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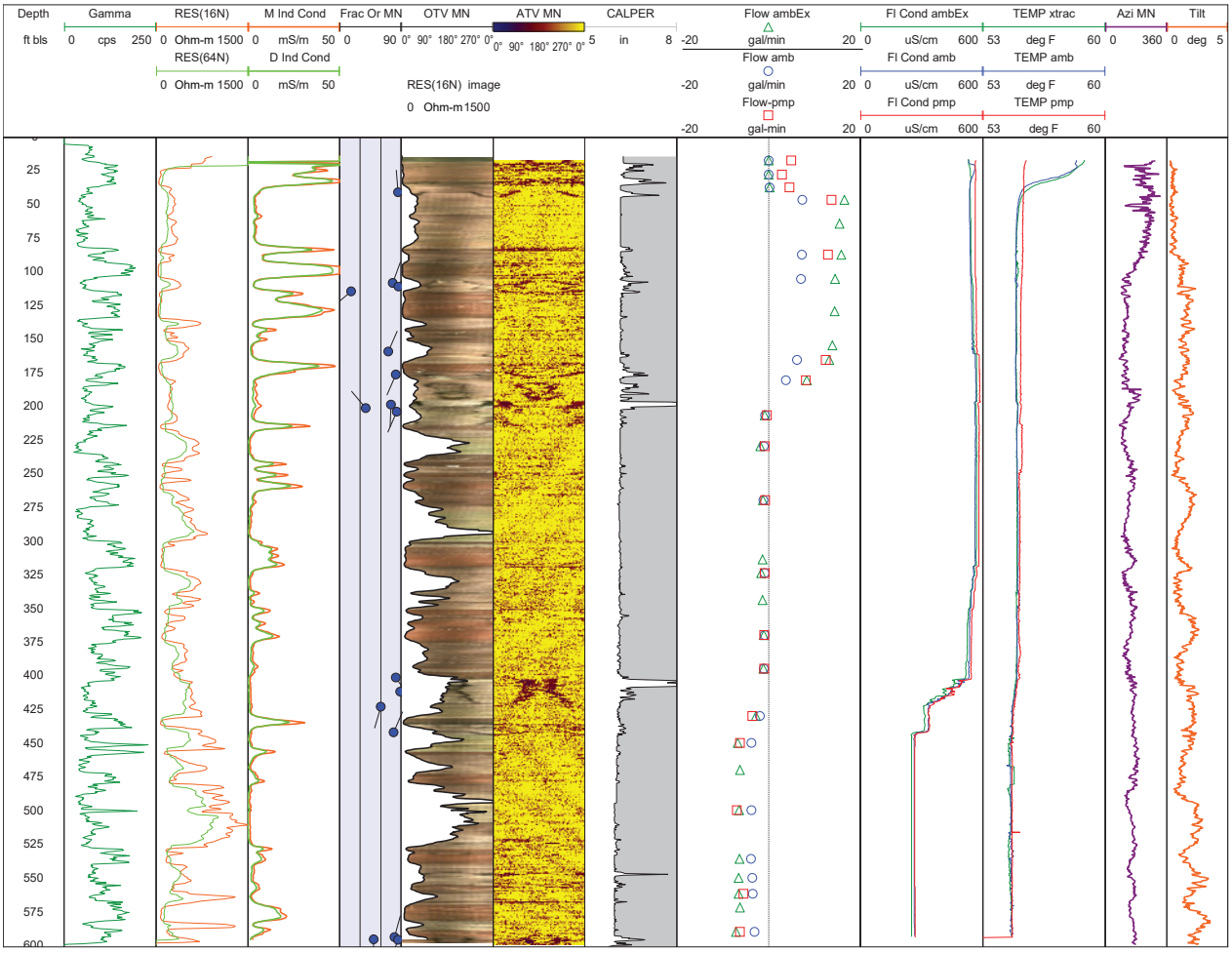
Geophysical and Video Logs of Selected Wells at and near the Former Naval Air Warfare Center Warminster, Bucks County, Pennsylvania, 2017–19



Open-File Report 2021–1025

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

Cover: Geophysical logs collected by the U.S. Geological Survey in well BK-3063 (Navy well HN-116), Warminster Township, Bucks County, Pennsylvania, May 24–25, 2018.

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By Lisa A. Senior, J. Alton Anderson, and Philip H. Bird

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Numerous U.S. Geological Survey colleagues provided assistance to the project, including Dennis W. Risser for assistance in geophysical log archiving, and Mark Kozar and John Williams for colleague technical reviews.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Specific capacity	
gallon per minute per foot ([gal/min]/ft)	0.2070	liter per second per meter ([L/s]/m)

System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	zArea	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
liter per second (L/s)	15.85	gallon per minute (gal/min)
	Specific capacity	
liter per second per meter ([L/s]/m)	4.831	gallon per minute per foot ([gal/min]/ft)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L), which are equivalent to parts per million (ppm), parts per billion (ppb), and parts per trillion (ppt), respectively.

Selected Abbreviations

ANG	Air National Guard
ATV	acoustic televiewer
DOD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
HAGS	Horsham Air Guard Station
LHA	Lifetime Health Advisory
NAD 83	North American Datum of 1983
NASJRB	(former) Naval Air Station Joint Reserve Base
NAVD 88	North American Vertical Datum of 1988
Navy	U.S. Navy
NAWC	(former) Naval Air Warfare Center
NBCMA	Northampton Bucks County Municipal Authority
NGVD 29	National Geodetic Vertical Datum of 1929
OTV	optical televiewer
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PHA	provisional health advisory
UCMR3	Third Unregulated Contaminant Monitoring Rule
USGS	U.S. Geological Survey
VOC	volatile organic compounds
WMA	Warminster Municipal Authority
WTWSA	Warwick Township and Sewer Authority

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Abstract

The U.S. Geological Survey (USGS) collected borehole geophysical and video logs in 17 open-hole wells in Northampton, Warminster, and Warwick Townships, Bucks County, Pennsylvania during 2017–19 to support detailed groundwater investigations at and near the former Naval Air Warfare Center (NAWC) Warminster, where groundwater contamination with per- and polyfluoroalkyl substances (PFAS) had become a concern since 2014. The area is underlain by the Triassic Stockton Formation, which forms a fractured-sedimentary-rock aquifer used for private, industrial, and public drinking-water supply. The geophysical and video logs were used to characterize the boreholes and identify potential water-bearing fractures for subsequent detailed investigations. Of the 17 wells that were logged, subsequent investigations were conducted by USGS in 15 wells and included hydraulic tests of discrete water-bearing zones using a straddle-packer system in 13 wells and depth-discrete point sampling in 2 wells. These 15 wells ranged in depth from about 210 to 604 feet (ft) below land surface (bls) and included six new 6-inch diameter wells drilled to initial depths of 600 ft bls on the former NAWC Warminster base property in 2018 and nine 8- to 12-inch diameter existing former production or unused test wells. Partial geophysical or video logs also were collected by USGS during 2018 in two other wells that were not included in subsequent detailed investigations.

Most wells had numerous water-bearing fractures or openings throughout the depth of the open boreholes. Most of these water-bearing features appeared to be openings parallel to bedding or high-angle fractures approximately orthogonal to bedding. Casing lengths ranged from about 19 to 93 ft bls. Depth to the ambient water level at the time of logging ranged from about 1.8 ft above land surface in a flowing well to about 55 ft bls. Measured borehole flow was predominantly downward in most of the deepest wells (greater than 400 ft), which were commonly located at the highest land-surface elevations, and contained inflow from fractures at relatively shallow depths and outflow through fractures near or below depths of 500 ft bls. Borehole flow was predominantly upward in most wells less than 400 ft in depth.

Introduction

Groundwater is a substantial source of public, domestic, and industrial water supply in areas underlain by the Stockton Formation, a fractured sandstone aquifer, in southern Montgomery and Bucks Counties, Pennsylvania, where two formerly active military bases are located. Both bases were active for at least 50 years from the 1940s until they were closed at the recommendation of the Base Realignment and Closure commission. The Naval Air Warfare Center (NAWC) Warminster (formerly the Naval Air Development Center, Johnsville) in Warminster and Northampton Townships, Bucks County (fig. 1) was active during 1944–96. Since 1996, all but about 4 acres of the former NAWC Warminster 824-acre property has been transferred from the U.S. Navy (Navy) to local municipalities, Bucks County, or private owners. About 3 miles (mi) west of NAWC Warminster, the former Naval Air Station Joint Reserve Base (NASJRB) Willow Grove in Horsham Township, Montgomery County, Pennsylvania was operated by the Navy from 1942 until September 2011, with a portion currently (2020) operated by the Pennsylvania Air National Guard (ANG) and designated Horsham Air Guard Station (HAGS) (fig. 1).

Previous investigations identified areas of groundwater contaminated by volatile organic compounds (VOCs) at both NAWC Warminster and NASJRB Willow Grove, which subsequently were addressed by remediation (Battelle, 2016). Ongoing remediation for VOCs at present (2020) includes bioremediation at NASJRB Willow Grove (Naval Facilities Engineering Command, 2018) and pump-and-treat technology at NAWC Warminster (Battelle, 2016).

In summer 2014, through sampling of production wells under the third Unregulated Contaminant Monitoring Rule (UCMR3; U.S. Environmental Protection Agency, 2012), groundwater at and near the former NAWC Warminster and former NASJRB Willow Grove was found to be contaminated with perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), compounds that may pose a risk to human health if present above certain concentrations in drinking water. In 2014, the U.S. Environmental Protection Agency (EPA) provisional health advisory (PHA) levels were 0.2

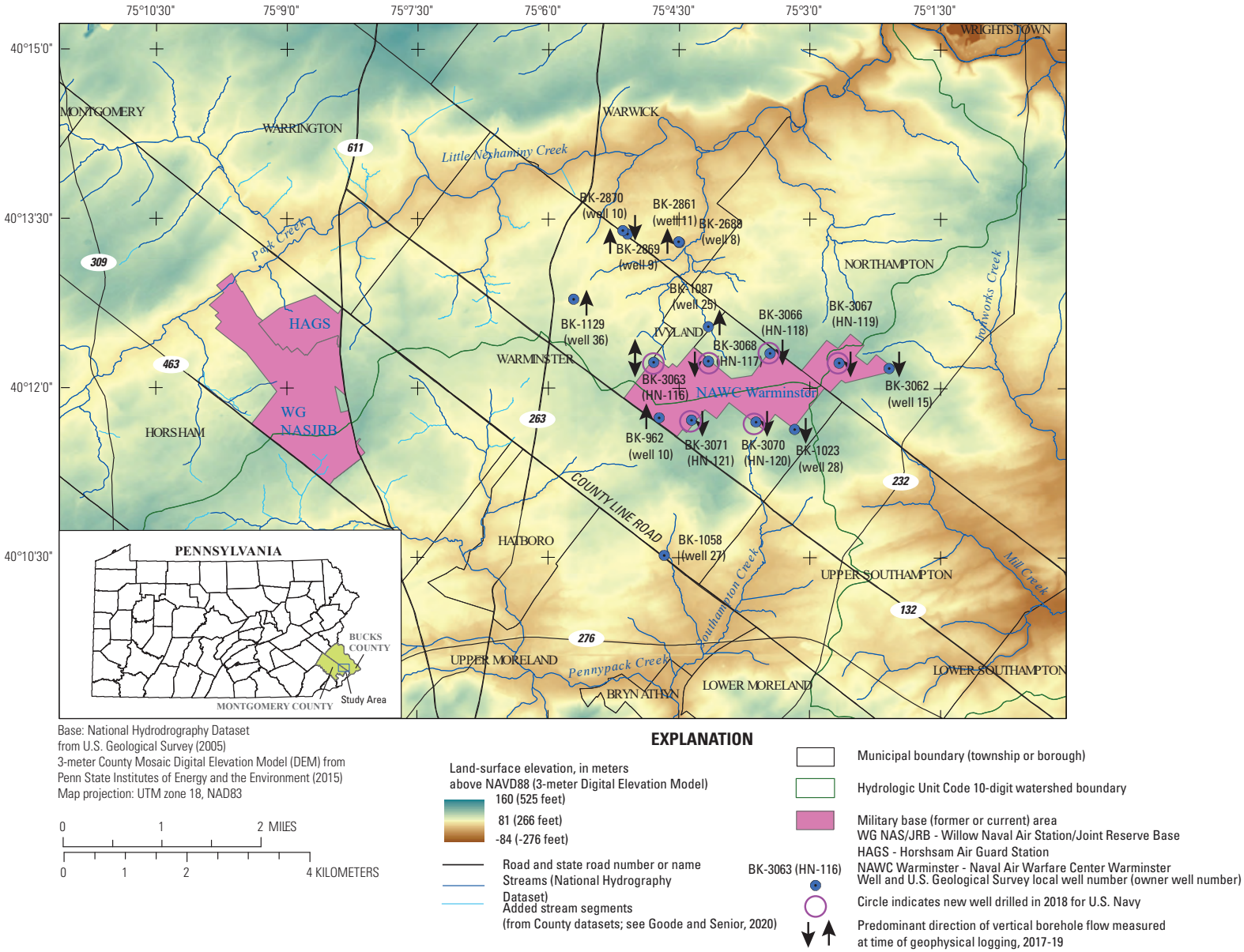


Figure 1. Location of former Naval Air Warfare Center (NAWC) Warminster, former Naval Air Station Joint Reserve Base (NASJRB) Willow Grove, and active Horsham Air Guard Station (HAGS), land-surface elevations, streams, and location of wells with geophysical and video logs collected by U.S. Geological Survey near NAWC Warminster during 2017–19, Bucks and Montgomery Counties, Pennsylvania.

micrograms per liter (µg/L) for PFOS and 0.4 ug/L for PFOA in drinking water (U.S. Environmental Protection Agency, 2014). PFOS and PFOA are part of a group of compounds more broadly designated per- and polyfluoroalkyl substances (PFAS). Five production wells in Horsham and Warrington Townships were shut down in 2014 after UCMR3 sampling showed that produced water had some PFAS concentrations that exceeded the PHA levels. In May 2016, the EPA revised the PFOS and PFOA health advisories to lower concentration levels and established a Lifetime Health Advisory (LHA) not to exceed 70 nanograms per liter (ng/L) or 70 parts per trillion (ppt; equivalent to 0.07 µg/L) for combined concentrations of PFOS and PFOA (U.S. Environmental Protection Agency, 2016). Groundwater from production or private domestic wells was still a primary source of water in the area in 2014, but after May 2016, additional (at least 13) production wells were shut down in Horsham, Warrington, and Warminster Townships because of health concerns related to the presence of PFOS and PFOA in concentrations above health advisory levels. Since 2016, some supply wells have remained active, or resumed active status, with treatment that was subsequently installed to remove PFOS and PFOA from pumped groundwater, as needed.

When PFOS and PFOA were identified in samples from production wells in 2014, production wells on and near the former NAWC Warminster and NASJRB Willow Grove were the primary source of public water supply for communities within and surrounding these facilities and private domestic wells supplied many nearby residences. Potential sources of PFOS and PFOA in the area include fire-suppressant compounds (fluorinated surfactants in aqueous film forming foams used on and (or) near these facilities when the bases were operating (TetraTech, 2014; Resolution Consultants, 2019).

After PFAS were discovered in the area surrounding the bases, the Navy and the ANG offered nearby residences with private domestic wells that yielded water with PFOS and PFOA concentrations greater than the LHA to be connected to public drinking water supplies. The Navy and ANG also have established a program to monitor PFOS and PFOA concentrations in water from nearby residential wells that have not been connected to public supply; these monitored wells include those for which combined PFOS plus PFOA concentrations were less than the LHA of 0.07 µg/L but higher than 0.04 µg/L (U.S. Navy, 2016; Battelle, 2017).

Management and mitigation of groundwater that is contaminated with PFOS and PFOA on and near the former NAWC Warminster and the nearby NASJRB Willow Grove requires assessment of the sources and distribution of contaminant occurrence. In 2014, the Navy and its contractors began sampling soils, streams, and groundwater through preliminary remedial investigations. The Navy also requested technical support from the USGS in conducting geophysical logging and aquifer-interval testing of wells as part of investigations to characterize PFAS distribution in groundwater.

Previous Investigations

Prior to 2014, in studies related to remedial investigations by the Navy and their contractors at or near the former NAWC Warminster base, the U.S. Geological Survey (USGS) collected geophysical logs (Conger, 1998; Conger and Bird, 1999; Sloto, 2008), collected geophysical logs and conducted aquifer-interval-isolation (packer) testing of wells (Sloto, 1997, 1998), conducted hydrologic investigations (Sloto and others, 1998), and prepared a water-table map (Sloto and Grazul, 1995a). Sloto and others (1995b) and Sloto (2010) investigated groundwater flow and VOC contaminant migration at a Superfund site near NAWC Warminster. The USGS also conducted townshipwide hydrogeologic studies for Warminster Township (Sloto and Davis, 1982) and Warwick Township (Bird, 1998) and prepared a water-table map for Warwick Township (Rowland, 1997). Sloto and others (1996) described the hydrology of the Stockton Formation in Hatboro Borough and Warminster Township.

Since 2014 when PFAS was detected in groundwater at or near the former bases, remedial investigations by the Navy, ANG, and their contractors have been conducted to describe PFAS concentrations in soils, groundwater, and streams at and near the former NASJRB Willow Grove, active Horsham Air Guard, and former NAWC Warminster (Battelle, 2016; Leidos, 2018; Resolution Consultants, 2019). The USGS also developed a preliminary regional groundwater flow model that simulated path lines from possible PFAS source areas at the Warminster and Willow Grove bases (Goode and Senior, 2020).

Additional investigations have been conducted by local water suppliers, by regulatory agencies, and by parties responsible for contamination of groundwater in the area. Many of these investigations are described in documents available in public record depositories. Specific investigations that provided data for this study are cited throughout this report.

Purpose and Scope

This report documents the complete geophysical and video log data collected by the USGS in 15 wells identified for further investigation from December 2017 through October 2019, including 6 new wells drilled by the Navy in 2018 and 9 existing wells on or near the former NAWC Warminster base. Partial geophysical or video logs were also collected in two other wells by the USGS during 2018. The geophysical data documented in this report include a summary of the type of logs collected at each of the 15 boreholes under ambient and (or) pumping conditions; and for each well, directions of vertical borehole flow under ambient and (or) pumping conditions and identification of probable or possible water-bearing fractures. Possible water-bearing fractures, as determined from partial logs, for the two other wells also are briefly described. The geophysical and video log data for the 15 boreholes were collected and interpreted to support

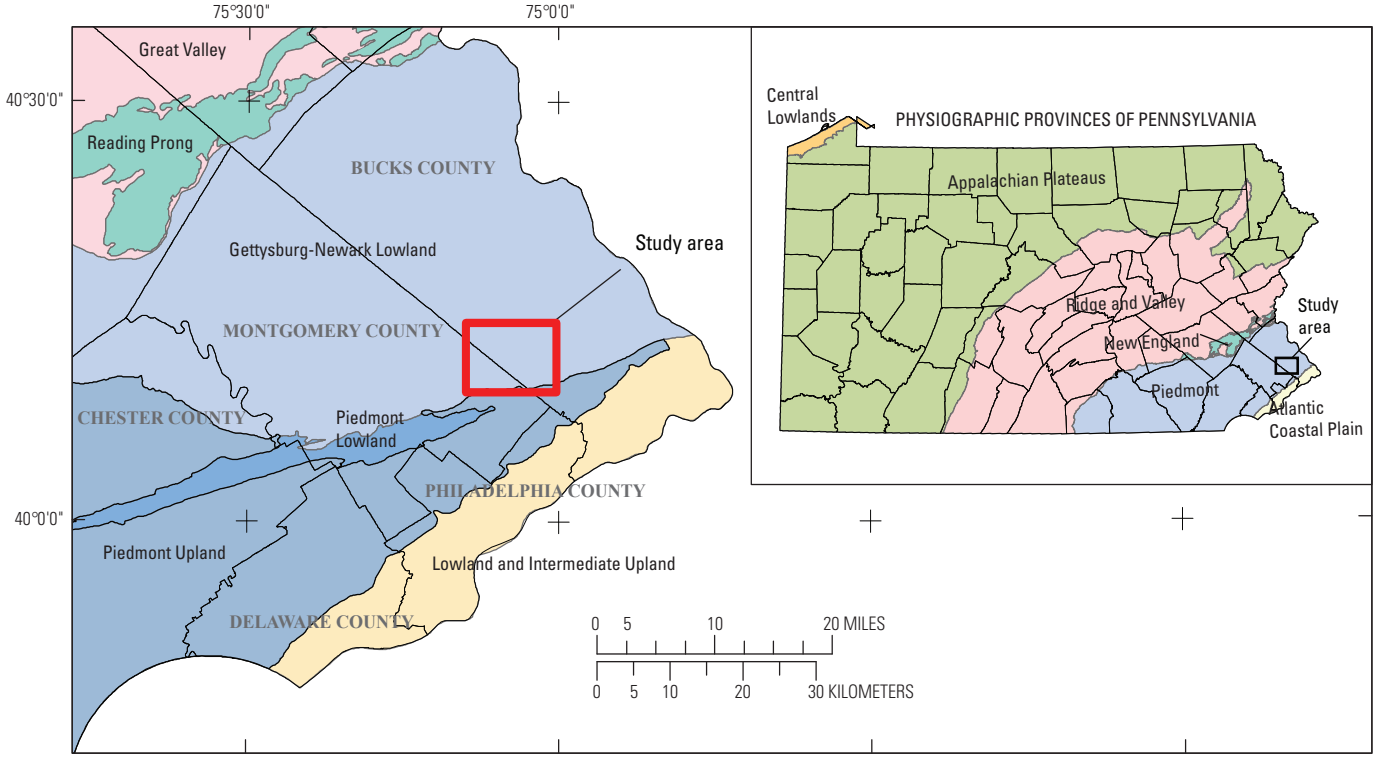
selection of discrete intervals in 13 boreholes to be tested using either straddle packers for assessing hydraulic properties and PFAS concentrations in water from those intervals or, in two wells, selection of depths for collection of water samples at discrete points for PFAS concentrations.

Hydrogeologic Setting

The study area lies within the Piedmont physiographic province, with most of the study area in the Gettysburg-Newark Lowlands Section, bounded on the south by Piedmont Upland and Lowland Sections (fig. 2), and characterized by rolling topography and shallow valleys (Sevon, 2000). The Gettysburg-Newark Lowlands are underlain by sedimentary rocks of the Newark Basin, which were deposited in a rift basin during the Triassic (about 252 to 201 million years ago) and subsequently buried, compacted, and faulted, and in places, intruded by diabase (Lyttle and Epstein, 1987). Sedimentary formations in the Newark Basin, in order of decreasing age, are the Stockton Formation, Lockatong Formation, and Brunswick Group. The Piedmont Upland and Lowland Sections are underlain by Paleozoic metasedimentary rocks and older (Proterozoic) metamorphic rocks.

The central part of the study area is underlain by the Triassic Stockton Formation (fig. 3), which consists of gray to reddish brown sandstones and conglomerates, with siltstone and shale. The Stockton Formation was deposited unconformably on folded and faulted metamorphic rocks of probable lower Paleozoic and Proterozoic age (Berg and others, 1980; Lyttle and Epstein, 1987), which crop out along the southern border of the Stockton Formation and include carbonates, quartzites, schists, and gneisses (fig. 3). The Stockton Formation has been divided into three members in Montgomery County that are present in a generally fining-upward sequence: a lower arkose member with the coarsest deposits (conglomerates and sandstones), a middle arkose member consisting of fine- to medium-grained sandstones, and the upper shale member containing the finest deposits (shales, siltstones, and fine-grained sandstones) (Rima and others, 1962). Locally, lithologies may interfinger in the Stockton Formation and beds may pinch out (Rima and others, 1962) or be laterally discontinuous, likely a result of the fluvial or deltaic origin of some deposits within the Stockton Formation (Turner-Peterson and Smoot, 1985).

The Lockatong Formation, which overlies and is conformable with the Stockton Formation, consists of fine-grained lacustrine deposits (siltstones and shales) and is relatively resistant to erosion, forming ridges that rise above flat or rolling topography underlain by the Stockton Formation to the south and rocks of the Brunswick Group (shales, siltstones, and fine-grained sandstones) to the north. (fig. 3). The Brunswick Group overlies the Lockatong Formation.



From Sevon (2000); Pennsylvania Bureau of Topographic and Geologic Survey (2008a, b)

Figure 2. Physiographic provinces of Pennsylvania (inset) and sections in study area in southeastern Pennsylvania.

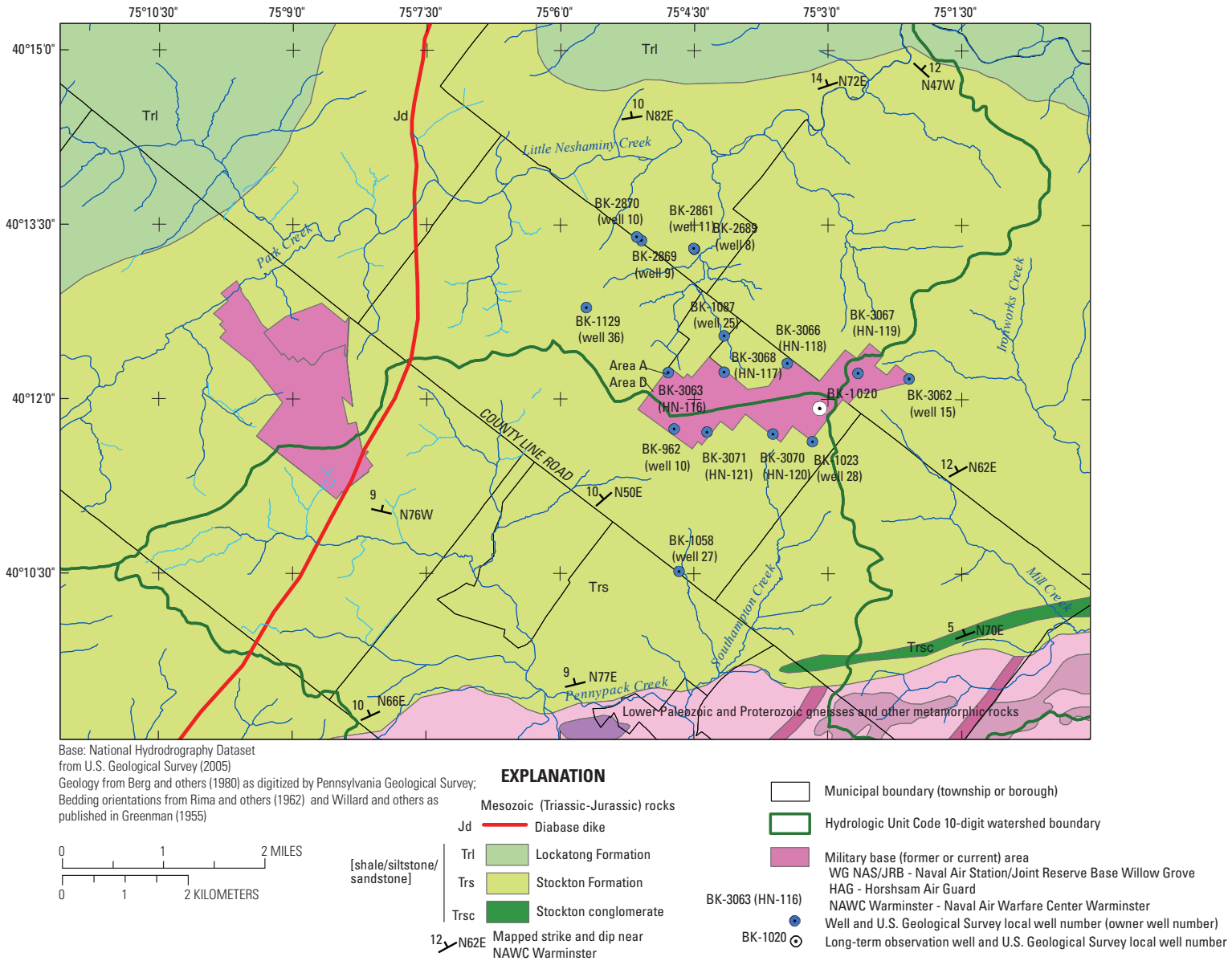


Figure 3. Mapped geology, including bedrock geologic units, that underlie the study area and bedding orientations in the Stockton Formation, as well as streams, location of wells with geophysical and video logs collected by U.S. Geological Survey near former Naval Air Warfare Center Warminster during 2017–19, and selected U.S. Geological Survey observation wells, Bucks and Montgomery Counties, Pennsylvania. Geology from Berg and others (1980); bedding orientations from Rima and others (1962) and Willard and others and published in Greenman (1955).

Bedding within the Stockton Formation in southeastern Montgomery and Bucks Counties generally strikes northeast or east-northeast and tilts to the northwest, dipping about 5 to 18 degrees to the northwest or north-northwest in this region, with an average dip of about 12 degrees (Rima and others, 1962). Although bedding in the Stockton Formation may be laterally discontinuous in places owing to interbedding of lithologies, the beds have been mapped as oriented with the overall general northwest-dipping structure. Close to NAWC Warminster, the mapped strike of bedding in the Stockton Formation is about N. 50° E. to N. 62° E., and ranges from about N. 66° E. to N. 77° E. south of NAWC Warminster close to the contact with older Paleozoic rocks and from about N. 72° E. to N. 82° E. north of NAWC Warminster near Little Neshaminy Creek (fig. 3). Northwest trending strikes have been mapped in a few locations in the area, suggesting possible displacement by faults. Other similar bedding orientations of the Stockton Formation near the former NAWC Warminster are reported as having an approximate strike of N. 65° E. and dip of 9° NW. (Sloto and others, 1995b) and strike of N. 71° E. and dip of 5–8° NW. (Sloto and others, 1998). Generally, other Triassic sedimentary rocks in the study area, in addition to the Stockton Formation, also strike northeast and dip northwest, except where interrupted by faulting (Schlische, 1992). Both major and minor faults are present in the area. A major regional fault (Chalfont Fault) is about 3 mi (5 kilometers [km]) north of NAWC Warminster and NASJRB Willow Grove, and a zone of intense normal faulting south of the Chalfont Fault has been mapped about 1 mi (1.5 km) west of the NASJRB Willow Grove (Schlische, 1992). A north-south trending, steeply dipping diabase dike is mapped (fig. 3) as intruding the Stockton Formation on the eastern border of the former NASJRB Willow Grove (Rima and others, 1962; Lyttle and Epstein, 1987). Other smaller dikes may be present, as indicated in mapping by Lyttle and Epstein (1987) that shows a minor dike about 1 mi or less west of the north-south trending dike on the eastern border of NASJRB Willow Grove.

Depth to competent bedrock generally is about 40 feet (ft) or less but varies depending on lithology and topographic setting (Low and others, 2002). The competent bedrock is overlain by weathered bedrock (saprolite) and soil formed in situ and, in a few places in the southern part of the study area, by thin deposits of Tertiary and Cretaceous age unconsolidated sediments.

The Triassic sedimentary geologic units that underlie the study area form fractured-rock aquifers. Recharge to the fractured-rock aquifers occurs through the overlying soil and weathered rock, and groundwater flows through a network of fractures both parallel and orthogonal to bedding, commonly resulting in apparent preferential flow and permeability in the strike direction (parallel to bedding). Lateral and vertical changes in lithology in the Stockton Formation affect aquifer water-bearing properties, as finer-grained deposits (shales, siltstones) commonly have lower permeability than coarser-grained deposits (sandstones and conglomerates) in the formation (Rima and others, 1962). The hydrogeology of the Stockton Formation and other geologic units of the study area has been described in more detail by Greenman (1955), Rima and others (1962), Longwill and Wood (1965), and Newport (1971). Low and others (2002) provide an overview of geohydrologic properties of the Stockton and other formations from well records and previous investigations in southeastern Pennsylvania.

Although precipitation commonly is distributed relatively evenly throughout the year, groundwater recharge varies seasonally, with the lowest recharge rates occurring when evapotranspiration rates are highest in late summer to fall, and the highest recharge rates occurring in winter to spring, as reflected in annual fluctuations in water levels. For example, in the USGS observation well BK-1020, located in the study area on NAWC Warminster (fig. 3), long-term (1975–2019) daily mean depth to water is greatest in the fall months and least in spring months (Goode and Senior, 2020), reflecting relatively lower and higher seasonal net recharge rates, respectively. Groundwater discharges locally to streams or to pumping wells. Streams draining the area near NAWC Warminster include Little Neshaminy Creek, Neshaminy Creek, Pennypack Creek, and their tributaries (figs. 1 and 3). Both the former Warminster and Willow Grove bases lie on high ground (fig. 1), which forms topographic divides between stream basins.

Methods

Geophysical and video logs were collected using the methods described below from boreholes at or near former NAWC Warminster from November 2017 through October 2019.

Geophysical Logs

Geophysical logs were collected by the USGS using a truck-mounted drawworks that holds approximately 2,000 ft of armored four-conductor cable. Each downhole tool (probe) is attached to the cable head and run down the well at the prescribed speed. Most tools collect data on multiple characteristics; for example, the fluid-conductivity probe collects fluid conductivity, temperature, and gamma logs simultaneously. Data-collection speeds (rates of descent or ascent) range from 20 feet per minute (ft/min) for most logging tools to about 5 ft/min for the optical and acoustic logging tools. Data from each tool are continually recorded on a laptop computer and are viewed in real time in the field.

The types of geophysical logs collected from the boreholes include caliper, natural gamma, electromagnetic-induction, electrical resistance, borehole-image, deviation, fluid-property (temperature and conductivity), and flowmeter logs (table 1). In addition, borehole video logs were collected in the boreholes. The caliper logs were collected by mechanical and acoustic methods. Borehole-image logs were collected

Table 1. Description of geophysical logs, reporting units, and abbreviations for logs collected by U.S. Geological Survey at and near Naval Air Warfare Center Warminster, Bucks County, Pennsylvania, 2017–19.

[EM, electromagnetic; N, normal; --, no data or none]

Type of log	Abbreviation for log	Units	Abbreviation for units
Depth	Depth	Feet below land surface	ft bls
Caliper	Caliper	Inches	in
Acoustic caliper	Acou Cal	Inches	in
Natural gamma	Gamma	Counts per second	cps
Medium EM-induction conductivity	M Ind Cond	MilliSiemens per meter	mS/m
Deep EM-induction conductivity	D Ind Cond	MilliSiemens per meter	mS/m
Medium EM-induction resistivity	M Ind Res	Ohm-meter	Ohm-m
Deep EM-induction resistivity	D Ind Res	Ohm-meter	Ohm-m
Single-channel EM-induction conductivity	COND	MilliSiemens per meter	mS/m
Single-channel EM-induction resistivity	RES	Ohm-meter	Ohm-m
Short normal (16 N) resistivity	RES(16N)	Ohm-meter	Ohm-m
Long normal (64 N) resistivity	RES(64N)	Ohm-meter	Ohm-m
Single-point resistance	RES(SP)	Ohms	Ohm
Tilt (from acoustic televiewer log)	Tilt ATV	Degrees from vertical	deg
Azimuth	Azi	Degrees from magnetic north	MN
Acoustic televiewer	ATV	Image displayed relative to magnetic north	--
Optical televiewer	OTV	Image displayed relative to magnetic north	--
Fracture orientation	Frac Or	Degrees from magnetic north	MN
Fluid temperature, ambient	TEMP amb	Degrees Fahrenheit	deg F
Fluid conductivity, ambient	Fl Cond amb	MicroSiemens per centimeter	µS/cm
Fluid resistivity, ambient	RES (FL) amb	Ohm-meter	Ohm-m
EM flowmeter, ambient	EMFM amb or Flow amb	Gallons per minute	gal/min
Heat-pulse flowmeter, ambient	HPFM amb	Gallons per minute	gal/min
Fluid temperature, pumping	TEMP pmp	Degrees Fahrenheit	deg F
Fluid conductivity, pumping	Fl Cond pmp	MicroSiemens per centimeter	µS/cm
Fluid resistivity, pumping	RES(FL) pmp	Ohm-meter	Ohm-m
EM flowmeter, pumping	EMFM pmp or Flow pmp	Gallons per minute	gal/min
Heat-pulse flowmeter, pumping	HPFM pmp	Gallons per minute	gal/min

with an optical televiewer (OTV) and an acoustic televiewer (ATV). Borehole-deviation logs were collected with three-axis fluxgate magnetometers and vertical inclinometers that are incorporated into the ATV and OTV probes. Flowmeter logs were collected by heat-pulse or electromagnetic methods. Fluid and flowmeter logs commonly were collected under both ambient and pumping conditions to help identify water-bearing fractures. For measurements of flow and fluid logs under pumping conditions, water in the well commonly was pumped at a constant rate of about 2 gallons per minute (gal/min) using a pump placed a few feet below the ambient water level in the well. Applications of geophysical logs in groundwater studies are described by Keys (1990) and Williams and Lane (1998). The geophysical logs used in this investigation are described briefly below. Technical descriptions of logs are from Keys (1990), Anderson and others (2009), and Reynolds and others (2015).

Mechanical and acoustic caliper logs record the diameter of the borehole. Changes in borehole diameter are related to drilling and construction procedures; lithologic contacts and competency of lithologic units; and the presence of various openings including fractures, faults, bedding-plane partings, joints, and solution features. Mechanical-caliper logs were collected with a spring-loaded, three-arm averaging tool;

acoustic-caliper logs were calculated from acoustic travel times collected with the ATV tool. Caliper logs were used in the delineation of fractures, solution features, and lithology, and to confirm well and casing depths and diameters.

Gamma logs measure the natural gamma radiation of the rock units penetrated by the borehole. Major gamma emitters are uranium, thorium, and daughter products of potassium-40. Sedimentary rocks with relatively high gamma radiation when compared to other lithologic units commonly include shales, mudstones, and other argillaceous units. Igneous and metamorphic rocks rich in potassium feldspar typically are also high gamma emitters. The gamma tool has a vertical resolution of 1 to 2 ft. Gamma logs collected in open holes and through steel casing may be used for lithologic identification and stratigraphic correlation.

Electromagnetic-induction conductivity and resistivity logs measure the electrical conductivity of bedrock and water surrounding the borehole. In this study, the logs were collected at a frequency of 40 kilohertz. The electromagnetic (EM)-induction tool has a vertical resolution of about 2 ft and primarily samples volumes to about 18 inches (in.) radially from the well. It generally is not affected by the electrical properties of the wellbore fluid for diameters less than 8 in. The volume of investigation of an induction probe is a function of coil spacing, with larger spacings measuring larger distances from the borehole. The EM-induction logs were collected using either a dual coil configuration (medium and deep depths of investigation) or single coil configuration (medium depth of investigation). Electrical conductivity measurements are affected by the argillaceous content and porosity of the rocks and by the concentration of dissolved solids in the pore fluid. Electromagnetic-induction conductivity logs are most effective in formations with high electrical conductivities (low resistivities), such as shales and mudstones. The inverse of EM-induction conductivity is EM-induction resistivity. The EM-induction resistivity logs generally are similar to normal-resistivity and single-point resistance logs in wells with fresh water and can be used as indicators of lithology. Resistivity is greater for sandstones than for shales under these conditions.

Normal-resistivity logs measure the electrical resistivity of the rocks and water surrounding the borehole. Electrical resistivity measurements made using variously spaced electrodes commonly consist of short-normal (16 in. spacing between electrodes) and long-normal (64 in. spacing between electrodes) resistivities, or near and far resistivities, respectively, that have two different volumes of investigation. Electrical resistivity measurements are similarly affected by the argillaceous content and porosity of the rocks and by the dissolved-solids concentration of the pore fluid (Archie, 1942). However, unlike the EM-induction logs, normal-resistivity logs are most effective in formations having high electrical resistivities (low conductivities). A lower resistivity corresponds to higher porosity and (or) smaller grain size because the surface area associated with fine particles promotes the transmission of electric current (Biella and others, 1983; Kwader, 1985). Due to the smaller area of investigation sampled by the near measurement, short-normal logs are more affected by the borehole fluid than are the far measurements. Correspondingly, the long-normal logs have a greater volume of investigation beyond the borehole and are proportionally less influenced by the borehole fluid than is the near measurement; however, their vertical resolution is less than that of the short-normal logs.

Single-point resistance logs measure the resistance, in ohms, between an electrode in the well and an electrode at the land surface. Single point logs are useful qualitative indicators of lithology. However, single-point-resistance logs are more affected by the borehole fluid than induction and normal-resistivity logs and cannot be related quantitatively to porosity or to the salinity of water in those pore spaces because no provision exists for determining the length or cross-sectional area of the travel path of the current between electrodes.

Acoustic televiewer (ATV) logs record a 360-degree magnetically oriented acoustic image of the borehole wall (Williams and Johnson, 2004). ATV logs can be collected in clear or turbid water. The ATV provides high-resolution information on the location and orientation (strike and dip) of fractures or bedding within a borehole, such that structural features with widths greater than 0.02 ft can be identified. ATV logs are presented relative to magnetic north. For this study, ATV logs were used to identify locations of fractures and bedding-plane openings and to determine orientation of selected features identified as hydraulically active water-bearing openings based on interpretation of other geophysical logs. The orientations of the selected water-bearing fractures as determined from analysis of the ATV and (or) optical televiewer (OTV) logs are presented in tadpole plots of the fracture azimuth and dip amplitude oriented to magnetic north.

Optical televiewer (OTV) logs record a 360-degree oriented optical image of the wellbore wall. OTV logs can be collected above the water level and below the water level where the water is clear. Features with widths greater than 0.008 ft can be identified. OTV logs can be used to characterize bedding, lithology, fractures, and solution features (Williams and Johnson, 2004). OTV logs are presented relative to magnetic north. For this study, the OTV logs were used to help identify locations of fractures and bedding-plane openings and to determine the orientation of selected features identified as hydraulically active water-bearing openings based on interpretation of other geophysical logs and in conjunction with ATV logs.

Deviation logs measure the inclination and direction of (deviation of) the well from vertical. Inclination generally is measured within ± 0.5 degree and direction within ± 2 degrees. Deviation direction is recorded relative to magnetic north. Borehole deviation plots can be corrected to account for magnetic declination and show geographic (true) north at 0 degrees. In wells that penetrate magnetite bearing zones, deviation direction can be affected by the secondary magnetic field generated by the ferrous minerals. Although magnetite has been identified as part of accessory heavy mineral suites in the Stockton Formation as described by D.B. McLaughlin

(Willard, 1959) and is associated with some diabase intrusion in the Newark Basin (Robinson, 1988), the magnitude of the possible effect on the deviation logs for this study is estimated to be small.

Fluid-temperature logs record the temperature of air and water in the wellbore. Temperature gradients that deviate from the geothermal gradient may indicate intervals of vertical flow within the borehole. Temperature logs were used to delineate possible changes in wellbore flow related to inflow or outflow and, thus, to help identify possible water-bearing fractures in the borehole.

Fluid-resistivity and conductivity logs record the electrical resistivity of water in the borehole. Fluid electrical resistivity is inversely related to the concentration of dissolved solids in borehole water. Fluid-conductivity logs are the inverse of fluid-resistivity logs. Fluid conductance is directly related to the concentration of dissolved solids in borehole water. Inflections or changes in the slope of fluid-resistivity (or fluid-conductivity) logs may indicate zones of inflow to, or outflow from, the borehole. Fluid-conductivity logs were used, in conjunction with fluid temperature logs, to delineate possible changes in wellbore flow and to identify possible water-bearing fractures in the borehole.

Flow logs record the direction and rate of vertical flow in the borehole. Vertical flow occurs in wells that penetrate two or more water-producing fracture zones with different hydraulic heads (water levels). Flow in the borehole is from zones of higher head to zones of lower head. An electromagnetic (EM) flowmeter with a flexible rubber diverter fitted to the borehole diameter (6 or 8 in.) and a measurement range of 0.05 to15 gal/min was used to measure flow in most boreholes. The EM flowmeter (Young and Pearson, 1995) measures fluid velocity, based on Faraday's Law, which states that the flow of an electrically conductive fluid through an induced magnetic field generates a voltage gradient that is proportional to its velocity. In four boreholes, a heat-pulse flowmeter with a flexible rubber diverter and a measurement range of 0.01 to 1.5 gal/min was used to measure flow in a stationary mode at various depths. The heat-pulse flow meter (Hess, 1982) measures the travel time of a thermal pulse between a set of upper and lower heat sensors (thermistors).

For the six boreholes greater than 8 in. in diameter, an 8-in. diverter (largest available with the equipment) was used in this investigation. Flow measured with the 8-in. diverter is less than actual flow in wells with diameters greater than 8 in. in diameter and may be considered semi-quantitative because some flow bypasses the diverter. Reported flow values generally reflect corrected field measurements to account for apparent differences between raw measurements and known flow values. The corrections were based on zero flow in casing under ambient conditions and known flow (as measured for discharge from an active pump in well) in casing under pumping conditions, when possible.

Flow logs and fluid-property (temperature and resistivity) logs were collected (when possible) under (1) steady-ambient (amb) conditions and (2) steady-pumping (pmp) conditions to provide a contrast of flow-rate gain or loss at discrete fracture zones, and thus can assist in identifying the presence and relative productivity of water-bearing fractures (Paillet, 2000, 2001). Pumping rates ranged from about 1 to 5 gal/min, but most commonly were about 2 gal/min, during collection of flow and fluid logs in wells logged for this study. Flow logs were primarily used to identify the presence of water-bearing features and were not analyzed to quantitatively determine transmissivity of water-bearing zones using methods described by Paillet (2000), partly because of the uncertainty associated with flow measurements in the large-diameter wells.

Video Logs

Borehole video logs record images of the borehole with a camera lens most commonly oriented as looking down the borehole. The depth of the borehole video log corresponds to the upper edge of the field of view. The video log is useful for describing the characteristics of the borehole construction, water visibility, lithology, fracture extent and general orientation for fractured-rock aquifers, and the presence of other features such as turbulence or cascading water. Field notes made during video logging summarize principal observations. Fractures described as horizontal are low-angle openings that may be parallel to bedding planes in the shallowly dipping sedimentary formations such as the Stockton Formation. Fractures described as vertical are high-angle openings that may be orthogonal to bedding or related to faulting.

Geophysical and Video Logs

Geophysical and video logs were collected during 2017–19 from 17 boreholes (figs. 1 and 3), including 15 wells identified for further investigation and 2 other wells (BK-1058 and BK-3069) (table 2 and 3). The most complete suite of geophysical and video logs (table 3) were collected in the 15 wells identified for subsequent investigation and which ranged from 201.5 to 604 ft in depth and 6 to 12 in. in diameter (table 2). Of the 15 boreholes, 9 were existing boreholes drilled as test wells or formerly active production wells originally drilled for the Northampton Bucks County Municipal Authority (NBCMA), Warminster Municipal Authority (WMA), or Warwick Township Water and Sewer Authority (WTWSA), and 6 were new 6-in. diameter boreholes drilled by the Navy during 2018 (fig. 1). Only a partial suite of geophysical logs and a video log were collected in the 485-ft-deep unused production well BK-1058 (well 27), and only a partial video log was collected in a new shallow observation well BK-3069 (HN-120S) (table 2 and 3).

Fluid and flow logs were collected under ambient and pumping conditions in most (12 of 15) wells to help identify water-bearing fractures. Ambient water levels were recorded at the time of logging and, if wells were pumped during geophysical logging, pumping rate and drawdown at end of

Table 2. Characteristics of wells with geophysical and video logs collected by U.S. Geological Survey at and near the former Naval Air Warfare Center (NAWC) Warminster, Bucks County, Pennsylvania, 2017–19.

[WMA, Warminster Municipal Authority; WTWSA, Warwick Township Water and Sewer Authority; NBCMA, Northampton Bucks County Municipal Authority; dd mm ss, degrees minutes seconds; ft bls, feet below land surface; gal/min, gallons per minute; ft, foot; in., inch; <, less than; --, no data]

USGS local well name	Owner	Owner well name	Latitude[1] (dd mm ss)	Longitude[1] (dd mm ss)	Casing length (ft bls)	Logged depth (ft bls)	Hole diameter (in.)	Date(s) of geophysical logs	Ambient depth to water at time of logging (ft bls)	Pumping rate during flow logging (gal/min)	Draw-down at end of pumping (ft)	Specific capacity [(gal/min)/ ft]	Notes
BK 962	WMA	NAWC10	40 11 44.51	75 04 43.51	50	385	8	12/1/2017	13.95	2	0.19	10.53	--
BK 1023	WMA	Well 28	40 11 38.26	075 03 10.45	57	604	8	9/6/2018	29.53	--	--	--	Severe deviation
BK 1087	WMA	Well 25	40 12 32.89	75 04 09.71	60	400	8	8/10/2018	13.39	1	1.52	0.66	--
BK 1129	WMA	Well 36	40 12 47.47	75 05 42.53	50	375	12	9/5/2018	< –1.8	--	--	--	Flowing at 8 gal/ min
BK 2698	WTWSA	Well 8	40 13 17.58	75 04 29.61	60	210.5	10	9/10/2019	–0.35	2	0.81	2.47	--
BK 2861	WTWSA	Well 11	40 13 17.96	75 04 30.33	83	160	10	9/12/2019	1.9	1.7	0.51	3.33	--
BK 2869	WTWSA	Well 9	40 13 22.12	75 05 05.33	63	315	10	6/17–18/2019	17.93	1.1	1.02	1.08	12-in. to 85 ft
BK 2870	WTWSA	Well 10	40 13 24.00	75 05 08.82	61	270	10	9/11/2019	27.88	1.8	0.32	5.63	Pipe at 63.2 ft, rocks at 85 ft
BK 3062	NBCMA	Well 15	40 12 10.71	75 02 05.35	93	400	10	11/28–29/2017	28.8	2	2.25	0.89	--
BK 3063	Navy	HN-116	40 12 13.87	75 04 47.38	19	601	6	5/24–25/2018	8.22	5	--	--	--
BK 3066	Navy	HN-118	40 12 18.67	75 03 27.27	19	602	6	8/6–7/2018	29.3	2	--	--	--
BK 3067	Navy	HN-119	40 12 13.68	75 02 39.77	20	602	6	8/8/2018	55	--	--	--	Cascading water
BK 3068	Navy	HN-117	40 12 14.18	75 04 09.81	19	600	6	8/9/2018	15.35	2.5	0.2	12.50	--
BK 3070	Navy	HN-120D	40 11 42.35	75 03 36.85	59	555	6	10/31/2018	15.44	1.8	0.2	9.00	600-ft hole collapsed at 555 ft
BK 3071	Navy	HN-121	40 11 43.33	75 04 21.23	20	415	6	11/1/2018	11.6	1.7	0.05	34.00	600-ft hole collapsed at 415 ft
Wells with partial logs													
BK 1058	WMA	Well 27	40 10 31.40	75 04 40.13	58	485	8	9/6/2018	23.92	--	--	--	Partial suite of logs
BK 3069	Navy	HN-120S	40 11 42.25	75 03 36.50	19	26	6	--	12.6	--	--	--	Video log only; collapsed hole

[1]Latitude and longitude for well location from the Global Positioning System (GPS) except for wells BK-1023, BK-2698, BK-2870, and BK-3062, which were located using Google Earth; all locations reported relative to North American Datum 1983.

Table 3. Type and dates of geophysical and video logs collected and archived by U.S. Geological Survey at and near Naval Air Warfare Center Warminster, Bucks County, Pennsylvania, 2017–19.

[WMA, Warminster Municipal Authority; WTWSA, Warwick Township Water and Sewer Authority; NBCMA, Northampton Bucks County Municipal Authority; Acoustic cal, acoustic caliper; M, D, medium and deep; EM, electromagnetic; Ind Cond, EM-induction conductivity; Ind Res, EM-induction resistivity; COND, conductivity; RES, resistivity; RES(16N), RES (64N), short, long-normal resistivity; RES(SP), single-point resistance; ATV, acoustic televiewer; OTV, optical televiewer; Tilt ATV, borehole tilt from ATV tool; Azi, azimuth of borehole tilt; TEMP, fluid temperature; RES(FL), fluid resistivity; EMFM, EM flowmeter; HPFM, heat-pulse flowmeter; amb, ambient; pmp, pumping; --, no data or not collected]

USGS local well name	Owner well name	USGS site ID	Date(s) of geophysical logs	Date(s) of video log	Caliper	Acoustic cal	Gamma	M, D Ind Cond; M, D Ind Res	COND RES	RES (16N) RES (64N)	RES (SP)	ATV image	OTV Res image	Tilt ATV	Azi	TEMP amb	RES (FL) amb	TEMP pmp	RES (FL) pmp	EMFM amb	HPFM amb	EMFM pmp	HPFM pmp
WMA wells																							
BK 962	NAWC 10	401146075041101	12/1/2017	11/28/2017 4/12/2018	x	--	x	x[1]	--	x	--	x	x	x	x	x	x	x	x	x	--	x	--
BK 1023	Well 28	401137075031301	9/6/2018	9/15/2018, 10/3/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	--	--	x	--	--	--
BK 1058	Well 27	401030075044001	9/6/2018	8/30/2018	x	x	--	--	--	--	--	x	x	x	x	--	--	--	--	--	--	--	--
BK 1087	Well 25	401232075041001	8/10/2018	8/29/2018	x	x	--	x	--	--	--	x	x	x	x	x	x	x	x	x	--	x	--
WTSA wells																							
BK 1129	Well 36	401247075054501	9/5/2018	6/21/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	--	--	x	--	--	--
BK 2698	Well 8	401317075043101	9/10/2019	8/27/2019	x	--	x	--	x	--	--	x	x	x	x	x	x	x	x	--	x	--	x
BK 2861	Well 11	401318075043201	9/12/2019	8/6/2019	x	--	x	--	x	--	--	x	x[2]	x	x	x	x	x	x	--	x	--	x
BK 2869	Well 9	401322075050501	6/17-18/2019	7/25/2019	x	--	x	--	x	--	--	x	x[2]	x	x	x	x	x	x	--	x	--	x
BK 2870	Well 10	401324075050701	9/11/2019	8/9/2019	x	--	x	--	x	--	--	x	--	x	x	x	x	x	x	--	x	--	x
NBMCA wells																							
BK 3062	Well 15	401214075044701	11/28-29/2017	11/9/2017	x	--	x	x	--	x	--	x	x	x	x	x	x	x	x	x	--	x	--
Navy wells																							
BK 3063	HN-116	401214075044701	5/24-25/2018	5/21/2018	x	x	x	x	--	x	x	x	x	x	x	x[3]	x[3]	x	x	x[3]	--	x	--
BK 3066	HN-118	401219075032701	8/6-7/2018	8/2/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	x	--	x	--
BK 3067	HN-119	401214075024001	8/8/2018	8/6/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	--	--	x	--	--	--
BK 3068	HN-117	401214075041001	8/9/2018	8/28/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	x	--	x	--
BK 3069	HN-0S	401142075033601	--	11/7/2018	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
BK 3070	HN-0D	401142075033701	10/31/2018	10/31/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	x	--	x	--
BK 3071	HN-121	401143075042101	11/1/2018	10/6/2018	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	x	--	x	--

[1]Induction resistivity not calculated from induction conductivity log in archived data for well BK-962.

[2]Low borehole visibility prevented collection of useable OTV.

[3]Fluid logs collected during ambient conditions with and without nearby extraction wells pumping.

pumping were also recorded and used to calculate the specific capacity of the well (table 2). Depths of logs, observed features, and water levels are reported in feet below land surface (ft bls).

The type of geophysical logs collected for each well is summarized in table 3. Abbreviations for logs and reporting units in table 3 and in log figures are listed in table 1. Digital data for the type of geophysical log collected for each well as summarized in table 3, except for the OTV and ATV logs, are available online from the USGS GeoLog Locator (U.S. Geological Survey, 2020); the OTV and ATV logs are available as images. The OTV and ATV log digital data are archived locally by the USGS New York Water Science Center. The borehole video logs are archived locally by the USGS Pennsylvania Water Science Center.

Interpretation of Individual Well Geophysical and Video Logs

For each well, borehole characteristics, vertical borehole flow directions under ambient conditions, and identification of probable hydraulically active water-bearing zones as determined from evaluation of the geophysical log suite are briefly described. Commonly (but not always), the most hydraulically active water-bearing fractures identified from the logs may also be the most productive water-bearing fractures. Other water-bearing fractures likely are present in the wells. Selected probable or possible water-bearing fractures and other features as observed on borehole video logs are noted.

The distribution and orientation of the probable hydraulically active fractures are presented as tadpole plots relative to magnetic north within the suite of geophysical logs in the sections that follow for each well and with stereonet plots (appendix 1). During the 2018–19 period of logging, magnetic declination (angle between true north and horizontal trace of magnetic field) was about –12 degrees 8 minutes, ranging from –12 degrees 6 minutes to –12 degrees 10 minutes depending on year and magnetic model as calculated using National Oceanic and Atmospheric Administration (2020) online tool.

BK-962 (NAWC 10)

Well BK-962 is a former production well (NAWC 10) for the NAWC Warminster base (figs. 1 and 3); it was transferred to Warminster Municipal Authority when the base closed and is no longer in use, partly because of elevated manganese concentrations (Timothy Hagey, Warminster Municipal Authority, oral commun., 2018). Prior to logging by USGS, the pump and plumbing were removed in fall 2017. The well has 10-in. diameter casing to a depth of about 50 ft bls and below that depth is an 8-in. diameter open hole to about 385 ft bls (table 2). The depth to static water level at the time of logging was about 13.95 ft bls.

The caliper and ATV logs show numerous fractures throughout the borehole (fig. 4). Most of the fractures appear to be low-angle, although the ATV indicates the presence of high-angle fractures at about 80, 170, and 200 ft bls. The fluid-temperature log shows the largest inflections at about 80 and 200 ft bls and the fluid-conductivity log shows small inflections at similar depths. The flow log collected under ambient conditions indicates upward flow from near the bottom of the borehole to about 200 ft bls, where water may be exiting the borehole (or where flow measurements may be lower than actual because of possible bypass around diverters), and then an increase in upward flow above 166 ft bls (table 4). The flow log collected under pumping conditions indicated that the fractures above 166 ft bls are the most hydraulically active water-bearing zones in the well.

The borehole video log, collected by USGS on November 28, 2017, when the water level was 13.8 ft bls, showed some horizontal and numerous vertical fractures throughout the borehole. Apparent turbulence was at about 167.8–174, 195.8–201, 210, and 262.8 ft bls and water appeared to be injecting into the borehole at 152.1 ft bls. Possible primary water-bearing zones were noted for fractures at about 76.6–79.4, 152.1, 167.8–174, and 196.5 ft bls. Video-log images for selected fractures in well BK-962 are shown in figure 5.

BK-1023 (WMA Well 28)

Well BK-1023 is an unused test well (WMA well 28 on the southeast edge of the former NAWC Warminster base (figs. 1 and 3). Prior to logging by USGS, a large tree growing into the casing and obstructing access to the well was removed by WMA. The well has 8-in. diameter casing to a depth of about 57 ft bls and below that depth is an 8-in. diameter open hole to about 604 ft bls (table 2). The depth to ambient water level at the time of logging was about 29.5 ft bls. The well is strongly deviated from vertical.

The caliper and ATV logs show fractures are present throughout the borehole, with the largest openings at depths above 200 ft bls (fig. 6). The fluid-temperature log shows decreasing temperature to about 350 ft bls, then increasing temperature below that depth to the bottom of the well at 604 ft. The fluid temperature log also shows small inflections at depths above 125 ft bls with a change in slope near 115 ft bls. The fluid-conductivity log shows the largest inflection at about 75 ft bls and appears almost constant below 100 ft bls. The flow log collected under ambient conditions indicates downward flow throughout the borehole starting from depths between 45 and 72 ft bls that increases below 82 ft bls and increases again at depths between 194 and 240 ft bls (table 5). The ambient fluid and flow logs indicate that water-bearing zones above 225 ft bls probably are the most hydraulically active in the well. The flow and fluid logs were not collected under pumping conditions.

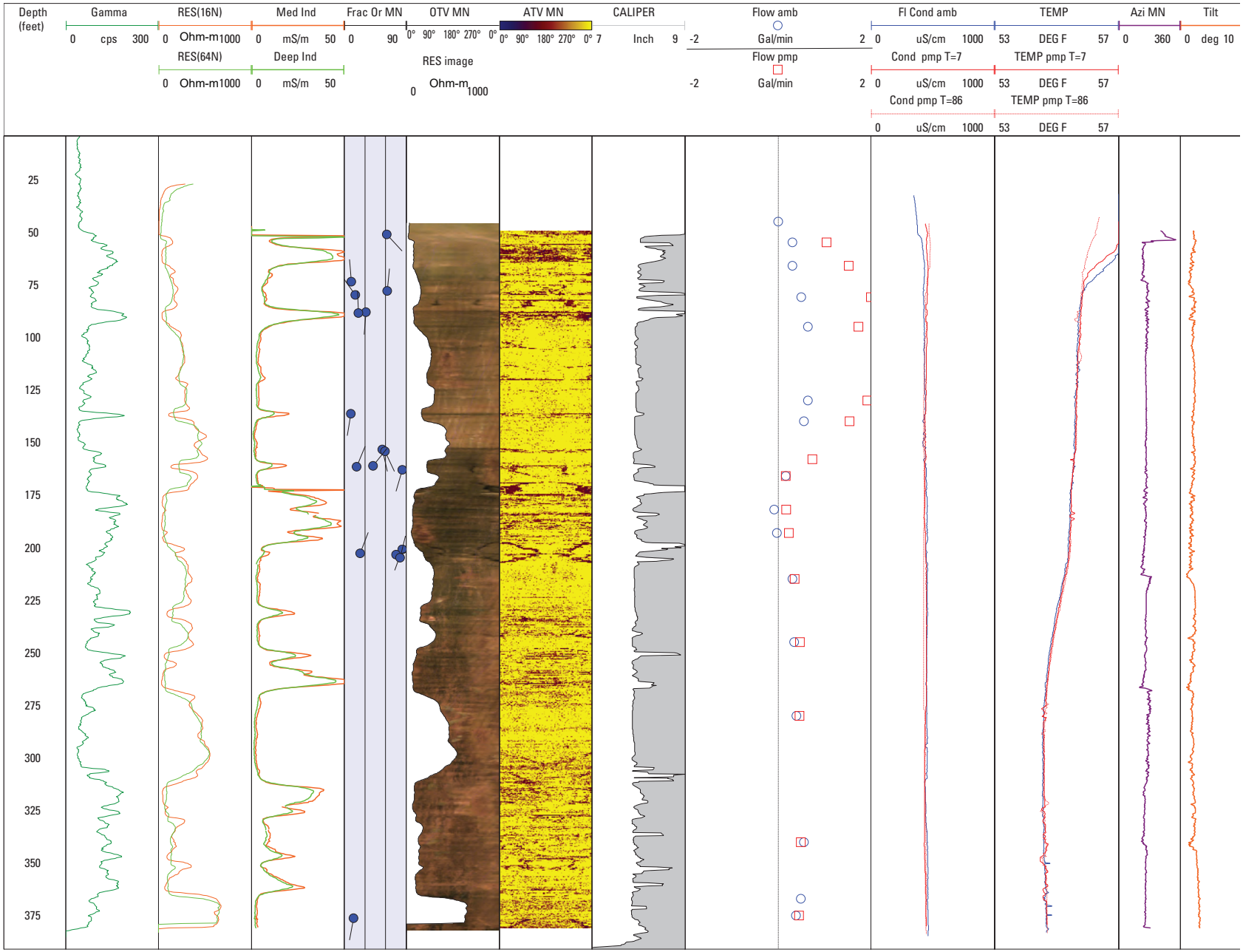


Figure 4. Geophysical logs collected by U.S. Geological Survey in well BK-962 (NAWC well 10), Warminster Township, Bucks County, Pennsylvania, December 1, 2017. See table 1 for explanation of abbreviations.

Table 4. Borehole flow-measurements collected by U.S. Geological Survey in well BK-962 (NAWC well 10), Warminster Township, Bucks County, Pennsylvania, December 1, 2017. Stationary measurements made using the electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb, corr (gal/min)	Depth (ft bls)	Flow pmp[1], corr (gal/min)
45	0.00	45	--
55	0.32	55	1.05
66	0.32	66	1.52
81	0.50	81	2.00
95	0.65	95	1.73
130	0.65	130	1.93
140	0.56	140	1.54
158	--	158	0.74
166	0.17	166	0.17
182	–0.09	182	0.18
193	–0.03	193	0.24
215	0.32	215	0.36
245	0.35	245	0.47
280	0.39	280	0.46
340	0.55	340	0.49
367	0.49	367	--
375	0.39	375	0.45

[1]Pumping rate = 2 gal/min; drawdown= 0.19 ft; start pump at 11:08, stop at 12:30; well may be affected by other nearby pumping.

The borehole video log, collected by USGS on October 3, 2018, when the water level was 27.3 ft bls, showed few notable horizontal and vertical fractures throughout the borehole. Possible principal water-bearing zones were noted for fractures at about 164 and 197.5 ft bls. Video-log images for selected fractures or openings in well BK-1023 are shown in figure 7. Although not identified as principal water-bearing fractures in video log notes, fractures near 62 ft and 74 ft bls (fig. 7A,B) appear to be water bearing as indicated by other geophysical logs.

BK-1058 (WMA Well 27)

Well BK-1058 is an unused test well (WMA well 27) about 1.2 mi south of the former NAWC Warminster base (figs. 1 and 3). The well has 8-in. diameter casing to a depth of about 58 ft bls and below that depth is an 8-in. diameter open hole to about 485 ft bls (table 2). The depth to ambient water level at the time of logging was about 23.9 ft bls.

Limited logs were collected in well BK-1058 (table 3) in 2018, which was not selected for further evaluation and straddle packer testing in 2018. Data for the 2018 logs collected from well BK-1058 are available online from the USGS GeoLog Locator (U.S. Geological Survey, 2020). Caliper, gamma, single-point resistance, fluid-temperature, and fluid-resistivity logs were previously collected by USGS for this well in 1995.

The 2018 caliper and ATV logs show numerous fractures throughout the borehole, including at depths near 60, 70–80, 182, 250–257, 280–290, 300, 335, 355–383, 387–400, 425–443, and 472–480 ft bls. No fluid or flow logs were collected in well BK-1058 in 2018.

The borehole video log, collected by USGS on August 30, 2018, when the water level was 23.6 ft bls, showed numerous horizontal and vertical fractures throughout the borehole. Possible principal water-bearing zones were noted for fractures at about 79.4, 99.6, 100.8–102.0, 252, 351, 387.5, and 391 ft bls. Other possible water-bearing fractures were noted in the borehole, including near 60, 72.2, 75.8, 11.4, 139.3–146, 180.1, 229.8, 277.3, 2. 285.6, 294.1, 333.8, 337.8, 385.7, and 387.5 ft bls. Visibility decreased with depth below 180 ft bls. At depths greater than 391 ft bls, visibility was poor and video log was ended. Water was observed to be injecting into borehole near fractures at 99.6 ft bls and turbulence was observed near fractures at 100.8–102 ft bls. Possible turbulence was also noted near fractures at 139.3–146 ft bls.

BK-1087 (WMA Well 25)

Well BK-1087 is an unused test well (WMA well 25) about 0.2 mi north of the former NAWC Warminster base (figs. 1 and 3). The well has 8-in. diameter casing to a depth of about 60 ft bls and below that depth is an 8-in. diameter open hole to about 400 ft bls (table 2). Depth to ambient water level at the time of logging was about 13.4 ft bls.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at depths above 125 ft bls (fig. 8). Most of the fractures appear to be low-angle, although the ATV indicates the presence of high-angle fractures at about 240 and 275 ft bls. The fluid-temperature log collected under ambient conditions shows the largest inflections at about 100 and 275 ft bls, with temperature decreasing below water level to about 100 ft bls and increasing slightly below 275 ft bls. The fluid-conductivity log collected under ambient and pumping conditions indicates an inflection at about 100 ft bls that likely corresponds to a water-bearing zone. The flow log collected under ambient conditions indicates possible slight upward flow starting from near the bottom of the borehole at 360 ft bls to about 330 ft bls and possible slight downward flow below 50 ft bls to about 140 ft bls (table 6). The flow log collected under pumping conditions

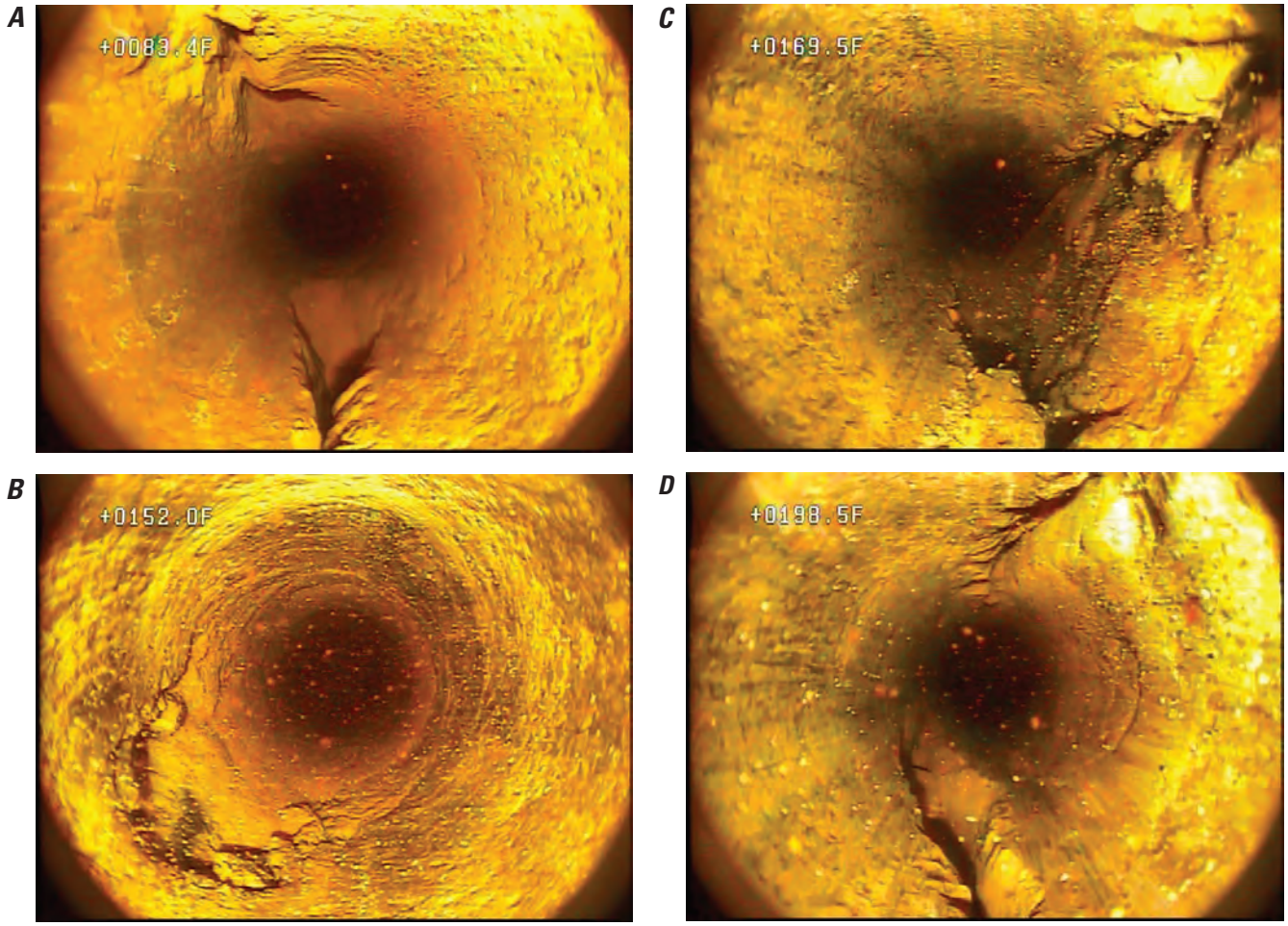


Figure 5. Still images from borehole video log of well BK-962 (NAWC 10) at *A*, 83.4 feet below land surface (ft bls) showing high-angle fractures, *B*, 152.0 ft bls showing oblique opening where water appeared to be injecting into the borehole, *C*, 169.5 ft bls showing vertical fractures crossing side of borehole, and *D*, 198.5 ft bls showing high-angle fractures. Video log collected by U.S. Geological Survey in well BK-962, Warminster Township, Bucks County, Pennsylvania, November 28, 2017.

indicated that the fractures above 105 ft bls (and specifically the fracture at about 100 ft bls) are the most hydraulically active water-bearing zones in the well.

The borehole video log, collected by USGS on August 29, 2018, when the water level was 14.6 ft bls, showed numerous horizontal and vertical fractures throughout the borehole. Possible water-bearing zones were noted for fractures at about 234.1–245.7 ft bls and the likely water-bearing fracture near 100 ft bls; other possible water-bearing fractures also were noted, including fractures near 127, 192–197, 271, and 332–334 ft bls. At 366.4 ft bls, the well appears to be blocked with pipes that may have fallen to the bottom of the borehole at an unknown time but prior to this investigation in 2018. Video-log images for selected fractures or openings in well BK-1087 are shown in figure 9.

BK-1129 (Warminster Well 36)

Well BK-1129 is a formerly active production well (WMA well 36) northwest of the former NAWC Warminster base (figs. 1 and 3) and scheduled for abandonment, partly because of high dissolved solids. The well has 12-in. diameter casing to a depth of about 58 ft bls and below that depth is a 12-in. diameter open hole to about 375 ft bls (table 2). The well was flowing at a rate of about 8 gal/min out of a pipe at the top of casing 1.8 ft above land surface at the time of logging.

The caliper and ATV logs show numerous fractures throughout the borehole, with the most numerous openings at depths above 275 ft bls (fig. 10). Most of the fractures appear to be low-angle, although the ATV indicates the presence of high-angle fractures at about 210, 240, and 325 ft bls. The fluid-temperature log collected under ambient conditions shows almost no to very slight inflections. The

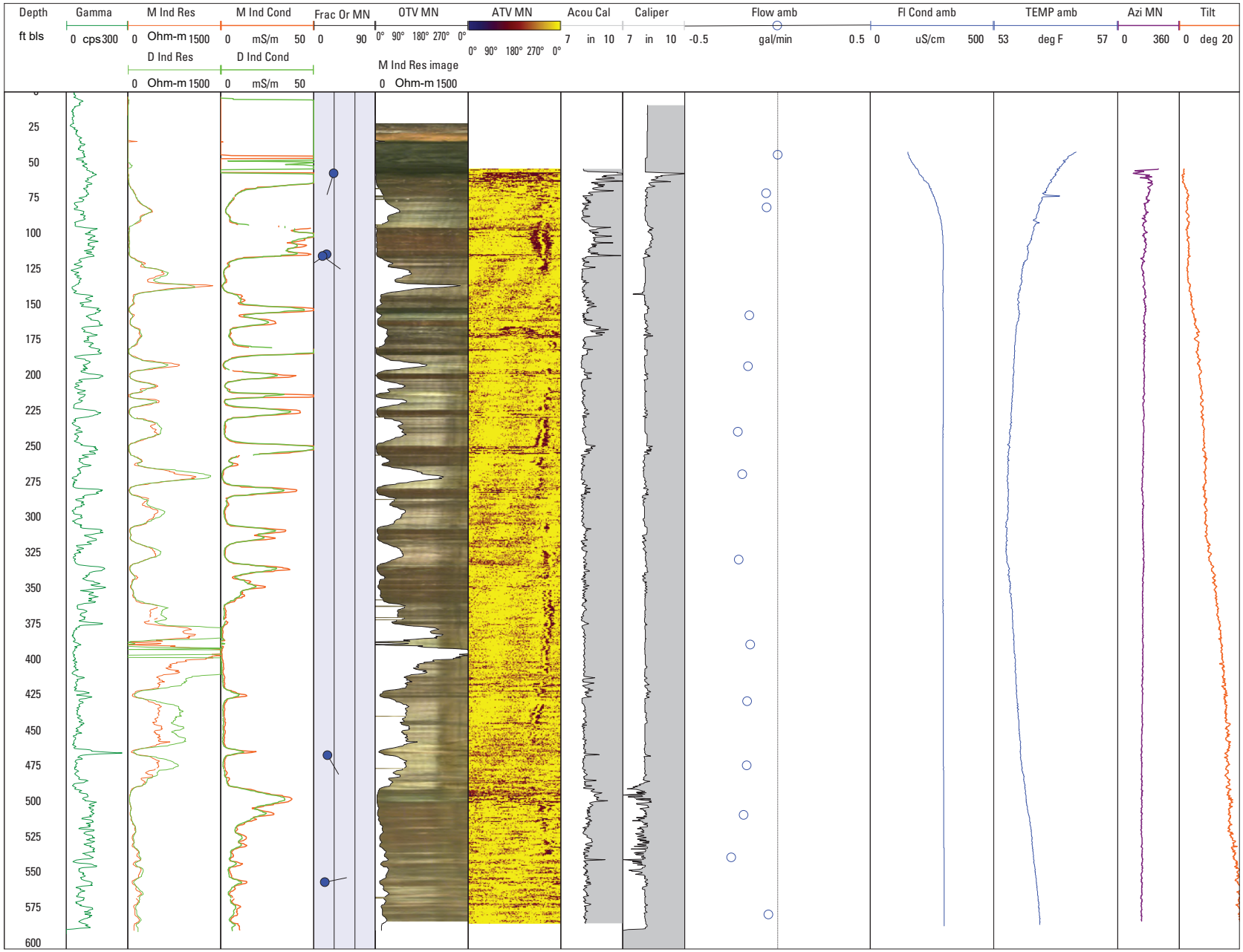


Figure 6. Geophysical logs collected by U.S. Geological Survey in well BK-1023 (WMA well 28), Warminster Township, Bucks County, Pennsylvania, September 6, 2018. See table 1 for explanation of abbreviations.

Table 5. Borehole flow-measurements collected by U.S. Geological Survey in well BK-1023 (WMA well 28), Warminster Township, Bucks County, Pennsylvania, September 6, 2018. Stationary measurements made using an electromagnetic flow meter under ambient conditions; negative values indicate downward flow and positive values indicate upward flow. No flow metering was done under pumping conditions for BK 1023.

[ft, feet; bls, below land surface; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions]

Ambient conditions	
Depth (ft bls)	Flow amb (gal/min)
45	0.00
72	–0.06
82	–0.06
158	–0.15
194	–0.16
240	–0.21
270	–0.19
330	–0.21
390	–0.15
430	–0.16
475	–0.17
510	–0.18
540	–0.25
580	–0.05

fluid-conductivity log collected under ambient conditions shows the largest inflections near about 175, 250, and 360 ft bls that probably correspond to water-bearing zones. The flow log collected under ambient conditions indicates upward flow throughout the borehole starting from near the bottom of the borehole above 370 ft bls, and increasing in magnitude at depths above 320, 265, 177, 168, 120, 74, and above 58 ft bls (table 7). The flow and fluid logs collected under ambient conditions indicate that water-bearing zones near depths of 160 and 360 ft bls likely are the most hydraulically active, although water-bearing zones above 74 and near 100, 175, 255, and 310 ft bls also appear to produce water. The flow measurements are uncertain because the heat-pulse flowmeter was equipped with an 8-in. diverter in a 12-in. diameter borehole that allows an unquantified amount of flow to bypass the meter, especially in sections of borehole with varying diameter, and thus should be interpreted with caution. The flow and fluid logs were not collected under pumping conditions.

The borehole video log, collected by USGS on June 21, 2018, when the well was flowing, showed numerous horizontal fractures throughout the borehole. Possible principal water-bearing zones were noted for fractures at about 160.5–162 and 176 ft bls. Other possible water-bearing fractures indicated by geophysical logs also included those observed at depths of about 237–242, 255, 310.7–314, and 357 ft bls, in addition to numerous fractures at depths of about 61–110 ft bls. Video-log images for selected fractures or openings in well BK-1129 are shown in figure 11.

BK-2698 (WTWSA Well 8)

Well BK-2698 is an unused production well (WTWSA well 8) about 1.3 mi north of the former NAWC Warminster base (figs. 1 and 3). Prior to logging by USGS, the pump and plumbing were removed in summer 2019. The well has 10-in. diameter casing to a depth of about 60 ft bls and below that depth is a 10-in. diameter open hole to about 210.5 ft bls (table 2). The depth to ambient water level at the time of logging in September 2019 was about 0.35 ft above land surface. Well BK-2698 was logged previously in the 1990s by USGS (Bird, 1998, p. 13).

The caliper and ATV logs show a few fractures throughout the borehole, with the largest openings at about 110 ft bls. Most of the fractures appear to be low angle (fig. 12). The fluid-temperature log collected under ambient conditions shows the largest inflections at about 60 and 145 ft bls. The fluid-conductivity log collected under ambient and pumping conditions indicates an inflection at about 145 ft bls that likely corresponds to a water-bearing zone. The flow log collected under ambient conditions indicates slight upward flow throughout the borehole starting near a depth of 145 ft bls (table 8). The flow log collected under pumping conditions indicated that the fractures near 145 ft bls may be the most hydraulically active water-bearing zones in the well. The flow measurements are uncertain because the heat-pulse flowmeter was equipped with an 8-in. diverter in a 10-in. diameter borehole, which allows an unquantified amount of flow to bypass the meter, and thus should be interpreted with caution.

The borehole video log, collected by USGS on August 27, 2019, when the water level was 1.2 ft bls, showed numerous horizontal and some vertical fractures throughout the borehole. Possible water-bearing zones were noted for discrete fractures in the range of depths from about 96–113 ft bls. The primary water-bearing fractures indicated by geophysical logs also included those observed at depths of 140.2–144.8 ft. Video-log images for selected fractures or openings in well BK-2698 are shown in figure 13.

BK-2861 (WTWSA Well 11)

Well BK-2861 is an unused production well (WTWSA well 11) about 1.3 mi north of the former NAWC Warminster base (figs. 1 and 3). Prior to logging by USGS, the pump and plumbing were removed in summer 2019. The well has 10-in. diameter casing to a depth of about 83 ft bls and below that depth is a 10-in. diameter open hole to about 160 ft bls (table 2). The depth to ambient water level at the time of logging in September 2018 was about 1.9 ft bls. Well BK-2861 was logged previously in the 1990s by USGS (Bird, 1998, p. 14).

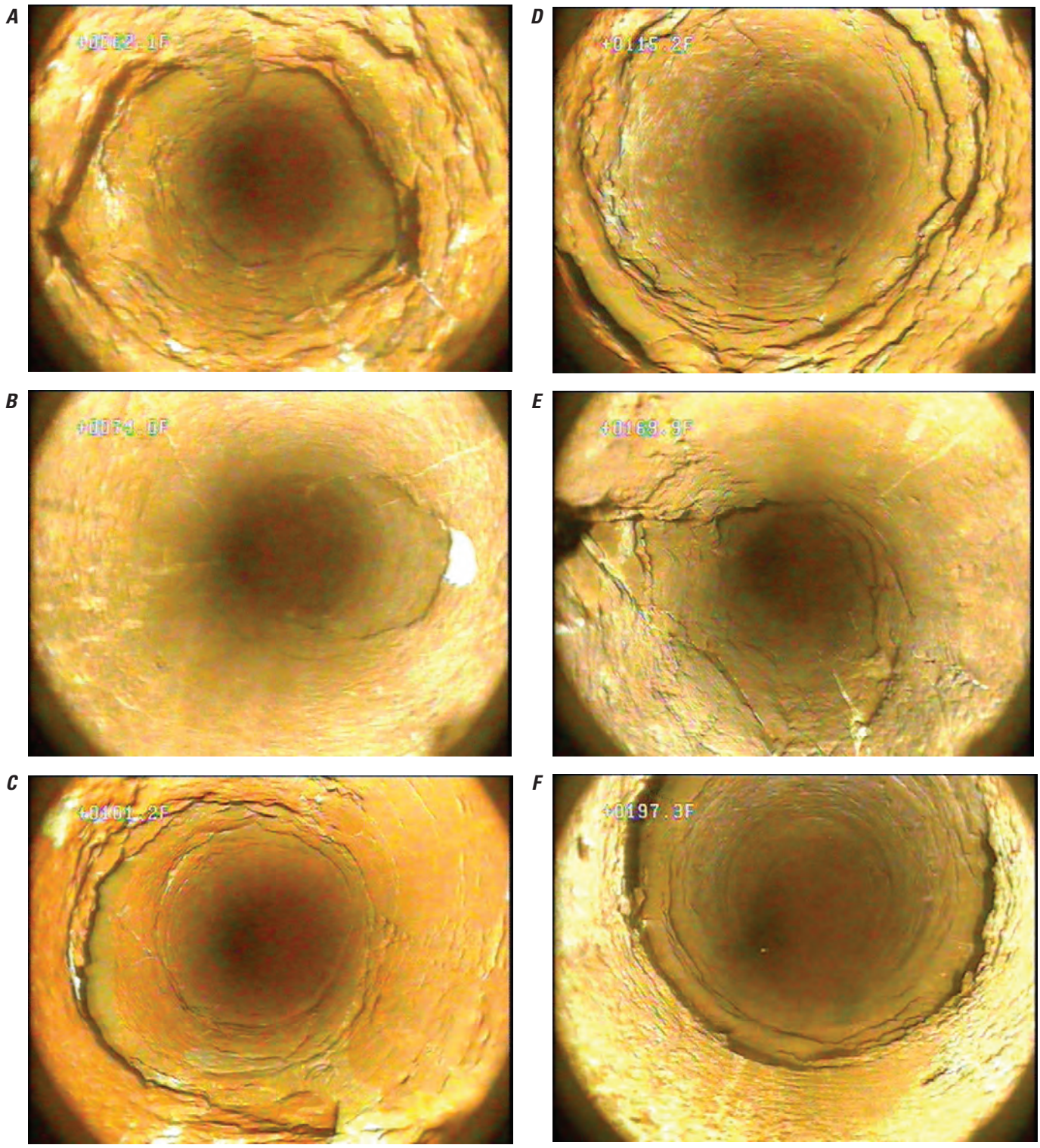


Figure 7. Still images from borehole video log of well BK-1023 (WMA well 28) at *A*, 62.1 feet below land surface (ft bls) showing large openings near bottom of casing, *B*, 74.0 ft bls showing high-angle opening, *C*, 101.2 feet ft bls showing possible bedding-plane opening, *D*, 115.2 ft bls showing possible bedding-plane openings, *E*, 169.4 ft bls showing high-angle fractures, and *F*, 197.3 ft showing possible bedding-plane openings. Video log collected by U.S. Geological Survey in well BK-1023, Warminster Township, Bucks County, Pennsylvania, October 3, 2018.

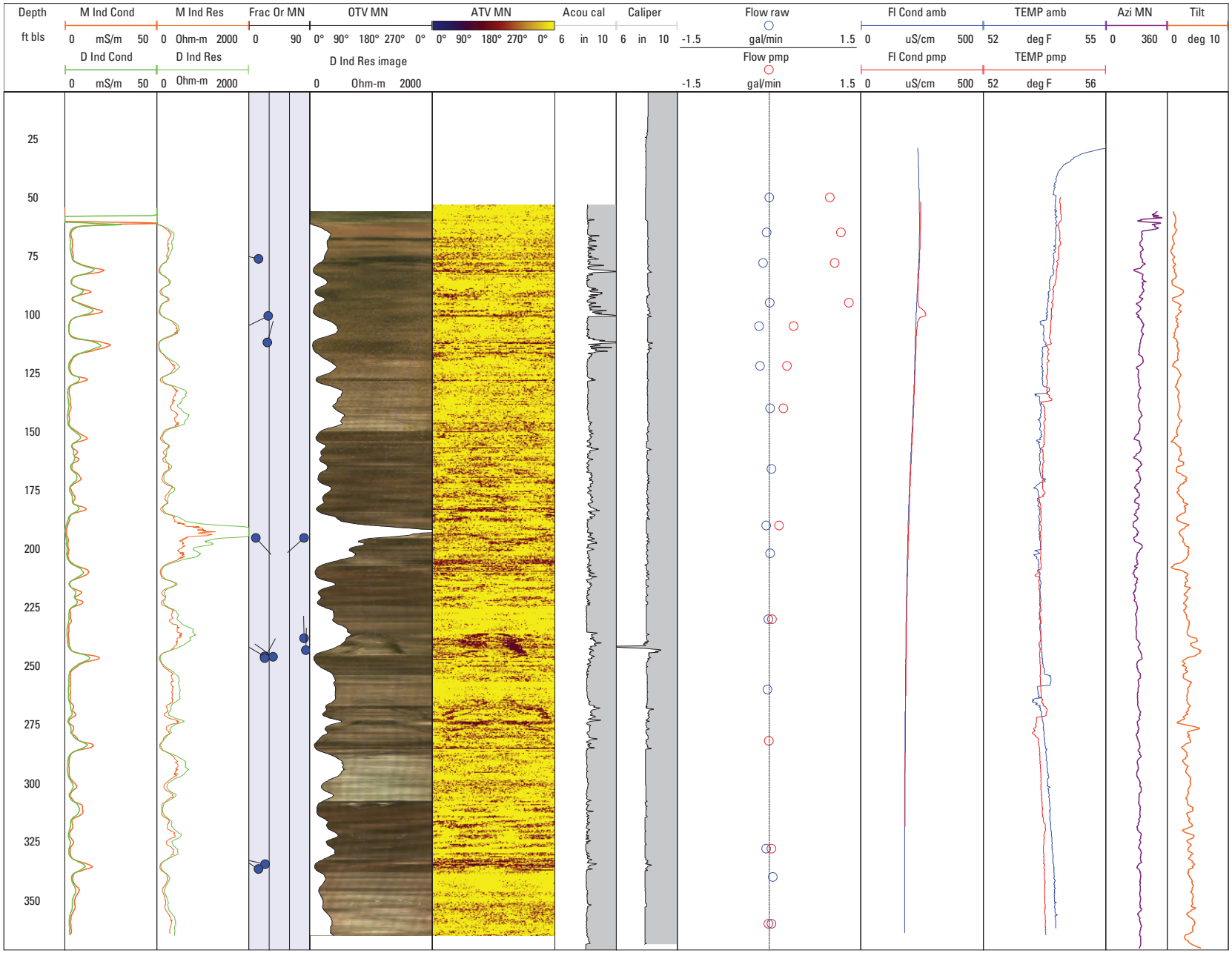


Figure 8. Geophysical logs collected by U.S. Geological Survey in well BK-1087 (WMA well 25), Warminster Township, Bucks County, Pennsylvania, August 10, 2018. See table 1 for explanation of abbreviations.

Table 6. Borehole flow-measurements collected by U.S. Geological Survey in well BK-1087 (WMA well 25), Ivyland Borough, Bucks County, Pennsylvania, August 10, 2018. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions			
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
50	0.00	50	1.00
65	–0.04	65	1.18
78	–0.10	78	1.08
95	0.01	95	1.31
105	–0.16	105	0.40
122	–0.15	122	0.29
140	0.02	140	0.24
166	0.04	166	--
190	–0.05	190	0.16
202	0.02	202	--
230	–0.01	230	0.05
260	–0.02	282	--
282	--	282	0.00
328	–0.05	328	0.04
340	0.06	340	--
360	0.04	360	-0.01

[1]Static water level = 13.39 ft bls.

[2]Pumping rate = 1.0 gal/min; pump on at 10:02, stop pump at 11:22; drawdown = 1.52 ft.

The caliper and ATV logs show several fractures throughout the borehole (fig. 14). Many of the fractures appear to be high angle. The fluid-temperature and fluid-conductivity logs collected under ambient and pumping conditions show no large inflections that could be used to identify depth of water-bearing fractures, although the temperature logs shown differences under ambient and pumping conditions at depths above about 130 ft bls. The flow log collected under ambient conditions indicates slight upward flow throughout the borehole starting near a depth of 144 ft bls, but this flow appears to decrease to less than detection (<0.001 gal/min) at 110 ft bls (table 9), which may indicate that water exits the borehole through fractures at about 120 ft bls. The flow logs collected under ambient and pumping conditions indicated that the fractures at depths near about 135–140 and 147–152 ft bls may be the most hydraulically active water-bearing zones in the well. The flow measurements are uncertain because the heat-pulse flowmeter was equipped with an 8-in. diverter in a 10-in. diameter borehole, which allows an unquantified amount of flow to bypass the meter, and thus should be interpreted with caution.

The borehole video log, collected by USGS on August 6, 2019, when the water level was 2.7 ft bls, showed that the well is overbored and out-of-round until about 102 ft bls and that there are several horizontal and vertical fractures throughout the borehole. Possible principal water-bearing zones were noted for fractures at about 136–141 ft bls. Other possible water-bearing fractures indicated by geophysical logs also included those observed at depths of about 86.5, 96–98, 118.5–121, and 149 ft bls. Visibility was poor in the video log of well owing to numerous particles in the water column after the recent removal of the pump from the well. Video-log images for selected fractures or openings in well BK-2861 are shown in figure 15.

BK-2869 (WTWSA Well 9)

Well BK-2869 is an unused production well (WTWSA well 9) about 1.5 mi north of the former NAWC Warminster base (figs. 1 and 3). Prior to logging by USGS, the pump and plumbing were removed in summer 2019. The well has 12-in. diameter casing to a depth of about 63 ft bls; below that depth is a 12-in. diameter open hole to 85 ft bls and then a 10-in. diameter borehole to about 315 ft bls (table 2). The depth to ambient water level at the time of logging was about 17.9 ft bls.

The caliper and ATV logs show several fractures throughout the borehole (fig. 16). Many of the fractures appear to be low angle. High turbidity in the well at the time of logging reduced visibility needed for the OTV log. The fluid-temperature logs collected under ambient and pumping conditions show similar inflections at about 85 and 220 ft bls that could be used to identify depth of water-bearing fractures. The fluid-conductivity logs collected under ambient and pumping conditions also show similar inflections at about 85 ft bls. The flow log collected under ambient conditions indicates slight downward flow starting near 80 ft bls, but this flow appears to decrease to less than detection (<0.001 gal/min) at about 243 ft bls (table 10), which may indicate that water exits the borehole through fractures at about 180 to 220 ft bls. The flow log collected under pumping conditions indicated that the fractures at depths above 85 ft bls are the most hydraulically active water-bearing zones in the well. The flow measurements are uncertain because the heat-pulse flowmeter was equipped with an 8-in. diverter in a 10-in. diameter borehole, which allows an unquantified amount of flow to bypass the meter, and thus should be interpreted with caution.

The borehole video log, collected by USGS on July 25, 2019, when the water level was 19.5 ft bls, showed several mostly horizontal and some vertical fractures throughout the borehole. The video shows that the well was overbored and has an irregular shape to a depth of about 85 ft bls. Possible

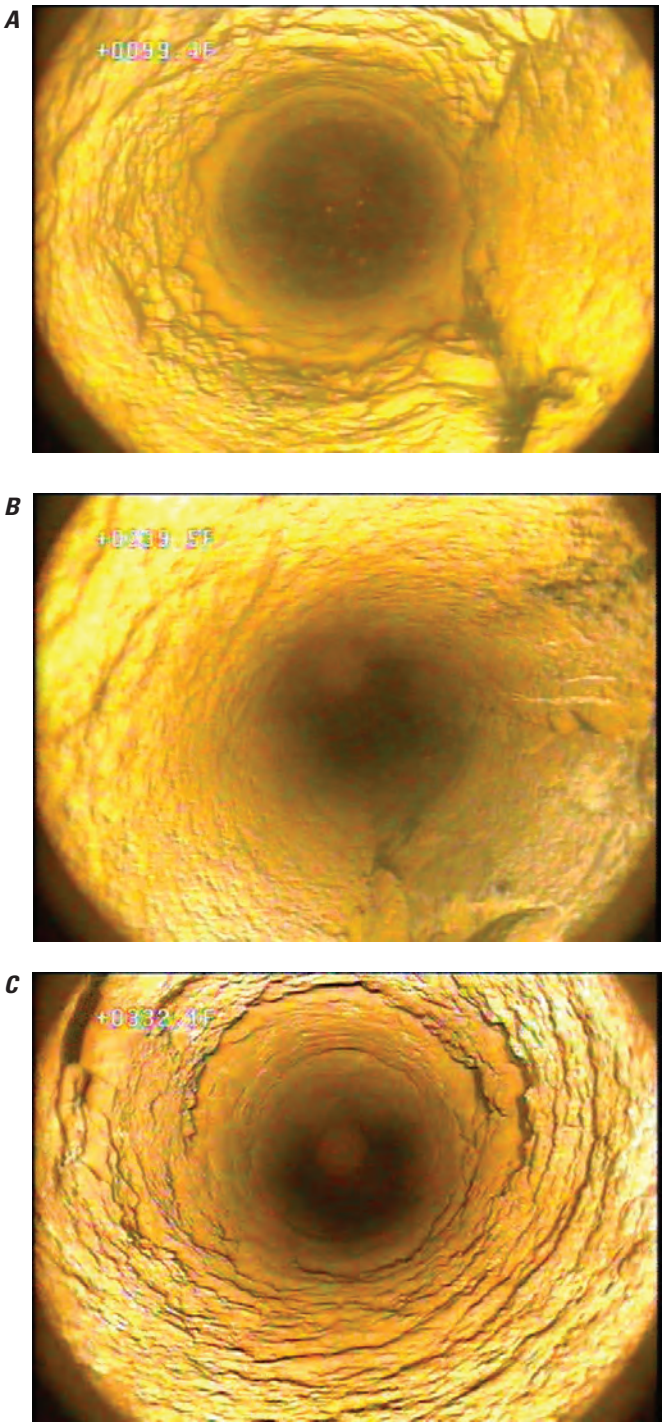


Figure 9. Still images from borehole video log of well BK-1087 (WMA well 25) at *A*, 99.4 feet below land surface (ft bls) showing possible high-angle fracture and bedding-plane opening, *B*, 239.5 ft bls showing high-angle fracture and reduced visibility, and *C*, 332.1 ft bls showing possible bedding-plane openings and good visibility at depth with upward ambient flow. Video log collected by U.S. Geological Survey in well BK-1087, Ivyland Borough, Bucks County, Pennsylvania, August 29, 2018.

water-bearing zones were noted for fractures at about 81.7–95, 155, 175, 265 and 280 ft bls. Video-log images for selected fractures or openings in well BK-2869 are shown in figure 17.

BK-2870 (WTWSA Well 10)

Well BK-2870 is an unused production well (WTWSA well 10) about 1.5 mi north of the former NAWC Warminster base (figs. 1 and 3). Prior to logging by USGS, the pump and plumbing were removed in summer 2019. The well has 10-in. diameter casing to a depth of about 61 ft bls and below that depth is a 10-in. diameter open hole to 270 ft bls (table 2). The depth to ambient water level at the time of logging was about 27.9 ft bls.

The caliper and ATV logs show several fractures throughout the borehole, with the largest openings at about 85, 95, and 118 ft bls that appear to be high angle (fig. 18). The presence of a polyvinyl chloride (PVC) pipe in the well prevented collection of the OTV log because the tool for this log needs to be centralized. The fluid-temperature logs collected under ambient and pumping conditions show inflections at about 65 and 220 ft bls. The fluid-conductivity log collected under ambient conditions shows an inflection at about 118 ft bls, and, under pumping conditions, shows an inflection at about 85 ft bls. The flow log collected under ambient conditions indicates slight upward flow starting near 256 ft bls, but this flow appears to decrease to less than detection (<0.001 gal/min), reported as 0.0 gal/min, at about 108 ft bls (table 11), which may indicate that water exits the borehole through fractures at about 118 ft bls but also could be related to bypass around the 8-in. diverter. The flow measurements are uncertain because the heat-pulse flowmeter was equipped with an 8-in. diverter in a 10-in. diameter borehole, which allows an unquantified amount of flow to bypass the meter, and thus should be interpreted with caution. The flow log collected under pumping conditions indicated that the fractures at depths above about 85 ft bls are the most hydraulically active water-bearing zones in the well, but fractures at other depths, including near 118, 220 and below 256 ft bls also appear to be hydraulically active.

The borehole video log, collected by USGS on August 9, 2019, when the water level was 24.1 ft bls, was collected only to about 87 ft bls at a depth where potentially loose rocks were observed. The video log showed the top of a 2-in. PVC pipe string at about 63 ft bls, apparently left in the borehole after pump removal. The video log also showed a horizontal fracture at about 67 ft bls and a large vertical fracture starting at 84.7 ft bls. Video-log images for selected fractures or openings in well BK-2870 are shown in figure 19.

BK-3062 (NBCMA Well 15)

Well BK-3062 is an unused test well (NBCMA well 15 near the northeast edge of the former NAWC Warminster base (figs. 1 and 3). The well has 10-in. diameter casing to a depth

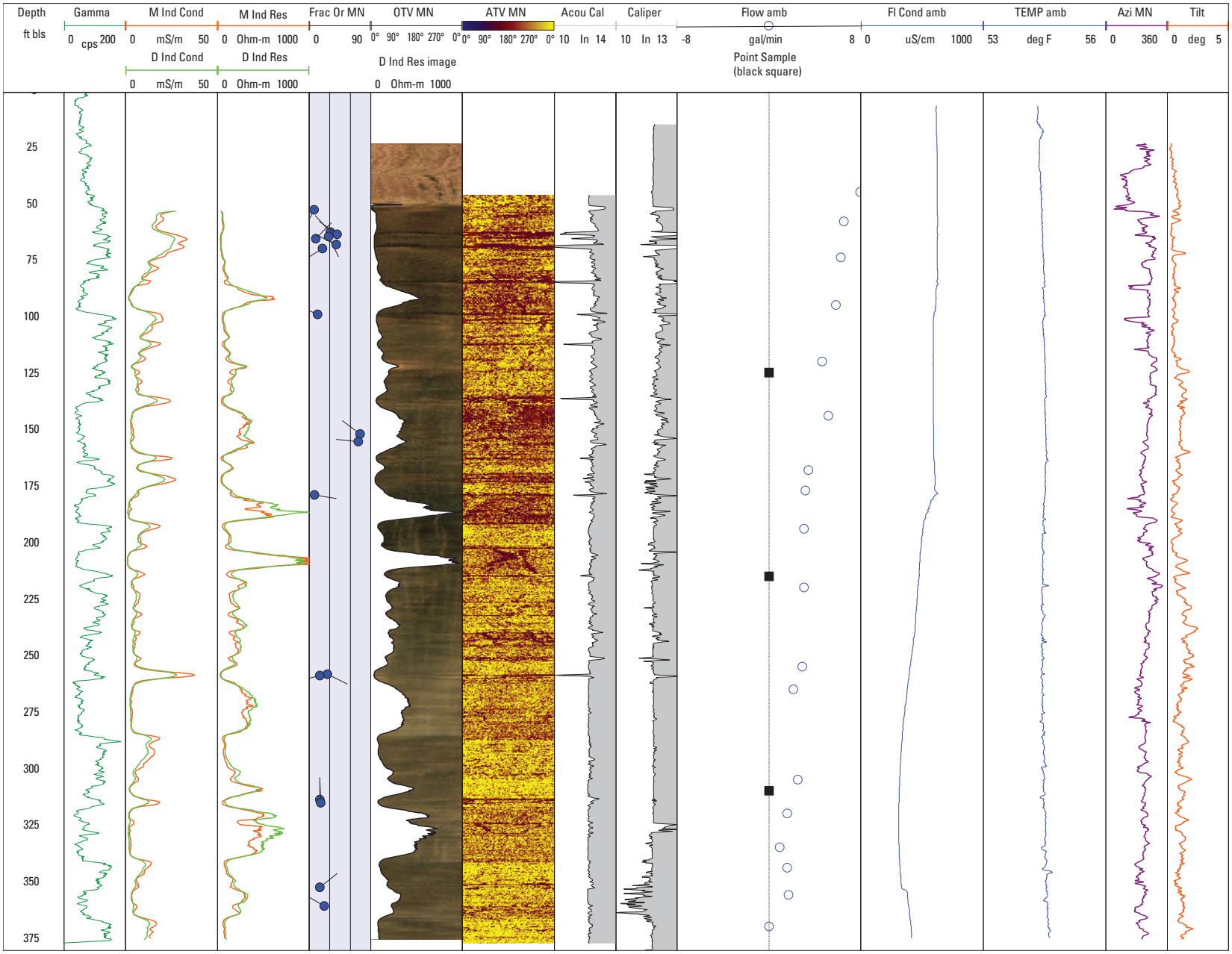


Figure 10. Geophysical logs collected by U.S. Geological Survey in well BK-1129 (WMA well 36), Warminster Township, Bucks County, Pennsylvania, September 5, 2018. See table 1 for explanation of abbreviations. Depth of point samples collected under ambient conditions shown on flow logs.

Table 7. Borehole flow-measurements collected by U.S. Geological Survey in well BK-1129 (WMA well 36), Warminster Township, Bucks County, Pennsylvania, September 5, 2018. Stationary measurements made using an electromagnetic flow meter under ambient conditions; negative values indicate downward flow and positive values indicate upward flow. Flow measured with 8-inch diameter diverter in 12-inch diameter well that was flowing at about 8 gallons per minute (gal/min). Reported flow adjusted so that flow in casing at a depth of 45 feet is equal to flow rate of 8 gal/min at top of casing.

[ft, feet; bls, below land surface; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions	
Depth (ft bls)	Flow amb[1] (gal/min)
45	7.98
58	6.52
74	6.25
95	5.85
120	4.66
144	5.19
168	3.46
177	3.19
194	3.06
220	3.06
255	2.93
265	2.13
305	2.53
320	1.60
335	0.93
344	1.60
356	1.73
370	0.00

[1]Well is flowing; flow measured on September 5, 2018, starting at 13:14; flow adjusted to account for measured overflow rate of 8 gal/min at top of well; all flow is upward.

of about 93 ft bls and below that depth is a 10-in. diameter open hole to 400 ft bls (table 2). The depth to ambient water level at the time of logging was about 28.8 ft bls.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at about 100, 120, 160–190 ft bls (fig. 20). Fractures at about 160–175 and 310–324 ft bls appear to be mostly high angle, and fractures at about 95, 120, 135, 185, 230, 240, 285, 305, 370, and 390 ft bls appear to be low angle. The fluid-temperature log collected under ambient conditions show inflections at about 120 and to a small extent, possibly at about 190 ft bls. The fluid-temperature log collected under pumping conditions shows inflections at about 240 and 290 ft bls. The fluid-conductivity logs collected under ambient and pumping conditions show small inflections at about 120 and 130 ft bls. During the collection of the ambient flow log, there appeared to be larger than typical variability in measured values at some depths, and therefore these flow logs should be interpreted with caution. Raw (uncorrected for bypass around diverter and zero flow in casing) ambient flow values are shown in figure 20 and listed in table 12, which also shows estimated flow values for ambient conditions (where estimated values have relatively greater than typical uncertainty) and corrected flow values for pumping conditions. Under ambient conditions, little borehole flow was indicated by the estimated field measurements above 280 ft bls and increasing downward flow below 280 ft bls (table 12). The flow log collected under pumping conditions indicated that the fractures at near depths of about 95 and 185 ft bls appear to be the most hydraulically active water-bearing zones in the well.

The borehole video log, collected by USGS on November 9, 2017, when the water level was 28.2 ft bls, showed numerous horizontal and vertical fractures throughout the borehole. The number of suspended particles observed in the water column increased below about 300 ft bls, suggesting limited amount of active borehole flow at depths greater than 300 ft bls under ambient conditions at time of logging. Possible principal water-bearing zones were noted for discrete fractures in the range of depths from about 117.6–121, 133, 162.5–174, and 386–389.2 ft bls. Other possible water-bearing fractures indicated by geophysical logs also included those observed at depths of 96.5, 100, 184.5–187, 230.9, 246.3, 289–301, 309–319, and 395–397 ft bls. Video-log images for selected fractures or openings in well BK-3062 are shown in figure 21.

BK-3063 (HN-116)

Well BK-3063 is a new monitor well (HN-116) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) that was logged and subsequently tested by USGS using straddle packers to isolate discrete intervals for hydraulic characterization and sampling in 2018 (Senior and others, 2020) before being reconstructed in 2019. The well was initially constructed with a 6-in. diameter casing to a depth of about 19 ft bls, and below that depth was a 6-in. diameter open hole to 601 ft bls (table 2). Well BK-3063 is near a cluster of active, relatively shallow (less than 100 ft in depth) extraction wells that are being pumped to address VOC contamination in Areas A and D of the former NAWC Warminster base (fig. 3; Battelle, 2016). Flow logs were collected under ambient and pumping conditions when extraction wells were shut down on May 24, 2018, and under ambient conditions when extraction wells were pumping on May 23, 2018. The depth to ambient water level at the time of logging was about 8.2 ft bls.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at about 25–50, 170–215, 400–420, 443, 547, and 595 ft bls being mostly high angle (fig. 22). The fluid-temperature log

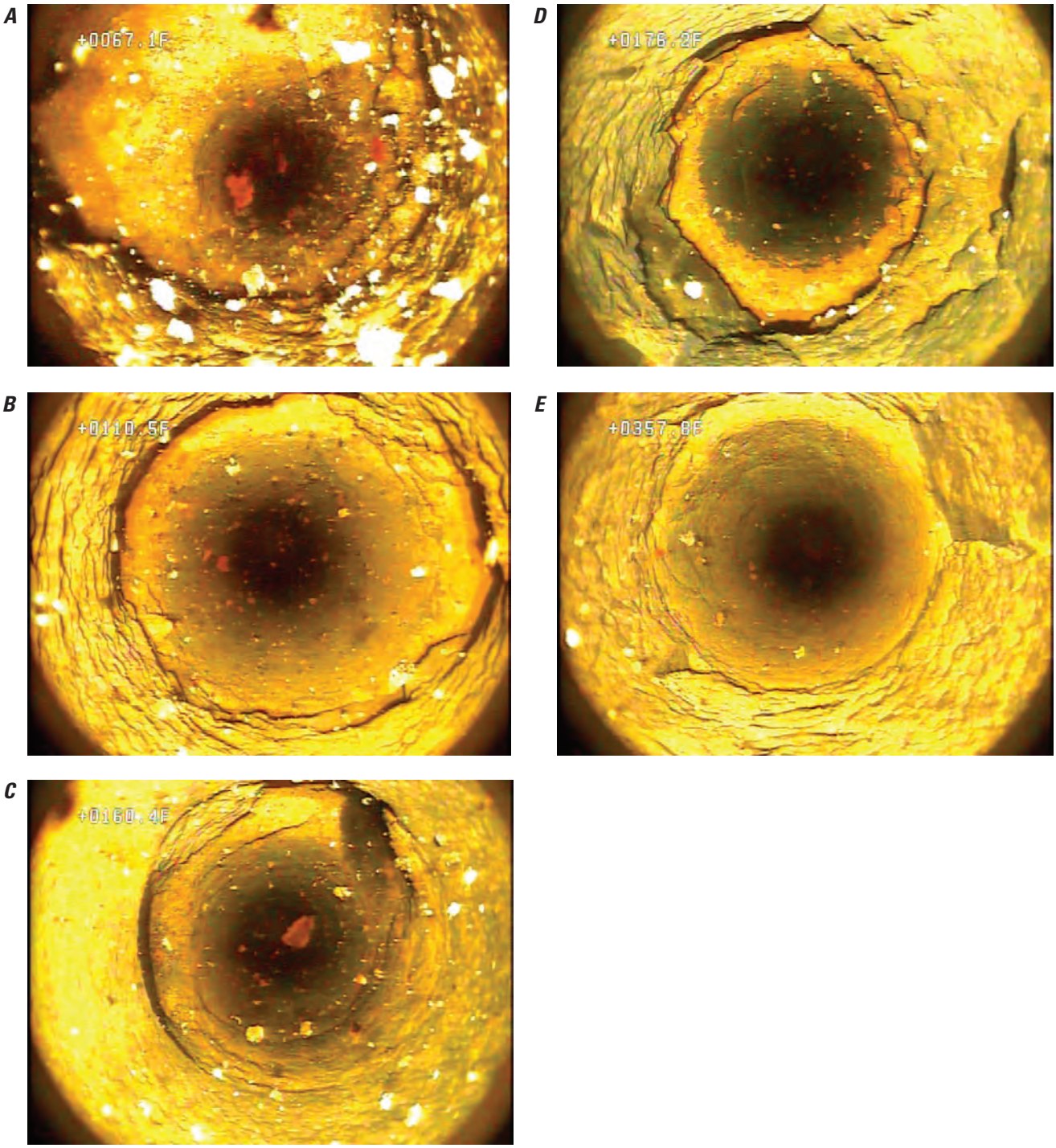


Figure 11. Still images from borehole video log of well BK-1129 (WMA well 36) at *A*, 67.1 feet below land surface (ft bls) showing bedding-plane opening and upward flow of particles, *B*, 110.5 ft bls showing bedding-plane opening and upward flow, *C*, 160.4 ft bls showing bedding-plane opening, *D*, 176.2 ft bls showing bedding-plane opening, and *E*, 357.8 ft bls showing possible bedding-plane openings and good visibility at depth with upward ambient flow. Video log collected by U.S. Geological Survey in well BK-1129, Warminster Township, Bucks County, Pennsylvania, August 29, 2018.

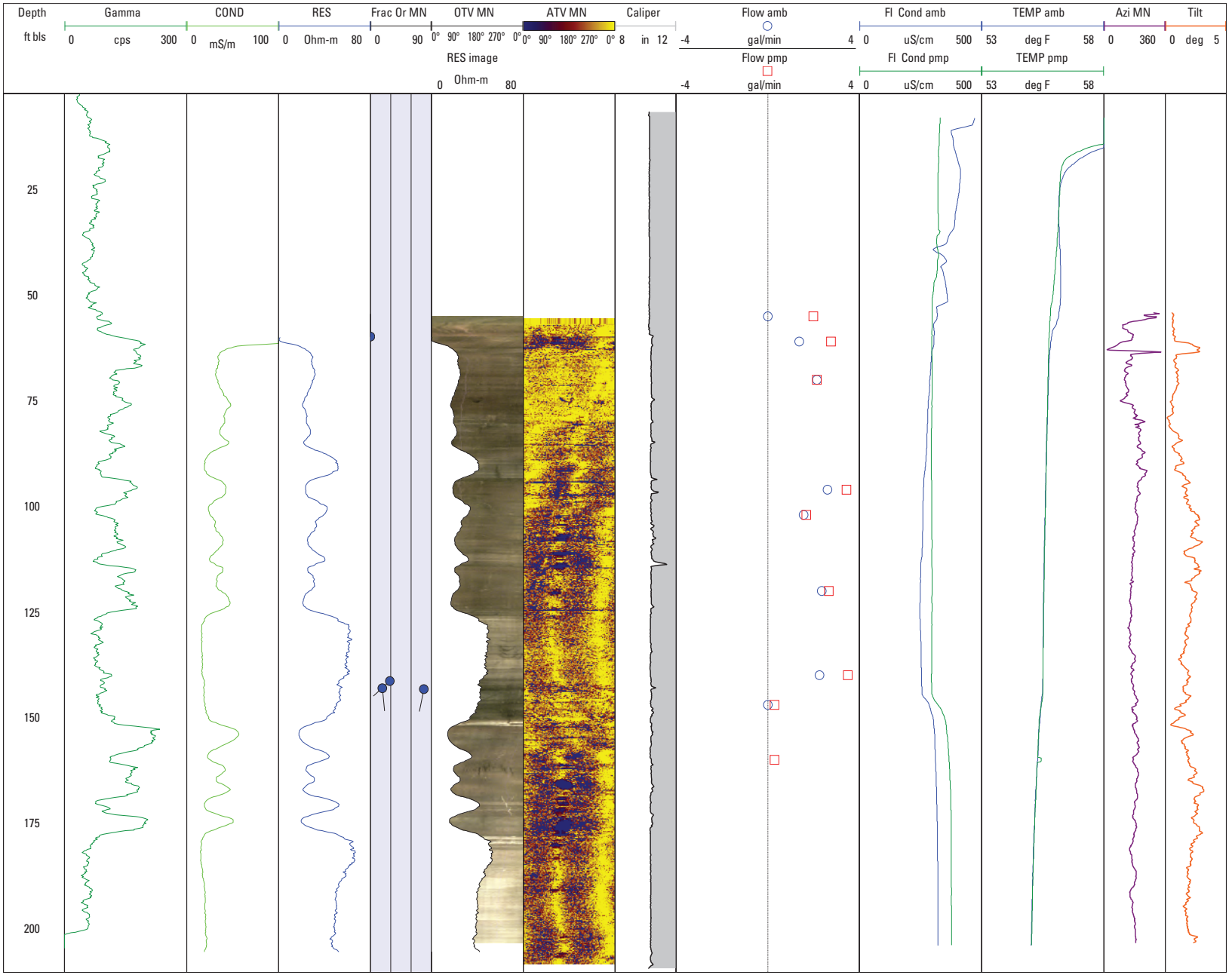


Figure 12. Geophysical logs collected by U.S. Geological Survey in well BK-2698 (WTWSA well 8), Warwick Township, Bucks County, Pennsylvania, September 10, 2019. See table 1 for explanation of abbreviations.

Table 8. Borehole flow-measurements collected by U.S. Geological Survey in well BK-2698 (WTWSA well 8), Warwick Township, Bucks County, Pennsylvania, September 10, 2019. Stationary measurements made using heat-pulse flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions. Flow measured with 8-inch diameter diverter in 10-inch diameter well, which affects accuracy of values as some flow bypasses the diverter.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
55	0.00	55	2.00
61	1.38	61	2.76
70	2.15	70	2.15
96	2.61	96	3.44
102	1.57	102	1.69
120	2.36	120	2.67
140	2.27	140	3.50
147	0.00	147	0.31
160	--	160	0.31

[1]Ambient flow measured starting at 14:58 on September 10, 2019.

[2]Pumping rate 2.0 gal/min; static water level is 1.20 ft bls at 15:22 prior to start of pumping; flow rate measured starting at 15:27; drawdown 0.81ft.

collected under ambient conditions shows inflections at about 35 and 400 ft bls that could be used to identify depth of water-bearing fractures. The fluid-temperature log collected under pumping conditions also shows an inflection at about 400 ft bls. The fluid-conductivity logs collected under ambient and pumping conditions show similar inflections at about 400, 425, and 440 ft bls. The flow log collected under ambient conditions when nearby extraction wells were shutdown indicates upward flow at depths above 181 ft bls, with upward flow decreasing substantially between depths of 47 and 38 ft bls, and downward flow below depths of 207 ft bls, with downward flow increasing substantially below depth of 395 ft bls (table 13). This pattern indicates that water enters the borehole through the fractures near 200 ft bls and flows up to exit fractures between 47 and 38 ft bls; water also enters the borehole through fractures near 200, 400, and 430 ft bls and flows down to exit fractures near the bottom of the borehole. The flow log collected under ambient conditions when nearby extraction wells were pumping shows a similar pattern but with generally larger upward flow rates when compared to the ambient flow log collected when extraction wells were

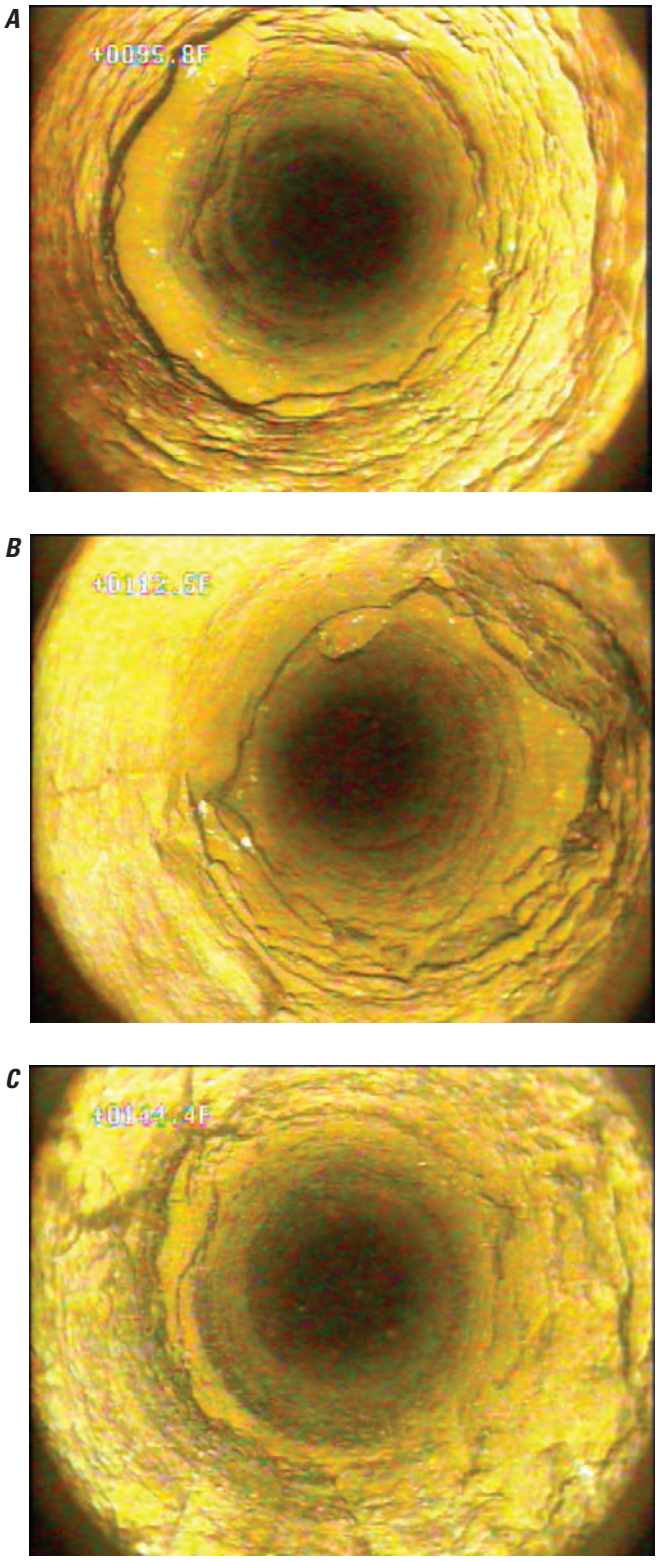


Figure 13. Still images from borehole video log of well BK-2698 (WTWSA well 8) at *A*, 95.8 feet below land surface (ft bls) showing possible bedding-plane opening, *B*, 112.8 ft bls showing possible bedding-plane opening, and *C*, 144.5 ft bls showing possible bedding-plane openings. Video log collected by U.S. Geological Survey in well BK-2698, Warwick Township, Bucks County, Pennsylvania, August 27, 2019.

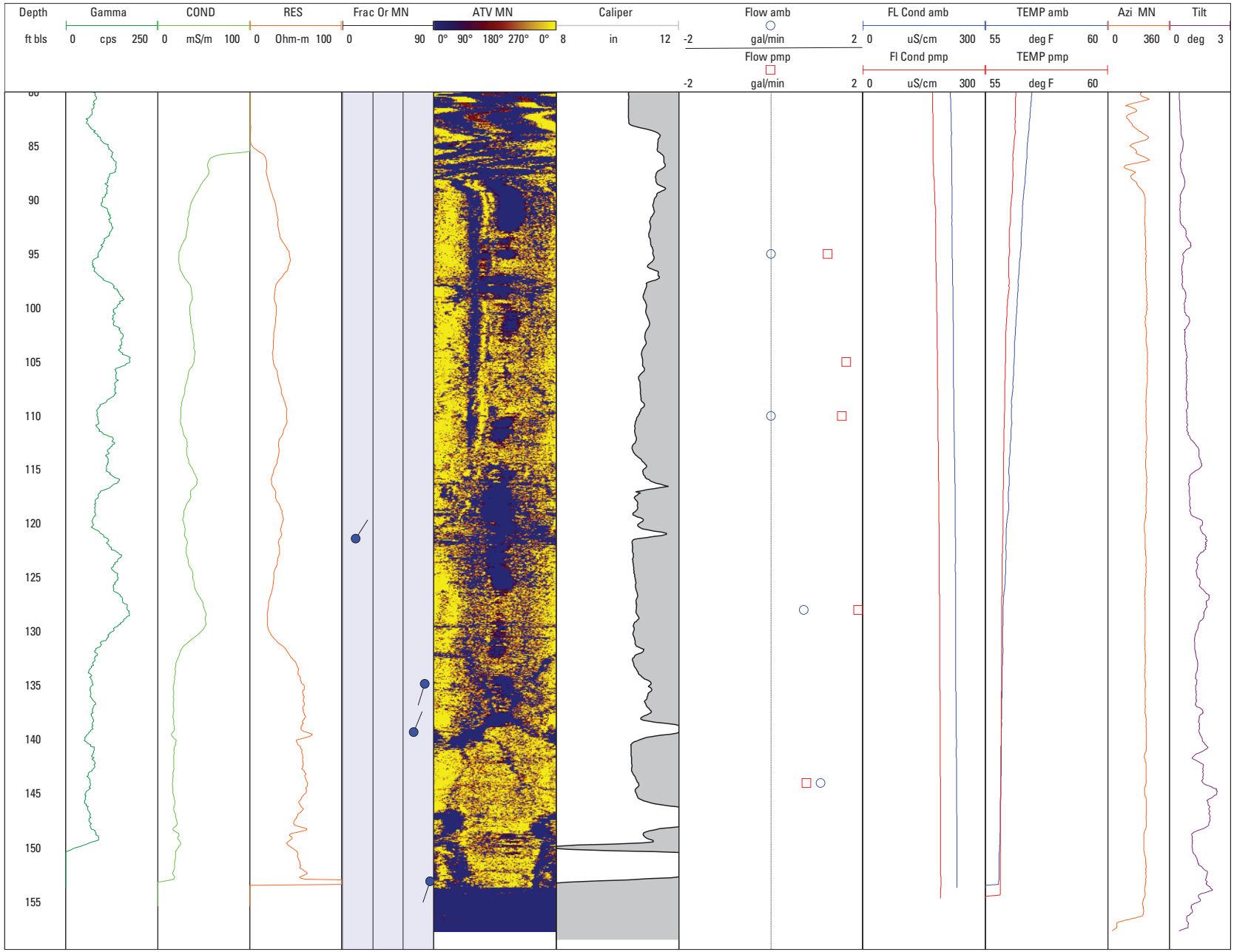


Figure 14. Geophysical logs collected by U.S. Geological Survey in well BK-2861 (WTWSA well 11), Warwick Township, Bucks County, Pennsylvania, September 12, 2019. See table 1 for explanation of abbreviations.

Table 9. Borehole flow-measurements collected by U.S. Geological Survey in well BK-2861 (WTWSA well 11), Warwick Township, Bucks County, Pennsylvania, September 12, 2019. Stationary measurements made using heat-pulse flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions. Flow measured with 8-inch diameter diverter in 10-inch diameter well, which affects accuracy of values as some flow bypasses diverter.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
70	--	70	1.70
95	0.00	95	1.24
105	--	105	1.65
110	0.00	110	1.55
128	0.72	128	1.91
144	1.08	144	0.77

[1]Static water level 1.9 ft bls on September 12, 2019.

[2]Pumping rate 1.7 gal/min; drawdown 0.51 ft.

shutdown, indicating nearby pumping enhances upward flow above 200 ft bls. The flow log collected under pumping conditions when nearby extraction wells were shutdown indicated that the fractures near 200 ft bls and above 47 ft bls are among the most hydraulically active water-bearing zones in the upper part of the borehole; fractures near 400, 430, and 590–595 ft bls are among the most hydraulically active water-bearing zones in the lower part of the borehole.

The borehole video log, collected by USGS on May 21, 2018, when the water level was 9.4 ft bls, showed numerous vertical and some horizontal fractures throughout the borehole. Probable water-bearing zones were noted for fractures at about 20.5, 33–35, 40–45, 105.8–114, 170–178.5, 181.6–213, 398–420, 433–441, 452.7, 474.8, 540–544.7, 563.5, and 588–597 ft bls. Turbulence was observed near fractures at about 40–45 and 181.6–213 ft bls. Video-log images for selected fractures or openings in well BK-3063 are shown in figure 23.

BK-3066 (HN-118)

Well BK-3066 is a new monitor well (HN-118) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) that was logged and subsequently tested by USGS using straddle packers to isolate discrete intervals for hydraulic characterization and sampling in 2018 (Senior and others, 2020)

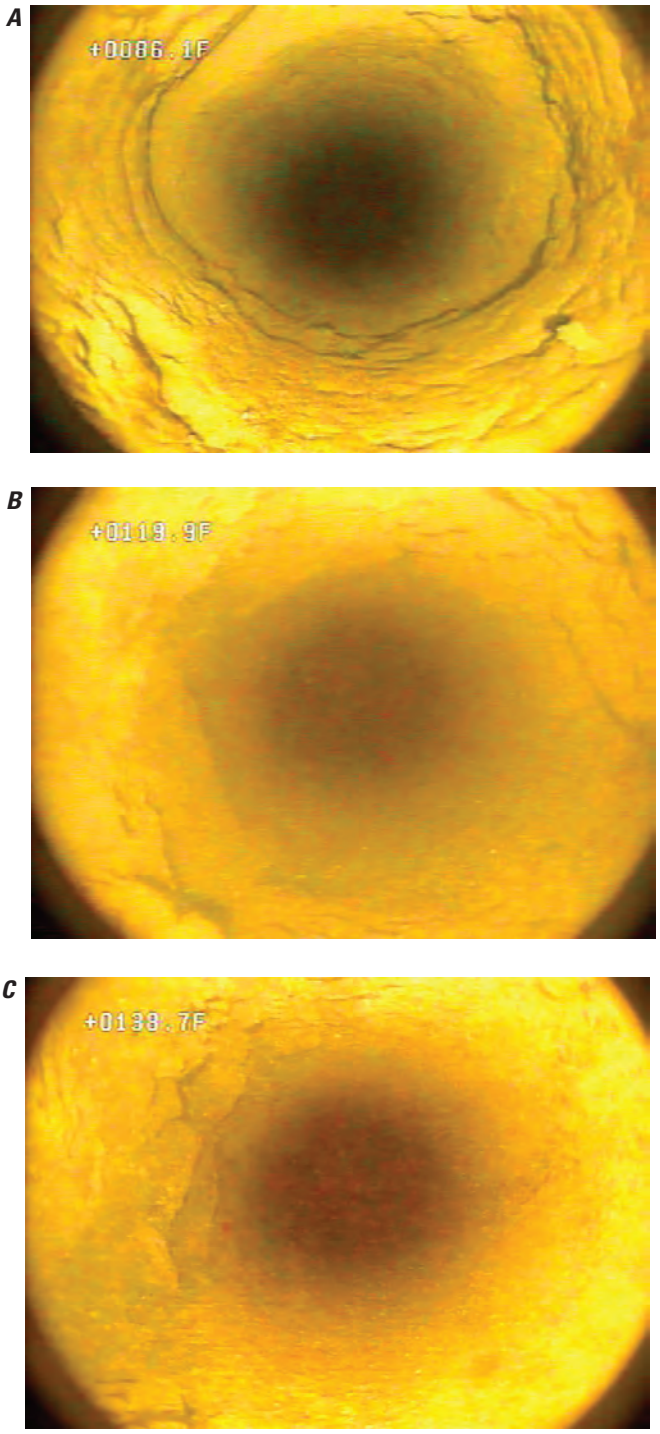


Figure 15. Still images from borehole video log of well BK-2861 (WTWSA well 11) at *A*, 86.1 feet below land surface (ft bls) showing possible bedding-plane opening out-of-round hole owing to overboring, *B*, 119.9 ft bls showing water-bearing openings obscured by poor visibility related to suspended particulates, and *C*, 138.7 ft bls showing possible water-bearing openings obscured by poor visibility related to suspended particulates. Video log collected by U.S. Geological Survey in well BK-2861, Warwick Township, Bucks County, Pennsylvania, August 6, 2019.

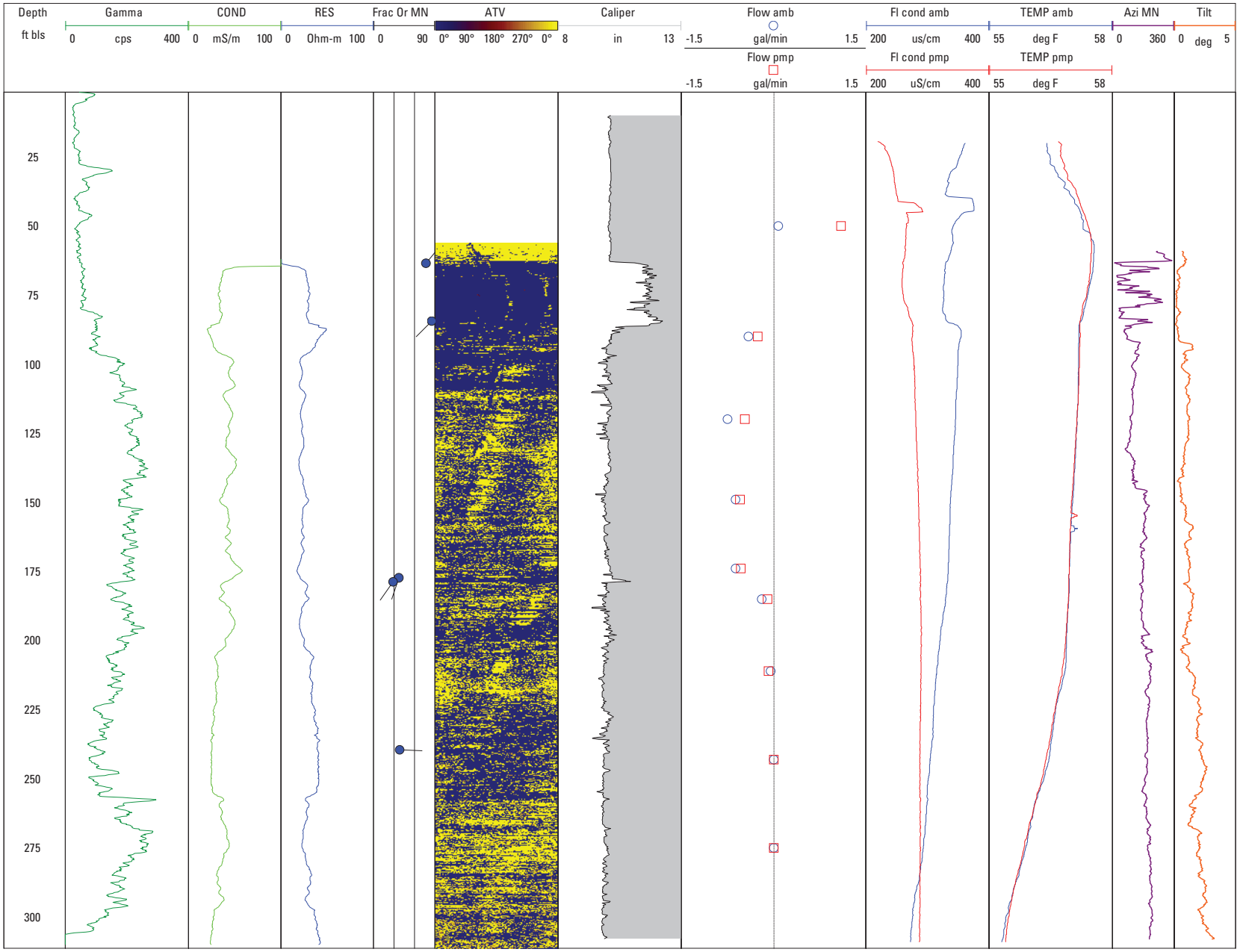


Figure 16. Geophysical logs collected by U.S. Geological Survey in well BK-2869 (WTWSA well 9), Warwick Township, Bucks County, Pennsylvania, June 16–17, 2019. See table 1 for explanation of abbreviations.

Table 10. Borehole flow-measurements collected by U.S. Geological Survey in well BK-2869 (WTWSA well 9), Warwick Township, Bucks County, Pennsylvania, June 16–17, 2019. Stationary measurements made using heat-pulse flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions. Flow measured with 8-inch diameter diverter in 10-inch diameter well, which affects accuracy of values as some flow bypasses diverter.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
50	0.08	50	1.10
90	–0.41	90	–0.25
120	–0.75	120	–0.46
149	–0.62	149	–0.55
174	–0.62	174	–0.53
185	–0.19	185	–0.10
211	–0.05	211	–0.08
243	0.00	243	0.00
275	0.00	275	0.00

[1]Ambient flow measured starting at 11:32 on September 12, 2019.

[2]Pumping rate 1.1 gal/min; static water level is 20.0 ft bls at 13:22 prior to start of pumping; flow rate measured starting at 14:01; drawdown 1.02 ft.

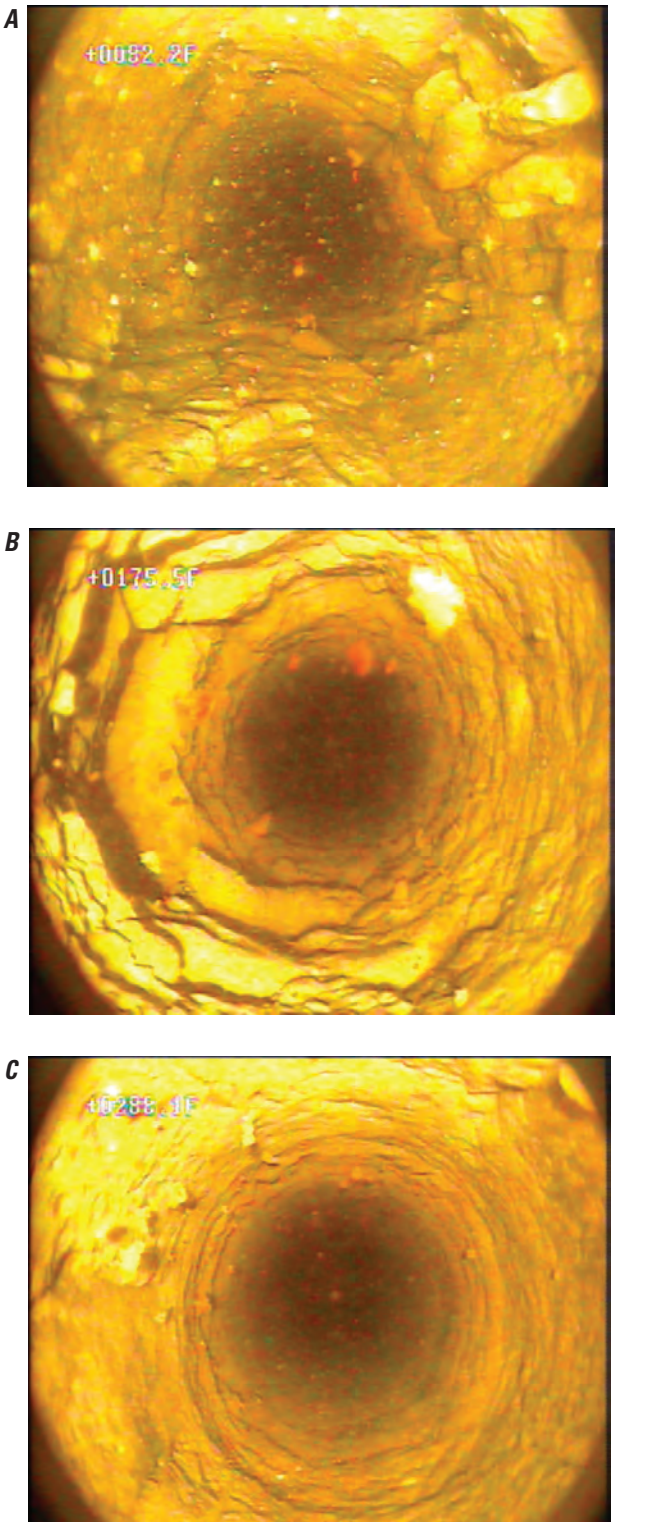


Figure 17. Still images from borehole video log of well BK-2869 (WTWSA well 9) at *A*, 82.2 feet below land surface (ft bls) showing high-angle fractures and out-of-round hole due to overboring, *B*, 175.5 ft bls showing bedding-plane opening, and *C*, 288.1 ft showing possible bedding-plane opening. Video log collected by U.S. Geological Survey in well BK-2869, Warwick Township, Bucks County, Pennsylvania, July 25, 2019.

before being reconstructed in 2019. The well was initially constructed with a 6-in. diameter casing to a depth of about 19 ft bls and below that depth was a 6-in. diameter open hole to 602 ft bls (table 2). The depth to ambient water level at the time of logging was not stable, suggesting the possible influence of nearby pumping. The measured depth to water level was 30.82 ft bls at 10:32 and 29.30 ft bls at 13:36 on August 7, 2018. Cascading water from fractures above ambient water level was heard and noted at the time of logging, conditions that could potentially affect accuracy of water levels measurements, although field notes do not indicate problems with water-level measurements.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at depths ranging from 19 to about 100 ft bls (fig. 24). Most fractures are low angle except for fractures near 100 and 540 ft bls that are high angle. The fluid-temperature logs collected under ambient and pumping conditions show inflections at about 100 and 590 ft bls that help identify depth of water-bearing fractures. The fluid-temperature log collected under ambient conditions also shows an inflection at about 80 ft bls. The

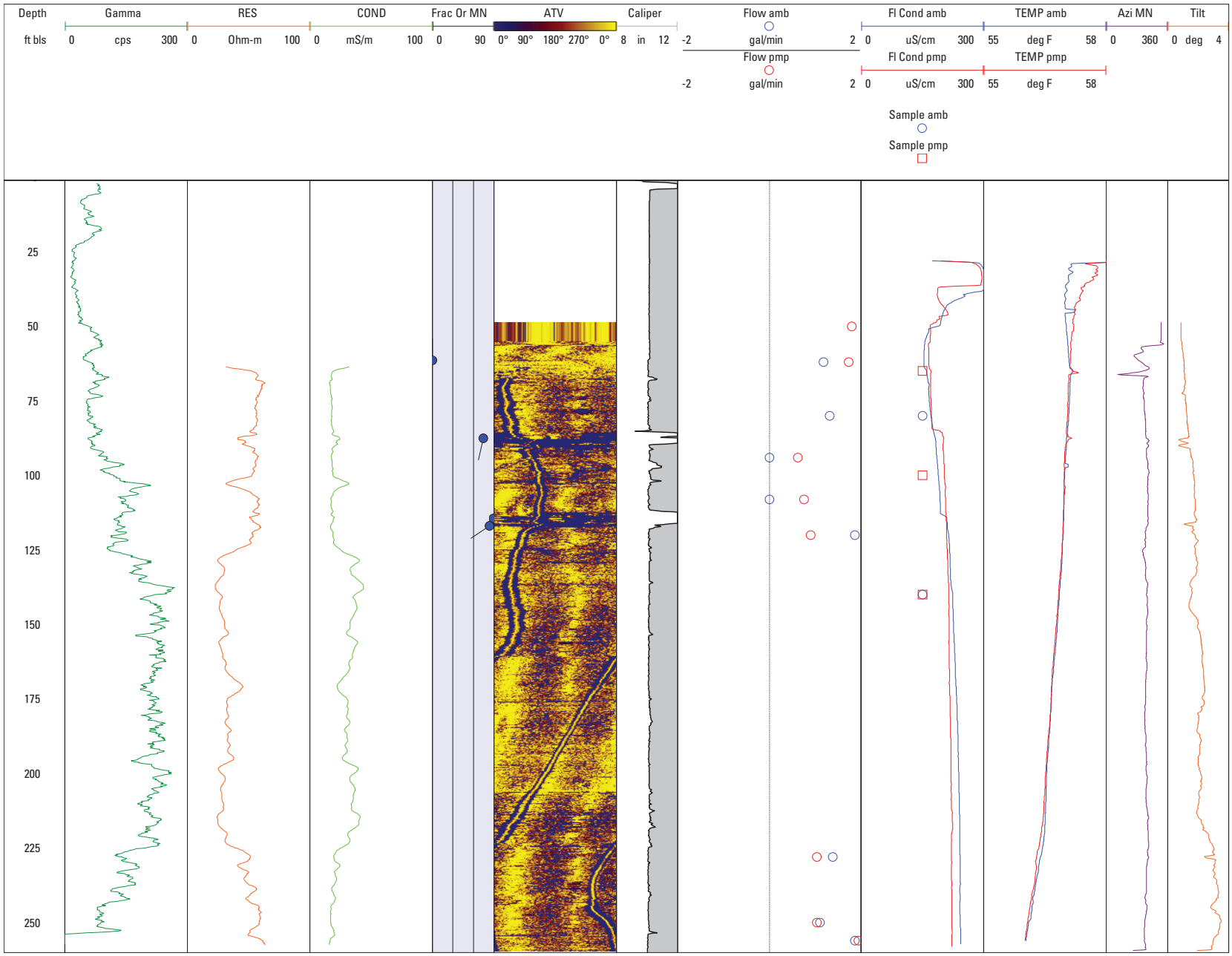


Figure 18. Geophysical logs collected by U.S. Geological Survey in well BK-2870 (WTWSA well 10), Warwick Township, Bucks County, Pennsylvania, September 11, 2019. See table 1 for explanation of abbreviations. Depth of point samples collected under ambient and pumping conditions shown on fluid conductivity logs.

Table 11. Borehole flow-measurements collected by U.S. Geological Survey in well BK-2870 (WTWSA well 10), Warwick Township, Bucks County, Pennsylvania, September 11, 2019. Stationary measurements made using heat-pulse flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions. Flow measured with 8-inch diameter diverter in 10-inch diameter well, which affects accuracy of values as some flow bypasses diverter.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
62	1.18	50	1.80
80	1.31	62	1.73
94	0.00	94	0.62
108	0.00	108	0.76
120	1.87	120	0.90
228	1.38	228	1.04
250	1.11	250	1.04
256	1.87	256	1.94

[1]Ambient flow measured starting at 11:51 on September 11, 2019.

[2]Pumping rate 1.8 gal/min; static water level is 29.38 ft bls at 16:17 prior to start of pumping; flow rate measured starting at 15:46; drawdown 0.32 ft.

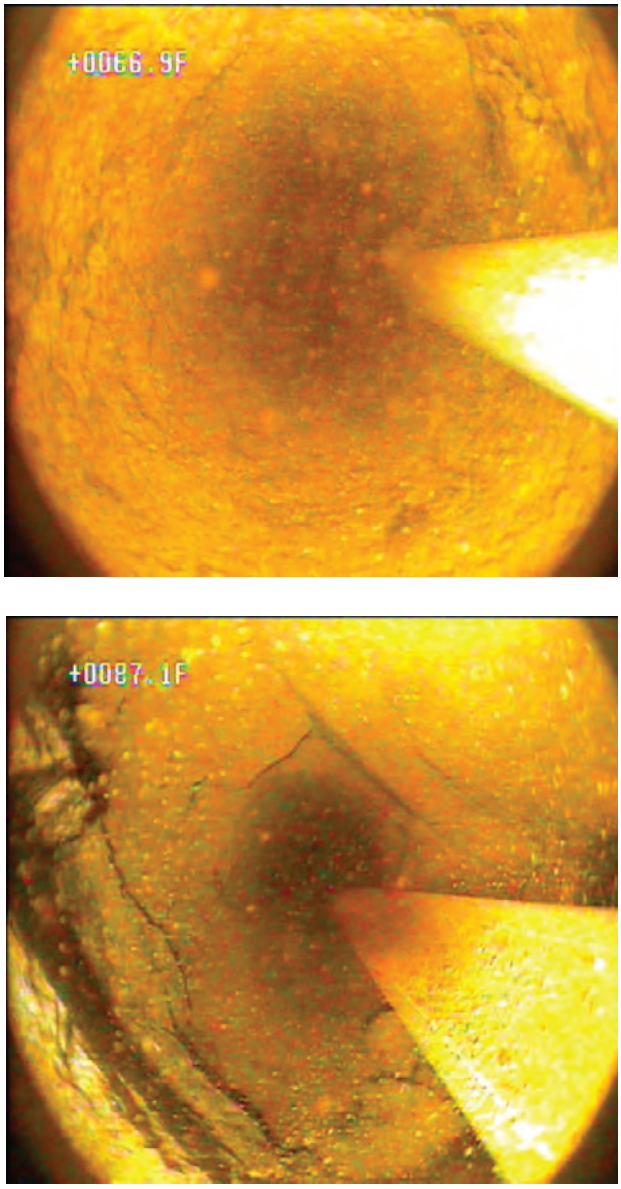


Figure 19. Still images from borehole video log of well BK-2870 (WTWSA well 10) at *A*, 66.9 feet below land surface (ft bls) showing low-angle opening and *B*, 87.1 ft bls showing vertical fracture and top of plastic pipe left in borehole. Video log collected by U.S. Geological Survey in well BK-2870, Warwick Township, Bucks County, Pennsylvania, August 9, 2019.

fluid-conductivity logs collected under ambient and pumping conditions both show small inflections at about 100 and 150 ft bls.

The flow log collected under ambient conditions indicates downward flow at depths below 35 ft bls, with downward flow increasing substantially between depths of 35 and 39 ft bls, then decreasing substantially between depths of 530 and 550 ft bls, and decreasing again between depths of 565 and 574 and also between 574 and 595 ft bls (table 14). This pattern indicates that water enters the borehole through the fractures near 19 to 39 ft bls and flows down to exit fractures near 540, 570, and 590 ft bls under ambient conditions at the time of logging. The flow log collected under pumping conditions indicated that the fractures between 35 and 39 ft bls are the most hydraulically active water-bearing zones in the well. Downward flow rates were greater when measured under pumping conditions than under ambient conditions, suggesting changes in aquifer conditions possibly related to changes in nearby pumping. Measured depth to water levels during pumping at a constant rate was unstable and does not reflect a typical drawdown pattern; levels rose from 30.45 ft bls at 14:15 (after 10 minutes of pumping) to 29.46 ft bls at 15:17 (after 72 minutes of pumping), then declined slightly to 29.70 ft bls at 15:28 (after 83 minutes of pumping) (table 14). An active 600-ft-deep production well is close enough (about 2,150 ft slightly down dip) to potentially affect aquifer conditions in the vicinity of well BK-3066.

The borehole video log, collected by USGS on August 2, 2018, when the water level was 32.9 ft bls, showed numerous horizontal and some vertical fractures throughout the

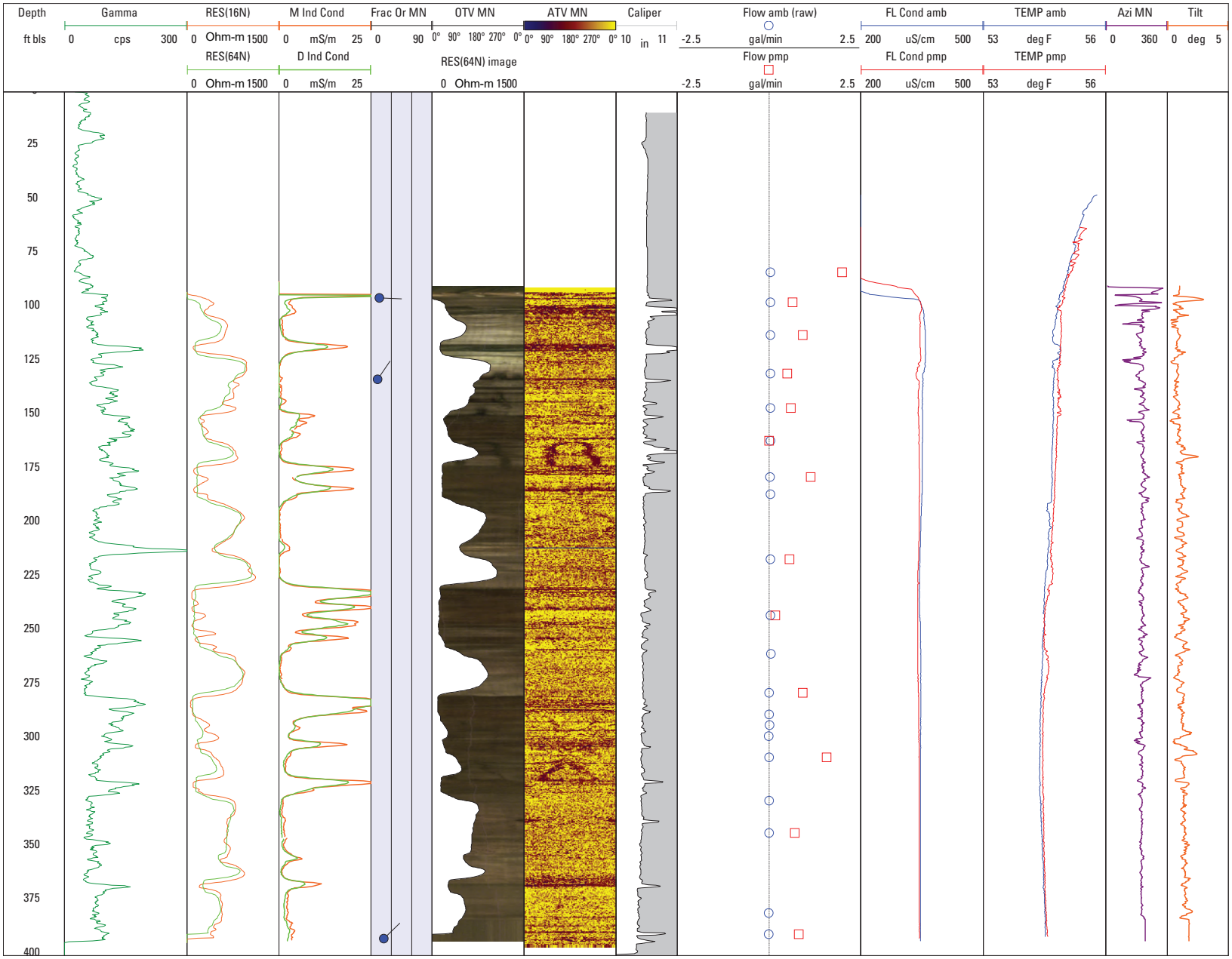


Figure 20. Geophysical logs collected by U.S. Geological Survey in well BK-3062 (NBCMA well 15), Northampton Township, Bucks County, Pennsylvania, November 28–29, 2017. See table 1 for explanation of abbreviations. Ambient flow values are raw uncorrected values; see table 12 for adjusted ambient flow values.

Table 12. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3062 (NBCMA well 15), Northampton Township, Bucks County, Pennsylvania, November 28–29, 2017. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions. Flow measured with 8-inch diameter diverter in 10-inch diameter well, which affects accuracy of values as some flow bypasses diverter.

[ft, feet; bls, below land surface; est, estimated value; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions			Pumping conditions	
Depth (ft bls)	Flow amb[1], raw (gal/min)	Flow amb[2], est (gal/min)	Depth (ft bls)	Flow pmp[3], corr (gal/min)
85	0.05	0.00	85	2.00
99	0.05	0.02	99	0.65
114	0.04	–0.15	114	0.92
132	0.04	–0.11	132	0.49
148	0.05	0.00	148	0.60
163	0.05	0.00	163	0.00
180	0.04	–0.26	180	1.14
188	0.04	–0.09	188	--
218	0.05	–0.02	218	0.56
244	0.04	–0.06	244	0.17
262	0.06	0.17	262	--
280	0.01	–0.84	280	0.92
290	0.01	–0.75	290	--
295	0.02	–0.56	295	--
300	0.00	–1.05	300	--
310	0.00	–1.01	310	1.57
330	0.00	–1.01	330	--
345	0.00	–1.01	345	0.71
382	–0.01	–1.16	382	--
392	0.00	–1.10	392	0.82

[1]Ambient water level = 30.49 ft bls when flow measurements started at 8:57 on November 29, 2017;

[2]Owing to larger than usual uncertainty in measurements indicated by variability in observed raw values at given depths, estimated flow may be inaccurate where estimated flow represents raw values that were adjusted based on zero flow in casing under ambient conditions and known upward flow of 2 gal/min under pumping conditions.

[3]Pumping rate = 2.0 gal/min; start pump at 11:24, end pump at 12:34; drawdown = 2.25 ft; flow corrected using same adjustment factors used to compute estimated values under ambient conditions

borehole. Water was observed cascading into the borehole at a depth of about 23 ft bls, above the ambient water level. Probable water-bearing zones were noted for fractures at about 23, 37, 99–104, 152.7, 318, 323, 479.8, 512.5, 525–540, and 568.2 ft bls. Other possible water-bearing fractures were noted near 60.8, 80.1, 201.9, 251.1, 290.2, 294.6, 299, 310.5, 337.6, 438.4–445, 483.3, 519.8, 549, and 573.3 ft bls. In addition, possible water-bearing fractures indicated by geophysical logs also included those observed at depths of 587.9–590 ft bls. Turbulence was observed near fractures at about 152.7, 201.9, and 568.2 ft bls. Video-log images for selected fractures or openings in well BK-3063 are shown in figure 25.

BK-3067 (HN-119)

Well BK-3067 is a new monitor well (HN-119) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) that was logged and subsequently tested by USGS using straddle packers to isolate discrete intervals for hydraulic characterization and sampling in 2018 (Senior and others, 2020) before being reconstructed in 2019. The well was initially constructed with a 6-in. diameter casing to a depth of about 20 ft bls and below that depth was a 6-in. diameter open hole to 602 ft bls (table 2). The depth to ambient water level at the time of logging was about 55 ft bls.

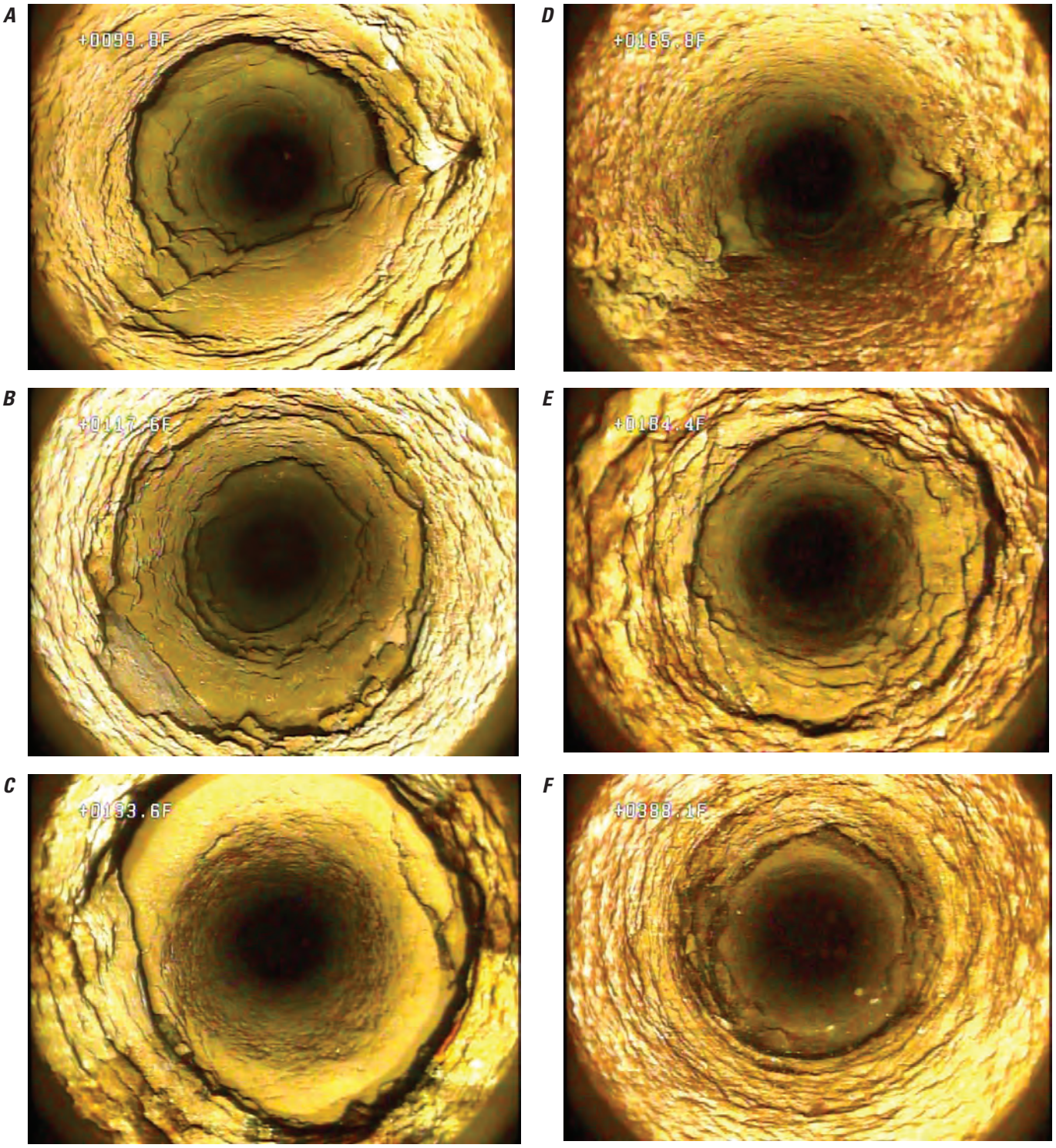


Figure 21. Still images from borehole video log of well BK-3062 (NBCMA 15) at *A*, 99.8 feet below land surface (ft bls) showing high-angle fractures and bedding-plane opening, *B*, 117.6 ft bls showing bedding-plane openings, *C*, 133.6 ft bls showing bedding-plane openings, *D*, 165.8 ft bls showing high-angle fractures, *E*, 184.4 ft bls showing bedding-plane openings, and *F*, 388.1 ft bls bedding-plane openings. Video log collected by U.S. Geological Survey in well BK-3062, Warminster Township, Bucks County, Pennsylvania, November 9, 2017.

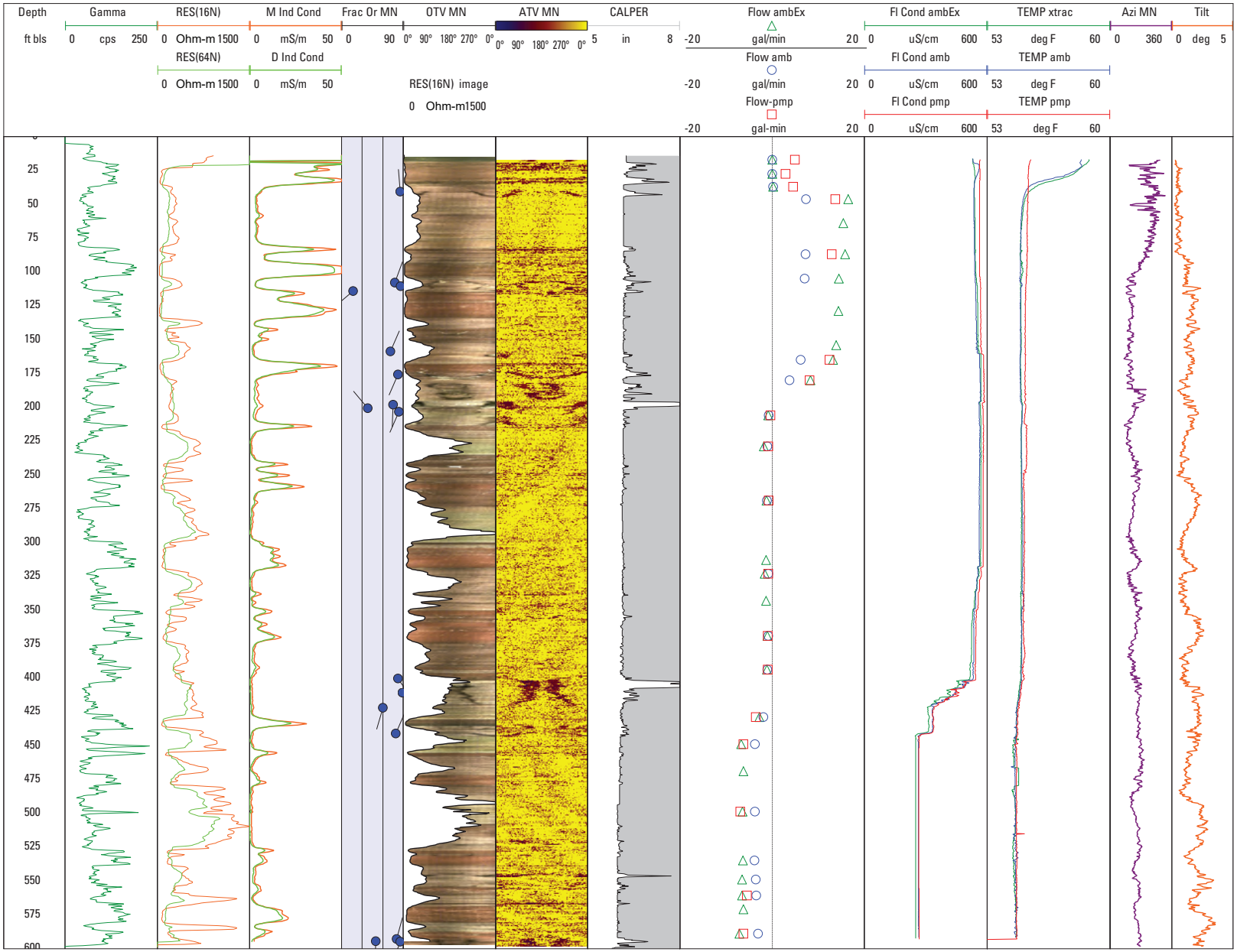


Figure 22. Geophysical logs collected by U.S. Geological Survey in well BK-3063 (HN-116), Warminster Township, Bucks County, Pennsylvania, May 24–25, 2018. See table 1 for explanation of abbreviations. Note that ambient flow and fluid logs were measured under conditions when nearby extraction wells were pumping (green symbols and lines) and not pumping (red).

Table 13. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3063 (HN-116), Warminster Township, Bucks County, Pennsylvania, May 24–25, 2018. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Ambient flow collected on May 24 when nearby extraction wells were pumping and on May 25 when nearby extraction wells were shutdown. Ambient and in-well pumping flow collected on May 25 when nearby extraction wells were shutdown. Flow values reported in table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

May 23, 2018, nearby pumping on, ambient conditions		May 24, 2018, nearby pumping off, ambient conditions		May 24, 2018, nearby pumping off, pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow amb[2], corr (gal/min)	Depth (ft bls)	Flow pmp[3], corr (gal/min)
18	0.00	18	0.00	18	5.00
28.5	0.02	28.5	0.01	28.5	2.95
38	0.25	38	0.23	38	4.60
47	16.48	47	7.40	47	13.70
65	15.44	65	--	65	--
88	15.87	88	7.23	88	12.97
106	14.54	106	7.07	106	--
130	14.42	130	--	130	--
155	13.90	155	--	155	--
166	13.21	166	6.22	166	12.47
181	8.30	181	3.78	181	8.16
207	–0.86	207	–0.77	207	–0.33
230	–1.77	230	–1.04	230	–0.82
270	–1.24	270	–1.10	270	–0.75
314	–1.32	314	--	314	--
324	–1.58	324	-0.82	324	-0.80
344	–1.32	344	--	344	--
370	–1.06	370	–0.82	370	–0.96
395	–1.06	395	–0.97	395	–0.94
430	–2.75	430	–1.87	430	–3.53
450	–6.72	450	–3.67	450	–6.23
470	–6.21	470	--	470	--
500	–6.43	500	–3.75	500	–6.90
536	–6.33	536	–3.77	536	--
550	–6.51	550	–3.48	550	--
562	–6.51	562	–3.43	562	–5.41
572	–6.23	572	--	572	--
590	–7.09	590	–3.02	590	–6.23

[1]Flow measured on May 23, 2018, starting at 13:44 under ambient conditions in well BK-3063 and nearby extraction wells were pumping; depth to water was 9.60 ft bls at 13:58 and fluctuated slightly during logging, ranging from a minimum of 9.42 ft bls at 14:43 to a maximum of 9.95 ft bls at 15:02 on May 23, 2018.

[2]Flow measured on May 24, 2018, starting at 07:45 under ambient conditions in well BK-3063 and nearby extraction wells were not pumping; depth to water was 8.54 ft bls at 07:41 and fluctuated slightly during logging under ambient conditions, ranging from a maximum of 8.58 ft bls at 08:41 to a minimum of 8.29 ft bls at 09:16 on May 24, 2018.

[3]Flow measured on May 24, 2018, starting at 11:44 under pumping conditions in well BK-3063; pump in well BK-3063 started at 11:03 at rate of 5 gal/min; nearby extraction wells were not pumping; depth to water was 8.22 ft bls at 11:00 and 8.72 ft bls at 11:40.

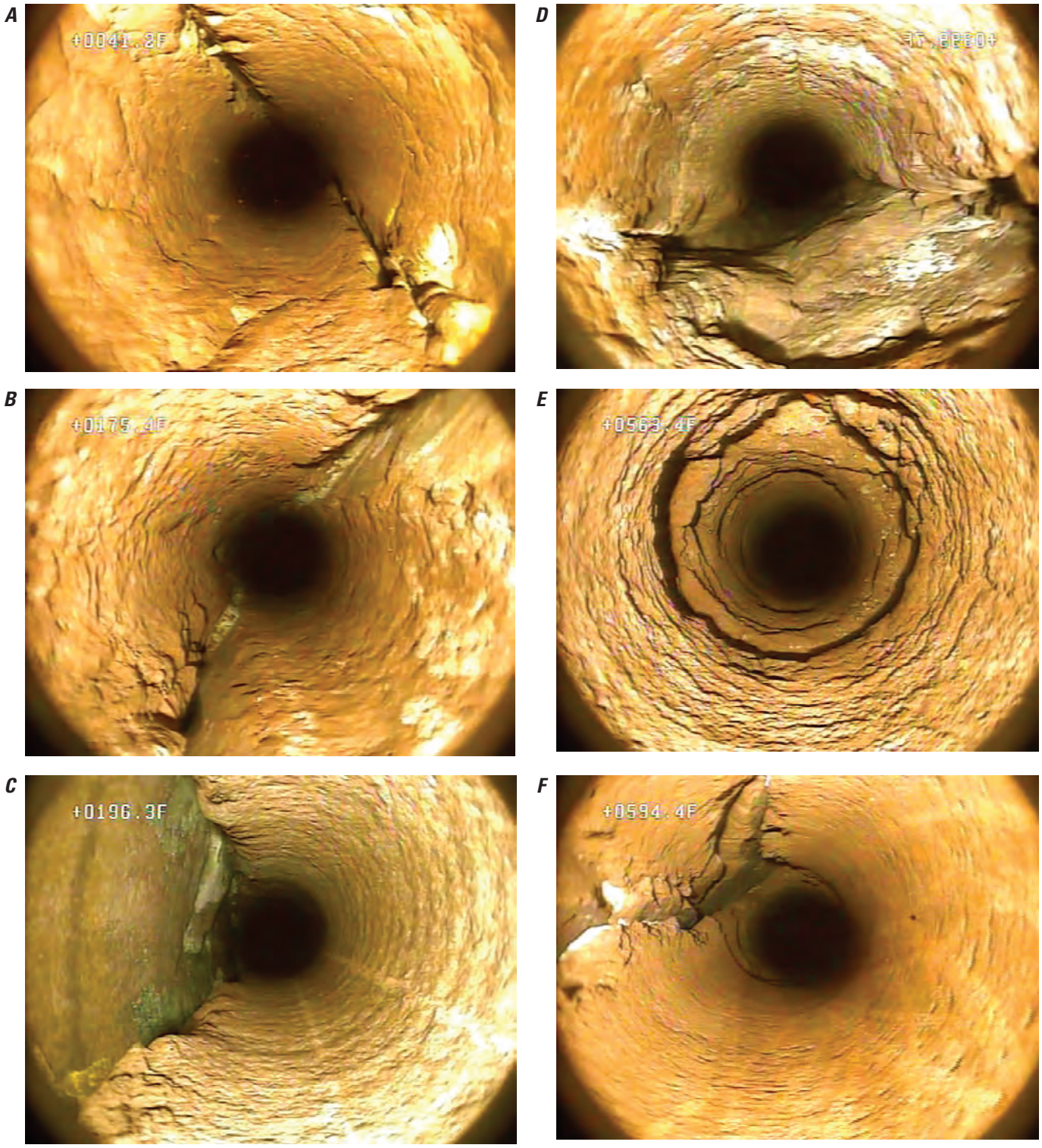


Figure 23. Still images from borehole video log of well BK-3063 (HN-116) at *A*, 41.2 feet below land surface (ft bls) showing high-angle fractures, *B*, 175.4 ft bls showing large high-angle fractures, *C*, 196.3 ft showing high-angle fracture plane at edge of borehole, *D*, 399.7 ft bls showing lithology change and high-angle fractures, *E*, 563.4 ft bls showing low-angle bedding-plane opening, and *F*, 594.4 ft bls showing high-angle fractures that terminates at bedding-plane opening. Video log collected by U.S. Geological Survey in well BK-3063, Warminster Township, Bucks County, Pennsylvania, May 21, 2018.

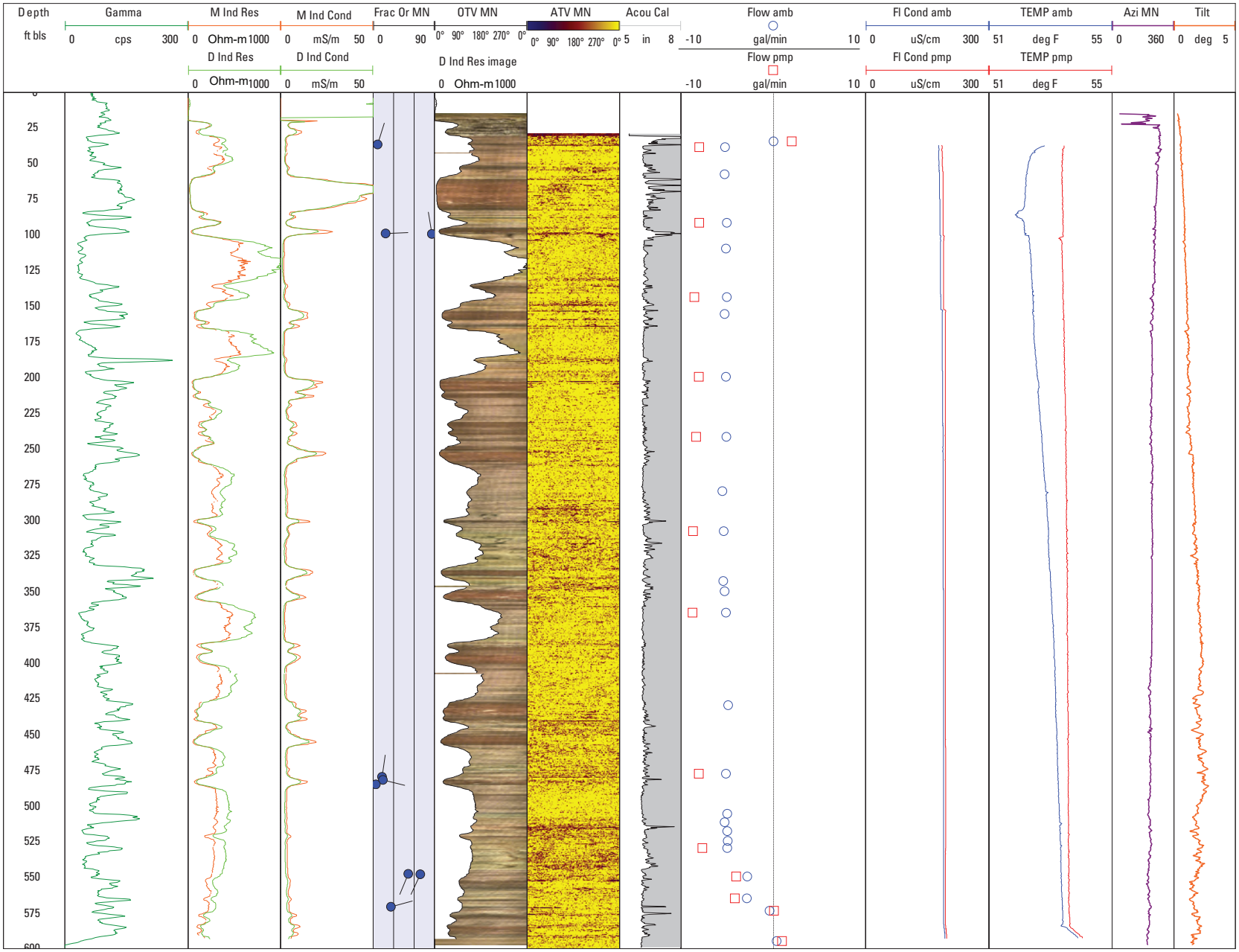


Figure 24. Geophysical logs collected by U.S. Geological Survey in well BK-3066 (HN-118), Warminster Township, Bucks County, Pennsylvania, August 6–7, 2018. See table 1 for explanation of abbreviations.

Table 14. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3066 (HN-118), Warwick Township, Bucks County, Pennsylvania, August 6–7, 2018. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
35	0.00	35	2.00
39	–5.24	39	–8.01
58	–5.28	58	--
92	–5.03	92	–8.01
110	–5.16	110	--
144	–5.03	144	–8.54
156	–5.26	156	--
200	–5.14	200	–8.05
242	–5.10	242	–8.38
280	–5.54	280	--
308	–5.37	308	–8.70
343	–5.44	343	--
350	–5.28	350	--
365	–5.13	365	–8.74
430	–4.91	430	--
478	–5.13	478	–8.07
506	–4.98	506	--
512	–5.28	512	--
518	–4.98	518	--
525	–4.95	525	--
530	–5.00	530	–7.67
550	–2.80	550	–4.03
565	–2.84	565	–4.17
574	–0.40	574	0.06
595	0.37	595	0.94

[1]Measured starting at 11:01 on August 7, 2018; depth to ambient water level was 30.82 ft bls at 10:32 and 29.30 ft bls at 13:36 on August 7, 2018.

[2]Pumping rate 2 gal/min started at 14:05 on August 7, 2018; flow measured under pumping conditions starting at 14:19 and ending at 15:21 on August 7, 2018; depth to water level was 30.45 ft bls at 14:15, 29.96 ft bls at 14:41, 29.46 ft bls at 15:17, and 29.70 at 15:28 on August 7, 2018.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at depths ranging from about 80 to 95, 125 to 160, and 175 to 185 ft bls (fig. 26). Many fractures are low angle but fractures near 150, 180, and 390 ft bls are high angle. Fluid and flow logs were collected only under ambient conditions. The fluid-temperature log collected under ambient conditions shows inflections near about 65, 125, 175, and 580 ft bls that could be used to identify depth of water-bearing fractures. The fluid-conductivity logs collected under ambient conditions show similar inflections near about 65, 125 and 175 ft bls.

The flow log collected under ambient conditions indicates downward flow at depths below 64 ft bls, with downward flow increasing between depths of 78–91, 118–144, 144–165, and also 176–194 ft bls, then decreasing between depths of 520 and 566 ft bls, and decreasing again below 595 ft bls (table 15). This pattern indicates that water probably enters the borehole through the fractures above 64 ft bls, near about 125, 150, and 185 ft bls, then flows down to exit fractures near 540 and below 595 ft bls under ambient conditions at the time of logging.

The borehole video log, collected by USGS on August 6, 2018, when the water level was 54.9 ft bls, showed numerous horizontal and vertical fractures throughout the borehole. Water was observed cascading into the borehole at depths of about 20.9, 29.4, and 31–35 ft bls, above the static water level. Probable water-bearing zones were noted for fractures at about 81.9, 151–153, 170.4, 177.6–185.3, 339, 371.7, 381.9, and 572–573 ft bls. Other possible water-bearing fractures were noted throughout the borehole. In addition, possible water-bearing fractures indicated by geophysical logs also included those observed at depths of 543, 544, 553.8, 563.2 (horizontal fractures) and 595 ft bls. Turbulence was observed near fractures at about 81.9, 120.4, and 339 ft bls. Video-log images for selected fractures or openings in well BK-3066 are shown in figure 27.

BK-3068 (HN-117)

Well BK-3068 is a new monitor well (HN-117) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) that was logged and subsequently tested by USGS using straddle packers to isolate discrete intervals for hydraulic characterization and sampling in 2018 (Senior and others, 2020) before being reconstructed in 2019. The well was initially constructed with a 6-in. diameter casing to a depth of about 19 ft bls and below that depth was a 6-in. diameter open hole to 600 ft bls (table 2). The depth to ambient water level at the time of logging was about 15.4 ft bls.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at depths in the range of 19 to 70 ft bls (fig. 28). Most fractures are low angle except for fractures near 25 and 325 ft bls that are high angle. The fluid-temperature logs collected under ambient and pumping conditions show the largest inflections at similar depths of about 45, 200, and 515 ft bls that could be used to

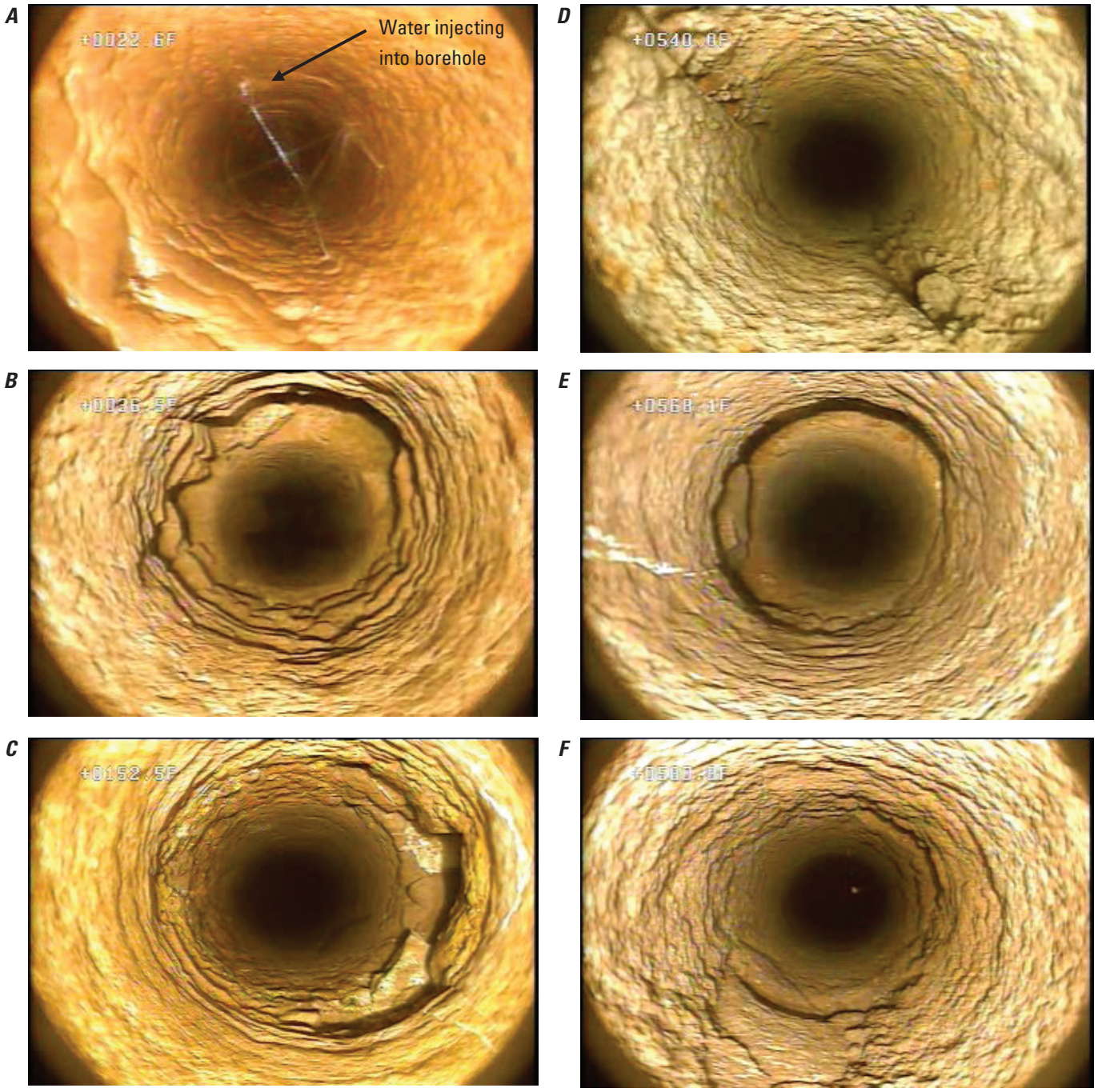


Figure 25. Still images from borehole video log of well BK-3066 (HN-118) at *A*, 22.6 feet below land surface (ft bls) showing water injecting into well from fractures above static water level of 32.8 ft bls, *B*, 36.5 ft bls showing bedding-plane openings, *C*, 152.5 ft bls showing bedding-plane openings near where turbulence was observed, *D*, 540.0 ft bls showing high-angle fractures, *E*, 568.1 ft bls showing bedding-plane openings, and *F*, 580.1.1 ft bls showing bedding-plane openings. Video log collected by U.S. Geological Survey in well BK-3066, Warminster Township, Bucks County, Pennsylvania, August 2, 2018.

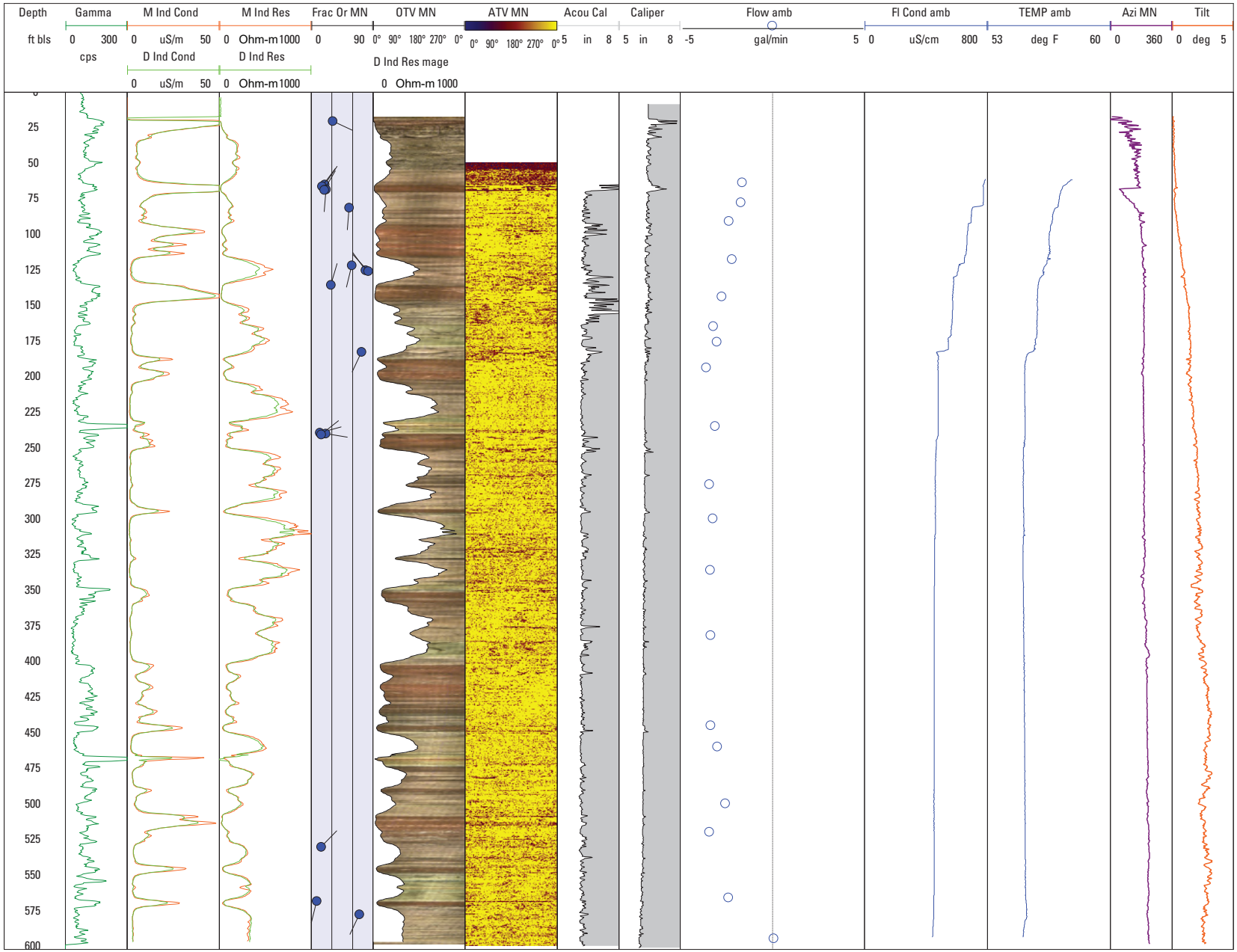


Figure 26. Geophysical logs collected by U.S. Geological Survey in well BK-3067 (HN-119), Warminster Township, Bucks County, Pennsylvania, August 8, 2018. See table 1 for explanation of abbreviations.

Table 15. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3067 (HN-119), Northampton Township, Bucks County, Pennsylvania, August 8, 2018. Stationary measurements made using an electromagnetic flow meter under ambient conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in table are raw measurements (not corrected).

[ft, feet; bls, below land surface; gal/min, gallons per minute; amb, ambient conditions]

Ambient conditions	
Depth (ft bls)	Flow amb[1] (gal/min)
64	–1.65
78	–1.72
91	–2.37
118	–2.21
144	–2.75
165	–3.23
176	–3.02
194	–3.61
235	–3.12
276	–3.44
300	–3.25
336	–3.39
382	–3.36
445	–3.37
460	–2.99
500	–2.56
520	–3.44
566	–2.41
595	0.07

[1]Flow measured under ambient conditions only starting at 13:39 on August 8, 2018; cascading water can be heard.

identify depth of water-bearing fractures. The fluid-conductivity logs collected under ambient and pumping conditions also show the largest inflections at about 45, 200, and 515 ft bls.

The flow log collected under ambient conditions indicates downward flow at depths below 19 ft bls but above 515 ft bls, with downward flow increasing most between depths of 19 and 35 ft bls and more gradually between depths of 35 and 200 ft bls, then decreasing slightly between depths of 322 and 340 and also between 495 and 509 ft bls (table 16). Small rates of upward flow were measured at 515 and 595 ft bls under ambient conditions (table 16). This pattern indicates that water probably enters the borehole through the fractures near the bottom of casing at 19 to 35 ft bls and also near numerous fractures in the range of depths from about 40 to 200 ft, including possibly near 45, 70, and 200 ft bls; water then flows down to exit fractures near 325 and 500 ft bls under ambient conditions at the time of logging. Under these conditions, water also enters the borehole below depths of 595 ft and appears to flow up to exit fractures near 500 ft bls. The flow log collected under pumping conditions (table 16) indicated that the fractures at depths above 32 and near 45 ft bls appear to be among the most hydraulically active water-bearing zones in the well.

The borehole video log, collected by USGS on August 28, 2018, when the water level was 14.8 ft bls, showed numerous horizontal and vertical fractures throughout the borehole and that the bottom of casing is 18.5 ft bls. Probable water-bearing zones were noted for fractures at about 18.5–30.4, 45.7–49.6, 64.9–70.7, 199.3, 327.5–333.5, 353.9, and 505.8–509.0 ft bls. Other possible water-bearing fractures were noted at 77.3–78.5 and 499.4 ft bls and elsewhere throughout the borehole. In addition, possible water-bearing fractures indicated by geophysical logs also included those observed at a depth of 596 ft bls. Turbulence was observed near fractures at about 18.5, 77.3–78.5, and 199.3 ft bls, with water injecting into the well at 199.3 ft bls. Video-log images for selected fractures or openings in well BK-3068 are shown in figure 29.

BK-3069 (HN-120S)

Well BK-3069 is a new monitor well (HN-120S) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) on October 23–24, 2018. The well was initially constructed with a 6-in. diameter casing to a depth of about 19 ft bls and below that depth was a 6-in. diameter open hole to 425 ft bls (table 2), but the borehole could not be completed to the target depth of 600 ft bls because of concern about ground collapse near the well head during drilling on October 24, 2018. The hole collapsed near 29 ft after drilling and was subsequently grouted to about that depth by the Navy's contractor.

The borehole video log collected by USGS on November 7, 2018, when the ambient water level was 12.6 ft bls was run only to a depth of 26 ft bls because of an obstruction near that depth. The video log showed large fractures and openings from below the bottom of the casing at 19 ft bls to 26 ft bls. The USGS did not collect geophysical logs in well BK-3069 (HN-120I). Video-log images for selected fractures or openings in well BK-3069 are shown in figure 30.

BK-3070 (HN-120D)

Well BK-3070 is a new monitor well (HN-120D) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) that was logged and subsequently tested by USGS using straddle packers to isolate discrete intervals for hydraulic characterization and sampling in 2018 (Senior and others, 2020) before being reconstructed in 2019. The well was initially constructed with a 6-in. diameter casing to a depth of about 59 ft bls and below that casing was a 6-in. diameter open hole to a reported depth of 580 ft bls, although at the

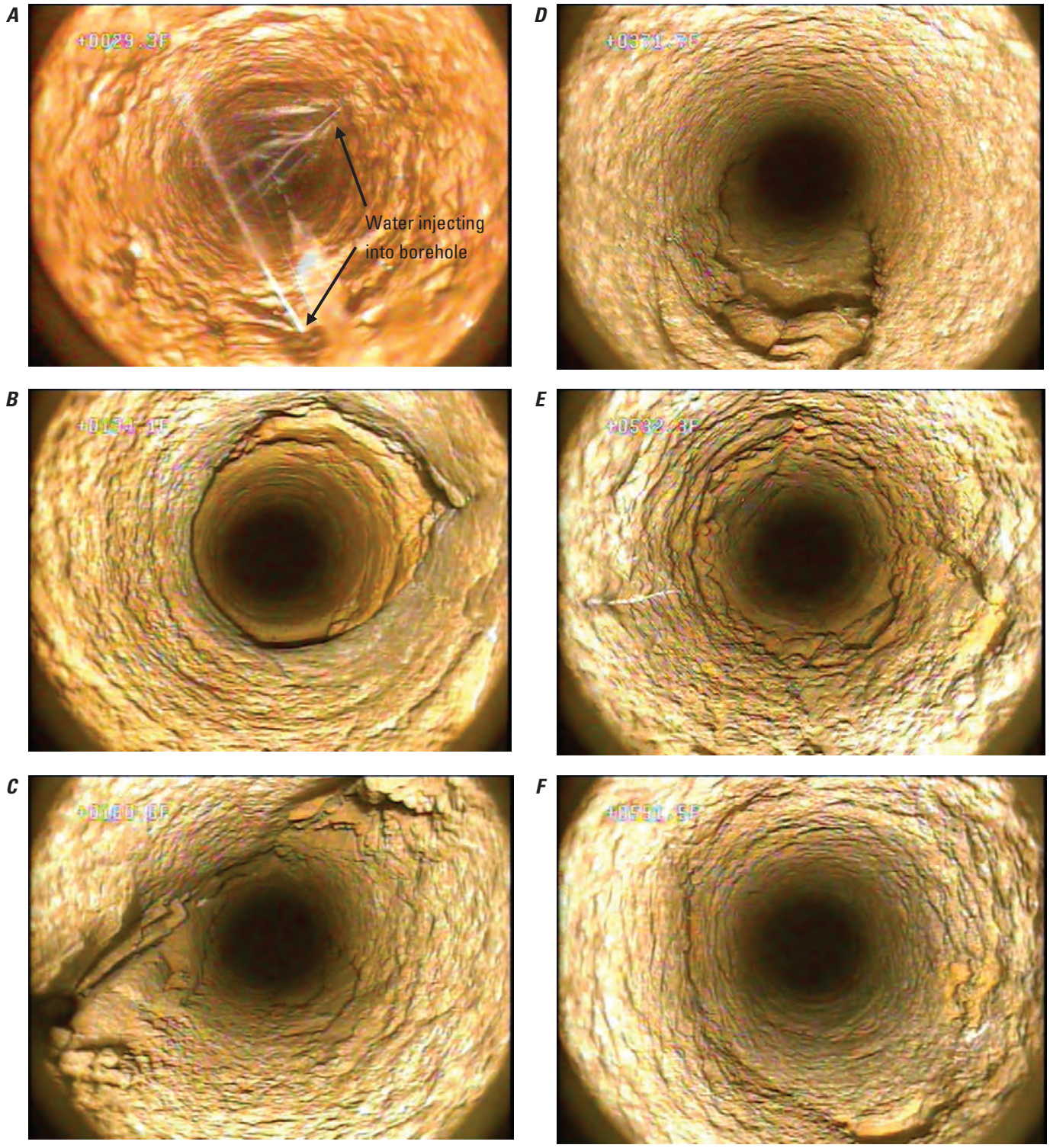


Figure 27. Still images from borehole video log of well BK-3067 (HN-119) at *A*, 29.3 feet below land surface (ft bls) showing water injecting into well from fractures above static water level of 54.9 ft bls, *B*, 134.1 ft bls bedding-plane openings at change in lithology, *C*, 180.7 ft bls showing high-angle fractures, *D*, 371.4 ft bls showing high-angle fractures, *E*, 532.3 ft bls showing bedding-plane openings, and *F*, 591.5 ft bls showing bedding-plane openings. Video log collected by U.S. Geological Survey in well BK-3067, Warminster Township, Bucks County, Pennsylvania, August 6, 2018.

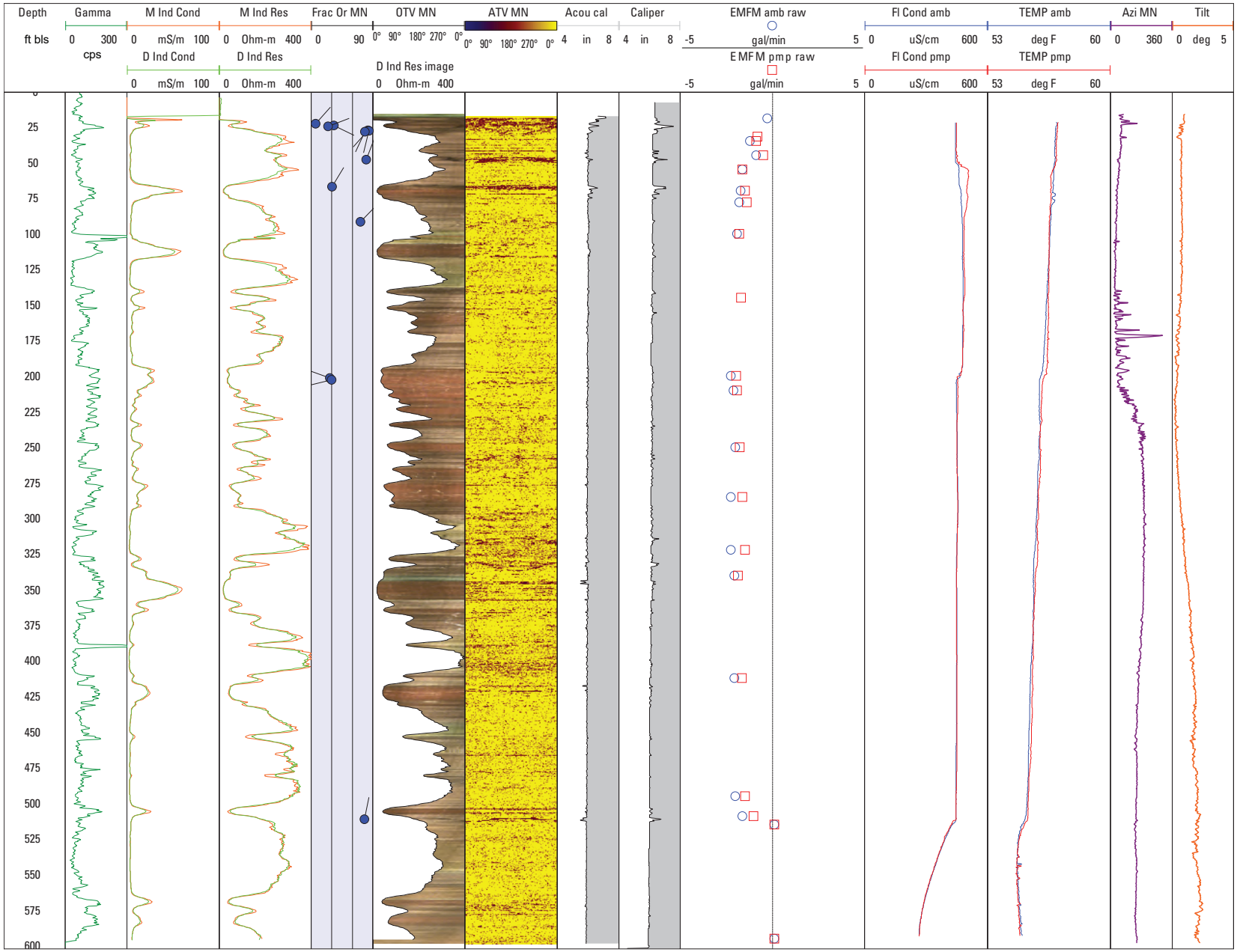


Figure 28. Geophysical logs collected by U.S. Geological Survey in well BK-3068 (HN-117), Warminster Township, Bucks County, Pennsylvania, August 9, 2018. See table 1 for explanation of abbreviations.

Table 16. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3068 (HN-117), Warminster Township, Bucks County, Pennsylvania, August 9, 2018. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in table are raw measurements (not corrected). Flow values at 45 feet below land surface may be smaller than actual because of borehole rugosity enlarging hole diameter.

[ft, feet; bls, below land surface; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1] (gal/min)	Depth (ft bls)	Flow pmp[2] (gal/min)
19	–0.28	19	--
32	--	32	–0.81
35	–1.23	35	–0.88
45	–0.88	45	–0.50
55	–1.63	55	–1.63
70	–1.72	70	–1.48
78	–1.80	78	–1.38
100	–1.91	100	–1.79
145	--	145	–1.70
200	–2.24	200	–1.96
210	–2.12	210	–1.92
250	–2.01	250	–1.78
285	–2.26	285	–1.62
322	–2.25	322	–1.49
340	–2.06	340	–1.88
412	–2.06	412	–1.64
495	–2.00	495	–1.47
509	–1.62	509	-0.03
515	0.10	515	0.10
595	0.10	595	0.10

[1]Flow measured starting at 11:52 on August 9, 2018.

[2]Pumping rate 2.5 gal/min; flow measured starting at 13:58 on August 9, 2018.

time of logging was only open to about 555 ft bls (table 2). The depth to ambient water level at the time of logging was about 15.4 ft bls. Well BK-3070 (HN-120D) was the second deep, new monitor well drilled at this location, to replace the first well (BK-3069, reconstructed as HN-120I) that could not be completed to a depth of 600 ft because of concern about ground collapse near the well head during drilling on October 23–24, 2018.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at depths in the range of 59 to 140 ft bls and near 195 ft bls (fig. 31). Many fractures are low angle but fractures near 100, 195, 350, and 375 ft bls are high angle. The fluid-temperature logs collected under ambient and pumping conditions show the largest inflections at similar depths of about 60, 195, 230 and 380 ft bls that could be used to identify depth of water-bearing fractures. The fluid-temperature log collected under pumping conditions also shows a small inflection near 290 ft bls. The fluid-conductivity logs collected under ambient and pumping conditions both show only a slight inflection at a depth of about 425 ft bls; the fluid-conductivity log collected under ambient conditions also shows a small inflection near 60 ft bls.

The flow log collected under ambient conditions indicates downward flow at depths below 62 ft bls, with downward flow increasing the most between depths of 62 and 68 ft bls and continued to increase to a depth of 124 ft bls; downward flow then starts to decrease, decreasing the most between depths of 185 and 205 ft bls and continuing to decrease substantially below the depth of 322 ft bls ft bls (table 17). Small rates of downward flow were measured from 380 to 545 ft bls under ambient conditions (table 17). This pattern indicates that water probably enters the borehole through the fractures near the bottom of the casing at 59 to 68 ft bls, then flows down to exit fractures near 130, 195, 230–300, 340, 380, 400, and possibly below 545 ft bls under ambient conditions at the time of logging. The flow log collected under pumping conditions (table 17) indicates that the fractures at depths above 68 ft bls appear to be the most hydraulically active water-bearing zones in the well.

The borehole video log, collected by USGS on October 31, 2018, when the water level was 15.4 ft bls, showed numerous horizontal and vertical fractures throughout the borehole and that the bottom of casing is 18.5 ft bls. Probable water-bearing zones were noted for fractures at about 58.3, 63.5, 110.1, 191.2, and 333.9 ft bls. Other possible water-bearing fractures were noted at 73.2–80.6, 92.2–94.5, 105.7, 116.7, 129.6, 143.5, 259.7, 302.3, 309.2, and 371 ft bls. Below 365 ft bls, haze in the water column increased with depth. Near 405 ft bls, visibility decreased to zero and video log collection was ceased. Turbulence with water injecting into the borehole was observed near fractures at about 63.5 ft bls and possibly near the bottom of casing at 58.3 ft bls. Possible turbulence was also noted near fractures at about 110.1 ft bls. Video-log images for selected fractures or openings in well BK-3070 are shown in figure 32.

BK-3071 (HN-121)

Well BK-3071 is a new monitor well (HN-121) drilled by the Navy on the former NAWC Warminster base (figs. 1 and 3) that was logged and subsequently tested by USGS using straddle packers to isolate discrete intervals for hydraulic characterization and sampling in 2018 (Senior and others, 2020) before being reconstructed in 2019. The well was initially constructed with a 6-in. diameter casing to a depth of about 20 ft bls and below that casing was a 6-in. diameter open hole to a reported depth of 600 ft bls, although at the time of logging

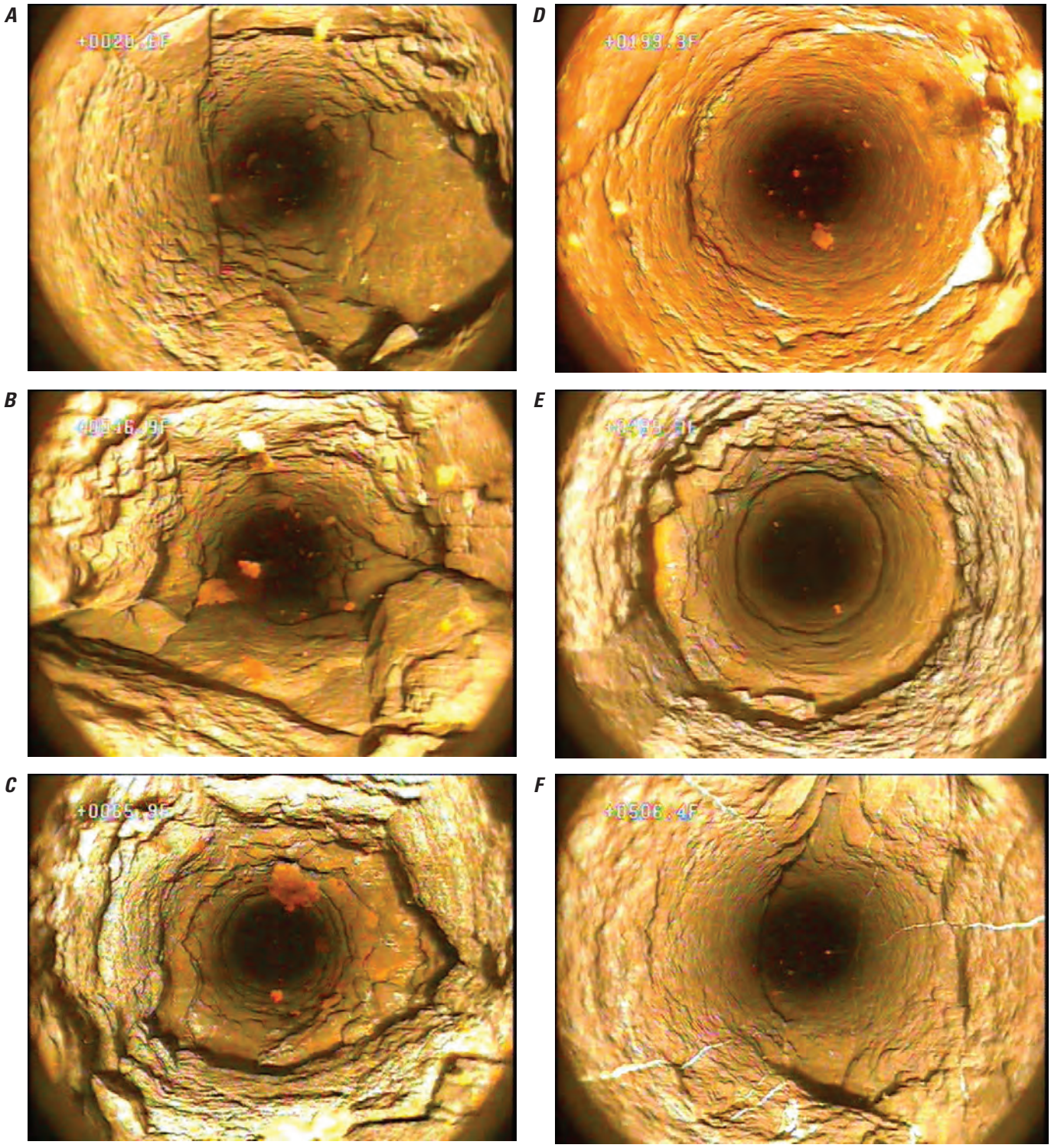


Figure 29. Still images from borehole video log of well BK-3068 (HN-117) at *A*, 20.4 feet below land surface (ft bls) showing high-angle fractures below bottom casing, *B*, 46.9 ft bls showing vertical fractures, *C*, 65.9 ft bls showing bedding- and fracture-plane openings, *D*, 199.3 ft bls showing low-angle opening where turbulence was observed, *E*, 499.6 ft bls showing bedding-plane openings, and *F*, 506.9 ft bls showing high-angle openings, Video log collected by U.S. Geological Survey in well BK-3068, Warminster Township, Bucks County, Pennsylvania, August 28, 2018.

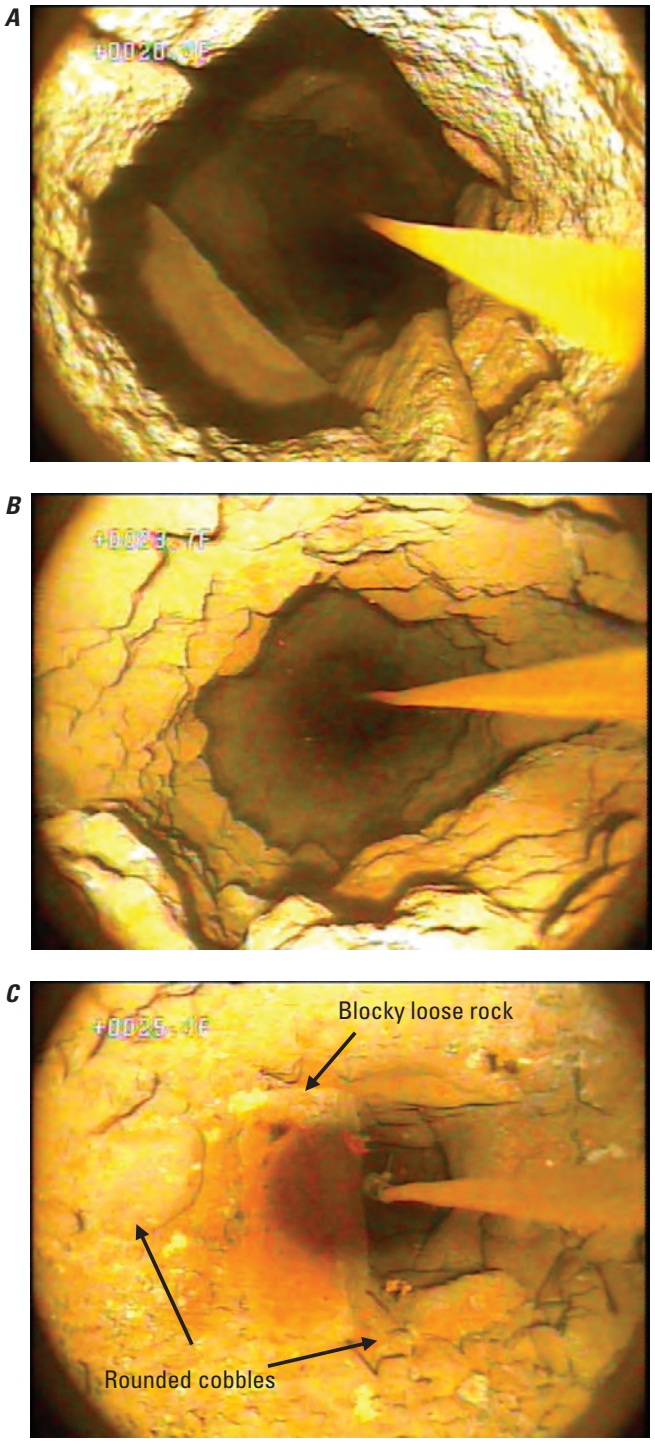


Figure 30. Still images from borehole video log of well BK-3069 (HN-120I) at *A*, 20.4 feet below land surface (ft bls) showing high-angle fractures just above large opening in borehole, *B*, 23.7 ft bls showing extensive openings possibly enhanced by dissolution, and *C*, 25.4 ft bls showing rounded cobbles and blocky loose rock in large void just above narrowing of borehole to 6 inch diameter hole. Cable in center of image is for a transducer suspended in well. Video log collected by U.S. Geological Survey in well BK-3069, Warminster Township, Bucks County, Pennsylvania, November 7, 2018.

was only open to about 415 ft bls (table 2) because of collapse below that depth. The depth to ambient water level at the time of logging was about 11.6 ft bls.

The caliper and ATV logs show numerous fractures throughout the borehole, with the largest openings at depths in the range of 20 to 115 ft bls and near 160, 290, 375, and 410 ft bls (fig. 33). The fluid-temperature logs collected under ambient conditions show small inflections at depths of about 30, 95, 305, and 345 ft bls that could be used to identify depth of water-bearing fractures. The fluid-conductivity logs collected under ambient and pumping conditions show only a slight inflection near 30 ft bls.

The flow log collected under ambient conditions indicates downward flow at depths below 34 ft bls, with downward flow increasing between depths of 34 and 110 ft bls, then decreasing between depths of 110 and 132 ft bls, remaining more or less constant from 132 to 238 ft bls before another slight decrease in downward flow between 256 and 360 ft bls, before decreasing again at 380 and 410 ft bls (table 18). This pattern indicates that water probably enters the borehole through the fractures near the bottom of casing at 20 to 34 ft bls and also through several fractures in the range from 34 to 110 ft bls, then travels down to possibly exit fractures near 250, 375, and below 410 ft bls under ambient conditions at the time of logging. The flow log collected under pumping conditions (table 18) indicated that the fractures at depths above 34 ft bls appear to be the most hydraulically active water-bearing zones in the well. Downward flow rates were greater when measured under pumping conditions than under ambient conditions, suggesting changes in aquifer conditions related to possible changes in nearby pumping or to other unknown factors. The closest known deep (600 ft) active production well is about 4,400 ft approximately along strike to the northeast of well BK-3070.

The borehole video log, collected by the USGS on November 6, 2018, when the water level was 11.4 ft bls, showed some horizontal and numerous vertical fractures throughout the borehole. Probable water-bearing zones were noted for fractures or openings at about 19.2–37.4, 69.4, 251.5, 283.3–289.8, 367.5–372 and 411 ft bls. Other possible water-bearing fractures were noted at 80.8–82.8, 83.6, 89.3, 108.3, 146, 154.1–157.3, 160.7, 201.8, 216, and 300.5 ft bls. Below about 411 ft bls, the borehole appeared to be collapsed and video log collection was ceased. Video-log images for selected fractures or openings in well BK-3071 are shown in figure 34.

Discussion of Log Lithology, Fracture Orientation, Borehole Deviation, and Borehole-flow Directions

The lithology of aquifer intervals penetrated by the wells as shown on optical televiewer, gamma, and resistivity logs appears to be alternating sequences of light-colored, relatively coarser-grained sandstones (lower gamma, higher resistivity)

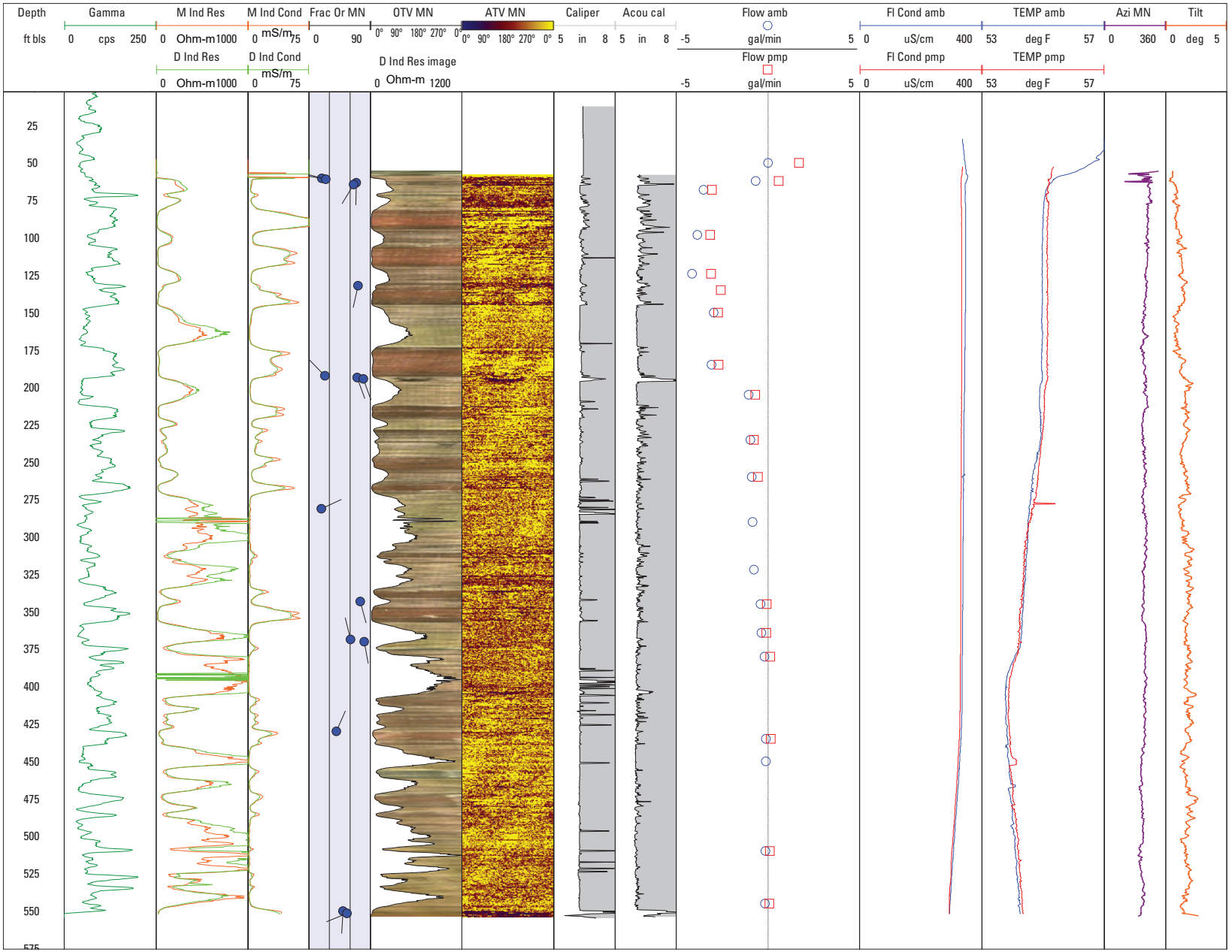


Figure 31. Geophysical logs collected by U.S. Geological Survey in well BK-3070 (HN-120D), Warminster Township, Bucks County, Pennsylvania, October 31, 2018. See table 1 for explanation of abbreviations.

Table 17. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3070 (HN-120D), Warminster Township, Bucks County, Pennsylvania, October 31, 2018. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
50	0.00	50	1.70
62	–0.66	62	0.58
68	–3.51	68	–3.06
98	–3.85	98	–3.15
124	–4.12	124	–3.10
135	--	135	–2.57
150	–2.95	150	–2.71
185	–3.08	185	–2.69
205	–1.04	205	–0.68
235	–0.95	235	–0.75
260	–0.88	260	–0.54
290	–0.82	290	--
322	–0.77	322	--
345	–0.40	345	–0.07
364	–0.36	364	–0.07
380	–0.18	380	0.12
435	–0.12	435	0.15
450	–0.12	450	--
510	–0.14	510	0.11
545	–0.15	545	0.08

[1]Static water level was 15.44 ft bls; ambient flow measured starting at 08:55 on October 31, 2018.

[2]Pumping rate 1.8 gal/min; flow measured starting at 11:52 on October 31, 2018; drawdown 0.2 ft.

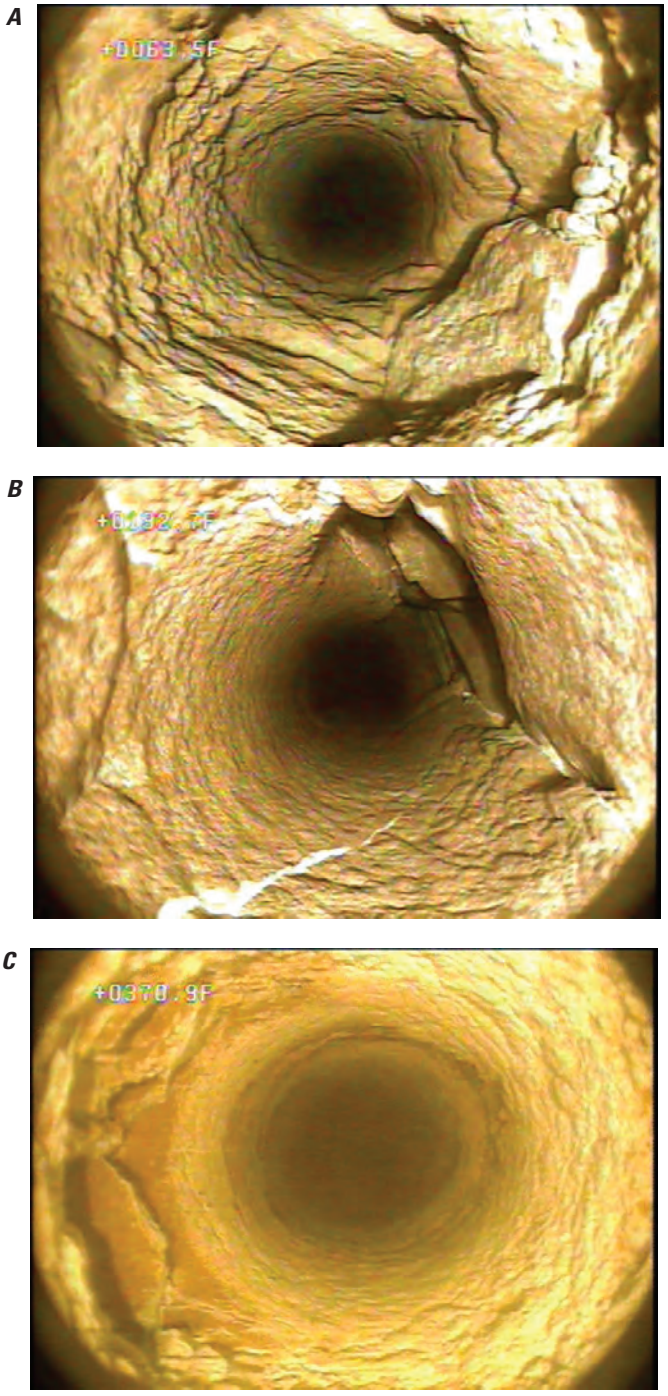


Figure 32. Still images from borehole video log of well BK-3070 (HN-120D) at *A*, 63.5 feet below land surface (ft bls) showing high-angle fractures and bedding-plane opening, *B*, 192.7 ft bls showing vertical fractures, and *C*, 370.9 ft bls showing bedding-plane openings and decreased visibility in borehole related to decreased vertical borehole flow. Video log collected by U.S. Geological Survey in well BK-3070, Warminster Township, Bucks County, Pennsylvania, October 31, 2018.

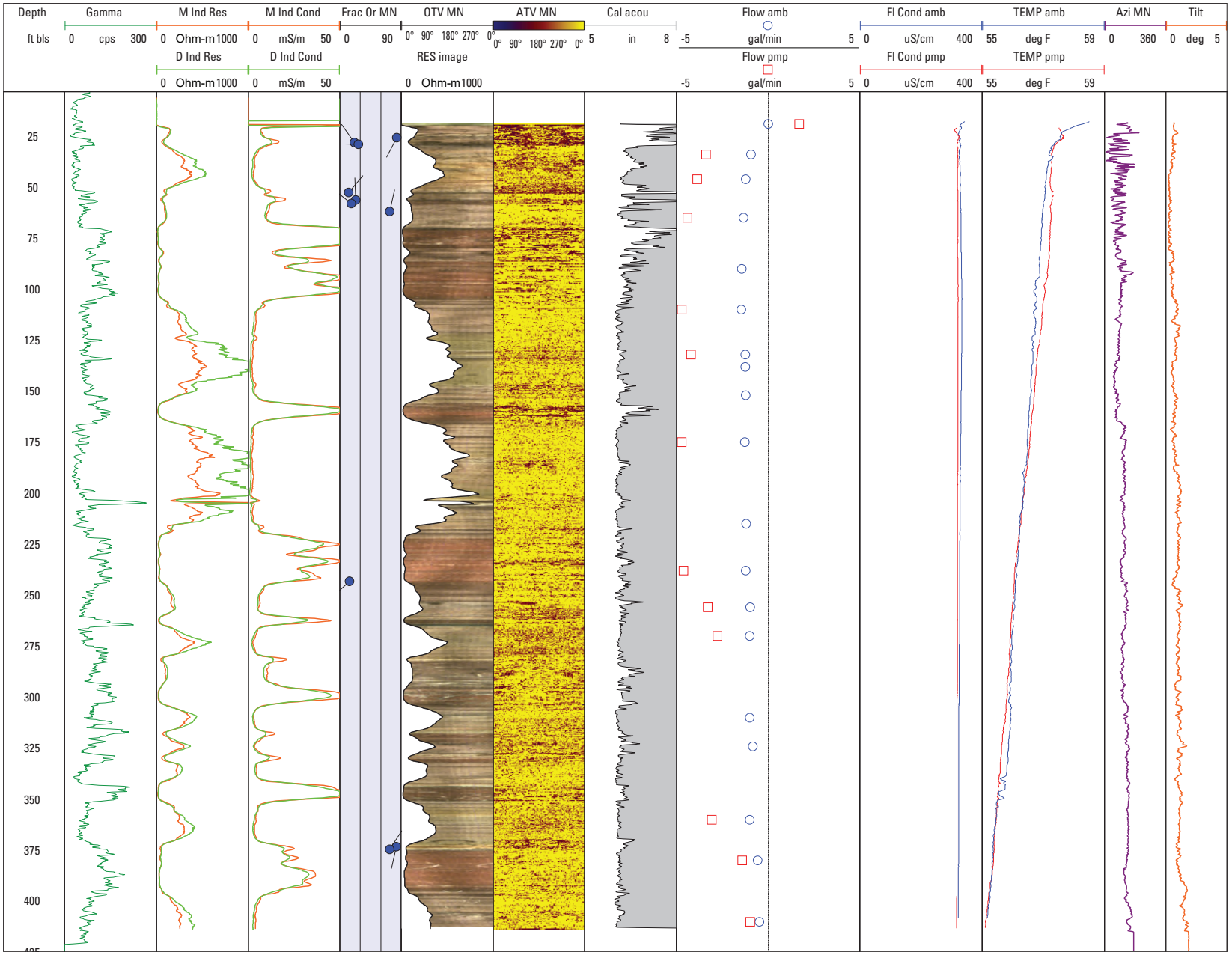


Figure 33. Geophysical logs collected by U.S. Geological Survey in well BK-3071 (HN-121), Warminster Township, Bucks County, Pennsylvania, November 1, 2018. See table 1 for explanation of abbreviations.

Table 18. Borehole flow-measurements collected by U.S. Geological Survey in well BK-3071 (HN-121), Warminster Township, Bucks County, Pennsylvania, November 1, 2018. Stationary measurements made using an electromagnetic flow meter under ambient and pumping conditions; negative values indicate downward flow and positive values indicate upward flow. Flow values reported in the table reflect corrections to raw measurements based on zero flow in casing under ambient conditions and known flow in casing under pumping conditions.

[ft, feet; bls, below land surface; corr, corrected value; gal/min, gallons per minute; amb, ambient conditions; pmp, pumping conditions; --, no data]

Ambient conditions		Pumping conditions	
Depth (ft bls)	Flow amb[1], corr (gal/min)	Depth (ft bls)	Flow pmp[2], corr (gal/min)
19	0.00	19	1.70
34	–0.94	34	–3.39
46	–1.21	46	–3.87
65	–1.33	65	–4.41
90	–1.44	90	--
110	–1.46	110	–4.70
132	–1.24	132	–4.19
138	–1.25	138	--
152	–1.22	152	--
175	–1.27	175	–4.71
215	–1.18	215	--
238	–1.21	238	–4.61
256	–0.99	256	–3.28
270	–1.01	270	–2.76
310	–1.00	310	--
324	–0.83	324	--
360	–1.00	360	–3.06
380	–0.56	380	–1.42
410	–0.47	410	–0.98

[1]Ambient flow measured starting at 08:55 on November 1, 2018; static water level is 11.59 ft bls at 07:56.

[2]Pumping rate 1.7 gal/min; static water level is 11.60 ft bls at 08:57 prior to start of pumping at 09:10 on November 1, 2018; water level is 11.65 ft bls at 10:24 and end of pumping; drawdown 0.5 ft.

and darker finer-grained sandstones, siltstones, or shales (higher gamma, lower resistivity). Thicknesses of the coarser-grained sandstone layers generally are greater than thicknesses of the finer-grained layers.

Most of the wells had water-bearing fractures throughout the depth of the open boreholes. The six new deep wells drilled in 2018 on the former NAWC Warminster base and many of the other existing wells had water-bearing fractures near the bottom of the casing (typically about 20 and as deep as 60 ft bls) that were among the most productive in each borehole. At least four of the six new deep wells drilled in 2018 on the former NAWC Warminster base appear to have active water-bearing fractures at depths greater than 500 ft bls, whereas the remaining two wells had water-bearing fractures near 400 ft bls and were either collapsed [BK-3071 (HN-121)] or nonproductive [BK-3070 (HN-120D)] below that depth.

High-angle fractures in relatively coarser-grained, lighter colored sandstone and associated with probable water-bearing zones are more common in some wells drilled on the former NAWC Warminster base than in other wells logged as part of this investigation. The wells with the most high-angle probable water-bearing fractures include BK-962 (NAWC well 10), BK-3063 (HN-116), and BK-3068 (HN-117) (figs. 4, 22, 28). Other wells on the former NAWC Warminster base with a few high-angle water-bearing fractures include BK-3066 (HN-118), BK-3067 (HN-119), BK-3070 (HN-120), and BK-3071 (HN-121) (figs. 24, 26, 31, and 33). The other eight wells logged for this investigation appeared to have water-bearing zones associated predominantly with bedding-plane openings. Bedding-plane or low-angle openings generally are associated with changes in lithology as indicated by natural gamma and formation resistivity logs; these low-angle openings commonly appear to be associated with relatively higher

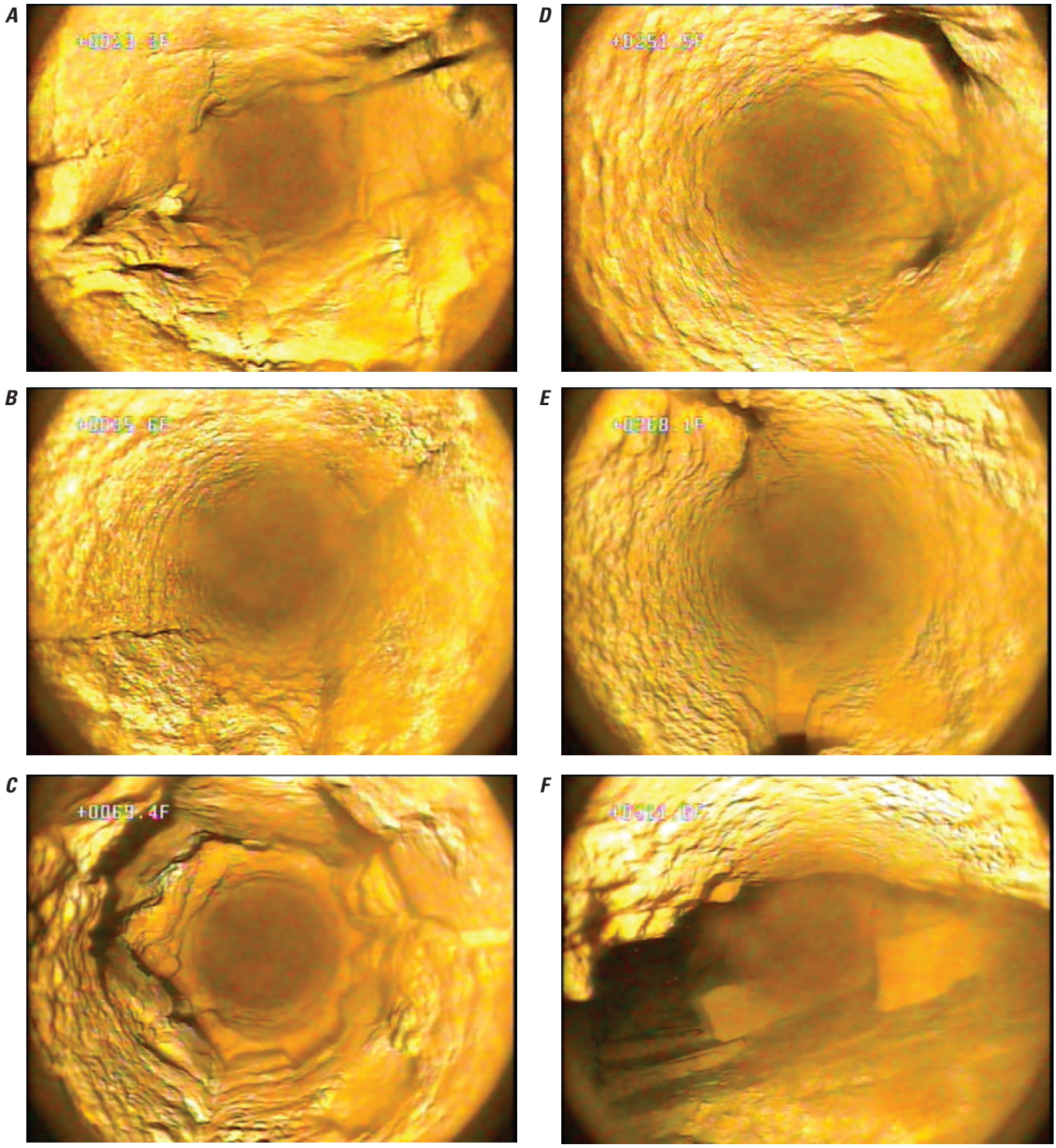


Figure 34. Still images from borehole video log of well BK-3071 (HN-121) at *A*, 23.3 feet below land surface (ft bls) showing high-angle fractures below bottom casing, *B*, 35.6 ft bls showing thin vertical fractures, *C*, 69.4 ft bls showing bedding- and fracture-plane openings, *D*, 251.5 ft bls showing low-angle openings, *E*, 368.1ft bls showing high-angle openings, and *F*, 411.6 ft bls showing large void and fractured rocks. Video log collected by U.S. Geological Survey in well BK-3071, Warminster Township, Bucks County, Pennsylvania, November 6, 2018.

gamma activity and relatively lower resistivity, such as shown in figures 6, 8, and 10 for wells BK-1023, BK-1087, and BK-1129, respectively.

The orientation of water-bearing fracture openings as determined from interpretation of the ATV logs for principal water-bearing zones are shown relative to magnetic north in tadpole plots as part of log figures for individual wells and with lower hemisphere stereonet plots in appendix 1 (figs. 1.1–1.15) and summarized in table 19. Directions reported relative to magnetic north can be converted to true north by adding 12 degrees 8 minutes (correction for magnetic declination in study area at time of logging). Generally, the high-angle (dip greater than 70 degrees) fracture planes most frequently were oriented either to the southwest or the northeast and the low-angle (dip less than 30 degrees) or bedding-plane openings appeared to be oriented in various directions. Variable types and orientations of lithologic contacts in the Stockton Formation, a fluvial deposit in origin, may be a factor in the apparent lack of a predominant direction for the low-angle openings often associated with these contacts; other factors may include reduced resolution (higher error) in interpreting low-angle features or other geologic controls, such as small faults that could tilt beds at a local scale.

The borehole deviation logs determined using data collected with the ATV logs show that the offset from vertical at the bottom of the wells ranged from 1.9 to as much as 96 ft for well BK-1023 (well 28) (table 19). As a percentage of well depth, the deviation was less than 4 percent for all wells except BK-1023, where deviation was 16 percent. Although deviation logs were not collected in well BK-1058 (well 27), video logs indicate that well BK-1058 also deviates substantially from vertical.

The direction of borehole deviation may tend to migrate up-dip normal to bedding planes, as has been reported to occur in some cases where bedding dips less than 45° (McLamore, 1971; Wilson, 1976; Brown and others, 1981). For wells that show borehole deviation to the southeast, the dip of the beds would be to the northwest, as was observed in nearby wells drilled in the Lockatong and Brunswick Formations about 10 mi (16 km) west of NAWC Warminster (Senior and others, 2008). A dip angle for bedding calculated from the total deviation (shallowest to deepest deviation measurements) does not account for probable non-linear inclination and underestimates actual bedding dip. As the hole is drilled, there is a tendency for increasing degrees of deviation with increasing depth because of greater flexibility in the drill string with additional rods. Thus, the dip angle calculated from the deviation logs is probably shallower than the actual formation dip.

The magnitude and direction (relative to magnetic north) of borehole deviation are shown in polar plots in appendix 2 (figs. 2.1–2.15). The direction of borehole deviation relative to magnetic north was to the southeast for five wells, BK-962, BK-1023, BK-3063, BK-3068 and BK-3071 figs. 2.1, 2.2, 2.10, 2.13, and 2.15, respectively) and to the south or southwest for the remainder (figs. 2.3–2.9, 2.11, 2.12, and 2.14). However, the amount of deviation was relatively small for most wells so that the deviation direction may not have migrated to any extent in a direction normal to bedding, which may partly be related to the lithology and sedimentary characteristics of the Stockton Formation. In the well with the largest deviation, BK-1023 (well 28), the deviation direction is about 134 degrees relative to true north (fig. 2.2) which, if normal to bedding, would correspond to a bedding plane direction (strike) of N. 44° E. and a NW dip (of as much as approximately 18 degrees at depth), consistent with the range of reported bedding orientation in the area (Rima and others, 1962). The direction of borehole deviation is approximately orthogonal to many of the low-angle/bedding-plane openings (appendix 1) as summarized in table 19.

The borehole flow directions measured under ambient conditions are controlled by vertical hydraulic gradients in the layered fractured-rock aquifer that are affected by hydrogeologic setting and (or) nearby pumping. The deepest wells (greater than 400 ft) are located at the highest elevations (table 19), where downward flow from shallow zones may be related to the recharge setting. Under ambient conditions, most of the new and existing deep (greater than 400 ft) wells logged for this study exhibited downward borehole flow. All but one (BK-3063 [HN-116]) of the six new deep (555 to 600-ft) boreholes drilled in 2018 at the former NAWC had predominantly downward flow (fig. 1). Well BK-3063 (HN-116), in an area of shallow (less than 100 ft bls) active pumping, had downward flow at depths greater than about 400 ft bls but upward flow above 200 ft bls (fig. 22; table 13). Under ambient conditions for five of the six new wells drilled in 2018, water entered open boreholes through shallow fractures in the upper portions of the boreholes and flowed down to exit fractures at depths generally near or greater than 400 to 500 ft bls. Cascading water from shallow fractures above the static water level in open boreholes was observed in wells BK-3066 (HN-118) and BK-3067 (HN-119).

Under ambient conditions, most wells less than 400 ft in depth logged for this study had upward flow and were located at relatively lower elevations (table 19). Well BK-1129 (well 36), a 380-ft-deep unused production well, located west of the former NAWC, was flowing and had upward flow from depths of 356 ft bls. Well BK-3063 (HN-116), a 600-ft-deep new monitor well located in the vicinity of active shallow (less than 100 ft) pumping for groundwater remediation at former NAWC Area A (fig. 3), had both upward flow above 200 ft and downward borehole flow below 400 ft.

Table 19. Summary of borehole deviation logs, directions of borehole flow, land-surface elevations at well heads, and other characteristics for wells logged by U.S. Geological Survey at and near the former Naval Air Warfare Center Warminster during 2017–19, Bucks County, Pennsylvania, listed in increasing magnitude of land-surface elevation at well head.

[WMA, Warminster Municipal Authority; WTWSA, Warwick Township Water and Sewer Authority; NBCMA, Northampton Bucks County Municipal Authority; ft bls, feet below land surface; in., inch; ft, foot; NAVD88, North American Vertical Datum 1988; <, less than; --, no data; ?, indicates uncertainty; N, north; NE, northeast; NW, northwest; E, east; S, south; SE, southeast; SW, southwest]

USGS local well name	Owner	Owner well name	Casing length (ft bls)	Logged depth (ft bls)	Hole diameter (in.)	Horizontal deviation from vertical at bottom of log (ft)	Horizontal deviation as percentage of well depth	Deviation from vertical (degrees)	Approximate direction of deviation[1]	General direction of deviation	Dip direction[2] of low-angle/ bedding-plane water-bearing opening	Dip direction[2] of high-angle water-bearing opening	Estimated land-surface elevation (ft above NAVD88)	Predominant borehole flow direction under ambient conditions
BK 2698	WTSA	Well 8	60	210.5	10	4.0	1.9	1.1	163	SE	S	SW	210	Up from 145 ft
BK 2861	WTSA	Well 11	83	160	10	1.5	0.9	0.5	205	SW	NE	SW	214	Up from 144 ft
BK 1058	WMA	Well 27	58	485	8	--	--	--	--	--	--	--	228	--
BK 2869	WTSA	Well 9	63	315	10	4.5	1.4	0.8	197	SW	SW	SW,NE	245	Slight down
BK 2870	WTSA	Well 10	61	270	10	7.1	2.6	1.5	224	SW	Flat	SW,NE	247	Slight up
BK 1129	WMA	Well 36	50	375	12	3.9	1.0	0.6	217	SW	NW,NE, SE,SW	NW	265	Up
BK 1087	WMA	Well 25	60	400	8	14.2	3.6	2.0	185	SW	NW,NE,SE	N, SW	273	Up from 360 ft
BK 3068	Navy	HN-117	19	600	6	6.6	1.1	0.6	134	SE	NE,NW,E	SW,NE	313	Down to 500 ft; up from bottom to 500 ft
BK 3063	Navy	HN-116	19	601	6	13.5	2.2	1.3	138	SE	SW	SW,NE,SE	313	Up above 200 ft; down below 400 ft
BK 3070	Navy	HN-120D	59	555	6	13.0	2.3	1.3	224	SW	NW,NE	SW,SE	327	Down to 380 ft
BK 3062	NBCMA	Well 15	93	400	10	5.7	1.4	0.8	202	SW	NE,E	--	343	None to slightly up above 99 ft; down (?) below 280 ft
BK 1023	WMA	Well 28	57	604	8	96.5	16.0	9.2	134	SE	SE,SW	--	345	Down
BK 962	WMA	NAWC10	50	385	8	11.5	3.0	1.7	148	SE	N,NE, NW	SW, NE	346	Up from bottom to 200 ft
BK 3066	Navy	HN-118	19	602	6	15.1	2.5	1.4	217	SW	E,N	SW	346	Down
BK 3071	Navy	HN-121	20	415	6	6.0	1.4	0.8	128	SE	NW,NE,SW,E	SW,NE	352	Down
BK 3067	Navy	HN-119	20	602	6	18.4	3.1	1.8	198	SW	NE,SE,S	SW,NW	360	Down

[1]Approximate direction of deviation relative to true north; magnetic declination about –12.13 degrees in study area.

[2]Estimated predominant direction, relative to magnetic north, of dip for low-angle/bedding-plane or high-angle water-bearing opening as interpreted from acoustic televiewer log and other logs, where low angle is less than 30 degrees and high angle is greater than 70 degrees.

Summary

Groundwater is a substantial source of public, domestic, and industrial water supply in areas underlain by the Triassic Stockton Formation, a fractured sandstone aquifer, in southern Montgomery and Bucks Counties, Pennsylvania, where two formerly active military bases are located. The Naval Air Warfare Center (NAWC) Warminster (formerly the Naval Air Development Center, Johnsville) in Warminster and Northampton Townships, Bucks County was active during 1944–96. About 3 miles west of NAWC Warminster, the Naval Air Station Joint Reserve Base (NASJRB) Willow Grove in Horsham Township, Montgomery County was operated by the U.S. Navy (Navy) from 1942 until September 2011, with a portion currently (2020) still active and operated by the Pennsylvania Air National Guard (ANG) and designated Horsham Air Guard Station (HAGS). Previous investigations identified areas of groundwater contaminated by volatile organic compounds (VOCs) at both NAWC Warminster and NASJRB Willow Grove, which subsequently were addressed by remediation.

In summer 2014, through sampling of production wells, groundwater at and near the former NAWC Warminster and former NASJRB Willow Grove was found to be contaminated with perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), compounds that may pose a risk to human health if present above certain concentrations in drinking water. PFOS and PFOA are part of a group of compounds more broadly designated per- and polyfluoroalkyl substances (PFAS). Potential sources of PFOS and PFOA in the area include fire-suppressant compounds (fluorinated surfactants in aqueous film forming foams) used on and (or) near these facilities when the bases were operating. Some production wells were shut down in response to the discovery of PFOS and PFOA, while others were restarted with treatment to remove the PFAS compounds. After PFAS was discovered in the area surrounding the bases, the Navy and the ANG have offered nearby residences with private domestic wells that yielded water with PFOS and PFOA concentrations greater than the lifetime health advisory for these compounds in drinking water (U.S. Environmental Protection Agency, 2016) to be connected to public drinking water supplies, and also established a program to monitor PFOS and PFOA concentrations in water from nearby residential wells that have not been connected to public supply.

Management and mitigation of groundwater that is contaminated with PFOS and PFOA on and near the former NAWC Warminster and the nearby Willow Grove NASJRB requires assessment of the sources and distribution of contaminant occurrence. In 2014, the Navy and its contractors began sampling soils, streams, and groundwater water through preliminary remedial investigations.

The U.S. Geological Survey (USGS) collected borehole geophysical and video logs in 15 open-hole wells in Northampton, Warminster, and Warwick Townships, Bucks County, Pennsylvania during 2017–19 to support detailed groundwater investigations by the Navy and its contractors at and near the former NAWC Warminster, where groundwater contamination PFAS had become a concern since 2014. The geophysical and video logs were used to characterize the boreholes and identify potential water-bearing fractures for subsequent detailed investigations that included aquifer-interval-isolation tests of discrete water-bearing zones using straddle packers in 13 wells and depth-discrete point sampling in 2 wells. The 15 wells ranged in depth from about 210 to 604 feet (ft) below land surface (bls) and included six new 6-inch diameter wells drilled to initial depths of 600 ft bls on the former NAWC Warminster base property in 2018 and nine 8- to 12-inch diameter existing former production or unused test wells. Partial geophysical or video logs also were collected by USGS during 2018 in two other wells that were not included in subsequent detailed investigations. Casing lengths ranged from about 19 to 93 ft bls. The depth to the static water level at the time of logging ranged from about 1.8 ft above land surface in a flowing well to about 55 ft bls.

The lithology of aquifer intervals intercepted by wells as shown on optical televiewer, gamma, and resistivity logs appears to be alternating sequences of light-colored, relatively coarser-grained sandstones (lower gamma, higher resistivity) and darker, finer-grained sandstones, siltstones, or shales (higher gamma, lower resistivity). Most wells had numerous water-bearing fractures throughout the depth of the open boreholes. High-angle fractures in relatively coarser-grained, lighter colored sandstone and associated with probable water-bearing zones are more common in some wells drilled on the former NAWC Warminster base than in other wells logged as part of this investigation, which had water-bearing zones associated with low-angle or bedding-plane openings. Measured borehole flow was predominantly downward in most of the deepest wells (greater than 400 ft) commonly located at the highest land-surface elevations, with inflow from fractures at relatively shallower depths and outflow through fractures near or below depths of 500 ft bls. Borehole flow was predominantly upward in most wells less than 400 ft in depth.

References Cited

Anderson, J.A., Morin, R.H., Cannia, J.C., and Williams, J.H., 2009, Geophysical log analysis of selected test holes and wells in the High Plains aquifer, Central Platte River basin, Nebraska: U.S. Geological Survey Scientific Investigations Report 2009–5033, 16 p., accessed September 2020 at https://doi.org/10.3133/sir20095003.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Transactions of the American Institute of Mining, Metallurgical and Petroleum Engineers, v. 146, no. 01, p. 54–62.

Battelle, 2016, Fourth five-year review for former Naval Air Warfare Center Warminster, Warminster, Pennsylvania: Report N62269.PF.001040 NAWC WARMINSTER 5090.3b prepared for the U.S. Navy Naval Facilities Engineering Command under contract no. N62583-11-D-0515 task order no. 0063, November 2016, variously paginated, accessed May 12, 2020, at https://www.navfac.navy.mil/niris/MID_ATLANTIC/WARMINSTER_NAWC/N62269_001040.pdf.

Battelle, 2017, Final Technical Review Committee meeting minutes regarding meeting held 12 July 2017 NAWC Warminster, PA: Report N62269_001113 NAWC WARMINSTER, PA SSIC 5000-33a, accessed October 20, 2020, at https://www.navfac.navy.mil/niris/MID_ATLANTIC/WARMINSTER_NAWC/N62269_001113.pdf.

Berg, T.M., Edmunds, W.E., Geyer, A.R., and others, comps., 1980, Geologic map of Pennsylvania (2d ed.): Pennsylvania Geological Survey, 4th Series, Map 1, scale 1:250,000, 2 sheets.

Biella, G., Lozej, A., and Tabacco, I., 1983, Experimental study of some hydrogeophysical properties of unconsolidated porous media: Ground Water, v. 21, no. 6, p. 741–751.

Bird, P.H., 1998, Geohydrology and ground-water quality of Warwick Township, Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 97-4267, 37 p., accessed April 19, 2019, at https://pubs.er.usgs.gov/publication/wri974267.

Brown, E.T., Green, S.J., and Sinha, K.P., 1981, The influence of rock anisotropy on hole deviation in rotary drilling—A review: International Journal of Rock Mechanics and Mining Sciences, v. 18, no. 5, p. 387–401.

Conger, R.W., 1998, Identification of water-bearing zones by the use of geophysical logs and borehole television surveys, collected February to September 1997, at the Former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania: U.S. Geological Survey Open-File Report 98–86, 26 p., accessed September 2020 at https://doi.org/10.3133/ofr9886.

Conger, R.W., and Bird, P.H., 1999, Identification of water-bearing fractures by the use of geophysical logs, May to July 1998, former Naval Air Warfare Center, Bucks County, Pennsylvania: U.S. Geological Survey Open-File Report 99–215, 27 p., accessed September 2020 at https://doi.org/10.3133/ofr99215.

Goode, D.J., and Senior, L.A., 2020, Groundwater withdrawals and regional flow paths at and near Willow Grove and Warminster, Pennsylvania—Data compilation and preliminary simulations for conditions in 1999, 2010, 2013, 2016, and 2017: U.S. Geological Survey Open-File Report 2019–1137, 127 p., accessed March 10, 2020, at https://doi.org/10.3133/ofr20191137.

Greenman, D.W., 1955, Groundwater resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Bulletin W11, 66 p., 1 plate., accessed September 2020 at http://elibrary.dcnr.pa.gov/GetDocument?docId=1751882&DocName=W11_GWRes_BucksCo.

Hess, A.E., 1982, A heat-pulse flowmeter for measuring low velocities in boreholes: U.S. Geological Survey Open-File Report 82–699, 44 p.

Keys, W.S., 1990, Borehole geophysics applied to groundwater investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E2, 150 p., accessed March 10, 2020, at https://doi.org/10.3133/twri02E2.

Kwader, T., 1985, Estimating aquifer permeability from formation resistivity factors: Ground Water, v. 23, no. 6, p. 762–766.

Leidos, 2018, Final groundwater monitoring report for the perfluorinated compound facility investigation at the Horsham Air Guard Station (111th Attack Wing) Horsham, Pennsylvania: Report prepared for Air National Guard Restoration Branch under contract no. W9133L-14-D-0007 delivery order no. 0005, variously paginated, accessed February 2021 at https://ar.afcec-cloud.af.mil/Search.aspx.

Longwill, S.M., and Wood, C.R., 1965, Ground-water resources of the Brunswick Formation in Montgomery and Berks Counties, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Bulletin W22, 59 p., 1 plate., accessed September 2020 at http://elibrary.dcnr.pa.gov/GetDocument?docId=1751893&DocName=W22_GWRes_BrunswickFm_Montgomery-BerksCos.

Low, D.J., Hippe, D.J., and Yannacci, D., 2002, Geohydrology of southeastern Pennsylvania: U.S. Geological Survey Water-Resources Investigation Report 2002–4166, 347 p., accessed September 2020 at https://doi.org/10.3133/wri004166.

Lyttle, P.T., and Epstein, J.B., 1987, Geologic map of the Newark 1 degree x 2 degrees quadrangle, New Jersey, Pennsylvania and New York: U.S. Geological Survey Miscellaneous Investigations Map I-1715, scale 1:250,000, accessed March 10, 2020, at https://doi.org/10.3133/i1715. [Also available at https://ngmdb.usgs.gov/Prodesc/proddesc_9892.html.]

McLamore, R.T., 1971, The role of rock strength anisotropy in natural hole deviation: Journal of Petroleum Technology, v. 23, no. 11, p. 1313–1321.

National Oceanic and Atmospheric Administration, 2020, Magnetic field calculators: National Oceanic and Atmospheric Administration web page, accessed October 20, 2020, at https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml.

Newport, T.G., 1971, Ground-water resources of Montgomery County, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Bulletin W29, 83 p., 2 plates., accessed September 2020 at http://elibrary.dcnr.pa.gov/GetDocument?docId=1751900&DocName=W29_GWRes_MontgomeryCo.

Paillet, F.L., 2000, A field technique for estimating aquifer parameters using flow log data: Ground Water, v. 38, no. 4, p. 510–521.

Paillet, F.L., 2001, Hydraulic head applications of flow logs in the study of heterogeneous aquifers: Ground Water, v. 39, no. 5, p. 667–675.

Penn State Institutes of Energy and Environment, 2015, PAMAP Program 3m county mosaic digital elevation model: Pennsylvania Spatial Data Access web page, accessed May 2016 at ftp://ftp.pasda.psu.edu/pub/pasda/pamap/LidarMosaics/CountyMosaics/county_DEM_3M/.

Pennsylvania Bureau of Topographic and Geologic Survey, 2008a, Physiographic provinces of Pennsylvania: Pennsylvania Spatial Data Access web page, accessed November 14, 2019, at https://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=1153.

Pennsylvania Bureau of Topographic and Geologic Survey, 2008b, Physiographic sections of Pennsylvania: Pennsylvania Spatial Data Access web page, accessed November 14, 2019, at https://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=1154.

Naval Facilities Engineering Command, 2018, Final second five-year review NAS Willow Grove PA: Report prepared for NAVFAC BRAC Program Management Office East, accessed April 13, 2020, at https://www.navfac.navy.mil/niris/MID_ATLANTIC/WILLOW_GROVE_NAS/N00158_000760.pdf.

Resolution Consultants, 2019, Remedial investigation report Per and Polyfluoroalkyl substances investigations activities Willow Grove, PA Report, volume I Text, Tables, Figures, Appendices A–G: Report N00158_001068 NASJRB WILLOW GROVE, PA SSIC 5000-33 prepared for the U.S. Navy Naval Facilities Engineering Command under contract no. N62470-11-D-8013, September 2019, variously paginated, accessed May 13, 2019, at https://www.navfac.navy.mil/niris/MID_ATLANTIC/WILLOW_GROVE_NAS/N00158_001068.pdf.

Reynolds, R.J., Anderson, J.A., and Williams, J.H., 2015, Geophysical log analysis of selected test and residential wells at the Shenandoah Road National Superfund Site, East Fishkill, Dutchess County, New York: U.S. Geological Survey Scientific Investigations Report 2014–5228, 30 p., accessed March 10, 2020, at https://dx.doi.org/10.3133/sir20145228.

Rima, D.R., Meisler, H., and Longwill, S., 1962, Geology and hydrology of the Stockton Formation in southeastern Pennsylvania: Pennsylvania Geological Survey, 4th Series, Bulletin W14, 110 p., 4 plates., accessed September 2020 at http://elibrary.dcnr.pa.gov/GetDocument?docId=1751885&DocName=W14_Geo-Hydro_StocktonFm_SEPa.

Robinson, G.R., Jr., 1988, Base- and precious-metal mineralization associated with igneous and thermally altered rocks in the Newark, Gettysburg, and Culpepper early Mesozoic basins of New Jersey, Pennsylvania, and Virginia, chap. 26 *in* Manspeizer, W., ed., Triassic-Jurassic rifting—Continental breakup and the origin of the Atlantic Ocean and passive margins: Developments in Geotectonics, v. 22, p. 621–648.

Rowland, C.J., 1997, Altitude and configuration of the potentiometric surface in Warwick Township, Bucks County, Pennsylvania, September 1994 through May 1995: U.S. Geological Survey Open-File Report 97-554, 1 sheet, accessed September 2020 at https://doi.org/10.3133/ofr97554.

Schlische, R., 1992, Structural and stratigraphic development of the Newark extensional basin, eastern North America—Evidence for the growth of the basin and its bounding structures: Geological Society of America Bulletin, v. 104, no. 10, p. 1246–1263.

Senior, L.A., Conger, R.W., and Bird, P.H., 2008, Geophysical logs, aquifer tests, and water levels in wells in and near the North Penn Area 7 Superfund site, Upper Gwynedd Township, Montgomery County, Pennsylvania, 2002–2006: U.S. Geological Survey Scientific Investigations Report 2008–5154, 277 p., accessed October 30, 2020, at https://pubs.usgs.gov/sir/2008/5154/sir2008-5154_rev1.pdf.

Senior, L.A., Zarr, L.F., Olson, L., and Rosman, R., 2020, Water-level data and selected field notes for aquifer-interval-isolation tests at and near the former Naval Air Warfare Center Warminster, Bucks County, Pennsylvania, 2018–19: U.S. Geological Survey data release, accessed February 2021 at https://doi.org/10.5066/P9TC92B5.

Sevon, W.D., 2000, comp., Physiographic provinces of Pennsylvania (4th ed.): Pennsylvania Geological Survey Map 13, scale 1:2,000,000, accessed October 5, 2020, at http://elibrary.dcnr.pa.gov/GetDocument?docId=1751225&DocName=Map13_PhysProvs_Pa.

Sloto, R.A., 1997, Results of borehole geophysical logging and aquifer-isolation tests conducted in the John Wagner and Sons, Inc former production well, Ivyland, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 1997–4095, 18 p., accessed September 2020 at https://pubs.er.usgs.gov/publication/wri974095.

Sloto, R.A., 1998, Results of borehole geophysical logging and hydraulic tests conducted in Area D supply wells, former U.S. Naval Air Warfare Center, Warminster, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 98–4129, 47 p., accessed September 2020 at https://doi.org/10.3133/wri984129.

Sloto, R.A., 2008, Interpretation of borehole geophysical logs at Area C, former Naval Air Warfare Center, Warminster Township, Bucks County, Pennsylvania, 2007: U.S. Geological Survey Open-File Report 2008–1207, 20 p., accessed June 2, 2020, at https://doi.org/10.3133/ofr20081207.

Sloto, R.A., 2010, Changes in groundwater flow and volatile organic compound concentrations at the Fischer and Porter Superfund Site, Warminster Township, Bucks County, Pennsylvania, 1993–2009: U.S. Geological Survey Scientific Investigations Report 2010–5054, 115 p., accessed June 2, 2020, at https://doi.org/10.3133/sir20105054.

Sloto, R.A., Conger, R.W., and Grazul, K.E., 1998, Geohydrology and distribution of volatile organic compounds in ground water in the Casey Village area, Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 1998–4010, 81 p., accessed September 2020 at https://pubs.er.usgs.gov/publication/wri984010.

Sloto, R.A., and Davis, D.K., 1982, Effect of urbanization on the water resources of Warminster Township, Bucks County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 82-4010, 78 p., accessed March 28, 2019, at https://pubs.er.usgs.gov/publication/wri824020.

Sloto, R.A., and Grazul, K.E., 1995a, Altitude and configuration of the potentiometric surface, Casey Village, Warminster and Upper Southampton Townships, Bucks County, Pennsylvania, August 3, 1995: U.S. Geological Survey Open-File Report 95-717, 2 maps on 1 sheet, accessed September 2020 at https://doi.org/10.3133/ofr95717.

Sloto, R.A., Macchioroli, P., and Conger, R.W., 1995b, 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, 3 plates, accessed December 9, 2020, at https://doi.org/10.3133/wri954220.

Sloto, R.A., Macchioroli, P., and Towle, M.T., 1996, Geohydrology of the Stockton Formation and cross-contamination through open boreholes, Hatboro Borough and Warminster Township, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 86-4047, 49 p., 2 plates, accessed March 28, 2019, at https://pubs.er.usgs.gov/publication/wri964047.

TetraTech, 2014, Evaluation of potential source of perfluorinated compounds, former Naval Air Warfare Center Warminster, Pennsylvania: Report prepared for Naval Facilities Engineering Command Mid-Atlantic, Norfolk, Virginia, contract number N62470-08-D-1001, contract task orderWE23, report N62269.AR.001000 NAWC WARMINSTER 5090.3a, November 2014, accessed November 11, 2019, at https://www.navfac.navy.mil/niris/MID_ATLANTIC/WARMINSTER_NAWC/N62269_001000.pdf.

Turner-Peterson, C.E., and Smoot, J.P., 1985, New thoughts on facies relationships in the Triassic Stockton and Lockatong Formations, Pennsylvania and New Jersey, *in* Gilpin, G.R., Jr., and Froehlich, A.J., eds., Proceedings of the second U.S. Geological Survey workshop on the early Mesozoic basins of the Eastern United States: U.S. Geological Survey Circular 946, p. 10–17, accessed September 2020 at https://doi.org/10.3133/cir946.

U.S. Environmental Protection Agency, 2012, Third Unregulated Contaminant Rule: U.S. Environmental Protection Agency web page, accessed January 31, 2019, at https://www.epa.gov/dwucmr/third-unregulated-contaminant-monitoring-rule.

U.S. Environmental Protection Agency, 2014, Peer Review of Health Effects Documents for PFOA and PFOS: U.S. Environmental Protection Agency web page, Office of Water EPA - 820-F-14-004, accessed April 10, 2015, at https://water.epa.gov/drink/standards/upload/Peer-Review-of-Health-Effects-Documents-for-PFOA-and-PFOS-Factsheet-February-2014.pdf.

U.S. Environmental Protection Agency, 2016, FACT SHEET PFOA & PFOS Drinking Water Health Advisories: U.S. Environmental Protection Agency web page, EPA 800-F-16-003, accessed March 28, 2018, at https://www.epa.gov/sites/production/files/2016-06/documents/drinkingwaterhealthadvisories_pfoa_pfos_updated_5.31.16.pdf.

U.S. Geological Survey, 2005, USGS National Hydrography Dataset (NHD)–High-resolution flowline features: U.S. Geological Survey National Hydrography Dataset, accessed June 3, 2009, at https://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=364.

U.S. Geological Survey, 2020, GeoLog locator: U.S. Geological Survey web page, accessed March 13, 2020, at https://webapps.usgs.gov/GeoLogLocator/#!/search.

U.S. Navy, 2016, Naval Air Station Joint Reserve Base Willow Grove PFOA/PFOS Information November 2016: Former Naval Air Station Joint Reserve Base Willow Grove web page, accessed October 20, 2020, at https://www.bracpmo.navy.mil/brac_bases/northeast/reserve_base_willow_grove/documents.html.

Willard, B., ed., 1959, Geology and mineral resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey, 4th series, Bulletin C9, 243 p., accessed September 2020 at http://elibrary.dcnr.pa.gov/GetDocument?docId=1751044&DocName=C9_Geo-MinRes_BucksCo.

Williams, J.H., and Johnson, C.D., 2004, Acoustic and optical borehole-wall imaging for fractured-rock aquifer studies: Journal of Applied Geophysics, v. 55, p. 151–159.

Williams, J.H., and Lane, J.W., 1998, Advances in borehole geophysics for groundwater investigations: U.S. Geological Survey Fact Sheet 002–98, 4 p., accessed September 2020 at https://water.usgs.gov/ogw/bgas/publications/FS-002-98/.

Wilson, G.E., 1976, How to drill a usable hole Part 1—Why deviation occurs: World Oil, v. 183, no. 2, p. 40–43.

Young, S.C., and Pearson, H.S., 1995, The electromagnetic borehole flowmeter—Description and application: Ground Water Monitoring and Remediation Review, v. 15, no. 4, p. 138–147.

Appendix 1. Orientation of Selected Water-bearing Fractures in Wells

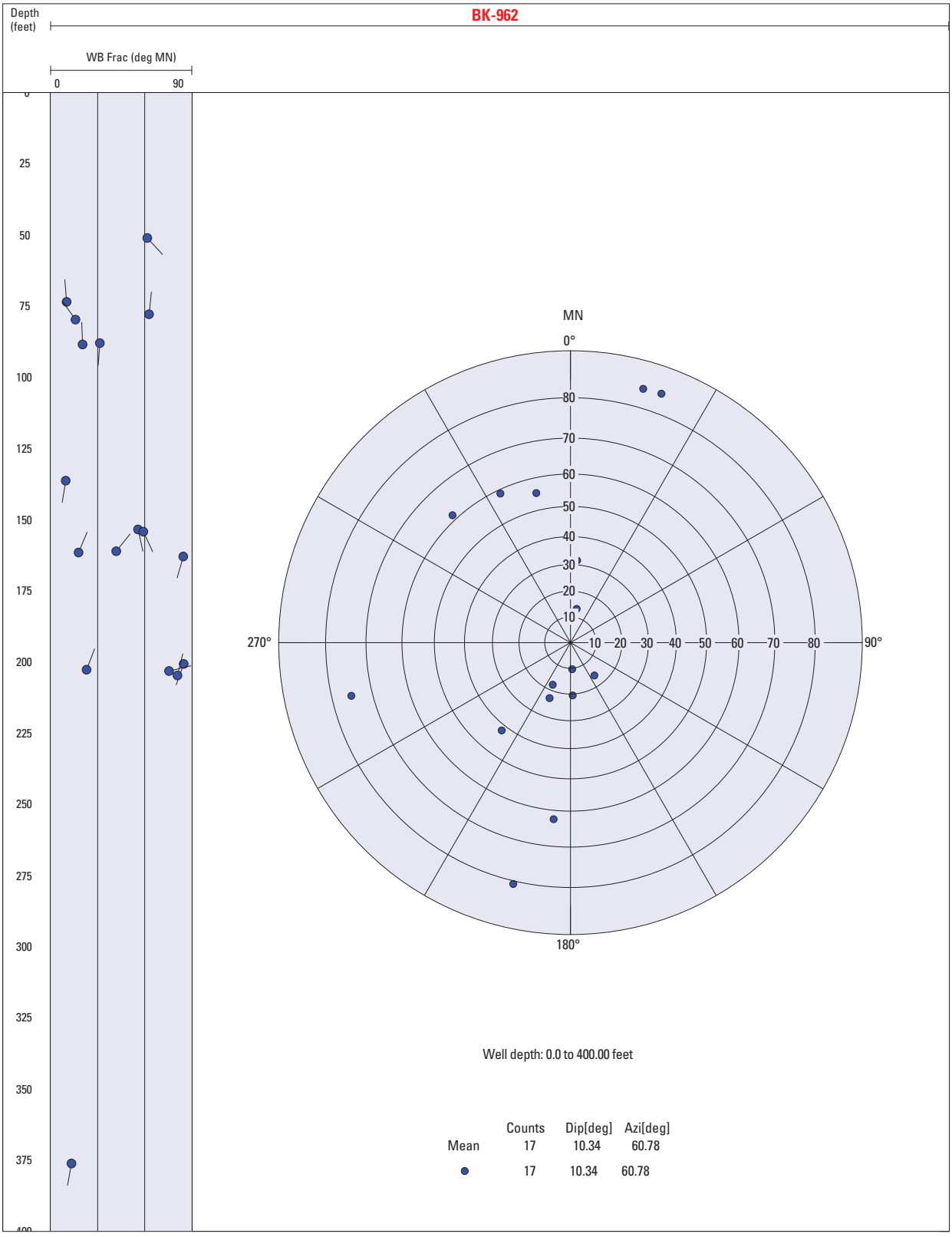


Figure 1.1. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-962, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

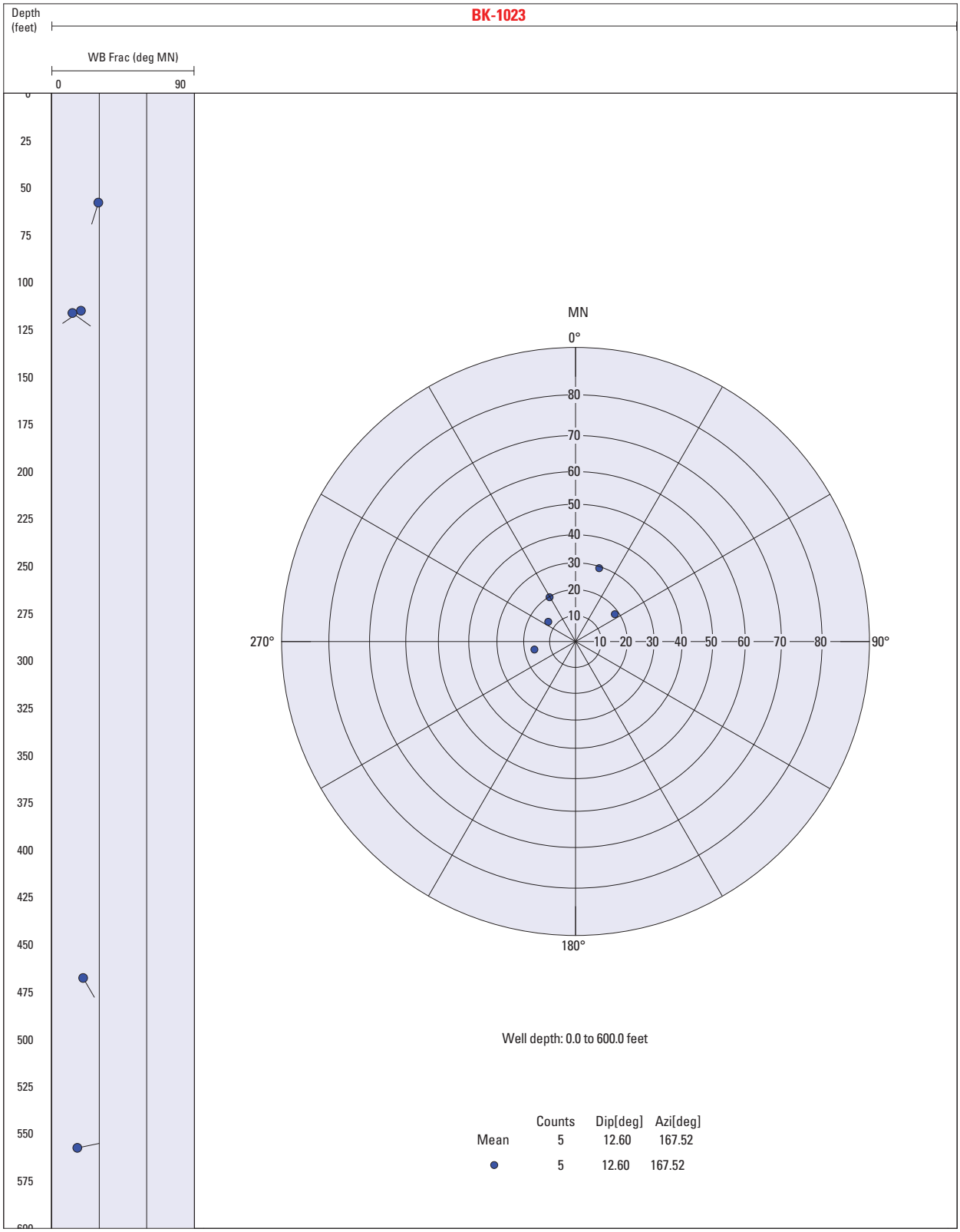


Figure 1.2. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-1023, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

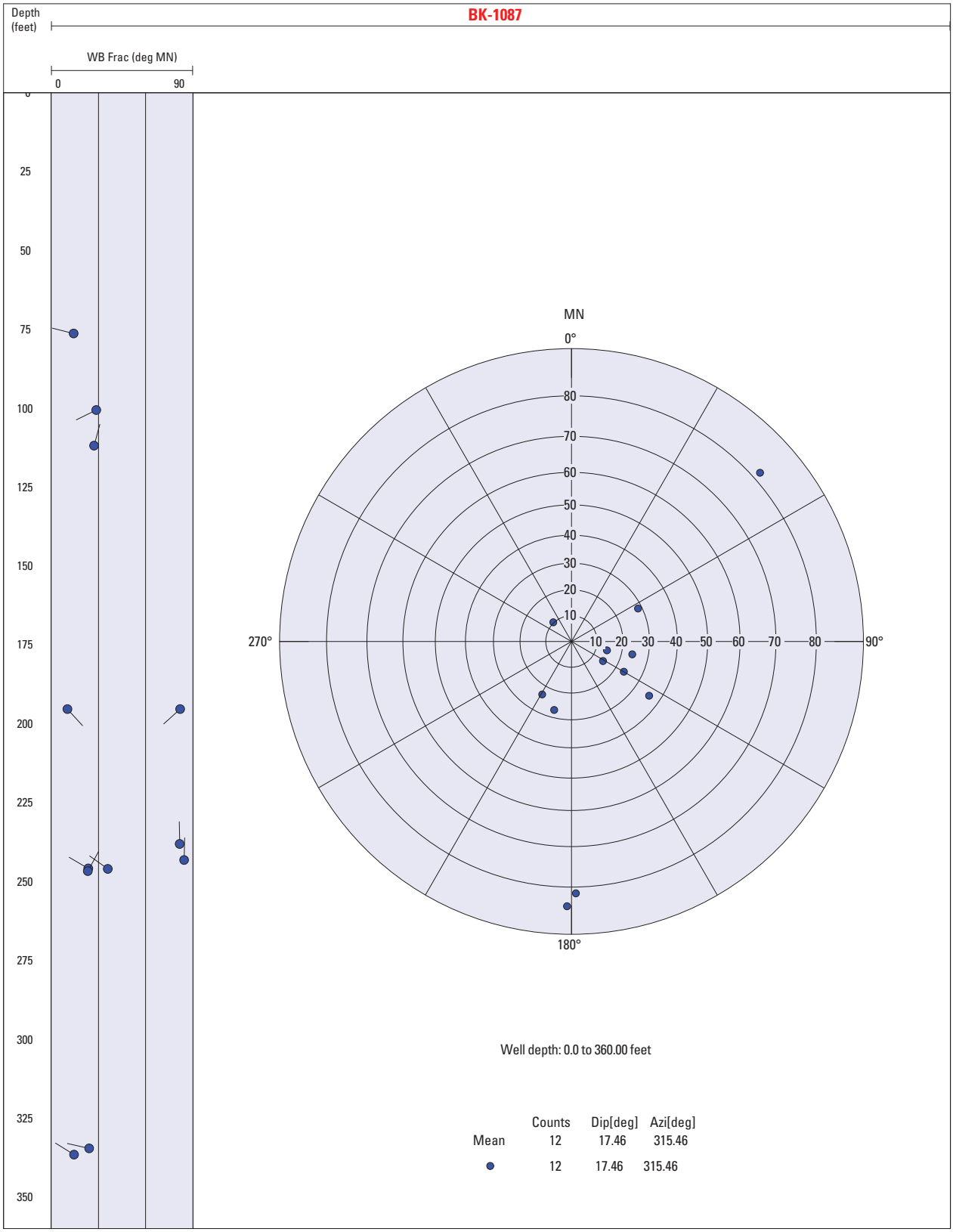


Figure 1.3. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-1087, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

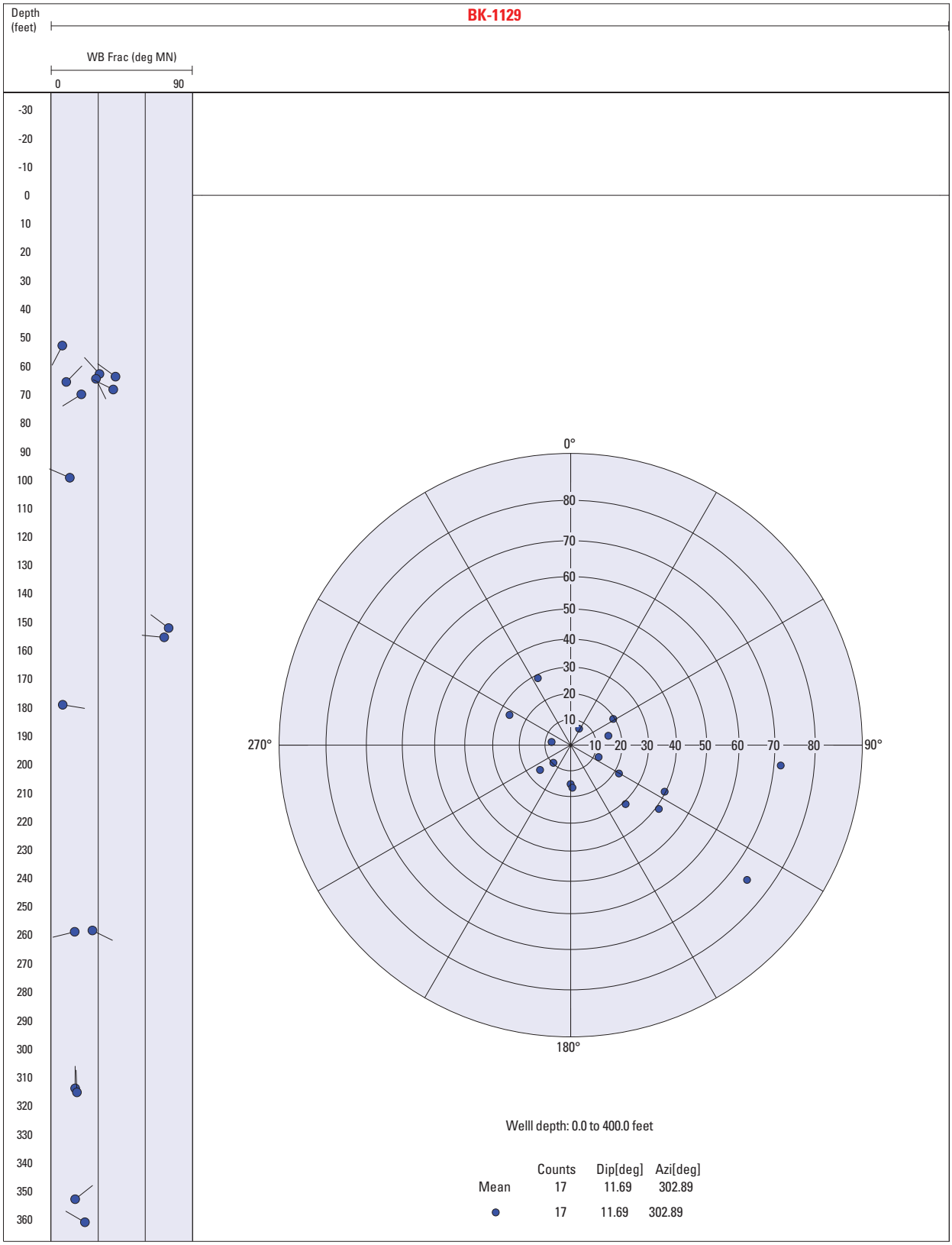


Figure 1.4. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-1129, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

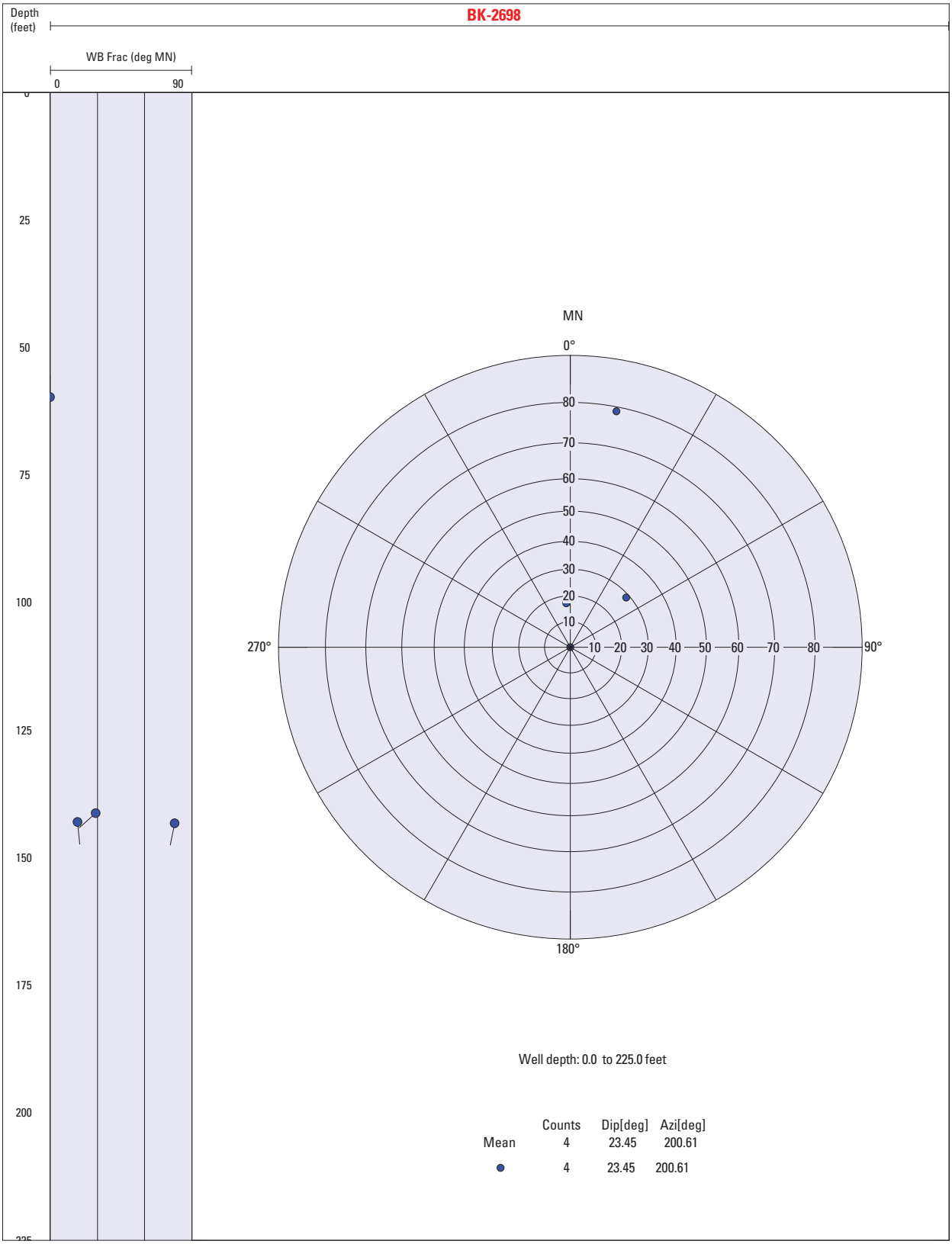


Figure 1.5. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-2698, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

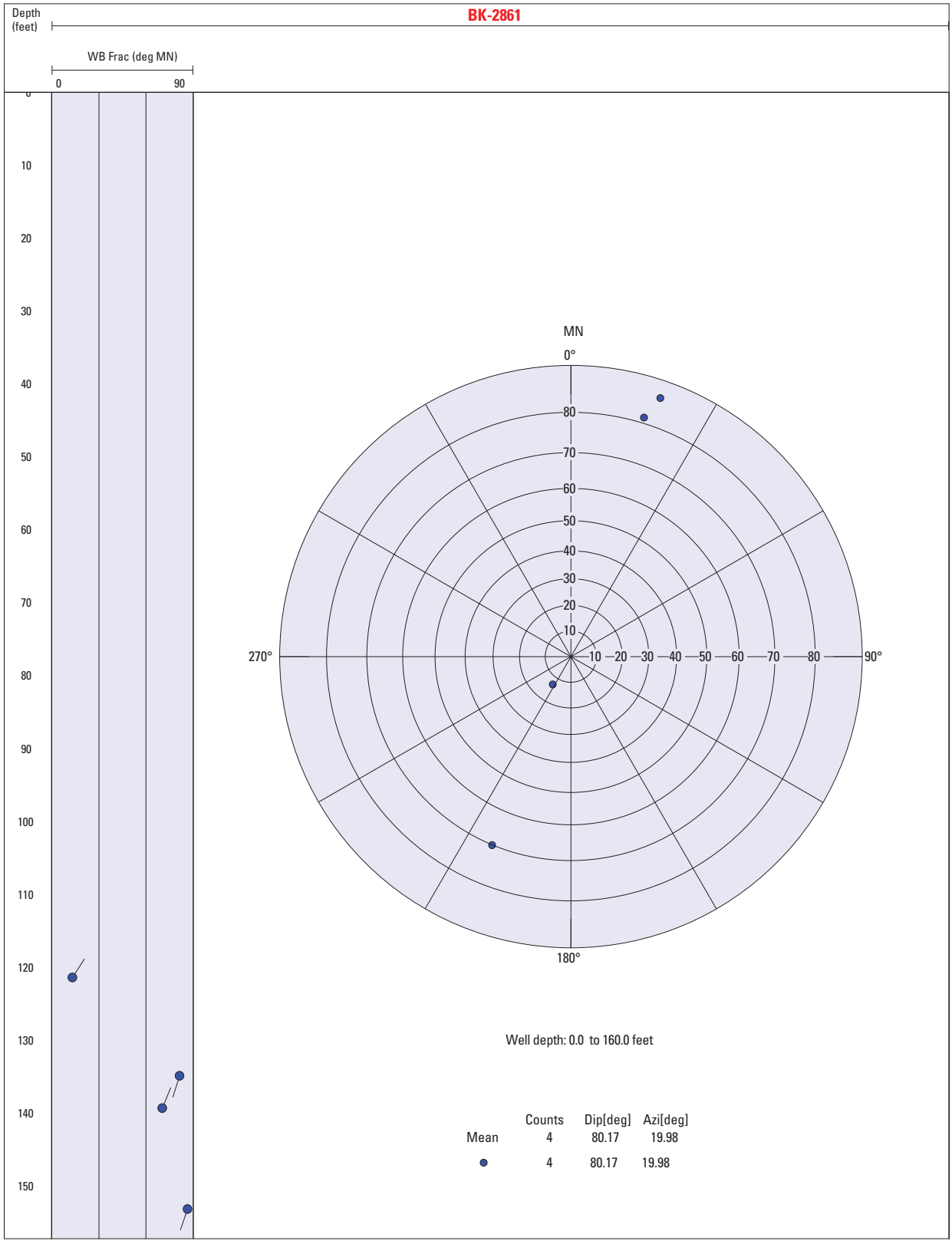


Figure 1.6. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-2861, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

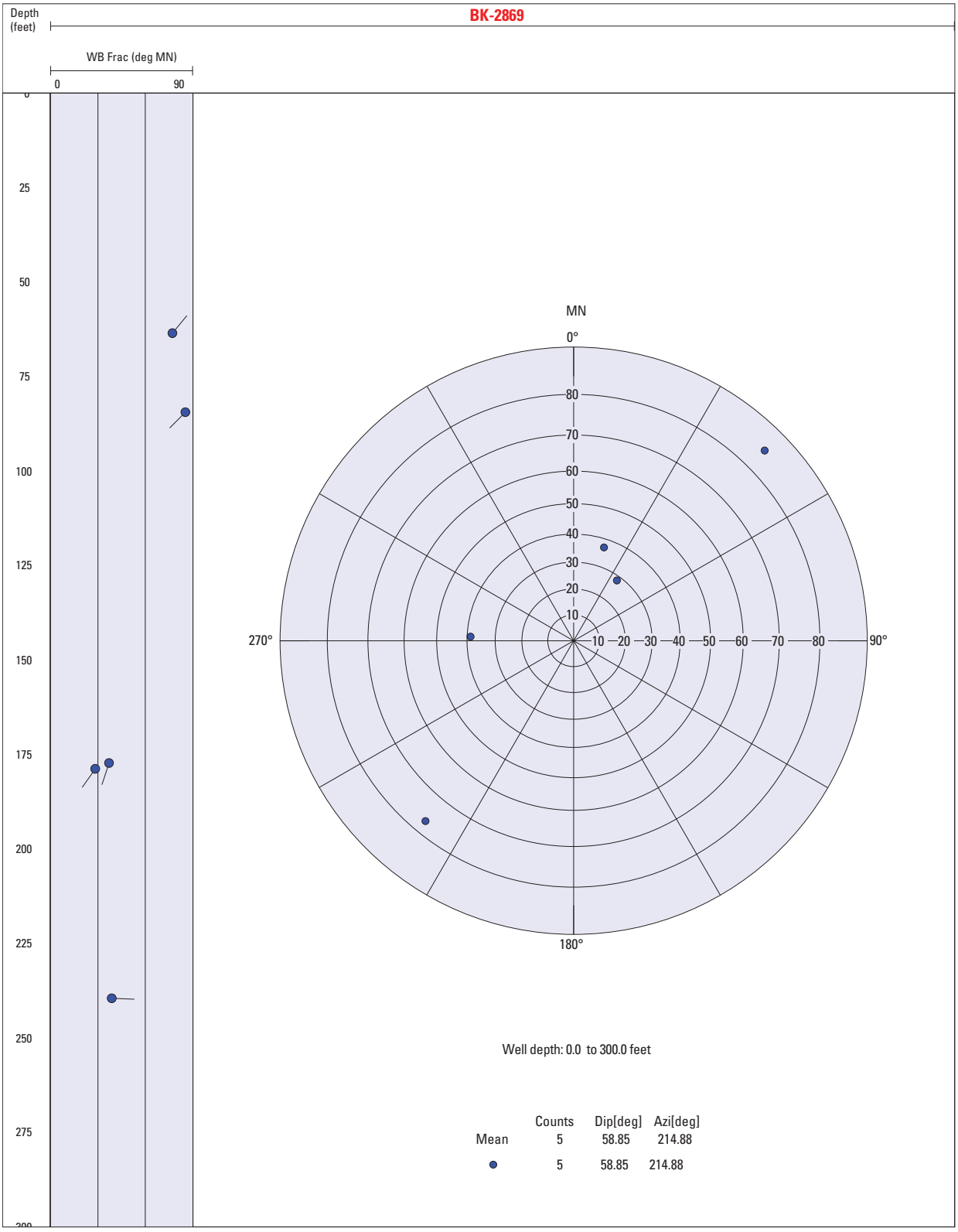


Figure 1.7. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-2869, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

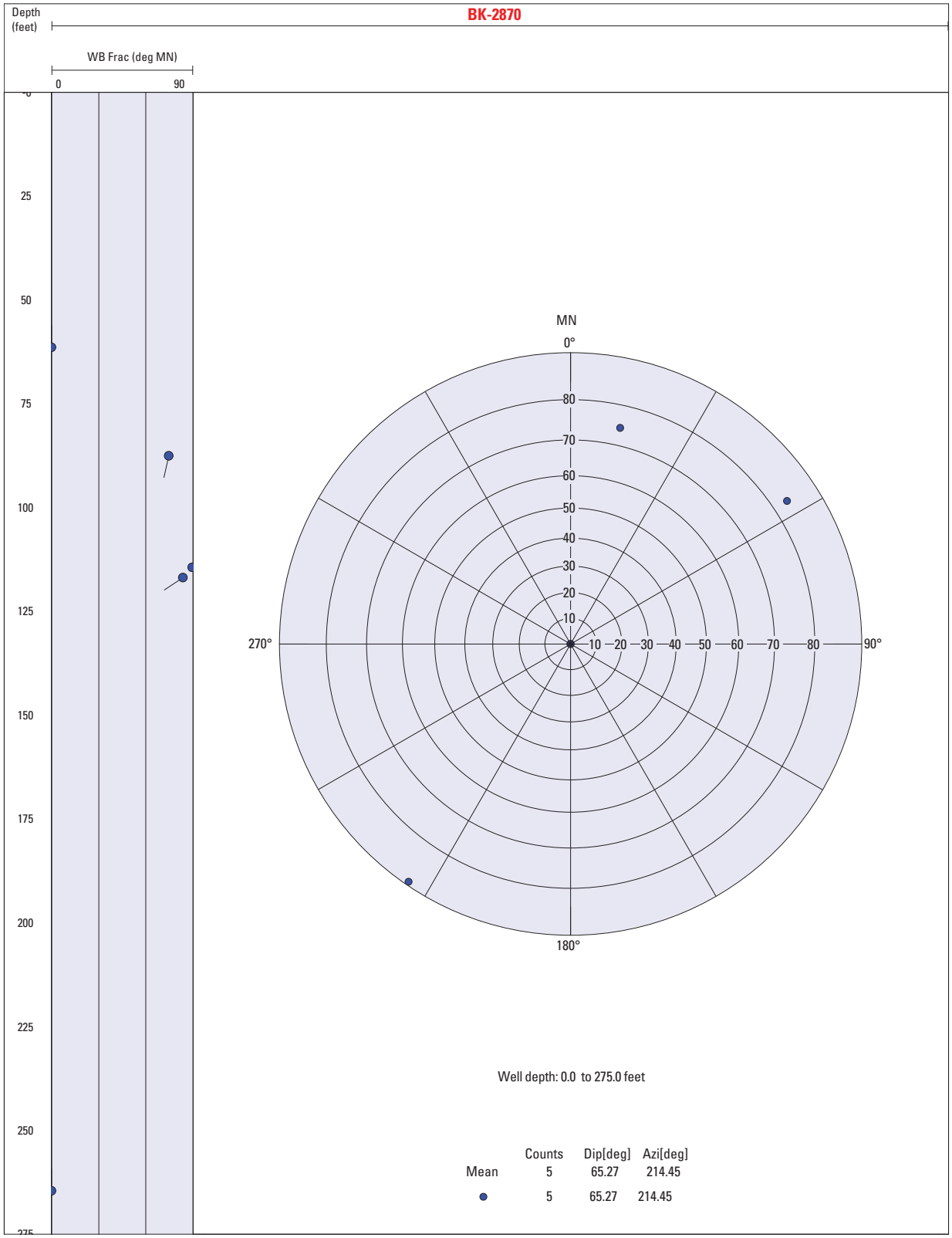


Figure 1.8. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-2870, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

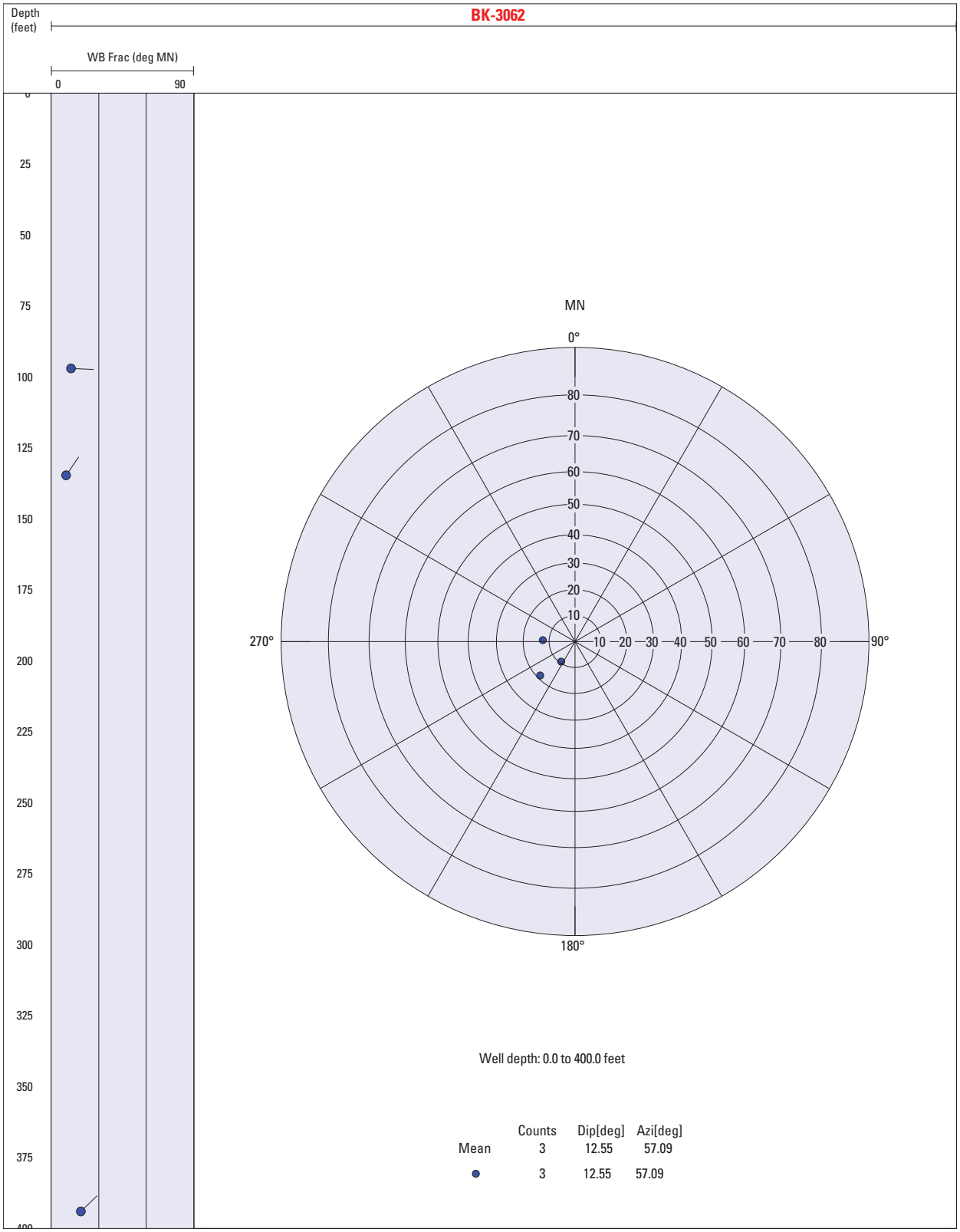


Figure 1.9. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3062, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

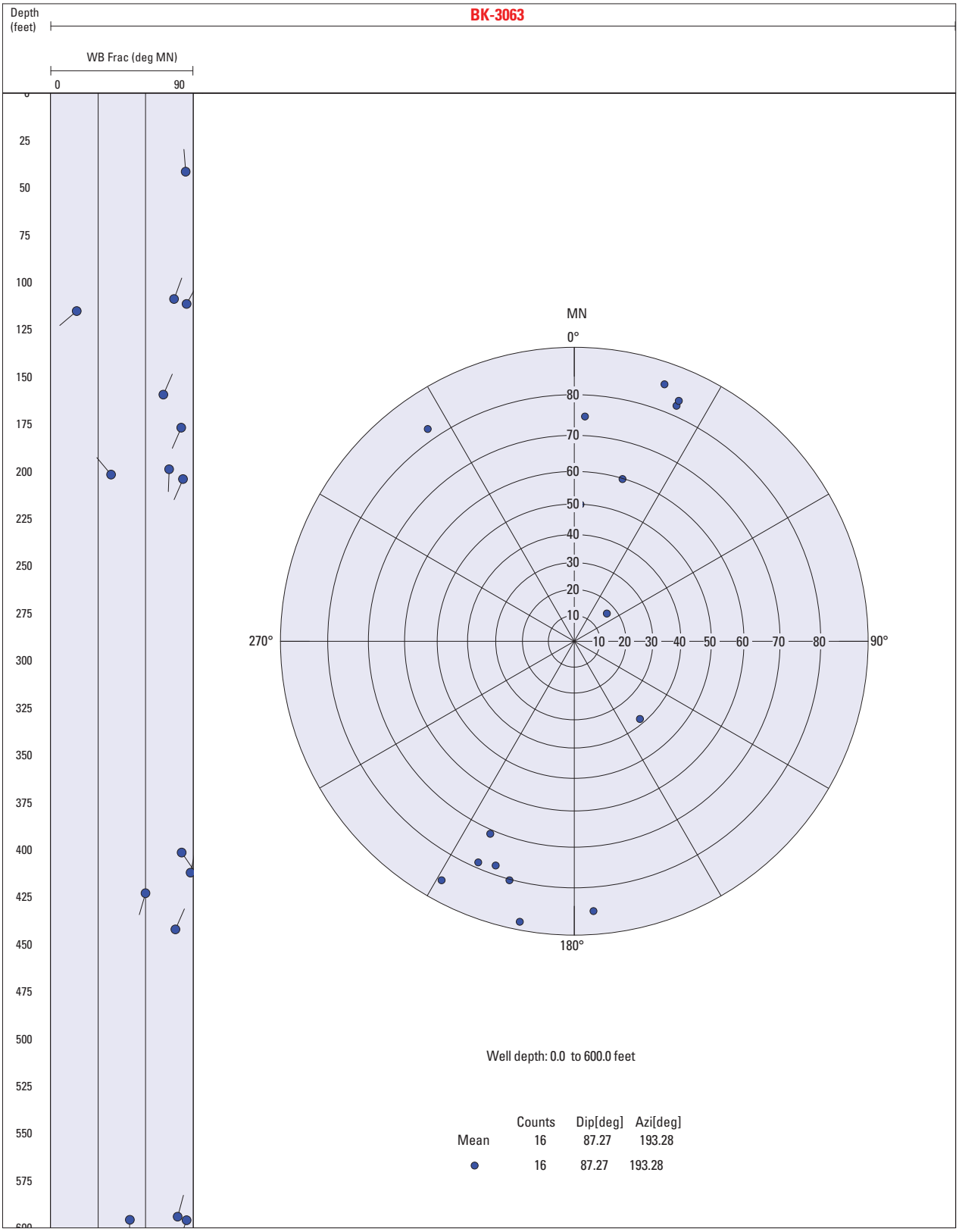


Figure 1.10. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3063, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

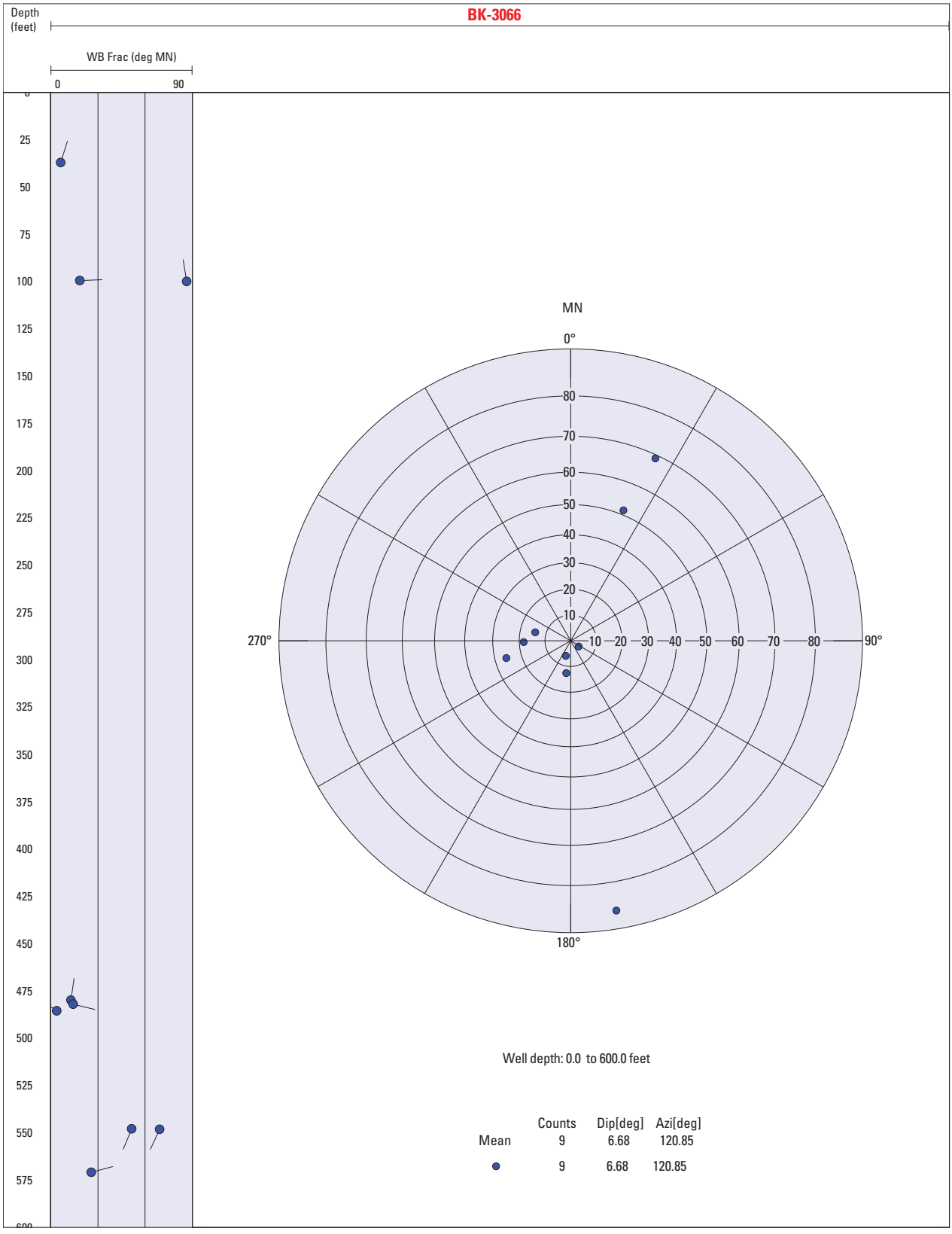


Figure 1.11. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3066, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

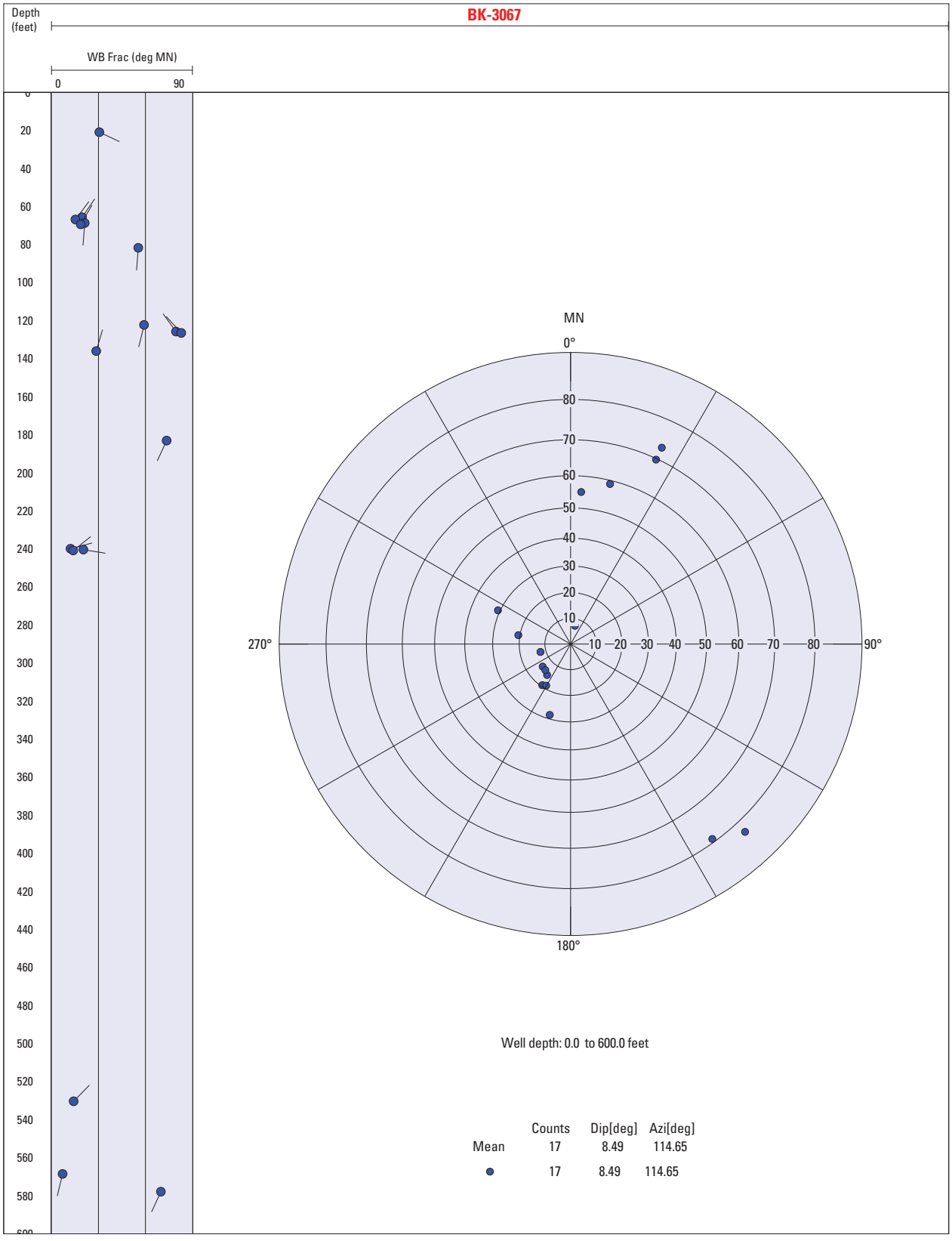


Figure 1.12. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3067, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

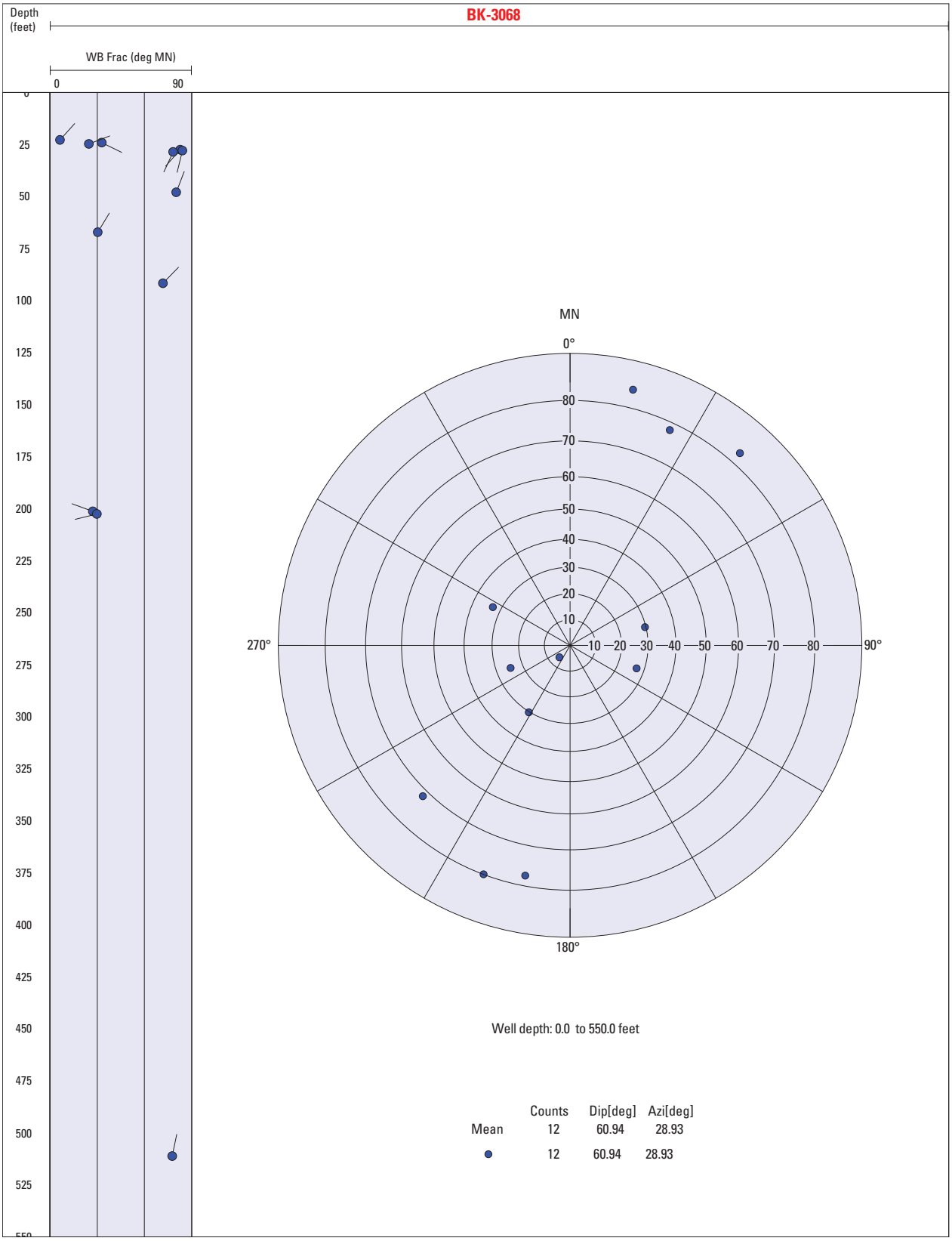


Figure 1.13. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3068, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

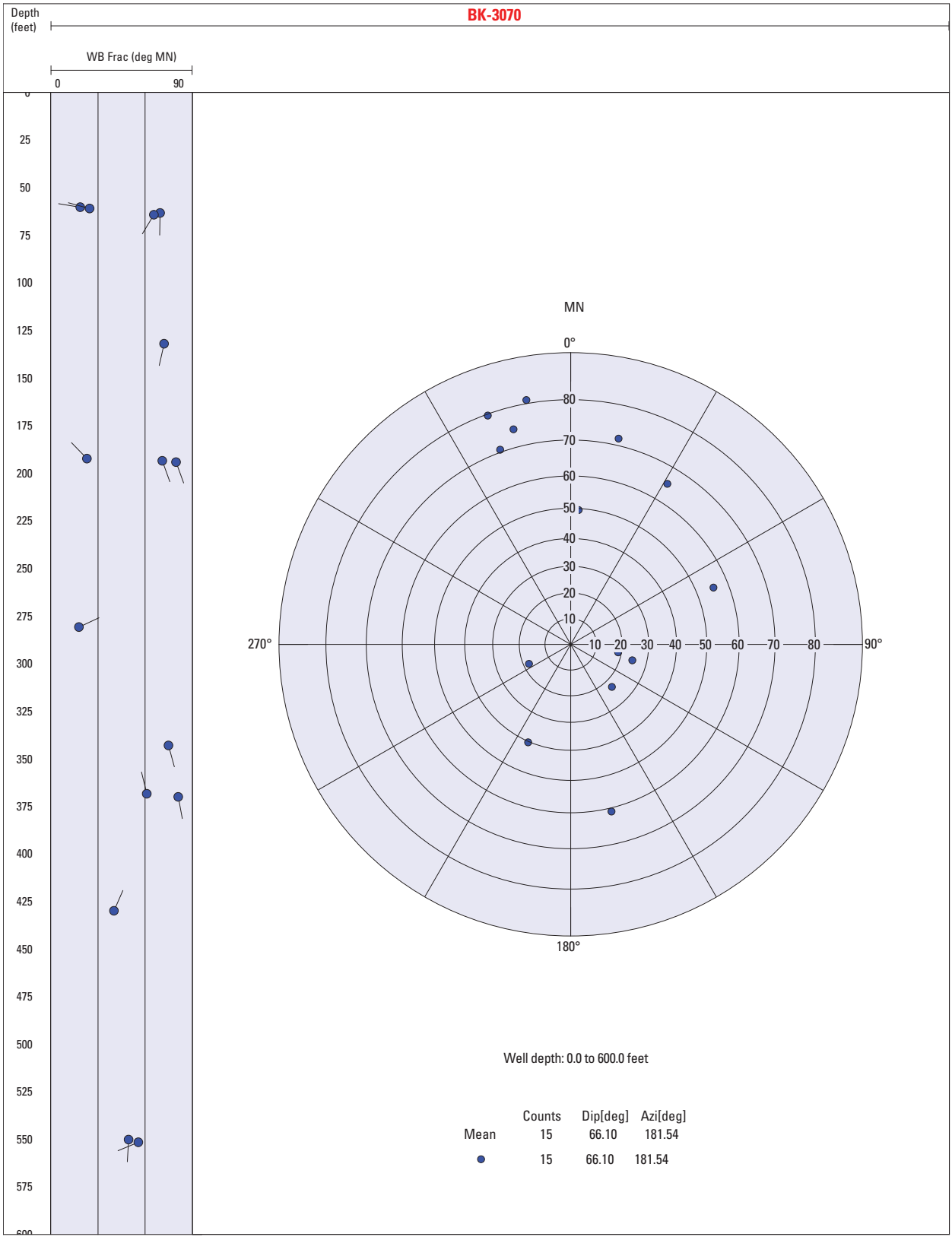


Figure 1.14. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3070, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

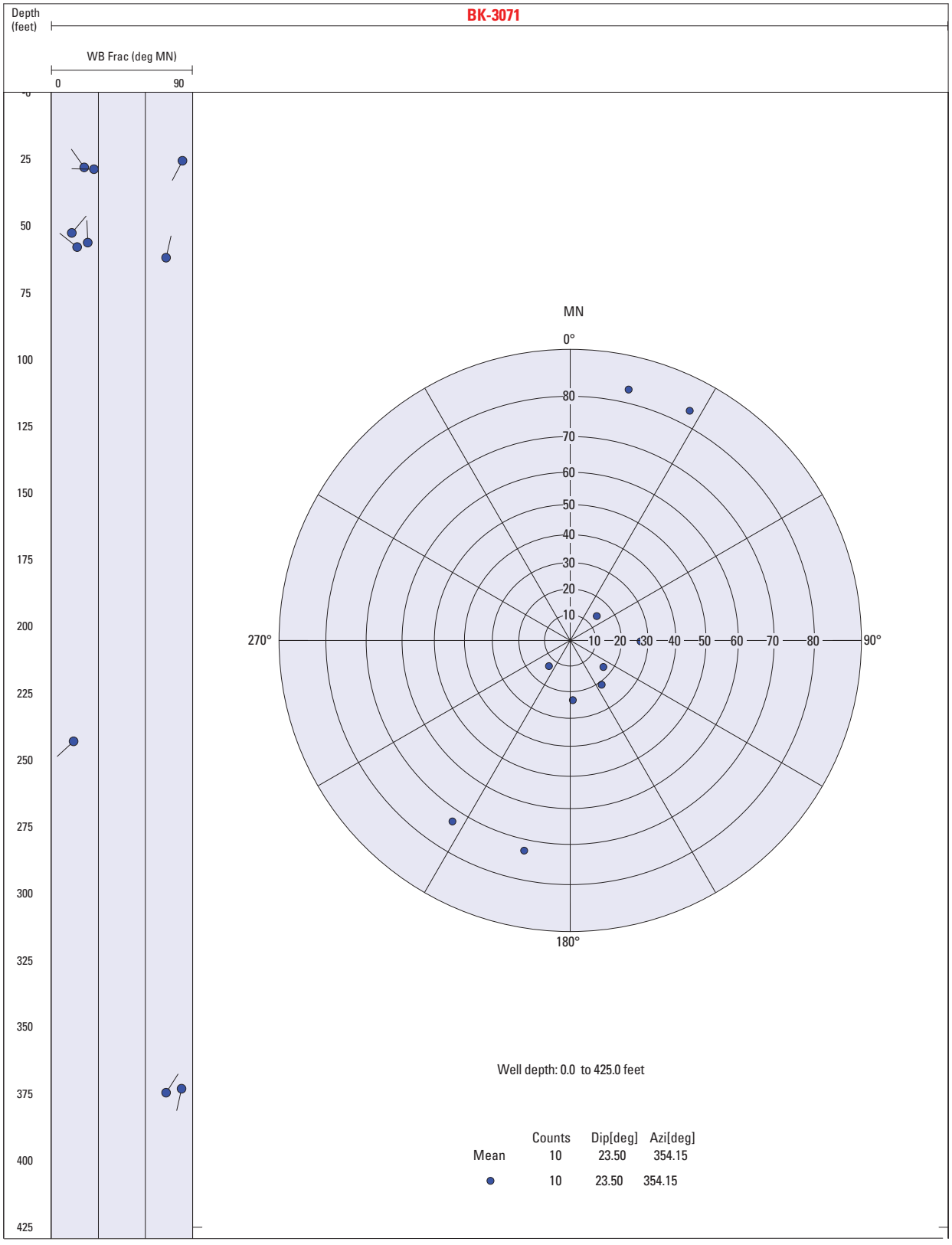


Figure 1.15. Orientation of selected water-bearing (WB) fractures relative to magnetic north (MN) as determined from evaluation of acoustic televiewer and other logs for well BK-3071, shown in (left) tadpole plot of fracture azimuth and dip in degrees by depth, and (right) lower hemisphere stereonet depicting projected pole to fracture plane and dip angle with distance from center of plot. Azi, azimuth; deg, degree; frac, fracture; ft, feet.

Appendix 2. Deviation and Drift of Boreholes

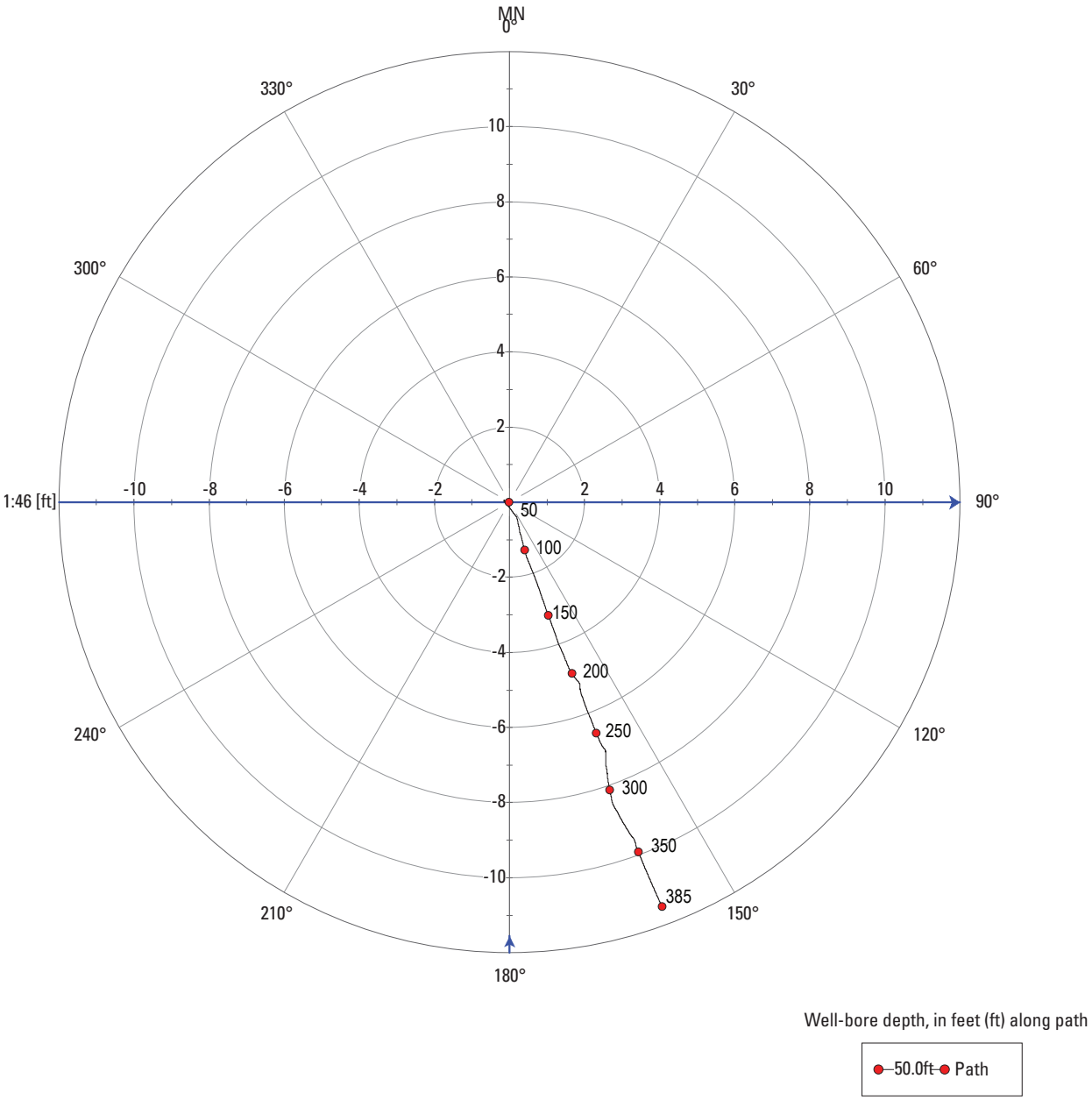


Figure 2.1. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-962. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

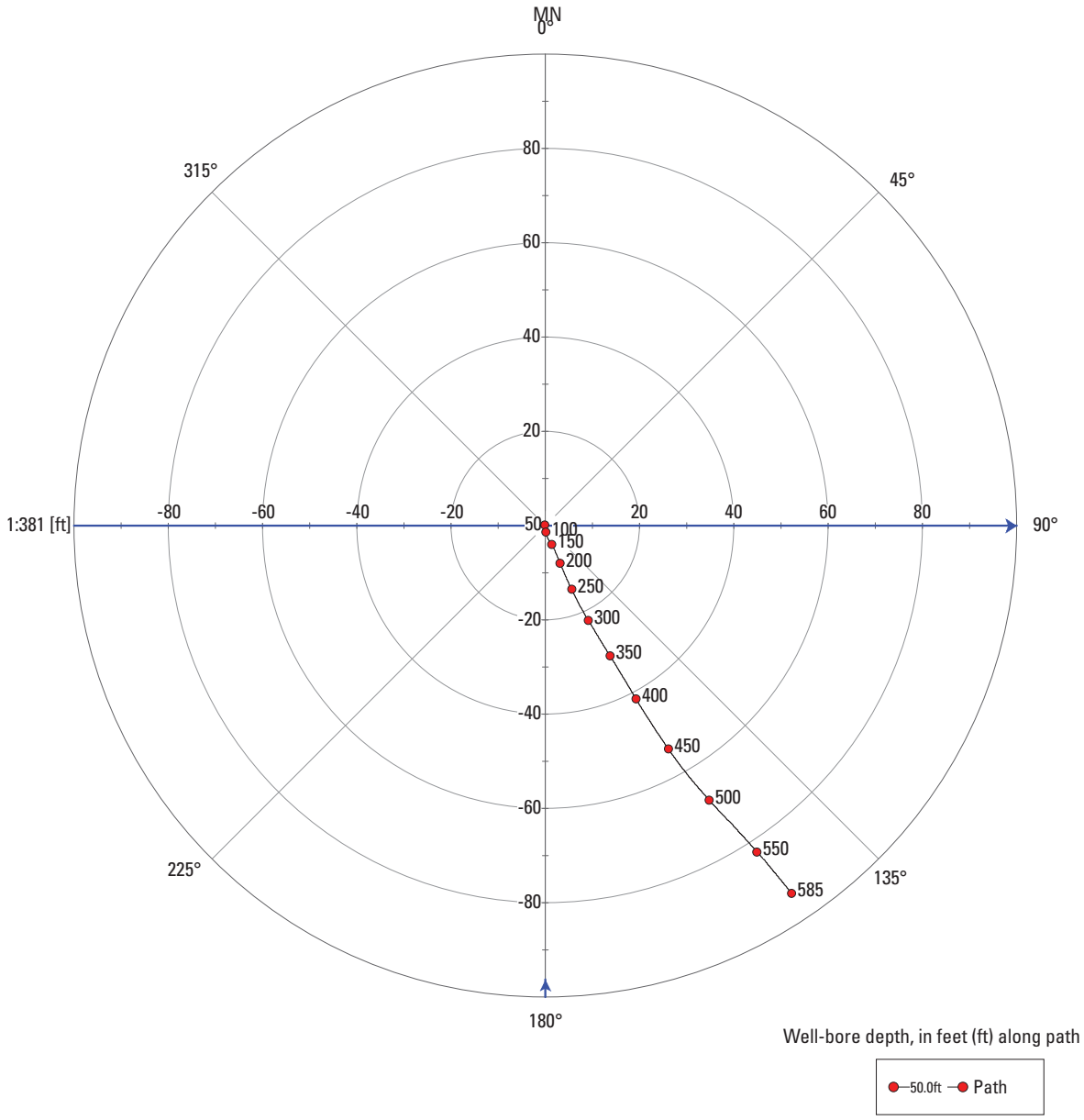


Figure 2.2. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-1023. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

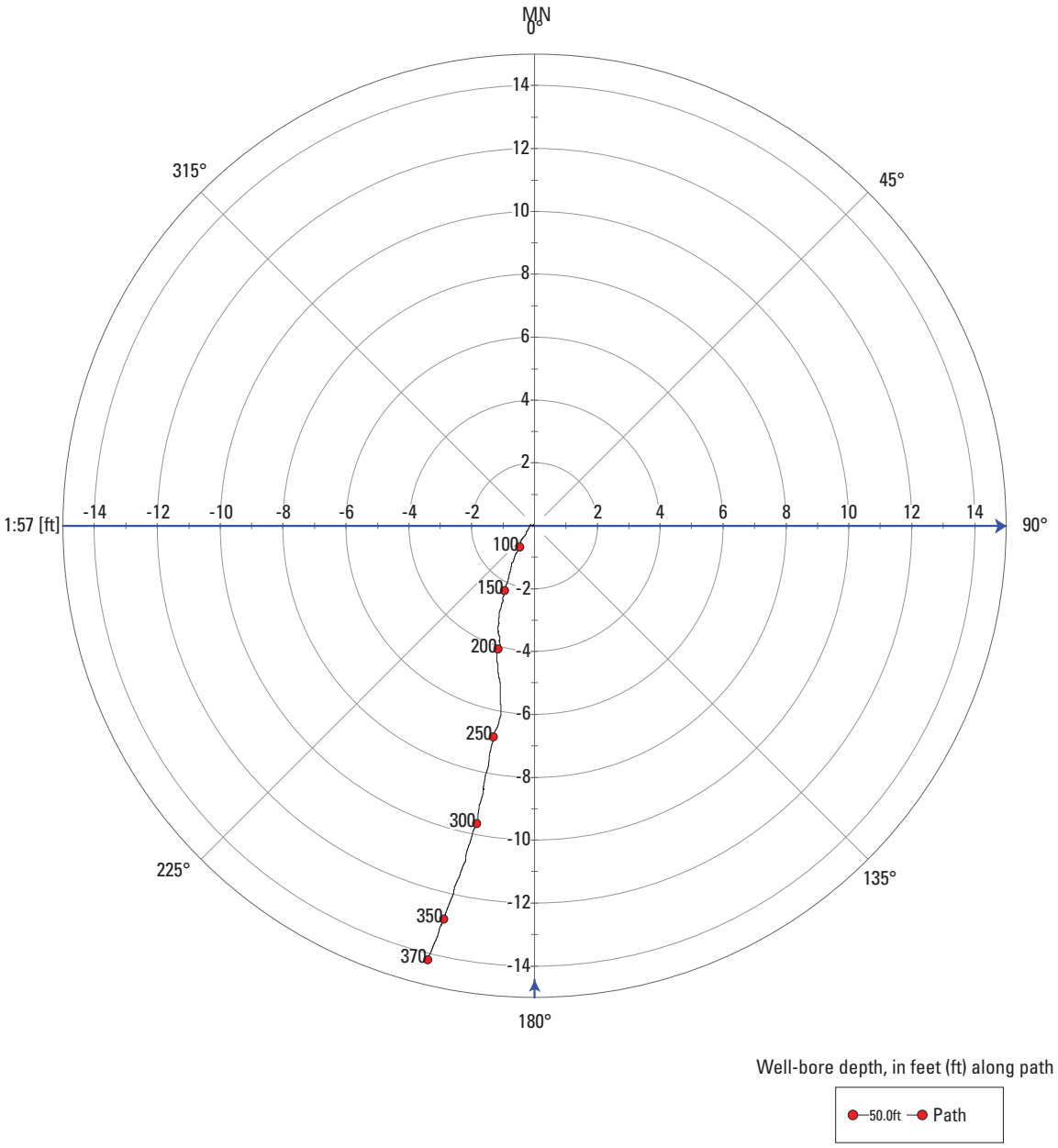


Figure 2.3. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-1087. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

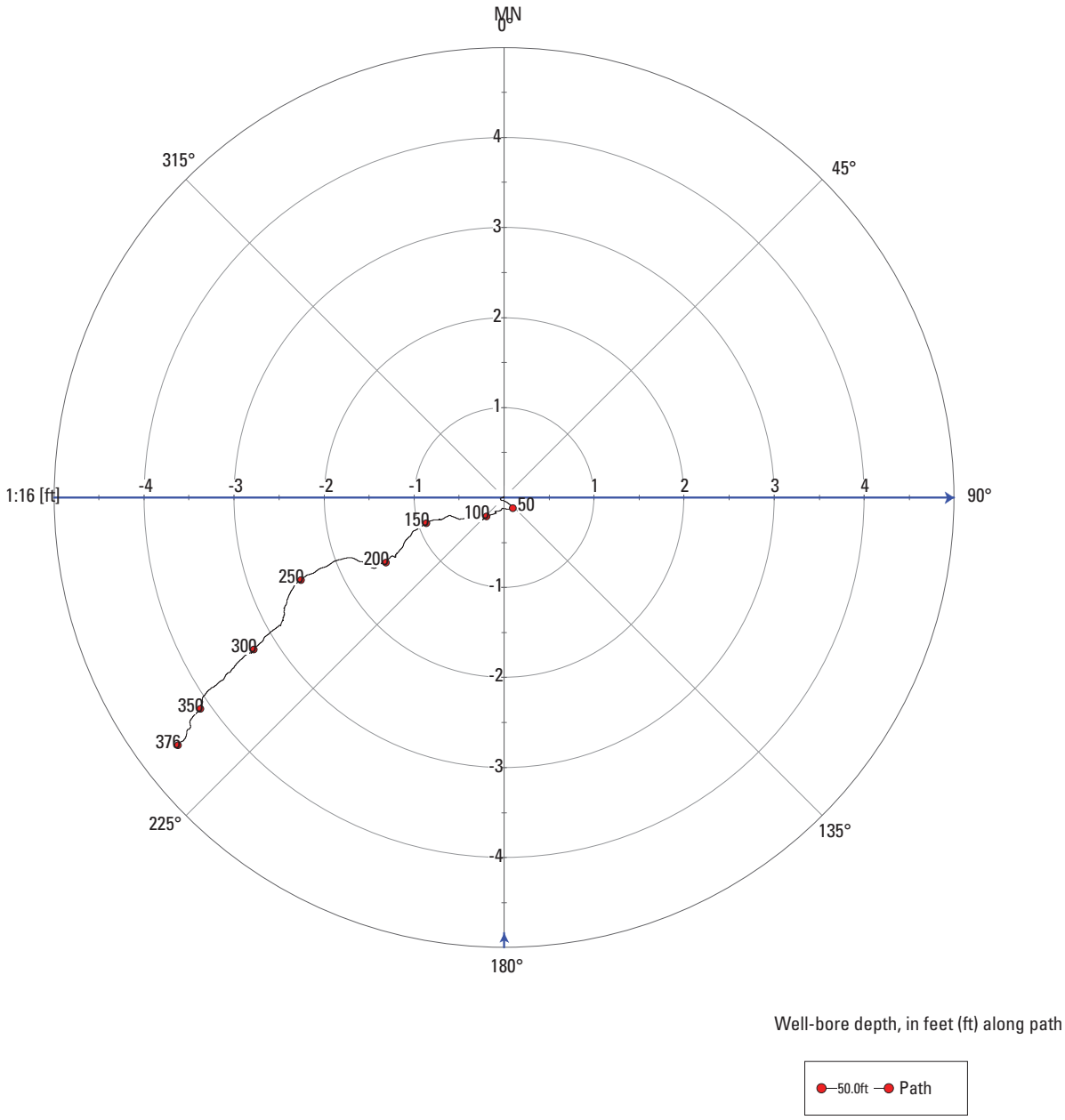


Figure 2.4. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-1129. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

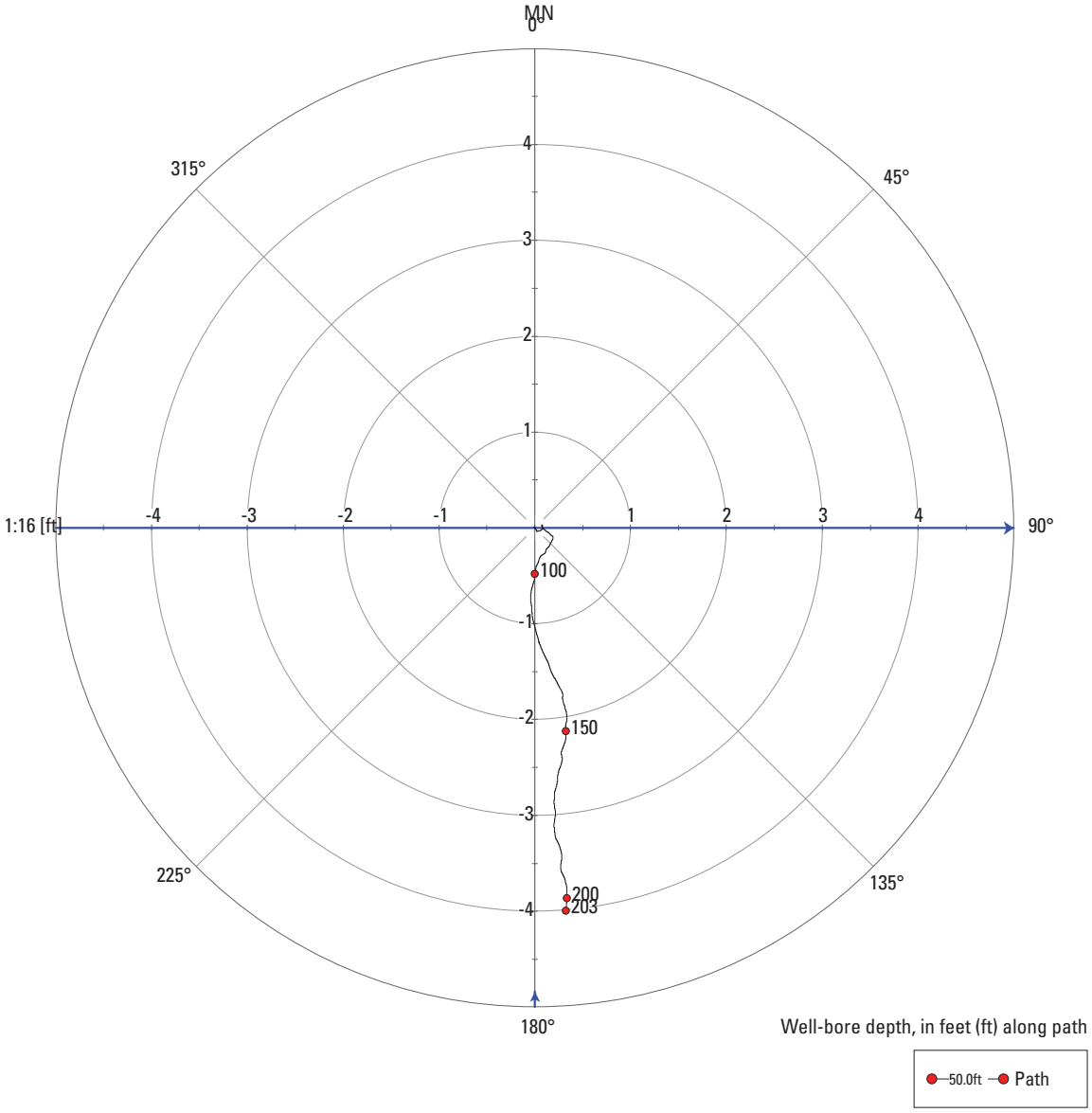


Figure 2.5. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-2698. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

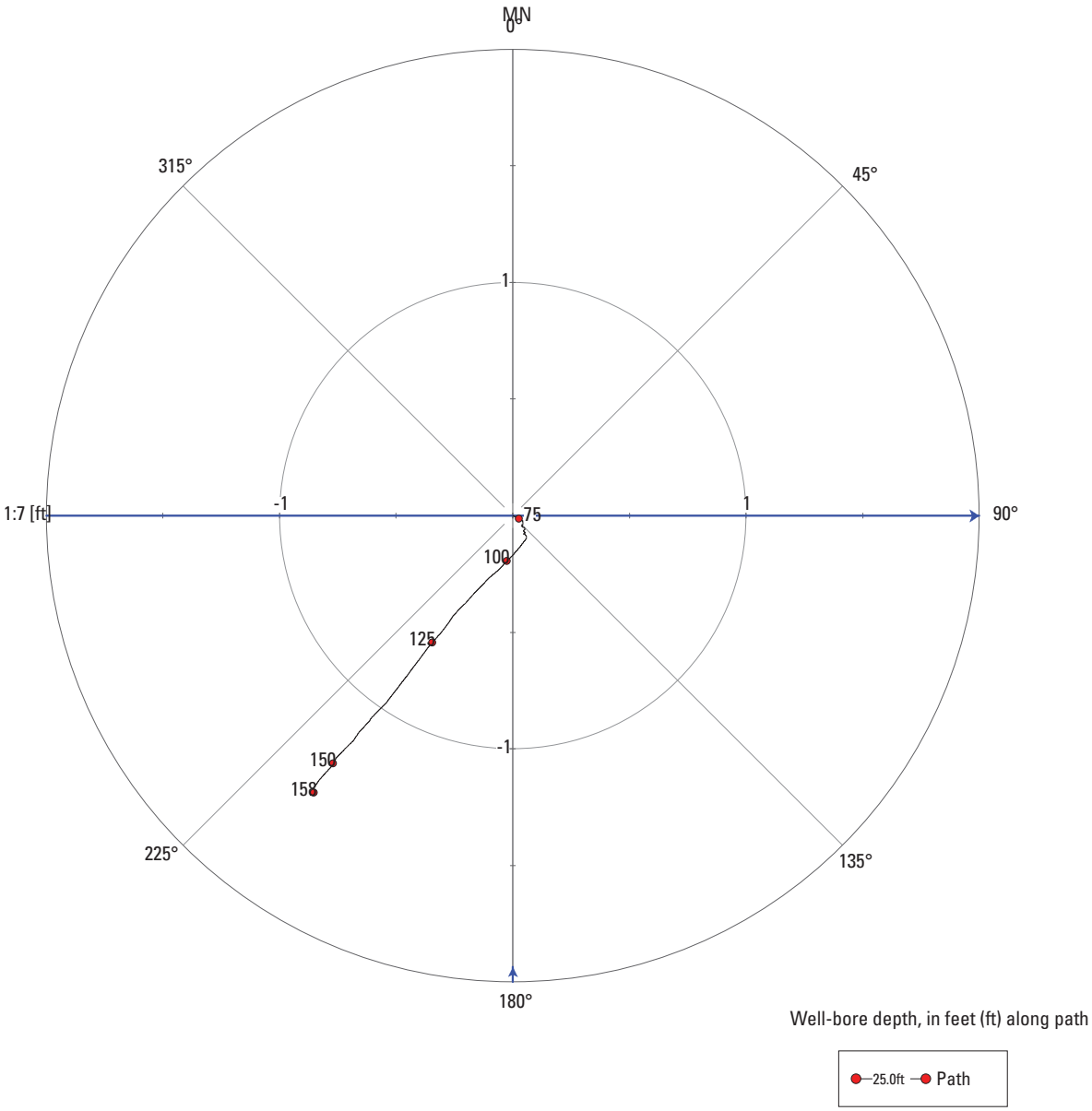


Figure 2.6. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-2861. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 25-foot depth intervals.

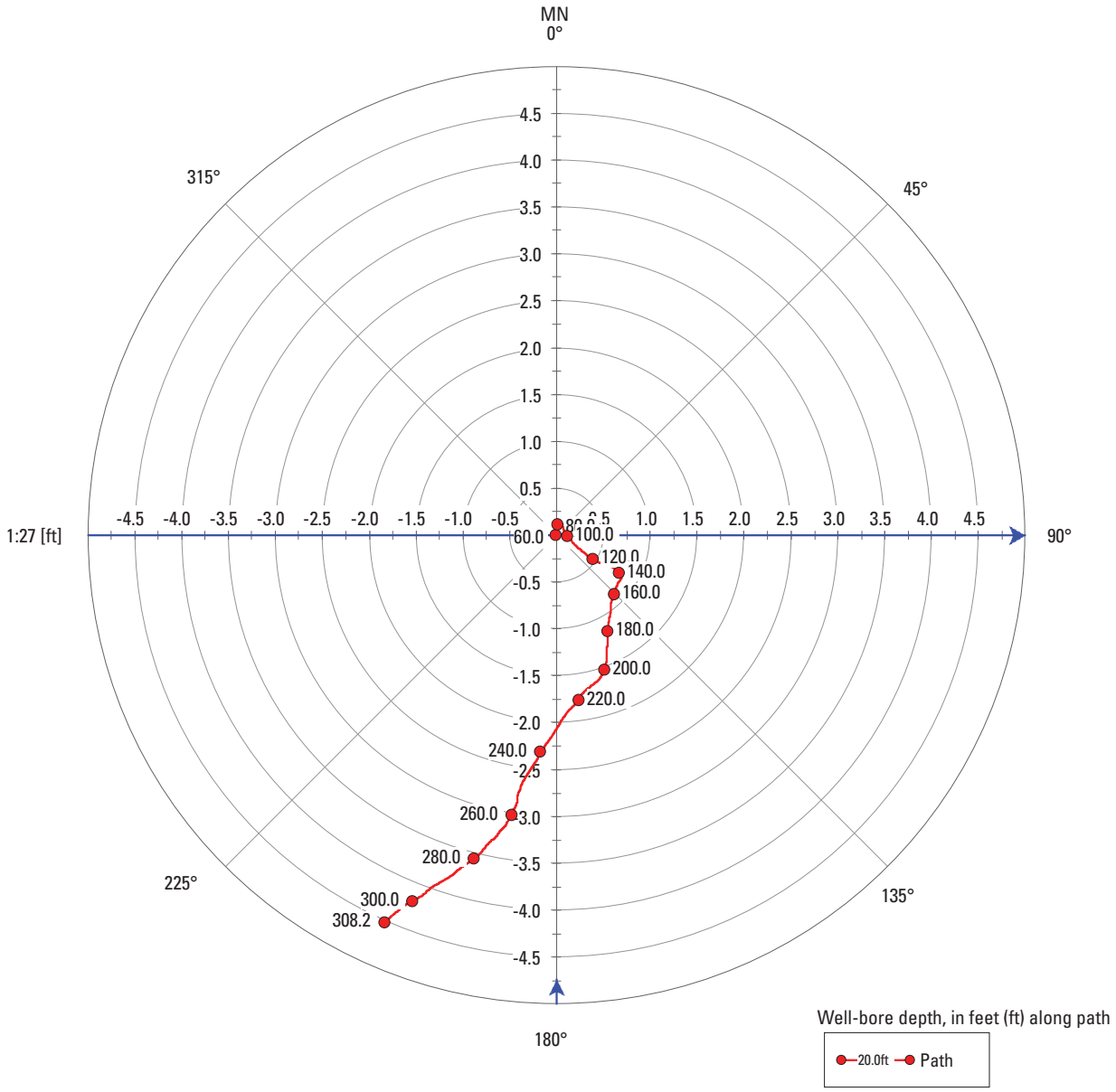


Figure 2.7. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-2869. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 20-foot depth intervals.

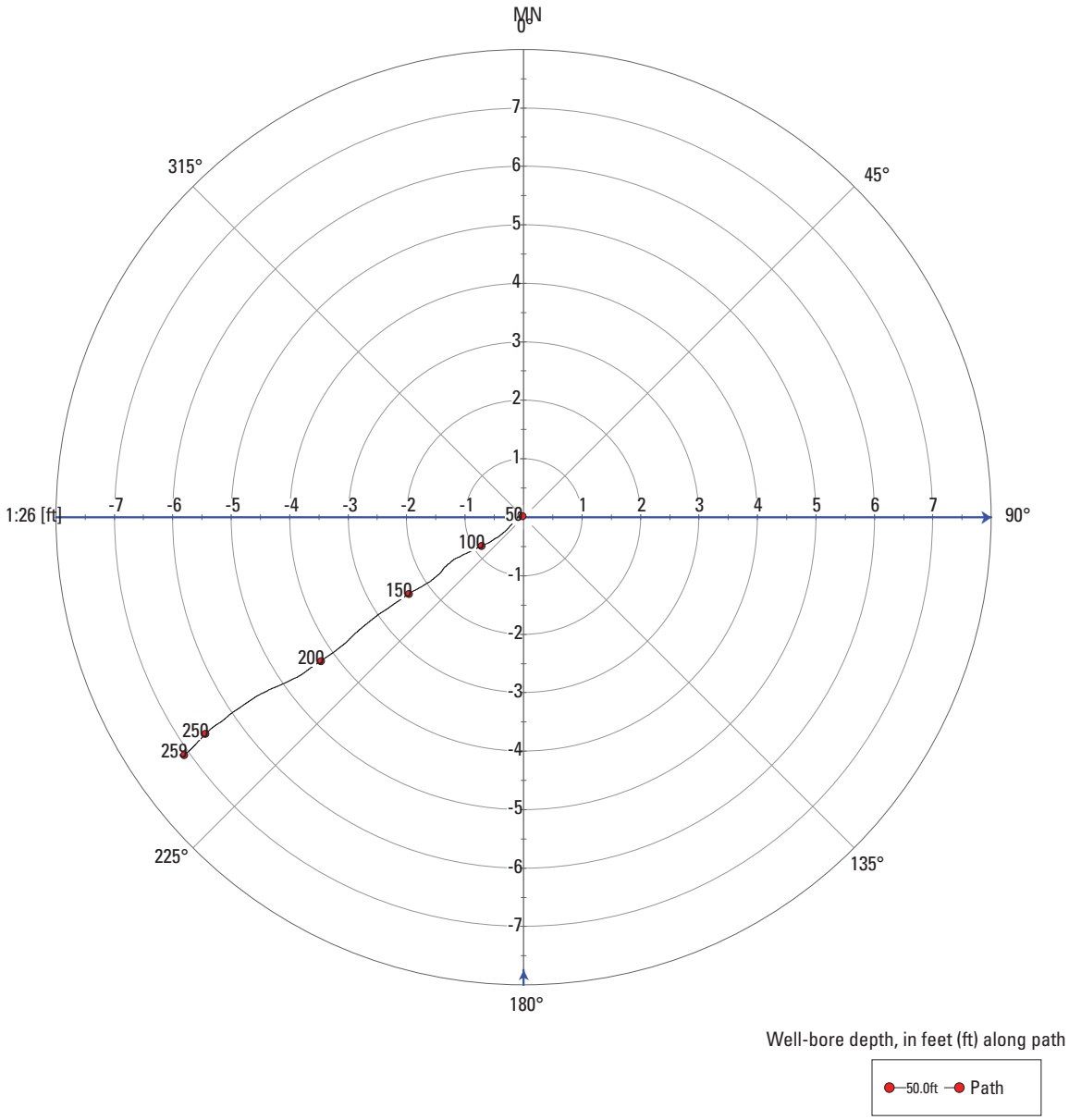


Figure 2.8. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-2870. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

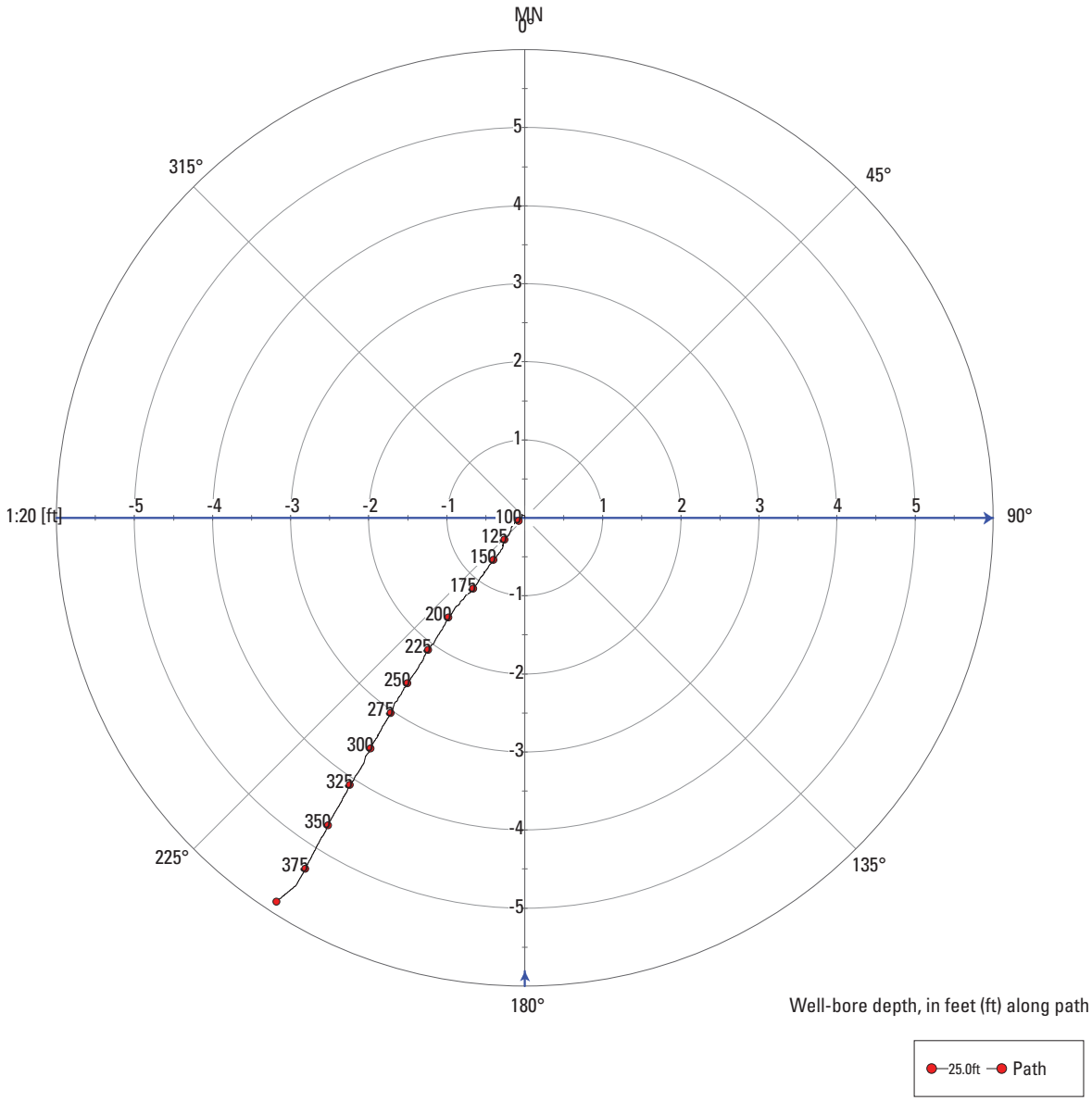


Figure 2.9. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3062. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 25-foot depth intervals.

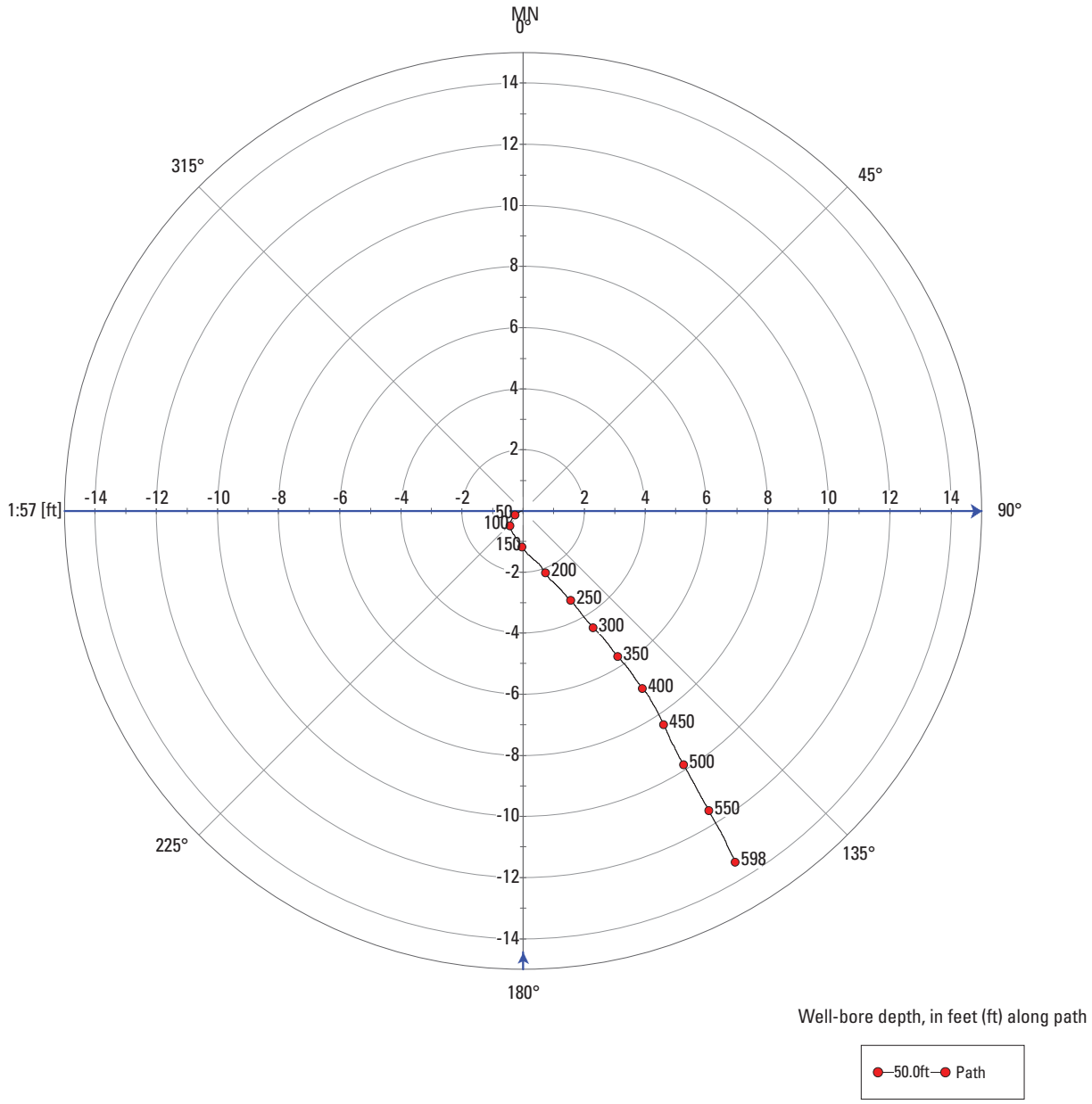


Figure 2.10. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3063. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

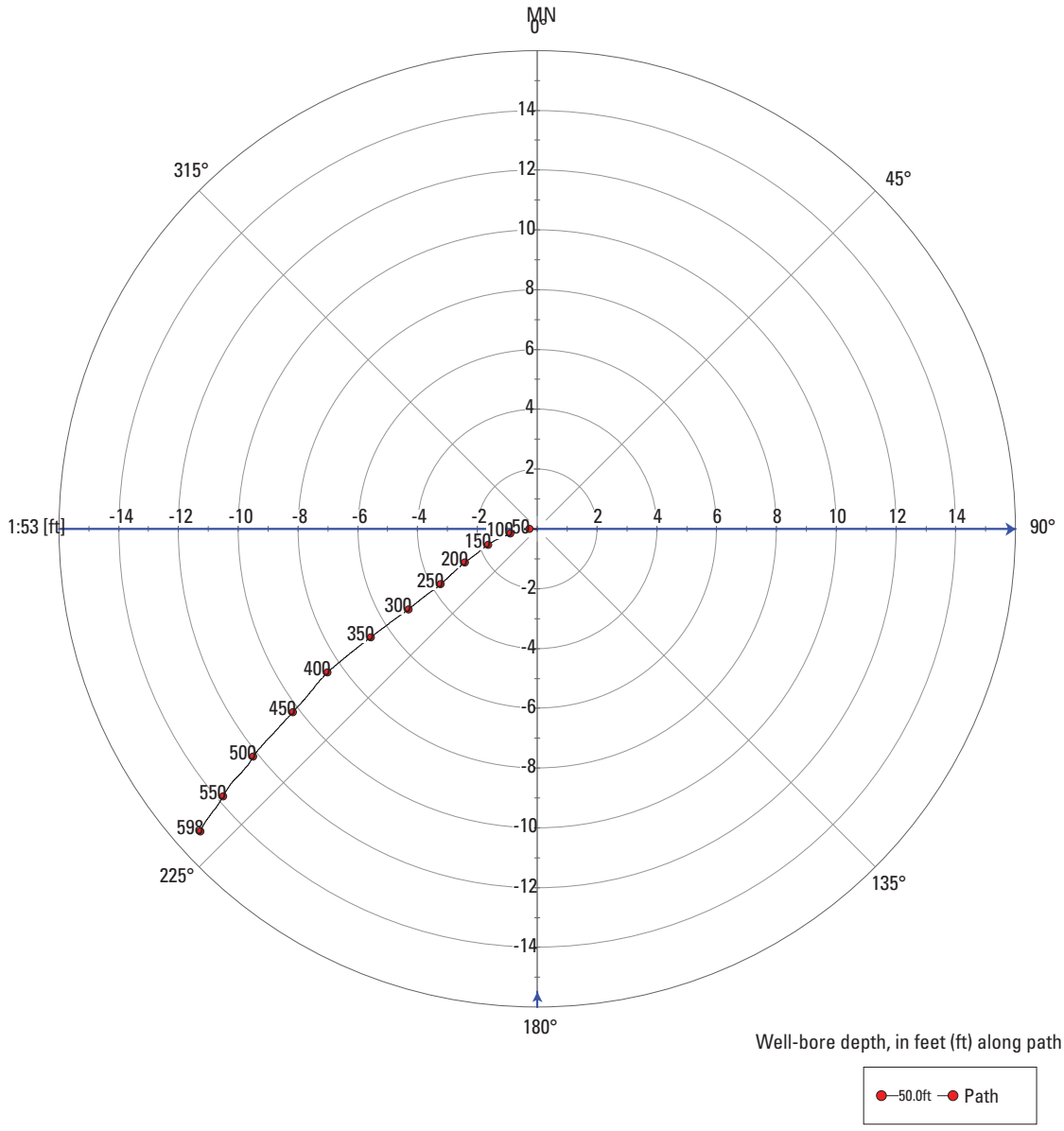


Figure 2.11. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3066. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

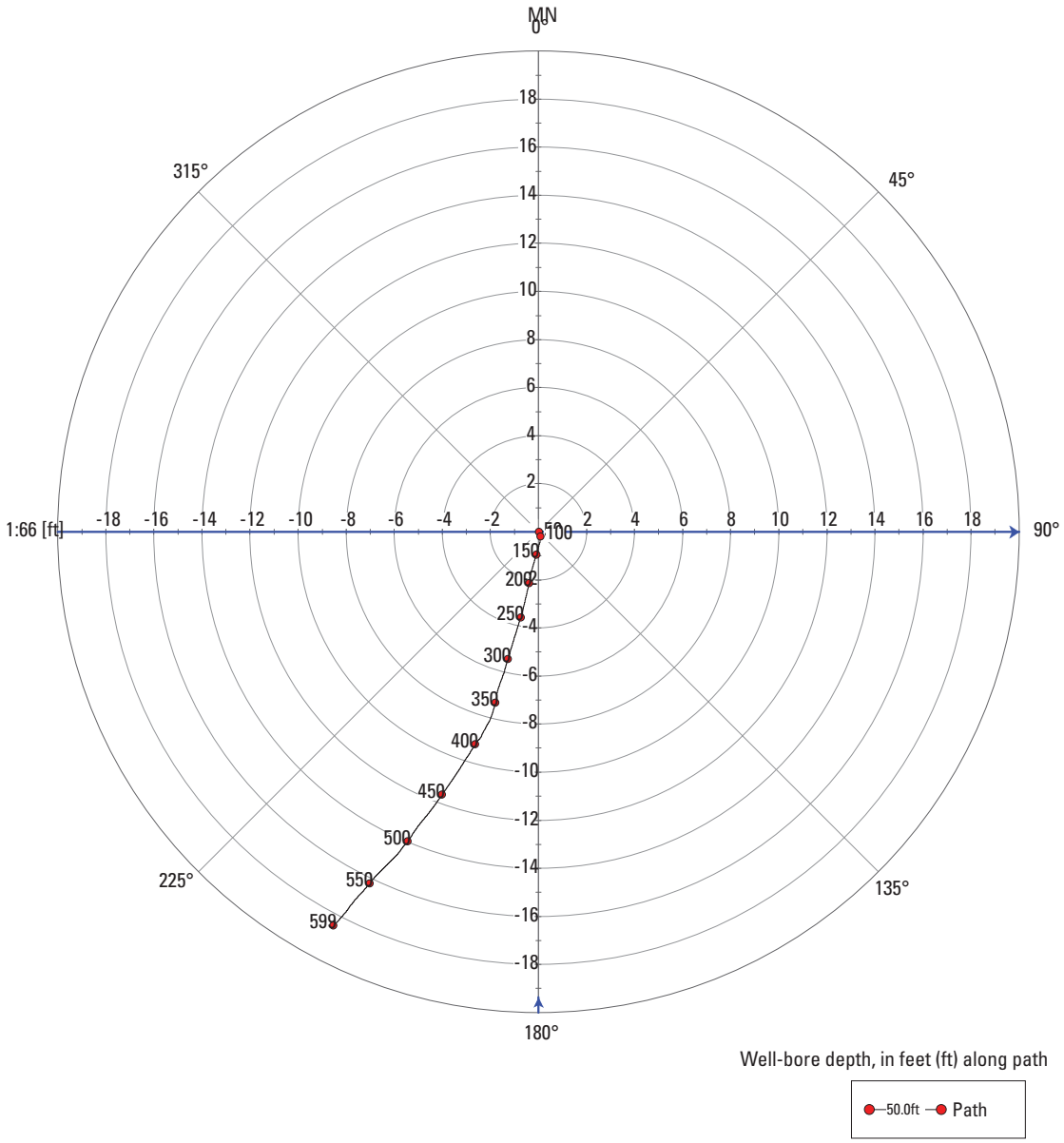


Figure 2.12. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3067. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

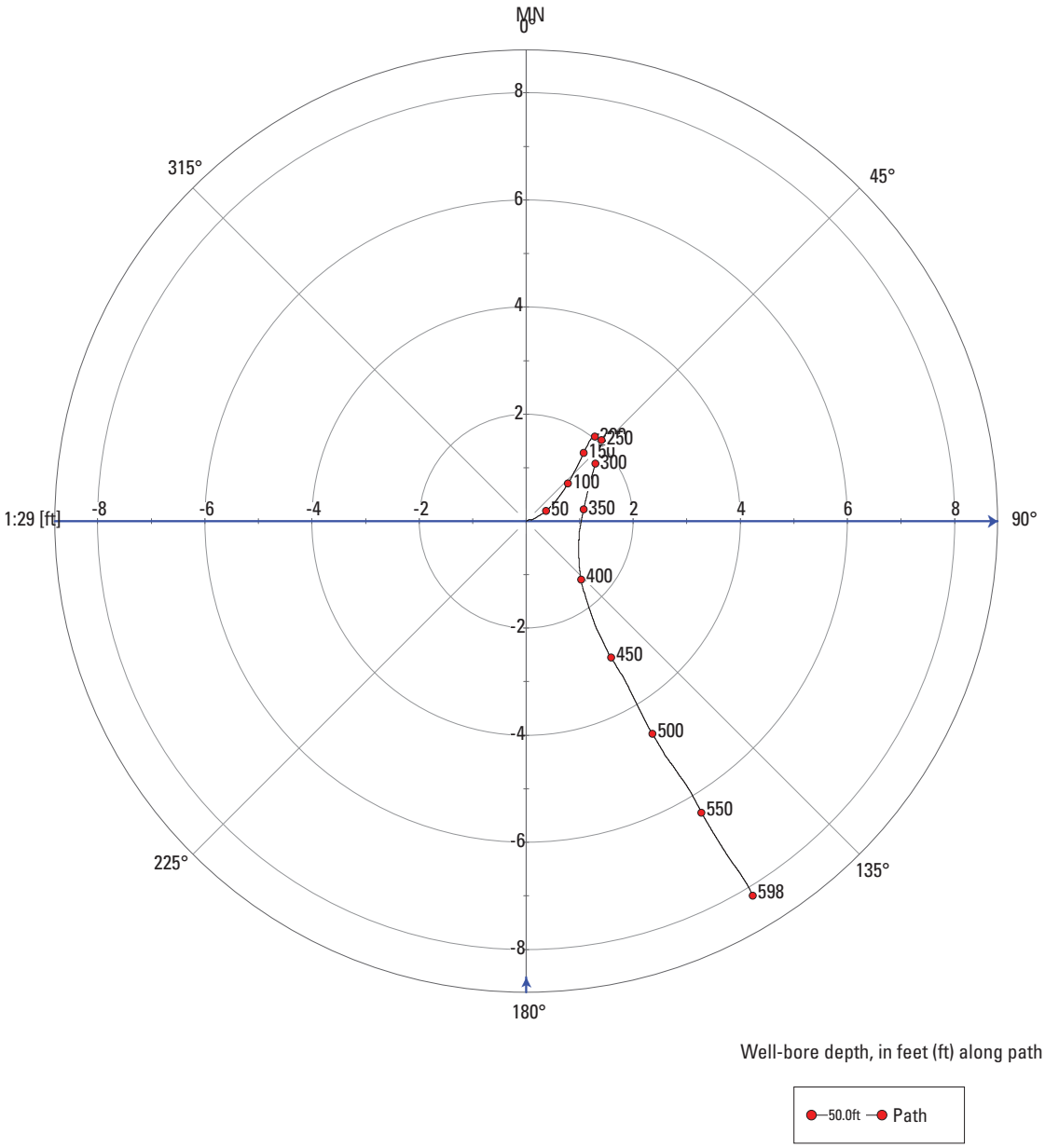


Figure 2.13. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3068. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

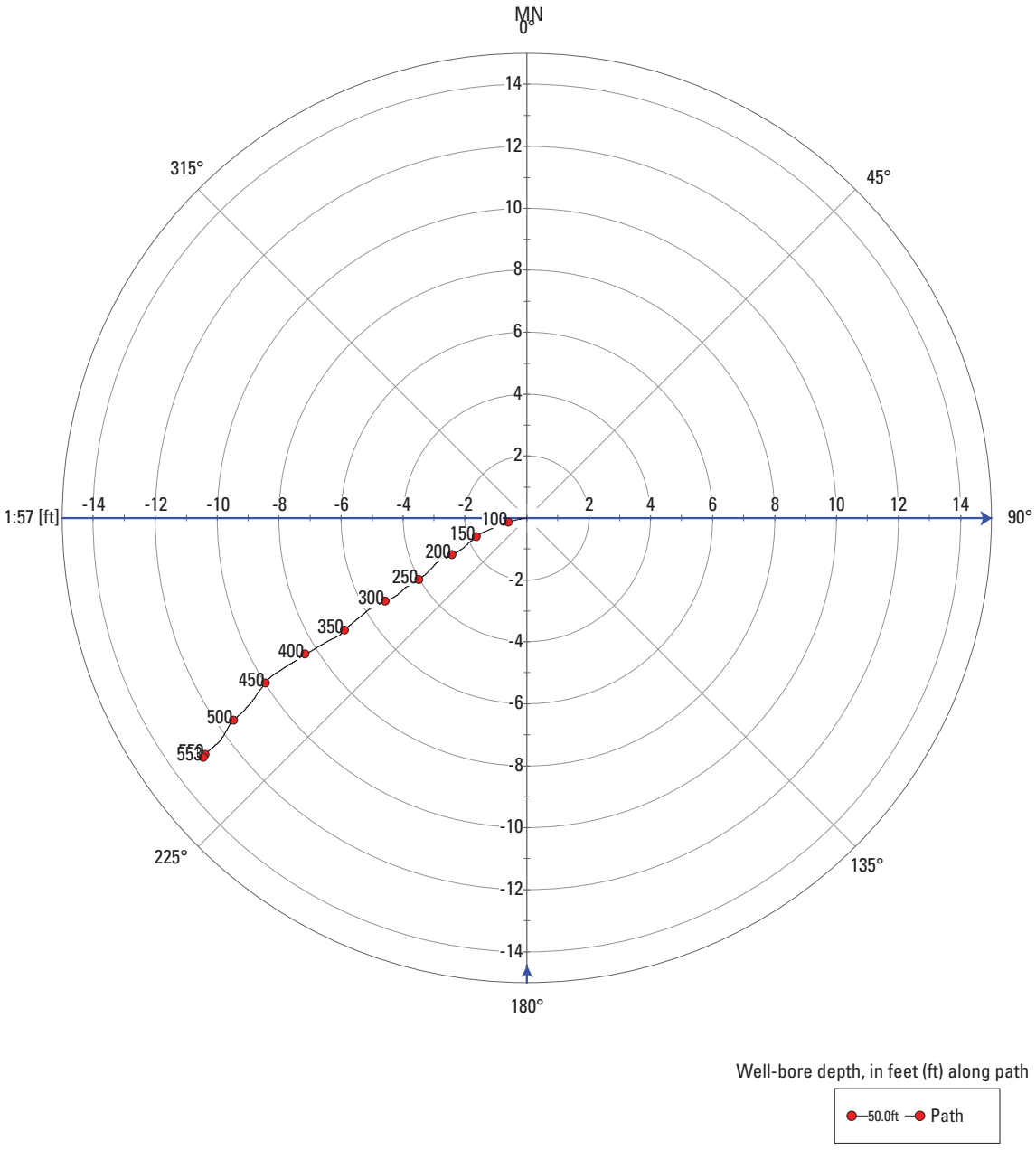


Figure 2.14. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3070. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 50-foot depth intervals.

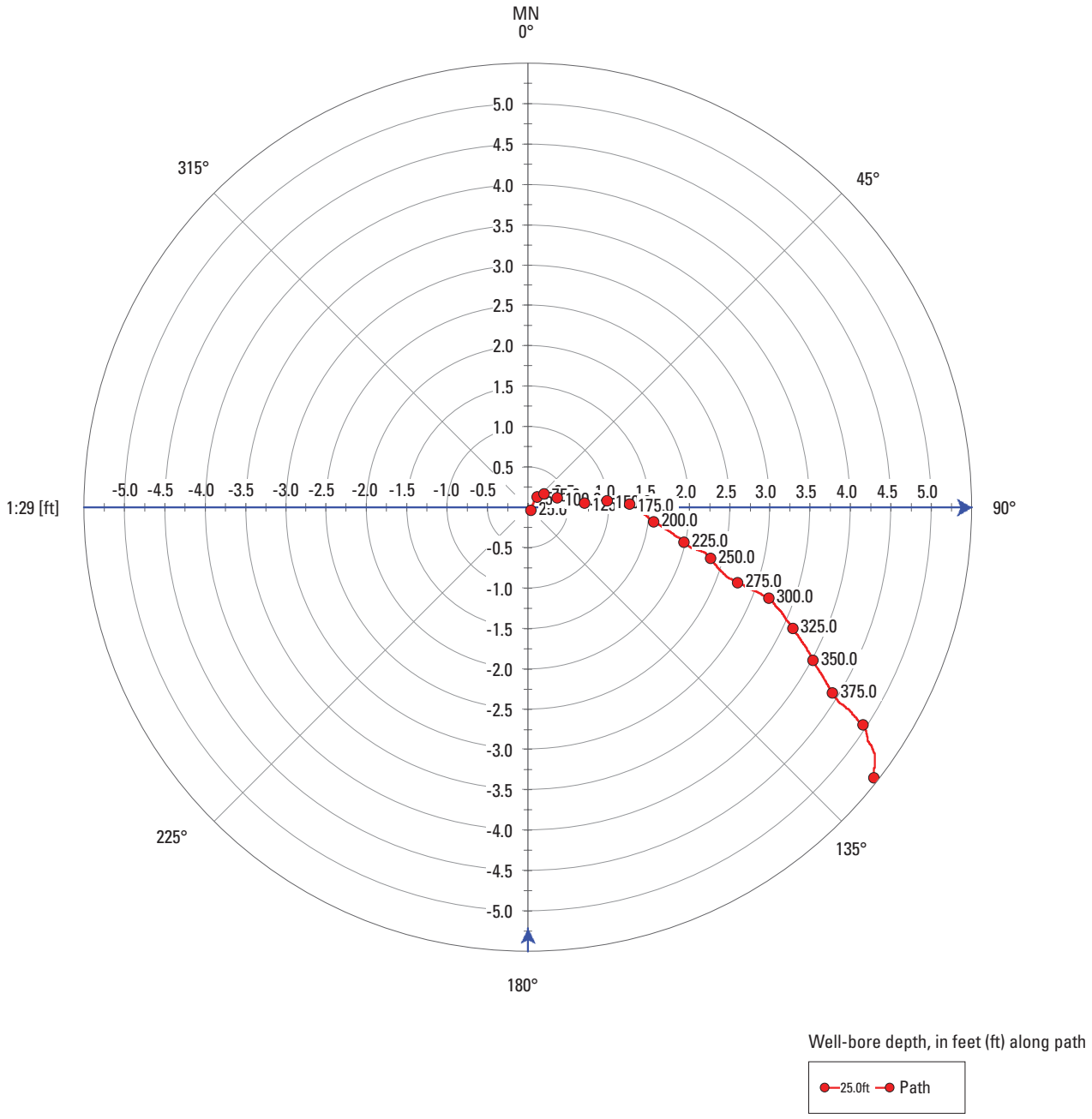


Figure 2.15. Interpretation of well-bore drift (path) as determined from orientation data collected with acoustic televiewer logs for well BK-3071. Direction of path in degrees relative to magnetic north (MN) and deviation from vertical in feet (ft) shown at selected depths. Top of borehole at center of plot. Path of borehole shown at 25-foot depth intervals.

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