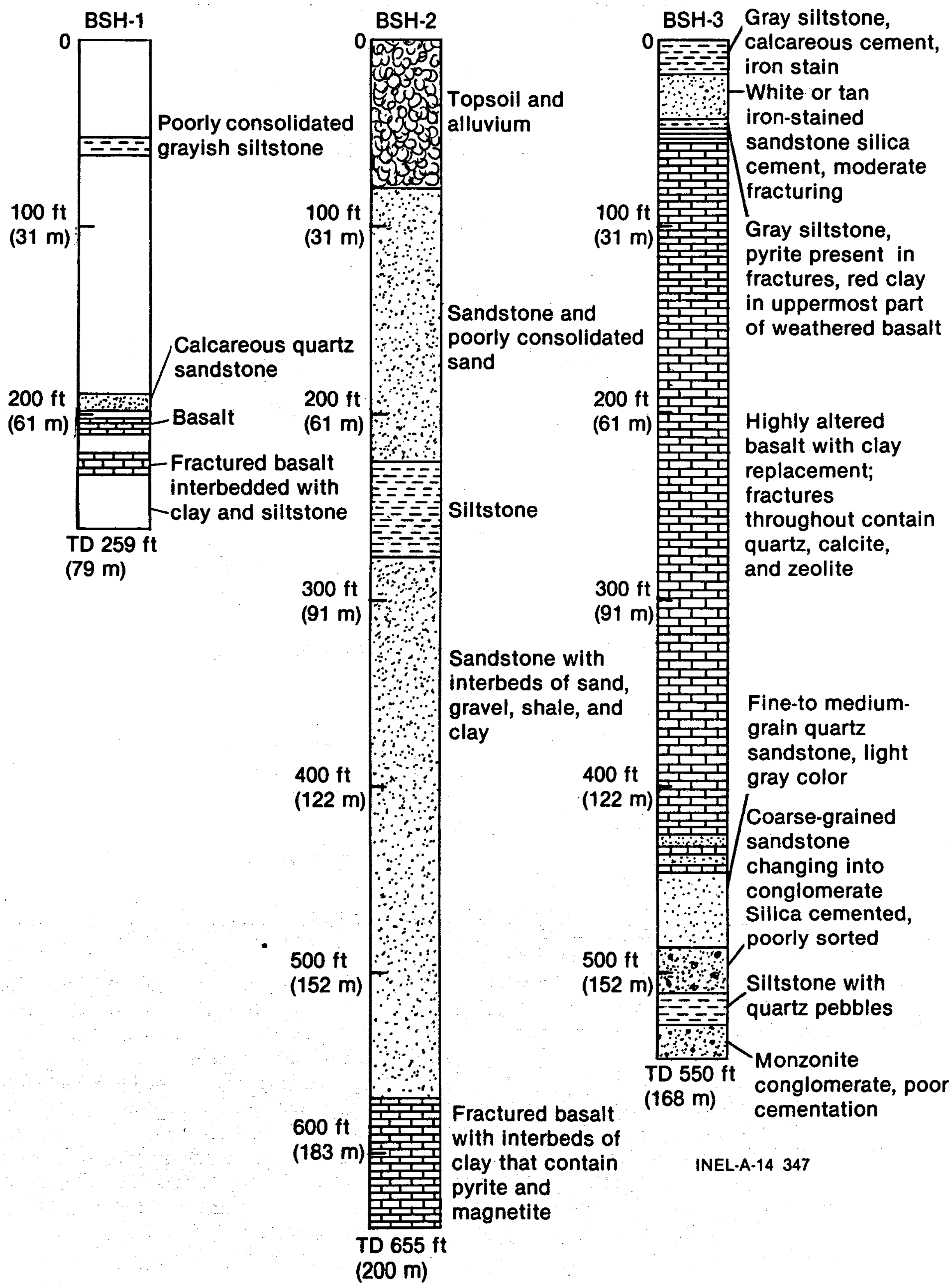


Figure 4. Lithologic columns of Boise slim-hole wells.

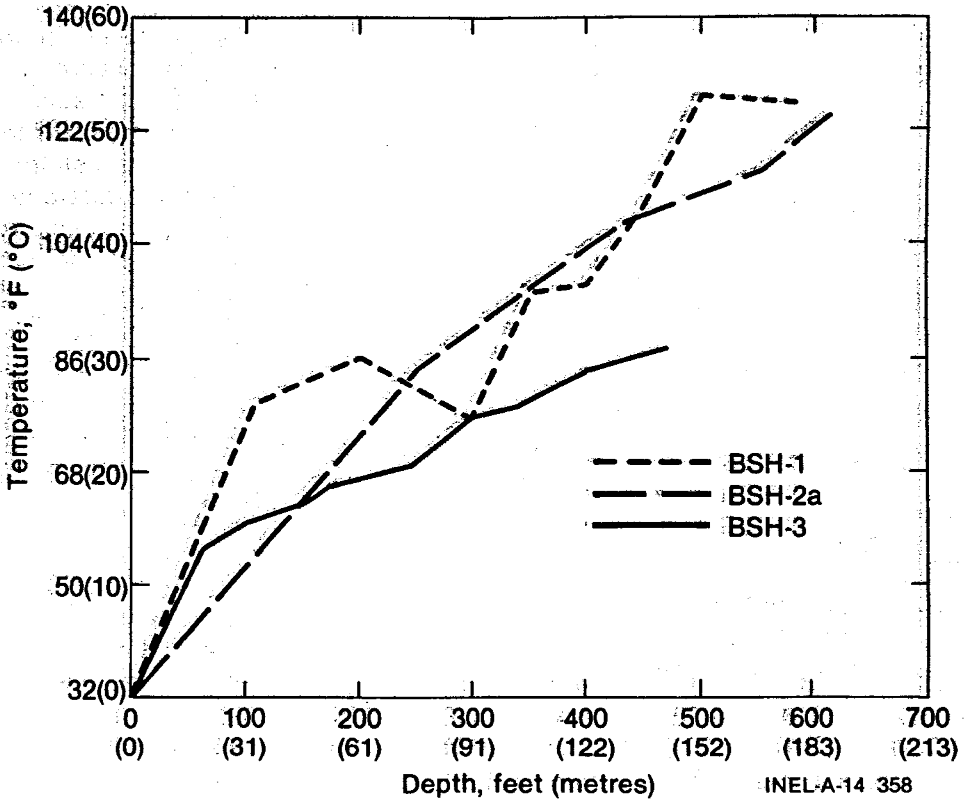


Figure 5. Thermal gradient of Boise slim-hole wells.

BEH-1 (BLM) Well

BEH-1 (Figure 8) was drilled with a rotary drill rig during February and March 1976. Eight-in. casing was run in the 10-5/8-in. (269.9-mm) hole, but encountered an obstruction at 340 ft (104 m). Seven-in. casing was then run inside the larger casing to 610 ft (186 m). The larger casing was subsequently removed with hydraulic jacks and the smaller casing cemented in place. During August 1976, slotted casing was hung from the production string to prevent caving and flow blockage.

The rock types encountered were similar to those in BHW-1; however, precise correlation of the two wells is difficult due to the varying degree to which the circulating geothermal water affected the subsurface, either by rock alteration or mineral deposition. Fracturing was less evident in BEH-1 than in BHW-1.

Temperature profiles recorded during drilling (Figure 9) revealed temperatures to be 20°F (11°C) lower for a given depth than BHW-1. Hot water flow was encountered at 1100 ft (335 m), but at a lower flow rate than BHW-1.

WELL TESTING

Instrumentation

The objective of the reservoir test was to evaluate hydraulic conductivities and storage parameters of the aquifer while estimating possible boundaries. The latter is only marginally practical, since there were only two wells available for evaluation. The test essentially consisted of stressing the aquifer by producing fluid, either by pumping or artesian flow, and observing changes, if any, in pressures or water levels at the production well and an observation well 1000 ft (305 m) away.

For production, a Johnson five-stage vertical shaft turbine pump, Number 6EC, with a 25-hp motor, was set at 185 ft (56 m) and 165 ft (50 m)

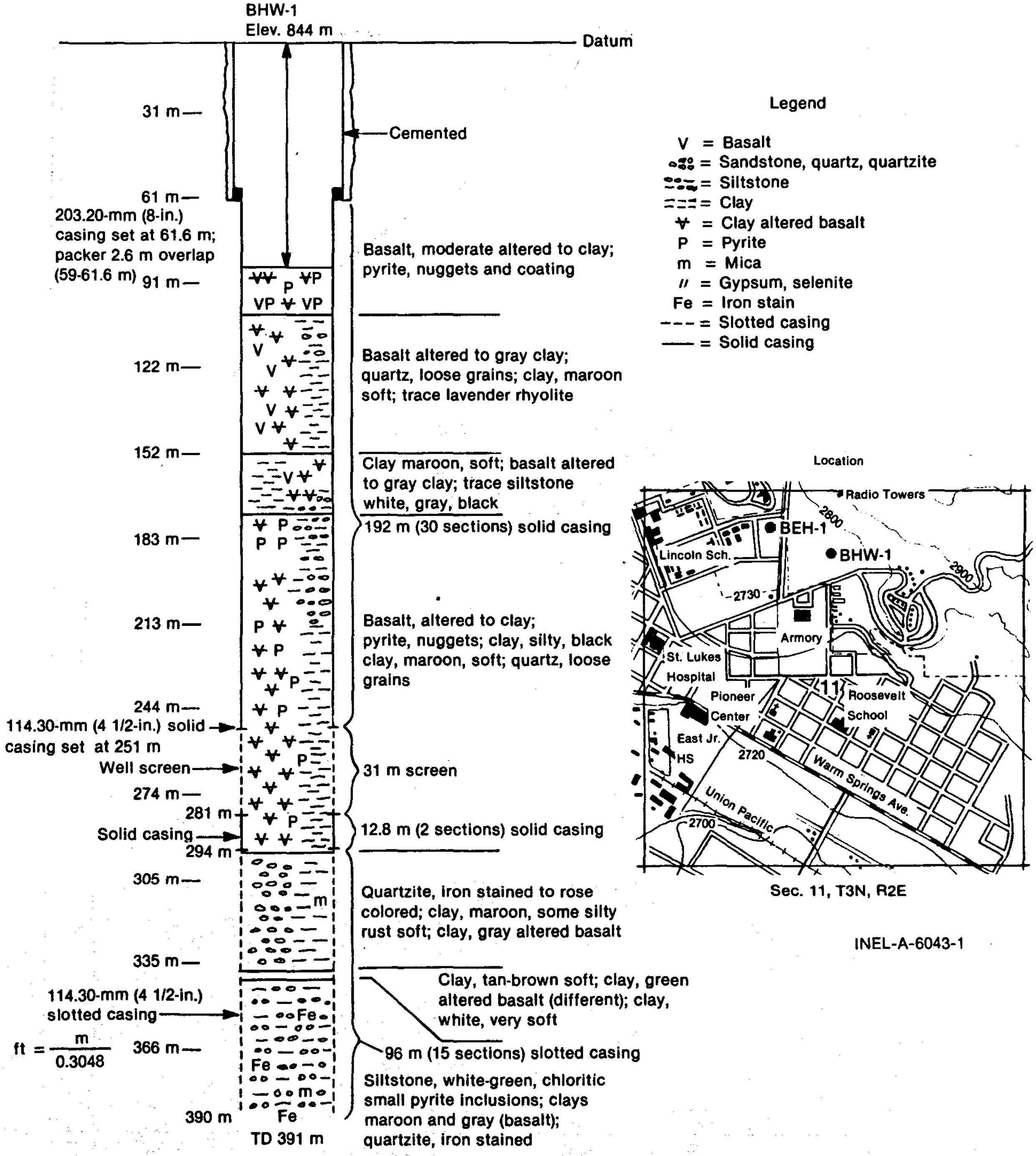


Figure 6. BHW-1 (Beard) well construction and lithology cross-section.

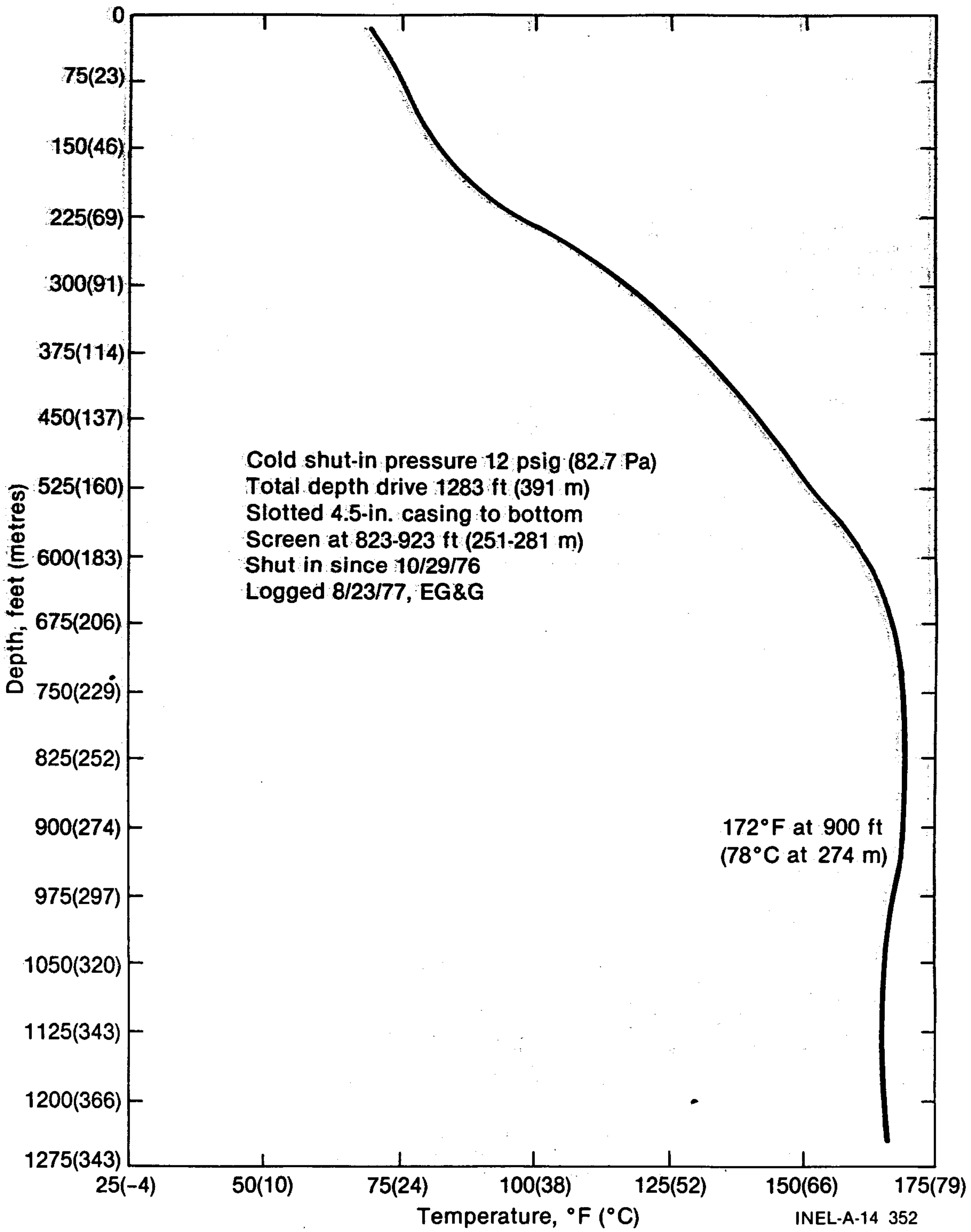


Figure 7. BHW-1 (Beard) well temperature profile of completed, shut-in well.

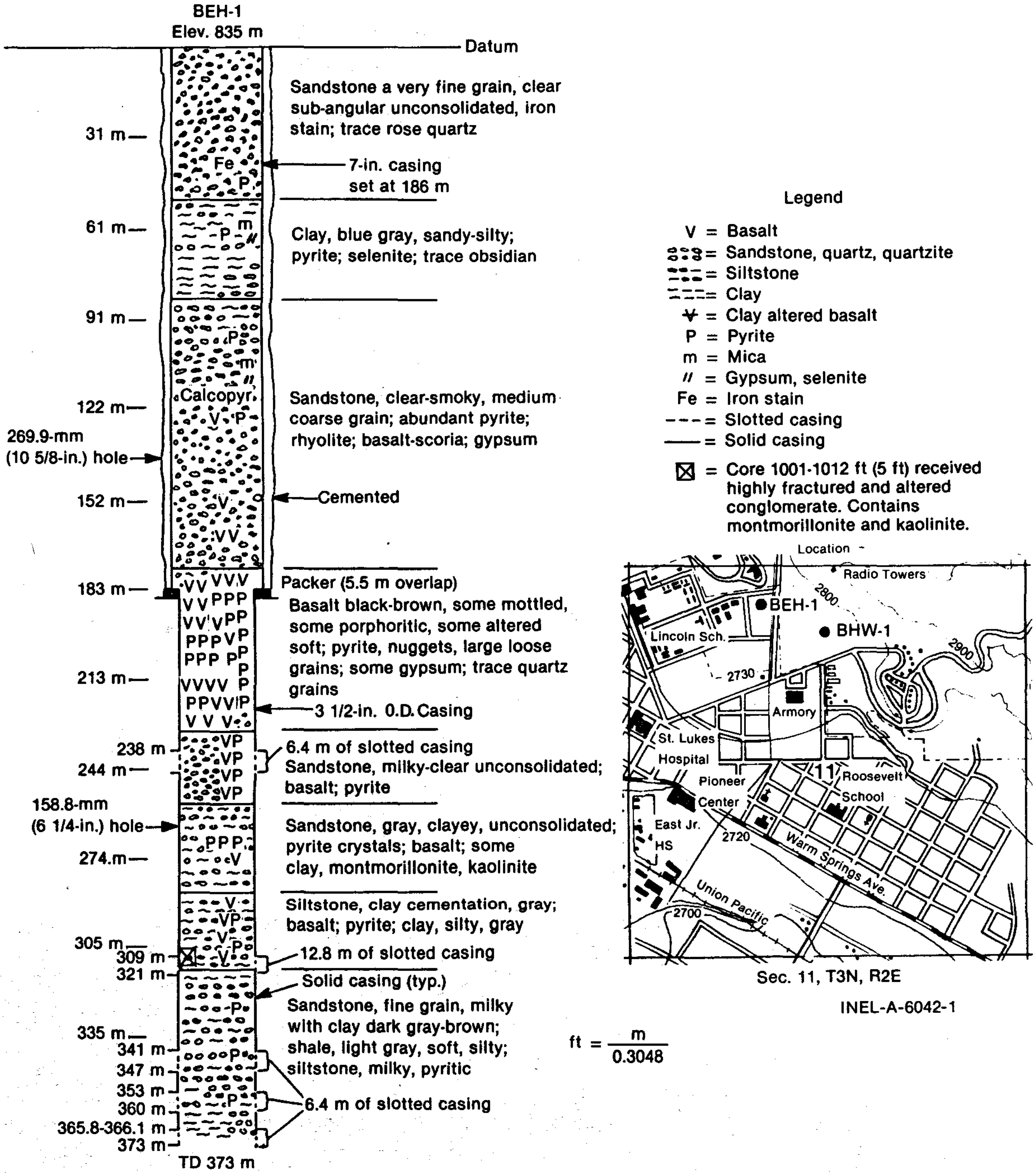


Figure 8. BEH-1 (BLM) well construction and lithology cross-section.

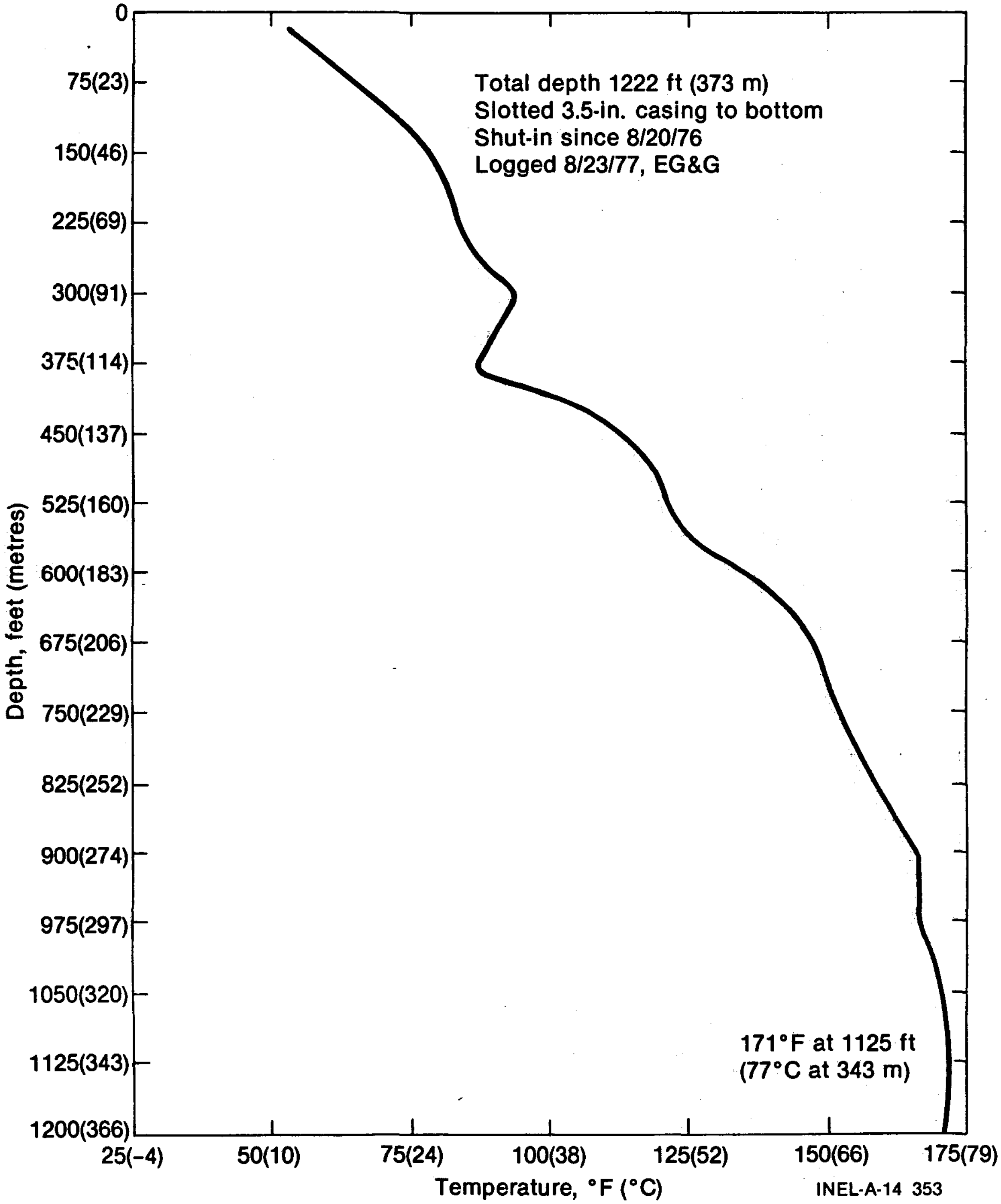


Figure 9. BEH-1 (BLM) well temperature profile of completed, shut-in well.

in BEH-1 and BHW-1, respectively. Power to drive the pump was provided by a 60-kW generator, mounted on a trailer for portability. Inherent RPM fluctuations in the generator caused fluctuations in the pump motor speed and, hence, in discharge. Data collected were of little value when the discharge variation was significant.

Drawdown measurements at the production well were taken at first by an electric tape inserted through a port in the side of the wellhead. This proved only marginally successful, since water vapor at the water-air interface within the pumping well activated the probe, resulting in a false water level reading. This method was used for two short tests conducted September 13-15, 1977.

A subsequent method for measuring drawdown in the pumped wells used a downhole bubbler system. In this method, a stainless steel tube was lowered into the well with the pump. The BEH-1 well tube was 165 ft (50 m) long, and the BHW-1 well tube was 185 ft (56 m) long. The tube was connected at the surface to a nitrogen supply in series with a temperature-compensated, 0- to 200-psi (1379-kPa) Heise pressure gauge. Pressurizing the tube allowed gas to bubble from the tube bottom. After the gas supply was shut off, gas would continue to flow from the tube until the gas pressure reached equilibrium with the weight of water column. The pressure was then read directly from the Heise gauge. Using this method, accuracy to within approximately 0.25 psi, or 0.5 ft (0.15 m) could be attained at the aquifer temperature.

Accurate water level data for the recovery of the water level in the production well after pumping ceased could not be effectively taken, due to the very rapid return of the water level to the wellhead. Thermal influence complicated recovery measurements even further.

Surface instrumentation monitored transient pressure changes at the observation well due to positive wellhead pressures (artesian) at both wells. The instrumentation consisted of a Paroscientific Digiquartz Pressure Transducer Model 2200-A-002 interfaced to a Hewlett-Packard Thermal Printer Model 5150 via a Paroscientific Digiquartz Pressure Computer Model 600. Accuracy of 0.005% full scale, over a 0- to 200-psi (1379-kPa) range, was achieved.

Power to operate the pressure transducer systems was provided by a 3-kW generator at BHW-1 and a commercial 60-Hz power source at BEH-1. Wellhead pressure data at BHW-1 well was frequently sporadic, due to the lack of a constant 60-Hz power source for the pressure computer and thermal printer.

A constant known discharge of the production well was maintained by allowing the water to pass through an orifice of known diameter while measuring the ΔP (pressure differential) across it. A constant ΔP could be maintained by manipulating a valve at the wellhead. A simple calculation permitted total discharge to be computed from ΔP. Wellhead discharge could be monitored to within 5 gpm (0.315 l/s) using this method.

Method of Analysis

Seven pump tests and one flow test were conducted between September 1977 and February 1978. These tests stressed the geothermal aquifer in the vicinity of BEH-1 and BHW-1. A one-day flow test was also conducted at BHW-1 beginning on October 28, 1976. Pump tests on BEH-1 were limited to 120 gpm (7.6 l/s), due to well construction characteristics and depth of pump placement. Pump tests on BHW-1 were limited to 380 gpm (23.9 l/s) due to pump size.

The theoretical basis for interpreting the test data involves the transient fluid potential distribution around a fully penetrating, constantly discharging well of infinitesimal radius in a homogeneous and isotropic aquifer of infinite size and finite thickness. The model can be extended to noninfinite (bounded) systems through superposition and the use of image concepts.

The model allows determination of the aquifer parameters, intrinsic transmissivity kh (where k is the intrinsic permeability of the aquifer and h is the thickness of the aquifer), and storitivity ϕch, (where ϕ is the porosity of the rock containing the aquifer and c is the compressibility of the aquifer). Boundaries of the aquifer can also be detected by deviations from the expected drawdown.

The Jacobs modified nonequilibrium method for aquifer analysis appears to satisfactorily define kh for the aquifer in the vicinity of the discharging well. The Jacobs method utilizes a semilogarithmic plot of observed data, with the drawdown or pressure decline plotted arithmetically versus log time since discharging commenced. The slope of the resulting straight line is used to calculate aquifer kh using the following equation:

$$kh = \frac{5759\,Q\mu}{\Delta P_{10}} \qquad (1)$$

where

k = aquifer intrinsic permeability

h = aquifer thickness (ft)

Q = well discharge (gpm)

μ = viscosity of water (cp) at 168°F (76°C)

ΔP_{10} = change in drawdown per log cycle (psi).

The time of zero drawdown on an extension of the straight line is used to estimate aquifer storitivity by the formula:

$$\phi ch = \frac{2.245\,wkht_0}{r_W^2} \qquad (2)$$

where

w = constant (4.396×10^{-6})

t_0 = time of zero drawdown (minutes)

r_W = distance (feet) from pumping well to observation well.

A change in the linear trend of production well data on a semilogarithmic plot could result from hydrologic discontinuities in the aquifer(s) penetrated, commingling effects between aquifers, temperature-induced changes, borehole fluid densities, and/or changes in discharge rate. A drawdown stabilization indicates an aquifer boundary with a constant hydraulic potential—an ideal recharge boundary. A linear drawdown slope doubling trend indicates that a portion of the aquifer has a zero hydraulic conductivity—a barrier boundary. Observation well data are usually considered superior to production well data as they integrate over a larger area of aquifer material, and are not affected by well losses.

The complex hydrogeologic conditions present at Boise such as the fracture control of groundwater flow and the location of BHW-1 in the fault zone, in contrast to the BEH-1 well's location adjacent to the fault zone, preclude the use of intrinsic transmissivity in the classical sense. Between-wells aquifer kh values presented in this report are not considered to represent a physical entity, and are included only as basis for comparing test results.

DATA PRESENTATION

BHW-1 Flow Test, October 28-29, 1976

The first test was a flow test performed at BHW-1 on October 28 and 29, 1976, after its completion. Wellhead pressure decline was monitored with the digiquartz system and, for this test only, a downhole pressure probe was installed at a depth of 1270 ft (387 m). Flow was maintained at 100 gpm (6.3 l/s) for approximately 26 hours. The maximum pressure decline observed during the production period was 2.89 psi (19.9 kPa), measured by the downhole probe. BEH-1 was not monitored during the test.

Semilog plots of the pressure drawdown from both wellhead and downhole instruments (Figure 10) obviously indicate different drawdown trends. The downhole probe data exhibit a pressure falloff, while the wellhead data show a general increase in pressure throughout the test.

The departure of the wellhead pressure from that of the downhole is attributed to thermal effects whereby the warm water entering the wellbore replaces cooler, denser water. This gradually decreasing density of the wellbore water continues until the temperature stabilizes within the wellbore. The time-dependent decrease in water density as it passes through the wellbore resulted in a corresponding increase in wellhead pressure. The downhole probe indicated that there is a real drawdown in pressure of the aquifer, since the probe is free of most thermal influence as the temperature at the aquifer remained essentially unchanged (Figure 10). In this case, the increase in

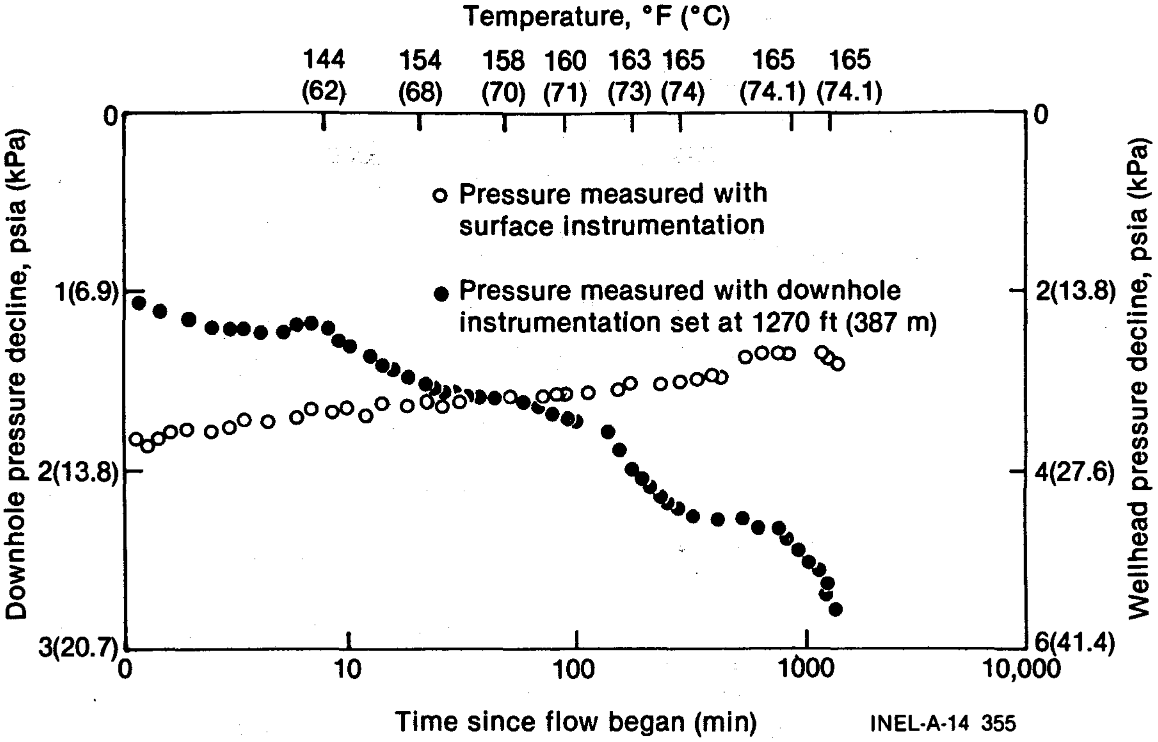


Figure 10. Semilog plot of BHW-1 well drawdown pressure response, October 28-29, 1976.

wellhead pressure due to a decrease in density of the water entering the wellbore was greater than the drawdown actually experienced at the aquifer. Once the temperature of the wellbore stabilizes with that of the aquifer, wellhead pressure and aquifer pressure should decline at the same rate. However, the total bottom hole pressure decline would be greater than that at the wellhead because of the density-related temporal drift in the zero drawdown pressure at the wellhead. Computations for kh in the vicinity of BHW-1 are based on the data from the downhole probe, using the Jacobs method. Estimated transmissivity is 350,000 md-ft.

BHW-1 Flow Test, October 13-25, 1977

BHW-1 was again flowed under artesian conditions between October 13 and 15. During the test the well was allowed to flow at a constant rate of 150 gpm (9.5 l/s). Figure 11 presents a semilog plot of the data taken with the digiquartz system at the wellhead. As described earlier, the wellhead pressure was affected by changes in the density of the wellbore water as a result of displacing cooler borehole fluids and heat transfer from the hot borehole fluid to the relatively cool country rock surrounding the wellbore. As was expected, wellhead pressure increased and did so for approximately 4.5 days, after which pressure decreased. The lack of data from 1800 minutes to 5000 minutes was due to instrument failure. A linear regression through the drawdown data collected after about 5 days results in an estimated kh value of 440,000 md-ft, which is consistent with values obtained from other BHW-1 tests.

BHW-1 Pump Test, January 19-20, 1978

BHW-1 had previously been pump-tested twice, on September 13 and 14, 1977, using an electric tape to monitor drawdown. Unreliable data were obtained, due to questionable water level readings with the electric tape. The well was pumped again, however, with the bubbler system installed at 165 ft (50.3 m) to measure drawdown.

For the test, the well was discharged at 380 gpm (23.9 l/s) for approximately 27 hours. The maximum pressure decline for the duration was

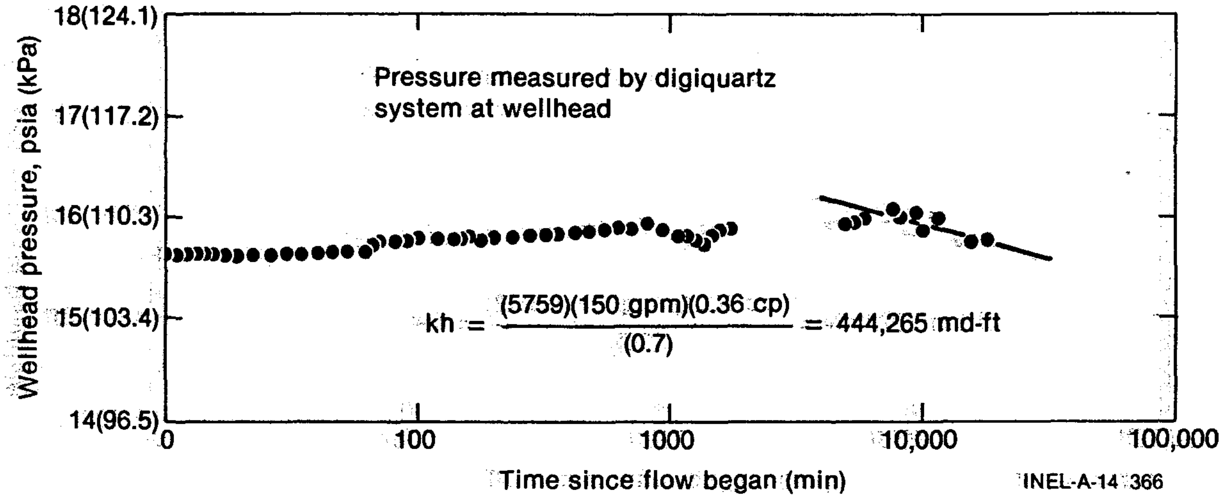


Figure 11. Semilog plot of BHW-1 (Beard) well 150-gpm (9.5 l/s) flow test data, October 3-25, 1977.

47.4 psi, or 79 ft (24.1 m), below ground level after removal of an initial 14-psi wellhead pressure. Figure 12 is a semilog presentation of the data collected from which the aquifer kh in the vicinity of the well is estimated to be 328,000 md-ft. This agrees with other tests for the well.

In addition to these tests just described, three other tests were performed at BHW-1 which are not presented. Two were monitored with the electric tape, which resulted in drawdown measurements far too sporadic to be interpretable. They are the pump tests conducted on September 13 and 14, 1977, at 250 gpm (15.7 l/s) and 350 gpm (22.0 l/s). The third was a test conducted January 24 and 25, 1978, at BHW-1, in which an undetected leak in the bubbler system forced termination of the test.

BEH-1 Pump Test, October 10-11, 1977

BEH-1 was first tested October 10 and 11, 1977, when it was pumped at 90 gpm (5.7 l/s). To monitor drawdown, a bubbler system was installed at a depth of 185 ft (56 m). Due to well construction, pump setting, and aquifer

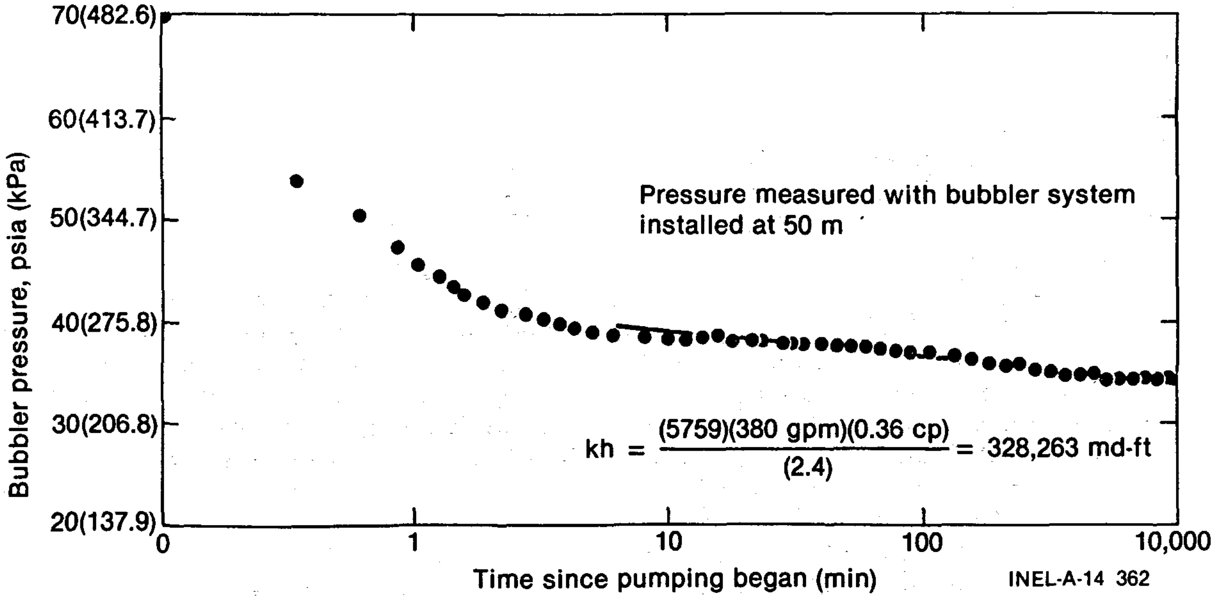


Figure 12. Semilog plot of BHW-1 (Beard) well 380-gpm (23.9 l/s) pump test data, January 19-20, 1978.

parameters, BEH-1 could not be pumped at a rate greater than 120 gpm (7.5 l/s) without excessive drawdown and possible pump damage caused by cavitation. As a result, 90 gpm (5.7 l/s) was chosen as the discharge rate, which would be safe for the pump and would provide adequate data for reservoir analysis. During the test, the well was pumped for approximately 30 hours at the aforementioned rate. Pressure decline for the test duration was 49 psi, 88 ft (26.8 m) below ground level, after removal of an approximate 12-psi artesian head.

Figure 13 is a semilog representation of the drawdown data. A straight line is fitted to the data, beginning 10 minutes after pumping began, from which kh in the vicinity of BEH-1 is estimated to be 33,000 md-ft.

A recharge boundary to the aquifer appears to occur at approximately 800 minutes. The distance and source of the recharge is uncertain, but will be discussed later.

BEH-1 Pump Tests, January 4-7 and 10-11, 1978

On December 29, 1977, 100 lb (45.36 kg) of sodium tripolyphosphate was injected, along with 1500 gal (5677 l) of water, into BEH-1 in an attempt to stimulate the well and increase its specific capacity. A small quantity of clay, believed to be drilling mud, was contained in the discharge water when the well was allowed to flow previously. Newly drilled water wells frequently do not produce at optimum efficiency due to a "mud cake" partially sealing the aquifer. It is common practice to alleviate this condition with a sodium phosphate complex which resuspends the mud cake and helps sequester any subsequent fluctuation of the clay and silt particles. The 1500-gal (5677-l) solution was first injected into the well and then surged with a small pump at the surface. It was allowed to stand in the well for approximately 24 hours, after which approximately 6000 gal (222,710 l) of solution were retrieved and discarded.

Following well stimulation, BEH-1 was tested at a constant rate of 120 gpm (7.5 l/s) chosen to encourage well stimulation, in a 72-hour pump test between January 4 and 7, 1978. During the test, the well sustained a 71-psi decline, or 141 ft (43.0 m) below ground level, after removal of an approximate 12-psi well head pressure (Figure 14). At 3000 minutes, the bubbler pressure increased. Discharge was maintained at 120 gpm (7.5 l/s). The pressure increase was attributed to well development resulting from well stimulation;

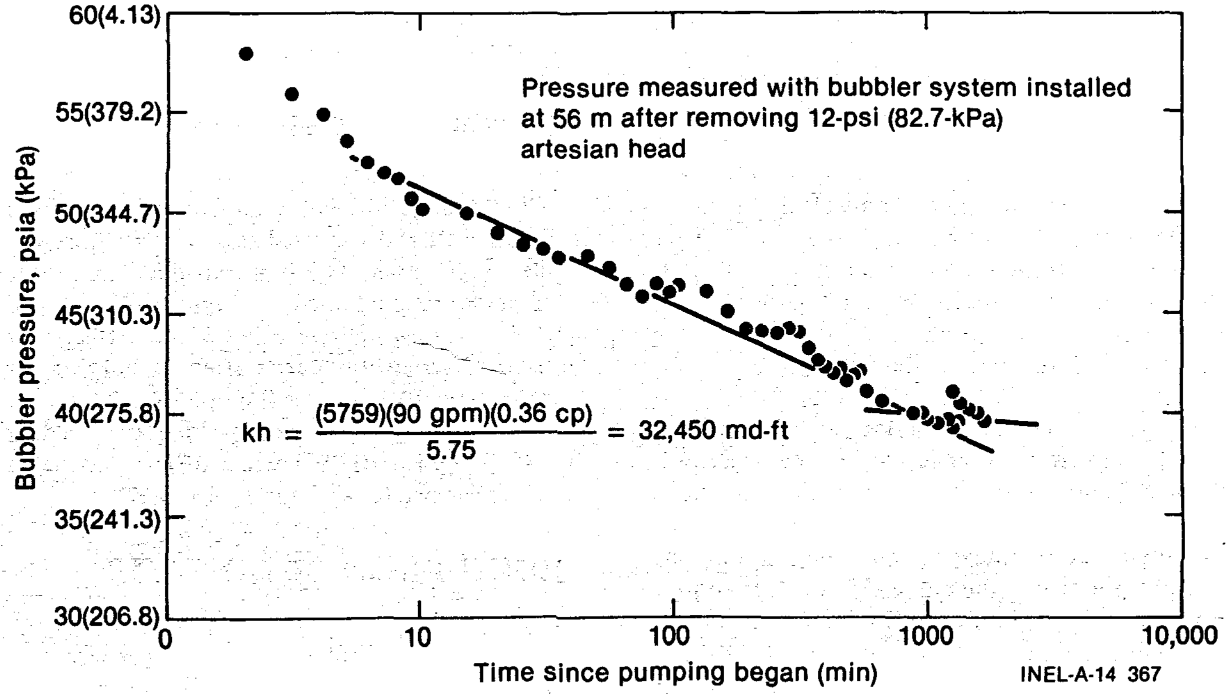


Figure 13. Semilog plot of BEH-1 (BLM) well 90-gpm (5.7 l/s) pump test data, October 10-11, 1977.

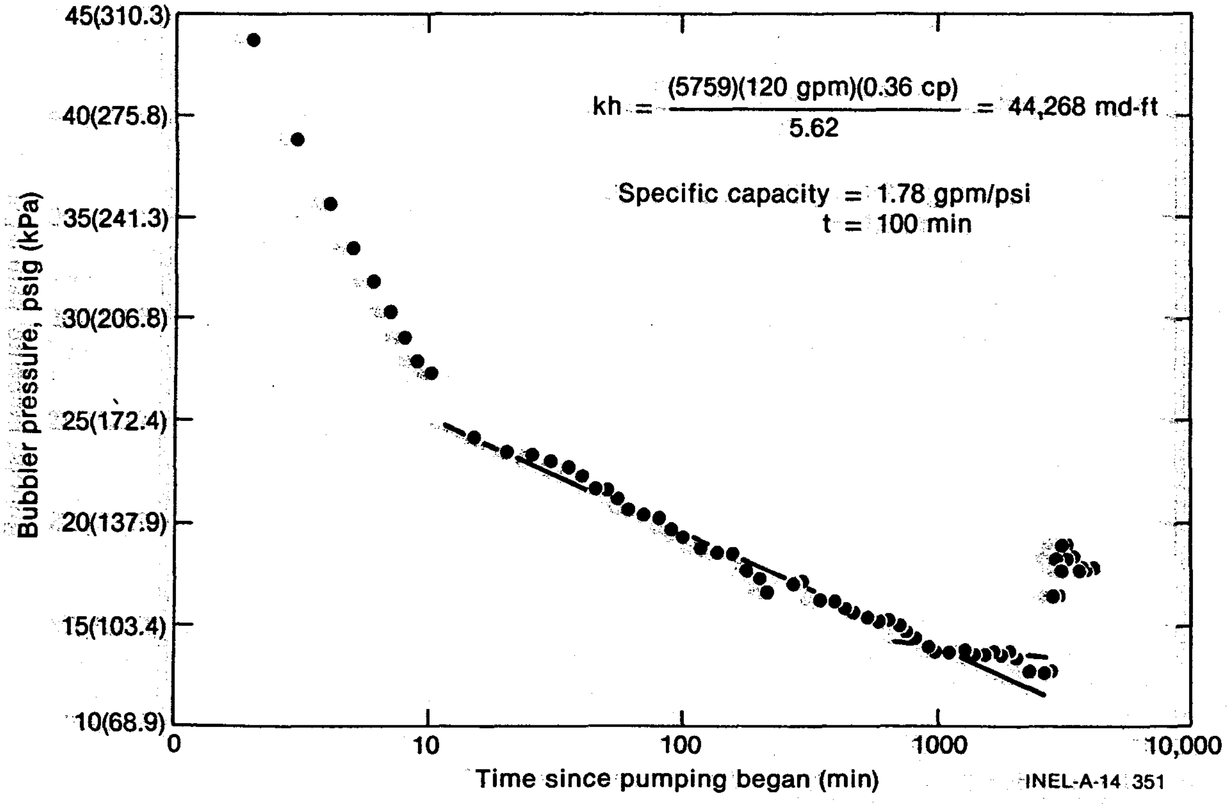


Figure 14. Semilog plot of BEH-1 (BLM) well 120-gpm (7.5 l/s) pump test data, January 4-7, 1978.

however, a mechanical failure in the generator powering the pump ended the test too soon to effectively interpret the change that had occurred in drawdown. As a result, any value for kh derived from the test is considered unreliable. A recharge boundary is indicated at about 1000 minutes.

The pump test of 120 gpm (7.5 l/s) was repeated between January 10 and 11 in an attempt to reproduce the drawdown experienced after 3000 minutes from the previous test. For this test, flow was maintained closely at 120 gpm (7.5 l/s) for approximately 30 hours, after which a generator failure terminated pumping.

Figure 15 presents a semilog interpretation of the drawdown data collected at the wellhead. Some data were lost due to periodic malfunctions in the bubbler system, so data were collected during only 700 minutes of pumping. From the straight portion of the curve (Figure 15), aquifer transmissivity is estimated to be 64,000 md-ft. Extending the line to the approximate time duration of the previous test, the data collected after 3000 minutes appear to fall on the line.

A small increase in aquifer performance adjacent to BEH-1 is suggested. At 100 minutes, specific capacity of the well had increased about 5%, from 1.78 gpm/psi to 1.86 gpm/psi.

Interference Well Data

The semilogarithmic plots of drawdown versus time when BEH-1 was used as an observation well while discharging BHW-1 are available for four tests and are contained in Figures 16, 17, 18, and 19. These figures exhibit the effects of apparent barrier boundaries after discharging for approximately 70 minutes (Figures 16, 17, and 19) and 1350 minutes (Figure 18). Interference data are available for BHW-1 while BEH-1 was being pumped for two tests (Figures 20 and 21).

DISCUSSION OF RESULTS

The suspected differences in the hydrogeologic setting of the two wells are exemplified when comparing results for the two wells as production

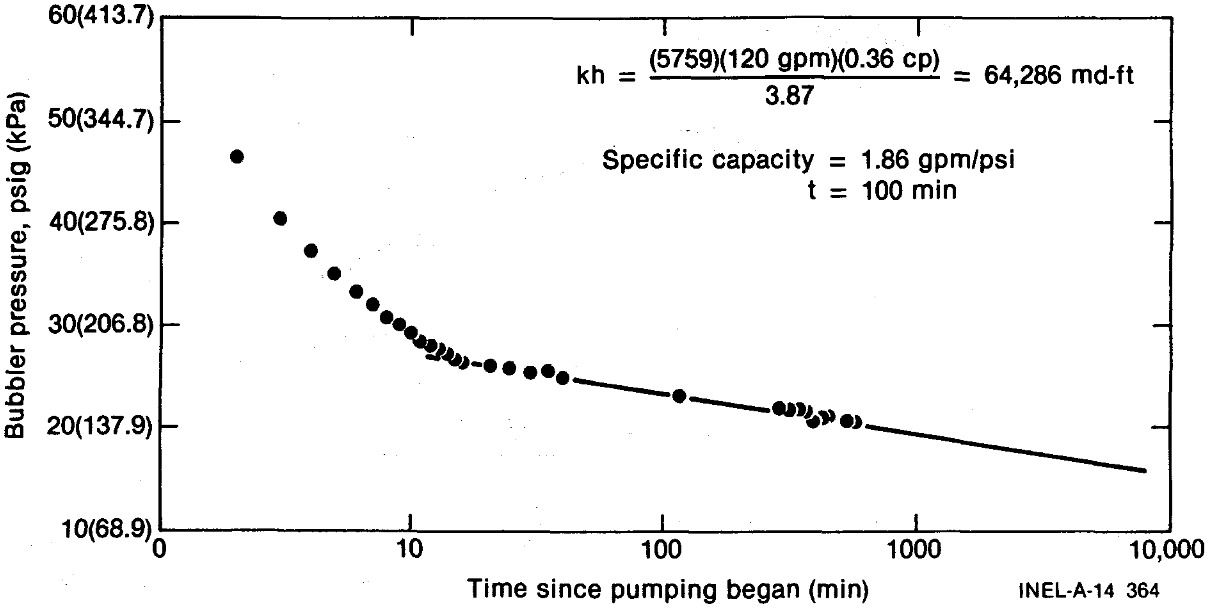


Figure 15. Semilog plot of BEH-1 (BLM) well 120-gpm (7.5 l/s) pump test data, January 10-11, 1978.

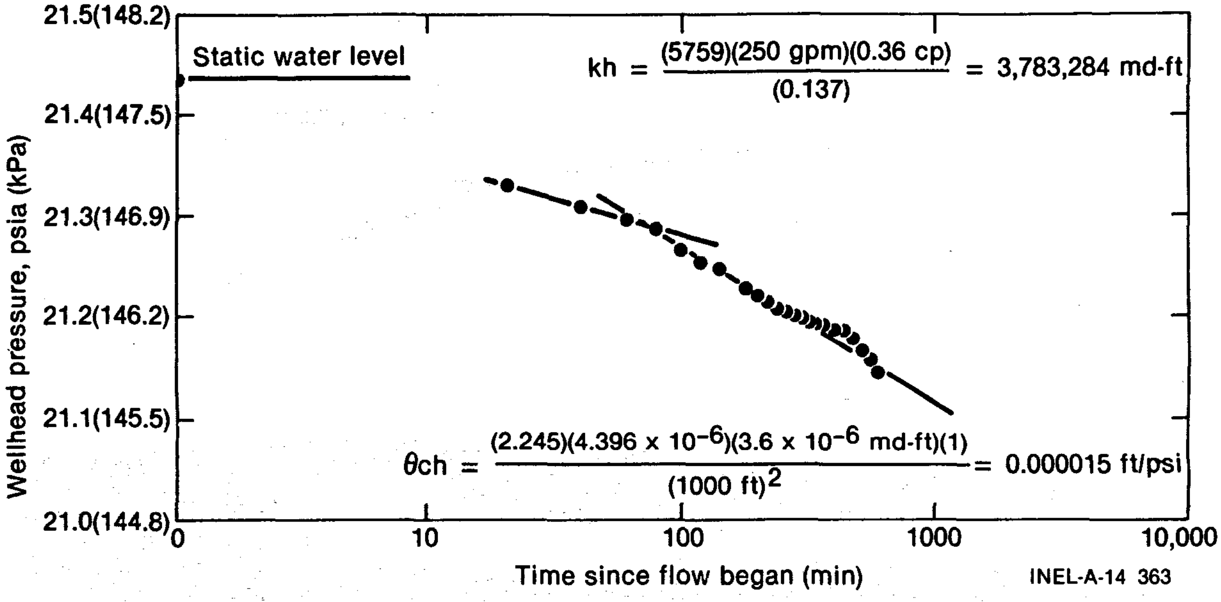


Figure 16. Semilog plot of BEH-1 (BLM) well drawdown data while pumping BHW-1 at 250 gpm (15 l/s), September 13, 1977.

wells. BHW-1 is located in a fault system, which results in a significantly greater effective kh than BEH-1, which is removed from the fault system. The section of the aquifer penetrated by BHW-1 could conceivably deliver more water than that penetrated by BEH-1.

The effective log mean kh values for BHW-1 and BEH-1 are 3.8 x 10^5 md-ft and 4.5 x 10^4 md-ft, respectively. The effective kh for BHW-1 is about 8 times greater than that of BEH-1. A 5% probability exists that there is not a significant difference between the effective kh values for BHW-1 and BEH-1. The difference between the effective kh values at this confidence level strongly implies that the aquifer in the immediate areas of BHW-1 and BEH-1 does not have homogeneous aquifer characteristics everywhere throughout the volumes of the aquifer affected by the various pump tests. The Jacobs equation for

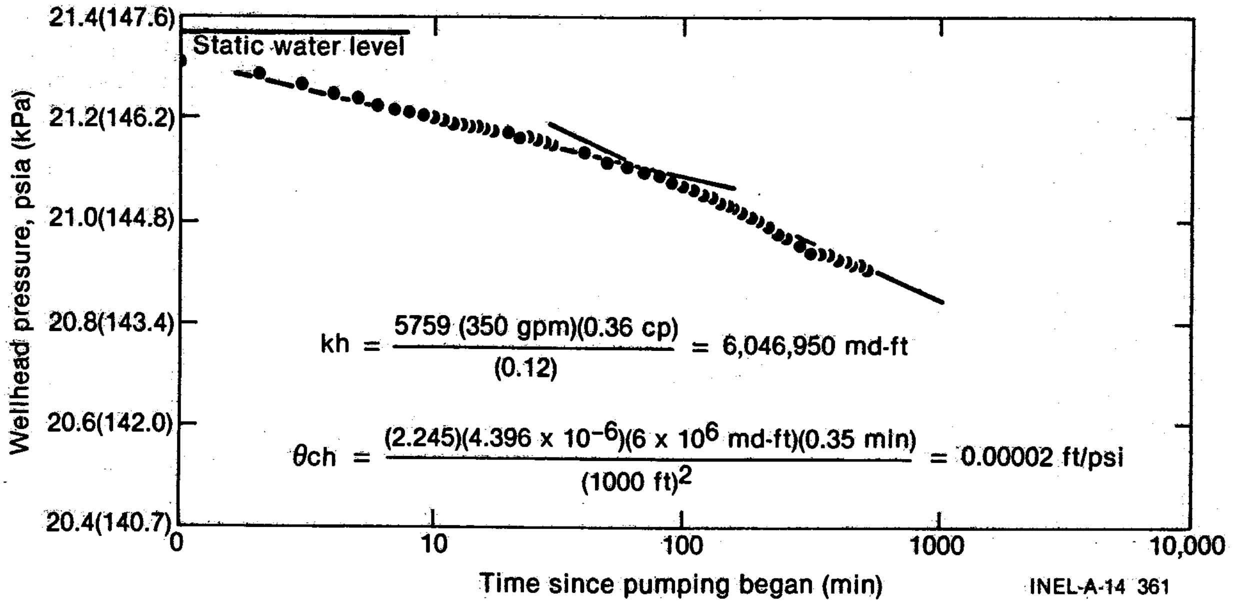


Figure 17. Semilog plot of BEH-1 (BLM) well drawdown data while pumping BHW-1 at 350 gpm (22 l/s), September 14, 1977.

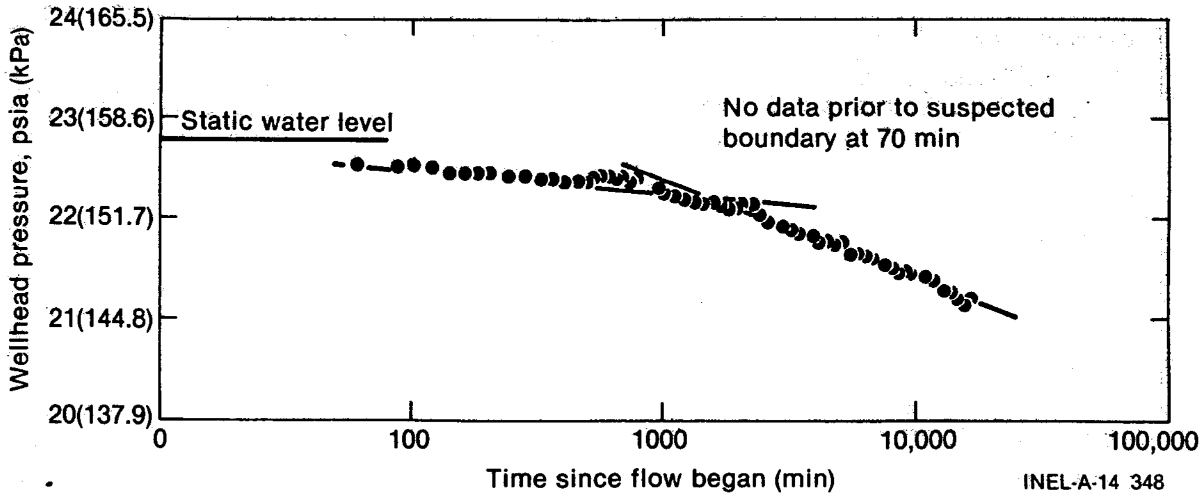


Figure 18. Semilog plot of BEH-1 (BLM) well drawdown data while flowing BHW-1 at 150 gpm (9.5 l/s), October 13-25, 1977.

evaluating aquifer characteristics requires that the aquifer be homogeneous. Here, the values just presented can be used to define aquifer characteristics in the immediate vicinity of the respective wells only.

The exact nature of the aquifer inhomogeneity is difficult to delineate. When BEH-1 was pumped, the zone penetrated by BHW-1 would behave similar to a falling head recharge boundary.[7] Data from the pump tests at BEH-1 on October 10 and 11, 1977 (Figure 13) and on January 4-7, 1978 (Figure 14) display the presence of this nonideal recharge boundary, which occurred at approximately 800 and 1000 minutes, respectively. There are no simple solutions to calculate the location of the boundary, but it is probably the fault that contains BHW-1.

The area of the aquifer within the fault zone is believed to be relatively narrow. A narrow fault zone would result in a strongly elongated cone of depression, caused by pumping, with the long axis superimposed over the fault zone. If the fault zone were relatively wide, the cone of influence caused by pumping BHW-1 would deform once it had

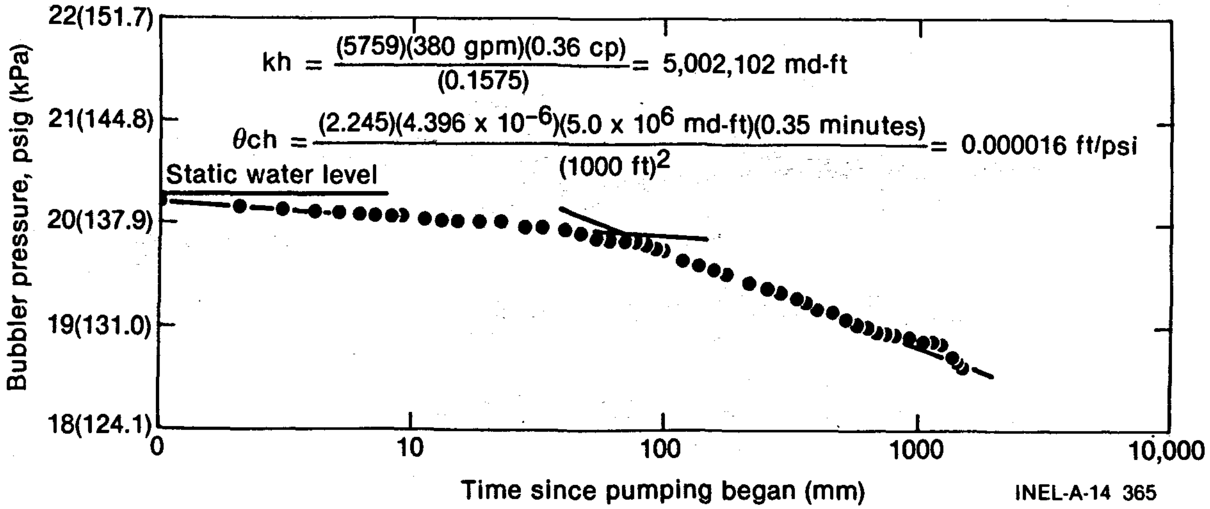


Figure 19. Semilog plot of BEH-1 (BLM) well drawdown data while pumping BHW-1 at 380 gpm (24 l/s), January 19-20, 1978.

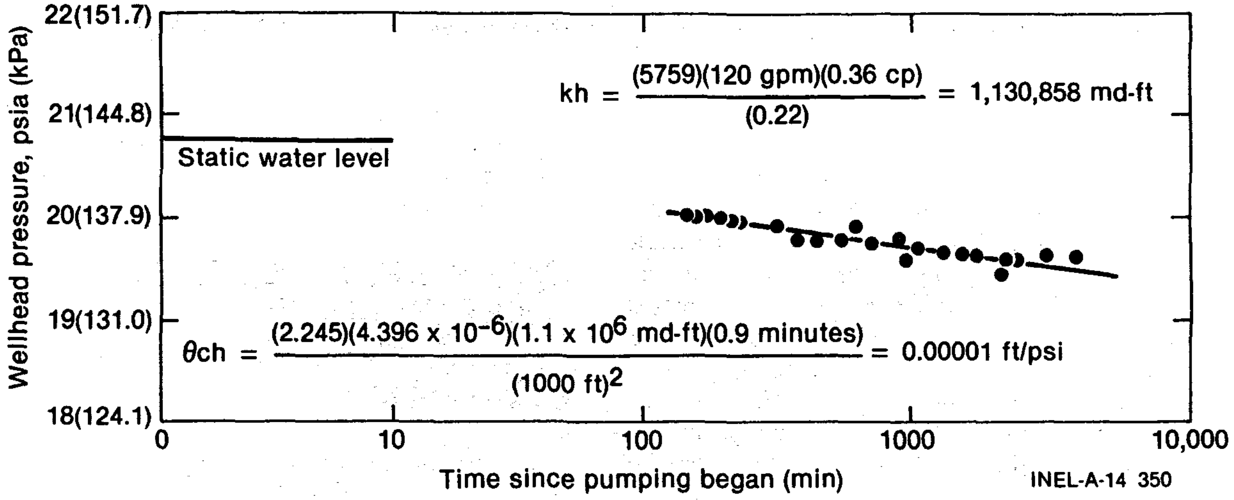


Figure 20. Semilog plot of BHW-1 (Beard) well drawdown data while pumping BEH-1 at 120 gpm (7.5 l/s), January 4-7, 1978.

encountered the unfractured portion of the aquifer. This would result in an increase in slope for the semilogarithmic plot of drawdown versus time for BHW-1. No such change in slope was observed for any of the tests. Pumping was of sufficient duration to extend the cone of depression into the aquifer adjoining the fault zone, as evidenced by observed declines in BEH-1. The implication is that the fault zone is indeed narrow. As a result, the estimates for kh derived from drawdown data at BHW-1 include the effects of the low-permeability aquifer surrounding the high-permeability fault zone.

Because of the anisotropic, nonhomogeneous hydrologic conditions throughout the cone of influence generated while pumping BEH-1 or BHW-1, responses in the potentiometric head in the nonpumping well can only be used qualitatively. When BEH-1 is pumped and BHW-1 is used as an observation well, the rate of decline in BHW-1 will be less than that in the unfractured aquifer (that which contains BEH-1) adjoining the fault zone. This will result because of the relative ease with which water can flow along the fault zone to the section where the potentiometric head is being drawn down by pumping BEH-1. Water flow along the fault zone reduces the potentiometric head rate of decline compared to that which would result if the fault zone were not present.

Since BHW-1 is located in a fault and BEH-1 is not, it becomes questionable to quantify any

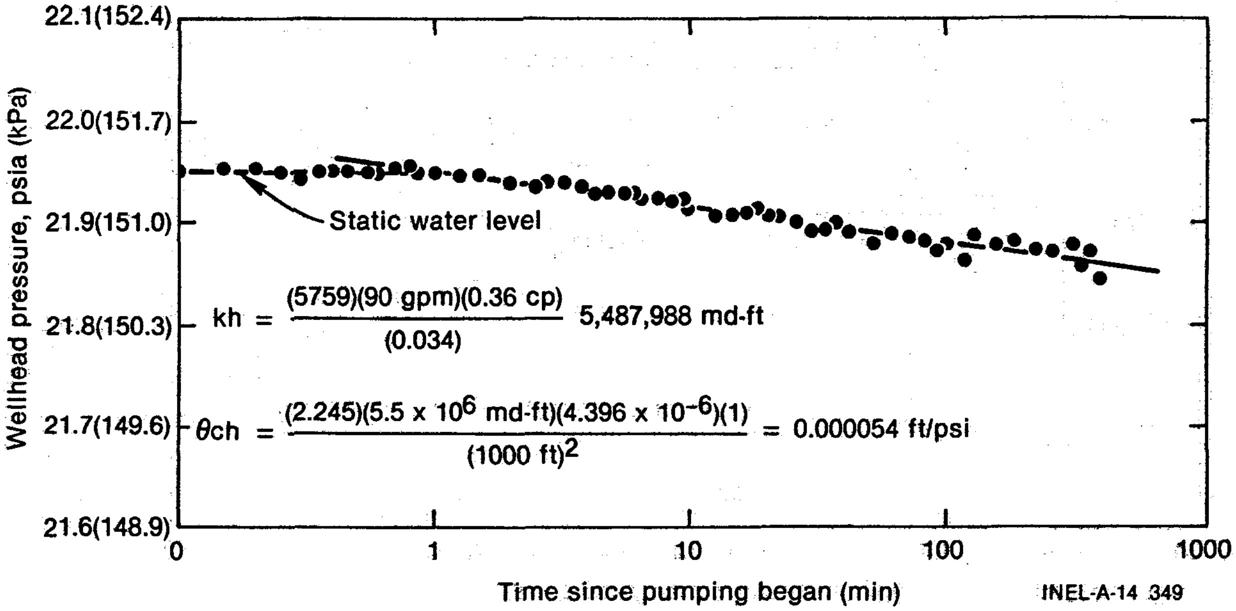


Figure 21. Semilog plot of BHW-1 (Beard) well drawdown data while pumping BEH-1 at 90 gpm (5.7 l/s), October 10-11, 1977.

estimates of kh between the wells. Further, it is invalid to locate the apparent boundaries displayed in the BEH-1 data which do not also appear in the BHW-1 data. Nonetheless, from the data (Figures 16, 17, 18, and 19), the log mean kh for BEH-1 as an observation well is about 4.5 x 10^6 md-ft, which is about 100 times greater than the effective kh for BEH-1 as a discharging well and 12 times greater than that for BHW-1 as a discharging well. This degree of departure from the effective kh values for BEH-1 and BHW-1 is too great to represent the aquifer characteristics between the two wells, and further discounts any analysis of the apparent boundary effects at BEH-1.

The data for BHW-1 as an observation well indicate a kh of about 1.1 x 10^6 md-ft and about 5.5 x 10^6 md-ft in Figures 20 and 21 respectively. The difference may be attributed to barrier boundary effects. Their locations, however, cannot be determined. The plot shown in Figure 21 is free from boundary effects since it represents aquifer performance early in the drawdown history. The plot in Figure 20 integrates a larger portion of the aquifer because of the longer test duration, while the lower apparent kh suggests that a barrier had been encountered early in the drawdown.

For both tests, however, computed values of the aquifer's transmissivity are unlikely to be much greater than the effective kh values for BHW-1 or BEH-1 as discharging wells. The values are discounted as being representative of the aquifer between the wells.

INTERFERENCE BETWEEN BOISE WARM SPRINGS WATER DISTRICT WELLS AND INEL WELLS

Insufficient data are available to determine the extent, if any, of communication between the Boise Warm Springs Water District wells and the INEL wells. To optimize geothermal water usage along the Boise Front in the event the geothermal resource is developed, the magnitude of communication between geothermal wells becomes important.

The BEH-1 (BLM) and BHW-1 (Beard) wells are located about 2 miles northwest of the Boise Warm Springs Water District wells. The water district currently utilizes two 400-ft (122-m) deep wells, each capable of a cumulative flow of 1900 gpm (120 l/s) at 170°F (77°C). Figure 2 shows the location of the Warm Springs wells in relation to known and inferred structures. It is evident from Figure 2 that the BLM and Beard wells have penetrated lithologies near the Foothills Fault. The Warm Springs wells are located in the vicinity of the same fault and are tapping geothermal water from it. If the circulating geothermal fluid is indeed controlled by the position of the Foothills Fault, a potential exists for interference between the Warm Springs wells and the INEL wells. The degree to which the interference is detrimental is presently unknown and warrants examination. At present, there is little data available from which to conclude that production at either of the two geothermal areas influences the other.

Figure 22 presents the BLM transient wellhead pressure from November 1976 through October 1978. The well was not monitored continuously between May 1977 and March 1978. Some data, however, are available for the period between September 1977 and January 1978 when the BLM and Beard wells were being tested. During this time, BLM wellhead pressure measurements were taken periodically while the well was quiescent.

The data reflect highs between August and December and lows between January and July. An obvious conclusion would be to suspect that the water level drops that occur after December of each year are the result of increased water usage by the Warm Springs wells for the winter heating months. However, when considering the atypical fluctuations of the water table aquifer (Figure 23), that is, spring lows followed by fall highs, there appears to be a coincidence with the water level trends recorded at the BLM well. This indicates a vertical communication between the near-surface water and the geothermal water, either by vertical leakage or by loading from the water table aquifer. The inference, then, is that the BLM well fluctuations are not caused by water usage at the Warm Springs wells, but instead by activity of shallower water.

Considering further the supposed anisotropic and nonhomogeneous conditions of the geothermal system, it may be improper to conclude the

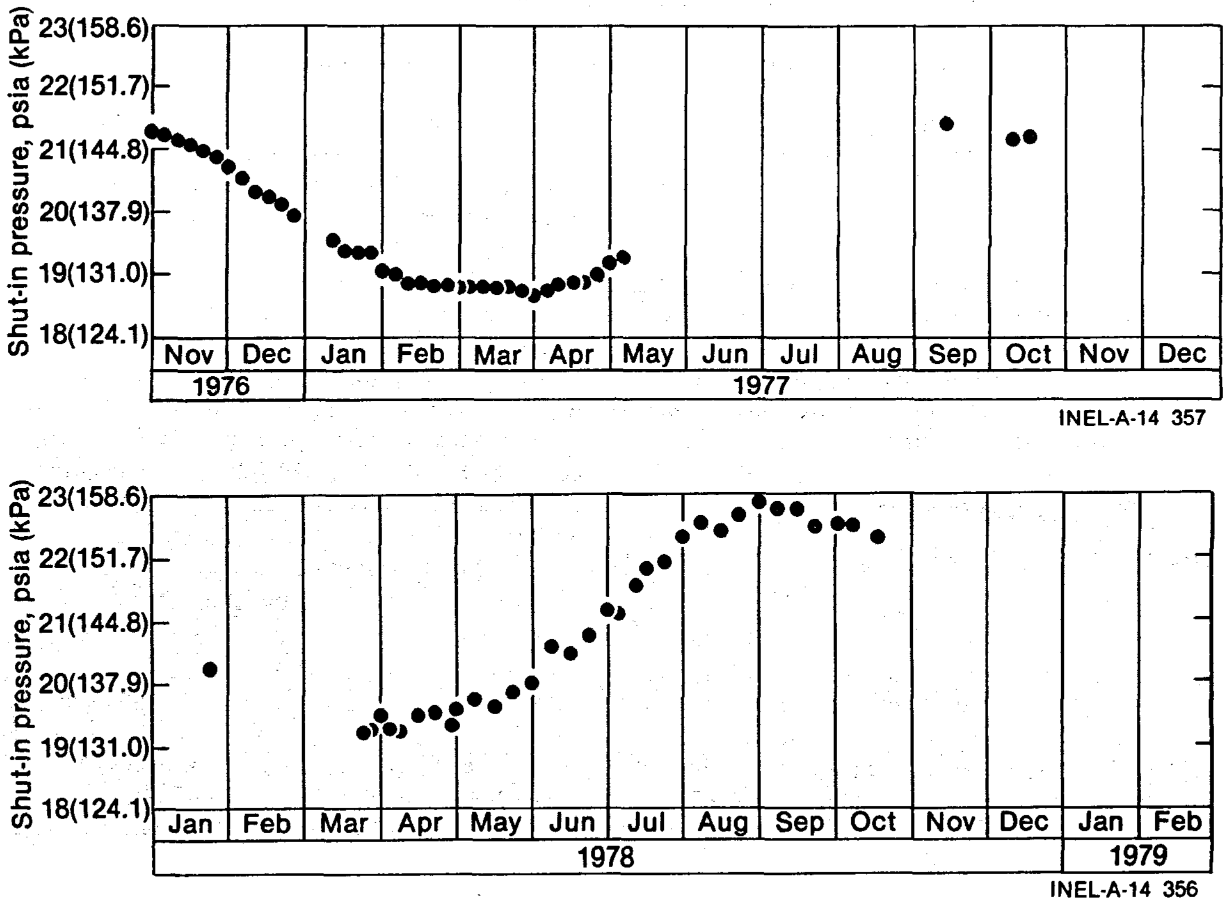
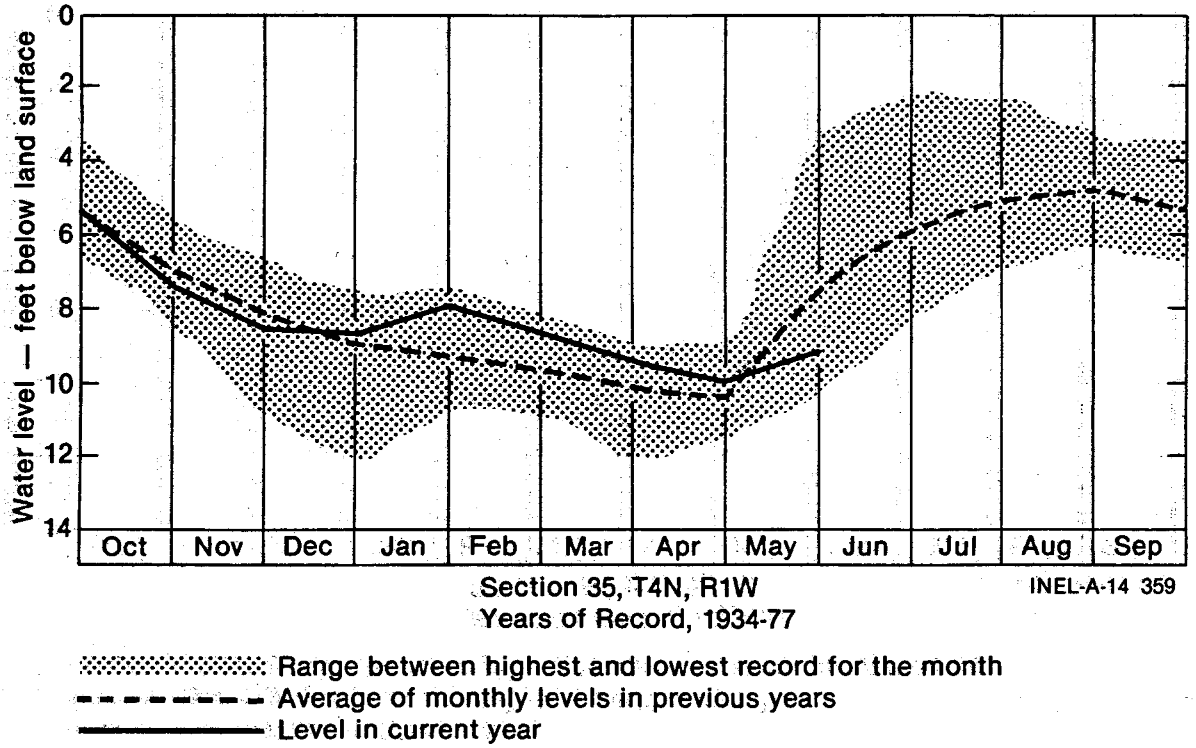


Figure 22. Semilog plot of BEH-1 (BLM) well shut-in pressure from November 1976 to October 1978.



SOURCE: U.S. Geological Survey, Pacific Northwest Water Resources Summary, May 1978

Figure 23. Month-end groundwater levels in key wells at Meridian, near Boise, Idaho.

presence or absence of Warm Springs/INEL communication based on measurements made at the BLM well. Insofar as the BLM well is removed from the more disturbed rock that contains the Beard and Warm Springs wells, response at the BLM well due to Warm Springs wells activity may go unnoticed, at least over the short term. The Beard well, then, should lend itself more effectively to interference testing between the two developments. Continuous pressure data are, however, unavailable from the Beard well.

CONCLUSIONS AND RECOMMENDATIONS

The INEL Boise Geothermal Project, culminating with the drilling and testing of several exploratory and test wells, has revealed a geothermal resource similar to the one in use at Warm Springs. The resource is present along the Boise Front in the vicinity of the Foothills Fault. The location of thermal areas along the front appears to be controlled by the distribution of linears that intersect the Foothills Fault and extend into the foothills area.

Thermal springs and more recent hot wells, including those described in this report, are located in the vicinity of the Foothills Fault and linear intersections. Test wells and exploratory wells BHW-1, BEH-1, and BSH-1, -2, and -3 have confirmed the presence of a fracture-controlled geothermal aquifer at one of these intersections near the Veterans Hospital at the Military Reserve Park. All tests of BHW-1 and BEH-1 indicate a highly transmissive aquifer capable of supplying 170°F (77°C) water from below 800 ft (244 m). A well should encounter enhanced subsurface permeability if it penetrates one of the northwest-southeast faults associated with the Foothills Fault System and in the vicinity of the northeast-southwest intersecting linears.

Preliminary indications suggest that permeabilities within the Foothills Fault near the Veterans Hospital are as much as an order of magnitude higher than the adjacent, less disturbed rocks. It follows that the materials containing the geothermal resource near the Veterans Hospital are anisotropic and nonhomogeneous. Consequently, future geothermal wells should be designed to accommodate local subsurface aquifer characteristics specific to future drill sites. If the Military Reserve Park is considered for future geothermal development, drill sites that will enable a well to tap the Foothills Fault should have a higher production potential than a well penetrating less disturbed rock.

Little can be said regarding the potential influence between the Warm Springs wells and wells in the Military Reserve Park. However, to confirm the presence of lack of communication between the two developments, two alternatives exist:

1. Begin monitoring the BHW-1 (Beard) well prior to and through a heating season to observe pressure transients that may result from increased activity at the Warm Springs wells.
2. If communication is minimal or lacking, drill a monitor well midway between the two developments and in the Foothills Fault. This will define more clearly the distance and magnitude of influence that production at one development has on the other.

Also, a new monitor well will aid in any future geothermal development in the area between the two developments by preventing resource overuse at a given location.

REFERENCES

1. L. L. Mink and D. L. Graham, *Geothermal Potential of the West Boise Area,* TREE-1162, October 1977.
2. O. M. J. Mohammad, *Hydrogeology of the Boise Ridge Area*, unpublished master's thesis, University of Idaho, 1970.
3. H. E. Malde and H. A. Powers, "Upper Cenozoic Stratigraphy of the Western Snake River Plain, Idaho," *Geological Society of America Bulletin, 73*, No. 10, October 1962.
4. K. M. Hollenbaugh, *The Evaluation of Geologic Processes in the Boise Foothills That May be Hazardous to Urban Development*, Boise State University Report to the ADA Council of Governments, May 1973.
5. W. B. Hall, *Boise Front Geothermal Project: Report on Remote Sensing, Idaho Bureau of Mines and Geology*, open file report, October 1975.
6. R. A. Freeze and P. A. Witherspoon, "Theoretical Analysis of Regional Ground Water," *Water Resources Research, 3*, No. 2, second quarter, 1967.
7. P. A. Witherspoon, I. Javandel, S. P. Neuman, and R. A. Freeze, *Interpretation of Aquifer Gas Storage Conditions from Water Pumping Tests*, monograph prepared on Project NS-38 at the University of California for the Pipeline Research Committee of the American Gas Association, Inc., New York: American Gas Association, Inc., 1967.