USGS
science for a changing world

DOE/ID-22235

Prepared in cooperation with the U.S. Department of Energy

Multilevel Groundwater Monitoring of Hydraulic Head and Temperature in the Eastern Snake River Plain Aquifer, Idaho National Laboratory, Idaho, 2011–13

Scientific Investigations Report 2015–5042

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

Cover: Hydrologic Technician, Jayson Blom (U.S. Geological Survey), collecting pressure and temperature profiles at well site USGS 137A. In the background is Big Southern Butte on the Idaho National Laboratory, Idaho. Photograph taken in March 2014 by Brian V. Twining, Supervisory Hydrologist, U.S. Geological Survey Idaho National Laboratory Project Office, Idaho Falls, Idaho.

Multilevel Groundwater Monitoring of Hydraulic Head and Temperature in the Eastern Snake River Plain Aquifer, Idaho National Laboratory, Idaho, 2011–13

By Brian V. Twining and Jason C. Fisher

DOE/ID-22235
Prepared in cooperation with the U.S. Department of Energy

Scientific Investigations Report 2015–5042

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

Suggested citation:
Twining, B.V., and Fisher, J.C., 2015, Multilevel groundwater monitoring of hydraulic head and temperature in the eastern Snake River Plain aquifer, Idaho National Laboratory, Idaho, 2011–13: U.S. Geological Survey Scientific Investigations Report 2015–5042 (DOE/ID-22235), 49 p., http://dx.doi.org/10.3133/sir20155042.

ISSN 2328-0328 (online)

Contents

Contents—Continued

Figures

Figures—Continued

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/ d)	0.09290	meter squared per day (m^2/d)

Supplemental Information

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 × °C) + 32.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude and hydraulic head, as used in this report, refer to distance above the vertical datum.

Abbreviations and Acronyms

ATR Complex	Advanced Test Reactor Complex
AVZ	Axial Volcanic Zone
bls	below land surface
BLR	Big Lost River
CFA	Central Facilities Area
ESRP	eastern Snake River Plain
head	hydraulic head
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
MFC	Materials and Fuels Complex
MLMS	multilevel monitoring system
NRF	Naval Reactors Facility
PBF	Power Burst Facility
PCC	Pearson correlation coefficient
psi	pounds per square inch
psia	pounds per square inch absolute
RWMC	Radioactive Waste Management Complex
TAN	Test Area North
USGS	U.S. Geological Survey
VRZ	Volcanic Rift Zone

Multilevel Groundwater Monitoring of Hydraulic Head and Temperature in the Eastern Snake River Plain Aquifer, Idaho National Laboratory, Idaho, 2011–13

By Brian V. Twining and Jason C. Fisher

Abstract

From 2011 to 2013, the U.S. Geological Survey's Idaho National Laboratory (INL) Project Office, in cooperation with the U.S. Department of Energy, collected depth-discrete measurements of fluid pressure and temperature in 11 boreholes located in the eastern Snake River Plain aquifer. Each borehole was instrumented with a multilevel monitoring system (MLMS) consisting of a series of valved measurement ports, packer bladders, casing segments, and couplers.

Multilevel monitoring at the INL has been ongoing since 2006 and this report summarizes data collected from 2011 to 2013 in 11 multilevel monitoring wells. Hydraulic head (head) and groundwater temperature data were collected from 11 multilevel monitoring wells, including 177 hydraulically isolated depth intervals from 448.0 to 1,377.6 feet below land surface. One port (port 3) within borehole USGS 134 was not monitored because of a valve failure.

Head and temperature profiles reveal unique patterns for vertical examination of the aquifer's complex basalt and sediment stratigraphy, proximity to aquifer recharge and discharge, and groundwater flow. These features contribute to some of the localized variability even though the general profile shape remained consistent over the period of record. Twenty-two major head inflections were described for 9 of 11 MLMS boreholes and almost always coincided with low-permeability sediment layers and occasionally thick layers of dense basalt. However, the presence of a sediment layer or dense basalt layer was insufficient for identifying the location of a major head change within a borehole without knowing the true areal extent and relative transmissivity of the lithologic unit. Temperature profiles for boreholes completed within the Big Lost Trough indicate linear conductive trends; whereas, temperature profiles for boreholes completed within volcanic rift zones and near the southern boundary of the Idaho National Laboratory, indicate mostly convective heat transfer. Select boreholes along the southern boundary show a temperature reversal and cooler water deeper in the aquifer resulting from the vertical movement of groundwater.

Vertical head and temperature change were quantified for each of the 11 multilevel monitoring systems. Vertical head gradients defined for the major inflections in the head profiles were as high as 2.9 feet per foot. In general, fractured basalt zones displayed relatively small vertical head differences and show a high occurrence within volcanic rift zones. Poor connectivity between fractures and higher vertical gradients were generally attributed to sediment layers and layers of dense basalt, or both. Groundwater temperatures in all boreholes ranged from 10.8 to 16.3 °C.

Normalized mean head values were analyzed for all 11 multilevel monitoring wells for the period of record (2007–13). The mean head values suggest a moderately positive correlation among all boreholes and generally reflect regional fluctuations in water levels in response to seasonal climatic changes. Boreholes within volcanic rift zones and near the southern boundary (USGS 103, USGS 105, USGS 108, USGS 132, USGS 135, USGS 137A) display a temporal correlation that is strongly positive. Boreholes in the Big Lost Trough display some variations in temporal correlations that may result from proximity to the mountain front to the northwest and episodic flow in the Big Lost River drainage system. For example, during June 2012, boreholes MIDDLE 2050A and MIDDLE 2051 showed head buildup within the upper zones when compared to the June 2010 profile event, which correlates to years when surface water was reported for the Big Lost River several months preceding the measurement period. With the exception of borehole USGS 134, temporal correlation between MLMS wells completed within the Big Lost Trough is generally positive. Temporal correlation for borehole USGS 134 shows the least agreement with other MLMS boreholes located within the Big Lost Trough; however, borehole USGS 134 is close to the mountain front where tributary valley subsurface inflow is suspected.

Introduction

The Idaho National Laboratory (INL) was established in 1949 by the U.S. Atomic Energy Commission (now the U.S. Department of Energy) for the development of peacetime atomic-energy applications, nuclear safety research, defense programs, and advanced energy concepts. The INL covers an area of about 890 mi^2 and overlies the west-central part of the eastern Snake River Plain (ESRP) in southeastern Idaho (fig. 1). Over 50 years of waste disposal at the INL has resulted in measurable concentrations of contaminants in the eastern Snake River Plain (ESRP) aquifer beneath the INL. Contaminants include several radiochemical, inorganic, and organic constituents (Mann and Beasley, 1994; Cecil and others, 1998; Bartholomay and others, 2000). The primary sources of contaminants are from facility wastewater disposal sites, such as lined evaporation ponds, unlined infiltration ponds and ditches, drain fields, and injection wells. Determining the long-term risks associated with contaminants in the aquifer, or that might be in the aquifer in the future, is difficult because of slow releases of residual contamination in the unsaturated zone or waste buried in shallow pits and trenches.

Since 1949, the U.S. Geological Survey (USGS) has maintained a network of monitoring wells used to record water levels and water quality in more than 200 boreholes with varying lengths of record. Most monitoring wells are open boreholes and groundwater flow is unrestricted, controlled by high transmissivity fractures, and can result in mixing and (or) dilution of chemical constituents (fig. 2). The fractured basalts of the ESRP aquifer are well suited as open-hole or partially screened construction; however, measurements collected from open-hole wells are independent of depth and represent a composite value that is a transmissivity-weighted average of all hydraulically conductive features in the borehole.

In 2005, the USGS began to monitor the vertical distribution of fluid pressure, temperature, and chemistry using multilevel monitoring systems (MLMSs) completed in discrete zones within the ESRP aquifer. The monitoring frequency was changed from quarterly to annually in 2011 for select MLMSs because of programmatic adjustments; however, two MLMSs (MIDDLE 2050A and MIDDLE 2051), near the Big Lost River (BLR), are monitored quarterly to capture episodic flow in the BLR. The MLMS data provide depth-discrete measurements of hydraulic head (head) and temperature in cored boreholes drilled to depths ranging from 818 to 1,427 feet below land surface (ft bls).

Purpose and Scope

The purpose of this report is to disseminate measurements of head and water-temperature data collected from 2011 to 2013 from 11 MLMS boreholes and review the methods used to collect depth-discrete measurements. A general description of the lithology and multilevel completion design for two MLMS completions installed during 2012 also are provided. In addition, normalized mean hydraulic head values were computed, graphed, and analyzed for MLMS data collected between 2007 and 2013.

Monitoring wells at the INL generally penetrate less than 200 ft into the ESRP aquifer and are often constructed as open hole or with well screen. This type of well construction results in a vertically averaged composite head controlled by transmissivity differences between fractures. Attempting to compare head data between open hole or screened wells completed to different depths can be difficult. The MLMS uses rubber bladders (packers) to isolate fractures and sediment layers and limit vertical flow between fractures at different depths within a well. By isolating fractures and sediment layers within the ESRP aquifer, the MLMS provides an effective method to examine change in head and water chemistry. Completion depths for MLMS boreholes far exceed those of the average INL monitoring wells; therefore, any additional information pertaining to deeper flow and contaminant transport conditions will support ongoing numerical modeling efforts.

Geohydrologic Setting

The study area is in the ESRP in Idaho, a relatively flat topographic depression, about 200 mi long and 50–70 mi wide (fig. 1). The INL lies within the west-central part of the ESRP and all MLMSs are inside the INL boundaries. Streams, some ephemeral, originate in mountain ranges north and west of the study site and include the BLR, the Little Lost River, Birch Creek, and Camas Creek. Streamflow-infiltration recharge fluctuates greatly in response to seasonality, such as spring snowmelt. Episodic recharge from the BLR channel, spreading areas, sinks, and playas represent a large transient stress within the ESRP aquifer at the INL (fig. 1). Episodic flood events can result in large pulses of surface-water infiltration near the southern boundary and have been shown to affect both the saturated and unsaturated zones in this region (Nimmo and others, 2002).

The ESRP at the INL mostly consists of olivine tholeiitic basaltic lava flows (about 85 percent by volume) with lesser amounts of interbedded terrestrial sediments (Kuntz and others, 1992). Basaltic rocks and sedimentary deposits combine to form the ESRP aquifer. Significant landforms of the ESRP in the vicinity of the INL include (fig. 1): (1) rhyolite domes (Kuntz and others, 1994), (2) Big Lost Trough (Blair, 2002), (3) volcanic rift zones (VRZ), and (4) axial volcanic zone (AVZ). The Big Lost Trough (fig. 1) is bounded to the northwest by mountains and on the other sides by informally named volcanic rift zones—the AVZ extends northeast and southwest and the Arco-Big Southern Butte VRZ extends northwest and southeast. The VRZs, including the Arco-Big Southern Butte VRZ and AVZ, are areas of focused volcanism resulting in high concentrations of volcanic vents and fissures (Anderson and others, 1999, p. 13; Hughes and others, 1999, p. 145), which are the major sources of basaltic rocks on the plain.

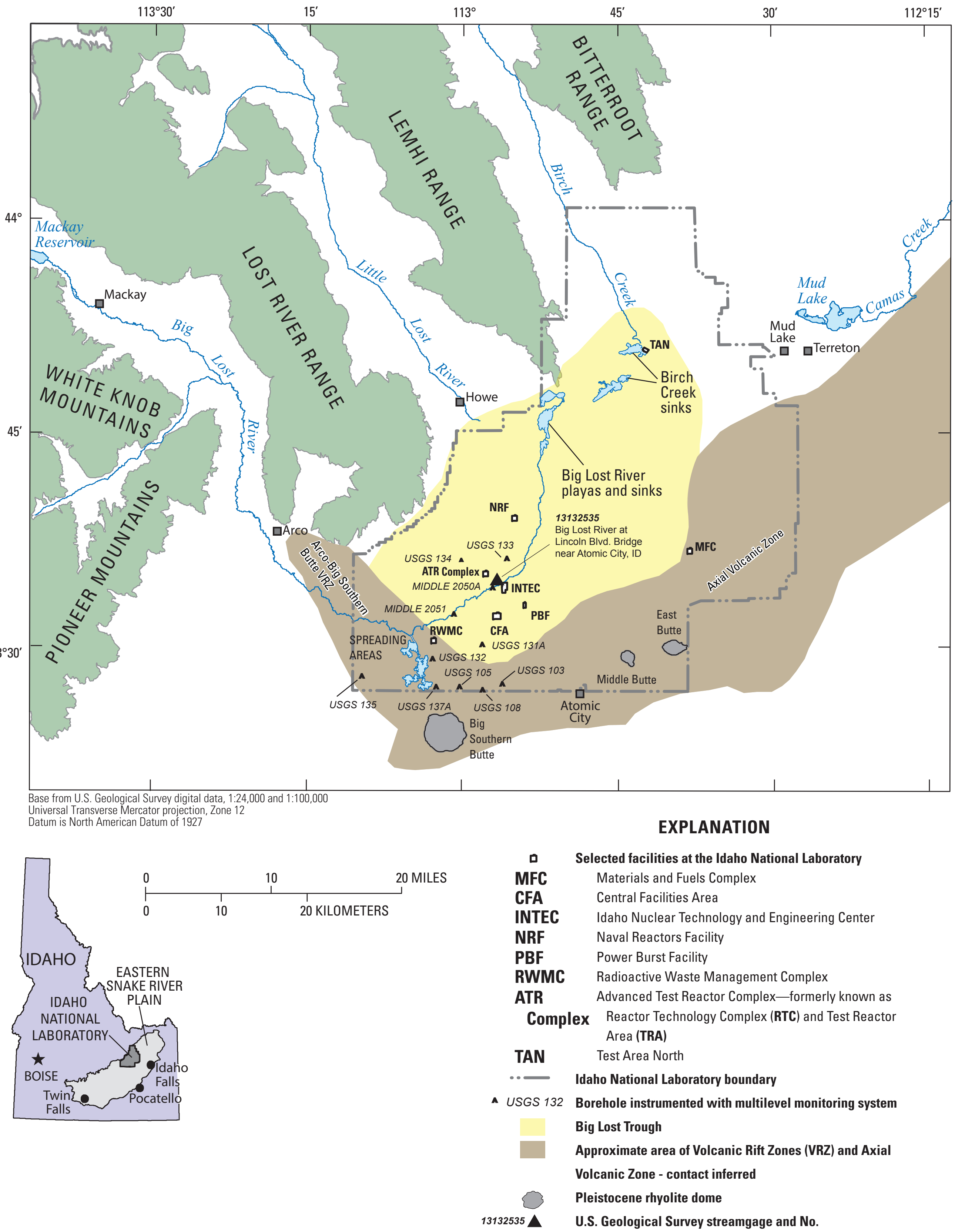

Figure 1. Location of selected facilities, multilevel monitoring wells, and volcanic rift zones bounding the Big Lost Trough, Idaho National Laboratory and vicinity, Idaho.

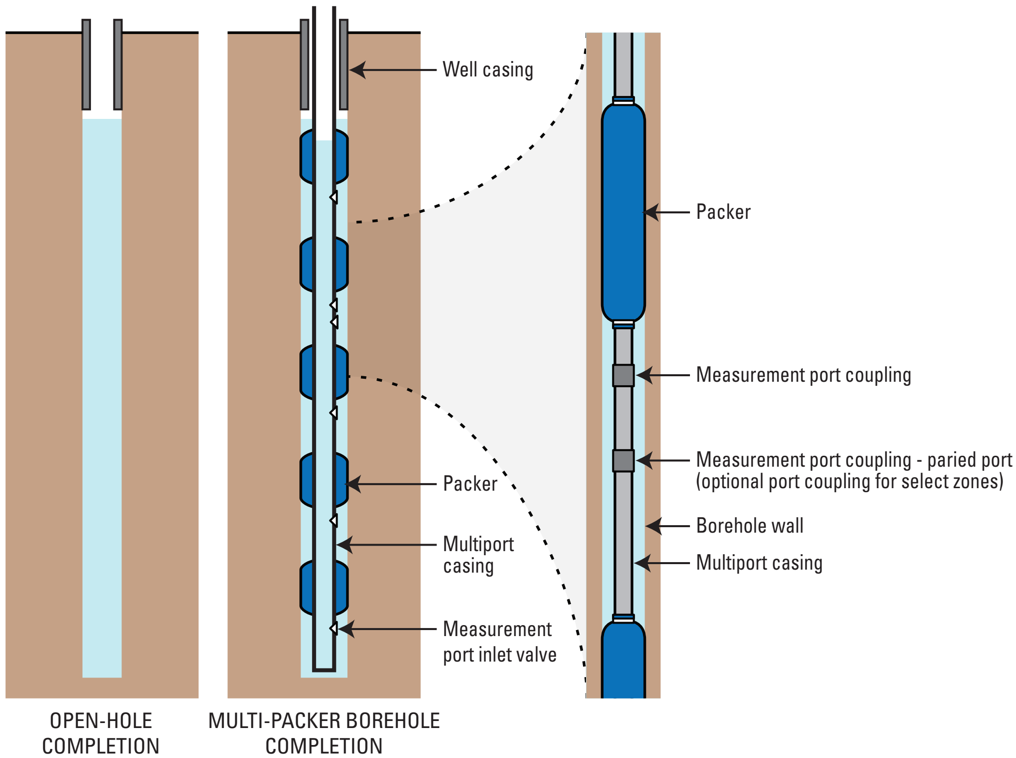

Figure 2. Open-hole and multi-packer borehole completions, eastern Snake River Plain aquifer, Idaho National Laboratory and vicinity, Idaho.

The BLR has been a major source of sediment since late Pliocene time, resulting in a depocenter known as the Big Lost Trough (fig. 1; Geslin and others, 2002). Boreholes drilled in the Big Lost Trough generally encounter greater amounts by volume of interbedded sediment than boreholes drilled in and near the Arco-Big Southern Butte VRZ and AVZ (Anderson and others, 1999, fig. 9, table 2; Hughes and others, 2002; Welhan and others, 2007). Interbedded sediments penetrated by boreholes on the INL range in thickness from equal to or less than 1 ft to equal to or greater than 313 ft and are thickest in the northwestern part of the INL (Anderson and others, 1996; Welhan and others, 2007).

The ESRP aquifer is one of the most productive aquifers in the United States (U.S. Geological Survey, 1985, p. 194). Along the northwestern mountain front, surface-water and groundwater underflow enter the aquifer system from three tributary valleys—BLR, Little Lost River, and Birch Creek (fig. 1). Groundwater moves horizontally through basalt interflow zones and vertically through joints and fracture zones. Infiltration of surface water, groundwater pumping, geologic conditions, and seasonal fluxes of recharge and discharge locally affect the movement of groundwater in the aquifer (Garabedian, 1986). Recharge primarily is from the infiltration of applied irrigation water, streamflow, precipitation, and underflow from the tributary valleys to the plain.

Across the INL, borehole water-table altitudes range from about 4,560 to 4,410 ft and groundwater generally flows in a southwestern direction (Davis and others, 2013, fig. 9). Depth to the water table ranges from about 200 ft below land surface (bls) north of the INL to more than 900 ft bls in the southeast. Aquifer thickness is variable and generally thins towards the mountain fronts and appears to thicken towards the southern boundary of the INL.

Aquifer wells open to less than 100 ft bls of the aquifer can yield as much as 7,000 gal/min with only a few feet of drawdown (Whitehead, 1992). Ackerman (1991, p. 30) and Bartholomay and others (1997, table 3) reported a range of relative transmissivities for basalt in the upper part of the aquifer of 1.1–760,000 ft^2/d. The hydraulic gradient at the INL generally flows from northeast to southwest and ranges from 2 to 10 ft/mi, with an average of about 4 ft/mi (Davis and others, 2013). Horizontal groundwater flow velocities ranging from 2 to 20 ft/d have been calculated based on the movement of various constituents in different areas of the aquifer beneath the INL (Robertson and others, 1974; Mann and Beasley, 1994; Cecil and others, 2000; Busenberg and others, 2001). Localized tracer tests at the INL have shown vertical and horizontal transport rates as high as 60–150 ft/d (Nimmo and others, 2002; Duke and others, 2007).

Previous Investigations

Several reports describing the geology and hydrology of the ESRP at the INL have been published. A comprehensive listing of publications by the USGS is available at: http://id.water.usgs.gov/INL/Pubs/index.html.

Water-quality data collected from MLMSs have been used to describe vertical movement of contaminants in the ESRP aquifer (Bartholomay and Twining, 2010; Bartholomay and others, 2015). Head and temperature data from MLMS boreholes was reported in Fisher and Twining (2011), and Twining and Fisher (2012).

Bartholomay and Twining (2010) analyzed chemical constituents sampled from multiple zones at six MLMS boreholes at the INL (MIDDLE 2050A, MIDDLE 2051, USGS 103, USGS 132, USGS 133, and USGS 134) from 2005 to 2008. The MLMSs were completed in the upper 350–700 ft of the aquifer, and have four to seven sample ports isolated by permanent packers. Results indicated that one to five zones in four MLMSs contained radiochemical constituents that originated from wastewater disposal from INL facilities.

Bartholomay and others (2015) analyzed chemical constituents sampled from multiple zones at 11 MLMS wells at the INL (MIDDLE 2050A, MIDDLE 2051, USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, and USGS 137A) from 2009 to 2013. Water chemistry in different zones was compared to water-source types throughout the INL. Additionally, facility wastewater from the INL is described for zones within MLMSs.

Fisher and Twining (2011) documented the use of MLMSs to examine head and temperature for six boreholes from 2007 to 2008; additionally, they described the MLMS components and specified the installation process, drilling methods, geology, and geophysical logs for boreholes USGS 103, USGS 132, USGS 133, USGS 134, MIDDLE 2050A, and MIDDLE 2051. From 2009 to 2010, the MLMS head and temperature monitoring network increased to nine boreholes (Twining and Fisher, 2012), including construction and monitoring of USGS 105, USGS 108, and USGS 135 in addition to the six boreholes of Fisher and Twining (2011). Twining and Fisher (2012) documented use of MLMSs to examine head and temperature for these nine boreholes; revisited methods used to construct head and temperature profiles; summarized data collected; and outlined quality-assurance methods that are summarized in this report.

Methods and Quality Assurance

The methods used to collect depth-discrete measurements of head and temperature were described by Fisher and Twining (2011) and Twining and Fisher (2012). Fisher and Twining (2011) described the modular MLMS components (MP38 versus MP55), sampling probe, acquisition system, system dimensions, and MLMS installation. A general summary and update to the methods for this report include: (1) “,” that describes the methods used to construct head and temperature profiles within a borehole; (2) “Data Processing”, that describe customized computer program “MLMS”; and (3) “Quality Assurance”, that describes the accuracy and precision of head and temperature measurements.

Profiling and Completions

An individual head or temperature profile represents a set of measurements collected over a relatively short time. The actual time required for each measurement period varied, and was dependent on the quantity and spacing of ports within a MLMS. Profile measurements in this study were less than 2 hours, a period considered instantaneous when contrasted to the slow response times of groundwater systems.

Fluid pressure and temperature measurements were made using a portable sampling probe, a wireline-operated probe that is lowered into the multiport casing from the land surface and positioned at a selected measurement port coupling (fig. 3). The positioned probe is then coupled with the measurement port inlet valve to allow monitoring of groundwater outside the multiport casing and within the monitoring zone, so that groundwater in this zone is vertically isolated between upper and lower packers. Coupling the probe with the measurement port inlet valve is done by extending the backing shoe on the probe to create a hydraulic seal between the probe and the port and to open the port. Fluid pressure and temperature measurements are then transmitted to the land surface through the wireline communication cable, processed using a data acquisition system, and recorded on a datalogger. The head at each measurement port, assuming 100 percent barometric efficiency, was expressed as:

$$H = \Psi_2 + Z - D = \left(\frac{P_2 - P_{\mathrm{Atm}}}{\gamma_w}\right) \times 144 + Z - D \qquad (1)$$

where

H is the hydraulic head, in ft;

Ψ_2 is the pressure head outside the multiport casing, in ft;

Z is the altitude of a referenced land-surface measurement point, in ft;

D is the depth to the pressure transducer sensor at the measurement port coupling, in ft bls;

P_2 is the fluid pressure measured outside the multiport casing, in pounds per square inch absolute (psia);

P_{Atm} is the atmospheric pressure measured at land surface, in psia; and

γ_w is the specific weight of water, in pounds per cubic foot (lb/ft^3).

Atmospheric pressure was monitored at the land surface using a handheld barometric sensor. The specific weight of water was calculated as a function of temperature only (McCutcheon and others, 1993), assuming negligible salinity and gravitational differences between measurements, and expressed as:

$$\gamma_{\mathrm{w}} = 62.42796 \times \left\{ 1 - \left(\left[\frac{T + 288.9414}{508929.2 \times (T + 68.12963)} \right] \times (T - 3.9863)^2 \right) \right\} \tag{2}$$

where

γ_{w} is in units of lb/ft^3 and

T is water temperature measured inside the multiport casing from the bridge of the pressure transducer in degrees Celsius.

The depth to the pressure transducer sensor at a port coupling was measured once (appendix A) and calculated as:

$$D = \Psi_1 + L_1 = \left(\frac{P_1 - P_{\mathrm{Atm}}}{\gamma_w} \right) \times 144 + L_1 \tag{3}$$

where

D is the depth to the pressure transducer, in ft bls;

Ψ_1 is the pressure head inside the multiport casing, in ft;

L_1 is the depth to water inside the multiport casing, in ft bls; and

P_1 is the fluid pressure measured inside the multiport casing, in psia.

The depth to water inside the multiport casing (L_1) was measured using an electronic measuring tape and corrected for borehole deviation. Simultaneous measurements of P_1, P_{Atm}, and L_1 were made at each port coupling to account for (1) temporal changes in atmospheric conditions, and (2) depth to water that was dependent on the volume of water displaced by the wireline communication cable.

Multilevel completions included the location of measurement port valves, port couplings, packers, and monitoring zones in the borehole (where a monitoring zone describes the volumetric space between consecutive packers outside the multiport casing). The location of a multilevel component in a borehole is based on the measured depth to the pressure transducer at a port coupling (eq. 3) and its position within the MLMS installation log. For example, the length of a monitoring zone is defined as the distance between two consecutive packer seals and calculated by subtracting the depth at the bottom of the upper packer from the depth at the top of the lower packer, or:

$$M_z = (D_{z-1} - a - b - c - d) - (D_z - a - b - c) = D_{z\text{-}1} - d - D_z \tag{4}$$

where

M_z is the distance between packer seals in monitoring zone z, in ft;

D_z is the depth to the pressure transducer sensor in the upper port coupling of zone z, in ft bls;

$D_{z\text{-}1}$ is the depth to the pressure transducer sensor in the uppermost port coupling of zone z-1, the zone located directly beneath zone z, in ft bls;

a is the distance between the pressure transducer sensor and the center of the measurement port inlet valve, in ft, 0.17 ft in both MP systems;

b is the distance between the center of the measurement port inlet valve and the top of the measurement port coupling, in ft, 0.50 ft in the MP55 system and 0.38 ft in the MP38 system;

c is the distance between the uppermost measurement port coupling and the bottom of the adjacent packer, in ft, 0.60 ft in both MP systems; and

d is the thickness of the inflated packer seal, in ft, 3.00 ft in both MP systems.

Parameters *a*, *b*, *c*, and *d* were defined using nominal component lengths specified in the MLMS installation log (fig. 3); however, actual parameter lengths may vary because of component deformation in the multiport casing and γ_w port couplings that results from mechanical stretch and thermal expansion during MLMS installation. However, de-stressing during packer inflation was used to reduce the total strain on the system. Measurement errors associated with component deformation were assumed to be negligible because nominal component lengths were relatively small when compared to the measured depth to a pressure transducer (*D*).

Standard procedures for collecting profile measurements were first described in Fisher and Twining (2011). The steps are summarized as follows: (1) the sampling probe is lowered to the deepest measurement port in the MLMS; (2) the probe is coupled with the monitoring port to continuously monitor fluid pressure and temperature; (3) measurements of fluid pressure, atmospheric pressure, and water temperature are recorded on a field sheet (appendix B) after temperature readings stabilize with fluctuations of less than 0.1 °C (generally in 30 minutes or less); and (4) after fluid pressure and temperature measurements are recorded, the probe is decoupled from the port and raised to the next highest measurement port. The process is repeated until all ports are measured and final measurements are recorded.

Data Processing

Statistical and graphical analysis of head and temperature data was completed using a customized computer program "MLMS" (R Development Core Team, 2014). The computer program was used to process field data collected from all 11 MLMS boreholes to streamline and make data analysis consistent. The program "MLMS" was also used to examine quality assurance data for both head and temperature measurements.

The software program "MLMS" consists of a series of processing functions that include: mlms.export.R, mlms.import.R, mlms.plotParedPort.R, mlms.plotProfile.R, and mlms.process.R. In addition, the software program "MLMS" requires a separate file (Completions.mps) that contains borehole information for graphing and analysis. This file (Completions.mps) includes: borehole identifier, units of measure, borehole location (latitude, longitude, and land-surface altitude), casing length, measurement point, borehole drilled depth, completion depth, drilled date, installation date, number of zones, zone number, zone top, zone bottom, measurement port number, and port depth.

Field measurements were collected electronically and recorded on paper forms using a standardized field sheet (appendix B). The electronically stored measurements for each borehole were copied to text file templates and processed using the software program "MLMS". The current text file names for each borehole include: USGS103.dat, USGS105.dat, USGS108.dat, USGS131A.dat, USGS132.dat, USGS133.dat, USGS134.dat, USGS135.dat, USGS137A.dat, MIDDLE2050A.dat, and MIDDLE2051.dat.

Quality Assurance

The accuracy and precision of MLMS head measurements within the ESRP aquifer were first quantified by Fisher and Twining (2011), by accounting for cumulative error of five variables in the hydraulic head equation (eq. 1). In summary, the cumulative error for all five variables for independent head readings is ±2.3 ft; a value determined by summing measurement accuracies for fluid pressure head (±1.15 ft), atmospheric pressure head (±0.01 ft), land-surface altitude (±0.01 ft), and pressure transducer sensor depth (±1.17 ft) (Fisher and Twining, 2011). Many of the sources of measurement error are minimized when considering the differences between two closely spaced readings of head, where head values are monitored using the same pressure probe, at similar depths, and at similar water densities. Under these conditions, vertical head differences have much less error than the error associated with any single head measurement because some sources of error subtract and are equal or nearly equal for adjacent port readings. Therefore, a ±0.1 ft measurement accuracy was assumed for vertical head differences (and gradients) calculated between adjacent monitoring zones (Fisher and Twining, 2011).

Calibration of the fluid pressure sensor was performed by the probe manufacturer and calibration test results from 2011 to 2013 are shown in appendix C. Each test was run over a referenced pressure range of 15 to 500 pounds per square inch absolute (psia), with probe temperature held constant at about 10 and 20 °C. Accounting for the range of fluid pressures measured in the field, from 30 to 350 psia, the calibration tests resulted in a measurement accuracy standard deviation of ±0.065 pounds per square inch (psi) (or ±0.15 ft at 10 °C) and ±0.057 psi (or ±0.13 ft at 20 °C). Tests indicate that fluid pressure error remained well below the specified accuracy of the sensor during the duration of the study. Calibration corrections were not applied to fluid pressure measurements because of the relatively high specified accuracy of the reference pressure sensor at ±0.100 psi (or ±0.23 ft at 13 °C), which is the average ambient temperature in these boreholes.

The precision of the fluid pressure measurement was determined by comparing fluid pressure measurements between consecutive profiles. Repeat measurements were made for each of the 11 MLMS boreholes, with 2 repeat measurements for each profile period. Repeat measurements were taken at the end of the profile period at pre-selected ports. Analysis indicates a 0.02 ft mean difference between consecutive measurements and a 0.02 ft standard deviation indicate consistently high precision for the instrument.

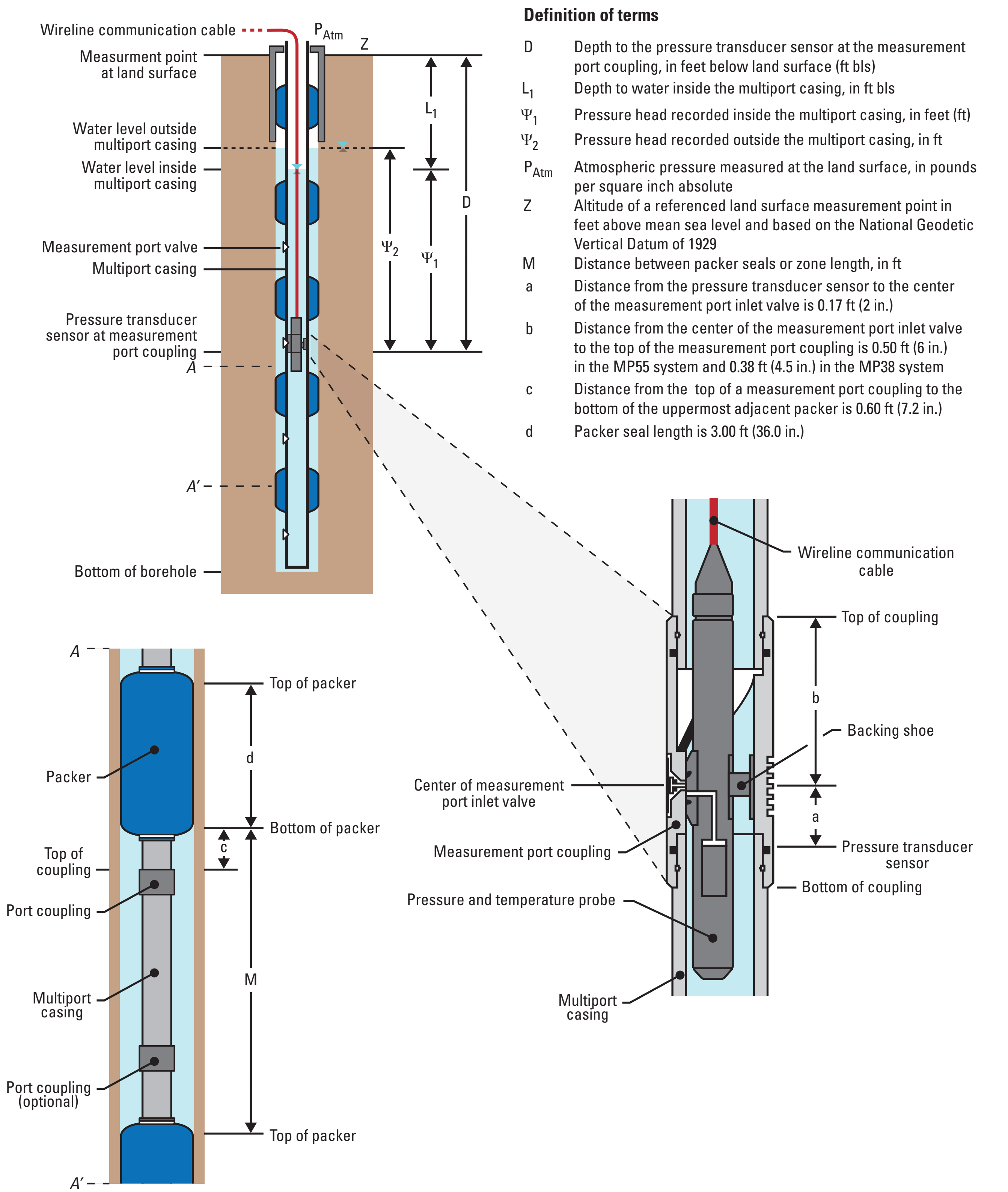

Figure 3. Terms used in the calculation of hydraulic head based on the portable probe position when coupled with a measurement port in the multilevel monitoring system (Fisher and Twining, 2011).

Measurement precision was tested again in 9 of 11 MLMSs by comparing head values between paired-ports, with two measurement ports located in the same monitoring zone (figs. 3 and 4). Theoretically, the distribution of head within a monitoring zone should be uniform; therefore, any significant head difference between paired-port measurements may indicate a malfunctioning measurement port, a well construction anomaly, or groundwater density variations because of differences in total dissolved solids. For 34 of 39 monitoring zones, paired-port head differences were small with an average value of 0.01 ft and a standard deviation of 0.04 ft for head measurements taken between 2011 and 2013 (fig. 4). Five MLMS zones display paired-port head differences that exceed ±0.2 ft: USGS 103 (zone 9) head measurements ranged from 0.26 to 0.33 ft; USGS 108 (zone 11) head measurements ranged from -0.11 to 0.88 ft; USGS 131A (zone 12) head measurements ranged from 1.83 to 2.44 ft; USGS 133 (zone 7) head measurements ranged from -0.44 to 0.02 ft; and USGS 134 (zone 15) head measurements ranged from 0.32 to 0.65 ft (appendix D).

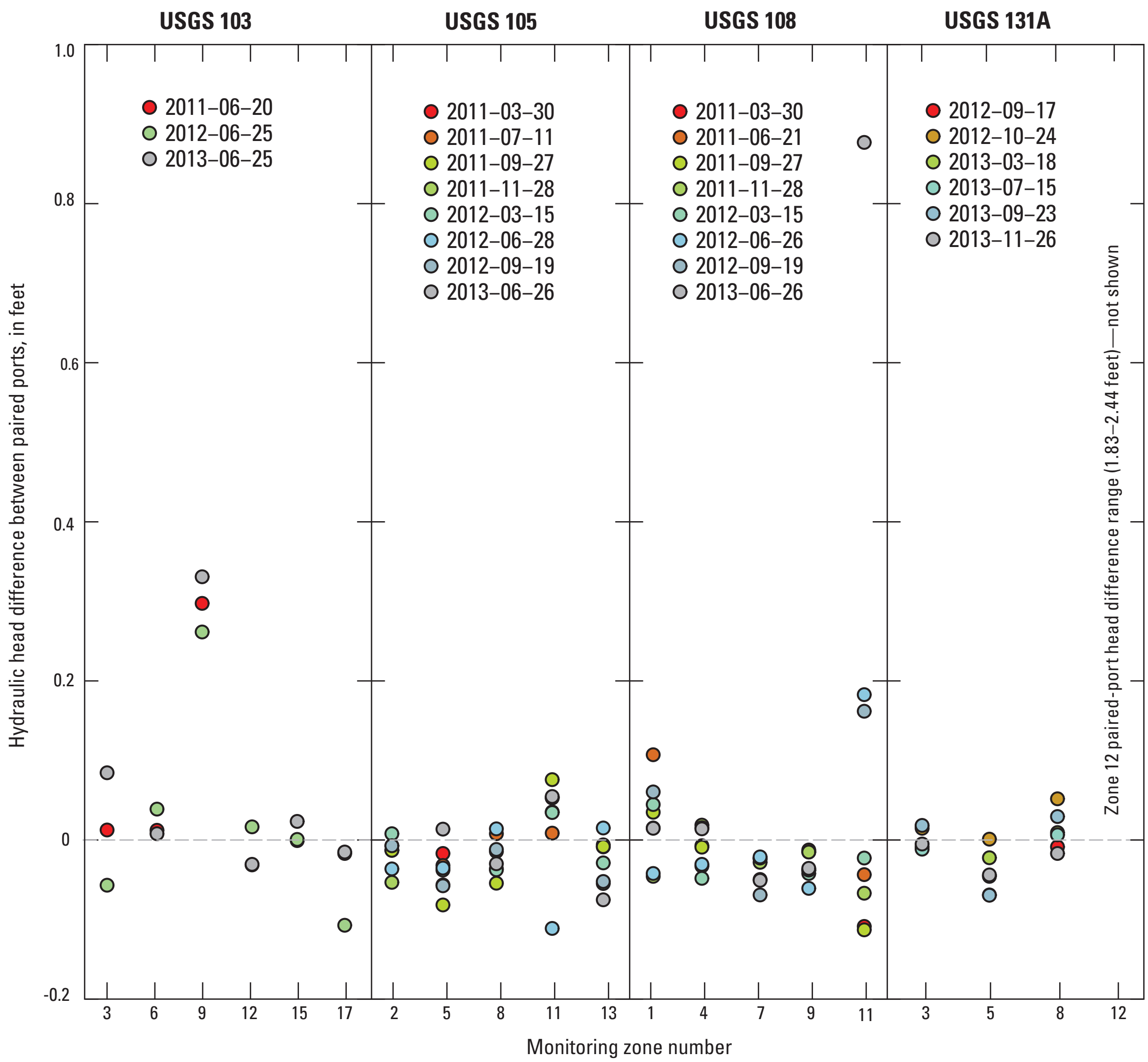

Figure 4. Hydraulic head differences between paired-ports and measurement ports in the same monitoring zone in boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, and USGS 137A Idaho National Laboratory, Idaho, 2011–13.

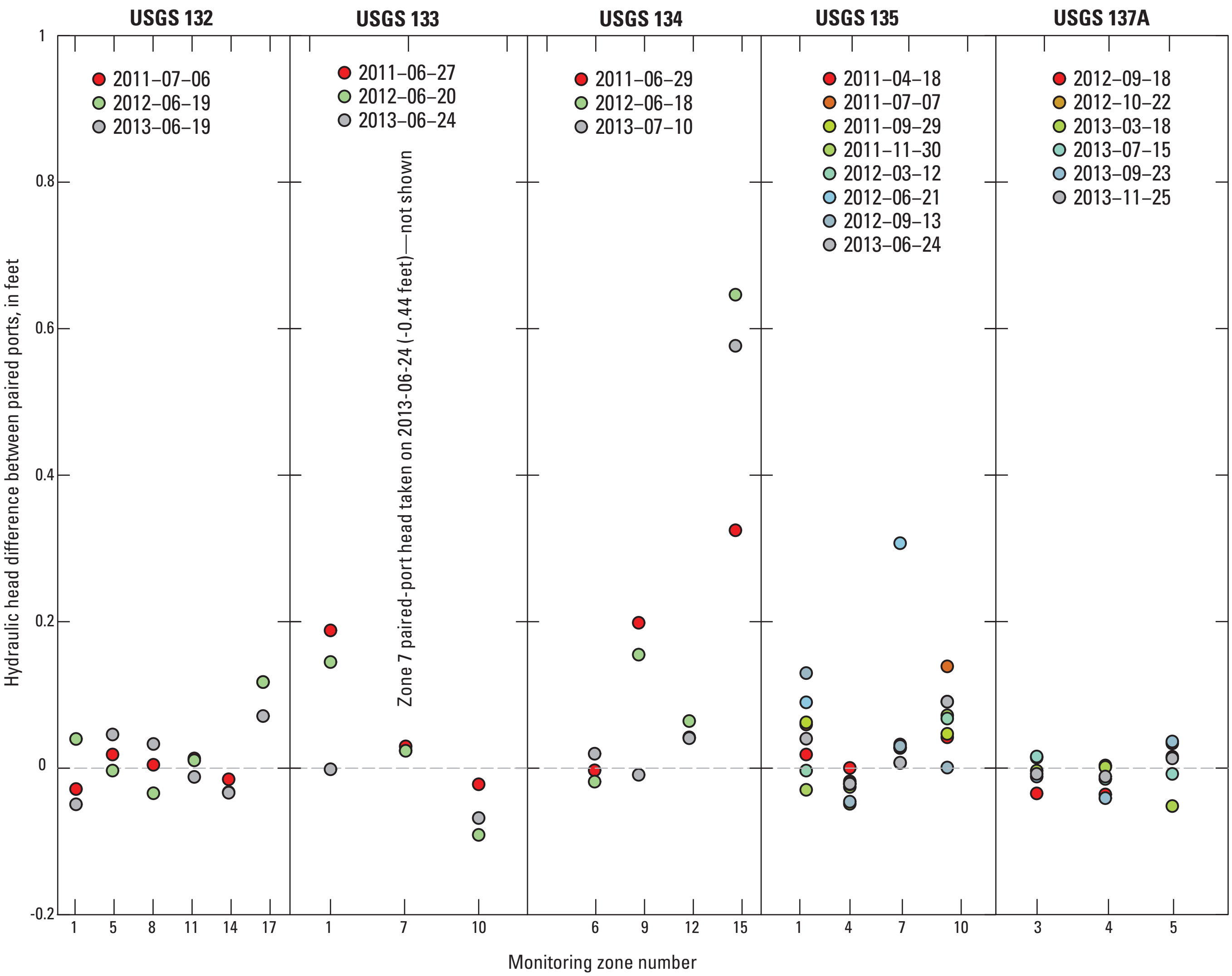

Figure 4.—Continued

The paired-port head difference for USGS 103 (ports 11 and 12) had a standard deviation of 0.03 ft and suggest a well construction anomaly that is consistent with previous reports (Fisher and Twining, 2011; Twining and Fisher, 2012). The paired-port head difference reported for USGS 108 (ports 15 and 16) had a standard deviation of 0.33 ft and review of the data suggest a port malfunction (port 16) that started to appear during the June 2012 measurement period. The paired-port head difference for USGS 131A (ports 15 and 16) had a standard deviation of 0.22 ft and head difference that exceeded 1.8 ft. The paired-port head difference in USGS 131A (zone 12) suggest that ports 15 and 16 have limited hydraulic connection that may have resulted from partial borehole collapse. The paired-port head difference for USGS 133 (ports 8 and 9) had a standard deviation of 0.27 ft and review of the data suggest a malfunction at port 8 (fig. 4). The head difference for USGS 134 were first described in Fisher and Twining (2011) and were attributed to a malfunction at port 20 and (or) a water density distribution within zone 15 that varied over space and time.

Hydraulic Head and Temperature Measurements

Head and temperature measurements were reported for the 11 MLMS boreholes for 2011 through 2013 (fig. 1, table 1). Head and temperature measurements were recorded in 177 hydraulically isolated monitoring zones located 448.0–1,377.6 ft bls (table 2). Detailed descriptions of the geophysical logs, the lithology log, the completion log, and profiles also are provided for the two new boreholes (USGS 131A and USGS 137A) constructed in 2012. Geophysical descriptions for the nine boreholes (USGS 103, USGS 105, USGS 108, USGS 132, USGS 133, USGS 134, USGS 135, MIDDLE 2050A, and MIDDLE 2051) are provided by Fisher and Twining (2011) and Twining and Fisher (2012). Profile shapes and inflection points were analyzed both temporally and spatially for each borehole.

Table 1. Data for multilevel groundwater monitoring wells and boreholes, Idaho National Laboratory, 2011–13.

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Site No.** is the unique numerical identifiers used to access well data (http://waterdata.usgs.gov/nwis). **Latitude and Longitude** is in degrees, minutes, seconds and based on the North American Datum of 1927. **Land-surface altitude** is in feet above National Geodetic Vertical Datum of 1929 (NGVD29). **Base of aquifer altitude** is in feet above NGVD29 (Whitehead, 1992; Anderson and Liszewski, 1997). **Hole depth** is in feet below land surface (ft bls)]

Boreholes						
Local name	Site No.	Latitude	Longitude	Land-surface altitude (ft)	Estimated base of aquifer altitude (ft)	Hole depth (ft bls)
USGS 103	432714112560701	43°27'13.57"	112°56'06.53"	5,007.42	2,470	1,307
USGS 105	432703113001801	43°27'03.40"	113°00'17.78"	5,095.12	2,540	1,409
USGS 108	432659112582601	43°26'58.79"	112°58'26.34"	5,031.36	2,495	1,218
USGS 131A	433036112581800	43°30'37.02"	112°58'15.76"	4,976.14	2,475	1,198
USGS 132	432906113025001	43°29'06.68"	113°02'50.93"	5,028.60	2,540	1,238
USGS 133	433605112554301	43°36'05.50"	112°55'43.80"	4,890.12	3,960	818
USGS 134	433611112595801	43°36'11.15"	112°59'58.27"	4,968.84	3,960	949
USGS 135	432753113093601	43°27'53.47"	113°09'35.62"	5,135.94	2,675	1,198
USGS 137A	432701113025800	43°27'03.07"	113°02'55.62"	5,053.81	2,580	1,058
MIDDLE 2050A	433409112570501	43°34'09.48"	112°57'05.38"	4,928.22	3,790	1,427
MIDDLE 2051	433217113004901	43°32'16.93"	113°00'49.38"	4,997.31	3,270	1,179

Table 2. Data for multilevel well completions, boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and Middle 2051, Idaho National Laboratory, Idaho, 2011–13.

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Site No.** is the unique numerical identifiers used to access port data (http://waterdata.usgs.gov/nwis). **Zone No.** is the identifier used to locate monitoring zones. **Zone depth interval** limits are in feet below land surface (ft bls) and length is in feet (ft). **Port No.** is the identifier used to locate port couplings. **Port coupling depth** is the depth to the top of the measurement port coupling in ft bls]

Boreholes							
Local name	Site No.	Zone No.	Zone depth interval			Port No.	Port coupling depth (ft bls)
			Bottom (ft bls)	Top (ft bls)	Length (ft)		
USGS 103	432714112560702	1	1,279.4	1,257.4	22.0	1	1,258.0
	432714112560703	2	1,254.4	1,242.9	11.5	2	1,243.5
	432714112560704	3	1,239.9	1,184.4	55.6	3	1,209.7
	432714112560705					4	1,185.0
	432714112560706	4	1,181.4	1,115.2	66.2	5	1,115.8
	432714112560707	5	1,112.2	1,100.6	11.5	6	1,101.2
	432714112560708	6	1,097.6	1,063.2	34.5	7	1,086.8
	432714112560709					8	1,063.8
	432714112560710	7	1,060.2	1,045.5	14.7	9	1,046.1
	432714112560711	8	1,042.5	1,016.5	26.0	10	1,017.1
	432714112560712	9	1,013.5	958.0	55.4	11	992.9
	432714112560713					12	958.6
	432714112560714	10	955.0	948.4	6.6	13	949.0
	432714112560715	11	945.4	922.6	22.8	14	923.2
	432714112560716	12	919.6	891.6	28.0	15	908.7
	432714112560717					16	892.2
	432714112560718	13	888.6	862.6	26.0	17	863.2
	432714112560719	14	859.6	835.1	24.5	18	835.7
	432714112560720	15	832.1	766.9	65.2	19	801.9
	432714112560721					20	767.5
	432714112560722	16	763.9	694.3	69.7	21	694.9
	432714112560723	17	691.3	669.6	21.7	22	680.3
	432714112560724					23	670.2
USGS 105	432703113001802	1	1,290.1	1,279.2	10.9	1	1,279.8
	432703113001803	2	1,276.2	1,224.8	51.4	2	1,242.2
	432703113001804					3	1,225.4
	432703113001805	3	1,221.8	1,165.9	55.9	4	1,166.5
	432703113001806	4	1,162.9	1,105.4	57.5	5	1,106.0
	432703113001807	5	1,102.4	1,034.6	67.8	6	1,071.6
	432703113001808					7	1,035.2
	432703113001809	6	1,031.6	1,005.1	26.5	8	1,005.7
	432703113001810	7	1,002.1	985.4	16.7	9	986.0
	432703113001811	8	982.4	929.3	53.1	10	951.6
	432703113001812					11	929.9
	432703113001813	9	926.3	909.6	16.7	12	910.2
	432703113001814	10	906.6	865.3	41.3	13	865.9
	432703113001815	11	862.3	830.4	31.9	14	851.2
	432703113001816					15	831.0
	432703113001817	12	827.4	754.9	72.5	16	755.5
	432703113001818	13	751.9	706.9	45.1	17	727.6
	432703113001819					18	707.4

Table 2. Data for multilevel well completions, boreholes USGS 103, USGS 105, USGS 108, USGS 131, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137, MIDDLE 2050A, and Middle 2051, Idaho National Laboratory, Idaho, 2011–13.—Continued

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Site No.** is the unique numerical identifiers used to access port data (http://waterdata.usgs.gov/nwis). **Zone No.** is the identifier used to locate monitoring zones. **Zone depth interval** limits are in feet below land surface (ft bls) and length is in feet (ft). **Port No.** is the identifier used to locate port couplings. **Port coupling depth** is the depth to the top of the measurement port coupling in ft bls]

Boreholes							
Local name	Site No.	Zone No.	Zone depth interval Bottom (ft bls)	Zone depth interval Top (ft bls)	Zone depth interval Length (ft)	Port No.	Port coupling depth (ft bls)
USGS 108	432659112582602	1	1,191.9	1,160.9	31.0	1	1,171.8
	432659112582603					2	1,161.5
	432659112582604	2	1,157.9	1,121.6	36.3	3	1,122.2
	432659112582605	3	1,118.6	1,062.6	56.0	4	1,063.2
	432659112582606	4	1,059.6	1,018.0	41.6	5	1,028.8
	432659112582607					6	1,018.6
	432659112582608	5	1,015.0	980.4	34.6	7	981.0
	432659112582609	6	977.4	906.7	70.7	8	907.3
	432659112582610	7	903.7	872.0	31.7	9	887.7
	432659112582611					10	872.6
	432659112582612	8	869.0	832.7	36.3	11	833.3
	432659112582613	9	829.7	791.4	38.3	12	808.8
	432659112582614					13	792.0
	432659112582615	10	788.4	681.8	106.6	14	682.4
	432659112582616	11	678.8	642.1	36.7	15	661.1
	432659112582617					16	642.7
USGS 131A	433036112581801	1	1,188.8	1,176.6	12.2	1	1,177.2
	433036112581802	2	1,173.6	1,160.1	13.5	2	1,160.7
	433036112581803	3	1,157.1	1,120.4	36.7	3	1,136.1
	433036112581804					4	1,121.0
	433036112581805	4	1,117.4	1,061.4	55.9	5	1,062.0
	433036112581806	5	1,058.4	956.3	102.1	6	980.3
	433036112581807					7	956.9
	433036112581808	6	953.3	928.4	24.9	8	929.0
	433036112581809	7	925.4	844.9	80.5	9	845.5
	433036112581810	8	841.9	795.4	46.6	10	811.2
	433036112581811					11	796.0
	433036112581812	9	792.4	733.0	59.4	12	733.6
	433036112581813	10	730.0	693.7	36.3	13	694.3
	433036112581814	11	690.7	634.6	56.0	14	635.2
	433036112581815	12	631.6	562.0	69.6	15	615.6
	433036112581816					16	562.6

Table 2. Data for multilevel well completions, boreholes USGS 103, USGS 105, USGS 108, USGS 131, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137, MIDDLE 2050A, and Middle 2051, Idaho National Laboratory, Idaho, 2011–13.—Continued

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Site No.** is the unique numerical identifiers used to access port data (http://waterdata.usgs.gov/nwis). **Zone No.** is the identifier used to locate monitoring zones. **Zone depth interval** limits are in feet below land surface (ft bls) and length is in feet (ft). **Port No.** is the identifier used to locate port couplings. **Port coupling depth** is the depth to the top of the measurement port coupling in ft bls]

Boreholes							
Local name	Site No.	Zone No.	Zone depth interval: Bottom (ft bls)	Zone depth interval: Top (ft bls)	Zone depth interval: Length (ft)	Port No.	Port coupling depth (ft bls)
USGS 132	432906113025001	1	1,213.6	1,152.3	61.3	1	1,173.0
	432906113025002					2	1,152.9
	432906113025003	2	1,149.3	1,144.1	5.2	3	1,144.7
	432906113025004	3	1,141.1	1,134.3	6.8	4	1,134.9
	432906113025005	4	1,131.3	1,046.1	85.3	5	1,046.7
	432906113025006	5	1,043.1	984.3	58.7	6	1,011.6
	432906113025007					7	984.9
	432906113025008	6	981.3	953.2	28.2	8	953.8
	432906113025009	7	950.2	938.4	11.8	9	939.0
	432906113025010	8	935.4	911.1	24.3	10	918.7
	432906113025011					11	911.7
	432906113025012	9	908.1	876.7	31.4	12	877.3
	432906113025013	10	873.7	866.8	6.8	13	867.4
	432906113025014	11	863.8	811.5	52.3	14	827.3
	432906113025015					15	812.1
	432906113025016	12	808.5	801.6	6.9	16	802.2
	432906113025017	13	798.6	790.1	8.5	17	790.7
	432906113025018	14	787.1	726.6	60.5	18	765.4
	432906113025019					19	727.2
	432906113025020	15	723.6	672.5	51.1	20	673.1
	432906113025021	16	669.5	662.6	6.9	21	663.2
	432906113025022	17	659.6	623.6	36.1	22	637.9
	432906113025023					23	624.2
USGS 133	433605112554301	1	766.4	724.8	41.6	1	745.5
	433605112554302					2	725.4
	433605112554303	2	721.8	715.0	6.8	3	715.6
	433605112554304	3	712.0	698.6	13.4	4	699.2
	433605112554305	4	695.6	685.5	10.1	5	686.1
	433605112554306	5	682.5	618.2	64.3	6	618.8
	433605112554307	6	615.2	593.7	21.6	7	594.3
	433605112554308	7	590.7	555.5	35.2	8	569.6
	433605112554309					9	556.1
	433605112554310	8	552.5	539.1	13.4	10	539.7
	433605112554311	9	536.1	483.2	52.8	11	483.8
	433605112554312	10	480.2	448.0	32.3	12	469.1
	433605112554313					13	448.6

Table 2. Data for multilevel well completions, boreholes USGS 103, USGS 105, USGS 108, USGS 131, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137, MIDDLE 2050A, and Middle 2051, Idaho National Laboratory, Idaho, 2011–13.—Continued

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Site No.** is the unique numerical identifiers used to access port data (http://waterdata.usgs.gov/nwis). **Zone No.** is the identifier used to locate monitoring zones. **Zone depth interval** limits are in feet below land surface (ft bls) and length is in feet (ft). **Port No.** is the identifier used to locate port couplings. **Port coupling depth** is the depth to the top of the measurement port coupling in ft bls]

Boreholes							
Local name	Site No.	Zone No.	Zone depth interval			Port No.	Port coupling depth (ft bls)
			Bottom (ft bls)	Top (ft bls)	Length (ft)		
USGS 134	433611112595801	1	886.8	881.0	5.8	1	881.6
	433611112595802	2	878.0	871.0	7.0	2	871.6
	433611112595803	3	868.0	846.0	22.0	3	856.1
	433611112595804					4	846.6
	433611112595805	4	843.0	831.0	12.0	5	831.6
	433611112595806	5	828.0	821.0	7.0	6	821.6
	433611112595807	6	818.0	782.0	36.0	7	806.6
	433611112595808					8	782.6
	433611112595809	7	779.0	747.0	32.0	9	747.6
	433611112595810	8	744.0	723.0	21.0	10	723.6
	433611112595811	9	720.0	690.9	29.0	11	706.5
	433611112595812					12	691.5
	433611112595813	10	687.9	664.9	23.0	13	665.5
	433611112595814	11	661.9	654.9	7.0	14	655.5
	433611112595815	12	651.9	638.9	13.0	15	645.5
	433611112595816					16	639.5
	433611112595817	13	635.9	604.8	31.1	17	605.4
	433611112595818	14	601.8	592.8	9.0	18	593.4
	433611112595819	15	589.8	553.8	36.0	19	578.5
	433611112595820					20	554.4
USGS 135	432753113093601	1	1,136.6	1,105.6	31.0	1	1,116.4
	432753113093602					2	1,106.1
	432753113093603	2	1,102.6	1,054.8	47.8	3	1,055.3
	432753113093604	3	1,051.8	1,010.6	41.2	4	1,011.1
	432753113093605	4	1,007.6	967.5	40.1	5	988.1
	432753113093606					6	968.0
	432753113093607	5	964.5	923.3	41.3	7	923.7
	432753113093608	6	920.3	864.2	56.1	8	864.7
	432753113093609	7	861.2	822.6	38.6	9	836.7
	432753113093610					10	823.1
	432753113093611	8	819.6	790.0	29.7	11	790.4
	432753113093612	9	787.0	765.3	21.6	12	765.8
	432753113093613	10	762.3	727.0	35.3	13	737.9
	432753113093614					14	727.5
USGS 137A	432701113025801	1	894.7	874.5	20.2	1	875.1
	432701113025802	2	871.5	864.7	6.8	2	865.3
	432701113025803	3	861.7	840.1	21.6	3	840.7
	432701113025804					4	787.8
	432701113025805	4	784.2	746.2	38.0	5	746.8
	432701113025806					6	721.7
	432701113025807	5	718.1	640.1	78.0	7	660.9
	432701113025808					8	640.7

Table 2. Data for multilevel well completions, boreholes USGS 103, USGS 105, USGS 108, USGS 131, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137, MIDDLE 2050A, and Middle 2051, Idaho National Laboratory, Idaho, 2011–13.—Continued

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Site No.** is the unique numerical identifiers used to access port data (http://waterdata.usgs.gov/nwis). **Zone No.** is the identifier used to locate monitoring zones. **Zone depth interval** limits are in feet below land surface (ft bls) and length is in feet (ft). **Port No.** is the identifier used to locate port couplings. **Port coupling depth** is the depth to the top of the measurement port coupling in ft bls]

Boreholes							
Local name	Site No.	Zone No.	Zone depth interval			Port No.	Port coupling depth (ft bls)
			Bottom (ft bls)	Top (ft bls)	Length (ft)		
MIDDLE 2050A	433409112570501	1	1,377.6	1,267.5	110.1	1	1,268.1
	433409112570502	2	1,264.5	1,229.7	34.7	2	1,230.3
	433409112570503	3	1,226.7	1,179.7	47.0	3	1,180.3
	433409112570504	4	1,176.7	1,081.3	95.4	4	1,081.9
	433409112570505	5	1,078.3	1,043.6	34.7	5	1,044.2
	433409112570506	6	1,040.6	998.7	41.9	6	999.3
	433409112570507	7	995.7	843.1	152.6	7	843.7
	433409112570508	8	840.1	810.4	29.8	8	811.0
	433409112570509	9	807.4	790.0	17.4	9	790.6
	433409112570510	10	787.0	719.5	67.5	10	720.1
	433409112570511	11	716.5	706.4	10.2	11	707.0
	433409112570512	12	703.4	643.3	60.1	12	643.9
	433409112570513	13	640.3	623.7	16.6	13	624.3
	433409112570514	14	620.7	541.6	79.1	14	542.2
	433409112570515	15	538.6	464.9	73.7	15	516.8
MIDDLE 2051	433217113004901	1	1,176.5	1,140.3	36.2	1	1,140.9
	433217113004902	2	1,137.3	1,130.5	6.8	2	1,131.1
	433217113004903	3	1,127.5	1,090.5	37.0	3	1,091.1
	433217113004904	4	1,087.5	1,002.2	85.3	4	1,002.8
	433217113004905	5	999.2	879.4	119.8	5	880.0
	433217113004906	6	876.4	826.2	50.1	6	826.8
	433217113004907	7	823.2	791.9	31.4	7	792.5
	433217113004908	8	788.9	773.8	15.0	8	774.4
	433217113004909	9	770.8	748.4	22.4	9	749.0
	433217113004910	10	745.4	646.7	98.8	10	647.3
	433217113004911	11	643.7	612.2	31.5	11	612.8
	433217113004912	12	609.2	561.8	47.4	12	602.9

MLMS Measurements

During the 2011–13 multilevel monitoring period, 137 profiles were collected and analyzed; these profiles represent individual quarterly and annual measurements of head and temperature from 11 MLMS boreholes (fig. 5; appendix E). The MLMS profile schedule was updated four times during 2011–13; these updates include: (1) during 2011, annual measurements were collected for MLMS boreholes USGS 103, USGS 132, USGS 133, and USGS 134 and quarterly measurements were collected for USGS 105, USGS 108, and USGS 135; (2) quarterly measurements were taken for MIDDLE 2050A and MIDDLE 2051 starting June 2011; (3) quarterly measurements taken for USGS 131A and USGS 137A starting September, 2012; and (4) boreholes USGS 105, USGS 108, and USGS 135 were updated to annual measurements after the third quarter of 2012 (September, 2012). Changes to the MLMS measurement schedule were based on profile consistency reported in Fisher and Twining (2011) and Twining and Fisher (2012) and program changes.

Throughout the 3-year monitoring period, head at all MLMS boreholes ranged from 4,415.3 to 4,464.0 ft at USGS 137A and USGS 133, respectively (fig.1, appendix E).

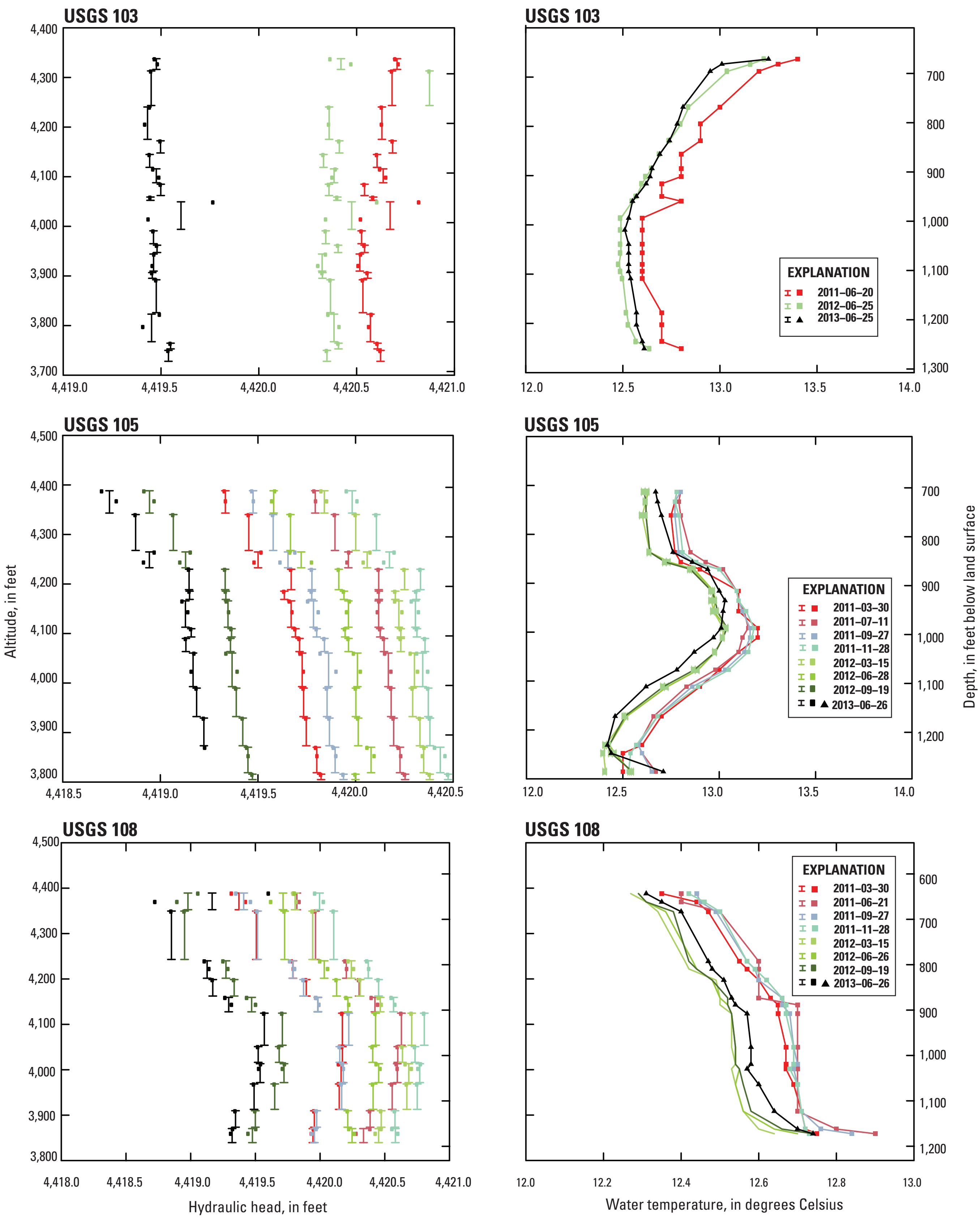

Figure 5. Vertical hydraulic head and water temperature profiles at boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho, 2011–13. Profiles are based on quarterly and annual measurements made during 2011–13.

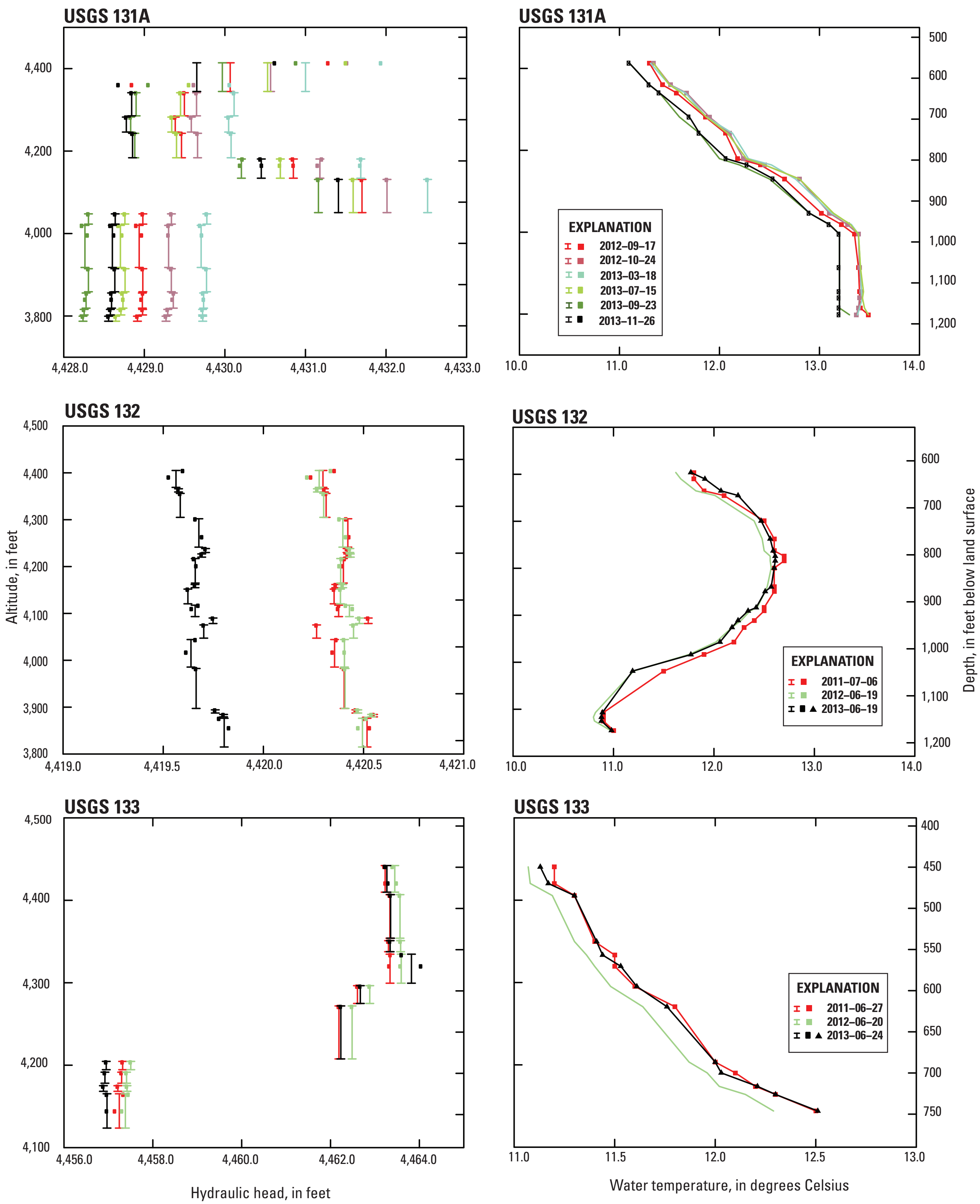

Figure 5.—Continued

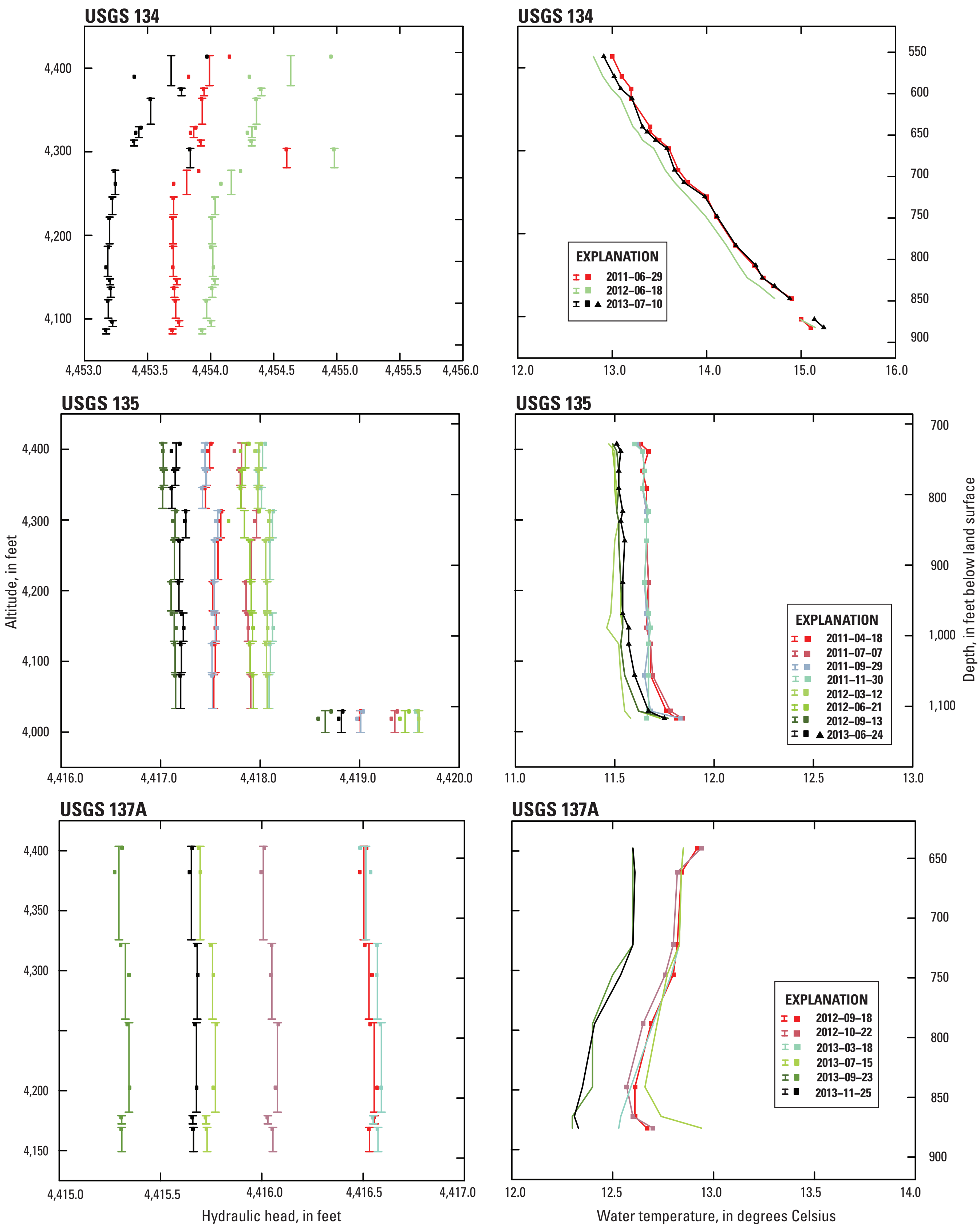

Figure 5.—Continued

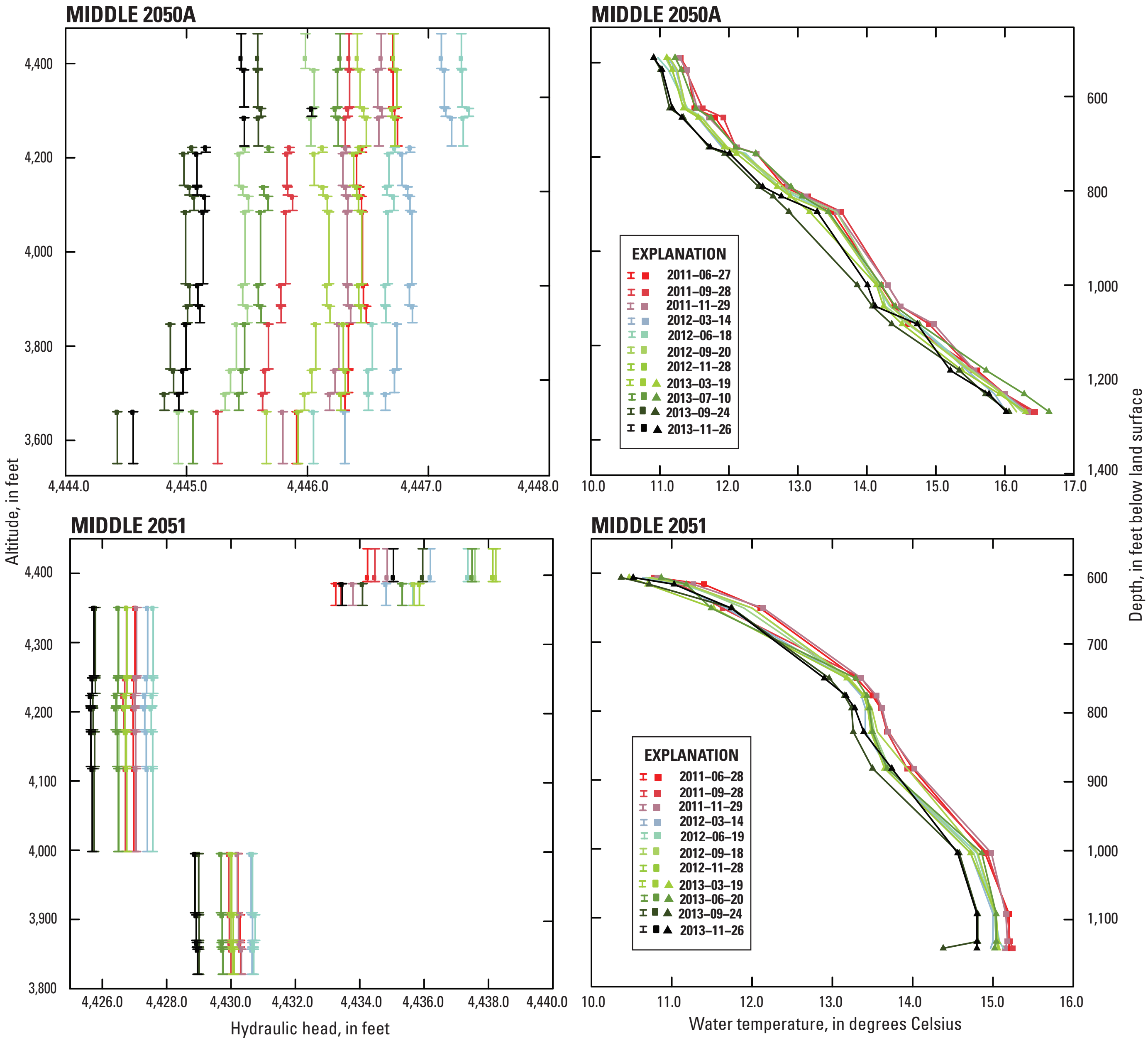

Figure 5.—Continued

The lowest head values were measured in the farthest downgradient boreholes USGS 103, USGS 105, USGS 108, USGS 132, USGS 135, and USGS 137A (near the southern boundary); the highest head values were in the farthest up gradient borehole USGS 133 (fig. 1). Water temperature ranged from 10.4 to 16.6 °C at boreholes MIDDLE 2051 and MIDDLE 2050A, respectively (appendix E), which is within the reported range for temperatures measured in the ESRP aquifer at or near the INL—9.0–19.1 °C (Davis and others, 2013).

To quantify temporal variability in MLMS head and temperature between profile periods from 2011 to 2013, a Pearson correlation coefficient (PCC) was computed for each profile; methods used to compute PCC are described by Fisher and Twining (2011). Computed PCCs range from -1 to 1; however, the closer the PCC is to either -1 or 1, the stronger the correlation. To evaluate the correlation among all head or temperature profiles in a borehole requires the calculation of PCC for all permutations of profiles taken two at a time for each port, and the minimum of these values reflects the poorest correlation between profiles in a borehole. During the examination of individual head measurements and computation of PCC, nine suspected erroneous head measurements were identified and noted in the comment field in table 3 and displayed in figure 6. Erroneous measurements can occur if there is an inadequate face seal between the measurement probe and measurement port or if the port is blocked. The general shapes of head and temperature profiles remained consistent for all 11 MLMSs over the measured time frame (figs. 5 and 6).

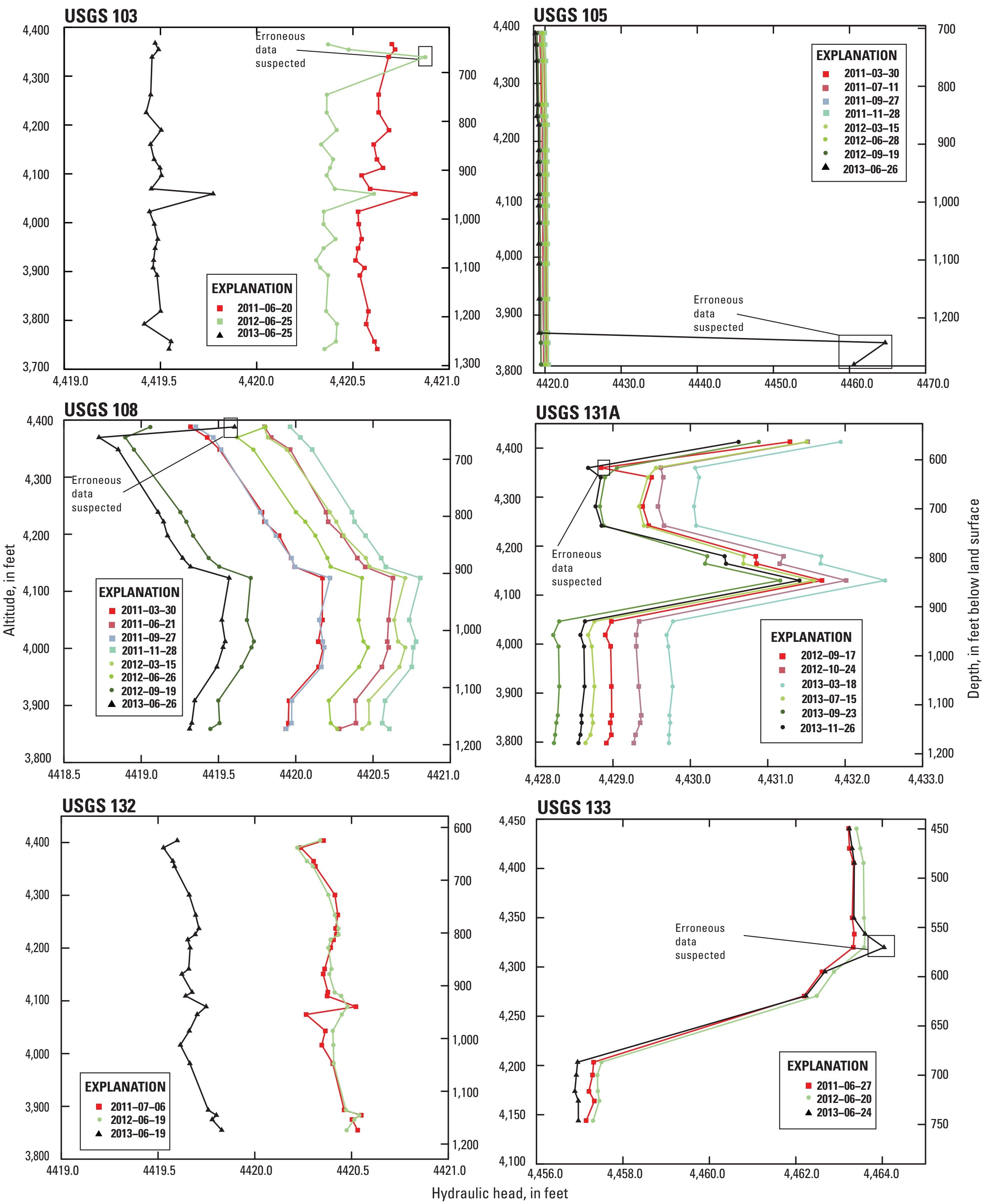

Figure 6. Individual hydraulic head measurements and suspected erroneous data taken during 2011–13 at boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho.

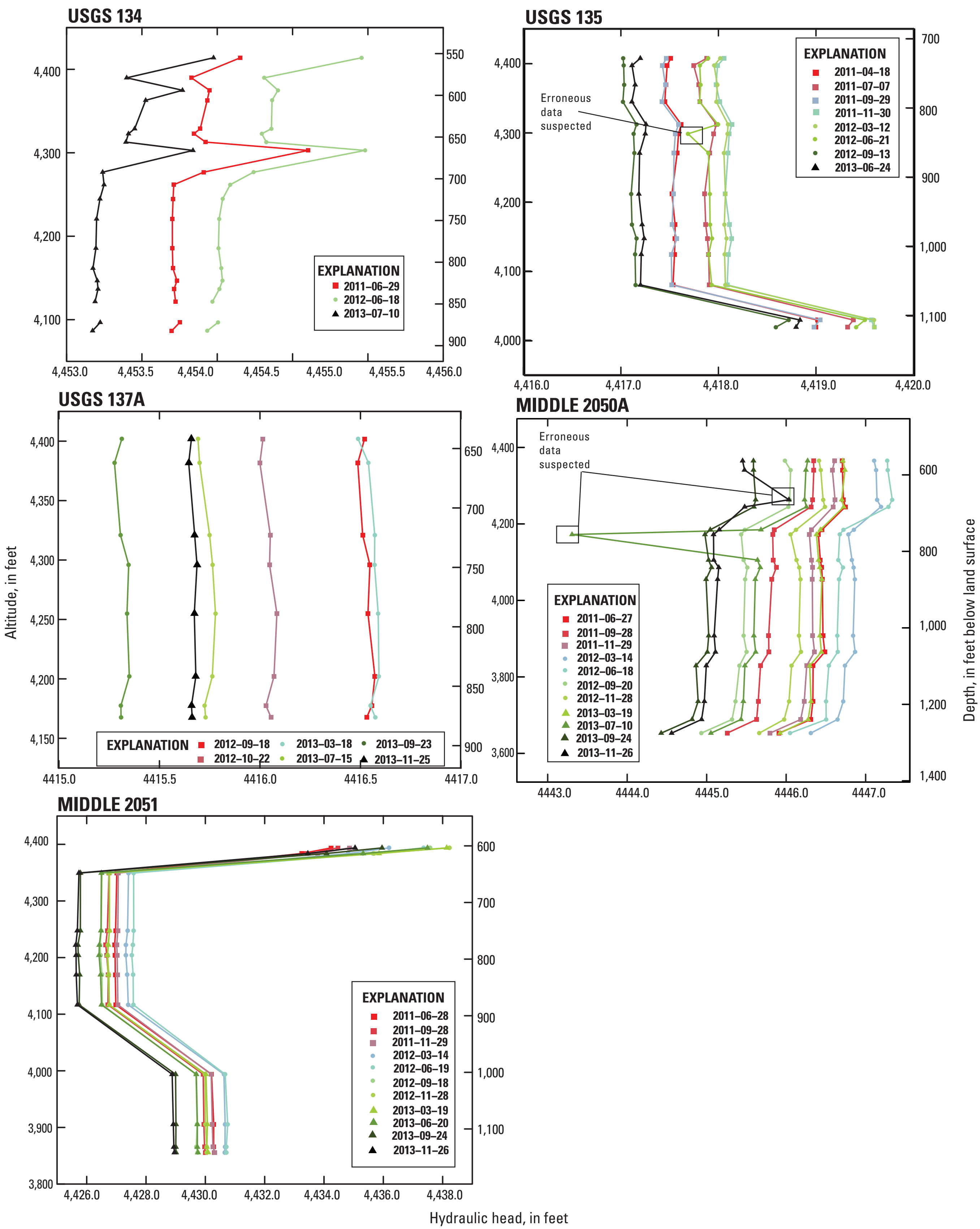

Figure 6.—Continued

Table 3. Minimum Pearson correlation coefficients for hydraulic head and temperature profiles at selected boreholes, Idaho National Laboratory, Idaho, 2011–13.

[**Local name:** Local well identifer used in this study. **Suspected Erroneous Data** are identified in figure 6 and measurements represent abnormal pressure readings that do not appear to reflect ambient pressure]

Local name	Pearson correlation coefficients		
	Hydraulic head	Temperature	Suspected erroneous data
USGS 103	0.63	0.97	Head data taken 06-25-12 (port 21)
USGS 105	0.96	0.83	Head data taken 06-26-13 (ports 1 and 2)
USGS 108	0.98	0.93	Head data taken 06-26-13 (port 16)
USGS 131A	0.96	1.00	Head data taken 09-17-12 (port 15)
USGS 132	0.80	0.99	None
USGS 133	1.00	1.00	Head data taken 06-24-13 (port 8)
USGS 134	0.84	1.00	None
USGS 135	0.99	0.27	Head data taken 06-21-12 (port 9)
USGS 137A	0.45	0.19	None
MIDDLE 2050A	0.95	1.00	Head data taken 07-10-13 (port 10) and 11-26-13 (port 13)
MIDDLE 2051	0.98	0.99	None

Minimum PCC values for head profiles ranged from 0.45 at borehole USGS 137A to 1.00 at borehole USGS 133 (table 3). In three boreholes (USGS 103, USGS 132, and USGS 137A), the minimum PCC was less than 0.90 and is attributed to small vertical head differences and a relative uncertainty for head differences between adjacent zones of ±0.1 ft; under these circumstances, measurement error can produce a lower PCC even though a strong correlation exists. Borehole USGS 134 has a minimum PCC of 0.84, partly because of the head difference between ports in monitoring zones 14 and 15. This head difference is believed to suggest evidence of a pressure response to mountain front recharge events and was previously described in Fisher and Twining (2011) and Twining and Fisher (2012). All other minimum PCC values were greater than or equal to 0.95 and suggest a strong positive correlation among head profiles.

Minimum PCC values for temperature profiles ranged from 0.19 in borehole USGS 137A to 1.00 in boreholes USGS 131A, USGS 133, USGS 134, and MIDDLE 2050A (table 3). The computed PCCs for most temperature profiles exceed 0.93 and suggest a strong positive correlation among temperature profiles. However, three MLMS boreholes (USGS 105, USGS 135, and USGS 137A) had computed PCCs of less than 0.90 (table 3). The PCC computed for USGS 105 suggests that measured aquifer temperature was not allowed to fully equilibrate during certain profile periods, producing an artificially low PCC. For boreholes USGS 135 and USGS 137A, the temperature range is about 0.2 °C and 0.3 °C, respectively. Under these circumstances a slight measurement error can produce a low PCC where a strong correlation exists.

The June 2012 profile period was selected to examine and describe head and temperature profiles for boreholes USGS 103, USGS 105, USGS 108, USGS 132, USGS 133, USGS 134, USGS 135, MIDDLE 2050A, MIDDLE 2051. The September 2012 profile period was selected for boreholes USGS 131A and USGS 137A after the MLMSs were installed. The profiles for all 11 MLMSs are presented with their corresponding borehole information (figs. 7–16, 18). Borehole information includes geophysical log data, a lithology log, and a multilevel completion log. Geophysical logs include:

1. A natural gamma log is a measure of the gamma radiation emitted by the naturally occurring radioisotopes within the rock and sediment of the borehole. In a basaltic system, elevated natural gamma can suggest the presence of a sedimentary layer, rhyolite unit, or a unique basalt unit.

2. Neutron logs provide a general measure for the hydrogen content of geologic media, which, when saturated, is directly related to the porosity. A high porosity, low neutron count, indicates that more hydrogen (water) is present and suggest areas related to fractured basalt or sediment media, or both; whereas, a low porosity, high neutron count, indicates less hydrogen atoms (water) present and suggest an area of dense basalt and (or) geologic media. A color gradient, ranging from red (high hydrogen content) to white (low hydrogen content), was applied to approximate the location of water producing zones.

3. The caliper log displays data collected from three extendable spring-loaded arms that measure drill-hole diameter. Changes in the drill-hole diameter may be due to collapse of loose or highly fractured rock—areas unsuitable for packer placement.

4. Short-spaced and long-spaced gamma-gamma dual density logs, also known as the induced gamma-density logs, are a measure of the bulk density of a rock material near a borehole wall. The bulk density of rock material is inversely related to its porosity.

Generalized lithology logs were constructed for each MLMS based on geophysical logs, borehole video, and visual inspection and description of the recovered drill core. The data were used to divide geologic media into three basic lithologic units: (1) dense basalt (gray), a rock material of moderate to low horizontal hydraulic conductivity and low to very low vertical hydraulic conductivity; (2) fractured basalt (orange), a rock material of high to very high hydraulic conductivity; and (3) sediment (yellow), a composite of coarse to fine-grained sand and silt with variable hydraulic conductivity. Depth intervals for generalized lithology are provided in appendix F for boreholes USGS 131A and USGS 137A. The generalized lithology for nine of the MLMS wells (USGS 103, USGS 105, USGS 108, USGS 132, USGS 133, USGS 134, USGS 135, MIDDLE 2050A, and MIDDLE 2051) were reported in Fisher and Twining (2011) and Twining and Fisher (2012). The percentage of lithologic composition in each borehole is provided in table 4. The reported effective hydraulic conductivity for the basalt and interbedded sediment that compose the ESRP aquifer at or near the INL ranges from about 1.0×10^{-2} to 3.2×10^{4} ft/d (Anderson and others, 1999). Reported porosity of the aquifer, based on a cumulative distribution curve for more than 1,500 individual cores, showed that the central 80 percent of samples had porosities between 0.08 and 0.25 (Knutson and others, 1992, figs. 4–10).

The multilevel completion(s) displayed for each MLMS borehole (figs. 7–16, 18) include the location of measurement ports, packers, and monitoring zones. Measurement ports and monitoring zones are labeled using ‘P’ and ‘Z’, respectively, followed by a unique index number that increases with decreasing depth. For example, P1 is the first measurement port from the bottom of the hole, and Z4 is the fourth monitoring zone from the bottom.

Table 4. Lithologic composition in selected boreholes, Idaho National Laboratory, Idaho, 2011–13.

[**Local name** is the local well identifier used in this study. **Percentage of lithologic units** interrogated by MLMS was divided into sub-categories (dense basalt, fractured basalt, and sediment) and was estimated from total drilled depth]

Boreholes			
Local name	Percentage of lithologic unit		
	Dense basalt	Fractured basalt	Sediment
USGS 103	55	41	4
USGS 105	45	52	3
USGS 108	49	46	5
USGS 131A	54	40	6
USGS 132	35	63	2
USGS 133	56	34	10
USGS 134	46	51	3
USGS 135	52	45	3
USGS 137A	53	44	3
MIDDLE 2050A	51	35	14
MIDDLE 2051	64	33	3

The shapes of the head profiles were analyzed using major head inflections for the June or September 2012 datasets in all 11 MLMSs. These inflections were identified using the difference between head measurements of adjacent monitoring zones. Head inflections were considered major where head differences exceeded ±0.1 ft, the relative uncertainty for head differences between adjacent zones. The head inflections were labeled using ‘H’ followed by a unique index number that increases with decreasing depth. For example, H1 identifies the vertical location of the first head inflection from the bottom of the hole. Vertical head gradients were calculated across the 3.0-ft-thick inflated packer length that separates monitoring zones (table 5; appendix G).

Table 5. Vertical hydraulic gradients at major inflection points for depth interval and hydraulic head profiles, Idaho National Laboratory, Idaho, June or September 2012.

[Major inflection points were identified using the differences between hydraulic head (head) measurements of adjacent monitoring zones. Head inflections were considered major where head differences exceeded the relative uncertainty for head differences between adjacent zones, ±0.1 foot. **Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Inflection index No.:** Identifier used to locate major inflection points in the head profile. **Zone No.:** Identifiers used to locate monitoring zones. **Port No.:** Identifiers used to locate port couplings. **Depth interval:** Depth to the bottom and top of the inflated packer separating the adjacent monitoring zone. **Hydraulic head:** Negative (-) and positive values indicate heads decreasing and increasing with depth, respectively. **Abbreviations:** ft bls, feet below land surface; ft, foot; ft/ft, foot per foot]

Boreholes								
Local name	Inflection index No.	Zone No.	Port No.	Depth interval			Hydraulic head	
				Bottom (ft bls)	Top (ft bls)	Length (ft)	Difference (ft)	Gradient (ft/ft)
USGS 103	H1	15, 16	19–21	766.9	763.9	3.0	-0.5	-0.2
	H2	16, 17	21–23	694.3	691.3	3.0	0.4	0.1
USGS 105	H1	10, 11	13–15	865.3	862.3	3.0	0.2	0.1
USGS 108	H1	2, 3	3, 4	1,121.6	1,118.6	3.0	-0.2	-0.1
	H2	6, 7	8–10	906.7	903.7	3.0	0.2	0.1
	H3	9, 10	12–14	791.4	788.4	3.0	0.3	0.1
USGS 131A	H1	6, 7	8, 9	928.4	925.4	3.0	-2.7	-0.9
	H2	7, 8	9–11	844.9	841.9	3.0	0.8	0.3
	H3	8, 9	10–12	795.4	792.4	3.0	1.4	0.5
	H4	11, 12	14–16	634.6	631.6	3.0	-0.6	-0.2
USGS 133	H1	4, 5	5, 6	685.5	682.5	3.0	-5.0	-1.7
	H2	5, 6	6, 7	618.2	615.2	3.0	-0.4	-0.1
	H3	6, 7	7–9	593.7	590.7	3.0	-0.7	-0.2
USGS 134	H1	9, 10	11–13	690.9	687.9	3.0	-0.8	-0.3
	H2	10, 11	13–14	664.9	661.9	3.0	0.6	0.2
	H3	14, 15	18–20	592.8	589.8	3.0	-0.2	-0.1
USGS 135	H1	1, 2	1–3	1,105.6	1,102.6	3.0	1.5	0.5
MIDDLE 2050A	H1	1, 2	1, 2	1,267.5	1,264.5	3.0	-0.4	-0.1
	H2	11, 12	11, 12	706.4	703.4	3.0	-0.6	-0.2
MIDDLE 2051	H1	4, 5	4, 5	1,002.2	999.2	3.0	3.2	1.1
	H2	10, 11	10, 11	646.7	643.7	3.0	-8.8	-2.9
	H3	11, 12	11, 12	612.2	609.2	3.0	-2.2	-0.7

USGS 103

Borehole USGS 103 was drilled and installed along the southern boundary of the INL about 5.5 mi south of the Central Facilities Area (CFA) (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 5,007.42 and 2,470 ft, respectively (table 1). The MP55 system extends to a depth of 1,279.4 ft bls and includes 23 measurement ports and 17 monitoring zones; 6 of these zones contain paired ports. Zone lengths range from 6.6 to 69.7 ft (fig. 7; table 2). A description of the drilling, MLMS completion, and lithology are described in Fisher and Twining (2011).

The range of computed head values for the June 2012 profile period was 4,420.3–4420.9 ft and includes two head inflections: (1) H1, located across the 3-ft packer separating zones 15 and 16 with a -0.5 ft (downward) head loss; and (2) H2, located between zones 16 and 17 with a 0.4 ft head gain (fig. 7, table 5). The H1 and H2 inflections occur where the MLMS enters steel casing near 760 ft bls and head pressure variation is likely the result of borehole construction and not attributed to aquifer response, as previously described in Twining and Fisher (2012). Borehole USGS 103 shows a high degree of vertical connectivity among adjacent fracture sets where the range in head is relatively small at 0.6 ft (table 6), starting at the bottom near zone 1 up to and including zone 15. Groundwater flow is dominantly horizontal and sediment layers appear to show minimal effect on head variation.

Water temperature measurements in the borehole USGS 103 during June 2012 range from 12.5 to 13.2 °C, and average 12.7 °C (fig. 7, table 6). Temperature generally decreases with depth in the upper part of the profile, and increases with depth in the lower part with a transition near 1,100 ft bls. The range and shape for the June 2012 temperature and head profiles for borehole USGS 103 are similar to the June 2010 profiles presented in Twining and Fisher (2012).

Table 6. Summary of depth range, hydraulic head statistics, fluid temperature statistics, water-level depth, and saturated thickness of the aquifer at each borehole, Idaho National Laboratory, Idaho, June or September 2012.

[**Local name** is the local well identifier used in this study. Location of boreholes is shown in figure 1. **Depth interval** is measured from the top of the uppermost monitoring zone to the bottom of the lowest zone in feet (ft). **Hydraulic head statistics** include the mean in feet above National Geodetic Vertical Datum of 1929 (NGVD29) in feet above mean sea level (ft amsl) and the range in ft. **Fluid temperature statistics** include the mean and the range in degrees Celsius (˚C). **Water-level depth** is reported in feet below land surface (ft bls) and refers to (land surface altitude, in ft) - (mean hydraulic head, in ft) for June or September 2012 profile period. **Saturated aquifer thickness** in feet is determined from subtracting the water-level depth from the aquifer thickness (appendix A)]

Boreholes							
Local name	Depth interval (ft)	Hydraulic head statistics		Fluid temperature statistics		Water-level depth (ft bls)	Saturated aquifer thickness (ft)
		Mean (ft)	Range (ft)	Mean (˚C)	Range (˚C)		
USGS 103	610	4,420.4	0.6	12.7	0.8	587.02	1,950
USGS 105	583	4,419.9	0.5	12.8	0.6	675.22	1,950
USGS 108	550	4,420.2	0.8	12.5	0.4	611.20	1,950
USGS 131A	627	4,429.6	2.9	12.6	2.2	546.54	1,950
USGS 132	590	4,420.4	0.3	11.9	1.8	608.19	1,880
USGS 133	318	4,461.1	6.3	11.6	1.2	429.07	500
USGS 134	333	4,454.2	1.1	13.8	2.4	514.61	500
USGS 135	410	4,418.1	1.8	11.5	0.2	717.84	1,870
USGS 137A	234	4,416.5	0.1	12.7	0.3	637.28	1,840
MIDDLE 2050A	913	4,446.8	1.3	13.2	5.3	481.45	660
MIDDLE 2051	615	4,430.1	9.8	13.4	4.4	567.21	1,160

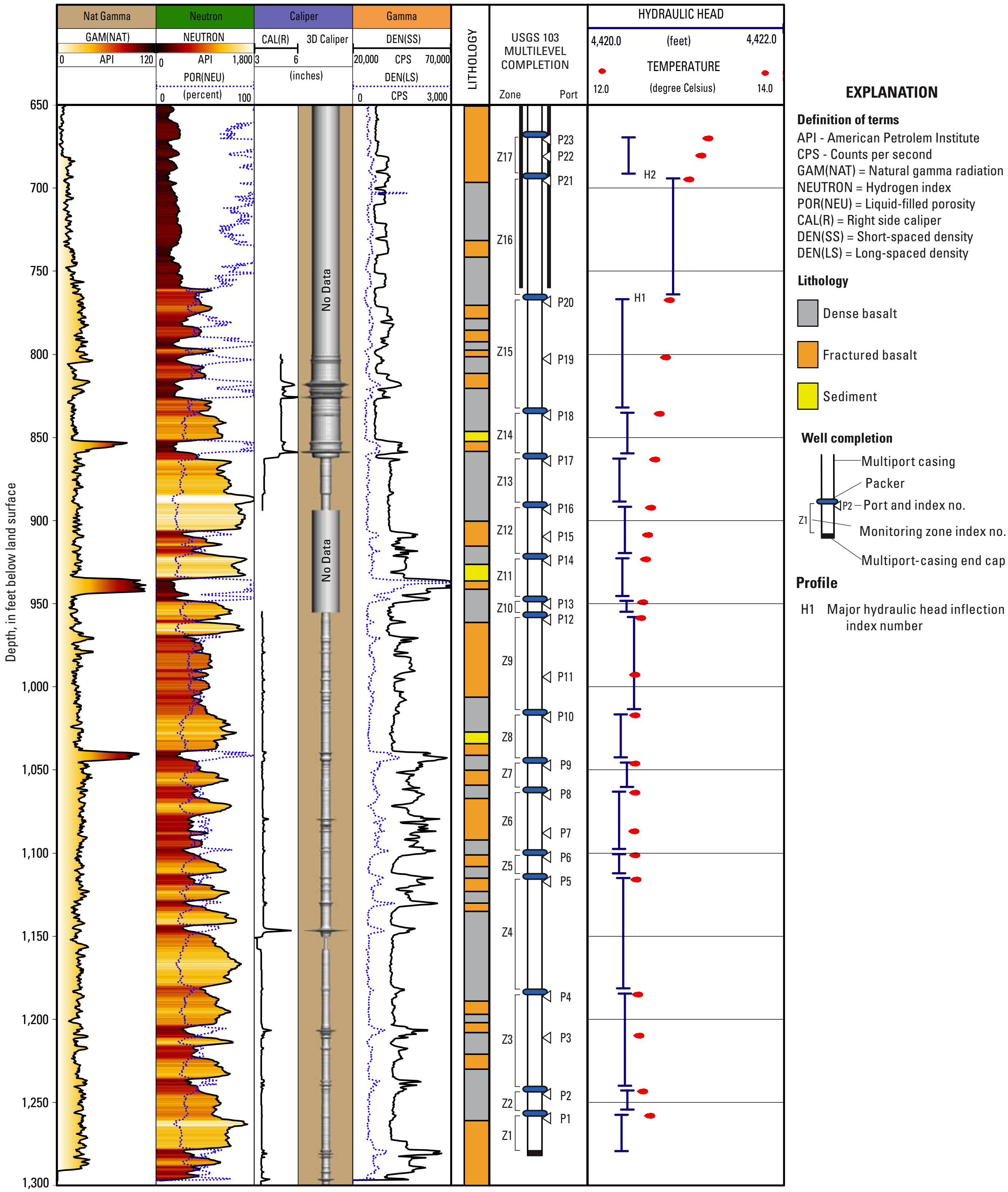

Figure 7. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 103, Idaho National Laboratory, Idaho, June 2012.

USGS 105

Borehole USGS 105 was drilled and installed along the southern boundary of the INL about 5.9 mi south of the CFA (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 5,095.12 and 2,540 ft, respectively (table 1). The MP55 system extends to a depth of 1,290.1 ft bls and includes 18 measurement ports and 13 monitoring zones; 5 of these zones contain paired ports. Zone lengths range from 10.9 to 72.5 ft (fig. 8; table 2). A description of the drilling, MLMS completion, and lithology are described in Twining and Fisher (2012).

The range of computed head values was 4,419.6–4420.1 ft for the June 2012 profile period and includes a single head inflection H1, located across the 3-ft packer separating zones 10 and 11 with a 0.2 ft head gain (fig. 8, table 5). The H1 inflection coincides with layers of low-permeability sediment, where sediment layers at this location obstructs the vertical connectivity between adjacent fracture sets as previously described by Twining and Fisher (2012). The range of head in borehole USGS 105 profile was relatively small at 0.5 ft and indicates flow that is dominantly horizontal (table 6). Sediment layers, comprise about 3 percent by volume of the lithology (table 4), and show minimal effect on hydraulic head.

Water temperatures in the borehole USGS 105 temperature profile ranged from 12.4 to 13.0 °C and averaged 12.8 °C for the June 2012 profile period (fig. 8, table 6). A reversal in the temperature gradient, near 1,000 ft bls, displays the coldest water temperature within the lowest ports (12.4 to 12.5 °C at ports 1 through 4). The range and shape for the June 2012 temperature and head profiles are similar to the June 2010 profiles presented for borehole USGS 105 in Twining and Fisher (2012).

USGS 108

Borehole USGS 108 was drilled and installed along the southern boundary of the INL about 6.3 mi south of the CFA (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 5,031.36 and 2,495 ft, respectively (table 1). The MP55 system extends to a depth of 1,191.9 ft bls and includes 16 measurement ports and 11 monitoring zones; 5 of these zones contain paired ports. Zone lengths range from 31.0 to 106.6 ft (fig. 9; table 2). A description of the drilling, MLMS completion, and lithology are described in Twining and Fisher (2012).

The range of computed head values for MLMS borehole USGS 108 was 4,419.6–4420.5 ft for the June 2012 profile period, and includes three head inflections: (1) H1, located across the 3-ft packer separating zones 2 and 3 with a -0.2 ft downward head loss; (2) H2, located between zones 6 and 7 with a 0.2 ft head gain; and (3) H3, located between zones 9 and 10 with a 0.3 ft head gain (fig. 9, table 5). The H1 and H2 inflections coincide with layers of low-permeability sediment, where the sediment at this location is believed to obstruct the vertical connectivity between adjacent fracture sets. The H3 inflection occurs where zone 10 is a long vertically averaged interval that is exposed to casing (fig. 9) as previously described in Twining and Fisher (2012). Borehole construction, related to the position of well casing, cannot be ruled out as the controlling factor for the H3 inflection; however, dense basalt at the bottom of zone 10 could result in a pressure change. The range of head in the profile was 0.8 ft (table 6) and indicates flow that is dominantly horizontal. Sediment layers in the borehole had minimal effect on head change.

Water temperatures ranged from 12.3 to 12.7 °C and averaged 12.5 °C for the June 2012 profile period (fig. 9). Temperature generally increased with depth within a very small range at 0.4 °C (table 6). The range and shape for the June 2012 temperature and head profiles are similar to the September 2010 profiles presented for borehole USGS 108 in Twining and Fisher (2012).

USGS 131A

Borehole USGS 131A was drilled and installed about 1.8 mi southwest of the CFA (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 4,976.14 and 2,475 ft, respectively (table 1). Borehole USGS 131A was completed with an MP55 system that extends to a depth of 1,188.8 ft bls and includes 16 measurement ports and 12 monitoring zones; four of these zones contain paired ports. Monitor zone lengths range from 12.2 to 102.1 ft (fig. 10; table 2).

Borehole USGS 131A was air rotary drilled, not cored, between September 9 and December 14, 2011, and restarted March 13–19, 2012. Drilling was suspended between December 15, 2011, and March 12, 2012, because of a hydraulic pump failure and winter snow that made access difficult. Borehole USGS 131A was drilled to replace borehole USGS 131 after drill rod became stuck and could not be recovered, which prevented installation of a MLMS. Borehole USGS 131 was continuously cored to 1,239 ft bls. Core and geophysical log data collected for borehole USGS 131 combined with geophysical log data collected from borehole USGS 131A were used to infer changes in geology between the two boreholes, which are separated by approximately 77 ft.

Borehole USGS 131A was drilled with tri-cone and down-hole hammer bits from 12 to 4.8in. in diameter. The interval of borehole USGS 131A (where the MLMS was installed) was drilled from 536 to 1,198 ft bls using a 4.8-in. tricone bit. Borehole USGS 131A was constructed with 12-in. surface casing to 8 ft bls; 5-in well casing and cement annular seal that extends from land surface to a depth of 536 ft bls; and 4.8-in. open hole below the 5-in. casing that extends from 536 to 1,189 ft, with rock chip and sluff between 1,189 and 1,198 ft bls. The MP55 MLMS was installed August 20–24, 2012.

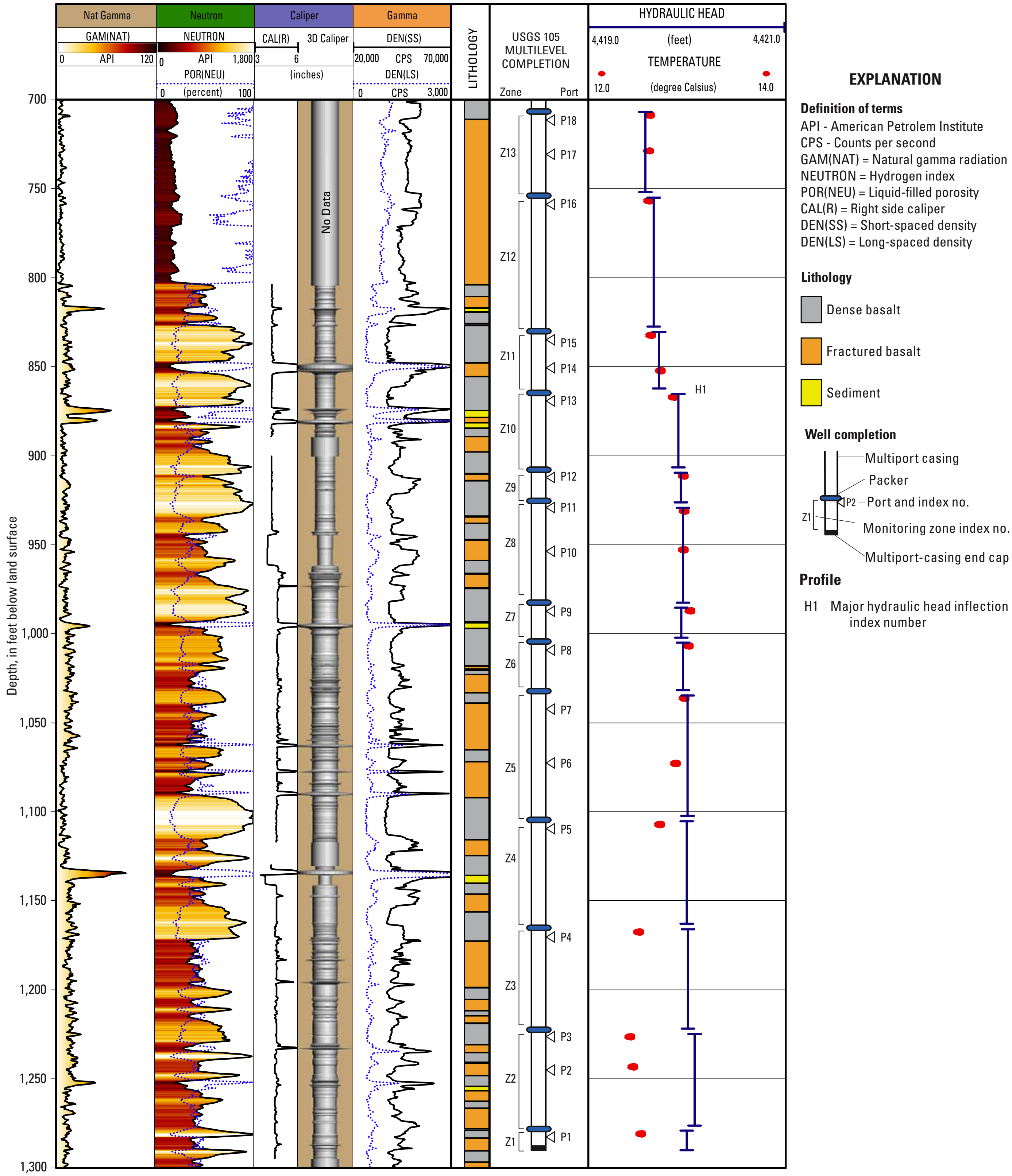

Figure 8. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 105, Idaho National Laboratory, Idaho, June 2012.

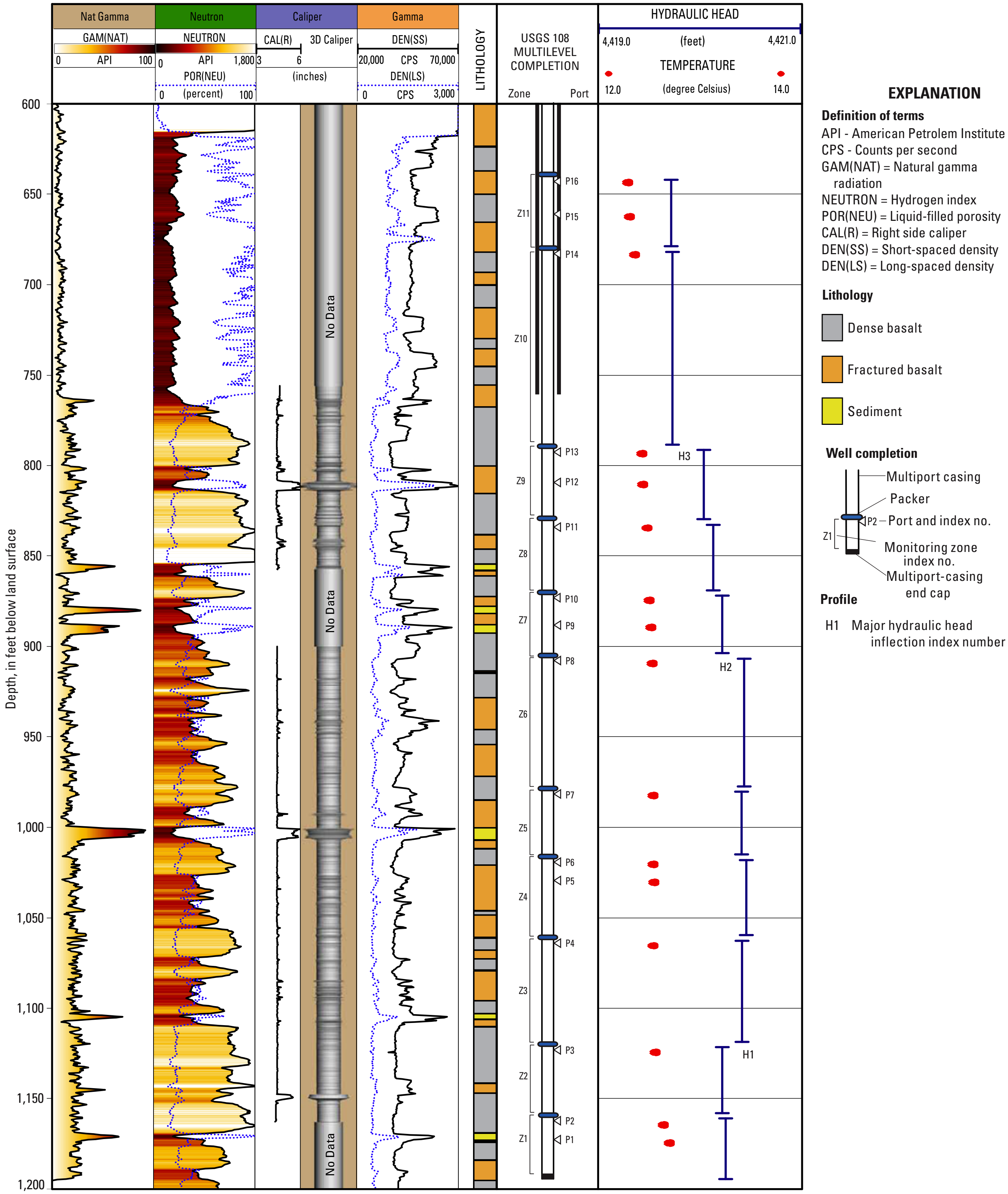

Figure 9. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 108, Idaho National Laboratory, Idaho, June 2012.

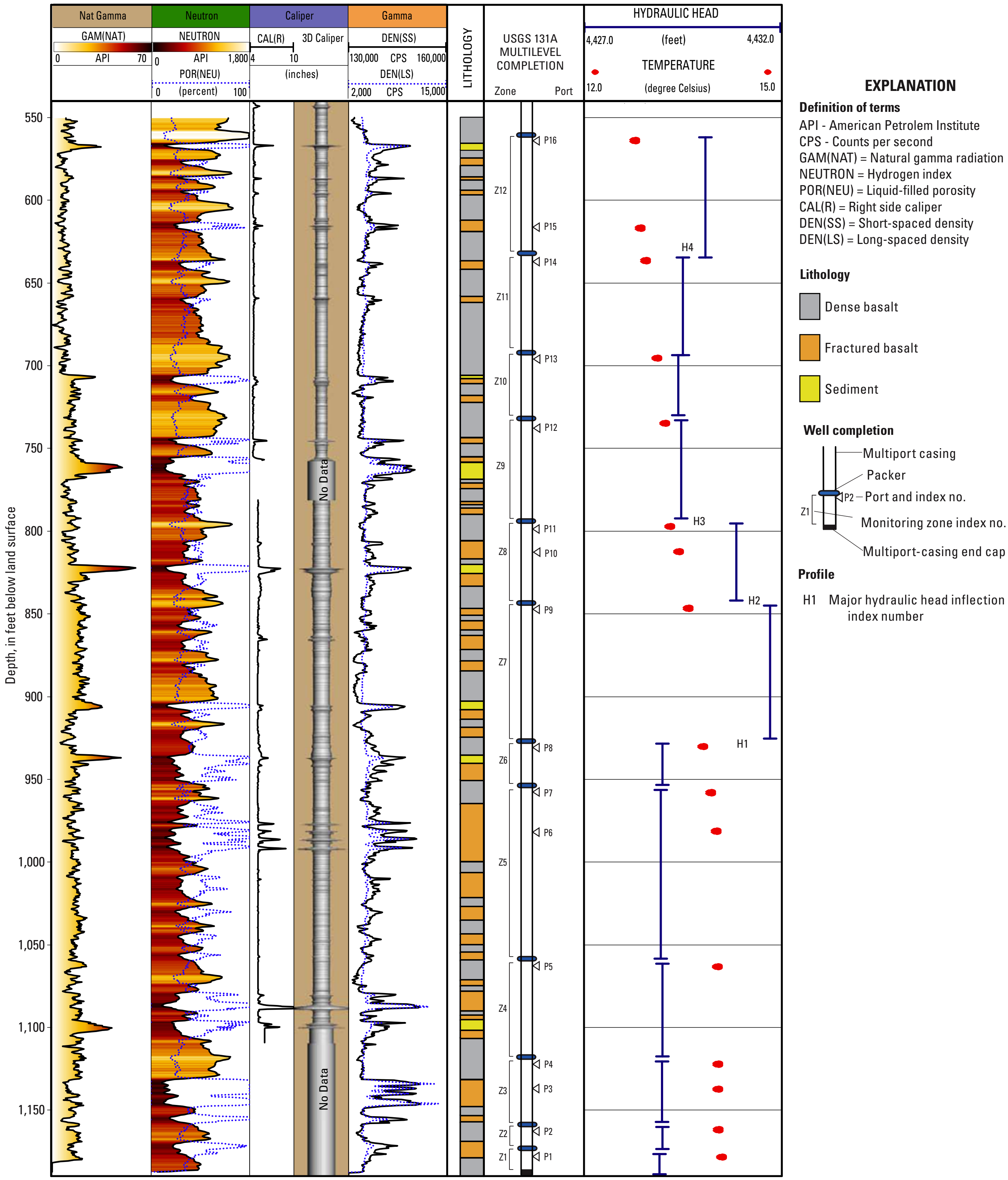

Figure 10. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 131A, Idaho National Laboratory, Idaho, September 2012.

The lithology log from 550 to 1,190 ft bls for borehole USGS 131A (fig. 10; appendix F) shows intervals that range in length 2–43 ft for dense basalt, 2–34 ft for fractured basalt, and 2–11 ft for sediment. The borehole is 54 percent dense basalt, 40 percent fractured basalt, and 6 percent sediment (table 4). Seven sediment layers were identified near depths of 565, 706, 758, 820, 902, 935, and 1,096 ft bls (fig. 10, appendix F). Sediment composition was not described for borehole USGS 131A because the borehole was not cored. Dense basalt is more frequent between 550 and about 750 ft bls and the occurrence of fractured basalt is more frequent between 950 and 1,190 ft bls. Layers of sediment interspersed with fractured and dense basalt mostly occur between about 750 and 950 ft bls, suggesting areas of vertical disconnectivity with fracture networks above and below this interval.

Four inflections were identified in the USGS 131A head profile: (1) H1, located across the 3-ft packer separating zones 6 and 7 with a -2.7 ft downward head loss; (2) H2, located between zones 7 and 8 with a 0.8 ft head gain; (3) H3, located between zones 8 and 9 with a 1.4 ft head gain; and (4) H4, located between zones 11 and 12 with a -0.6 ft head loss (fig. 10, table 5, appendix G). Paired port data suggest head difference between ports 15 and 16, inflection H4, is the result of a partial or full collapse of a sediment layer near 565 ft bls (fig. 10). Ports 15 and 16, zone 12, display a head difference of 1.8 ft and greater (appendix D); furthermore, the head change occurs just below a layer of unstable sediment, as suggested by driller notes (fig. 10). Head measurements collected from port 15, zone 12, are inline with adjacent zones.

Vertical head change remained relatively small below inflection H1 and above inflection H3, not taking into consideration inflection H4 for reasons previously mentioned. Below inflection H1, the lithology is mostly fractured basalt, suggesting vertical connectivity between zones below about 950 ft bls. Above inflection H3, lithology is mostly comprised of dense basalt, suggesting limited vertical connectivity where groundwater flow is generally horizontal within fractures located between layers of dense basalt and sediment. Between inflections H3 and H2 head gains 1.4 ft and 0.8 ft, respectively, before a -2.7 ft head loss below inflection H1 (table 5). The major head change within borehole USGS 131A occurs above the top of zone 6 and below the bottom of zone 9 (fig. 10). Interbedded sediment layers near 758, 820, 902, and 935 ft bls likely limit the vertical connectivity of fracture networks between zones 6, 7, 8, and 9 and affect head pressure. Head data and occurrence interval of fractures suggest the ESRP aquifer is stratified near borehole USGS 131A and suggest aquifer transmissivity increases below inflection H1. These data are further supported by temperature profiles that suggest a subtle disconnect within the ESRP aquifer below 950 ft bls (figs. 5 and 10).

Groundwater temperature in borehole USGS 131A ranges from 11.3 to 13.5 °C and averages 12.6 °C for the September 2012 profile period. The temperature profile in borehole USGS 131A shows a gradual increase in temperature between about 550 and 950 ft bls, though between 950 and 1,190 ft bls the temperature variation is subtle (figs. 5 and 10). The temperature profile shift coincides with head inflections below H1 and suggest a high degree of vertical connectivity between fracture networks below about 950 ft bls.

USGS 132

Borehole USGS 132 was drilled and installed about 0.9 mi south of the Radioactive Waste Management Complex (RWMC) (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 5,028.60 and 2,540 ft, respectively (table 1). The MP55 system extends to a depth of 1,213.6 ft bls and has a total of 23 measurement ports and 17 monitoring zones; 6 of these zones contain paired ports. Zone lengths range from 5.2 to 85.3 ft (fig. 11; table 2). A description of the drilling, MLMS completion, and lithology are described in Fisher and Twining (2011).

No inflections were identified in the USGS 132 head profile (fig. 11). The absence of inflections and the abundance of fractured basalt (63 percent, table 4) indicate a high degree of vertical connectivity among adjacent fracture sets. The range of head in the profile was relatively small at 0.3 ft (table 6) and indicates groundwater flow that is dominantly horizontal.

Groundwater temperature in borehole USGS 132 ranges from 10.8 to 12.6 °C and averaged 11.9 °C for the June 2012 profile period (fig. 11). A reversal in the temperature gradient occurs near 850 ft bls, with temperatures decreasing with depth below about 850 ft bls and increasing with depth above. The range and shape for the June 2012 temperature and head profiles are similar to the June 2010 profiles presented for borehole USGS 132 in Twining and Fisher (2012).

USGS 133

Borehole USGS 133 was drilled and installed about 1.9 mi north of the Idaho Nuclear Technology and Engineering Center (INTEC) (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 4,890.12 and 3,960 ft, respectively (table 1). The MP55 system extends to a depth of 766.4 ft bls and includes 13 measurement ports and 10 monitoring zones; 3 of the zones contain paired ports. Zone lengths ranged from 6.8 to 64.3 ft (fig. 12; table 2). A description of the drilling, MLMS completion, and lithology are described in Fisher and Twining (2011).

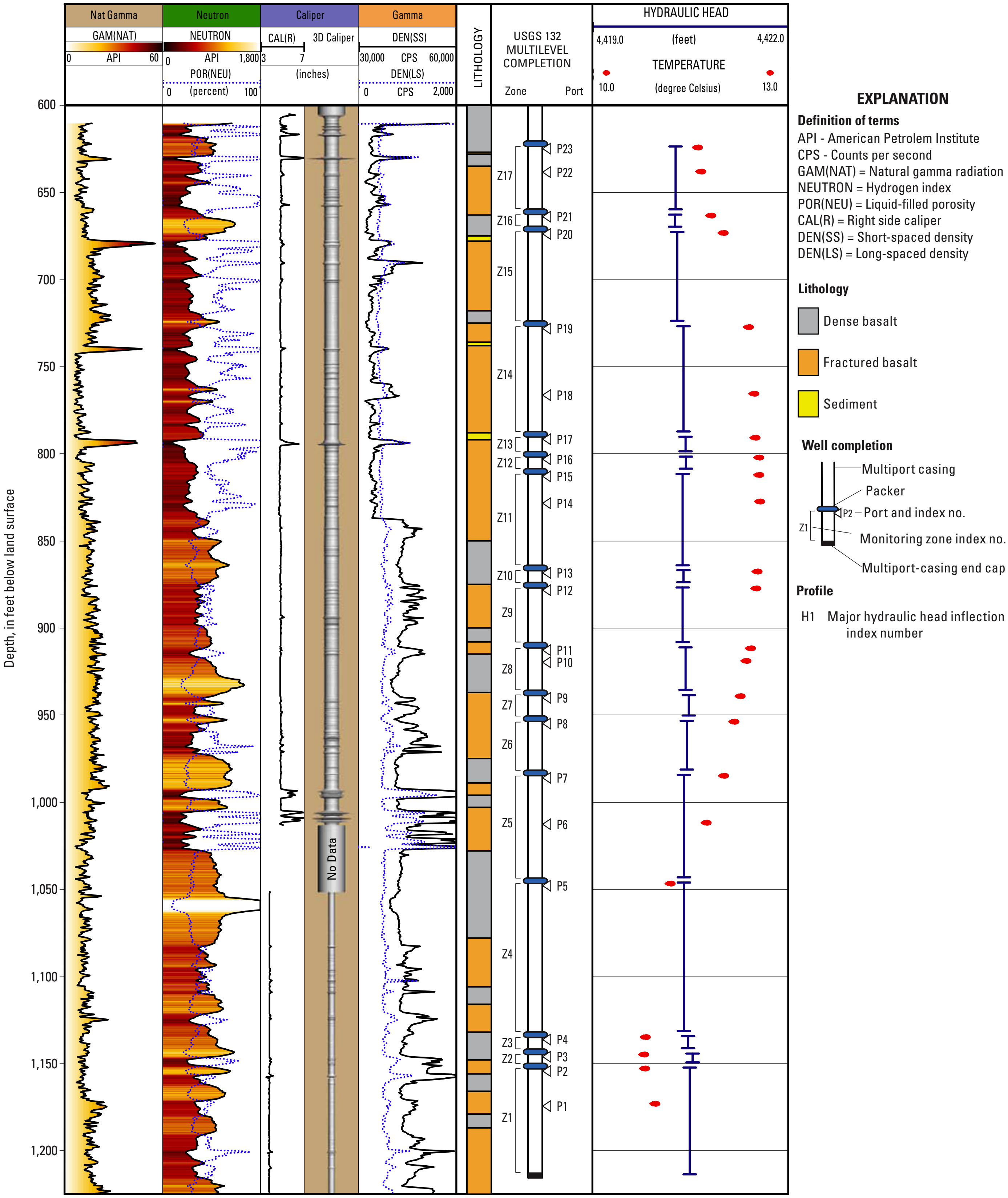

Figure 11. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 132, Idaho National Laboratory, Idaho, June 2012.

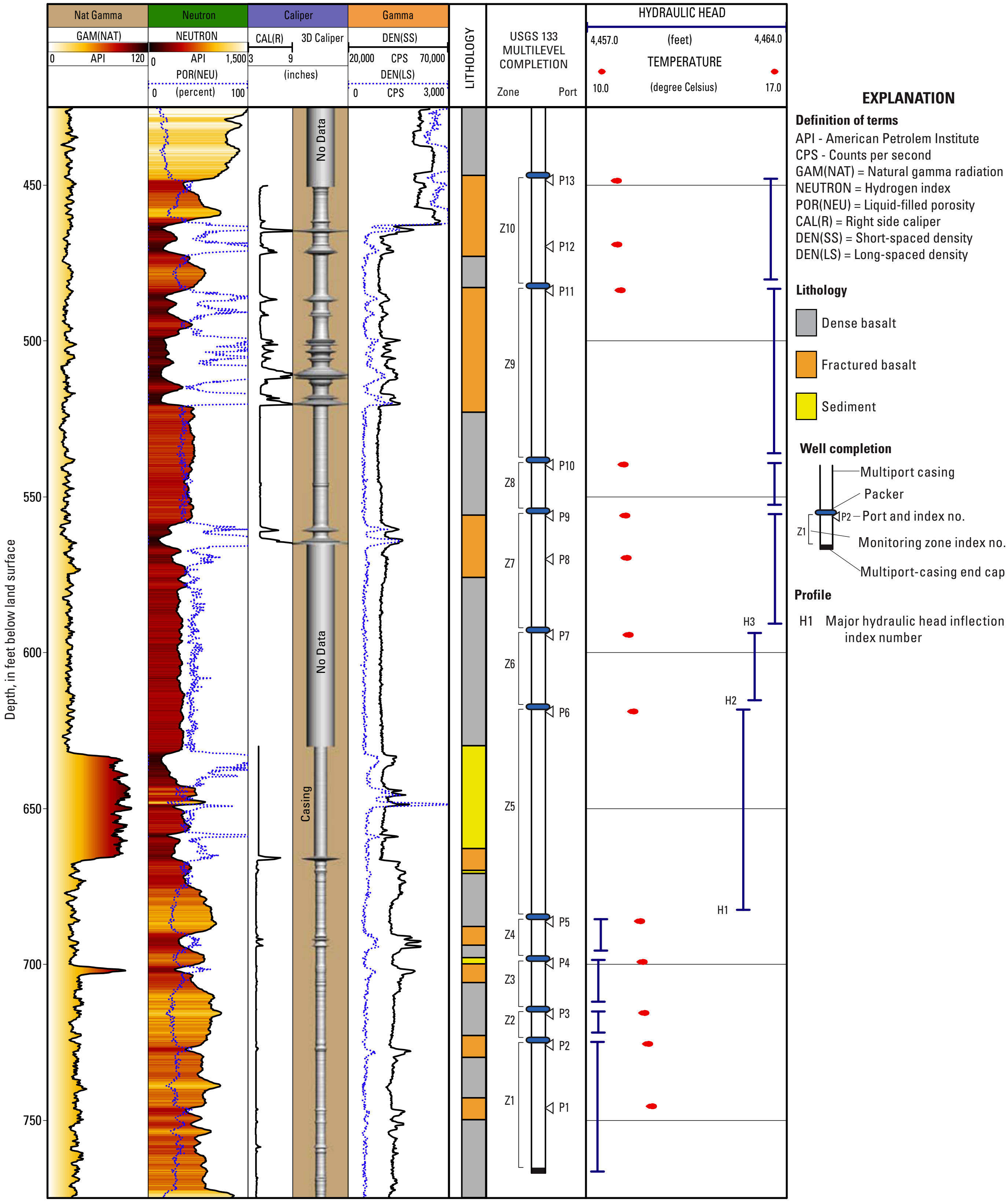

Figure 12. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 133, Idaho National Laboratory, Idaho, June 2012.

Three major inflections were identified in the borehole USGS 133 head profile: (1) H1, located across the 3-ft packer separating zones 4 and 5 with a -5.0 ft downward head loss; (2) H2, located between zones 5 and 6 with a -0.4 ft downward head loss; and (3) H3, located between zones 6 and 7 with a -0.7 ft downward head loss (fig. 12; table 5). Inflections H1, H2, and H3 occur near a 33-ft thick fine-grained sediment layer (fig. 12). The H1 inflection directly coincides with this sediment layer and has a downward vertical hydraulic gradient of -1.7 ft/ft. Vertical gradients measured above the 33-ft sediment layer are somewhat less in magnitude at -0.1 and -0.2 ft/ft for the H2 and H3 inflections (negative values indicate a downward gradient), respectively, and reflect a transition from low-permeability sediment and dense basalt to high-permeability fractured basalt. Head differences below the H1 inflection and above the H3 inflection remained relatively small, indicating flow that is dominantly horizontal.

Water temperatures in the borehole USGS 133 temperature profile gradually increased with depth, ranged from 11.1 to 12.3 °C, and averaged 11.6 °C for the June 2012 profile period (fig. 12). The range and shape for the June 2012 temperature and head profiles are similar to the June 2010 profiles presented for borehole USGS 133 in Twining and Fisher (2012).

USGS 134

Borehole USGS 134 was drilled and installed about 1.8 mi northwest of the Advanced Test Reactor (ATR) Complex (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 4,968.84 and 3,960 ft, respectively (table 1). The MP38 system extends to a depth of 886.8 ft bls and includes 20 measurement ports and 15 monitoring zones; 5 of these zones contain paired ports. Port 3 (zone 3) was damaged and was not included in head and temperature analysis for this report. Zone lengths range from 5.8 to 36.0 ft (fig. 13; table 2). A description of the drilling, MLMS completion, and lithology are described in Fisher and Twining (2011).

Three major inflections were identified in the borehole USGS 134 head profile: (1) H1, located across the 3-ft packer separating zones 9 and 10 with a -0.8 ft downward head loss; (2) H2, located between zones 10 and 11 with a 0.6 ft upward head gain; and (3) H3, located between zones 14 and 15 with a -0.2 ft downward head loss (fig. 13; table 5). The vertical hydraulic gradients for the H1, H2, and H3 inflections are -0.3, 0.2, and -0.1 ft/ft, respectively. The response of inflections H1 and H2 result from a localized head increase in zone 10. This head increase probably is hydraulically isolated in zone 10 because of the relatively small 0.1-ft head difference between zones 9 and 11, and possibly because fractures in this zone are poorly connected to the larger hydraulic system. The H3 inflection occurs within the upper 50 ft of the aquifer and fractures within zone 15 appear to be partially isolated by dense basalt. The location of the H3 inflection and proximity to mountain fronts (fig. 1) may suggest the upper aquifer is responding to periodic tributary valley subsurface inflow. Excluding zone 10, the variability in head was small, with a range of 1.1 ft (table 6).

Borehole USGS 134 temperature profile gradually increased with depth, ranged from 12.8 to 15.2 °C, and averaged 13.8 °C for the June 2012 profile period (fig. 13). The range and shape for the June 2012 temperature and head profiles are similar to the June 2010 profiles presented for borehole USGS 134 in Twining and Fisher (2012).

USGS 135

Borehole USGS 135 was drilled and installed near the southwestern corner of the INL, about 5.0 mi southwest of the RWMC (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 5,135.94 and 2,675 ft, respectively (table 1). The MP55 system extends to a depth of 1,136.6 ft bls and includes 14 measurement ports and 10 monitoring zones; 4 of these zones contain paired ports. Zone lengths range from 21.6 to 56.1 ft (fig. 14; table 2). A description of the drilling, MLMS completion, and lithology are described in Twining and Fisher (2012).

A single inflection was identified in the borehole USGS 135 head profile: (1) H1, located across the 3-ft packer separating zones 1 and 2 with a 1.5 ft head gain (fig. 14; table 5). The H1 inflection has a vertical hydraulic gradient of 0.5 ft/ft and coincides with layers of fractured basalt (starting near 1,115 ft bls) overlain by a 50-ft-thick layer of dense basalt. The low permeability associated with dense basalt above H1 creates a hydraulic disconnect between the high-permeability fractured basalt, resulting in a measurable head gain. Head difference above H1 inflection remained relatively small.

Water temperatures for the borehole USGS 135 show subtle increase with depth, ranging from 11.5 to 11.7 °C, and averaged 11.5 °C for the June 2012 profile period (fig. 14). The range in temperature data (0.2 °C) over about 400 ft aquifer support the concept of vertical connectivity between fractures. The range and shape for the June 2012 temperature and head profiles are similar to the June 2010 profiles presented for borehole USGS 135 in Twining and Fisher (2012).

USGS 137A

Borehole USGS 137A was drilled and installed near the southern boundary of the INL about 3.4 mi south of the RWMC (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 5,053.81 and 2,580 ft, respectively (table 1). Borehole USGS 137A was completed with an MP55 system that extends to a depth of 894.7 ft bls and includes eight measurement ports and five monitoring zones; three of these zones contain paired ports. Monitoring zone lengths range from 6.8 to 78.0 ft (fig. 15; table 2).

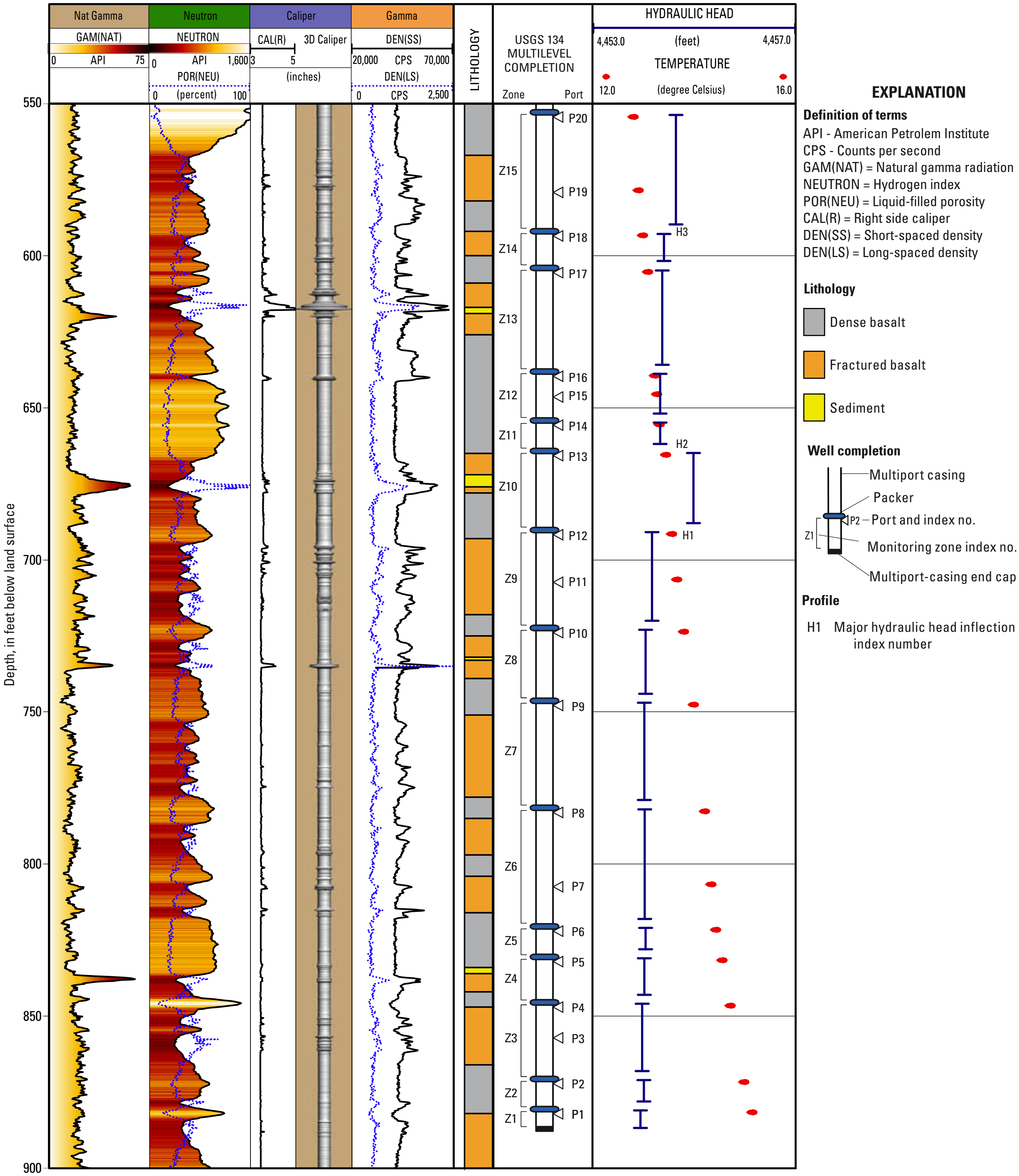

Figure 13. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 134, Idaho National Laboratory, Idaho, June 2012.

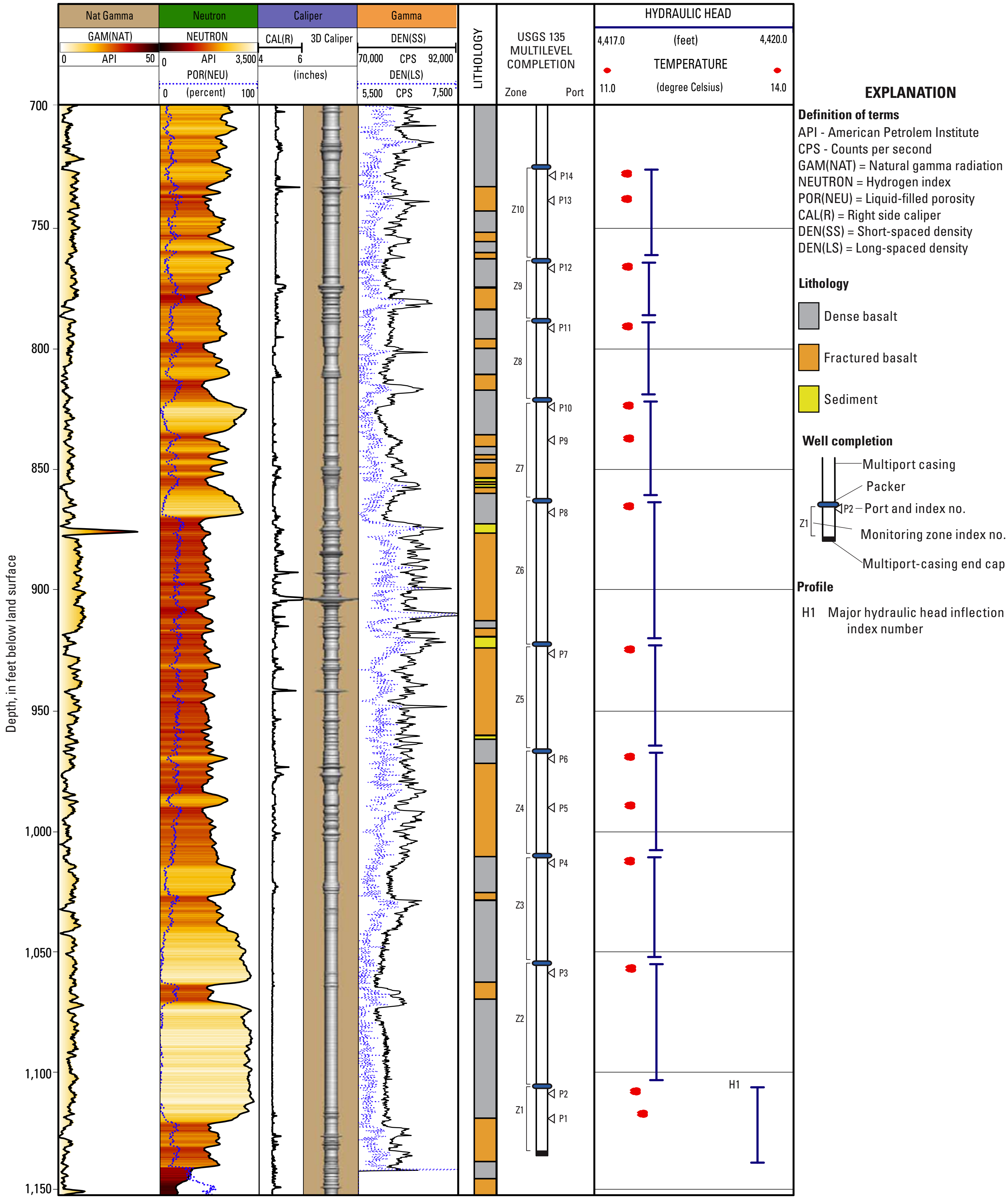

Figure 14. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 135, Idaho National Laboratory, Idaho, June 2012.

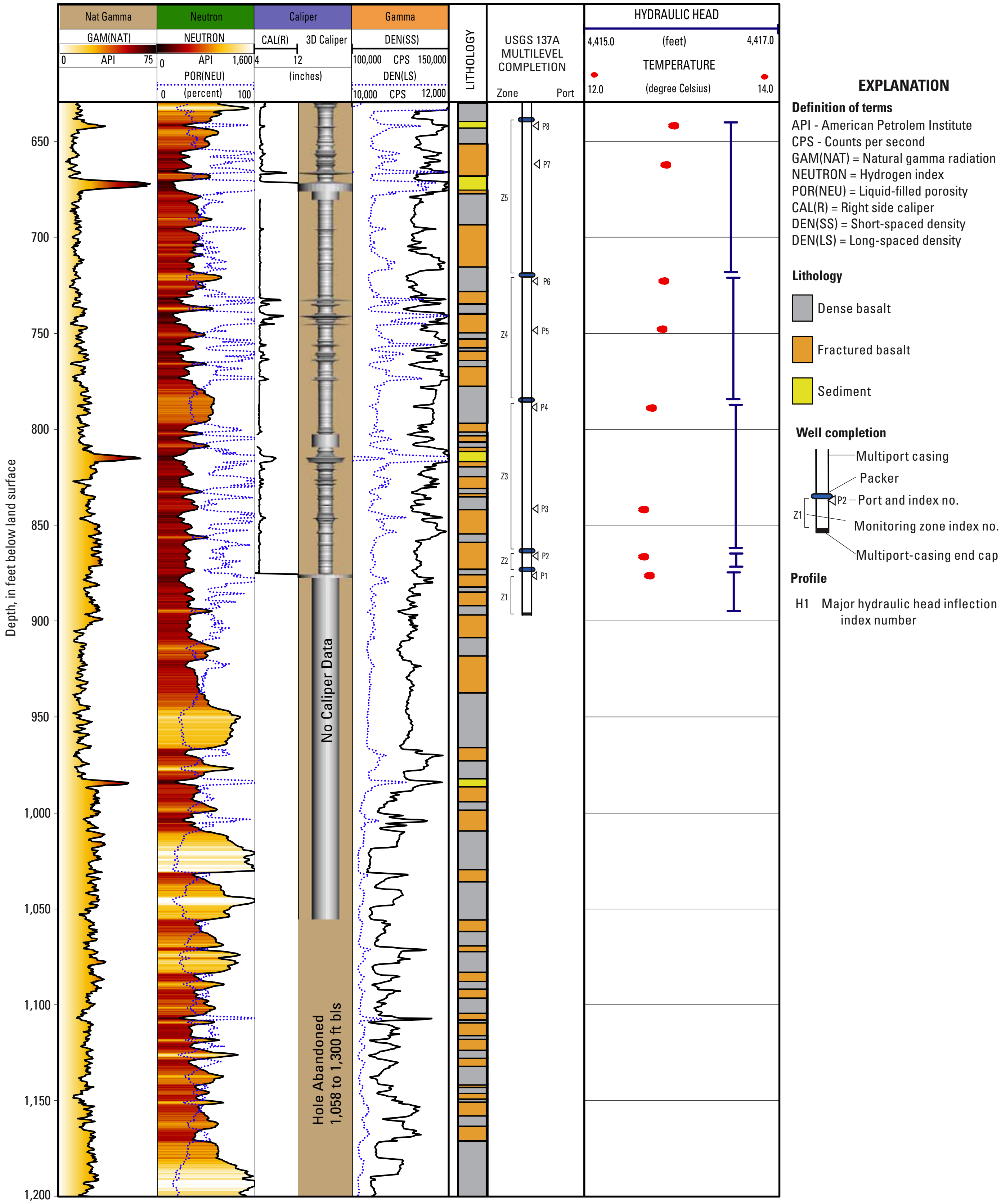

Figure 15. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole USGS 137A, Idaho National Laboratory, Idaho, September 2012.

Borehole USGS 137A was air rotary drilled to 984 ft bls and cored from 984 to 1,317 ft bls between June 4 and August 27, 2012. Borehole USGS 137A was drilled to replace borehole USGS 137, located approximately 120 ft away. Borehole USGS 137 was abandoned after a drill bit twisted off during reaming; however, borehole USGS 137 was cored to about 990 ft bls before abandonment. A lithology log from core and geophysical data collected from borehole USGS 137 was combined with geophysical data collected from borehole USGS 137A to infer the geology of uncored parts of USGS 137A. Borehole USGS 137A was drilled in several stages using tri-cone, down-hole hammer, and diamond core bits ranging from 10 to 3.8 in. in diameter. After drilling, 8-in and 5-in steel casings were set to 39 and 331 ft bls, respectively. Borehole USGS 137A was drilled from 331 to 984 ft bls using a 4.8-in tricone drill bit and HQ-size (3.8 in.) cored from 984 to 1,317 ft bls. After HQ-size coring to 1,317 ft bls, attempts were made to ream and clear out obstructions in borehole USGS 137A to total depth. Those attempts were halted near 1,058 ft bls because attempts to stabilize the borehole beyond that depth failed and resulted in a decision to abandon borehole USGS 137A between the depths of 1,058 to 1,317 ft bls.

The MP55 MLMS was installed in borehole USGS 137A between August 27 and 30, 2012. On August 27, 2012, while attempting to lower the MLMS to 1,058 ft, the MP55 casing would not lower past 900 ft bls, so the MP55 casing was extracted and redesigned to sit just above the 900 ft interval. The first zone (zone 1) in borehole USGS 137A likely interrogates below the total length of the MLMS system (894.7 ft bls); however, it is uncertain if borehole collapse occurred during or after installation of the MP 55 system.

The lithology log constructed from 640 to 1,300 ft bls for borehole USGS 137A (fig. 15; appendix F) shows units that range in length from 2 to 33 ft for dense basalt, 1 to 23 ft for fractured basalt, and 4 to 8 ft for sediment. The composition of lithologic units in the borehole is 53 percent dense basalt, 44 percent fractured basalt, and 3 percent sediment (table 4). Four sediment layers were identified near depths of 640, 668, 812, and 982 ft bls (fig. 15). Sediment composition was not described for borehole USGS 137A where this borehole was not cored. Layers of fractured and dense basalt are numerous and seem to be well distributed throughout the borehole.

No inflections were identified in the USGS 137A head profile (fig. 15). The absence of inflections and the abundance of fractured basalt (44 percent) and absence of sediment layers (3 percent) indicate a high degree of vertical connectivity among adjacent fracture sets (table 4). The range of head in the profile was relatively small at 0.1 ft (table 6) and indicates groundwater flow that is dominantly horizontal.

Water temperatures in the USGS 137A temperature profile ranged from 12.6 to 12.9 °C and averaged 12.7 °C for the September 2012 profile period (fig. 15). The range in temperature data (0.3 °C) support the concept of vertical connectivity between fractures.

MIDDLE 2050A

Borehole MIDDLE 2050A was drilled and installed about 0.8 mi west of the INTEC and approximately 0.5 miles west and upstream of USGS streamgaging station 13132535, Big Lost River at Lincoln Boulevard Bridge, near Atomic City, Idaho (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 4,928.22 and 3,790 ft, respectively (table 1). The MP55 system extends to a depth of 1,377.6 ft bls and includes 15 measurement ports and 15 monitoring zones. Zone lengths range from 10.2 to 152.6 ft (fig. 16; table 2). A description of the drilling, MLMS completion, and lithology are described in Fisher and Twining (2011).

Two major inflections were identified in the MIDDLE 2050A head profile: (1) H1, located across the 3-ft packer separating zones 1 and 2 with a -0.4 ft downward head loss; and (2) H2, located between zones 11 and 12 with a -0.6 ft head loss (fig. 16, table 5). These head inflections are similar, with H2 being slightly higher, in magnitude but similar in direction than previously described in Twining and Fisher (2012). For example, the H1 and H2 inflections for June 2010 were both -0.4 ft (Twining and Fisher, 2012) and suggest a greater head loss across inflection H2 occurred during the June 2012 profile event. The greater head loss across H2 inflection occurs in the same year that six months of BLR surface water flow was reported for streamgaging station USGS 13132535 (Big Lost River at Lincoln Boulevard Bridge near Atomic City [figs. 1 and 17], http://waterdata.usgs.gov/id/nwis/nwisman/?site_no=13132535). Surface water flow in the BLR likely resulted in a buildup of head above inflection H2 near MIDDLE 2050A. Flow for BLR was reported for the months February–June 2012; however, during 2010, BLR flow was only reported for the month of June (fig. 17). The vertical hydraulic gradient of the H1 inflection was -0.1 ft/ft and coincides with the 100-ft-thick layer of sediment. The head in zone 1 likely is controlled by the units of fractured basalt above and below this sediment layer, where flow is allowed to bypass the low-permeability sediment through the open borehole (Fisher and Twining, 2011). The inflection near H2 resulted in a vertical hydraulic gradient of -0.2 ft/ft, and coincides with layers of low-permeability sediment; where the sediment at these locations obstructs the vertical connectivity between adjacent fracture sets. Head differences between the major inflections remained relatively small and indicate flow that is dominantly horizontal; however, head decreased incrementally with depth in the borehole, creating the potential for downward flow. Water temperatures gradually increased with depth, ranged from 11.0 to 16.3 °C, averaging 13.3 °C for the June 2012 profile period (fig. 16).

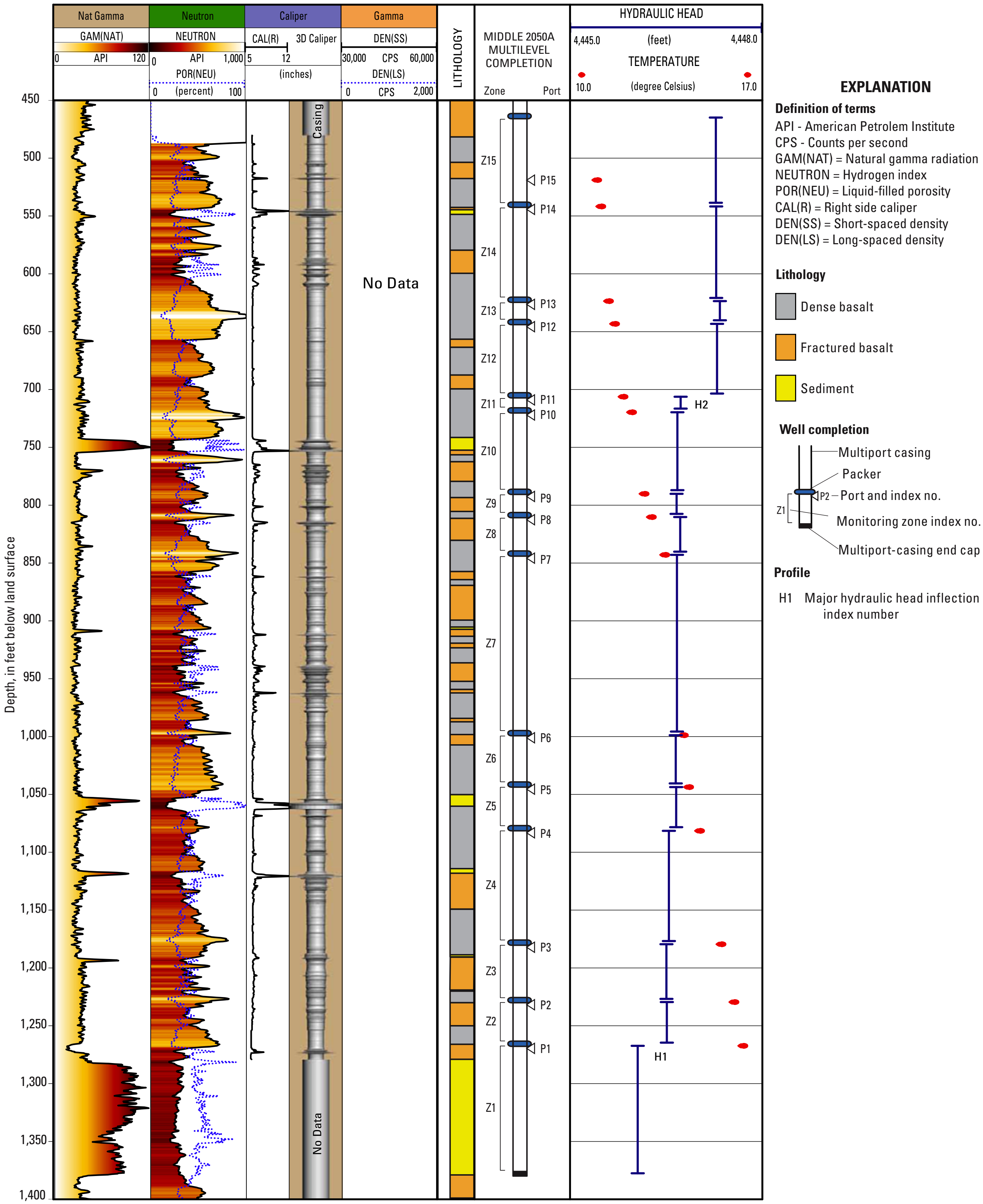

Figure 16. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole MIDDLE 2050A, Idaho National Laboratory, Idaho, June 2012.

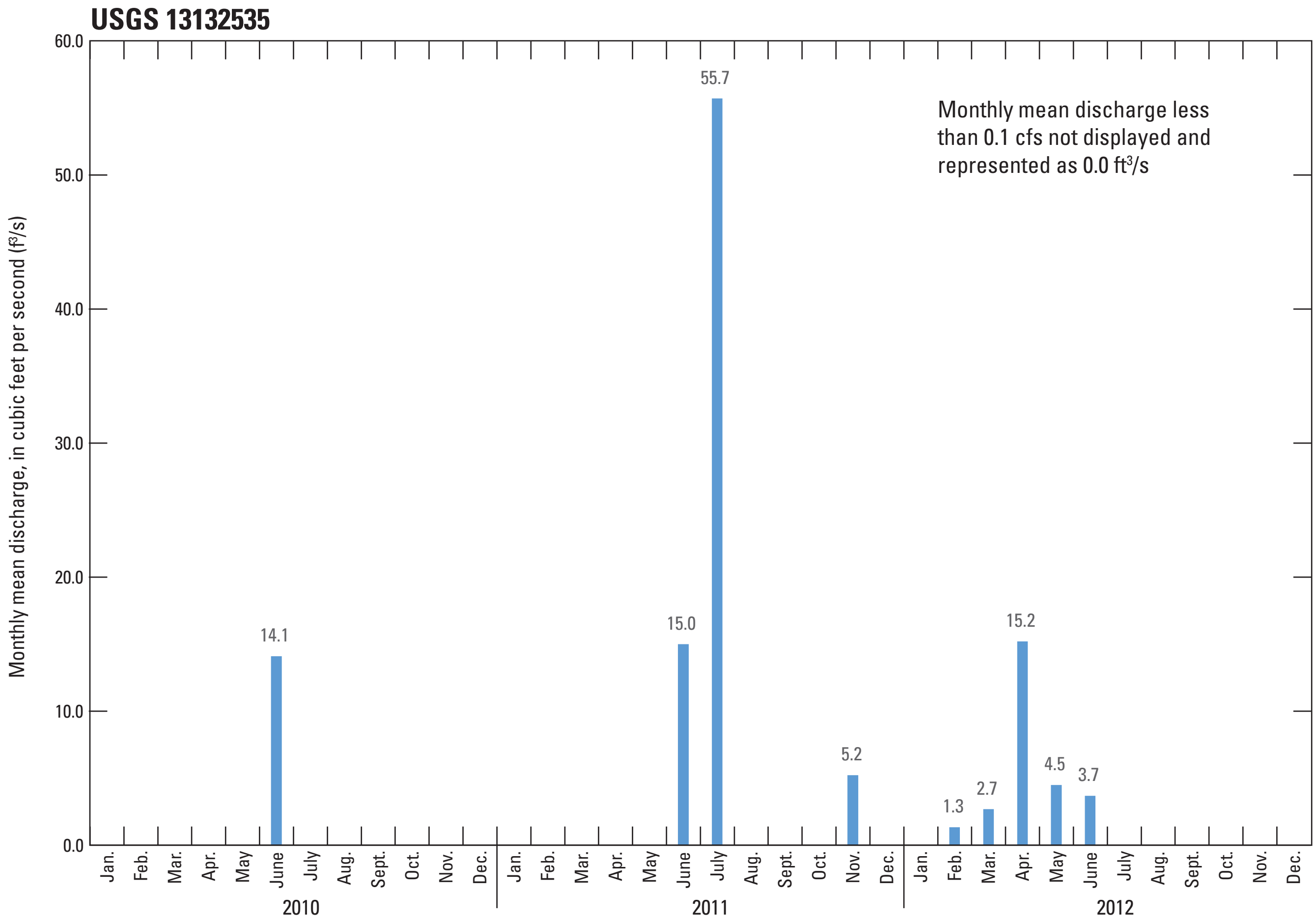

Figure 17. Big Lost River surface water flow measured at USGS streamgaging station 13132535, Big Lost River at Lincoln Boulevard Bridge, near Atomic City, Idaho National Laboratory, Idaho, January 2010 to January 2014.

MIDDLE 2051

Borehole MIDDLE 2051 was drilled and installed about 2.75 mi northeast of the RWMC and approximately 4.5 miles west and upstream of USGS streamgaging station 13132535, Big Lost River at Lincoln Boulevard Bridge, near Atomic City, Idaho (fig. 1). The land-surface altitude and the estimated altitude of the base of the aquifer at this location are 4,997.31 and 3,270 ft, respectively (table 1). The MP55 system extends to a depth of 1,176.5 ft bls and includes 12 measurement ports and 12 monitoring zones. Zone lengths range from 6.8 to 119.8 ft (fig. 18; table 2). A description of the drilling, MLMS completion, and lithology are described in Fisher and Twining (2011).

Three major inflections were identified in the borehole MIDDLE 2051 head profile: (1) H1, located across the 3-ft packer separating zones 4 and 5 with a 3.2 ft head gain; (2) H2, located between zones 10 and 11 with a -8.8 ft head loss; and (3) H3, located between zones 11 and 12 with a -2.2 ft head loss (fig. 18; table 5). Two of three head inflections are slightly higher in magnitude but similar in direction than previously described in Twining and Fisher (2012). For example, in 2010 the H1, H2, and H3 inflections were 3.3, -6.3, and -0.8 ft, respectively, and suggest a greater head loss across inflections H2 and H3 occurred during the June, 2012 when compared to June, 2010. The greater head loss across H2 and H3 inflections occur in the same year that six months of BLR surface water flow was reported for streamgaging station USGS 13132535 (BLR at Lincoln Boulevard Bridge near Atomic City [figs. 1 and 17], http://waterdata.usgs.gov/id/nwis/nwisman/?site_no=13132535). The increased head loss across inflections H2 and H3 between measurement events taken June 2010 (Twining and Fisher, 2012) and June 2012 suggest an increased surface water recharge, from channel leakage, resulted in a head buildup across zones 11 and 12 in borehole MIDDLE 2051. Additionally, the geology for borehole MIDDLE 2051 indicates two sediment layers within zone 11 potentially retard vertical flow (fig. 18). The H1 inflection has a vertical hydraulic gradient of 1.1 ft/ft and coincides with layers of fractured basalt separated by a 5-ft-thick layer of fine-grained sediment and a 75-ft-thick layer of dense basalt (fig. 18). The low permeability associated with these layers creates a hydraulic disconnect between the high-permeability fracture sets above and below zone 5.

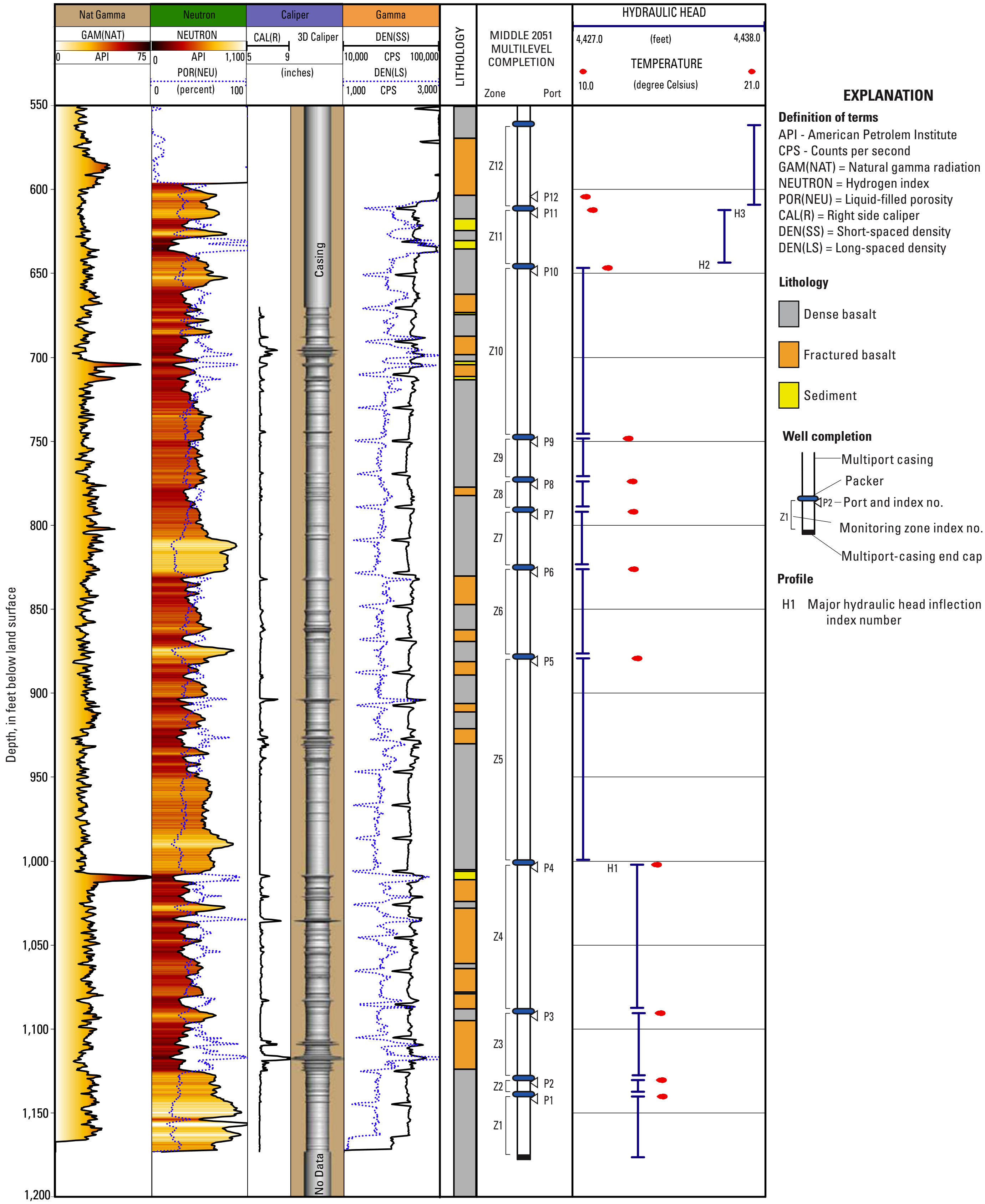

Figure 18. Geophysical logs of natural gamma, neutron, caliper, and gamma-gamma dual density; lithology log; multilevel completion diagram; and hydraulic head and water temperature profiles for borehole MIDDLE 2051, Idaho National Laboratory, Idaho, June 2012.

The H2 and H3 inflections have vertical hydraulic gradients of -2.9 and -0.7 ft/ft, respectively, and also result from a restriction in vertical connectivity (table 5), where fracture sets coinciding with zones 10 and 12 are hydraulically isolated from one another by two layers of low-permeability sediment (5 and 7 ft thick) within zone 11. Head differences below the H1 inflection and between the H1 and H2 inflections remained relatively small, indicating flow is dominantly horizontal. Water temperatures during June 2012 generally decreased with depth, ranged from 10.7 to 15.1 °C, and averaged 13.4 °C.

Borehole Profile Comparison

The range in head and temperature data were examined between MLMS boreholes to better understand groundwater flow beneath the INL for aquifer depth intervals ranging from 234 to 913 ft (table 6). The range in head for all MLMS boreholes was from 0.1 to 9.8 ft for boreholes USGS 137A and MIDDLE 2051, respectively; the range in temperature for all MLMS boreholes was from 0.2 to 5.3 °C for boreholes USGS 135 and MIDDLE 2050A, respectively (table 6). Previously reported head ranges were from 0.3 to 7.2 ft for boreholes USGS 103 and MIDDLE 2051, respectively; the previously reported temperature ranges were from 0.2 to 5.2 °C for boreholes USGS 135 and MIDDLE 2050A, respectively (Twining and Fisher, 2012).

With the exception of borehole USGS 135, the MLMS boreholes within the AVZ and Arco-Big Southern Butte VRZ (boreholes USGS 103, USGS 105, USGS 108, USGS 132, and USGS 137A) display a head range less than 1 ft (0.1–0.8 ft); furthermore, MLMS boreholes completed within the AVZ and Arco-Big Southern Butte VRZ (fig. 1) were completed where the estimated saturated aquifer thickness can exceed 1,840 ft (table 6) and where sediment volume generally represent less than 5 percent of the interrogated depth (table 4). Additionally, MLMS wells completed within the AVZ and Arco-Big Southern Butte VRZ (fig. 1) had fracture networks that generally were hydraulically connected, as suggested by the small range in head and through geophysical and core material analysis. MLMS boreholes in the Big Lost Trough (boreholes USGS 131A, USGS 133, USGS 134, MIDDLE 2050A, MIDDLE 2051) display a head range that exceeds 1 ft (1.1–9.8 ft); furthermore, with the exception of borehole USGS 131A, the estimated saturated aquifer thickness was generally less than 1,160 ft (table 6).

With the exception of borehole USGS 132, the MLMS boreholes completed in the AVZ and Arco-Big Southern Butte VRZ (boreholes USGS 103, USGS 105, USGS 108, USGS 135, and USGS 137A) display a relatively small range in temperature (0.2–0.8 °C), fig. 1 and table 6. Furthermore, MLMS boreholes completed within the AVZ and Arco-Big Southern Butte VRZ (fig. 1) do not display a linear increase in temperature with depth (with the exception of borehole USGS 108); whereas, MLMS boreholes located in the Big Lost Trough display a linear increase in temperature with depth (figs. 1 and 5). The reported range for head and temperature data for MLMS wells located in the Big Lost Trough is generally higher than for MLMS wells located within the AVZ and Arco-Big Southern Butte VRZ (fig. 1, table 6). The higher head and temperature range reported for MLMS wells located in the Big Lost Trough can be attributed to geohydrologic considerations including saturated aquifer thickness, sediment volume, and proximity to groundwater recharge from mountain front underflow and BLR surface flow.

Lithologic units that appear to influence major head inflections typically coincided with sediment layers and dense basalt sequences that display minimal fracturing (Fisher and Twining, 2011; Twining and Fisher, 2012). Without knowing the true areal extent and transmissivity of lithologic units it is difficult to predict head change, especially for dense basalt units that can have vertical fracturing that cannot be detected through geophysical methods and(or) core analysis. The vertical connectivity between fracture networks of adjacent units is controlled by the geologic setting. Groundwater can move through vertical joints in dense basalt or through gaps in sediment layers that are not evident in core samples or geophysical data; however, MLMS data can detect slight variations in pressure. It is important to make the connection between geology and groundwater flow to gain a better understanding of which units create the greatest potential for pressure change and result in the largest vertical gradients.

Low vertical gradients generally indicate potential vertical connectivity and flow, and large gradient inflections indicate zones of relatively lower vertical connectivity, where vertical flow is potentially retarded (Fisher and Twining, 2011). With the exception of USGS 135, the lowest vertical gradients are represented by MLMS boreholes completed in the AVZ and Arco-Big Southern Butte VRZ (boreholes USGS 103, USGS 105, USGS 108, USGS 137A) and the highest vertical gradients are represented by boreholes located in the Big Lost Trough (boreholes USGS 131A, USGS 133, USGS 134, MIDDLE 2050A, and MIDDLE 2051) (fig. 1 and table 5). Beneath the INL, groundwater volume, velocity, and vertical direction continue to shift in space and time; and MLMS data suggest, as the aquifer thins, there is the potential for higher vertical gradients. With the exception of USGS 131A, the saturated aquifer thickness for MLMS boreholes completed in the Big Lost Trough range from 500 to 1,160 ft and the saturated aquifer thickness for boreholes completed in the AVZ and Arco-Big Southern Butte VRZ (fig. 1) range from 1,840 to 1,950 ft (table 6).

The temporal correlation among MLMSs was analyzed for head data collected from 2007 to 2013 using the normalized mean head, $\hat{\bar{H}}$; these values of head were calculated for each MLMS and are expressed as:

$$\hat{\bar{H}}_t = \frac{\bar{H}_t - \bar{\bar{H}}}{s} \qquad \text{for } t = 1,\ldots,n \tag{5}$$

where

$\bar{H}_t$ is the profile mean head for measurement event t, in ft, and defined as

$$\bar{H}_t = \frac{1}{n}\sum_{i=1}^{n} H_i \tag{6}$$

where

n is the total number of port head measurements in the MLMS borehole;

H_i is the head measurement at port i, in ft;

$\bar{\bar{H}}$ is the mean of the profiles mean head values for all measurement events, in ft; and defined as

$$\bar{\bar{H}} = \frac{1}{n}\sum_{t=1}^{n} \bar{H}_t \; ; \tag{7}$$

and

s is the standard deviation of the profiles mean head values for all measurement events, in ft, and defined as

$$s = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(H_t - \bar{\bar{H}}\right)} \,. \tag{8}$$

The values of $\hat{\bar{H}}$ for each of the 11 MLMS boreholes (fig. 19; appendix H) suggest a moderate positive correlation among all boreholes, which reflects regional fluctuations in water levels in response to seasonality and location. Normalized mean head was examined for MLMS wells located in the Big Lost Trough and for MLMS wells located in the AVZ and Arco-Big Southern Butte VRZ (figs. 1 and 19) because temporal correlation is stronger when borehole location is considered. For example, boreholes within the AVZ and Arco-Big Southern Butte VRZ (USGS 103, USGS 105, USGS 108, USGS 132, USGS 135, and USGS 137A, fig. 1) are completed in an area of highly permeable media and relatively large saturated thickness and display a positive temporal correlation between the six boreholes. Temporal correlation between MLMS completed in the Big Lost Trough is generally positive (fig. 19), but temporal correlation for borehole USGS 134 shows the least agreement with other MLMS boreholes located in the Big Lost Trough. Borehole USGS 134 is closest to the mountain front, where tributary valley subsurface inflow is suspected, which may account for the difference between borehole USGS 134 and other Big Lost Trough boreholes. Subtle temporal differences in normalized mean head are attributed to recharge from snowmelt or surface water flow in the BLR, or both (figs. 1 and 19).

Groundwater temperature profiles for MLMS boreholes located along AVZ and Arco-Big Southern Butte VRZ (USGS 103, USGS 105, USGS 108, USGS 132, USGS 135, USGS 137A) were mostly dominated by convective heat transfer (fig. 1). With the exception of borehole USGS 132, MLMS temperature data fluctuate with a narrow range from 0.2 to 0.8 °C. Convective heat transfer is the result of interconnected fractures resulting from the vertical movement of groundwater as the aquifer thickens and as the transmissivity increases along the southern boundary of the INL. Borehole USGS 132 is located adjacent to the spreading areas and its temperature data could be influenced by groundwater mounding local to that area of aquifer.

Groundwater temperature profiles for MLMS boreholes located within the Big Lost Trough (USGS 131A, USGS 133, USGS 134, MIDDLE 2050A, MIDDLE 2051) were mostly dominated by conductive heat transfer and MLMS temperature data fluctuate within a more broad range (1.2–5.3 °C), than compared to southern boundary boreholes. Boreholes located within the Big Lost Trough were generally completed within a section of the ESRP aquifer where core and geophysical data (figs. 7–16 and 18) reveal high concentrations of fine grained sediment. Temperature trends in MLMS boreholes were similar to those reported in Fisher and Twining (2011) and Twining and Fisher (2012), and suggest groundwater temperature is stable over the period of record sampled.

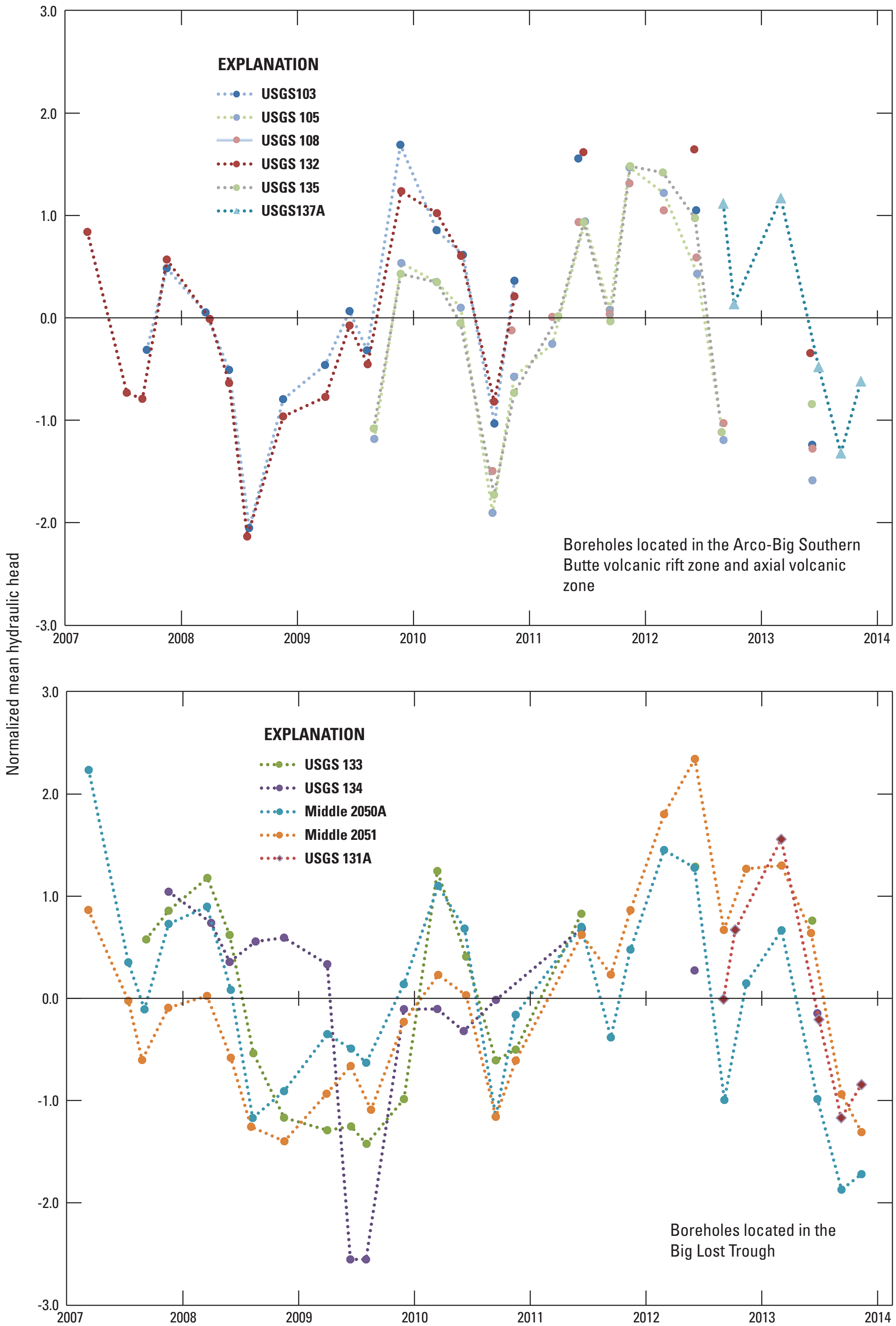

Figure 19. Quarterly values of the normalized mean hydraulic head at boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho, 2007–13.

Summary

During 2011–13, depth-discrete measurements of head and water temperature were collected from multilevel monitoring systems (MLMS) installed in 11 boreholes at the Idaho National Laboratory in cooperation with the U.S. Department of Energy. The boreholes are completed within the eastern Snake River Plain (ESRP) aquifer that generally consists of Quaternary basalt of the Snake River Group and sediment layers of varying thickness and composition. MLMSs have been installed to various depths that range from 818 to 1,427 feet below land surface (ft bls) and monitor zones that vary in thickness from 5.2 to 152.6 ft. Head and temperature measurements were recorded in 177 hydraulically isolated monitoring zones located from 448.0 to 1,377.6 ft bls. The MLMS provides a unique approach for collecting head and temperature data from discrete aquifer zones to better understand and characterize groundwater flow through fractured basalt and sediment media. Completion depths for MLMS boreholes range from 234 to 913 ft below the water table surface, where a typical open hole or screen monitoring well might interrogate 100 ft or less. Head, water temperature, and water chemistry information will assist ongoing efforts to better characterize the ESRP aquifer beneath the Idaho National Laboratory.

Head and temperature profiles reveal unique vertical patterns for examination of the aquifer's complex basalt and sediment stratigraphy, proximity to aquifer recharge and discharge, and groundwater flow. Hydrogeologic features contribute to some of the localized variability even though the general profile shape remained consistent between 2011 and 2013. Major inflections in the head profiles almost always coincided with low-permeability sediment layers and occasionally with thick sequences of dense basalt. However, the presence of a sediment layer or dense basalt layer was insufficient for identifying the location of a major head change within a borehole without knowing the true areal extent and relative transmissivity of the lithologic unit. Temperature profiles for boreholes completed within the Big Lost Trough indicate linear conductive trends; whereas, temperature profiles for boreholes completed within the axial volcanic zone (AVZ) and Arco-Big Southern Butte volcanic rift zone (VRZ) indicate mostly convective heat transfer.

Head and temperature change were examined for each of the 11 multilevel monitoring systems for the June or September 2012 measurement period. The vertical head gradients were defined for the major inflections in the head profiles and were as high as -2.9 ft/ft. Groundwater temperatures in all boreholes ranged from 10.8 to 16.3 °Celsius. Low vertical head gradients indicate potential vertical connectivity and flow, and large gradient inflections indicated zones of relatively lower vertical connectivity and the potential for vertical flow. Generally, zones that primarily are composed of fractured basalt displayed relatively small vertical head differences, inferring flow is dominantly horizontal. Large head differences were attributed to poor vertical connectivity between fracture units which are the result of sediment layering and (or) dense basalt.

Normalized mean head values were analyzed for all 11 multilevel monitoring wells for the period of record (2007–13). The mean head values suggest a moderately positive correlation among all boreholes and generally reflect regional fluctuations in water levels in response to seasonal climatic changes. However, the temporal trend is slightly different depending on the borehole location. Boreholes located within the AVZ and Arco-Big Southern Butte VRZ (USGS 103, USGS 105, USGS 108, USGS 132, USGS 135, USGS 137A) display a temporal correlation that is strongly positive. Boreholes located within the Big Lost Trough display some variations in temporal correlations that result from proximity recharge areas. During 2012, boreholes MIDDLE 2050A and MIDDLE 2051 showed head buildup within the upper zones when compared to the June 2010 profile event, which correlates to years that flow was reported for the BLR several months preceding the measurement period. With the exception of borehole USGS 134, temporal correlation between MLMS boreholes completed within the Big Lost Trough is generally positive. Temporal correlation for borehole USGS 134 shows the least agreement with other MLMS boreholes located within the Big Lost Trough; however, borehole USGS 134 is close to the mountain front where tributary valley subsurface inflow is suspected.

References Cited

Ackerman, D.J., 1991, Transmissivity of the Snake River Plain aquifer at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 91–4058 (DOE/ID22097), 35 p. [Also available at http://pubs.er.usgs.gov/publication/wri914058.]

Anderson, S.R., Ackerman, D.J., Liszewski, M.J., and Freiburger, R.M., 1996, Stratigraphic data for wells at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 96–248 (DOE/ID–22127), 27 p. and 1 diskette. [Also available at http://pubs.er.usgs.gov/publication/ofr96248.]

Anderson, S.R., Kuntz, M.A., and Davis, L.C., 1999, Geologic controls of hydraulic conductivity in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 99–4033 (DOE/ID–22155), 38 p. [Also available at http://pubs.er.usgs.gov/publication/wri994033.]

Bartholomay, R.C., Tucker, B.J., Ackerman, D.J., and Liszewski, M.J., 1997, Hydrologic conditions and distribution of selected radiochemical and chemical constituents in water, Snake River Plain aquifer, Idaho National Engineering Laboratory, Idaho, 1992 through 1995: U.S. Geological Survey Water-Resources Investigations Report 97-4086 (DOE/ID-22137), 57 p. [Also available at http://pubs.er.usgs.gov/publication/wri974086.]

Bartholomay, R.C., Tucker, B.J., Davis, L.C., and Greene, M.R., 2000, Hydrologic conditions and distribution of selected constituents in water, Snake River Plain aquifer, Idaho National Engineering and Environmental Laboratory, Idaho, 1996 through 1998: U.S. Geological Survey Water-Resources Investigations Report 2000–4192 (DOE/ID–22167), 52 p. [Also available at http://pubs.er.usgs.gov/publication/wri004192.]

Bartholomay, R.C., Hopkins, C.B, and Maimer, N.V., 2015, Chemical constituents in groundwater from multiple zones in the eastern Snake River Plain aquifer at the Idaho National Laboratory, Idaho, 2009–13: U.S. Geological Survey Scientific Investigations Report 2015–5002 (DOE/ID–22232), 110 p., http://dx.doi.org/10.3133/sir20155002.

Bartholomay, R.C., and Twining, B.V., 2010, Chemical constituents in groundwater from multiple zones in the eastern Snake River Plain aquifer at the Idaho National Laboratory, Idaho, 2005–08: U.S. Geological Survey Scientific Investigations Report 2010–5116, 82 p. [Also available at http://pubs.er.usgs.gov/publication/sir20105116.]

Blair, J.J., 2002, Sedimentology and stratigraphy of sediments of the Big Lost trough subsurface from selected coreholes at the Idaho National Engineering and Environmental Laboratory: Pocatello, Idaho, Idaho State University, master's thesis, 148p.

Busenberg, Eurybiades, Plummer, L.N., and Bartholomay, R.C., 2001, Estimated age and source of the young fraction of ground water at the Idaho National Engineering and Environmental Laboratory: U.S. Geological Survey Water-Resources Investigations Report 2001–4265 (DOE/ID–22177), 144 p. [Also available at http://pubs.er.usgs.gov/publication/wri014265.]

Cecil, L.D., Frape, S.K., Drimmie, R., Flatt, H., and Tucker, B.J., 1998, Evaluation of archived water samples using chlorine isotopic data, Idaho National Engineering and Environmental Laboratory, Idaho, 1966–93: U.S. Geological Survey Water-Resources Investigations Report 98–4008 (DOE/ID–22147), 27 p. [Also available at http://pubs.er.usgs.gov/publication/wri984008.]

Cecil, L.D., Welhan, J.A., Green, J.R., Frape, S.K., and Sudicky, E.R., 2000, Use of chlorine-36 to determine regional-scale aquifer dispersivity, eastern Snake River Plain aquifer, Idaho/USA: Nuclear Instruments and Methods in Physics Research, section B, v. 172, issue 1–4, p. 679–687.

Davis, L.C., Bartholomay, R.C., and Rattray, G.W., 2013, An update of hydrologic conditions and distribution of selected constituents in water, Snake River Plain aquifer and perched groundwater zones, Idaho National Laboratory, Idaho, emphasis 2009–11: U.S. Geological Survey Scientific Investigations Report 2013–5214 (DOE/ID–22226), 90 p.

Duke, C.L., Roback, R.C., Reimus, P.W., Bowman, R.S., McLing, T.L., Baker, K.E., and Hull, L.C., 2007, Elucidation of flow and transport processes in a variably saturated system of interlayered sediment and fractured rock using tracer tests: Vadose Zone Journal, v. 6, no. 4, p. 855–867.

Fisher, J.C., and Twining, B.V., 2011, Multilevel groundwater monitoring of hydraulic head and temperature in the eastern Snake River Plain aquifer, Idaho National Laboratory, Idaho, 2007–08: U.S. Geological Survey Scientific Investigations Report 2010–5253, 62, p. [Also available at http://pubs.er.usgs.gov/publication/sir20105253.]

Garabedian, S.P., 1986, Application of a parameter–estimation technique to modeling the regional aquifer underlying the eastern Snake River Plain, Idaho: U.S. Geological Survey Water-Supply Paper 2278, 60 p. [Also available at http://pubs.er.usgs.gov/publication/wsp2278.]

Geslin, J.K., Link, P.K., Riesterer, J.W., Kuntz, M.A., and Fanning, C.M., 2002, Pliocene and Quaternary stratigraphic architecture and drainage systems of the Big Lost Trough, northeastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colo., Geological Society of America Special Paper 353, p. 11–26.

Hughes, S.S., Smith, R.P., Hackett, W.R., and Anderson, S.R., 1999, Mafic volcanism and environmental geology of the eastern Snake River Plain, Idaho, *in* Hughes S.S., and Thackray, G.D., eds., Guidebook to the geology of eastern Idaho: Pocatello, Idaho, Idaho Museum of Natural History, p. 143–168.

Hughes, S.H., Wetmore, P.H., and Casper, J.L., 2002, Evolution of Quaternary tholeiitic basalt eruptive centers on the eastern Snake River Plain, Idaho, *in* Bonnichsen, B., White, C.M., and McCurry, M., eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Idaho Geological Survey Bulletin, v.30, p. 363–385.

Knutson, C.F., McCormick, K.A., Crocker, J.C., Glenn, M.A., and Fishel, M.L., 1992, 3D RWMC vadose zone modeling (including FY–89 to FY–90 basalt characterization results): E G and G Idaho, Inc., Report EGG–ERD–10246 [variously paged].

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

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

Mann, L.J., and Beasley, T.M., 1994, Iodine–129 in the Snake River Plain aquifer at and near the Idaho National Engineering Laboratory, Idaho, 1990–91: U.S. Geological Survey Water-Resources Investigations Report 94–4053 (DOE/ID–22115), 27 p. [Also available at http://pubs.er.usgs.gov/publication/wri944053].

McCutcheon, S.C., Martin, J.L., and Barnwell, T.O., Jr., 1993, Water quality, *in* Maidment, D.R., ed., Handbook of hydrology: New York, McGraw–Hill, chap. 11, p. 3–73.

Nimmo, J.R., Perkins, K.S., Rose, P.E., Rousseau, J.P., Orr, B.R., Twining, B.V., and Anderson, S.R., 2002, Kilometer–scale rapid transport of naphthalene sulfonate tracer in the unsaturated zone at the Idaho National Engineering and Environmental Laboratory: Vadose Zone Journal, v. 1, no. 1, p. 89–101.

R Development Core Team, 2014, R—A language and environment for statistical computing: Vienna, Austria, R Foundation for Statistical Computing, ISBN 3–900051v07–0, accessed October 7, 2014, at http://www.R-project.org.

Robertson, J.B., Schoen, Robert, and Barraclough, J.T., 1974, The influence of liquid waste disposal on the geochemistry of water at the National Reactor Testing Station, Idaho, 1952–1970: U.S. Geological Survey Open-File Report 73–238 (IDO–22053), 231 p. [Also available at http://pubs.er.usgs.gov/publication/ofr73238.]

Twining, B.V., and Fisher, J.C., 2012, Multilevel groundwater monitoring of hydraulic head and temperature in the eastern Snake River Plain aquifer, Idaho National Laboratory, 2009–2010: U.S. Geological Survey Investigations Report 2012-5259, 44 p., plus appendixes.

U.S. Geological Survey, 1985, National water summary, 1984—Hydrologic events, selected water–quality trends, and ground–water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p. [Also available at http://pubs.er.usgs.gov/publication/wsp2275.]

Welhan, J.A., Farabaugh, R.L., Merrick, M.J., and Anderson, S.R., 2007, Geostatistical modeling of sediment abundance in a heterogeneous basalt aquifer at the Idaho National Laboratory, Idaho: U.S. Geological Survey Scientific Investigations Report 2006–5316 (DOE/ID–22201), 32 p. [Also available at http://pubs.er.usgs.gov/publication/sir20065316.]

Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U. S. Geological Survey Professional Paper 1408-B, 32 p. [Also available at http://pubs.er.usgs.gov/publication/pp1408B.]

Appendixes

Appendix files are available for download at http://pubs.usgs.gov/sir/2015/5042.

Appendix A. Data Used to Calculate Pressure Probe Transducer Depths at Measurement Port Couplings, Boreholes USGS 131A and USGS 137A, Idaho National Laboratory, Idaho, 2011–13

Appendix B. Field Sheet used for Data Collection at Multilevel Monitoring Boreholes, Idaho National Laboratory, Idaho

Appendix C. Calibration Results for Fluid Pressure Sensor, a Component of the Sampling Probe Used in Boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134,USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho, 2011–13

Appendix D. Paired Port Statistics for Boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134,USGS 135, and USGS 137A, Idaho National Laboratory, Idaho, 2011–13

Appendix E. Barometric Pressure, Water Temperature, Fluid Pressure, and Hydraulic Head Data from Port Measurements for Boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho, 2011–13

Appendix F. Lithology logs for Multilevel Groundwater Monitoring Boreholes USGS 131A, USGS 137A, Idaho National Laboratory, Idaho, 2011–13

Appendix G. Vertical Hydraulic Head Gradient Data Between Adjacent Monitoring Zones for Boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho, June or September 2012

Appendix H. Quarterly Mean and Normalized Mean Hydraulic Head Values for Boreholes USGS 103, USGS 105, USGS 108, USGS 131A, USGS 132, USGS 133, USGS 134, USGS 135, USGS 137A, MIDDLE 2050A, and MIDDLE 2051, Idaho National Laboratory, Idaho, 2007–13

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma Publishing Service Center

For more information concerning the research in this report, contact the
Director, Idaho Water Science Center
U.S. Geological Survey
230 Collins Road
Boise, Idaho 83702
http://id.water.usgs.gov

USGS

Twining and Fisher—**Multilevel Groundwater Monitoring of Hydraulic Head and Temperature, Eastern Snake River Plain Aquifer, Idaho, 2011–13**—Scientific Investigations Report 2015–5042

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20155042