U.S. Department of the Interior
U.S. Geological Survey

# Identification of Water-Bearing Fractures by the Use of Geophysical Logs, May to July 1998, Former Naval Air Warfare Center, Bucks County, Pennsylvania

by Randall W. Conger and Phillip H. Bird

**Open-File Report 99-215**

*prepared in cooperation with the*
**U.S. DEPARTMENT OF THE NAVY**

Lemoyne, Pennsylvania
1999

**U.S. DEPARTMENT OF THE INTERIOR**
**BRUCE BABBITT, *Secretary***

**U.S. GEOLOGICAL SURVEY**
**Charles G. Groat, *Director***

For additional information
write to:

District Chief
U.S. Geological Survey
840 Market Street
Lemoyne, Pennsylvania 17043-1584

Copies of this report may be
purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Building 810
Denver, Colorado 80225-0286

## CONTENTS

Page

Abstract ..... 1
Introduction ..... 2
    Purpose and scope ..... 3
    Location and physiography ..... 4
    Borehole geophysical logs ..... 4
Evaluation of borehole geophysical logs and video surveys ..... 6
    BK-2943 (HN-84-S) ..... 6
    BK-2944 (HN-84-I) ..... 8
    BK-2945 (HN-85-S) ..... 10
    BK-2946 (HN-85-I) ..... 12
    BK-2947 (HN-86-S) ..... 14
    BK-2948 (HN-86-I) ..... 16
    BK-2949 (HN-87) ..... 18
    BK-2950 (HN-66-S) ..... 20
    BK-2951 (HN-66-I) ..... 23
    BK-2952 (HN-66-D) ..... 25
Conclusions ..... 27
References cited ..... 27

## ILLUSTRATIONS

Page

Figure 1. Map showing location of boreholes where geophysical logging and video surveys were conducted near the Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania ..... 2
2-4. Borehole geophysical logs for boreholes at the former Naval Air Warfare Center:
2. BK-2943 (HN-84-S) ..... 7
3. BK-2944 (HN-84-I) ..... 9
4. BK-2945 (HN-85-S) ..... 11
5-7. Borehole geophysical logs and direction of nonpumping vertical flow within boreholes at the former Naval Air Warfare Center:
5. BK-2946 (HN-85-I) ..... 13
6. BK-2947 (HN-86-S) ..... 15
7. BK-2948 (HN-86-I) ..... 17
8. Borehole geophysical logs for borehole BK-2949 (HN-87), former Naval Air Warfare Center ..... 19
9. Borehole geophysical logs and direction of nonpumping vertical flow within borehole BK-2950 (HN-66-S), former Naval Air Warfare Center ..... 21
10. Natural-gamma log correlation of boreholes at 960 Jacksonville Road ..... 22
11. Borehole geophysical logs for borehole BK-2951 (HN-66-I), former Naval Air Warfare Center ..... 24
12. Borehole geophysical logs and direction of nonpumping flow within borehole BK-2952 (HN-66-D), former Naval Air Warfare Center ..... 26

## TABLES

Table 1. Depth, casing length, and depth to water for boreholes logged by the U.S. Geological Survey at and near the former Naval Air Warfare Center, Bucks County, Pennsylvania ..... 3
2-5. Summary of heatpulse-flowmeter measurements for boreholes at the former Naval Air Warfare Center
2. Borehole BK-2946 (HN-85-I) ..... 12
3. Borehole BK-2947 (HN-86-S) ..... 14
4. Borehole BK-2948 (HN-86-I) ..... 16
5. Borehole BK-2952 (HN-66-D) ..... 25

## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 25.40 | millimeter |
| foot (ft) | 0.3048 | meter |
| | Volume | |
| gallon per minute (gal/min) | 0.00006309 | cubic meter per second |
| | Temperature | |
| degree Celsius (°C) | °F=1.8 °C+32 | degree Fahrenheit |

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.

# IDENTIFICATION OF WATER-BEARING FRACTURES BY THE USE OF GEOPHYSICAL LOGS, MAY TO JULY 1998, FORMER NAVAL AIR WARFARE CENTER, BUCKS COUNTY, PENNSYLVANIA

*by Randall W. Conger and Phillip H. Bird*

## ABSTRACT

Between May and July 1998, 10 monitor wells were drilled near the site of the former Naval Air Warfare Center (NAWC), Warminster, Bucks County, Pa., to monitor water levels and sample ground water in shallow and intermediate water-bearing fractures. The sampling will determine the horizontal and vertical distribution of contaminated ground water migrating from known or suspected sources. Three boreholes were drilled on the property at 960 Jacksonville Road, at the northwestern side of NAWC, along strike from Area A; seven boreholes were drilled in Area B in the southeastern corner of NAWC. Depths range from 40.5 to 150 feet below land surface.

Borehole geophysical logging and video surveys were used to identify water-bearing fractures so that appropriate intervals could be screened in each monitor well. Geophysical logs were obtained at the 10 monitor wells. Video surveys were obtained at three monitor wells in the southeastern corner of the NAWC property.

Caliper logs and video surveys were used to locate fractures. Inflections on fluid-temperature and fluid-resistivity logs were used to locate possible water-bearing fractures. Heatpulse-flowmeter measurements verified these locations. Natural-gamma logs provided information on stratigraphy. After interpretation of geophysical logs, video surveys, and driller's logs, all wells were screened such that water-level fluctuations could be monitored and water samples collected from discrete water-bearing fractures in each monitor well.

# INTRODUCTION

The former Naval Air Warfare Center (NAWC) occupies approximately 734 acres in Bucks County, Pa. (fig. 1). It was commissioned by the Navy in 1942 and was previously operated by the Brewster Aircraft Company. The Navy offically closed the NAWC facility on September 30, 1997, to all activity except environmental remediation. During the operation of the NAWC, numerous wastes were generated during the maintenance and repair of aircraft, machine-shop operations, spray painting, pest control, fire-fighting training, and laboratory research activities.

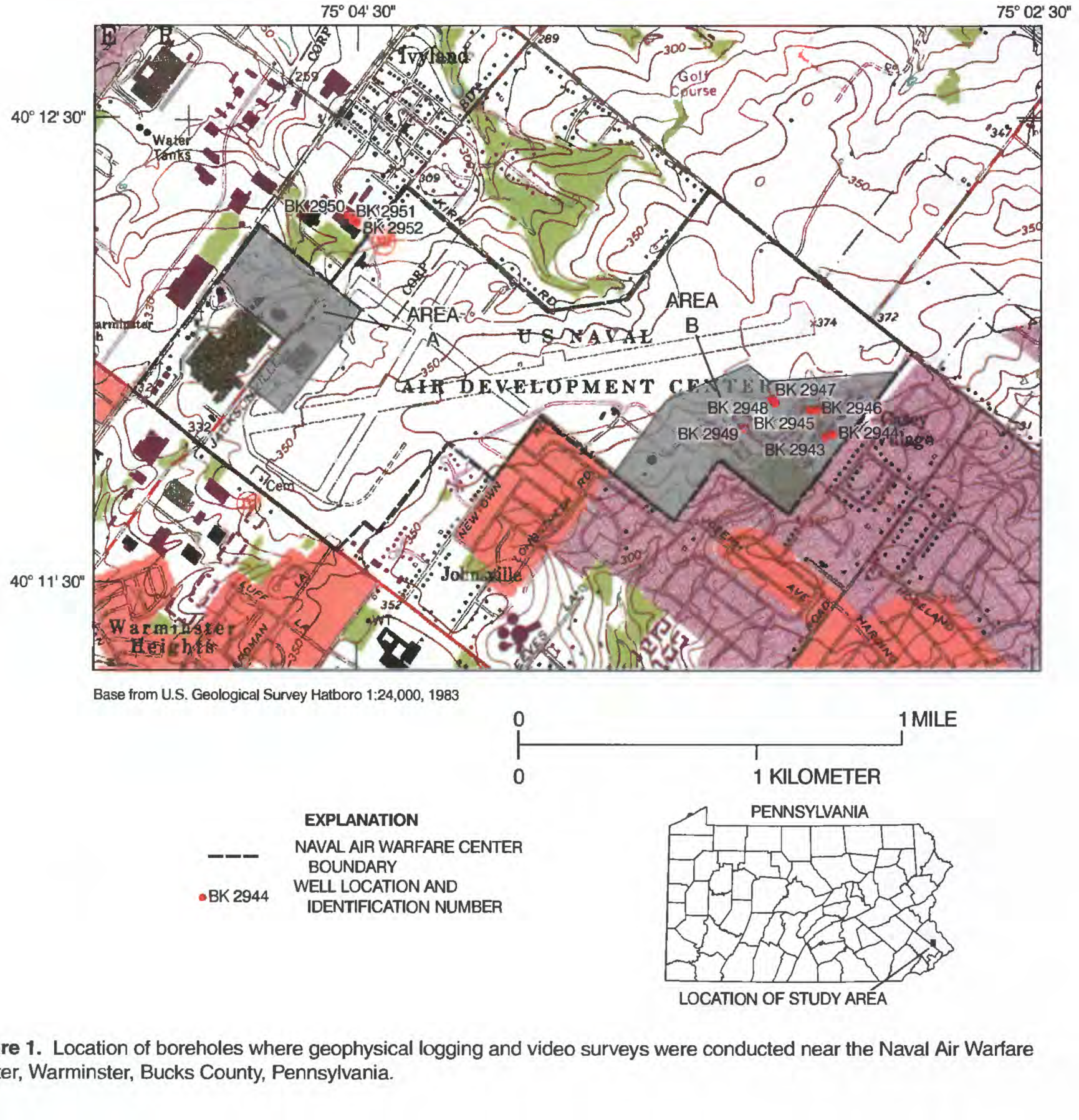


**Figure 1.** Location of boreholes where geophysical logging and video surveys were conducted near the Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

Boreholes were installed for the U.S. Navy by Tetra Tech NUS Inc., (TTNUS) to monitor water levels and sample ground-water contaminants in the shallow and intermediate water-bearing fractures adjacent to Areas A and B (fig. 1). Area A is located on the northwestern side of the NAWC and includes disposal sites 1, 2, and 3. Area B is located on the southeastern side of the NAWC, on or near the enlisted housing area, and includes disposal sites 5, 6, and 7. Areas A and B are two of four major contaminated sites within the NAWC that were described in the Phase II Remedial Investigation Report (Halliburton NUS Environmental Corporation, 1992).

A hydrogeological investigation is being conducted by TTNUS as part of the Navy's Installation Restoration Program to address ground-water contamination at Areas A and B and other sites. The U.S. Navy requested that the U.S. Geological Survey (USGS) provide technical assistance to the hydrological investigation and conduct borehole geophysical logging to identify water-bearing fractures that could be monitored by properly completed wells.

## Purpose and Scope

This report evaluates borehole geophysical logs and video surveys run by the USGS in 10 boreholes located near NAWC from May to July 1998 (table 1 and fig. 1). This report identifies one or more water-bearing fractures in each well on the basis of geophysical logs and video surveys. Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature logs were run and heatpulse-flowmeter measurements were made in 10 boreholes. Video surveys were conducted in three boreholes, BK-2944, BK-2946, BK-2948. A cross-reference between USGS borehole-identification numbers and TTNUS borehole-identification numbers is shown in table 1.

***Table 1.*** *Depth, casing length, and depth to water for boreholes logged by the U.S. Geological Survey at and near the former Naval Air Warfare Center, Bucks County, Pennsylvania*

| U.S. Geological Survey borehole-identification number | Tetra Tech NUS identification number | Depth of well below land surface (feet) | Length of casing below land surface (feet) | Depth to water below land surface (feet) | Date water level measured |
|---|---|---|---|---|---|
| BK-2943 | HN-84-S | 50 | 19 | 12.03 | 5/4/98 |
| BK-2944 | HN-84-I | 120 | 19 | 18.33 | 5/4/98 |
| BK-2945 | HN-85-S | 40.5 | 17 | 11.0 | 5/8/98 |
| BK-2946 | HN-85-I | 91.5 | 18.5 | 12.0 | 5/8/98 |
| BK-2947 | HN-86-S | 49 | 18 | 17.7 | 5/7/98 |
| BK-2948 | HN-86-I | 101 | 18 | 17.3 | 5/7/98 |
| BK-2949 | HN-87 | 60.5 | 19 | 2.85 | 5/4/98 |
| BK-2950 | HN-66-S | 49 | 20 | 14.16 | 7/14/98 |
| BK-2951 | HN-66-I | 80 | 19 | 16.25 | 7/14/98 |
| BK-2952 | HN-66-D | 150 | 19 | 15.58 | 7/14/98 |

## Location and Physiography

The NAWC is located in the Gettysburg-Newark Lowlands Section of the Piedmont Physiographic Province. The site and adjoining area are underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. The Stockton Formation is divided into three lithologic units—the lower arkose, middle arkose, and upper shale members (Rima and others, 1962). The middle arkose member crops out at the site. At the NAWC, this unit consists of very fine- to medium-grained arkosic red sandstone interbedded with red shale, siltstone, and mudstone. Quartz, calcite, and feldspar are the predominant minerals. The Stockton Formation is approximately 6,000 ft thick at the Bucks-Montgomery County line. At this location, the middle arkose member has a maximum thickness of about 4,200 ft (Rima and others, 1962). Bedding planes in the Stockton Formation adjacent to NAWC strike N. 78° E. and dip 10° NW [as determined from boreholes BK-2950, BK-2951, and BK-2952]. Vertical and horizontal fractures are commonly seen on borehole video surveys.

Ground-water storage and movement within the Stockton Formation is through secondary openings such as interconnected fractures, bedding-plane separations, and joints (Sloto and others, 1995). Deeper wells may penetrate several water-bearing fractures with different hydraulic properties that are under different hydraulic head. In this report, wells that penetrate more than one water-bearing fracture are called multiaquifer wells. The static hydraulic head in a multiaquifer well is the result of the combined heads of all water-bearing fractures penetrated. Where water-bearing fractures under different hydraulic head are interconnected by a borehole, water in that borehole will flow either up or down in the direction of lower head (Sloto and others, 1995).

At the NAWC, water in the upper part of the aquifer generally is under unconfined conditions, and water in deeper parts of the aquifer may be confined or partially confined. Local artesian conditions are common.

## Borehole Geophysical Logs

Geophysical logs provide information on location of fractures (caliper logs and video surveys), water-producing and water-receiving zones (caliper logs and video surveys), intervals of vertical fluid flow (fluid-resistivity and fluid-temperature logs), quantification of vertical flow within the borehole (heatpulse-flowmeter measurements), lithologic correlation (gamma and single-point resistance logs), and well construction (caliper and single-point resistance logs) where unknown.

Caliper logs record the average borehole diameter, which may be related to fractures, lithology, or drilling methods. Caliper logs can be used to identify fractures and possible water-bearing openings and to correct other geophysical logs for changes in borehole diameter. Correlation of caliper logs with fluid-resistivity and fluid-temperature logs is used to identify fractures, water-producing zones, and water-receiving zones.

The term fracture used in association with the caliper-log interpretations might identify a change in borehole diameter that may not necessarily indicate a bedding-plane separation, lithologic contact, or water-producing or water-receiving zones but may simply indicate an enlargement of the borehole.

The natural-gamma or gamma log measures the natural-gamma radiation (photons) emitted from rocks penetrated by the borehole. The most common emitters of gamma radiation are uranium-238, thorium-232, their daughter elements, and potassium-40. These radioactive elements are concentrated in clays by adsorption, precipitation, and ion exchange. Fine-grained sediments, such as shale or siltstone, usually emit more gamma radiation than sandstone, limestone, or dolomite. Geophysical logging with a gamma probe can be conducted in the fluid-filled, dry, cased, or uncased parts of a borehole. However, casing does reduce the gamma response. The gamma log is used to correlate geologic units between wells (Keys, 1990).

The single-point-resistance log records the electrical resistance of a formation between the probe in a water filled borehole below casing and an electrical ground at land surface. Generally, electrical resistance increases with formation grain size and decreases with increasing borehole diameter, water-bearing fractures, and increasing dissolved-solids concentration of borehole water. The single-point-resistance log is used to correlate geology and lithology between wells and may help identify water-bearing fractures (Keys, 1990).

Fluid resistivity is the inverse of fluid conductivity. The fluid-resistivity log records the electrical resistivity of the water column in the well. The fluid-resistivity probe measures the resistivity of borehole water between electrodes in the probe. Fluid-resistivity logs reflect changes in the dissolved-solids concentration of water in the borehole. Fluid-resistivity logs are used to identify water-producing and water-receiving zones and to determine intervals of vertical borehole flow. Water-producing and water-receiving zones usually are identified by distinct changes in resistivity. Intervals of vertical borehole flow are usually identified by a low-resistivity gradient between a water-producing and a water-receiving zone.

Fluid-temperature logs provide a continuous record of the temperature of the water in a borehole. Fluid-temperature logs are used to identify water-producing and water-receiving zones and to determine zones of vertical borehole flow. Intervals of vertical borehole flow are characterized by little or no temperature gradient (Williams and Conger, 1990).

The direction and rate of borehole-water movement was determined by the use of a heatpulse flowmeter. The heatpulse flowmeter operates by heating a small sheet of water between two sensitive thermistors (heat sensors). A measurement of direction and rate is computed when a peak temperature is recorded by one of the thermistors. The range of flow measurement is about 0.01 to 1.5 gal/min in a 2- to 10-in.-diameter borehole (Conger, 1996).

Some heatpulse-flowmeter measurements may be influenced by (1) poor seal integrity between the borehole and heatpulse flowmeter and (2) contributions of water from storage within the borehole. If the seal between the borehole and flowmeter is not complete, some water can bypass the flowmeter, resulting in measurements of flow that are less than the actual rate. During pumping, flow measurements are made after drawdown has stabilized. Otherwise, some of the measured flow will be derived from storage within the borehole rather than from water-bearing fractures in the aquifer. Although the heatpulse flowmeter is a calibrated probe, the data are used primarily as a relative indicator to identify water-producing fractures.

Video surveys were conducted by lowering a waterproof camera down the borehole and recording the image on video tape. The depth indicated on the video survey may not correspond exactly to the geophysical logs because of some minor slippage (plus or minus 1 ft) of the television cable.

## EVALUATION OF BOREHOLE GEOPHYSICAL LOGS AND VIDEO SURVEYS

The locations of boreholes logged are shown on figure 1. The reference measuring point for all geophysical logs and video surveys is in feet below land surface. Depth, casing length, and water level for each borehole at the time of logging are given in table 1.

### BK-2943 (HN-84-S)

The caliper log shows the total depth of the borehole is 50 ft, and it is cased with 6-in.-diameter casing to 19 ft below land surface (bls) (fig. 2). The static water level was 12.03 ft bls at the time of logging. The caliper log shows major fractures at 24 and 26-27 ft bls plus additional minor fractures. The natural-gamma log shows a rock unit with elevated gamma readings from 41-44 ft bls that might be used for stratigraphic correlation of geologic units with other wells. The fluid-resistivity and fluid-temperature logs show changes in slope at 24 and 26 ft bls that correlate to fractures shown on the caliper log and indicate possible fluid-bearing zones. The driller's log shows that during drilling water production slowly increased with depth from 0.5 gal/min at 34 ft bls to about 2.5 gal/min at 50 ft bls. Under nonpumping conditions, the heatpulse flowmeter was unable to detect any vertical movement of water at 39 ft bls. A screen and sand pack were placed at 36-50 ft bls to isolate the lower section of the borehole (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

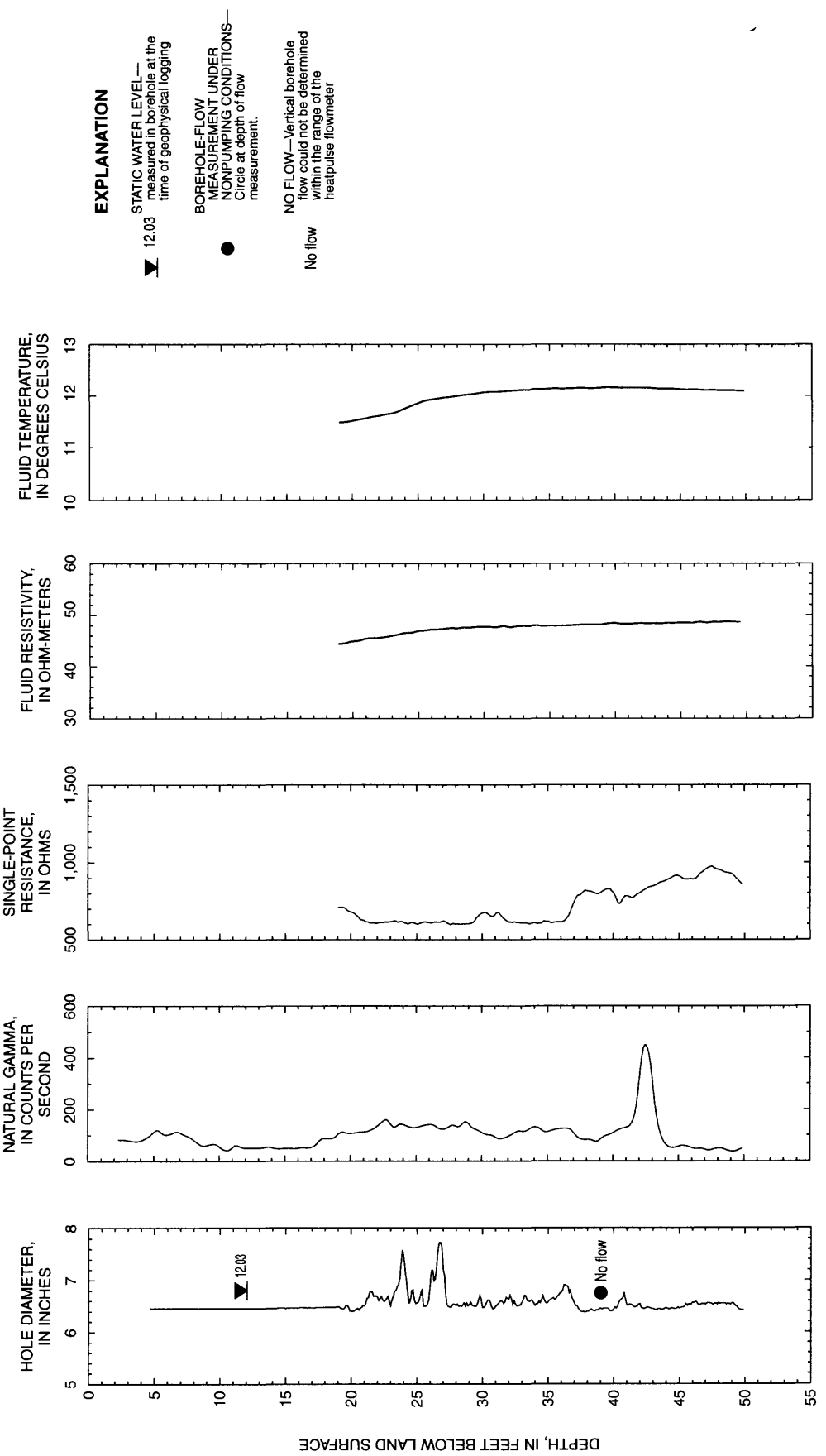


**Figure 2.** Borehole geophysical logs for borehole BK-2943 (HN-84-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

**BK-2944 (HN-84-I)**

The caliper log shows the total depth of the borehole is 120 ft, and it is cased with 6-in.-diameter casing to about 19 ft bls (fig. 3). The static water level was 18.33 ft bls at the time of logging. The caliper log shows a fracture zone from 19.5-38 ft bls and fractures at 83 and 85 ft bls plus numerous minor fractures throughout the open-hole interval. The video survey showed near vertical fractures at 64 and 74-78 ft bls. The fluid-resistivity and fluid-temperature logs show changes in slope at 28 and 84 ft bls that correlate to fractures on the caliper log and may be fluid-bearing fractures. The change in slope on the fluid-resistivity log at 119 ft bls indicates mud at the bottom of the borehole. Under nonpumping conditions, the heatpulse flowmeter measured no borehole flow at 78, 90, and 100 ft bls but detected turbulent flow at 29, 40, and 49 ft bls, which usually indicates lateral flow. A screen and sand pack were placed at 107.5-120 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

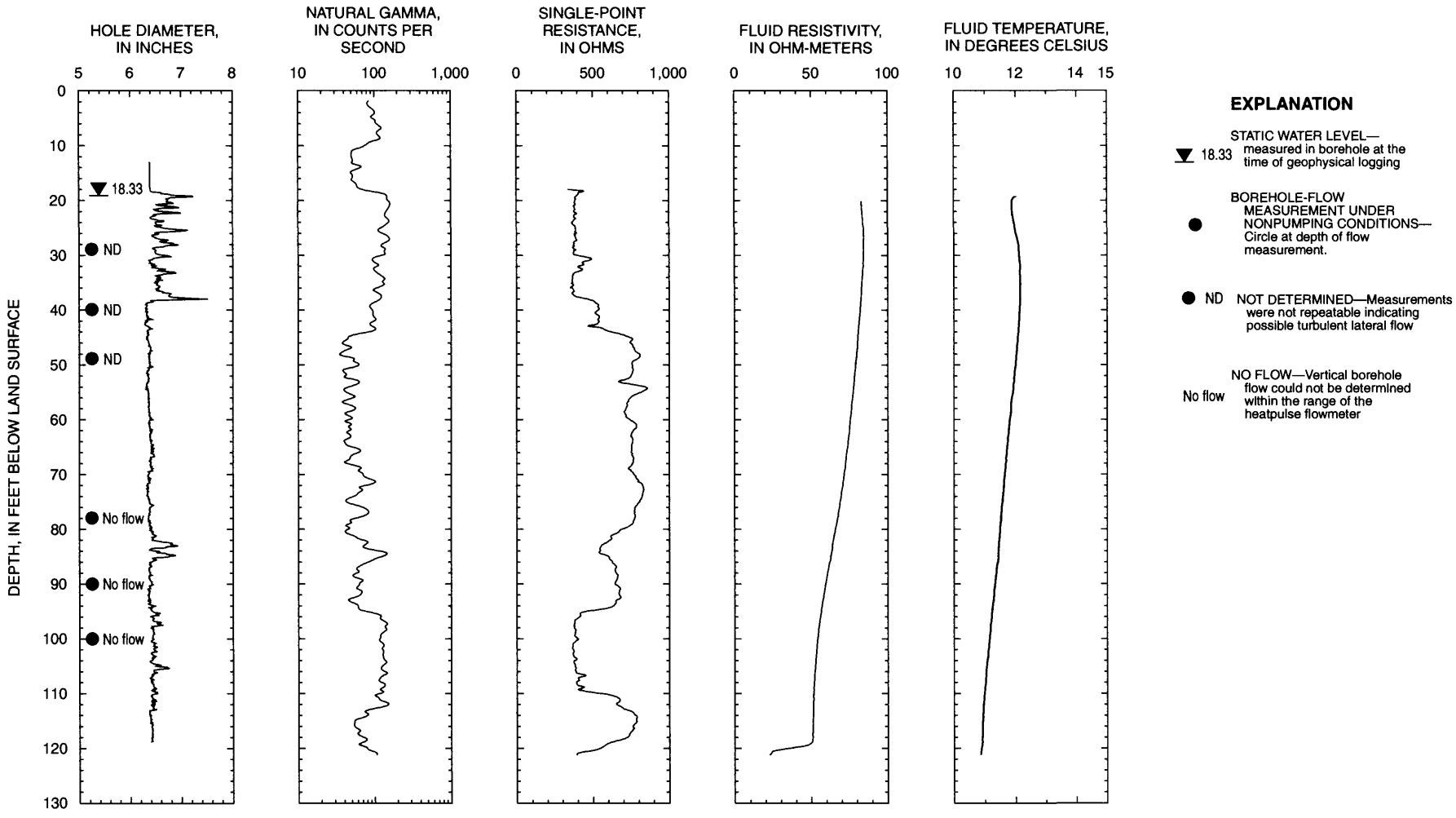


**Figure 3.** Borehole geophysical logs for borehole BK-2944 (HN-84-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2945 (HN-85-S)

The caliper log shows the total depth of the borehole is 40.5 ft, and it is cased with 6-in.-diameter casing to 17 ft bls (fig. 4). The static water level was 11.0 ft bls at the time of logging. The caliper log shows major fractures at 20-22 and 23 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity and fluid-temperature logs show a sudden change in slope at 21 ft bls that correlates to a large fracture shown on the caliper log. Under nonpumping conditions, the heatpulse flowmeter was unable to detect any vertical movement of water at 30 ft bls. The driller's log shows that during drilling water production slowly increased with depth from 2 gal/min at 20 ft bls to about 5 gal/min at 40.5 ft bls. A screen and sand pack were placed at 19-34 ft bls, which includes the greatest water-bearing interval indicated during drilling (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

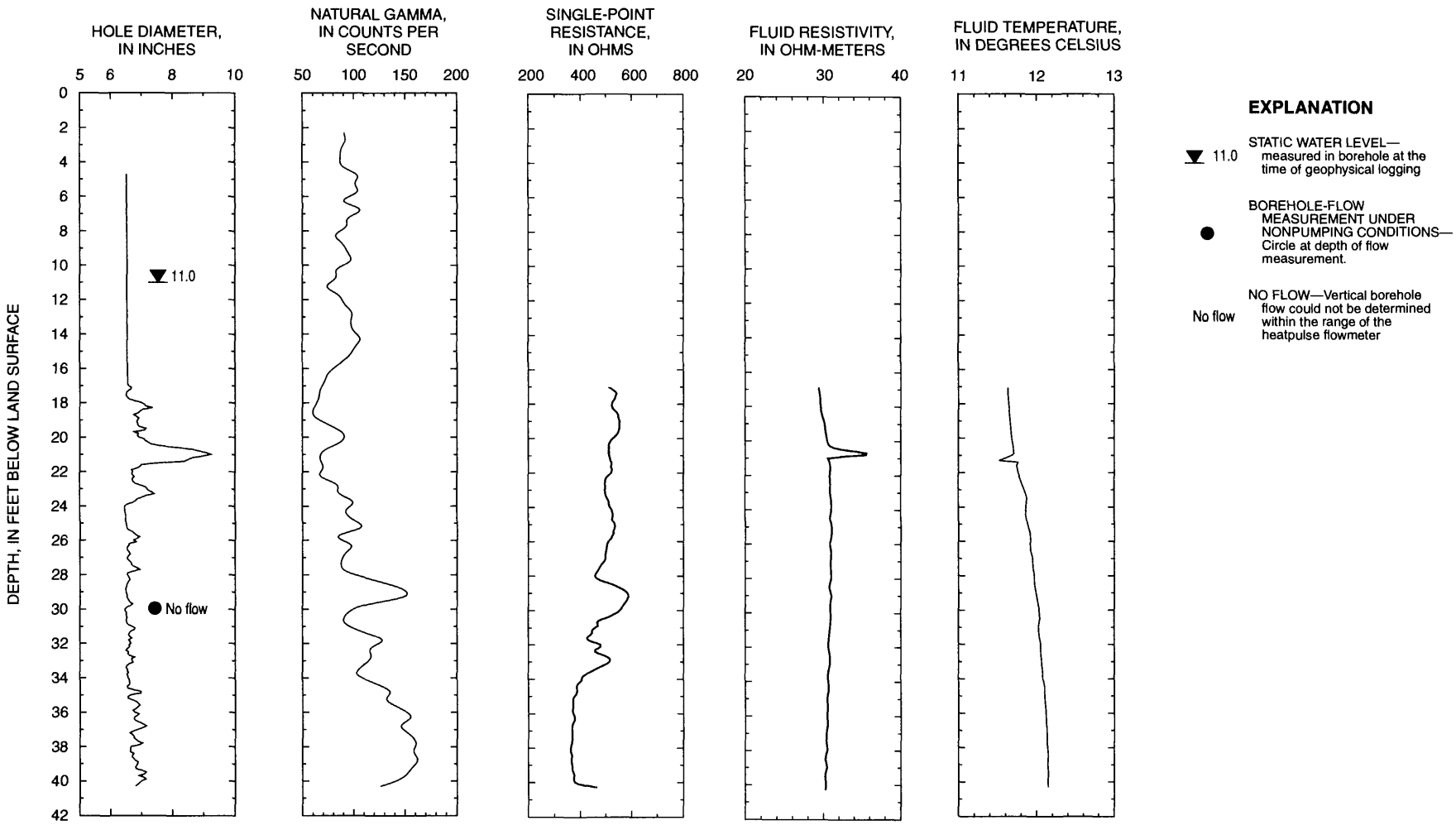


**Figure 4.** Borehole geophysical logs for borehole BK-2945 (HN-85-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2946 (HN-85-I)

The caliper log shows the total depth of the borehole is 91.5 ft, and it is cased with 6-in.-diameter casing to 18.5 ft bls (fig. 5). The static water level was 12.0 ft bls at the time of logging. The caliper log shows major fractures at 35, 39, 43, 46-50, and 59 ft bls plus numerous other minor fractures throughout the open-hole interval. The video survey indicates a near vertical fracture zone extends from 46-51 ft bls. The fluid-resistivity log shows a change in slope at 21 ft bls that correlates to fractures shown on the caliper log and indicates a possible fluid-bearing zone. The fluid-temperature log shows a change in slope at 20 ft bls. Under nonpumping conditions, the heatpulse flowmeter measured downward movement of water at 27, 45, 61, 80, and 88 ft bls (table 3). The heatpulse-flowmeter measurements at 45 ft bls were turbulent and inconsistent and may be less than the actual flow rate. The geophysical logs and the heatpulse-flowmeter measurements indicate water enters the borehole through a fracture at 20 ft bls, moves downward, and exits the borehole through a fracture at 90 ft bls. A screen and sand pack were placed in the borehole at 72-85.5 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

***Table 2.*** *Summary of heatpulse-flowmeter measurements for borehole BK-2946 (HN-85-I) at the former Naval Air Warfare Center, Bucks County, Pennsylvania*

| Depth (feet below land surface) | Flow rate under nonpumping conditions (gallons per minute) | Flow direction under nonpumping conditions |
|---|---|---|
| 27 | 1.4 | Down |
| 45 | [1].9 | Down |
| 61 | 1.5 | Down |
| 80 | 1.5 | Down |
| 88 | 1.4 | Down |

[1] Poor heatpulse flowmeter seal assumed.

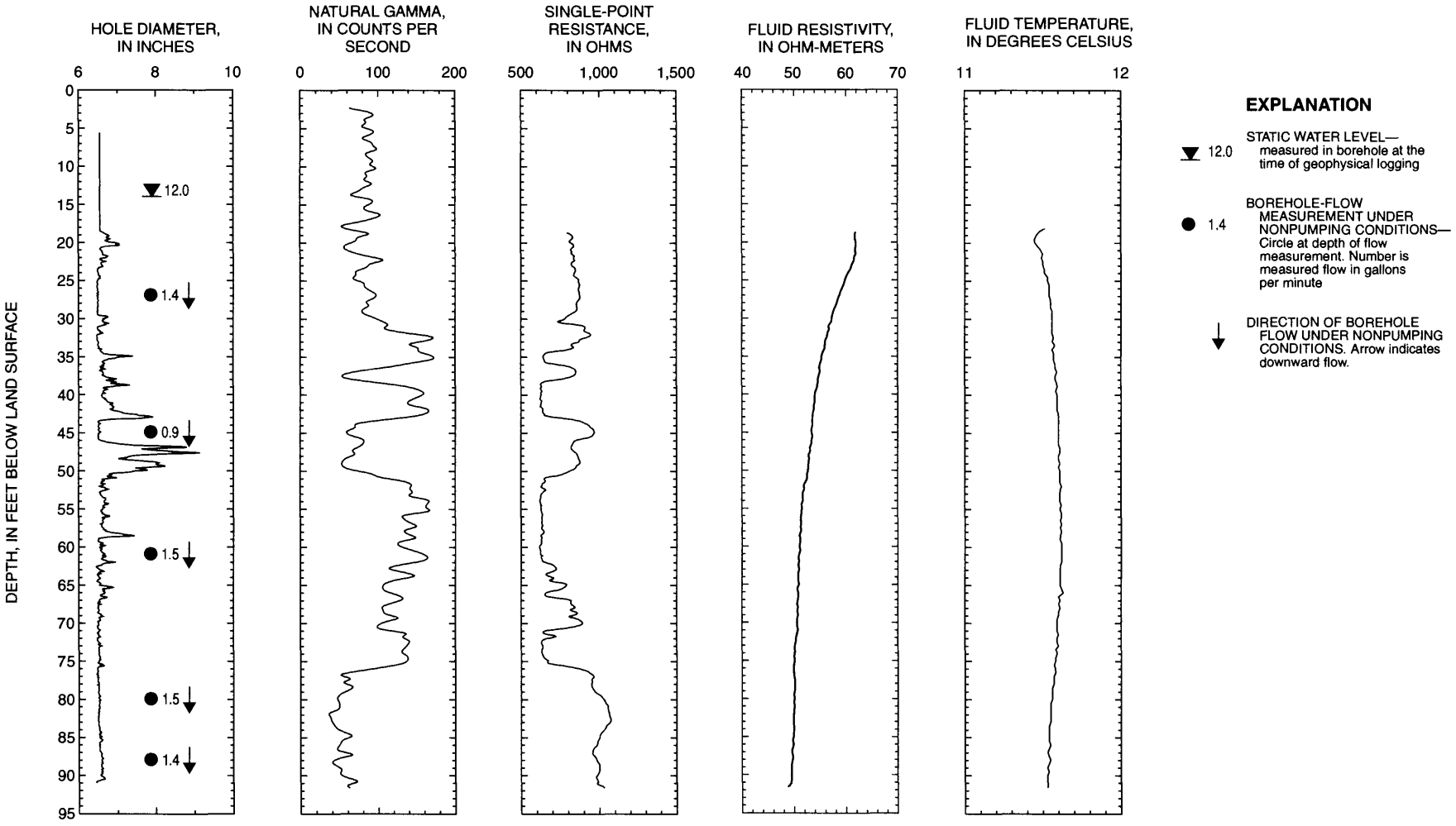


**Figure 5.** Borehole geophysical logs and direction of nonpumping vertical flow within borehole BK-2946 (HN-85-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2947 (HN-86-S)

The caliper log shows the total depth of the borehole is 49 ft, and it is cased with 6-in.-diameter casing to 18 ft bls (fig. 6). The static water level was 17.7 ft bls at the time of logging. The caliper log shows major fractures at 19, 21, and 25 ft bls plus numerous smaller fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 25, 42, and 48 ft bls that suggest fluid-producing or fluid-receiving zones. Under nonpumping conditions, the heatpulse flowmeter measured downward borehole flow at 20 and 24 ft bls and upward flow at 27, 34, and 37 ft bls (table 4). The geophysical logs and the heatpulse-flowmeter measurements indicate water enters the borehole through fractures at 19 and 39-49 ft bls, moves downward and upward, and exits the borehole through the fractures at 25 ft bls. A screen and sand pack were placed at 34.5-50 ft bls to isolate the water-bearing interval at 39-49 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

***Table 3.*** *Summary of heatpulse-flowmeter measurements for borehole BK-2947 (HN-86-S) at the former Naval Air Warfare Center, Bucks County, Pennsylvania*

| Depth (feet below land surface) | Flow rate under nonpumping conditions (gallons per minute) | Flow direction under nonpumping conditions |
|---|---|---|
| 20 | 0.30 | Down |
| 24 | .26 | Down |
| 27 | .1 | Up |
| 34 | .15 | Up |
| 37 | .1 | Up |

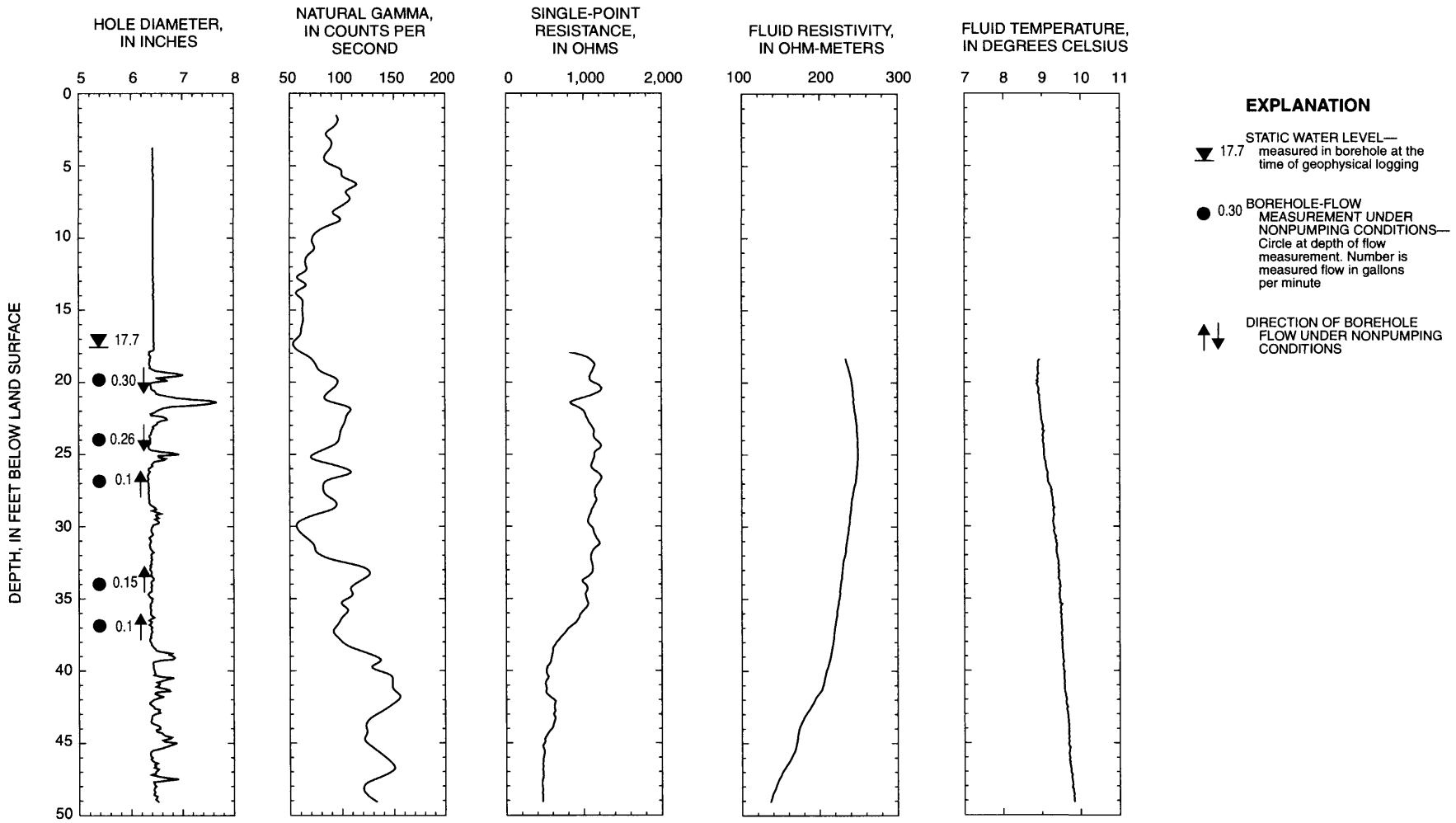


**Figure 6.** Borehole geophysical logs and direction of nonpumping vertical flow within borehole BK-2947 (HN-86-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2948 (HN-86-I)

The caliper log shows the total depth of the borehole is 101 ft, and it is cased with 6-in.-diameter casing to 18 ft bls (fig. 7). The static water level was 17.3 ft bls at the time of logging. The caliper log shows major fractures at 19 and 43 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity and fluid-temperature logs show changes in slope at 30 and 84 ft bls that are in proximity to a fluid-producing and fluid-receiving zone, respectively. Under nonpumping conditions, the heatpulse flowmeter measured downward borehole flow at 22, 28, 63, and 80 ft bls and no flow at 85 ft bls (table 5). The geophysical logs and video survey show particles entering the borehole at 19 and 26 ft bls. The heatpulse-flowmeter measurements indicate water enters the borehole through fractures at 19 and 26 ft bls, moves downward, and exits the borehole through a fracture at 82 ft bls. A screen and sand pack were placed at 72-86 ft bls to include the water-receiving fracture at 82 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

***Table 4.*** *Summary of heatpulse-flowmeter measurements for borehole BK-2948 (HN-86-I) at the former Naval Air Warfare Center, Bucks County, Pennsylvania*

[--, not applicable]

| Depth (feet below land surface) | Flow rate under nonpumping conditions (gallons per minute) | Flow direction under nonpumping conditions |
|---|---|---|
| 22 | 0.2 | Down |
| 28 | 1.5 | Down |
| 63 | 1.4 | Down |
| 80 | 1.5 | Down |
| 85 | No flow | -- |

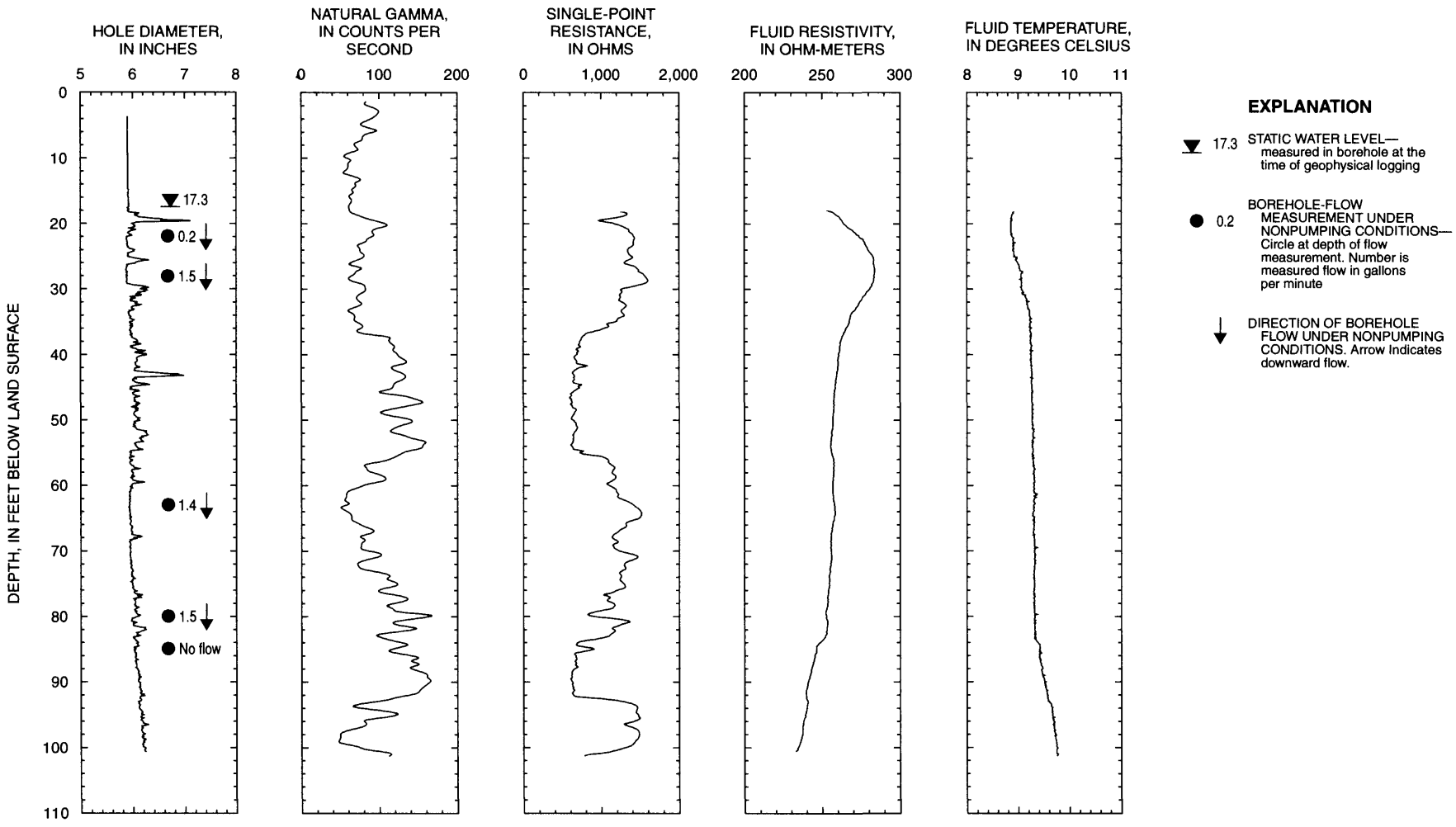


**Figure 7.** Borehole geophysical logs and direction of nonpumping vertical flow within borehole BK-2948 (HN-86-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2949 (HN-87)

The caliper log shows the total depth of the borehole is 60.5 ft, and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 8). The static water level was 2.85 ft bls at the time of logging. The caliper log shows minor fractures at 20, 21, 29, and 56 ft bls plus numerous other minor fractures throughout the open-hole interval. The fluid-temperature and fluid-resistivity logs do not show any significant changes. Under nonpumping conditions, the heatpulse flowmeter measured no borehole flow at 24 and 40 ft bls. The driller's log reports a minor quantity of water was produced at 47, 50, and 58 ft bls and possibly from 61 ft bls; the total yield was 1.5 to 2 gal/min. A screen and sand pack were placed at 46.5-61 ft bls to include possible water-bearing fractures from 47-61 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

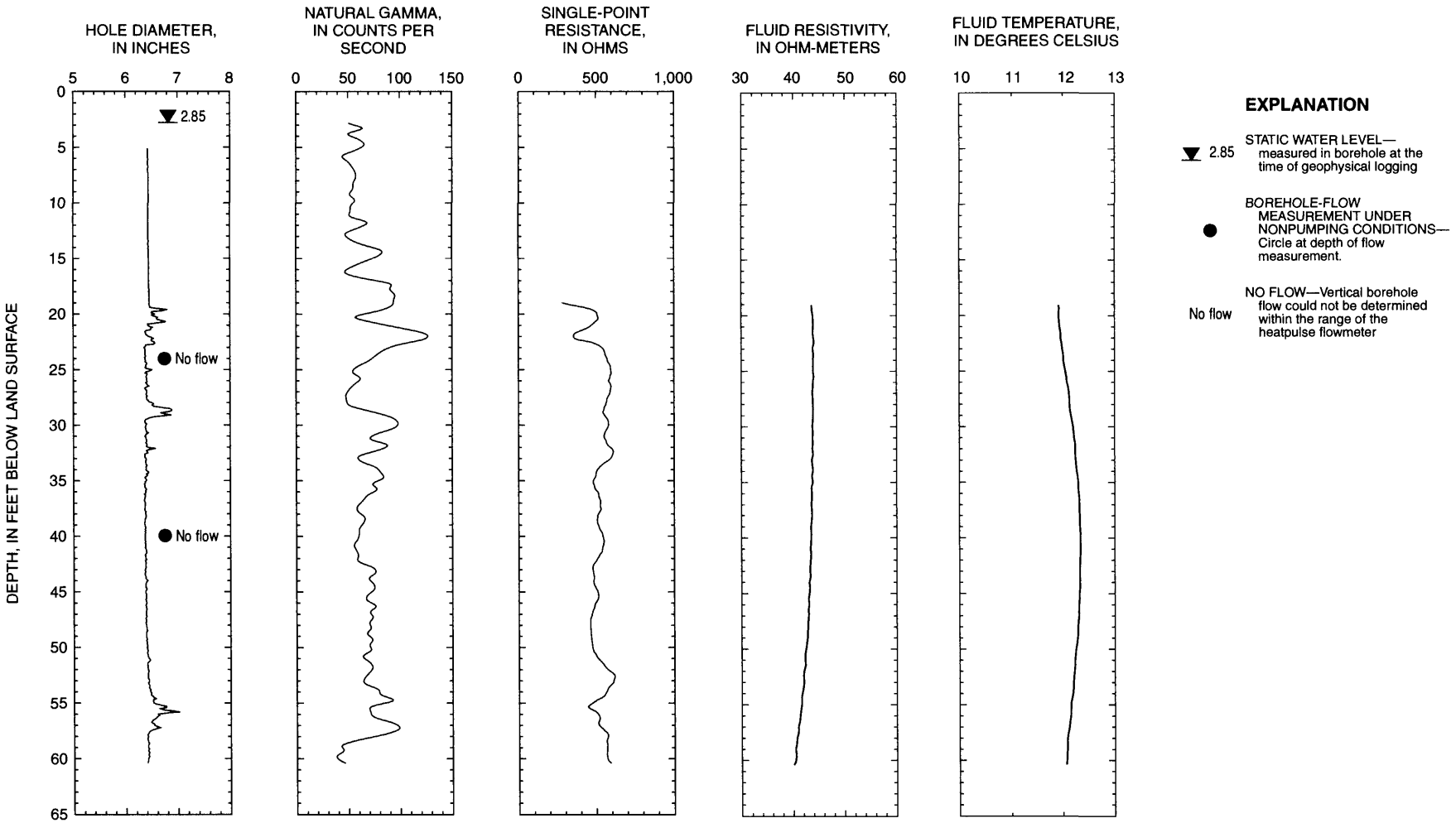


**Figure 8.** Borehole geophysical logs for borehole BK-2949 (HN-87), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2950 (HN-66-S)

The caliper log shows the total depth of the borehole is 49 ft, and it is cased with 6-in.-diameter casing to 20 ft bls (fig. 9). The static water level was 14.16 ft bls at the time of logging. The caliper log shows major fractures at 20-22 ft bls and minor fractures from 36 to 44 ft bls. The natural-gamma log shows a rock unit with elevated gamma counts (probably shale or siltstone units) at 37, 41, and 49 ft bls that correlates with the natural-gamma logs of BK-2951 and BK-2952 and was used to determine local strike and dip (fig. 10). The caliper, natural-gamma, and single-point-resistance logs show that most fractures occur at lithologic changes. The fluid-resistivity and fluid-temperature logs show a change in slope at 40 ft bls. Under nonpumping conditions, the heatpulse flowmeter measured possible downward borehole flow (0.1 gal/min) at 32 ft bls. The geophysical logs and the heatpulse-flowmeter measurements suggest that water enters the borehole through fractures at 20-22 ft bls, moves downward, and exits the borehole through fractures at 36.5-44 ft bls. A screen and sand pack were placed at 32-52 ft bls to include the water-receiving fractures at 36.5-44 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

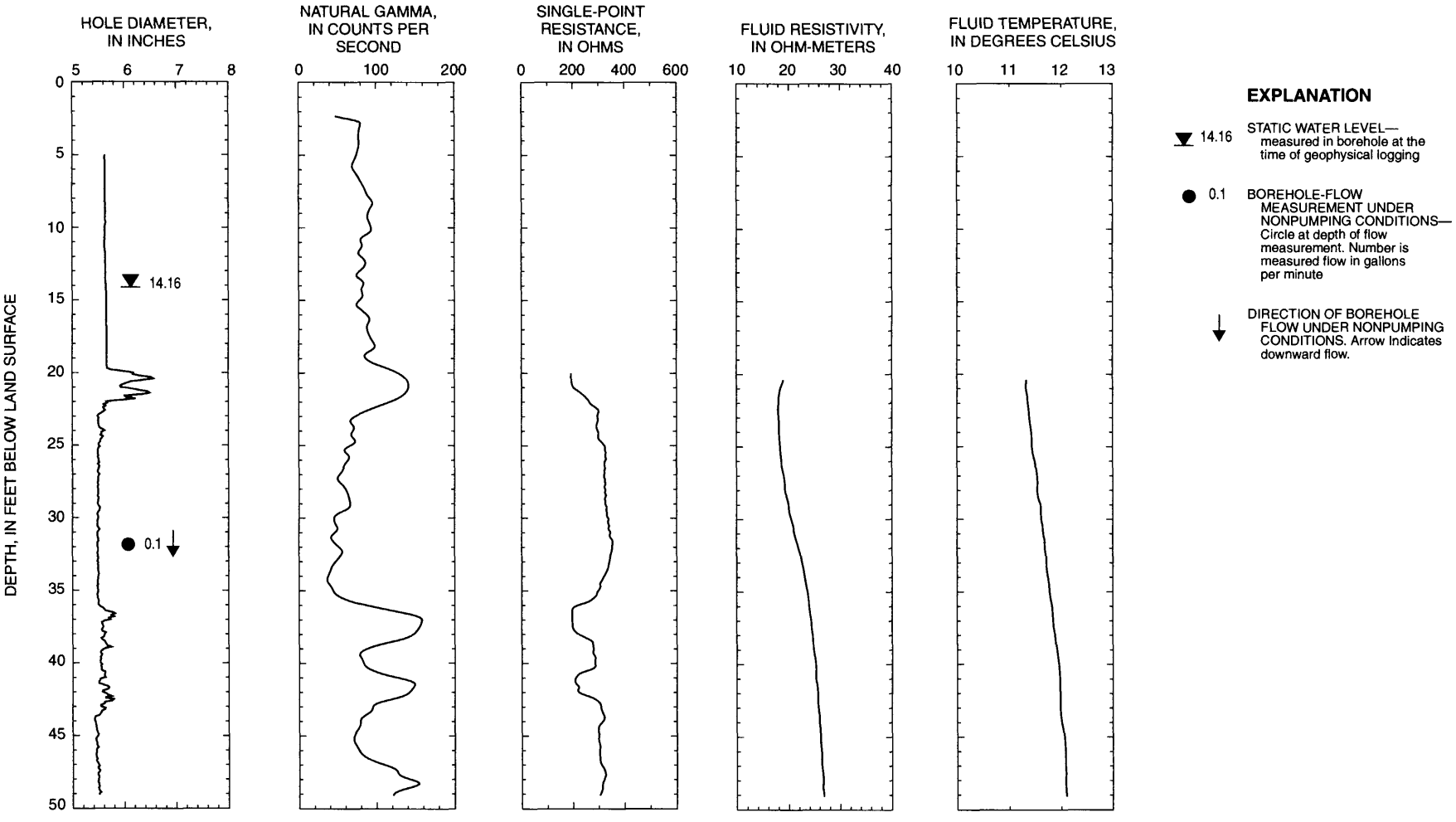


**Figure 9.** Borehole geophysical logs and direction of nonpumping vertical flow within borehole BK-2950 (HN-66-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

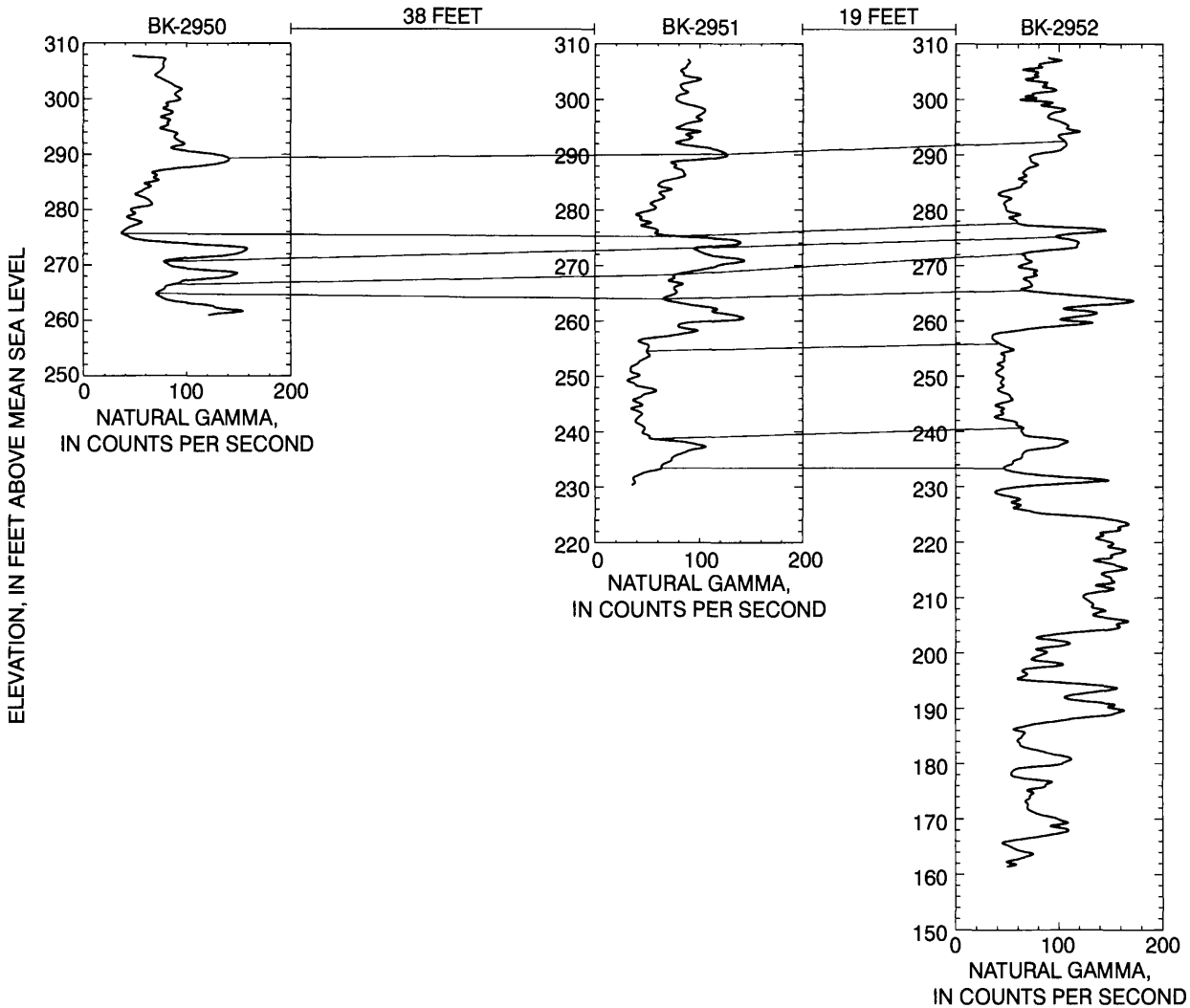


**Figure 10.** Natural-gamma log correlation of boreholes at 960 Jacksonville Road. Local strike and dip determined from 3-point problem to be N. 78° E., 10° NW.

## BK-2951 (HN-66-I)

The caliper log shows the total depth of the borehole is 80 ft, and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 11). The static water level was 16.25 ft bls at the time of logging. The caliper log shows major fractures at 69-71, 73, and 76.5 ft bls plus minor fractures throughout the open-hole interval. The natural-gamma log shows rock units with elevated gamma counts (probably shale or siltstone units) at 35, 39, and 50 ft bls that correlates with the natural-gamma logs of BK-2950 and BK-2952 and was used to determine local strike and dip (fig. 10). The fluid-resistivity and fluid-temperature logs show changes in slope at 38 and 52 ft bls that may indicate water-bearing fractures. Under nonpumping conditions, the heatpulse flowmeter was unable to detect any vertical movement of water at 26, 46, 56, and 67 ft bls. The driller's log reports a yield of approximately 4 gal/min near the bottom of the borehole. A screen and sand pack were placed at 65-80 ft bls to include the water-bearing fractures at the bottom of the borehole (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

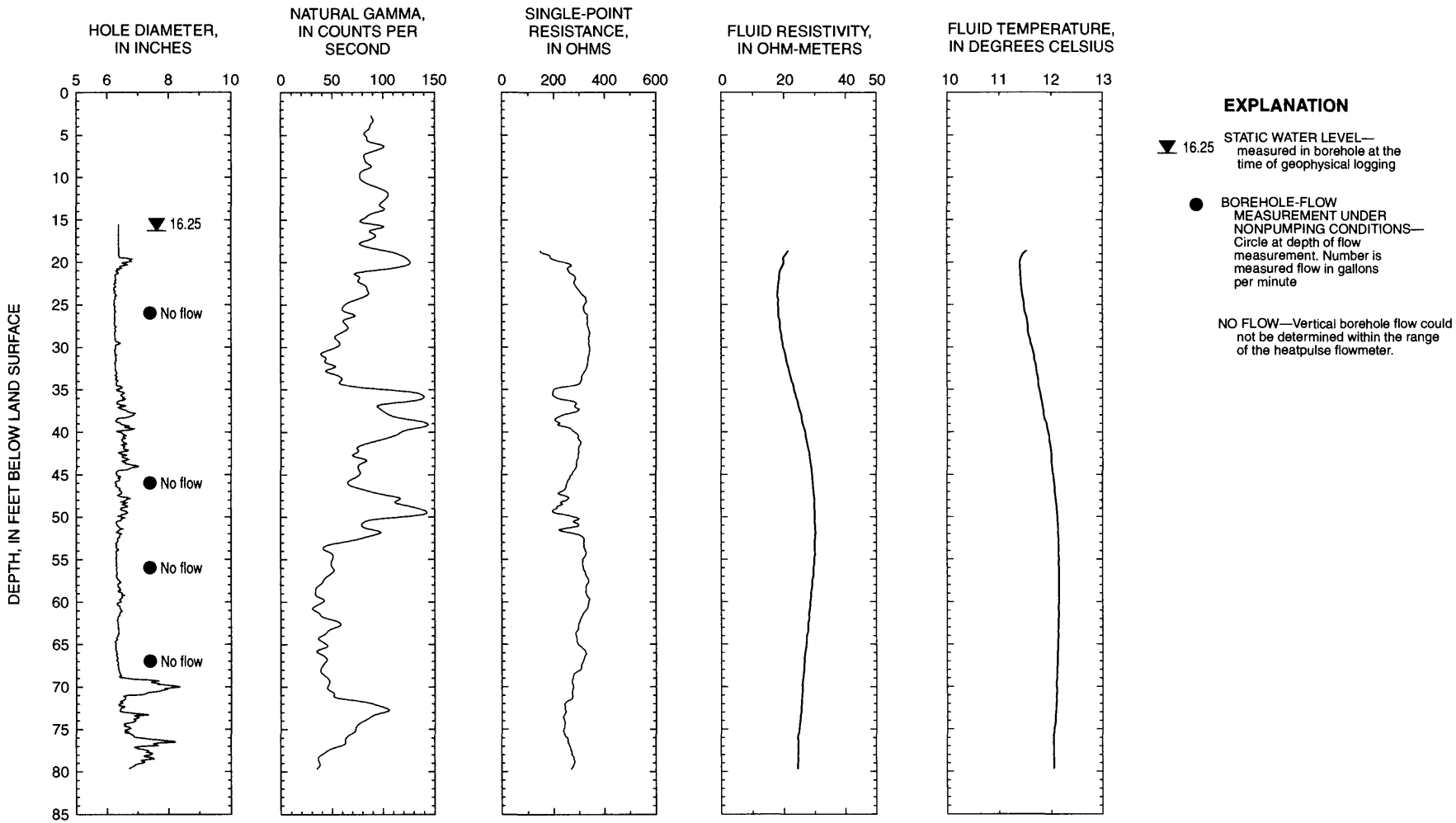


**Figure 11.** Borehole geophysical logs for borehole BK-2951 (HN-66-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## BK-2952 (HN-66-D)

The caliper log shows the total depth of the borehole is 150 ft, and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 12). The static water level was 15.58 ft bls at the time of logging. The caliper log shows major fractures at 37 and 85 ft bls plus numerous minor fractures throughout the open-hole interval. The natural-gamma log shows rock units with elevated gamma counts (probably shale or siltstone units) at 33, 36, and 48 ft bls that correlate with the natural-gamma logs of BK-2950 and BK-2951 and were used to determine local strike and dip (fig. 10). The caliper, natural-gamma, and single-point resistance logs show that the major fractures, and many of the minor fractures, occur at lithologic changes. The fluid-resistivity and fluid-temperature logs show changes in slope at 32 and 125 ft bls that correlate to fractures shown on the caliper log and indicate water-bearing fractures. Under nonpumping conditions, the heatpulse flowmeter measured downward movement of water at 40, 57, 69, 102, and 118 ft bls, and no flow at 138 ft bls (table 8). The geophysical logs and the heatpulse-flowmeter measurements indicate water enters the borehole through fractures at 20 to 37 ft bls, moves downward, and exits the borehole through a fracture at 125 ft bls. A screen and sand pack were placed at 110-125.5 ft bls to include the water-receiving fracture at 125 ft bls (Don Whalen, Tetra Tech NUS Inc., written commun., 1998).

***Table 5.*** *Summary of heatpulse-flowmeter measurements for borehole BK-2952 (HN-66-D) at the former Naval Air Warfare Center, Bucks County, Pennsylvania*

[--, not applicable]

| Depth (feet below land surface) | Flow rate under nonpumping conditions (gallons per minute) | Flow direction under nonpumping conditions |
|---|---|---|
| 40 | 1.3 | Down |
| 57 | 1.3 | Down |
| 69 | 1.1 | Down |
| 102 | 1.1 | Down |
| 118 | 1.1 | Down |
| 138 | No flow | -- |

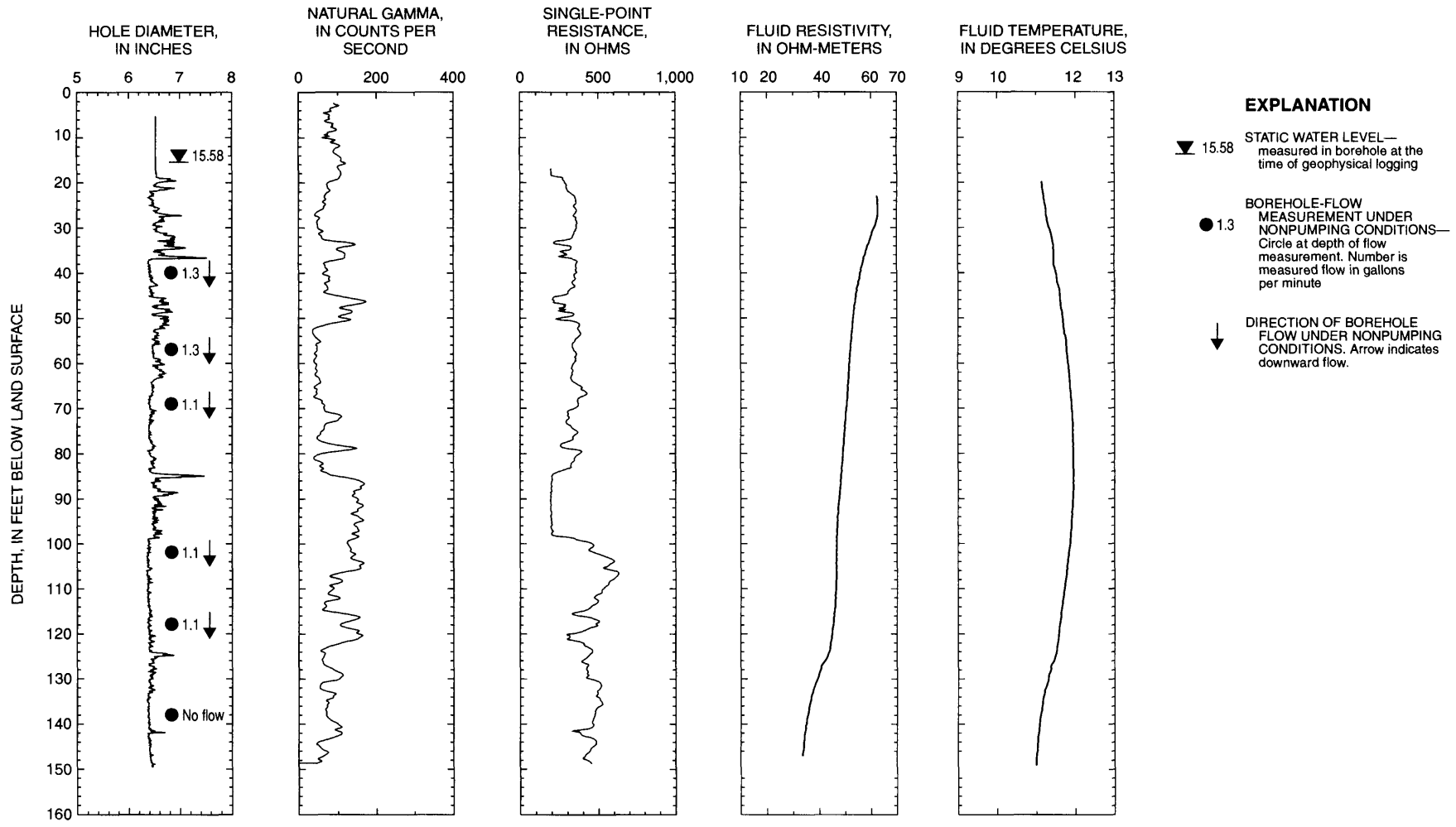


**Figure 12.** Borehole geophysical logs and direction of nonpumping flow within borehole BK-2952 (HN-66-D), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

## CONCLUSIONS

The NAWC site is underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. The middle arkose member crops out at the site. This unit consists of very fine- to medium-grained arkosic red sandstone interbedded with red shale, siltstone, and mudstone. Generally, the shale, siltstone, and mudstone units show the most fractures and subsequently more water-producing and water-receiving zones. Water-producing and water-receiving zones and intervals of vertical borehole flow were identified by the use of geophysical logs, heatpulse-flowmeter measurements, video surveys, and driller's logs. This enabled well screens to be placed at selected water-producing or water-receiving intervals so that ground water could be sampled.

Natural-gamma logs from boreholes BK-2950, BK-2951, and BK-2952 adjacent to Area A were correlated to determine a local strike and dip of N. 78° E., 10° NW. Vertical borehole flow in these wells, if detected, was downward and ranged from 0.1 to 1.3 gal/min. In Area B, if vertical borehole flow was detected it was downward and ranged from 0.2 to 1.5 gal/min, except for BK-2947 where upward and downward flow were measured within the borehole.

The video surveys show most boreholes have several horizontal and vertical fractures that generally decrease in frequency with depth. The vertical movement of water in boreholes BK-2946, BK-2947, and BK-2948 in Area B and BK-2950 and BK-2952 adjacent to Area A indicates they penetrate more than one water-bearing zone with differing hydraulic heads.

## REFERENCES CITED


Conger, R.W., 1996, Borehole geophysical logging for water-resources investigation in Pennsylvania: U.S. Geological Survey Fact Sheet 218-95, 2 p.

Halliburton NUS Environmental Corporation, 1992, Phase II Remedial Investigation Report for Naval Air Warfare Center, Warminster, Pennsylvania: Wayne, Pa.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E2, 150 p.

Rima, D.R., Meisler, Harold, and Longwill, Stanley, 1962, Geology and hydrology of the Stockton Formation in southeastern Pennsylvania: Pennsylvania Geology Survey, 4th ser., Water Resources Report 14, 111 p., 4 pl.

Sloto, R.A., Macchiaroli, Paola, and Conger, R.W., 1995, Geohydrology and vertical distribution of volatile organic compounds in ground water, Fischer and Porter Company Superfund Site, Warminster, Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 95-4220, 137 p.

Williams, J.H., and Conger, R.W., 1990, Preliminary delineation of contaminated water-bearing fractures intersected by open-hole bedrock wells: Groundwater Monitoring Review, Fall 1990, p. 118-126.