LA-UR-09-0679
February 2009
EP2009-0078

Completion Report for Regional Aquifer Well R-38, Revision 1

Los Alamos
NATIONAL LABORATORY
EST. 1943

Prepared by the Environmental Programs Directorate

LA-UR-09-0679
EP2009-0078

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EXECUTIVE SUMMARY

This well completion report describes the drilling, installation, development, and aquifer testing of Los Alamos National Laboratory regional aquifer well R-38, which is located in the north fork of Cañada del Buey within Technical Area 54 (TA-54) in Los Alamos County, New Mexico. The well was installed at the direction of the New Mexico Environment Department (NMED), and this report was written in accordance with the requirements in Section IV.A.3.e.iv of the March 1, 2005, Compliance Order on Consent. Well R-38 was drilled as a single-screen well in the regional aquifer to monitor groundwater quality in support of remedy selection for Material Disposal Area (MDA) L. Well R-38 also assesses the conceptual model for contaminant fate and transport from TA-54 and serves as a downgradient monitoring well for MDA L.

The R-38 borehole was drilled using dual-rotary and open-hole drilling. Fluid additives used during the drilling included potable water and foam. Foam-assisted drilling was used only in the vadose zone; no drilling-fluid additives other than small amounts of potable water added to the air were used within the regional aquifer. Additive-free drilling provides minimal impacts to the groundwater and aquifer materials. The R-38 borehole was successfully completed to total depth using casing-advance and open-hole drilling methods. A retractable 16-in. casing was advanced through the Bandelier Tuff and the Guaje Pumice Bed to the top of the Cerros del Rio basalt. A 15-in. open borehole was advanced with fluid-assisted air-rotary methods and downhole hammer into the Cerros del Rio basalt to a depth of 515 ft below ground surface (bgs). Then 12-in. casing was advanced with a 12.75-in. underreaming hammer bit to a depth of 758.5 ft bgs. Fluid-assisted air-rotary methods were utilized to complete the R-38 borehole to total depth of 914.7 ft bgs in an open hole. Well R-38 was completed with a screen near the top of the regional aquifer in the lower Puye Formation.

The well was completed in accordance with an NMED-approved well design. The well was thoroughly developed and all target water-quality parameters were achieved. A dedicated submersible pump sampling system was installed in the R-38 well, and groundwater sampling will be performed as part of the facility-wide groundwater-monitoring program.

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Acronyms and Abbreviations

μS/cm	microsiemens per centimeter
amsl	above mean sea level
bgs	below ground surface
DO	dissolved oxygen
EES-14	Earth and Environmental Sciences Group
EP	Environmental Programs
ICPMS	inductively coupled (argon) plasma mass spectrometry
ICPOES	inductively coupled (argon) plasma optical emission spectroscopy
ID	identification
I.D.	inside diameter
LANL	Los Alamos National Laboratory
mV	millivolt
NMED	New Mexico Environment Department
NTU	nephelometric turbidity unit
O.D.	outside diameter
ORP	oxygen-reduction potential
PVC	polyvinyl chloride
Qal	Quaternary alluvium

Qbo	Quaternary Otowi Member of the Bandelier Tuff
Qbog	Quaternary Guaje Pumice Bed of Otowi Member of the Bandelier Tuff
Qbt	Tshirege Member
Qct	Cerro Toledo interval
RPF	Records Processing Facility
SOP	standard operating procedure
TA	technical area
Tb 4	Tertiary Cerros del Rio basalt
TBD	to be determined
TD	total depth
TOC	total organic carbon
Tpf	Tertiary Puye Formation
WCSF	waste characterization strategy form

1.0 INTRODUCTION

This completion report summarizes the site preparation, drilling, and well construction for well R-38. An addendum to this report will be submitted following the completion of aquifer testing, dedicated sampling system installation, surface completion installation, and geodetic surveying. The report and addendum are written in accordance with the requirements in Section IV.A.3.e.iv of the March 1, 2005, Compliance Order on Consent (the Consent Order). Well R-38 was drilled and constructed from October 23, 2008, to December 8, 2008, at Los Alamos National Laboratory (LANL or the Laboratory) for the Environmental Programs (EP) Directorate Water Stewardship Project. Aquifer testing was conducted between December 13 and December 17, 2008, and the results are presented in this revised completion report.

The R-38 project site is in the north fork of Cañada del Buey within Technical Area 54 (TA-54) in Los Alamos County, New Mexico (Figure 1.0-1). The purposes of the R-38 monitoring well are to monitor potential releases of contaminants from Material Disposal Area L to groundwater, assess the conceptual model for contaminant fate and transport from TA-54, monitor water levels within the regional aquifer, and measure pumping effects from municipal production wells in the vicinity.

The primary objective of the drilling activities was to drill and install a single-screened regional aquifer monitoring well in the upper portion of the regional aquifer. Secondary objectives were to collect drill-cutting samples, conduct borehole geophysical logging, and investigate potential perched groundwater zones.

The R-38 borehole was successfully drilled to a total depth (TD) of 914.7 ft below ground surface (bgs). A monitoring well was installed with a screened interval between 821.2 and 831.2 ft bgs. The depth to water in the open borehole was 810.2 ft bgs. Depth to water in the well following well development was 810.77 ft bgs on December 10, 2008. Cuttings samples were collected at 5-ft intervals in the borehole from ground surface to TD. Postinstallation activities included well development, aquifer testing, surface completion, dedicated sampling system installation, and geodetic surveying. Future activities include site restoration and waste management.

The information presented in this report was compiled from field reports and daily activity summaries. Records, including field reports, field logs, and survey information, will be on file at the Records Processing Facility (RPF). This report contains brief descriptions of activities and supporting figures, tables, and appendixes completed to date associated with the R-38 project.

2.0 PRELIMINARY ACTIVITIES

Preliminary activities included preparing administrative planning documents and preparing the drill site and drill pad. All preparatory activities were completed in accordance with Laboratory policies and procedures.

2.1 Administrative Preparation

The following documents guided the implementation of the scope of work for well R-38: “Drilling Plan for Regional Aquifer Well R-38” (TerranearPMC 2008, 103941); “Integrated Work Document for Regional and Intermediate Aquifer Well Drilling” (LANL 2007, 100972); “Storm Water Pollution Prevention Plan Addendum” (LANL 2006, 092600); and “Waste Characterization Strategy Form for the R-38, R-41, R-44, R-45, and R-46 Regional Groundwater Well Installation and Corehole Drilling” (LANL 2008, 103916).

2.2 Site Preparation

Site preparation was performed between October 21 and October 22, 2008, and included mobilizing the drill rig, air compressors, trailers, and support vehicles to the drill site and staging alternative drilling tools and construction materials at the Pajarito Road lay down yard.

Office supply trailers, generators, and general field equipment were moved on-site after mobilization of drilling equipment. Potable water was obtained from the Puye Road fire hydrant and a fire hydrant near the Los Alamos County landfill on East Jemez Road. Safety barriers and signs were installed around the borehole-cuttings containment pit and along the perimeter of the work area.

3.0 DRILLING ACTIVITIES

This section describes the drilling strategy and provides a chronological summary of field activities conducted at monitoring well R-38.

3.1 Drilling Approach

The selection of drilling equipment and drill-casing sizes for R-38 was designed to ensure successful completion of the borehole. This strategy retained the ability to case off perched groundwater and reach TD with sufficiently sized casing to meet the required 2-in. minimum annular thickness of the filter pack. Further, it was anticipated that if perched groundwater was encountered at R-38, the perched zone would be isolated and sealed off either with casing or by cementing to avoid commingling perched groundwater with the regional aquifer.

Dual-rotary air-drilling techniques and a Foremost DR-24HD drill rig were employed to drill the R-38 borehole. Dual-rotary drilling has the advantage of simultaneously advancing and casing the borehole. The Foremost DR-24HD drill rig was equipped with conventional direct circulation drilling rods, tricone bits, downhole hammer bits, one deck-mounted 900 ft^3/min air compressor, and general drilling equipment. On-site equipment included two Wagner/Sullair 1150 ft^3/min trailer-mounted air compressors. Two sizes of flush-welded mild carbon-steel casing (16-in. and 12-in.) were used for the R-38 project. The 16-in. casing was used for drilling from ground surface to the top of the Cerros del Rio basalt. The 12-in. casing was used when unstable conditions were encountered within the basalt. When stable conditions resumed, open-hole drilling methods were utilized and continued to TD in the lower Puye Formation.

Drilling fluids, other than air, used in the vadose zone included municipal water and a mixture of municipal water with Baroid AQF-2 foaming agent. The fluids cool the bit and help lift cuttings from the borehole. A cumulative total of drilling fluids were introduced into the borehole; those that recovered are recorded and presented in Table 3.1-1. No additives other than municipal water were used for drilling within the regional aquifer.

3.2 Chronological Drilling Activities

Drilling equipment and supplies were mobilized to the site from October 21 to October 22, 2008. On October 23, 2008, the R-38 borehole was initiated with dual-rotary methods using 16-in. casing and a 15-in. conventional hammer bit. On October 25, 2008, the 16-in. casing was advanced through the alluvium, the Tshirege Member of the Bandelier Tuff (unit 1g), the Cerro Toledo interval, the Otowi Member of the Bandelier Tuff, and upper Puye Formation; the casing was landed at 259.1 ft bgs, approximately 2 ft into the top of the Cerros del Rio basalt. Drilling resumed below the top of the Cerros del Rio basalt using open-hole drilling methods with the 15-in. hammer bit.

During October 25–26, 2008, drilling proceeded in the upper part of the Cerros del Rio basalt to a depth of 493 ft bgs. Because of binding and poor circulation, the decision was made to seal the basalt with Portland cement. On October 27, 2008, 17 yd^3 of Portland cement and sand was installed in the borehole. The top of cured cement was measured at 243 ft bgs. Early on the morning of October 28, 2008, open-hole drilling with a 15-in. hammer bit resumed. Cuttings from the cemented interval were redirected into on-site rolloff bins rather than into the cuttings pit. After reaching 515 ft bgs on October 29, 2008, the borehole again became unstable. A Laboratory video log revealed cement chunks caked to the borehole wall. That day, the cemented open-hole section was reamed with the 15-in. hammer bit.

To address the unstable basalts, drilling was changed to casing advance with a 12-in. casing. Before hanging and welding the 12-in. casing string in the hole, the 16-in. casing drive shoe was cut off at 258.0 ft bgs on October 30, 2008. On October 31, 2008, drilling resumed with 12-in. casing advance utilizing a 12.75-in. underreaming hammer bit. Drilling with this method progressed slowly through variable zones of dense competent basalt, unstable basaltic cinders, and sediment intervals to a casing depth of 758.5 ft bgs that was reached on November 4, 2008. Several possible minor water-bearing zones were investigated and sampled. After circulating the borehole dry, the water did not reappear. Therefore, the water was likely introduced and not groundwater.

On November 5, 2008, open-hole drilling began again with a 12-in. hammer bit when more stable conditions were encountered, still within the Cerros del Rio basalt. Multiple water samples were collected during the next 24 h until the borehole reached a final TD of 914.7 ft bgs. The Cerros del Rio basalts transitioned into Puye sediments from 820 to 834 ft bgs. The borehole reached TD in saturated, unstable, lower Puye Formation gravels on November 6, 2008. The 12-in. casing drive shoe was cut off at 738.0 ft bgs on November 7, 2008.

On the night of November 7, 2008, a Schlumberger logging unit was mobilized for geophysical logging, which concluded in the morning of the next day. A TD of 893.4 ft was measured on November 8, 2008, indicating some sloughing and loss of open borehole. The drill rig was removed from the well site on November 8, 2008.

Over the course of drilling, the R-38 borehole field crews worked two 12-h shifts per day, 7 d/wk. Operations sustained no weather delays throughout the duration of drilling and only minor mechanical delays affected progress.

4.0 SAMPLING ACTIVITIES

This section describes the cuttings and groundwater-sampling activities at well R-38. All sampling activities were conducted in accordance with all applicable Laboratory procedures.

4.1 Cuttings Sampling

Cuttings samples were collected from the R-38 borehole at 5-ft intervals from ground surface to the TD of 914.7 ft bgs. At each interval, approximately 500 mL of bulk cuttings were collected from the discharge hose, sealed in resealable plastic bags, labeled, and archived in core boxes. Sieved fractions (>#10 and >#35 mesh) were processed from the bulk sample and placed in chip trays along with unsieved (whole rock) cuttings. Radiation control technicians screened all cuttings before they were removed from the site.

Drilling and sample collection methods used at R-38 did not retain a majority of the fine fraction (silt and clay) of the drill cuttings, and much of the fine material throughout the borehole stratigraphy was lost. This effect was particularly evident with increasing depth and in the unconsolidated sedimentary units below the Cerros del Rio basalt. The foaming agent helped to retain the fines and acquire more representative samples in the intervals where it was used. The high volume of compressed air required for circulation made catching samples difficult because samples were manually collected with a wire mesh basket directly from the discharge hose, and discharge velocities forced the fine fraction of sample through the mesh. Recovery of the coarser fraction of the cuttings samples was excellent in nearly 100% of the borehole. The borehole log for R-38 is presented in Appendix A.

4.2 Water Sampling

Groundwater-screening samples were collected from the drilling discharge hose in the R-38 borehole. The driller stopped water circulation (if injecting water) and circulated air to clean out the borehole. As the discharge cleared, a water sample was collected directly from the discharge hose.

Regional groundwater samples were collected at regular intervals (approximately one sample every 2 h) during well development and aquifer testing (approximately one sample every 4 h). The groundwater samples were collected from the surface discharge port on the submersible development pump riser pipe and submitted for analyses.

All groundwater samples were submitted to the Laboratory's Earth and Environmental Sciences groundwater chemistry laboratory. The filtered samples were analyzed for cations, anions, perchlorate, and metals. Unfiltered samples were also analyzed for total organic carbon (TOC). Sampling documentation and containers were provided by the Laboratory and were processed through the Laboratory's Sample Management Office. Groundwater analytical results and details of groundwater chemistry at R-38 are presented in Appendix B. Table 4.2-1 presents a summary of all groundwater samples collected during drilling, well development, and pump testing activities.

Ten to 60 d following well development, groundwater characterization samples will be collected from the completed well in accordance with the Consent Order. The samples will be analyzed for the full suite of constituents, including radioactive elements; metals/cations; general inorganic chemicals; volatile and semivolatile organic compounds; and stable isotopes of hydrogen, nitrogen, and oxygen. These groundwater analytical results will be reported in the annual update to the "Interim Facility-Wide Groundwater Monitoring Plan."

5.0 GEOLOGY AND HYDROGEOLOGY

A brief description of the geologic and hydrogeologic features encountered at R-38 is presented below. The Laboratory's geology task leader and site geologists examined cuttings and geophysical logs to determine geologic contacts and hydrogeologic conditions. Drilling observations, drill cuttings, video logging, water-level measurements, and geophysical logs were used to characterize groundwater occurrences encountered at R-38.

5.1 Stratigraphy

The stratigraphy for the R-38 borehole is presented below in order of youngest to oldest geologic units. Lithologic descriptions are based on cuttings samples collected from the discharge hose. Cuttings and borehole geophysical logs were used to identify geologic contacts. Figure 5.1-1 illustrates the stratigraphy at R-38. A detailed lithologic log is presented in Appendix A.

Quaternary Alluvium, Qal (0–52 ft bgs)

Quaternary alluvium consisting of unconsolidated tuffaceous silty sand to sandy silt with volcanic pebbles and gravels was encountered from 0 to 52 ft bgs. No evidence of alluvial groundwater was observed.

Unit 1g, Tshirege Member of the Bandelier Tuff, Qbt (52–136 ft bgs)

Unit 1g of the Tshirege Member of the Bandelier Tuff occurs from 52 to 135 ft bgs. Unit 1g is a poorly welded ash-flow tuff that is pumiceous, lithic-poor, locally crystal-rich, and generally has abundant ash matrix. Characteristics of unit 1g are white, fibrous, glassy pumice lapilli, locally minor volcanic lithic inclusions (predominantly dacites, up to 15 mm in diameter), and abundant quartz and sanidine crystals.

Cerro Toledo Interval, Qct (136–156 ft bgs)

The Cerro Toledo interval, a thin layer of poorly consolidated volcaniclastic sediments that occurs stratigraphically between the Tshirege and Otowi Members of the Bandelier Tuff, is present from 136 to 156 ft bgs. Locally, this unit consists of silty to clayey sands and gravels made up of detrital dacites and minor rhyolite (clasts up to 15 mm in diameter), white vitric pumice fragments, abundant quartz and sanidine crystal grains, and volcanic ash.

Otowi Member of the Bandelier Tuff, Qbo (156–230 ft bgs)

The Otowi Member of the Bandelier Tuff is present from 156 to 230 ft bgs. The Otowi Member is a poorly welded, pumiceous, locally lithic-rich, ash-flow tuff. Abundant pumice lapilli are white to pale orange, glassy, and quartz- and sanidine-phyric. Locally abundant volcanic lithic fragments or xenoliths (up to 13 mm in diameter) are commonly subangular to subrounded and of intermediate volcanic composition, including hornblende- and biotite-dacites and rhyodacites.

Guaje Pumice Bed of the Otowi Member of the Bandelier Tuff, Qbog (230–240 ft bgs)

The Guaje Pumice Bed occurs from 230 to 240 ft bgs. The pumice bed contains abundant (98%–100% by volume) pristine-appearing vitric, phenocryst-poor pumice fragments, and lapilli with minor amounts of volcanic lithics, quartz and sanidine phenocrysts, and fine ash.

Upper Puye Formation, Tpf (240–250 ft bgs)

A thin layer of Puye Formation fanglomeratic sediments is recognized from 240 to 250 ft bgs. Detrital constituents consist of abundant white vitric pumices, pebbles and grains of diverse volcanic lithologies (andesite, dacite, and rhyodacite), plus quartz and sanidine crystals. Lost circulation during drilling resulted in poor sample capture in this interval.

Basalt Lava/Volcaniclastic Sediments (250–255 ft bgs)

At approximately 250 ft bgs, the upper Puye Formation transitions from brown volcaniclastic sediments with pumice, intermediate volcanics, and quartz and sanidine crystals to a predominance of basalt fragments. The basalt fragments appear to be derived from the underlying Cerros del Rio basalt lava.

Cerros del Rio Basalt, Tb 4 (255–834 ft bgs)

The Cerros del Rio basalt, encountered from 255 to 834 ft bgs, is locally a complex package of volcanic and intercalated sedimentary layers that includes discrete lava flows; basaltic cinder deposits; basaltic sandstone/tuffs; and both coarse- and fine-grained clastic sediments with basaltic, mixed volcanic, and Precambrian quartzo-feldspathic constituents. An upper succession of flows and interlayered cinder deposits from 255 to 470 ft bgs includes olivine- and clinopyroxene-basalt lavas. The section from 470 to 760 ft bgs is represented by a complex sequence of thin basalt flows, hydromagmatic basaltic tuffs containing quartzo-feldspathic detritus, basaltic scoria and cinder deposits, and locally siliceous clay-rich beds of possible lacustrine origin. The lowermost basalt flow and 5-ft-thick basal breccia occurs from 760 to 815 ft bgs. A basalt-rich mixed transitional zone occurs from approximately 820 to 834 ft bgs.

Lower Puye Formation, Tpf (834–915 ft bgs)

The lower section of Puye Formation sediments encountered from 834 to 915 ft bgs consists of poorly sorted basalt-rich gravels and siltstones and volcaniclastic sediments with predominantly dacitic detritus and quartz-bearing (i.e., well-rounded Precambrian quartzite and granitic constituents) volcaniclastic gravels that likely represent axial river deposits. These sediments are made up of gray, grayish brown, and pinkish tan coarse- to fine-gravels and sandstones with little apparent silt or clay.

5.2 Groundwater

Groundwater was first encountered at R-38 during drilling at approximately 758.5 ft bgs in the lower Cerros del Rio basalt on November 5, 2008. Groundwater was not encountered in the basalt at later dates; this water may have been introduced during the drilling activities. After the well was drilled to final depth of 914.7 ft bgs, the static water level was measured at approximately 810.1 ft bgs in the open hole. Following well development, depth to regional groundwater in R-38 was 810.77 ft bgs in the lower Puye Formation on December 10, 2008. A discussion of groundwater chemistry is presented in Appendix B. Aquifer testing data and interpretation for R-38 are presented in Appendix C.

6.0 BOREHOLE LOGGING

Several video logs and a limited suite of geophysical logs were collected during the R-38 drilling project using Laboratory-owned equipment. A summary of video and geophysical logging runs is presented in Table 6.0-1.

6.1 Video Logging

Video logging of the R-38 borehole occurred on multiple occasions and aided both drilling and well construction activities (Table 6.0-1). On October 29, 2008, the Laboratory video tool was run to inspect borehole conditions after cementing the Cerros del Rio basalt. It revealed remnants of cement caking on the borehole wall, and the hole was reamed.

During well construction, the Laboratory video camera was run on November 17, 2008, to locate the top and condition of a section of 2-in. tremie pipe that was separated and lost from the bottom of the tremie pipe string. Unfortunately, because of tight annular space, the tool could not get past 430 ft bgs and was unsuccessful. As part of the ensuing fishing operations, Jet West Geophysical ran a video camera on three separate occasions (November 19, 21, and 22, 2008) for the same purpose. The last run was inside a 3-in. conductor pipe and guided an overshot tool to retrieve the lost tremie pipe. Selected video logs from the borehole are presented on a digital video disc as part of Appendix D included with this document.

6.2 Geophysical Logging

A suite of Schlumberger geophysical logs was run in both the open-hole and cased section of the R-38 borehole on November 8, 2008. At the time of logging, the terminations of the two casing strings in the borehole were located at the following depths: 16-in. casing at 259.1 ft bgs and 12-in. casing at 758.5 ft bgs. The geophysical suite included Array Induction Imager, Natural Gamma Ray Spectroscopy, Accelerator Porosity, Formation MicroImager, magnetic resonance, and combined gamma ray and caliper tools (Table 6.0-1). Interpretation and details of the logging are presented on CD in the Geophysical Logging Report as part of Appendix E.

7.0 WELL INSTALLATION

R-38 well casing and annular fill were installed between November 15, 2008, and December 7, 2008.

7.1 Well Design

The R-38 well was designed in accordance with the Consent Order. NMED approved the well design before installation. The well was designed with a single screened interval to monitor groundwater quality in the lower Puye Formation sediments within the uppermost productive zone of the regional aquifer.

7.2 Well Construction R-38

The R-38 monitoring well was constructed of 5.0-in.-inside diameter (I.D.)/5.56-in.-outside diameter (O.D.) type A304 stainless-steel unthreaded casing fabricated to American Society for Testing and Materials A312 standards. Welding with compatible stainless-steel welding rods was used to join all individual casing and screen sections. The screen section utilized had a 10-ft length of 5.0-in.-I.D. rod-based 0.020-in. wire-wrapped well screen. Both casing and screen were steam-cleaned and pressure-cleaned on-site before installation. Both 2-in. and 3-in.-I.D. steel threaded/coupled tremie pipe strings were used to deliver backfill and annular fill materials during well construction.

A single screened interval was chosen for the R-38 well design. The resulting nominal 10-ft long screened interval had the top of the screen set at 821.2 ft bgs, and a 21.2-ft stainless-steel sump was placed below the well screen. Four stainless-steel centralizers were welded to the well casing approximately 1.7 ft above and below the screen. A Semco work-over rig was used for well construction and development activities—a Smeal rig was also used additionally for fishing purposes. Figure 7.2-1 presents an as-built schematic showing construction details for the completed well.

The well casing was welded as it was installed in the borehole, with particular care taken to avoid welding slag falling into the borehole. After landing the casing, the process of installing annular backfill materials started. The filter pack, fine sand collar, and associated bentonite seals were placed via tremie pipe. When the annular fill reached the bottom of the 12-in. casing at 758.4 ft bgs, the backfilling activity had two components—installing materials and retracting the drill casing—in addition to raising the tremie pipe. As each section of drill casing was cut off the string, it was picked up and laid down. During this part of the process, the well casing was hung on a wireline in the borehole, and the drill casing was supported by a ring and slips. Short lengths of 12-in. (20.5-ft casing and shoe) and 16-in. (1.1-ft casing and shoe) drill casing remained in the borehole. The 12-in. casing was buried in bentonite, and the 16-in. casing was set in cement to avoid unwanted impacts in the future.

Formation slough backfill occurred from 914.7 to 889.6 ft bgs. Backfill in the form of 10/20 sand was placed above the slough from 889.6 to 846.4 ft bgs. The volume of sand used for the sand backfill (164.9 ft^3) was five times greater than calculated because of apparent borehole washouts, as noted by the Schlumberger caliper log. The bentonite seal was placed from 835.2 to 846.4 ft bgs. The filter pack of 10/20 silica sand was then placed across the screened interval from 816.6 to 835.2 ft bgs. After installation of the filter pack, the work-over rig was used to surge the screened interval with a surge block to promote settling and compaction of the filter pack. A fine-grained transition sand collar of 20/40 silica sand was placed above the filter pack from 812.5 to 816.6 ft bgs. The well's upper bentonite seal then capped the transition sand collar and was installed from 321 to 812.5 ft bgs. A surface seal composed of a mix of 97% Portland cement and 3% bentonite was installed from 3 to 321 ft bgs. Figure 7.2-1 depicts depths and volumes used in each interval. Table 7.2-1 details volumes of materials used during well construction.

Overall, well construction proceeded relatively smoothly from November 11, 2008, to December 7, 2008, and was briefly interrupted when the lower four sections of the tremie pipe parted and dropped in the borehole on November 17, 2008. The tremie was recovered several days later on November 23, 2008, when video wireline equipment was used to guide a 2-in. grapel run inside a 3-in. conductor pipe. Well construction progressed to completion on December 7, 2008, without incident.

8.0 POSTINSTALLATION ACTIVITIES

Following well installation, well development began on December 8, 2008, and was finished on December 10, 2008. An aquifer test consisting of several short-duration pumping tests, a 24-h constant rate pumping test, and two 24-h background data collection periods will be performed. A dedicated submersible pump was installed and the wellhead and surface pad were constructed. A geodetic survey of the wellhead was performed. Site restoration activities will be completed following final disposition of contained drill cuttings and groundwater in accordance with the NMED-approved waste-decision trees and regulatory requirements.

8.1 Well Development

Well development was conducted between December 8, 2008, and December 10, 2008. Initially, the screened interval was swabbed and bailed to remove suspended solids in the well and formation fines in the filter pack. Bailing and swabbing methods were used until returned water was clear, and then a submersible pump was utilized to complete development. The swabbing tool was a 4.75-in.-O.D. 1-in.-thick nylon disc attached to a steel rod. The swabbing tool was lowered by wireline and drawn repeatedly across the screened interval. After bailing and swabbing, a 5-hp, 4-in.-Berkeley submersible pump was lowered into the well for the final stage of well development.

During the pumping stage of well development, turbidity, temperature, pH, dissolved oxygen (DO), oxygen-reduction potential (ORP), and specific conductance parameters were collected. In addition, water samples for total organic carbon (TOC) analysis were collected. The required values for TOC and turbidity by the end of well development are less than 2.0 ppm and less than 5 nephelometric turbidity units (NTUs), respectively. The turbidity measurement at the end of well development was 0.4 NTU.

Approximately 10,600 gal. of groundwater was purged during development activities. Discussion of analytical results is presented in Appendix B.

8.1.1 Field Parameters

Field parameters, including pH, temperature, DO, ORP, specific conductance, and turbidity, were measured at regular time intervals; results are provided in Appendix B. Field parameters were measured at well R-38 by collecting aliquots of groundwater from the discharge pipe without the use of a flow-through cell, allowing the samples to be exposed to the atmosphere. This condition probably resulted in a slight variation of field parameters during well development and during the pumping test, most notably, temperature, pH, and DO. Measurements of pH and temperature varied from 7.75 to 8.15 and from 17.71°C to 19.59°C, respectively, at well R-38. Several of the low temperature measurements for groundwater samples were probably influenced by land surface atmosphere conditions during sampling. Concentrations of DO varied from 5.36 to 7.19 mg/L in the well. ORP varied from 113 to 190 millivolts (mV). Regional aquifer groundwater is relatively oxidizing at well R-38, based on DO and ORP measurements, with most of the ORP readings greater than +150 mV. Specific conductance ranged from 83 to 181 microsiemens per centimeter (μS/cm). Turbidity was measured for the majority of sampling, and values ranged from 0.1 to 53.4 NTUs for the nonfiltered groundwater samples collected.

8.2 Aquifer Testing

Aquifer pumping tests were conducted at R-38 between December 13 and December 17, 2008. Several short-duration tests with short-duration recovery periods were performed on the first day of testing followed by a 40-h background data collection period. A 24-h pumping test followed by a 24-h recovery period completed the testing. The same 5-hp Grundfos pump used during well development was used to perform the aquifer tests. The results of the R-38 aquifer test are presented in Appendix C.

8.3 Dedicated Sampling System Installation

A dedicated 3-hp, 4-in.-O.D. environmentally retrofitted Grundfos submersible pump and an In-Situ Level Troll 500 transducer were installed in R-38 on January 12, 2009. Pump riser pipe consisted of threaded and coupled 1-in.-diameter stainless steel. Two 1-in.-diameter polyvinyl chloride (PVC) tubes were installed and banded to the pump riser. One tube is to be used for the dedicated pressure transducer and the other for manual water-level measurements. The tubes are 1.0-in.-I.D. flush-threaded schedule 80 PVC pipe. Each PVC tube has a 6-in. long 0.010-in. screen-slot interval at the bottom of the tube. Postinstallation construction and sampling system component installation details for R-38 are presented in Figure 8.3-1a. Figure 8.3-1b presents technical notes for R-38.

8.4 Wellhead Completion

A reinforced concrete surface pad, 10 ft × 10 ft × 6 in. thick, was installed at the R-38 well head on February 4, 2009. The pad will provide long-term structural integrity for the well. A brass survey monument imprinted with well identification information was placed in the northwest corner of the pad. A 10-in.-I.D. steel protective casing with a locking lid was installed around the stainless-steel well riser. A weep hole was installed to prevent water buildup inside the protective casing. The concrete pad is slightly elevated above the ground surface to promote runoff. A total of four bollards, painted yellow for visibility, were set at the outside edges of the pad to protect the well from traffic. All of the bollards are designed for easy removal to allow access to the well.

8.5 Geodetic Survey

A New Mexico licensed professional land surveyor conducted a geodetic survey on February 10, 2009 (Table 8.5-1). The survey data collected conforms to Laboratory Information Architecture project standards IA-CB02, “GIS Horizontal Spatial Reference System,” and IA-D802, “Geospatial Positioning Accuracy Standard for A/E/C and Facility Management.” All coordinates are expressed as New Mexico State Plane Coordinate System Central Zone (NAD 83); elevation is expressed in feet above mean sea level (amsl) using the National Geodetic Vertical Datum of 1929. Survey points include ground-surface elevation near the concrete pad, the top of the brass pin in the concrete pad, the top of the well casing, and the top of the protective casing.

8.6 Waste Management and Site Restoration

Waste generated from the R-38 project includes contact waste, decontamination fluids, petroleum contaminated soil, drill cuttings, discharged drilling water, cement slurry, and purged groundwater. Waste characterization samples of drill cuttings, purge water, and cement slurry will be collected. A summary of the waste samples collected for the R-38 well to date is presented in Table 8.6-1.

Fluids, cuttings, cement slurry, and contact waste produced during drilling and development were containerized and sampled in accordance with “Waste Characterization Strategy Form for the R-38, R-41, R-44, R-45, and R-46 Regional Groundwater Well Installation and Corehole Drilling” (LANL 2008, 103916).

Fluids produced during drilling and well development are expected to be land-applied after a review of associated analytical results per the waste characterization strategy form (WCSF) and the EP-Directorate Standard Operating Procedure (SOP) 010.0, Land Application of Groundwater. If it is determined that drilling fluids are nonhazardous but cannot meet the criterion for land application, the water will be evaluated for treatment and disposal at one of the Laboratory’s six wastewater treatment facilities. If analytical data indicate that the drilling fluids are hazardous/nonradioactive or mixed low-level waste, the waste will be disposed of at an authorized facility.

Cuttings produced during drilling are anticipated to be land-applied after a review of associated analytical results per the WCSF and ENV-RCRA SOP-011.0, Land Application of Drill Cuttings. If the drill cuttings do not meet the criterion for land application, they will be removed from the pit and disposed of at an authorized facility. The cement slurry waste stream will be managed as industrial nonhazardous waste pending analytical review. Disposal of this concrete slurry will take place at an authorized disposal facility. Characterization of contact waste will be based upon acceptable knowledge, pending analyses of the waste samples collected from the drill cuttings, purge water, and cement slurry.

Site restoration activities included removing water from the cuttings containment pit, removing the polyethylene liner, removing the containment area berms, and backfilling and regrading the containment area. Cuttings will be managed in accordance with SOP-011.0, referenced above. The Laboratory will restore the site.

9.0 DEVIATIONS FROM PLANNED ACTIVITIES

Drilling, sampling, and well construction at R-38 were performed as specified in the “Final Drilling Plan for Regional Aquifer Well R-38” (TerranearPMC 2008, 103941).

9.1 NMED-Approved Modifications to the Work Plan

Drilling, sampling, and well construction at R-38 were performed as specified in the “Drilling Work Plan for Regional and Intermediate Wells at Technical Area 54” (LANL 2007, 099662).

10.0 ACKNOWLEDGMENTS

Pat Longmire wrote Appendix B, Groundwater Analytical Results.

Boart Longyear drilled the R-38 borehole and installed the well.

Jet West Geophysical ran downhole video equipment in support of fishing the lost tremie pipe.

Schlumberger Wireline Services performed the final geophysical logging of the borehole.

Right Bit Services and Equipment Repair welded the stainless well screen and casing.

TerranearPMC provided oversight on all preparatory and field-related activities.

11.0 REFERENCES

The following list includes all documents cited in this report. Parenthetical information following each reference provides the author(s), publication date, and ER ID number. This information is also included in text citations. ER ID numbers are assigned by the Environmental Programs Directorate's RPF and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

LANL (Los Alamos National Laboratory), March 2006. "Storm Water Pollution Prevention Plan for SWMUs and AOCs (Sites) and Storm Water Monitoring Plan," Los Alamos National Laboratory document LA-UR-06-1840, Los Alamos, New Mexico. (LANL 2006, 092600)

LANL (Los Alamos National Laboratory), October 4, 2007. "Integrated Work Document for Regional and Intermediate Aquifer Well Drilling (Mobilization, Site Preparation and Setup Stages)," Los Alamos National Laboratory, Los Alamos, New Mexico. (LANL 2007, 100972)

LANL (Los Alamos National Laboratory), November 2007. "Drilling Work Plan for Regional and Intermediate Wells at Technical Area 54," Los Alamos National Laboratory document LA-UR-07-7578, Los Alamos, New Mexico. (LANL 2007, 099662)

LANL (Los Alamos National Laboratory), October 2008. "Waste Characterization Strategy Form for the R-38, R-41, R-44, R-45, and R-46 Regional Groundwater Well Installation and Corehole Drilling," Los Alamos, New Mexico. (LANL 2008, 103916)

TerranearPMC, October 2008. "Final Drilling Plan for Regional Aquifer Well R-38," plan prepared for Los Alamos National Laboratory, Los Alamos, New Mexico. (TerranearPMC 2008, 103941)

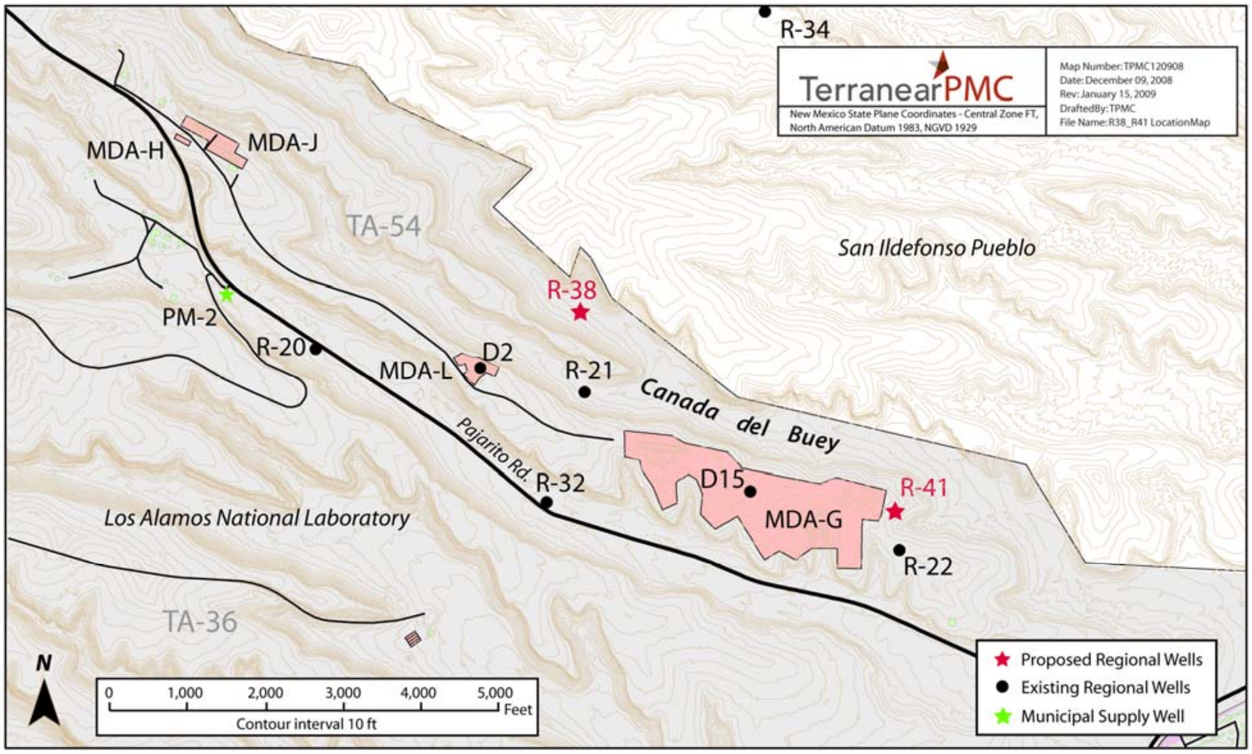

Figure 1.0-1 Regional aquifer well R-38

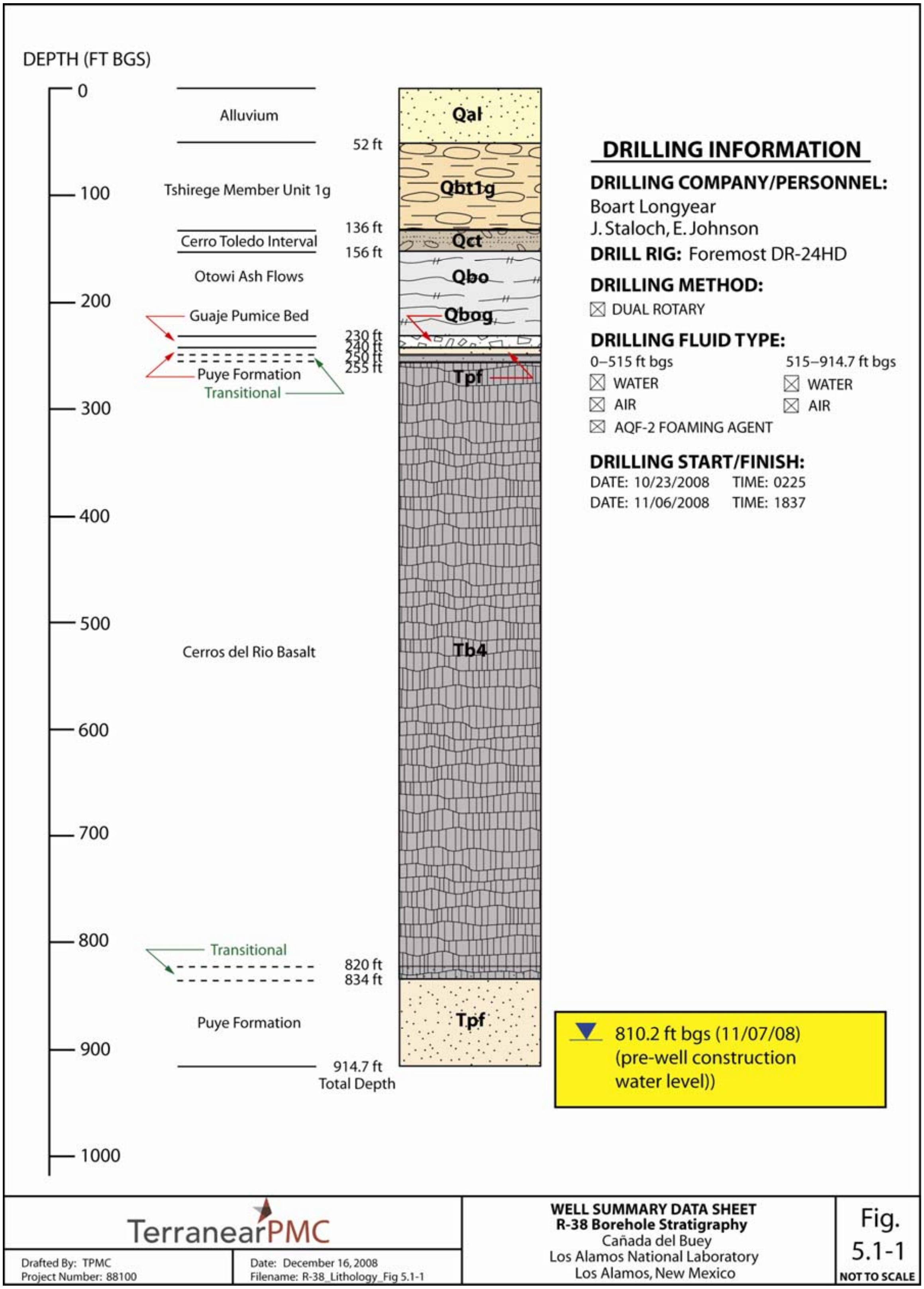

Figure 5.1-1 R-38 borehole stratigraphy

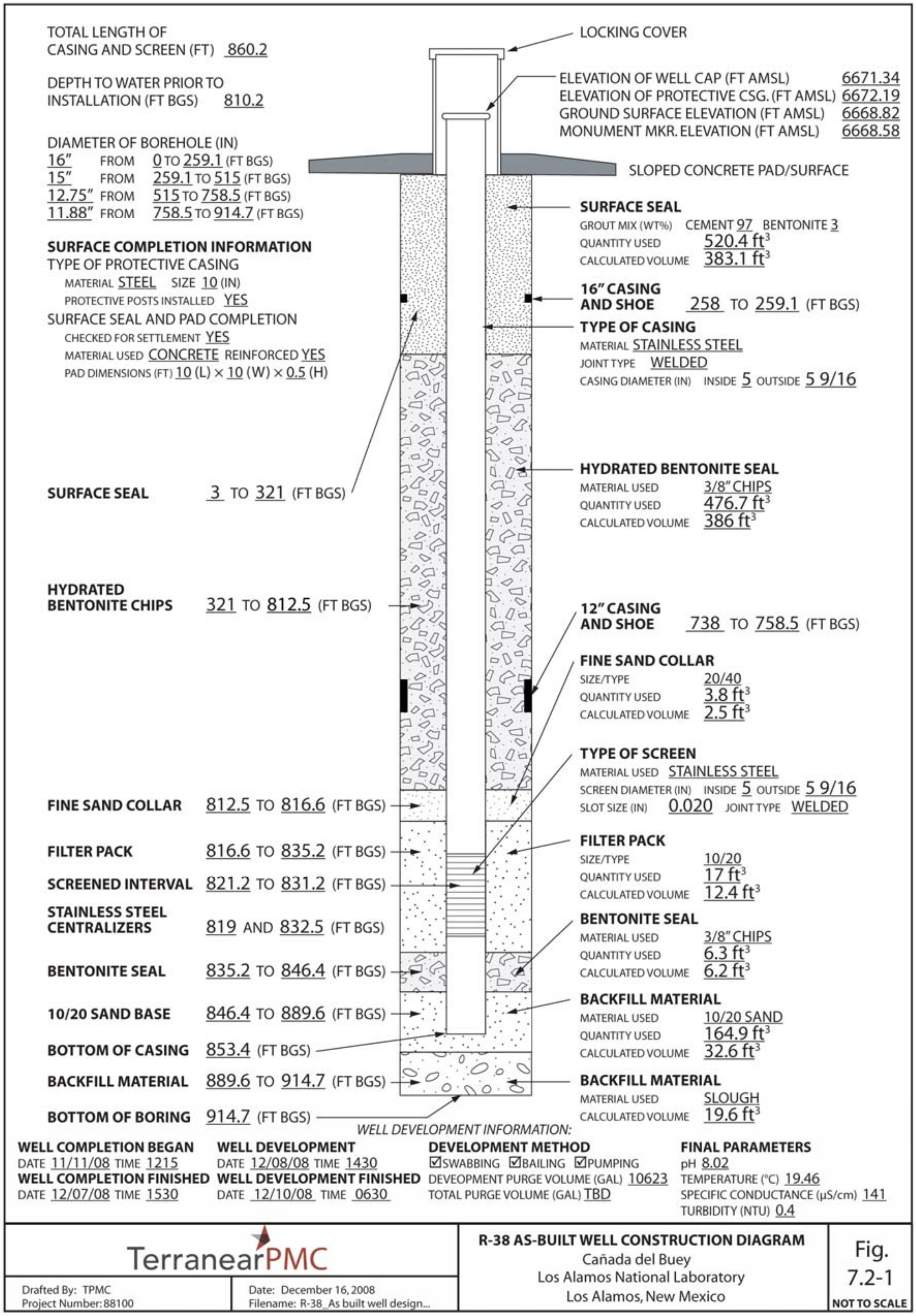

Figure 7.2-1 R-38 as-built well construction diagram

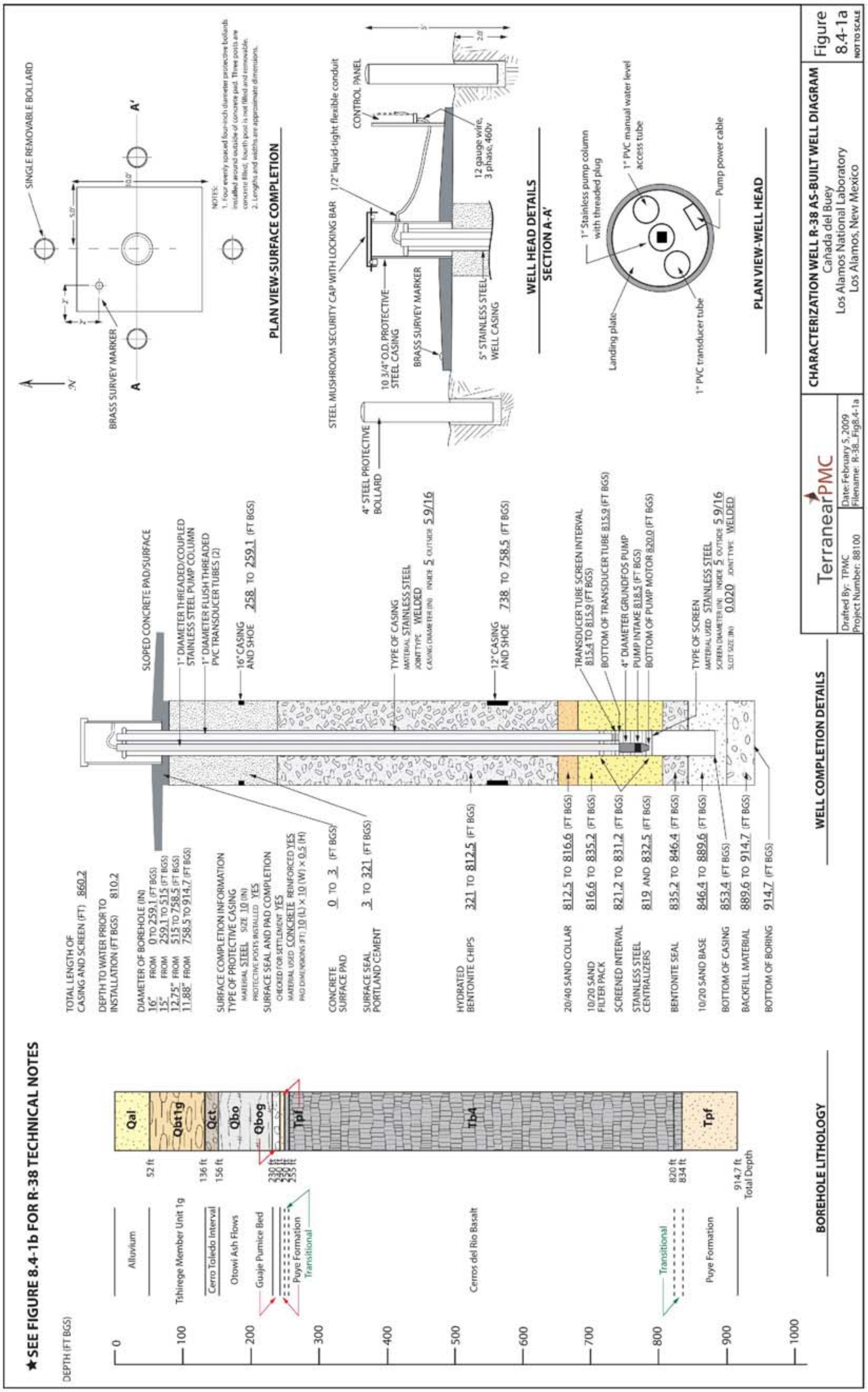

Figure 8.3-1a As-built schematic for regional well R-38

R-38 TECHNICAL NOTES: [1]

SURVEY INFORMATION[2]

Brass Marker

Northing:	1760235.0742 ft
Easting:	1640998.6596 ft
Elevation:	6668.58 ft AMSL

Well Casing (top of stainless steel)

Northing:	1760230.7455 ft
Easting:	1641002.2518 ft
Elevation:	6671.34 ft AMSL

BOREHOLE GEOPHYSICAL LOGS

Schlumberger

DRILLING INFORMATION

Drilling Company
Boart Longyear

Drill Rig
Foremost DR-24HD

Drilling Methods
Dual Rotary
Fluid-assisted air rotary, Foam-assisted air rotary

Drilling Fluids
Air, potable water, AQF-2 Foam

MILESTONE DATES

Drilling

Start:	10/23/2008
Finished:	11/08/2008

Well Completion

Start:	11/11/2008
Finished:	12/07/2008

Well Development

Start:	12/08/2008
Finished:	12/10/2008

WELL DEVELOPMENT

Development Methods
Performed swabbing, bailing, and pumping
Total Volume Purged: 10623 gallons

Parameter Measurments (Final)

pH:	8.02
Temperature:	19.46 °C
Specific Conductance:	141 μS/cm
Turbidity:	0.4 NTU

AQUIFER TESTING

Constant Rate Pumping Test

Water Produced:	8,411 gallons
Average Flow Rate:	5.3 gpm
Performed on:	12/13–15/08

DEDICATED SAMPLING SYSTEM

Pump
Make: Grundfos, Type: 5S30-320 CBMC 5
Model: 96023161-P10827476
Capacity: 3 U.S. gpm, intake at 818.5 ft bgs
Environmental Retrofit

Motor
Make: Framklin Electric, model: 2343262604, 3HP, 3-phase

Pump Column
1" threaded/coupled sched. 40 stainless-steel tubing

Transducer Tube
1" flush threaded schd. 80 PVC tubing
0.01-in. slot screen at 815.4–815.9 ft bgs

Transducer
Make: In-Situ, Inc. Model: Level TROLL 500, 30 psig range (vented)
S/N: 140455

NOTES:
1) Additional information available in "Final Completion Report, Characterization Well R-38, Los Alamos National Laboratory, Los Alamos, New Mexico, date TBD.
2) Coordinates based on New Mexico State Plane Grid Coordinates, Central Zone (NAD83); Elevation expressed in feet above mean sea level using the National Geodetic Vertical Datum of 1929.

TerranearPMC		R-38 TECHNICAL NOTES Cañada del Buey Los Alamos National Laboratory Los Alamos, New Mexico	Figure 8.4-1b NOT TO SCALE
Drafted By: TPMC Project Number: 88100	Date: February 10, 2009 Filename: R-38_TechnicalNotes_Fig 8.4-1b		

Figure 8.3-1b As-built technical notes for R-38

Table 3.1-1
Fluid Quantities Used during Drilling and Well Construction

Date	Water (gal.)	Cumulative Water (gal.)	AQF-2 Foam (gal.)	Cumulative AQF-2 Foam (gal.)	Cumulative Returns in Pit: Fluids (gal.)
Drilling					
10/23/08	175	175	0	0	na[a]
10/24/08	1600	1775	18	18	na
10/25/08	3200	4975	28	46	na
10/26/08	5500	10,475	41	87	na
10/27/08	850	11,325	2	89	na
10/28/08	4300	15,625	60	149	na
10/31/08	1650	17,275	n/a[b]	n/a	na
11/01/08	5500	22,775	n/a	n/a	na
11/02/08	400	23,176	n/a	n/a	na
11/03/08	4500	27,675	n/a	n/a	na
11/04/08	4000	31,675	n/a	n/a	na
11/05/08	1300	32,975	n/a	n/a	na
11/06/08	2000	34,975	n/a	n/a	na
Well Construction					
11/14/08	100	35,075	n/a	n/a	na
11/15/08	3350	38,425	n/a	n/a	na
11/16/08	1650	40,075	n/a	n/a	na
11/24/08	5800	45,875	n/a	n/a	na
11/25/08	1700	47,575	n/a	n/a	na
12/02/08	3000	50,575	n/a	n/a	na
12/03/08	3200	53,775	n/a	n/a	na
12/04/08	3000	56,775	n/a	n/a	na
Total Volume (gal.)					
R-38	56,775				30,500

[a] na = Not available.

[b] n/a = Not applicable. Foam use and pit use discontinued after drilling activities; therefore, no additional fluids were produced.

Table 4.2-1
Summary of Groundwater Screening Samples
Collected during Drilling, Well Development, and Aquifer Testing of Well R-38

Location ID	Sample ID	Date Collected	Collection Depth (ft bgs)	Sample Type
Drilling				
R-38	GW38-09-934	11/04/08	635	Groundwater
R-38	GW38-09-935	11/04/08	720	Groundwater
R-38	GW38-09-936	11/06/08	764	Groundwater
R-38	GW38-09-937	11/06/08	784	Groundwater
R-38	GW38-09-938	11/06/08	804	Groundwater
R-38	GW38-09-939	11/06/08	824	Groundwater
R-38	GW38-09-940	11/06/08	844	Groundwater
R-38	GW38-09-941	11/06/08	864	Groundwater
R-38	GW38-09-942	11/06/08	884	Groundwater
R-38	GW38-09-943	11-06-08	904	Groundwater
Well Development				
R-38	GW38-09-914	11/09/08	829.89	Groundwater
R-38	GW38-09-915	11/09/08	829.89	Groundwater
R-38	GW38-09-916	11/09/08	822.89	Groundwater
R-38	GW38-09-917	11/09/08	822.89	Groundwater
R-38	GW38-09-918	11/09/08	822.89	Groundwater
Aquifer Pump Test				
R-38	GW38-09-919	12/15/08	821.2–831.2	Groundwater
R-38	GW38-09-920	12/15/08	821.2–831.2	Groundwater
R-38	GW38-09-921	12/15/08	821.2–831.2	Groundwater
R-38	GW38-09-922	12/15/08	821.2–831.2	Groundwater
R-38	GW38-09-923	12/16/08	821.2–831.2	Groundwater

Table 6.0-1
R-38 Video and Geophysical Logging Runs

Date	Depth (ft bgs)	Description
10/29/08	Surface–515	Ran LANL video tool to inspect borehole condition after cementing off Cerros del Rio basalt. The run revealed "chunks of cement sticking to borehole wall"; a reamer was run as a result.
11/08/08	Surface–893.4	Ran Schlumberger Array Induction Imager, Natural Gamma Ray Spectroscopy, Accelerator Porosity, Formation MicroImager, magnetic resonance, and combined gamma ray and caliper tools—the 14-h logging job went smoothly.
11/17/08	Surface–430	Ran LANL video tool to determine location and condition of top of four lost stick of 2-in. tremie pipe at ≥785 ft bgs. Tool run in 12-in. × 5.5-in. annular space; could not get past 430 ft bgs—run unsuccessful.
11/19/08	Surface–808	Ran Jet West Geophysical video tool inside 3-in. fishing pipe to determine location and condition of top of four lost sticks of 2-in. tremie pipe at ≥785 ft bgs. The top collar of lost tremie was found at 806 ft bgs (water at 808 ft bgs), wedged between 5-in. well casing and the borehole wall.
11/21/08	Surface–818	Ran Jet West Geophysical video tool both in 5.5-in. well casing (to inspect screen) and in 12-in. × 5.5-in. annular space (to inspect lost 2-in. tremie pipe location and condition). In-well casing run showed screen OK. Two annular runs not able to get below 361.7 ft bgs. Decide to pull 3-in. fishing pipe.
11/22/08	Surface–853	Ran Jet West Geophysical video tool in both 12-in. × 5.5-in. annulus and newly rerun 3-in. fishing pipe. Showed top of lost 2-in. tremie pipe at 824.5 ft bgs and guided fishing pipe over top of lost 2-in. tremie successfully. Lost tremie pipe recovered shortly thereafter.

Table 7.2-1
R-38 Annular Fill Materials

Material	Volume
Surface seal: cement slurry	262.5 ft^3
Bentonite seal: bentonite chips	476.7 ft^3
Fine sand collar: 20/40 silica sand	3.8 ft^3
Primary filter: 10/20 silica sand	17.0 ft^3
Bentonite lower seal: bentonite chips	6.3 ft^3
Backfill material: 10/20 sand	164.9 ft^3
Backfill material: slough	19.6 ft^3
Potable water used in the intermediate aquifer (drilling and well construction)	56,775 gal.

Table 8.5-1
R-38 Survey Coordinates

North	East	Elevation (ft amsl)	Identification
1760235.0742	1640998.6596	6668.5809	R-38 brass pin embedded in pad
1760230.4840	1641001.2465	6668.8257	R-38 ground surface near pad
1760230.8789	1641002.9254	6672.1914	R-38 top of 10-in. protective casing
1760230.7455	1641002.2518	6671.3391	R-38 top of stainless-steel well casing

Note: All coordinates are expressed as New Mexico State Plane Coordinate System Central Zone (NAD 83); elevation is expressed in feet above mean sea level using the National Geodetic Vertical Datum of 1929.

Table 8.6-1
Summary of Waste Samples Collected during Drilling and Development of R-38

Location ID	Sample ID	Date Collected	Description	Sample Type
WST-600902	GW38-09-966	11/03/2008	Diesel contaminated soil	New Mexico special waste soil
WST-600902	GW38-09-968	11/03/2008	Diesel contaminated soil	New Mexico special waste soil
R-38 well	RC38-09-1515	12/04/2008	Decontamination water	Water
R-38 well	RC38-09-1516	12/04/2008	Decontamination water	Water
R-38 well	RC38-09-1517	12/04/2008	Decontamination water	Water
R-38 well	RC38-09-1518	12/04/2008	Decontamination water	Water

Appendix A

Rotary Borehole R-38 Lithologic Log

Los Alamos National Laboratory
Regional Hydrogeologic Characterization Project
Borehole Lithologic Log

COREHOLE IDENTIFICATION (ID): R-38	**TECHNICAL AREA (TA):** 54	**PAGE:** 1 of 15
DRILLING COMPANY: Boart Longyear Company	**START DATE/TIME:** 8/12/08: 1420	**END DATE/TIME:** 9/10/08: 1410
DRILLING METHOD: Dual Rotary	**MACHINE**: Foremost DR24 HD	**SAMPLING METHOD:** Grab
GROUND ELEVATION: TO BE DETERMINED **(**TBD)		**TOTAL DEPTH** (TD): 915 ft below ground surface (bgs)
DRILLERS: J. Staloch/J. Bowen	**SITE GEOLOGISTS:** R. McQuill, J. R. Lawrence, A. Miller	

DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
0–52	**ALLUVIUM:** Unconsolidated sediments—pinkish to reddish gray (5YR 5/2 to 5YR 7/2) silty fine to medium sand with minor pebble gravel; detrital grains/clasts of indurated tuff, quartz and sanidine crystals, pumice and volcanic lithics. 0–6 ft surficial construction fill. 35–52 ft light pinkish gray (5YR 8/3) clayey sand with gravel to clayey gravel.	Qal	Note: Drill cuttings for microscopic and descriptive analysis were collected at 5-ft intervals from 0 ft bgs to borehole TD at 915 ft bgs. Quaternary alluvial sediments, from 0 to 52 ft bgs are estimated to be 52 ft thick. Estimated Qal–unit 1g, Qbt contact at 52 ft bgs.
52–90	**UNIT 1g, TSHIREGE MEMBER OF THE BANDELIER TUFF:** Volcanic tuff—white (10YR 8/1), poorly to moderately welded, pumiceous, crystal-rich, lithic-poor, locally abundant ash matrix. 55–60 ft +10F: 95%–97% white, fibrous, vitric pumices, quartz- and sanidine-phyric, also abundant black Cpx and/or clots of Fe-oxide; 3%–5% dacite lithic fragments (up to 5 mm); +35F: abundant pumice fragments plus quartz and sanidine crystals, trace volcanic lithics. 60–65 ft similar to 55–60 ft. 65–75 ft WR: abundant pinkish white (5YR 8/2) volcanic ash matrix. 75–80 ft +10F: 85%–90% white glassy pumices, quartz- and sanidine-phyric and distinctive clots of black Fe-oxide; 10%–15% lithics (dacite and pinkish welded tuff). 85–90 ft +10F: 97% glassy pumices, 1%–3% fragments of welded tuff indicating locally increased degree of welding in unit 1g, Qbt.	Unit 1g, Qbt	Unit 1g of the Tshirege Member of the Bandelier Tuff, from 52 to 135 ft bgs, is estimated to be 83 ft thick.

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 2 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
90–95	Volcanic tuff—white (10YR 8/1), poorly welded, pumiceous, crystal-rich, lithic-bearing abundant ash matrix. +10F: 85%–90% white glassy fibrous quartz- and sanidine-phyric pumices with black clots of secondary Fe-oxides; 10%–15% volcanic lithic fragments (dacite, rhyolite) up to 15 mm.	Unit 1g, Qbt	
95–135	Volcanic tuff—white (10YR 8/1), poorly welded, pumiceous (vitric pumices), crystal-rich, lithic-poor, locally abundant ash matrix. 95–100 ft +10F: 97% white glassy quartz- and sanidine-phyric pumices with black clots of secondary Fe-oxides; 3% volcanic lithic fragments (i.e., xenoliths) composed of dacite, rhyodacite. +35F: abundant pumice fragments, quartz and sanidine crystals. 110–115 ft WR: abundant white (10YR 8/1) to pinkish white (5YR 8/2) volcanic ash matrix; +10F: 97% white glassy pumices, 1%–3% dacite lithics (up to 17 mm). 115–135 ft WR: abundant volcanic ash matrix.		Estimated unit 1g, Qbt–Qct contact at 135 ft bgs.
135–140	**CERRO TOLEDO INTERVAL:** Volcaniclastic sediments—light pinkish tan (5YR 7/3) silty to clayey sand and gravel, detrital volcanic clasts broken to subangular. WR: abundant volcanic ash. +10F: 90%–95% clasts (up to 15 mm), predominantly of pinkish and gray dacites and white rhyolite (?); 5%–10% white glassy pumices; +35F: 70% quartz and sanidine crystals, 20% pumice fragments, 10% dacite grains.	Qct	Section of Cerro Toledo interval sediments, from 135 to 140 ft bgs, is estimated to be 5 ft thick. Estimated Qct–Qbo contact at 140 ft bgs.

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54	**PAGE:** 3 of 15

DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
140–180	**OTOWI MEMBER OF THE BANDELIER TUFF:** Volcanic tuff—light pinkish tan (5YR 8/3) to orange tan (5YR 7/6), poorly welded, pumiceous (vitric pumices), crystal-rich, lithic-rich, locally abundant ash matrix. 140–150 ft: No sample is available for description. 150–155 ft +10F: 45%–50% white to pale orange, glassy, quartz- and sanidine-phyric pumices; 45%–55% volcanic lithic fragments (i.e., xenoliths) composed of dacite, rhyodacite, flow-banded rhyolite; +35F: 50%–60% quartz and sanidine crystals, 30%–40% volcanic lithic fragments, 5%–10% pumice fragments. 155–160 ft +10F: 80%–85% volcanic lithic fragments (up to 13 mm) including biotite-dacite, rhyodacite, flow-banded rhyolite; 10%–15% glassy pumices. 160–180 ft similar to 155–160 ft. 170–180 ft: No sample is available for description.	Qbo	
180–190	Volcanic tuff—pinkish white (5YR 8/2), poorly welded, pumiceous, lithic- and crystal-bearing, locally abundant ash matrix. 180–185 ft WR: abundant volcanic ash. +10F: 45%–50% vitric pumice fragments with local orange limonitic (Fe-oxide) staining; 40%–50% dacite lithic fragments (i.e., xenoliths) up to 5 mm; +35F: 50% quartz and sanidine crystals, 30% volcanic lithic fragments, 20% pumice fragments. 185–190 ft similar to 180–185 ft.		189–190 ft poor recovery, low-volume samples.

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 4 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
190–220	<u>Volcanic tuff</u>—pinkish white (5YR 8/2), poorly welded, pumiceous, lithic-rich, crystal-bearing, locally abundant ash matrix. 190–195 ft WR: abundant lithics; little or no ash matrix; +10F: 40%–50% vitric pumice fragments (up to 15 mm); 40%–50% volcanic lithic fragments, predominantly hornblende- and biotite-dacites (up to 27 mm); +35F: 50%–60% quartz and sanidine crystals, 20%–25% volcanic lithic fragments, 15%–20% pumice fragments. 195–200 ft WR: abundant orange to white ash matrix; +10F: 40%–50% white vitric, quartz- and sanidine-vitric pumice fragments; 40%–50% volcanic lithic fragments, predominantly gray hornblende dacites (up to 10 mm); +35F: 60%–70% quartz and sanidine crystals, 15%–20% volcanic lithic fragments, 15%–20% pumice fragments. 200–205 ft +10F: glassy fibrous-textured pumices are locally orange colored, limonite-stained. 205–220 ft similar to 200–205 ft.	Qbo	Estimated Qbo–Qbog contact at 220 ft bgs.
220–234	**GUAJE PUMICE BED:** <u>Volcanic tuff</u>—white (5YR 8/1), poorly welded to nonwelded, strongly pumiceous, lithic-poor, no apparent volcanic ash matrix. 220–225 ft WR/+10F: 100% vitric pumices (up to 10 mm); phenocryst-poor to aphyric, having pristine, very fresh appearance; +35F: trace amounts quartz and sanidine crystals, volcanic lithic fragments, and pumice fragments. 225–230 ft +10F: 98% vitric pumices, 2% dacite lithics. 230–234 ft similar to 225–230 ft.	Qbog	Guaje Pumice Bed, from 220 to 234 ft bgs, is estimated to be 14 ft thick. Estimated Qbo–Qbog contact at 220 ft bgs.

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 5 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
234–250	**PUYE FORMATION:** Pumiceous volcaniclastic sediments–White (5YR 8/1), pebble gravel and fine to medium sand, subangular to subrounded detritus composed of mixed glassy pumices, diverse volcanic rocks and fragments of pumice-bearing fine-grained sandstone. 234–2400 ft +10F: 60%–70% white vitric pumices, 15%–20% sunangular clasts made up of volcanic lithologies (andesite, dacite, rhyodacite), 15%–20% fragments of indurated tuffaceous sandstone containing grains of white pumice, quartz and sanidine crystals, and volcanics. 240–250 ft: No sample is available for description.	Tpf	Estimated Qbog–Tpf contact at 234 ft bgs. This section of Puye Formation pumiceous-volcaniclastic sediments is estimated to be 16 ft thick. Estimated Tpf-Tb4 contact at 250 ft bgs.
250–255	**CERROS DEL RIO BASALT:** Basalt lava/volcaniclastic sediments–pinkish white (5YR 8/2) fragments and/or clasts of strongly vesicular olivine-basalt. 250–255 ft WR/+10F: predominantly angular fragments (up to 44 mm) of vesicular olivine-phyric basalt, vesicles infilled with very fine-grained sandstone; less than 5% fragments of volcaniclastic sandstone; +35F: mixed basalt fragments, pumices, quartz and sanidine crystals, and fragments of indurated sandstone. This interval marks the transition from volcaniclastic sediments with pumice to the top of the Tb4 basalt section.	Tb4	The entire Cerros del Rio basalt section, including lavas, basaltic cinder deposits, hydromagmatic tuffs and intercalated basaltic clastic sediments intersected from 250 to 820 ft bgs, is estimated to be 570 ft thick.
255–260	Basalt lava–pinkish white (5YR 8/2) mixed fragments of strongly vesicular olivine-basalt and those of fine-grained volcaniclastic sandstone. 255–260 ft WR: silty to clayey matrix. +10F: 90%–95% broken basalt chips strongly vesicular olivine basalt; 5%–10% fragments of indurated pinkish tan (5YR 7/3) very fine-grained sandstone.		

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 6 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
260–275	Basalt lava–dark gray (GLEY1 4/1) angular chips vesicular olivine-phyric basalt, porphyritic with aphanitic groundmass, locally abundant clay. 260–265 ft +10F: 100% broken basalt chips, phenocrysts (5%–7% by volume) of small (up to 1 mm) translucent green olivine, minor black opaque clinopyroxene, minor plagioclase and rare xenocrystic quartz. 265–275 ft similar to 260–265 ft.	Tb4	
275–300	Basalt lava–dark gray (GLEY1 4/1) angular chips, vesicular olivine-phyric basalt, porphyritic with aphanitic groundmass. 275–280 ft WR/+10F: 100% broken basalt chips, strongly vesicular, phenocrysts (5%–7% by volume) of small (up to 1 mm) green olivine, minor plagioclase; fragments coated and vesicles filled with locally abundant light pinkish tan clay. 280–295 ft similar to 275–280 ft. 295–300 ft: No sample is available for description.		
300–325	Basalt lava–dark gray (GLEY1 4/1) angular chips, vesicular olivine-phyric basalt, porphyritic with aphanitic groundmass, locally strong secondary Fe-oxide. 300–305 ft WR/+10F: 100% broken basalt chips, strongly to weakly vesicular, phenocrysts (5%–7% by volume) of small (up to 1 mm) green olivine (locally iddingsitized), locally abundant light reddish brown (i.e., Fe-oxide) and/or pale tan clay filling vesicles. 305–325 ft similar to 300–305 ft.		
325–355	Basalt lava–dark gray (GLEY1 4/1) to locally dark reddish brown (2.5YR 4/6), vesicular to scoriaceous olivine-phyric basalt, porphyritic with aphanitic groundmass, local clay and/or secondary Fe-oxide. 325–330 ft WR/+10F: 100% strongly vesicular to scoriaceous basalt chips, phenocrysts (5%–7% by volume) of small (up to 1 mm) green olivine and plagioclase (olivine and feldspar commonly intergrown); locally abundant white clay and/or reddish secondary hematite lining vesicles. 330–355 ft similar to 325–330 ft.		

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 7 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
355–380	Basaltic cinder deposits–dark gray (GLEY1 4/1) to light reddish brown (2.5YR 6/6), strongly vesicular to scoriaceous olivine-phyric basalt, porphyritic with aphanitic groundmass, commonly limonite-stained with local minor white clay. 355–360 ft WR/+10F: 100% basalt chips, mostly scoriaceous, phenocrysts (3%–5% by volume) of olivine (frequently replaced by iddingsite) and plagioclase, moderate limonite and/or weak white clay lining vesicles. 360–380 ft similar to 355–360 ft.	63.0	
380–420	Basalt lava–dark gray (GLEY1 4/1) vesicular olivine-phyric basalt, porphyritic with aphanitic groundmass, local minor secondary Fe-oxide. 380–385 ft WR/+10F: 100% moderately vesicular basalt chips, phenocrysts (3%–5% by volume) of small (up to 2 mm) plagioclase and green olivine (up to 1 mm); locally weak reddish earthy hematite lining vesicles. Olivine-plagioclase intergrowths common. 385–400 ft similar to 380–385 ft. 400–405 ft +10F: olivine phenocrysts commonly replaced by iddingsite; locally strong secondary hematite lining vesicles. 405–410 ft +10F: euhedral olivines proportionately more prominent and larger (up to 3 mm), locally strong hematite staining. 410–420 ft similar to 380–385 ft.		

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 8 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
420–450	<u>Basalt lava</u>–medium gray (GLEY1 6/1) to dark reddish brown (2.5YR 4/6) vesicular to scoriaceous olivine- and clinopyroxene-phyric basalt, porphyritic with aphanitic groundmass, local strong secondary Fe-oxide. 420–425 ft WR/+10F: 100% basalt chips, partly scoriaceous, phenocrysts (3%–5% by volume) of euhedral plagioclase (up to 3 mm), black opaque clinopyroxene (anhedral or as partial replacement after olivine), and minor olivine. The three mineral phases frequently occur as cumulophyric intergrowths. Strong earthy hematite occurs locally as vesicle linings. Weak hydrothermal alteration appears to affect groundmass feldspars. 425–430 ft similar to 420–425 ft. 430–435 ft +10F: 100% basalt chips exhibit hydrothermal alteration and resultant bleaching of groundmass; bleaching is progressive stronger downward in this flow unit. Olivine phenoscrysts show prominent replacement, or partial replacement, by black Cpx. 435–440 ft similar to 420–425 ft. 440–450 ft +10F: black opaque clinopyroxene becoming more prominent over the occurrence of olivine downward in the section.	Tb4	

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 9 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
420–450	<u>Basalt lava</u>–medium gray (GLEY1 6/1) to dark reddish brown (2.5YR 4/6) vesicular to scoriaceous olivine- and clinopyroxene-phyric basalt, porphyritic with aphanitic groundmass, local strong secondary Fe-oxide. 420–425 ft WR/+10F: 100% basalt chips, partly scoriaceous, phenocrysts (3%–5% by volume) of euhedral plagioclase (up to 3 mm), black opaque clinopyroxene (anhedral or as partial replacement after olivine), and minor olivine. The three mineral phases frequently occur as cumulophyric intergrowths. Strong earthy hematite occurs locally as vesicle linings. Weak hydrothermal alteration appears to affect groundmass feldspars. 425–430 ft similar to 420–425 ft. 430–435 ft +10F: 100% basalt chips exhibit hydrothermal alteration and resultant bleaching of groundmass; bleaching is progressive stronger downward in this flow unit. Olivine phenoscrysts show prominent replacement, or partial replacement, by black Cpx. 435–440 ft similar to 420–425 ft. 440–450 ft +10F: black opaque clinopyroxene becoming more prominent over the occurrence of olivine downward in the section.	Tb4	
450–470	<u>Basalt lava</u>–light gray (GLEY1 7/1) to dark reddish brown (2.5YR 4/6), strongly vesicular olivine- and clinopyroxene-phyric basalt, porphyritic with aphanitic groundmass, local moderate secondary Fe-oxide. 450–455 ft WR/+10F: 100% basalt chips, strongly vesicular, phenocrysts (2%–4% by volume) of anhedral clinopyroxene, euhedral plagioclase (up to 2 mm), and green olivine. Black opaque clinopyroxene frequently replaces or forms rims (overgrowths) on olivine. Moderate hematite frequently lines vesicles. Commonly bleached groundmass indicates weak hydrothermal alteration. 455–470 ft +10F: weak to moderate white clay lining vesicles, local secondary hematite.		

Borehole Lithologic Log (continued)

<table>
<tr><td>BOREHOLE ID: R-38</td><td colspan="2">TA: 54</td><td>PAGE: 10 of 15</td></tr>
<tr><th>DEPTH (ft bgs)</th><th>LITHOLOGY</th><th>LITHOLOGIC SYMBOL</th><th>NOTES</th></tr>
<tr><td>470–495</td><td><u>Basaltic cinder deposits</u>–dark reddish brown (2.5YR 4/6) to light gray (GLEY1 7/1), mixed scoriaceous and strongly vesicular basalt, porphyritic with aphanitic groundmass, pervasive ferruginous alteration and local bleaching of groundmass.
470–475 ft +10F/+35F: 100% basalt chips, phenocrysts (2%–4% by volume) of clinopyroxene, plagioclase and olivine (frequently replaced by iddingsite) and plagioclase. Scoria fragments are strongly ferruginous (i.e., hematite), whereas vesicular basalt chips exhibit bleached/altered groundmass with minor white clay.
475–495 ft +10F/+35F: predominantly ferruginous scoria/cinders.</td><td rowspan="3">Tb4</td><td></td></tr>
<tr><td>495–525</td><td><u>Basaltic cinders/clastic sediments</u>–dark reddish brown (2.5YR 4/6) and light gray (GLEY1 7/1), mixed basalt cinders, massive basalt and detrital grains composed of Precambrian quartzite and quartzo-feldspathic rocks and volcanic lithologies.
495–500 ft +10F: 95%–98% gray and reddish basalt scoria/cinders.
500–520 ft +10F: similar to 495–500 ft. +35F: 75%–85% basalt chips, scoria/cinders and glassy basalt cinders; 10%–20% subangular sand-size grains of quartz and dacitic volcanics.
520–525 ft +10F: 85%–90% basalt/basalt scoria, 10%–15% rounded detrital pebbles (up to 18 mm) composed of intermediate to felsic volcanic rocks. +35F: no sample preserved of this size fraction.</td><td rowspan="2">495–525 ft: Occurrence of ferruginous basalt scoria and frothy basaltic glass mixed with sand-size detritus of Precambrian quartzite and granitic lithologies indicates tuffaceous-clastic layer, possibly of hydromagmatic origin.

Estimated contact between base of lava section and top of basalt cinders at 562 ft bgs</td></tr>
<tr><td>525–562</td><td><u>Basalt lava</u>—light gray (GLEY1 7/1),vesicular to massive Cpx-bearing basalt, porphyritic with aphanitic groundmass, limonitic coating of local fracture surfaces.
525–530 ft +10F: 100% basalt chips, phenocrysts (5%–7% by volume) of small (up to 1 mm) black anhedral Cpx and minor plagioclase; groundmass exhibits hydrothermal alteration as seriticization of feldspar microlites and bleaching; +35F: 98% basalt fragments, 2% subangular quartz detritus.
530–535 ft +35F: 100% basalt chips.
535–545 ft +10F: abundant limonite on fracture surfaces and lining vesicles; apparent highly fractured rock.
545–562 ft +10F: increased vesicularity, grading to more massive basalt with depth.</td></tr>
</table>

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA:** 54		**PAGE:** 11 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
562–575	Basaltic hydromagmatic deposits—brick red (10YR 6/8) fine-grained basaltic sandstone/tuff with basaltic glass and clay. 562–575 ft +10F: 100% fragments of indurated basaltic sandstone/tuff containing fine- to very fine-grained reddish "frothy" basaltic glass, cinders, Cpx and olivine crystals, abundant subangular quartz grains, and interstitial clay; clast supported.	Tb4	
575–590	Basaltic hydromagmatic deposits—grayish brown (10YR 5/2) to reddish gray (5YR 5/2) fine- to medium-grained basaltic sandstone with mixed volcanic detrital pebbles. 575–580 ft +10F: 85%–90% fragments of indurated fine-grained tuffaceous sandstone containing predominantly grains of basaltic glass cemented by tan palagonitic clay; 10%–15% broken and subangular clasts (up to 13 mm) mixed volcanic rocks (basalt, rhyodacite); +35F: predominantly grains of basaltic glass scoria with adhered clay. 580–595 ft +10F: mixed fragments of indurated fine-grained basaltic sansdstone and anguilar clasts (up to 15 mm) basalt and dacite brown; local grains of quartz at 585–590 ft. .		
590–605	Basaltic hydromagmatic deposits—reddish gray (5YR 5/2) to pinkish tan (5YR 7/3) basaltic sandstone/tuff, matrix supported with abundant silt and clay; becoming finer grained, more clay rich with depth. 595–600 ft +10F: 80% indurated silt fragments with very fine-grained volcanic sand and clasts (up to 10 mm) of basaltic glass. 600–605 ft +10F: pinkish tan (5YR 7/3) fragments of indurated silt/clay with mixed volcanic clasts (10%–15% by volume, up to 10 mm) including basalt, dacite, and basaltic glass.		

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA** 54		**PAGE:** 12 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
605–615	Fine clastic sediments—light pinkish tan (5YR 7/3) clay, high plasticity, with volcanic pebble gravel. 605–610 ft WR: abundant clay: +10F: 100% subrounded light gray dacite clasts (up to 3.2 cm). +35F: mixed grains of basalt and fragments of very fine-grained sandstone. 610–615 ft WR: abundant clay: +10F/+35F: no sample preserved (apparently no coarse clastic component).	Tb4	
615–638	Fine clastic sediments—light pinkish tan (5YR 7/3) clay, hard dessicated clay. 615–638 ft WR/ +10F: brittle clay fragments having pseudoconcoidal fracture and apparent siliceous chertlike quality.		615–638 ft siliceous cherty clay possibly of lucustrine origin.
638–670	Basalt lava—medium gray (GLEY1 5/1), massive (nonvesicular) basalt, weakly porphyritic with aphanitic groundmass, olivine-phyric. 638–650 ft +10F: 99% basalt chips, phenocrysts (2%–4% by volume) green subhedral olivine (up to 3 mm); 1% pinkish siliceous clay. 650–660 ft +10F/+35F: 95%–98% basalt chips partly rounded to subrounded, groundmass partly bleached, weakly altered; 2%–5% pink siltstone fragments. 660–670 ft +10F: 100% chips olive-basalt with bleached (altered) groundmasss, local fractured surfaces coated with white clay and/or SiO_2.		650–670 ft rounded basalt pebbles suggest basalt gravel layer.
670–685	Basalt lava—light gray (GLEY1 7/1), massive basalt, porphyritic with aphanitic groundmass, olivine-phyric, groundmass weakly altered/bleached. 670–680 ft +10F: 99%–100% angular basalt chips, phenocrysts (3%–5% by volume) anhedral olivine (up to 2 mm); altered groundmass feldspars; trace pinkish clay flakes. 680–685 ft +10F: 99% well-rounded basalt clasts (up to 4.0 cm) suggesting detrital pebbles; 1% white fine-grained sandstone with quartz grains.	Tb4	680–685 ft rounded basalt clasts indicate thin basalt gravel layer.

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38		**TA** 54		**PAGE:** 13 of 15
DEPTH (ft bgs)	LITHOLOGY		LITHOLOGIC SYMBOL	NOTES
685–733	Basalt lava—light gray (GLEY1 7/1), massive basalt, weakly porphyritic with aphanitic groundmass, olivine-phyric, groundmass weakly altered/bleached. 685–705 ft +10F: 100% angular basalt chips, phenocrysts (2%–4% by volume) of olivine (up to 2 mm); groundmass altered/bleached resulting in very fine particles making up WR. 705–733 ft +10F: 99% angular basalt with altered/bleached groundmass; 1% very pale secondary SiO_2 fragments (i.e., likely fracture filling, veinlet).		Tb4	
733–760	Basaltic fine clastic sediments—varicolored, light pinkish tan (5YR 7/4) to medium gray (GLEY1 5/1) clay and clay with vesicul;ar basalt fragments/clasts. 740–50 ft 50% angular chips basalt scoria; 50% chips/flakes of brittle clay and minor very fine-grained sandstone. 750–755 ft +10F: 40% black scoriaceous basalt; 20% pinkish clay, 5%–10% white earthy pumices, 30% very fine-grained silty sandstone with abundant with pumice particles. 755–760 ft +10F: 100% vesicular subrounded basalt clasts with adhered rinds of pumiceous very fine-grained sandstone; +35F: mixed basalt chips, clay flakes and white pumice fragments.		Tb4	
760–815	Basalt lava—very light gray (GLEY1 7/1), weakly vesicular basalt, phenocryst-poor, aphanitic groundmass, olivine-phyric, groundmass altered/bleached. 760–765 ft +10F: 100% angular basalt chips, phenocrysts (less than 1% by volume) olivine (up to 1 mm); bleaching indicates moderate hydrothermal alteration and seritization of groundmass feldspars. 765–775 ft +10F: scoriaceous basalt, moderate to strong pervasive hydrothermal alteration/bleaching of groundmass. 775–780 ft +10F: 85% gray scoriaceous basalt chips; 15% subrounded detrital pebbles (up to 10 mm) composed of quartzite, granite. 780–814 ft similar to 760–765 ft.		Tb4	

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA** 54		**PAGE:** 14 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
815–820	Basalt lava/clastic sediments—varicolored mixed basalt, clay, and sandstone. 815–820 ft +10F: 50% dark gray chips vesicular basalt; 50% light pink (5YR 8/2) fragments of claystone with minor fine -grained sandstone. +35F: 60% basalt chips; 40% claystone fragments.	Tb4	815–820 ft interpreted to be a rubbly breccia zone at base of lowermost Tb4 basalt flow. Tb4-Tpf contact estimated at 820 ft bgs.
820–834	**PUYE FORMATION:** Basaltic clastic sediments—varicolored, medium gray (GLEY1 4/1) to light pinkish tan (5YR 7/4) coarse basalt gravel, siltstone/claystone and fine-grained sandstone. 820–825 ft WR/+10F: 100% chips of gray strongly vesicular basalt pebble clasts (up to 3.0 cm) exhibiting significant rounding/subrounding. 825–830 ft WR/+10F: predominantly angular chips phenocryst-poor basalt with minor fragments of siltone/claystone; +35F: 50% dark gray basalt and minor reddish basalt scoria/cinders; 40% fragments of siltsone/claystone; 10% indurated fine-grained volcanic sandstone. 830–834 ft WR/+10F: 85%–90% basalt chips and subrounded clasts; 10%–15% fragments of siltone/claystone; +35F: 50% dark gray basalt and minor reddish basalt scoria/cinders; 40% fragments of siltsone/claystone; 10% indurated fine-grained volcanic sandstone.	Tpf	Lower section of Puye Formation encountered from 820 to 915 ft bgs, estimated to be 95 ft thick. 820–834 ft predominance of basalt chips may be fragments of larger clasts that are subrounded to rounded (i.e., coarse gravels); possible soil or colluvial layer.
870–875	Contains trace rounded quartzite grains. 870–875 ft +10F: 60%–70% subrounded to rounded dacite clasts; 30%–40% fragments of indurated fine-grained sandstone; +35F: also minor basaltic glass, up to 5% quartzite and quartz crystal grains.		

Borehole Lithologic Log (continued)

BOREHOLE ID: R-38	**TA** 54		**PAGE:** 15 of 15
DEPTH (ft bgs)	LITHOLOGY	LITHOLOGIC SYMBOL	NOTES
875–915	<u>Quartzose volcaniclastic sediments</u>—pinkish white (5YR 8/23) pebble- to coarse gravels with fine to coarse sand subrounded to rounded detritus composed of diverse volcanic lithologies and Precambrian quartzites and granitic rocks. 875–890 ft WR: abundant silt matrix. +10F: detritus subrounded to rounded; 60%–70% volcanic clasts (dacites, minor basalt); 15%–20% well-rounded quartzites (up to 15 mm) and minor granites, microcline feldspar; 10%–15% fine-grained volcanic sandstone fragments. 890–900 ft +10F: subrounded rounded detrital clasts composed of 80%–95% volcanic rocks (dacite, andesite); 15%–20% clasts (up to 2.0 cm) of Precambrian quartzites and granites. 900–915 ft +10F: 90%–95% subrounded to rounded detrital clasts (up to 2.3 cm) composed of dacites and rhyodacites; 5%–15% Precambrian quartzites and granitic clasts; up to 5% sandstone fragments.	Tpf	875–915 ft interpreted to be quartz-bearing axial river-gravel deposits. 900–915 ft frequency of Precambrian constituents diminishes downward. Note: R-38 borehole drilling concluded at a total depth of 915 ft bgs.

ABBREVIATIONS

5YR 8/1 = Munsell soil color notation where hue (e.g., 5YR), value (e.g., 8), and chroma (e.g.,1) are expressed. Hue indicates soil color's relation to red, yellow, green, blue, and purple. Value indicates soil color's lightness. Chroma indicates soil color's strength.
bgs = below ground surface
cpx = clinopyroxene
ft = foot
GM = groundmass
ol = olivine
Qal = Quaternary Alluvium
Qbo = Otowi Member of Bandelier Tuff.
Qbog = Guaje Pumice Bed
Tb4 = Cerros del Rio basalt
Tpf = Puye Formation
Tmps = Miocene pumiceous sediments
Y = yellow
YR = yellow red
+10F = plus No. 10 sieve sample fraction
+35F = plus No. 35 sieve sample fraction

Appendix B

Groundwater Analytical Results

B-1.0 SAMPLING AND ANALYSIS OF GROUNDWATER AT R-38

Ten groundwater-screening samples were collected at borehole R-38 during drilling, five above the regional water table (from 635 to 804 ft below ground surface [bgs]), within the unsaturated zone representing drilling water, and five within the regional aquifer (from 824 to 904 ft bgs). A total of 10 groundwater-screening samples were collected from the completed well: five during well development and five during aquifer testing. The samples were collected from the screen interval of 821.2 to 831.2 ft bgs within the regional aquifer. The filtered samples were analyzed for cations, anions, perchlorate, and metals. A total of 10793 gal. of groundwater was pumped from well R-38 during well development. An additional 7911 gal. of groundwater was pumped during the aquifer testing at R-38.

B-1.1 Field Preparation and Analytical Techniques

Chemical analyses of groundwater-screening samples were performed at Los Alamos National Laboratory's (LANL's, or the Laboratory's) Earth and Environmental Sciences Group 14 (EES-14). Groundwater samples were filtered (0.45-µm membranes) before preservation and chemical analyses. Samples were acidified at the EES-14 wet chemistry laboratory with analytical grade nitric acid to a pH of 2.0 or less for metal and major cation analyses.

Groundwater samples were analyzed using techniques specified in the U.S. Environmental Protection Agency SW-846 manual. Ion chromatography was the analytical method for bromide, chloride, fluoride, nitrate, nitrite, oxalate, perchlorate, phosphate, and sulfate. The instrument detection limit for perchlorate was 0.002 ppm. Inductively coupled (argon) plasma optical emission spectroscopy (ICPOES) was used for analyses of dissolved aluminum, barium, boron, calcium, total chromium, iron, lithium, magnesium, manganese, potassium, silica, sodium, strontium, titanium, and zinc. Dissolved aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, cesium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, molybdenum, nickel, rubidium, selenium, silver, thallium, thorium, tin, vanadium, uranium, and zinc were analyzed by inductively coupled (argon) plasma mass spectrometry (ICPMS). The precision limits (analytical error) for major ions and trace elements were generally less than ±7% using ICPOES and ICPMS. Several of the above trace elements in groundwater samples were not analyzed by ICPMS collected during well development and aquifer testing due to an inoperable analytical instrument. These included antimony, arsenic, beryllium, cadmium, cesium, cobalt, copper, lead, mercury, molybdenum, nickel, rubidium, selenium, silver, thallium, thorium, tin, uranium, and vanadium. Concentrations of total organic carbon (TOC) in nonfiltered groundwater samples collected during well development and aquifer testing were determined by using an organic carbon analyzer. Charge balance errors for total cations and anions were generally less than ±9% for complete analyses of the above inorganic chemicals. The negative cation-anion charge balance values indicate excess anions for the filtered samples. Total carbonate alkalinity was measured using standard titration techniques.

B-1.2 Field Parameters

Results of field parameters, consisting of pH, temperature, dissolved oxygen (DO), oxidation-reduction potential (ORP), specific conductance, and turbidity, measured during well development and aquifer testing are provided in Table B.1-1. Measurements of pH and temperature varied from 7.75 to 8.15 and from 12.7°C to 23.3°C, respectively, at well R-38. Several of the low temperature measurements for groundwater samples were probably influenced by land surface atmosphere conditions during sampling. Percent saturation of DO varied from 5.36 to 7.19, suggesting that DO was measured between 0.39 and 0.52 mg/L at the well. This assumes that 7.29 mg/L of DO represents complete (100%) saturation at 6000 ft and 20°C. Regional aquifer groundwater is relatively oxidizing at well R-38, based on DO and ORP measurements, with ORP varying from 113 to 190 millivolts (mV) (Table B.1-1), with most of the ORP readings greater than +150 mV. Specific conductance ranged from 83 to 181 microsiemens per centimeter (μS/cm). Values of turbidity measured at R-38 ranged from 0.1 to 53 nephelometric turbidity units (NTUs) for the nonfiltered groundwater samples. Ten of the 40 turbidity measurements recorded during well development exceeded 5 NTUs (Table B.1-1).

B-1.3 Analytical Results for Groundwater-Screening Samples

Analytical results for groundwater-screening samples collected at well R-38 during drilling, well development, and aquifer testing are provided in Table B.1-2. Calcium and sodium are the dominant cations in groundwater pumped from well R-38. During well development and aquifer testing, dissolved concentrations of calcium and sodium ranged from 11.5 to 13 ppm (11.5 to 13 mg/L) and from 10 to 12 ppm, respectively. Dissolved concentrations of chloride and fluoride varied slightly from 3.22 to 3.34 ppm and from 0.28 to 0.48 ppm, respectively, during development and aquifer testing of well R-38. Dissolved concentrations of nitrate(N) and sulfate ranged from 0.64 to 0.67 ppm and from 3.34 to 4.14 ppm, respectively, at the well. Dissolved concentrations of chloride, nitrate(N), and sulfate at well R-38 do not exceed Laboratory background within the regional aquifer (LANL 2007, 095817). Maximum background concentrations for dissolved chloride, nitrate plus nitrite(N), and sulfate in the regional aquifer are 5.95 mg/L, 1.05 mg/L, and 8.63 mg/L, respectively (LANL 2007, 095817). Concentrations of TOC ranged from 0.20 to 1.02 mgC/L at well R-38 (Table B.1-1). Concentrations of perchlorate were less than detection (<0.002 ppm) at well R-38.

Dissolved concentrations of iron and manganese ranged 0.160 to 0.850 ppm (160 to 850 μg/L or 160 to 850 ppb) and from 0.008 to 0.017 ppm, respectively, in groundwater-screening samples collected at well R-38 (Table B.1-2). Dissolved concentrations of iron exceed the maximum background value of 0.147 mg/L in the regional aquifer (LANL 2007, 095817). Dissolved concentrations of manganese are less than the maximum background value 0.124 mg/L (LANL 2007, 095817). Dissolved concentrations of boron ranged from 0.012 to 0.033 ppm (Table B.1-2) at well R-38, which is below the maximum background value of 51.6 μg/L for the regional aquifer. Dissolved concentrations of zinc ranged from 0.009 to 0.023 ppm in groundwater-screening samples collected at R-38, with no samples exceeding the maximum background concentration of this trace metal in filtered samples (Table B.1-2). Background mean, median, and maximum concentrations of zinc in filtered samples are 3.08 μg/L, 1.45 μg/L, and 32.0 μg/L, respectively, for the regional aquifer (LANL 2007, 095817). Total dissolved concentrations of chromium ranged from 0.001 to 0.003 ppm at well R-38 (Table B.1-2), analyzed by ICPOES. Background mean, median, and maximum concentrations of total dissolved chromium are 3.07 μg/L, 3.05 μg/L, and 7.20 μg/L, respectively, for the regional aquifer (LANL 2007, 095817).

B-2.0 REFERENCES

The following list includes all documents cited in this appendix. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

LANL (Los Alamos National Laboratory), May 2007. "Groundwater Background Investigation Report, Revision 3," Los Alamos National Laboratory document LA-UR-07-2853, Los Alamos, New Mexico. (LANL 2007, 095817)

Table B-1.1
Well Development Volumes, Aquifer Testing Volumes, and Associated Field Water-Quality Parameters for Well R-38

Date	pH	Temp (°C)	DO (%)	ORP (mV)	Specific Conductivity (µS/cm)	Turbidity (NTU)	Purge Volume between Samples (gal.)	Cumulative Purge Volume (gal.)
Well Development								
12/08/08	Bailing; parameters not collected						NA*	155
	Bailing; parameters not collected						15	170
12/9/08	7.75	18.94	7.06	184.1	181	8.7	49	219
	8.13	19.19	7.01	155.3	149	13.6	720	769
	8.15	19.13	6.96	151.2	146	9.9	375	1470
	8.12	17.71	7.02	153.8	148	5.1	304	1774
	8.12	18.83	7.10	151.9	146	2.0	388	2162
	8.11	19.32	7.18	146.9	145	2.9	294	2456
	8.09	19.28	7.09	156.3	145	2.7	352	2808
	8.08	19.24	7.06	159.5	144	1.7	342	3150
	8.06	19.44	7.00	160.6	145	2.2	303	3453
	8.06	19.30	7.00	163.7	145	3.2	315	3768
	8.04	19.56	7.06	166.3	146	53.4	259	4027
	8.04	18.87	7.06	166.5	145	1.2	312	4339
	8.04	19.56	7.00	167.5	144	1.5	284	4623
12/10/08	8.02	19.51	7.02	169.0	144	0.1	298	4921
	8.02	19.59	7.02	171.6	143	1.9	312	5233
	8.03	19.26	7.05	173.2	143	0.1	281	5514
	8.02	19.34	7.01	174.6	143	NA	301	5815
	8.03	19.31	7.03	175.7	143	NA	317	6132
	8.02	19.31	7.03	176.5	142	NA	276	6408
	8.02	19.08	7.00	177.7	143	1.0	300	6708
	8.02	19.40	7.05	176.8	143	0.7	202	6910
	8.01	19.49	7.09	176.1	142	NA	199	7109
	8.02	19.31	7.01	178.4	142	NA	204	7313
	8.03	19.24	7.05	179.3	142	NA	204	7517
	8.00	19.34	7.01	177.9	143	NA	187	7704
	7.99	19.36	7.10	169.1	142	NA	181	7885
	8.03	19.31	7.01	178.1	142	0.2	200	8085
	8.02	19.45	7.14	175.7	142	NA	85	8170
	8.02	19.49	7.08	176.7	142	NA	90	8260
	8.01	19.47	7.00	177.2	142	0.7	101	8361
	8.00	19.46	7.04	176.9	142	0.8	92	8453
	8.01	19.15	7.02	175.2	142	NA	93	8546

Table B.1-1 (continued)

Date	pH	Temp (°C)	DO (%)	ORP (mV)	Specific Conductivity (µS/cm)	Turbidity (NTU)	Purge Volume between Samples (gal.)	Cumulative Purge Volume (gal.)
12/10/08	8.02	19.08	7.07	175.3	142	NA	51	8597
	8.02	19.29	7.04	171.6	142	0.7	46	8643
	8.02	19.07	7.09	170.3	142	NA	49	8692
	8.02	19.46	7.03	168.7	141	NA	47	8739
	8.02	12.72	7.19	190.2	143	8.3	1050	9789
	7.96	21.73	6.67	180.8	142	52.0	62	9851
	8.00	20.16	6.99	172.4	83	12.5	153	10004
	8.02	20.09	7.12	174.8	144	6.1	171	10175
	8.00	20.28	6.91	175.1	143	6.5	148	10323
	7.98	20.30	6.90	175.0	143	3.1	149	10472
	7.99	20.27	6.88	175.1	93	3.3	129	10601
	8.00	23.30	6.89	176.3	141	5.2	72	10673
	7.99	20.26	6.85	177.1	142	4.3	120	10793
Aquifer Testing Volumes								
12/13/08	Mini-test #1; parameters not collected						85	85
	Mini-test #2; parameters not collected						146	231
	Mini-test #3; parameters not collected						324	555
12/15/08 (24 h)	7.89	20.69	5.45	149.6	144	1.1	1379	1934
	7.96	20.90	5.47	158.6	142	1.1	460	2394
	7.97	19.88	5.79	170.3	144	1.3	613	3007
	7.97	20.34	5.66	143.8	143	1.0	1226	4233
	7.93	20.30	5.39	166.4	144	1.2	613	4846
	7.94	20.87	5.48	133.1	142	0.7	613	5459
12/16/08 (24 h)	7.92	21.35	5.48	146.6	141	0.7	613	6072
	7.93	20.61	5.53	147.4	143	0.6	613	6685
	7.90	20.83	5.36	112.8	141	0.8	613	7298
	Parameters not collected						613	7911

* NA = Not analyzed.

Table B.1-2
Analytical Results for Groundwater Screening Samples Collected at R-38, Cañada del Buey

Sample ID	Date Received	Sample Type	ER/RRES-WQH	depth (feet)	Ag rslt (ppm)	stdev (Ag)	Al rslt (ppm)	stdev (Al)	As rslt (ppm)	stdev (As)	B rslt (ppm)	stdev (B)	Ba rslt (ppm)	stdev (Ba)	Be rslt (ppm)	stdev (Be)
GW38-09-934	11/8/2008	Borehole	09-231	635	0.001	U[a]	0.01	0.00	0.0014	0.0000	0.036	0.000	0.009	0.000	0.001	U
GW38-09-935	11/8/2008	Borehole	09-231	720.5	0.001	U	0.91	0.01	0.0010	0.0001	0.037	0.001	0.004	0.000	0.001	U
GW38-09-936	11/8/2008	Borehole	09-231	764	0.001	U	1.45	0.19	0.0006	0.0001	0.025	0.000	0.056	0.000	0.001	U
GW38-09-937	11/8/2008	Borehole	09-231	784	0.001	U	5.89	0.16	0.0013	0.0000	0.024	0.000	0.107	0.001	0.001	U
GW38-09-938	11/8/2008	Borehole	09-231	804	0.001	U	1.24	0.02	0.0005	0.0000	0.020	0.000	0.024	0.000	0.001	U
GW38-09-939	11/8/2008	Borehole	09-231	824	0.001	U	1.44	0.01	0.0006	0.0000	0.016	0.000	0.102	0.000	0.001	U
GW38-09-940	11/8/2008	Borehole	09-231	844	0.001	U	0.30	0.00	0.0004	0.0000	0.016	0.001	0.043	0.001	0.001	U
GW38-09-941	11/8/2008	Borehole	09-231	864	0.001	U	0.10	0.00	0.0008	0.0000	0.014	0.000	0.033	0.001	0.001	U
GW38-09-942	11/8/2008	Borehole	09-231	884	0.001	U	0.65	0.00	0.0004	0.0000	0.013	0.000	0.030	0.001	0.001	U
GW38-09-943	11/8/2008	Borehole	09-231	904	0.001	U	0.10	0.00	0.0004	0.0000	0.051	0.001	0.027	0.000	0.001	U
GW38-09-914	12/10/2008	Well Development	09-475	821.2-831.2	NA[b]	Not applicable	0.005	0.000	NA	Not applicable	0.033	0.000	0.029	0.000	NA	Not applicable
GW38-09-915	12/10/2008	Well Development	09-475	821.2-831.2	NA	Not applicable	0.005	0.000	NA	Not applicable	0.025	0.000	0.029	0.000	NA	Not applicable
GW38-09-916	12/10/2008	Well Development	09-475	821.2-831.2	NA	Not applicable	0.005	0.000	NA	Not applicable	0.020	0.000	0.029	0.000	NA	Not applicable
GW38-09-917	12/10/2008	Well Development	09-475	821.2-831.2	NA	Not applicable	0.004	0.000	NA	Not applicable	0.017	0.000	0.029	0.000	NA	Not applicable
GW38-09-918	12/10/2008	Well Development	09-475	821.2-831.2	NA	Not applicable	0.005	0.000	NA	Not applicable	0.016	0.001	0.029	0.001	NA	Not applicable
GW38-09-919	12/17/2008	Aquifer Performance	09-534	821.2-831.2	NA	Not applicable	0.004	0.000	NA	Not applicable	0.017	0.001	0.027	0.000	NA	Not applicable
GW38-09-920	12/17/2008	Aquifer Performance	09-534	821.2-831.2	NA	Not applicable	0.004	0.000	NA	Not applicable	0.014	0.001	0.028	0.000	NA	Not applicable
GW38-09-921	12/17/2008	Aquifer Performance	09-534	821.2-831.2	NA	Not applicable	0.004	0.000	NA	Not applicable	0.013	0.001	0.028	0.000	NA	Not applicable
GW38-09-922	12/17/2008	Aquifer Performance	09-534	821.2-831.2	NA	Not applicable	0.004	0.000	NA	Not applicable	0.013	0.000	0.028	0.000	NA	Not applicable
GW38-09-923	12/17/2008	Aquifer Performance	09-534	821.2-831.2	NA	Not applicable	0.004	0.000	NA	Not applicable	0.012	0.000	0.027	0.000	NA	Not applicable

Table B.1-2 (continued)

Sample ID	Date Received	Sample Type	Br(-) ppm	Br(-) (U)	TOC rslt (ppm)	TOC (U)	Ca rslt (ppm)	stdev (Ca)	Cd rslt (ppm)	stdev (Cd)	Cl(-) ppm	ClO4(-) ppm	ClO4(-) (U)	Co rslt (ppm)	stdev (Co)
GW38-09-934	11/8/2008	Borehole	0.26	Detected	NA	Not applicable	20	0	0.001	U	6.56	NA	Not applicable	0.001	U
GW38-09-935	11/8/2008	Borehole	0.03	Detected	NA	Not applicable	15	0	0.001	U	6.26	NA	Not applicable	0.001	U
GW38-09-936	11/8/2008	Borehole	0.02	Detected	NA	Not applicable	10	0	0.001	U	8.75	NA	Not applicable	0.001	U
GW38-09-937	11/8/2008	Borehole	0.05	Detected	NA	Not applicable	9	0	0.001	U	11.3	NA	Not applicable	0.003	0.000
GW38-09-938	11/8/2008	Borehole	0.02	Detected	NA	Not applicable	9	0	0.001	U	8.11	NA	Not applicable	0.001	U
GW38-09-939	11/8/2008	Borehole	0.04	Detected	NA	Not applicable	13	0	0.001	U	6.59	NA	Not applicable	0.001	U
GW38-09-940	11/8/2008	Borehole	0.01	U	NA	Not applicable	13	0	0.001	U	5.13	NA	Not applicable	0.001	U
GW38-09-941	11/8/2008	Borehole	0.04	Detected	NA	Not applicable	13	0	0.001	U	4.56	NA	Not applicable	0.001	U
GW38-09-942	11/8/2008	Borehole	0.04	Detected	NA	Not applicable	12	0	0.001	U	2.84	NA	Not applicable	0.001	U
GW38-09-943	11/8/2008	Borehole	0.04	Detected	NA	Not applicable	12	0	0.001	U	2.91	NA	Not applicable	0.001	U
GW38-09-914	12/10/2008	Well Development	0.02	Detected	0.24	Detected	13	0	NA	Not applicable	3.38	0.002	U	NA	Not applicable
GW38-09-915	12/10/2008	Well Development	0.05	Detected	0.21	Detected	13	0	NA	Not applicable	3.28	0.002	U	NA	Not applicable
GW38-09-916	12/10/2008	Well Development	0.04	Detected	0.39	Detected	12	0	NA	Not applicable	3.34	0.002	U	NA	Not applicable
GW38-09-917	12/10/2008	Well Development	0.05	Detected	0.26	Detected	12	0	NA	Not applicable	3.31	0.002	U	NA	Not applicable
GW38-09-918	12/10/2008	Well Development	0.03	Detected	0.49	Detected	12	0	NA	Not applicable	3.22	0.002	U	NA	Not applicable
GW38-09-919	12/17/2008	Aquifer Performance	0.05	Detected	1.02	Detected	11.8	0.1	NA	Not applicable	3.27	0.002	U	NA	Not applicable
GW38-09-920	12/17/2008	Aquifer Performance	0.04	Detected	0.20	U	11.8	0.1	NA	Not applicable	3.24	0.002	U	NA	Not applicable
GW38-09-921	12/17/2008	Aquifer Performance	0.07	Detected	0.20	U	11.7	0.1	NA	Not applicable	3.28	0.002	U	NA	Not applicable
GW38-09-922	12/17/2008	Aquifer Performance	0.06	Detected	0.24	Detected	11.5	0.0	NA	Not applicable	3.33	0.002	U	NA	Not applicable
GW38-09-923	12/17/2008	Aquifer Performance	0.06	Detected	0.20	U	11.5	0.1	NA	Not applicable	3.29	0.002	U	NA	Not applicable

Table B.1-2 (continued)

Sample ID	Date Received	Sample Type	Alk-CO3 rslt (ppm)	ALK-CO3 (U)	Cr rslt (ppm)	stdev (Cr)	Cr 6+ rslt (ppm)	Cs rslt (ppm)	stdev (Cs)	Cu rslt (ppm)	stdev (Cu)	F(-) ppm	Fe rslt (ppm)	stdev (Fe)	Alk-CO3+HCO3 rslt (ppm)	Hg rslt (ppm)	stdev (Hg)
GW38-09-934	11/8/2008	Borehole	0.8	U	0.001	U	NA	0.001	U	0.003	0.000	1.54	0.01	U	127	0.00010	0.00001
GW38-09-935	11/8/2008	Borehole	6.26	Detected	0.002	0.000	NA	0.001	U	0.009	0.001	0.43	1.36	0.02	131	0.00010	0.00001
GW38-09-936	11/8/2008	Borehole	0.8	U	0.001	0.000	NA	0.001	U	0.046	0.000	0.68	3.78	0.37	117	0.00006	0.00003
GW38-09-937	11/8/2008	Borehole	0.8	U	0.003	0.000	NA	0.001	U	0.069	0.007	1.84	7.52	0.19	188	0.00016	0.00001
GW38-09-938	11/8/2008	Borehole	0.8	U	0.002	0.000	NA	0.001	U	0.010	0.000	0.76	2.54	0.03	124	0.00015	0.00000
GW38-09-939	11/8/2008	Borehole	0.8	U	0.001	0.000	NA	0.001	U	0.005	0.000	0.74	2.51	0.00	107	0.00012	0.00001
GW38-09-940	11/8/2008	Borehole	0.8	U	0.001	U	NA	0.001	U	0.001	0.000	0.47	0.68	0.00	93	0.00008	0.00001
GW38-09-941	11/8/2008	Borehole	0.8	U	0.001	U	NA	0.001	U	0.008	0.000	0.61	0.17	0.00	107	0.00016	0.00001
GW38-09-942	11/8/2008	Borehole	0.8	U	0.001	0.000	NA	0.001	U	0.001	0.000	0.45	0.71	0.01	79	0.00005	U
GW38-09-943	11/8/2008	Borehole	0.8	U	0.001	U	NA	0.001	U	0.001	0.000	0.50	0.13	0.00	77	0.00005	U
GW38-09-914	12/10/2008	Well Development	0.8	U	0.001	0.000	NA	NA	Not applicable	NA	Not applicable	0.39	0.16	0.00	85.1	NA	Not applicable
GW38-09-915	12/10/2008	Well Development	0.8	U	0.002	0.000	NA	NA	Not applicable	NA	Not applicable	0.36	0.30	0.00	87.7	NA	Not applicable
GW38-09-916	12/10/2008	Well Development	0.8	U	0.002	0.000	NA	NA	Not applicable	NA	Not applicable	0.37	0.33	0.00	82.5	NA	Not applicable
GW38-09-917	12/10/2008	Well Development	0.8	U	0.001	0.000	NA	NA	Not applicable	NA	Not applicable	0.48	0.34	0.00	82.2	NA	Not applicable
GW38-09-918	12/10/2008	Well Development	0.8	U	0.002	0.000	NA	NA	Not applicable	NA	Not applicable	0.30	0.37	0.00	81.5	NA	Not applicable
GW38-09-919	12/17/2008	Aquifer Performance	0.8	U	0.003	0.001	NA	NA	Not applicable	NA	Not applicable	0.29	0.77	0.01	85.5	NA	Not applicable
GW38-09-920	12/17/2008	Aquifer Performance	0.8	U	0.003	0.001	NA	NA	Not applicable	NA	Not applicable	0.29	0.85	0.01	81.0	NA	Not applicable
GW38-09-921	12/17/2008	Aquifer Performance	0.8	U	0.003	0.001	NA	NA	Not applicable	NA	Not applicable	0.28	0.84	0.01	80.4	NA	Not applicable
GW38-09-922	12/17/2008	Aquifer Performance	0.8	U	0.003	0.001	NA	NA	Not applicable	NA	Not applicable	0.28	0.76	0.00	79.8	NA	Not applicable
GW38-09-923	12/17/2008	Aquifer Performance	0.8	U	0.003	0.000	NA	NA	Not applicable	NA	Not applicable	0.28	0.78	0.01	79.7	NA	Not applicable

Table B.1-2 (continued)

Sample ID	Date Received	Sample Type	K rslt (ppm)	stdev (K)	Li rslt (ppm)	stdev (Li)	Mg rslt (ppm)	stdev (Mg)	Mn rslt (ppm)	stdev (Mn)	Mo rslt (ppm)	stdev (Mo)	Na rslt (ppm)	stdev (Na)	Ni rslt (ppm)	stdev (Ni)	NO2(ppm)	NO2-N rslt
GW38-09-934	11/8/2008	Borehole	2.36	0.00	0.028	0.001	4.84	0.05	0.014	0.001	0.094	0.001	14	0	0.002	0.000	0.01	0.003
GW38-09-935	11/8/2008	Borehole	2.57	0.02	0.034	0.002	3.00	0.02	0.018	0.003	0.017	0.000	27	0	0.004	0.000	0.01	0.003
GW38-09-936	11/8/2008	Borehole	4.73	0.10	0.032	0.000	3.72	0.05	0.042	0.001	0.183	0.002	27	0	0.003	0.000	0.01	0.003
GW38-09-937	11/8/2008	Borehole	7.00	0.16	0.049	0.002	3.44	0.08	0.068	0.002	0.197	0.001	51	0	0.006	0.000	0.01	0.003
GW38-09-938	11/8/2008	Borehole	4.77	0.01	0.031	0.000	3.37	0.03	0.016	0.001	0.044	0.000	29	0	0.002	0.000	0.01	0.003
GW38-09-939	11/8/2008	Borehole	2.93	0.01	0.032	0.000	4.05	0.03	0.034	0.000	0.040	0.000	19	0	0.003	0.000	0.01	0.003
GW38-09-940	11/8/2008	Borehole	2.20	0.01	0.032	0.001	3.91	0.02	0.031	0.001	0.022	0.000	13	0	0.002	0.000	0.01	0.003
GW38-09-941	11/8/2008	Borehole	3.51	0.02	0.035	0.000	3.89	0.01	0.021	0.001	0.288	0.001	14	0	0.002	0.000	0.01	0.003
GW38-09-942	11/8/2008	Borehole	1.83	0.01	0.029	0.001	3.65	0.00	0.038	0.002	0.009	0.000	10	0	0.003	0.000	0.01	0.003
GW38-09-943	11/8/2008	Borehole	2.01	0.02	0.029	0.000	3.44	0.04	0.011	0.000	0.006	0.000	10	0	0.002	0.000	0.01	0.003
GW38-09-914	12/10/2008	Well Development	1.54	0.02	0.027	0.000	3.65	0.02	0.009	0.000	NA	Not applicable	12	0	NA	Not applicable	0.01	0.003
GW38-09-915	12/10/2008	Well Development	1.54	0.01	0.026	0.000	3.61	0.02	0.008	0.000	NA	Not applicable	11	0	NA	Not applicable	0.01	0.003
GW38-09-916	12/10/2008	Well Development	1.51	0.01	0.026	0.000	3.59	0.03	0.008	0.000	NA	Not applicable	11	0	NA	Not applicable	0.01	0.003
GW38-09-917	12/10/2008	Well Development	1.49	0.00	0.026	0.000	3.55	0.02	0.008	0.000	NA	Not applicable	11	0	NA	Not applicable	0.01	0.003
GW38-09-918	12/10/2008	Well Development	1.50	0.01	0.026	0.000	3.57	0.03	0.008	0.000	NA	Not applicable	11	0	NA	Not applicable	0.01	0.003
GW38-09-919	12/17/2008	Aquifer Performance	1.44	0.01	0.026	0.000	3.51	0.01	0.017	0.000	NA	Not applicable	11	0	NA	Not applicable	0.01	0.003
GW38-09-920	12/17/2008	Aquifer Performance	1.45	0.01	0.026	0.000	3.51	0.01	0.017	0.000	NA	Not applicable	10	0	NA	Not applicable	0.01	0.003
GW38-09-921	12/17/2008	Aquifer Performance	1.44	0.02	0.026	0.000	3.48	0.02	0.016	0.000	NA	Not applicable	11	0	NA	Not applicable	0.01	0.003
GW38-09-922	12/17/2008	Aquifer Performance	1.45	0.00	0.026	0.000	3.53	0.02	0.016	0.000	NA	Not applicable	10	0	NA	Not applicable	0.01	0.003
GW38-09-923	12/17/2008	Aquifer Performance	1.43	0.00	0.025	0.000	3.45	0.02	0.016	0.000	NA	Not applicable	10	0	NA	Not applicable	0.01	0.003

Table B.1-2 (continued)

Sample ID	Date Received	Sample Type	NO2-N (U)	NO3 ppm	NO3-N rslt	NO3-N (U)	C2O4 rslt (ppm)	C2O4 (U)	Pb rslt (ppm)	stdev (Pb)	pH	PO4(-3) rslt (ppm)	PO4(-3) (U)	Rb rslt (ppm)	stdev (Rb)	S2- rslt (ppm)	S2- (U)	Sb rslt (ppm)
GW38-09-934	11/8/2008	Borehole	U	0.93	0.210	Detected	0.01	U	0.0004	0.0000	8.06	0.01	U	0.002	0.000	NA	Not applicable	0.001
GW38-09-935	11/8/2008	Borehole	U	0.01	0.002	U	0.01	U	0.0007	0.0001	8.38	0.01	U	0.003	0.000	NA	Not applicable	0.005
GW38-09-936	11/8/2008	Borehole	U	0.01	0.002	U	0.15	Detected	0.0014	0.0000	7.63	0.01	U	0.007	0.000	NA	Not applicable	0.001
GW38-09-937	11/8/2008	Borehole	U	0.01	0.002	U	0.17	Detected	0.0027	0.0000	8.36	1.29	Detected	0.008	0.000	NA	Not applicable	0.001
GW38-09-938	11/8/2008	Borehole	U	0.01	0.002	U	0.04	Detected	0.0007	0.0000	7.70	0.38	Detected	0.005	0.000	NA	Not applicable	0.001
GW38-09-939	11/8/2008	Borehole	U	0.01	0.003	Detected	0.02	Detected	0.0066	0.0000	7.70	0.05	Detected	0.004	0.000	NA	Not applicable	0.001
GW38-09-940	11/8/2008	Borehole	U	2.03	0.458	Detected	0.02	Detected	0.0015	0.0000	7.81	0.11	Detected	0.003	0.000	NA	Not applicable	0.001
GW38-09-941	11/8/2008	Borehole	U	2.50	0.565	Detected	0.04	Detected	0.0010	0.0001	7.79	0.14	Detected	0.004	0.000	NA	Not applicable	0.001
GW38-09-942	11/8/2008	Borehole	U	2.72	0.614	Detected	0.01	U	0.0011	0.0001	7.85	0.04	Detected	0.003	0.000	NA	Not applicable	0.001
GW38-09-943	11/8/2008	Borehole	U	3.18	0.717	Detected	0.01	U	0.0009	0.0000	7.92	0.05	Detected	0.003	0.000	NA	Not applicable	0.001
GW38-09-914	12/10/2008	Well Development	U	2.82	0.638	Detected	0.01	U	NA	Not applicable	8.06	0.06	Detected	NA	Not applicable	NA	Not applicable	NA
GW38-09-915	12/10/2008	Well Development	U	2.84	0.640	Detected	0.01	U	NA	Not applicable	7.99	0.04	Detected	NA	Not applicable	NA	Not applicable	NA
GW38-09-916	12/10/2008	Well Development	U	2.83	0.640	Detected	0.01	U	NA	Not applicable	7.87	0.02	Detected	NA	Not applicable	NA	Not applicable	NA
GW38-09-917	12/10/2008	Well Development	U	2.89	0.653	Detected	0.01	U	NA	Not applicable	7.85	0.01	U	NA	Not applicable	NA	Not applicable	NA
GW38-09-918	12/10/2008	Well Development	U	2.86	0.645	Detected	0.01	U	NA	Not applicable	7.86	0.03	Detected	NA	Not applicable	NA	Not applicable	NA
GW38-09-919	12/17/2008	Aquifer Performance	U	2.90	0.655	Detected	0.01	U	NA	Not applicable	7.90	0.01	U	NA	Not applicable	NA	Not applicable	NA
GW38-09-920	12/17/2008	Aquifer Performance	U	2.87	0.648	Detected	0.01	U	NA	Not applicable	7.74	0.02	Detected	NA	Not applicable	NA	Not applicable	NA
GW38-09-921	12/17/2008	Aquifer Performance	U	2.98	0.672	Detected	0.01	U	NA	Not applicable	7.68	0.05	Detected	NA	Not applicable	NA	Not applicable	NA
GW38-09-922	12/17/2008	Aquifer Performance	U	2.90	0.654	Detected	0.01	U	NA	Not applicable	7.63	0.01	U	NA	Not applicable	NA	Not applicable	NA
GW38-09-923	12/17/2008	Aquifer Performance	U	2.88	0.651	Detected	0.01	U	NA	Not applicable	7.67	0.06	Detected	NA	Not applicable	NA	Not applicable	NA

Table B.1-2 (continued)

Sample ID	Date Received	Sample Type	stdev (Sb)	Se rslt (ppm)	stdev (Se)	Si rslt (ppm)	stdev (Si)	SiO2 rslt (ppm)	stdev (SiO2)	Sn rslt (ppm)	stdev (Sn)	SO4(-2) rslt (ppm)	Sr rslt (ppm)	stdev (Sr)	Th rslt (ppm)	stdev (Th)	Ti rslt (ppm)
GW38-09-934	11/8/2008	Borehole	U	0.001	U	15.9	0.1	34.1	0.2	0.001	U	4.53	0.077	0.001	0.001	U	0.002
GW38-09-935	11/8/2008	Borehole	0.000	0.001	U	24.0	0.2	51.3	0.5	0.001	U	3.59	0.013	0.001	0.001	U	0.027
GW38-09-936	11/8/2008	Borehole	U	0.001	U	26.5	0.3	56.6	0.6	0.001	U	3.95	0.074	0.001	0.001	U	0.100
GW38-09-937	11/8/2008	Borehole	U	0.001	0.000	28.1	1.0	60.1	2.1	0.001	U	7.03	0.102	0.001	0.001	0.000	0.468
GW38-09-938	11/8/2008	Borehole	U	0.001	U	23.8	0.1	51.0	0.3	0.001	U	3.62	0.061	0.001	0.001	U	0.076
GW38-09-939	11/8/2008	Borehole	U	0.001	U	25.3	0.3	54.0	0.7	0.001	U	3.95	0.077	0.001	0.001	0.000	0.587
GW38-09-940	11/8/2008	Borehole	U	0.001	U	26.9	0.2	57.6	0.5	0.001	U	3.90	0.057	0.000	0.001	U	0.118
GW38-09-941	11/8/2008	Borehole	U	0.001	U	24.1	0.1	51.6	0.1	0.001	U	5.04	0.056	0.001	0.001	U	0.033
GW38-09-942	11/8/2008	Borehole	U	0.001	U	34.7	0.1	74.2	0.3	0.001	U	2.98	0.043	0.000	0.001	U	0.064
GW38-09-943	11/8/2008	Borehole	U	0.001	U	33.4	0.5	71.4	1.0	0.001	U	3.37	0.044	0.000	0.001	U	0.027
GW38-09-914	12/10/2008	Well Development	Not applicable	NA	Not applicable	32.3	0.2	69.2	0.4	NA	Not applicable	4.14	0.054	0.000	NA	Not applicable	0.002
GW38-09-915	12/10/2008	Well Development	Not applicable	NA	Not applicable	32.4	0.3	69.3	0.6	NA	Not applicable	3.90	0.051	0.000	NA	Not applicable	0.002
GW38-09-916	12/10/2008	Well Development	Not applicable	NA	Not applicable	32.2	0.3	68.8	0.6	NA	Not applicable	3.70	0.050	0.000	NA	Not applicable	0.002
GW38-09-917	12/10/2008	Well Development	Not applicable	NA	Not applicable	31.8	0.2	68.0	0.4	NA	Not applicable	3.61	0.050	0.001	NA	Not applicable	0.002
GW38-09-918	12/10/2008	Well Development	Not applicable	NA	Not applicable	31.9	0.2	68.4	0.4	NA	Not applicable	3.54	0.050	0.000	NA	Not applicable	0.002
GW38-09-919	12/17/2008	Aquifer Performance	Not applicable	NA	Not applicable	31.7	0.2	67.9	0.5	NA	Not applicable	3.46	0.049	0.000	NA	Not applicable	0.002
GW38-09-920	12/17/2008	Aquifer Performance	Not applicable	NA	Not applicable	31.7	0.3	67.9	0.7	NA	Not applicable	3.45	0.048	0.000	NA	Not applicable	0.002
GW38-09-921	12/17/2008	Aquifer Performance	Not applicable	NA	Not applicable	31.6	0.1	67.7	0.2	NA	Not applicable	3.37	0.047	0.000	NA	Not applicable	0.002
GW38-09-922	12/17/2008	Aquifer Performance	Not applicable	NA	Not applicable	31.9	0.3	68.4	0.6	NA	Not applicable	3.40	0.047	0.000	NA	Not applicable	0.002
GW38-09-923	12/17/2008	Aquifer Performance	Not applicable	NA	Not applicable	31.3	0.3	67.0	0.6	NA	Not applicable	3.34	0.046	0.000	NA	Not applicable	0.002

Table B.1-2 (continued)

Sample ID	Date Received	Sample Type	stdev (Ti)	Tl rslt (ppm)	stdev (Tl)	U rslt (ppm)	stdev (U)	V rslt (ppm)	stdev (V)	Zn rslt (ppm)	stdev (Zn)	TDS (ppm)	Cations	Anions	Balance
GW38-09-934	11/8/2008	Borehole	U	0.001	U	0.0008	0.0000	0.014	0.000	0.003	0.000	217.5	2.1	2.5	-0.09
GW38-09-935	11/8/2008	Borehole	0.000	0.001	U	0.0005	0.0000	0.006	0.001	0.007	0.000	249.2	2.2	2.7	-0.08
GW38-09-936	11/8/2008	Borehole	0.009	0.001	U	0.0007	0.0000	0.003	0.000	0.013	0.000	239.3	2.1	2.3	-0.05
GW38-09-937	11/8/2008	Borehole	0.044	0.001	U	0.0031	0.0001	0.013	0.000	0.018	0.001	355.9	3.2	3.8	-0.09
GW38-09-938	11/8/2008	Borehole	0.001	0.001	U	0.0009	0.0000	0.005	0.000	0.006	0.000	238.7	2.1	2.4	-0.07
GW38-09-939	11/8/2008	Borehole	0.003	0.001	U	0.0029	0.0001	0.011	0.000	0.023	0.000	217.5	1.9	2.1	-0.05
GW38-09-940	11/8/2008	Borehole	0.001	0.001	U	0.0012	0.0000	0.005	0.000	0.007	0.000	196.3	1.6	1.8	-0.07
GW38-09-941	11/8/2008	Borehole	0.000	0.001	U	0.0012	0.0000	0.005	0.000	0.005	0.000	207.8	1.7	2.1	-0.11
GW38-09-942	11/8/2008	Borehole	0.001	0.001	U	0.0006	0.0000	0.004	0.000	0.005	0.000	191.9	1.4	1.6	-0.07
GW38-09-943	11/8/2008	Borehole	0.000	0.001	U	0.0005	0.0000	0.004	0.000	0.005	0.000	186.9	1.4	1.5	-0.06
GW38-09-914	12/10/2008	Well Development	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.014	0.001	195.8	1.5	1.7	-0.06
GW38-09-915	12/10/2008	Well Development	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.009	0.001	197.9	1.5	1.7	-0.08
GW38-09-916	12/10/2008	Well Development	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.019	0.001	191.6	1.4	1.6	-0.06
GW38-09-917	12/10/2008	Well Development	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.020	0.001	190.2	1.4	1.6	-0.06
GW38-09-918	12/10/2008	Well Development	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.022	0.002	189.3	1.4	1.6	-0.06
GW38-09-919	12/17/2008	Aquifer Performance	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.019	0.001	192.6	1.4	1.7	-0.09
GW38-09-920	12/17/2008	Aquifer Performance	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.015	0.001	187.8	1.4	1.6	-0.07
GW38-09-921	12/17/2008	Aquifer Performance	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.014	0.002	187.1	1.4	1.6	-0.07
GW38-09-922	12/17/2008	Aquifer Performance	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.023	0.001	186.8	1.4	1.6	-0.07
GW38-09-923	12/17/2008	Aquifer Performance	U	NA	Not applicable	NA	Not applicable	NA	Not applicable	0.017	0.001	185.0	1.3	1.6	-0.07

[a] U = Not detected.

[b] NA = Not analyzed.

Appendix C

Aquifer Testing Report

C-1.0 INTRODUCTION

This appendix describes the hydraulic analysis of pumping tests at well R-38 located in the north fork of Cañada del Buey within Technical Area 54 (TA-54). The primary objective of the analysis was to determine the hydraulic properties of the formation screened by R-38. Testing consisted primarily of constant-rate pumping tests.

Consistent with most of the R-well pumping tests conducted on the plateau, an inflatable packer system was used in R-38 to eliminate the effects of casing storage on the test data.

Conceptual Hydrogeology

R-38 is completed in the regional aquifer at the base of the Cerros del Rio basalt in a transitional zone just above the Puye Formation. It is a single-screen completion with 10 ft of screen between 821.2 and 831.2 ft below ground surface (bgs). The transitional zone was identified as 14 ft thick, extending from 820 to 834 ft bgs. The static water level before testing was 809.85 ft bgs. The estimated ground surface elevation at R-38 was 6670 ft above mean sea level (amsl), making the static water level elevation about 5860 ft amsl.

As described below, the pumping test data did not show the usual flattening of the drawdown and recovery curves (often indicative of vertical expansion of the cone of depression and/or, in some cases, unconfined conditions) as seen in almost all wells on the plateau. Therefore, it was assumed that the top of the underlying Puye Formation was an effective aquitard beneath the screened interval. Also, because the water level was about 11 ft above the top of the screen, which was overlain by thick lava flows, confined conditions were assumed for R-38. In other words, the aquifer was interpreted as consisting of just the 14-ft-thick transitional zone. Nevertheless, it is possible that the contiguous hydraulic unit penetrated by R-38 could include a portion of the overlying basalt or underlying Puye Formation. If this were the case, the hydraulic conductivity values cited below would be scaled back in proportion to the ratio of the transitional zone thickness (14 ft) and the actual (but unknown) effective thickness of the contiguous permeable zone penetrated by the well screen. As described below, the pumping test data indicated the possibility of a permeable thickness greater than 14 ft, perhaps on the order of 30 ft.

R-38 Testing

R-38 was tested from December 13 to December 17, 2008. Testing consisted of an initial pumping event to fill the drop pipe and set the discharge rate, two trial tests, and a 24-h constant-rate test.

Because of the limited distance between the static water level and the top of the well screen, it was necessary to place the pump intake within the well screen to ensure that the inflatable packer would be submerged. This created the risk that when the pump was started against low head (empty drop pipe), the discharge rate could be great enough to pull the water level into the screen, exposing the top of the screen to air. This could have resulted in entraining air in the filter pack, causing casing-storagelike effects in the test data. To avoid this, the pump intake was initially placed just a few feet below the water table and run long enough to fill the drop pipe and valve back the discharge rate to an acceptable level. Then the pump was lowered to the target depth and the packer was inflated for subsequent testing.

Trial 1 consisted of pumping R-38 for 30 min from 12:30 to 1:00 p.m. on December 13. The initial discharge rate was 2.5 gpm. Midway through the test, the rate was increased to 5.8 gpm. Following shutdown, recovery was measured for 120 min until 3:00 p.m.

Trial 2 was conducted for 60 min from 3:00 to 4:00 p.m. The initial discharge rate was 5.64 gpm, declining to 5.54 gpm part way through the test. Following pump shutoff, recovery/background data were collected for 40 h until 8:00 a.m. on December 15.

The 24-h constant-rate pumping test was conducted from 8:00 a.m. on December 15 to 8:00 a.m. on December 16. The initial discharge rate was 5.7 gpm, falling off quickly to 5.45 gpm. Recovery data were recorded for 24 h until 8:00 a.m. on December 17.

During each test, a slight discharge rate reduction was observed after 10 to 20 min of pumping. There were two possible causes for this. First, the generator output appeared to vary at times based upon gauge readings on the instrument panel, so this may have affected the discharge rate. Second, when pumping began, the discharge hose filled slowly, with water eventually reaching its distant end where the hose ran up the side of the water storage tank and emptied into the port at the top of the tank. The increase in head at the tank location where the vertical segment of hose filled with water would have reduced the discharge rate by a small amount.

C-2.0 BACKGROUND DATA

The background water-level data collected with running the pumping tests allow the analyst to see what water-level fluctuations occur naturally in the aquifer and help to distinguish between water-level changes caused by conducting the pumping test and changes associated with other causes.

Background water-level fluctuations have several causes, among them barometric pressure changes, operation of other wells in the aquifer, earth tides, and long-term trends related to weather patterns. The background data hydrographs from the monitored wells were compared with barometric pressure data from the area to determine if a correlation existed.

Previous pumping tests on the plateau have demonstrated a barometric efficiency for most wells between 90% and 100%. Barometric efficiency is defined as the ratio of water-level change divided by barometric pressure change, expressed as a percentage. In the initial pumping tests conducted on the early R-wells, downhole pressure was monitored using a *vented* pressure transducer. This equipment measures the *difference* between the total pressure applied to the transducer and the barometric pressure, this difference being the true height of water above the transducer.

Subsequent pumping tests, including R-38, have utilized *nonvented* transducers. These devices simply record the total pressure on the transducer, that is, the sum of the water height plus the barometric pressure. This results in an attenuated “apparent” hydrograph in a barometrically efficient well. Take as an example a 90% barometrically efficient well. When monitored using a vented transducer, an *increase* in barometric pressure of 1 unit causes a *decrease* in recorded downhole pressure of 0.9 unit because the water level is forced downward 0.9 unit by the barometric pressure change. However, using a nonvented transducer, the total measured pressure *increases* by 0.1 unit (the combination of the barometric pressure increase and the water-level decrease). Thus, the resulting apparent hydrograph changes by a factor of 100 minus the barometric efficiency and in the same direction as the barometric pressure change, rather than in the opposite direction.

Barometric pressure data were obtained from the TA-54 tower site from the Risk Reduction and Environmental Stewardship–Meteorology and Air Quality (RRES-MAQ). The TA-54 measurement location is at an elevation of 6548 ft level amsl, whereas the wellhead elevation is approximately 6670 ft amsl. The static water level was about 810 ft below land surface, making the water-table elevation roughly 5860 ft amsl. Therefore, the measured barometric pressure data from TA-54 had to be adjusted to reflect the pressure at the elevation of the water table within R-38.

The following formula was used to adjust the measured barometric pressure data:

$$P_{WT} = P_{TA54} \exp\left[-\frac{g}{3.281R} \left(\frac{E_{R38} - E_{TA54}}{T_{TA54}} + \frac{E_{WT} - E_{R38}}{T_{WELL}} \right) \right] \qquad \textbf{Equation C-1}$$

Where, P_{WT} = barometric pressure at the water table inside R-38,

P_{TA54} = barometric pressure measured at TA-54,

g = acceleration of gravity, in m/sec^2 (9.80665 m/sec^2)

R = gas constant, in J/Kg/degree Kelvin (287.04 J/Kg/degree Kelvin),

E_{R38} = land-surface elevation at R-38 site, in feet (6670 ft estimated),

E_{TA54} = elevation of barometric pressure measuring point at TA-54, in feet (6548 ft),

E_{WT} = elevation of the water level in R-38, in feet (approximately 5860 ft),

T_{TA54} = air temperature near TA-54, in degrees Kelvin (assigned a value of 30.1 degrees Fahrenheit, or 272.1 degrees Kelvin), and

T_{WELL} = air temperature inside R-38, in degrees Kelvin (assigned a value of 65.5 degrees Fahrenheit, or 291.8 degrees Kelvin).

This formula is an adaptation of an equation RRES-MAQ provided. It can be derived from the ideal gas law and standard physics principles. An inherent assumption in the derivation of the equation is that the air temperature between TA-54 and the well is temporally and spatially constant and that the temperature of the air column in the well is similarly constant.

The corrected barometric pressure data reflecting pressure conditions at the water table were compared with the water-level hydrographs to discern the correlation between the two.

C-3.0 IMPORTANCE OF EARLY DATA

When pumping or recovery first begins, the vertical extent of the cone of depression is limited to approximately the well screen length, filter pack length, or aquifer thickness in relatively thin permeable strata. For many pumping tests on the plateau, the early pumping period is the only time that the effective height of the cone of depression is known with certainty. Thus, the early data often offer the best opportunity to obtain hydraulic conductivity information because conductivity would equal the earliest-time transmissivity divided by the well screen length.

Unfortunately, in many pumping tests, casing-storage effects dominate the early-time data, hindering the effort to determine the transmissivity of the screened interval. The duration of casing-storage effects can be estimated using the following equation (Schafer 1978, 098240).

$$t_c = \frac{0.6\left(D^2 - d^2\right)}{\frac{Q}{s}} \qquad \textbf{Equation C-2}$$

Where, t_c = duration of casing storage effect, in minutes,

D = inside diameter of well casing, in inches,

d = outside diameter of column pipe, in inches

Q = discharge rate, in gallons per minute, and

s = drawdown observed in pumped well at time t_c, in feet.

In some instances, it is possible to eliminate casing-storage effects by setting an inflatable packer above the tested screen interval before conducting the test. Therefore, this option has been implemented for the R-well testing program, including the R-38 pumping tests.

C-4.0 TIME-DRAWDOWN METHODS

Time-drawdown data can be analyzed using a variety of methods. Among them is the Theis method (1934-1935, 098241). The Theis equation describes drawdown around a well as follows:

$$s = \frac{114.6Q}{T}W(u)$$ **Equation C-3**

Where,

$$W(u) = \int_u^\infty \frac{e^{-x}}{x}dx$$ **Equation C-4**

and

$$u = \frac{1.87r^2S}{Tt}$$ **Equation C-5**

and where, s = drawdown, in feet,

Q = discharge rate, in gallons per minute,

T = transmissivity, in gallons per day per foot,

S = storage coefficient (dimensionless),

t = pumping time, in days, and

r = distance from center of pumpage, in feet.

To use the Theis method of analysis, the time-drawdown data are plotted on log-log graph paper. Then Theis curve matching is performed using the Theis type curve—a plot of the Theis well function $W(u)$ versus $1/u$. Curve matching is accomplished by overlaying the type curve on the data plot and, while keeping the coordinate axes of the two plots parallel, shifting the data plot to align with the type curve, effecting a match position. An arbitrary point, referred to as the match point, is selected from the overlapping parts of the plots. Match-point coordinates are recorded from the two graphs, yielding four values: $W(u)$, $1/u$, s, and t. Using these match-point values, transmissivity and storage coefficient are computed as follows:

$$T = \frac{114.6Q}{s} W(u)$$ **Equation C-6**

$$S = \frac{Tut}{2693r^2}$$ **Equation C-7**

Where, *T* = transmissivity, in gallons per day per foot,

S = storage coefficient,

Q = discharge rate, in gallons per minute,

W(*u*) = match point value,

s = match point value, in feet,

u = match point value, and

t = match point value, in minutes.

An alternative solution method applicable to time-drawdown data is the Cooper–Jacob method (1946, 098236), a simplification of the Theis equation that is mathematically equivalent to the Theis equation for most pumped well data. The Cooper–Jacob equation describes drawdown around a pumping well as follows:

$$s = \frac{264Q}{T} \log \frac{0.3Tt}{r^2 S}$$ **Equation C-8**

The Cooper–Jacob equation is valid whenever the u value is less than about 0.05. For small radius values (e.g., corresponding to borehole radii), u is less than 0.05 at very early pumping times and therefore is less than 0.05 for most or all measured drawdown values. Thus, for the pumped well, the Cooper–Jacob equation usually can be considered a valid approximation of the Theis equation.

According to the Cooper–Jacob method, the time-drawdown data are plotted on a semilog graph, with time plotted on the logarithmic scale. Then a straight line of best fit is constructed through the data points and transmissivity is calculated using

$$T = \frac{264Q}{\Delta s}$$ **Equation C-9**

Where, *T* = transmissivity, in gallons per day per foot,

Q = discharge rate, in gallons per minute, and

Δs = change in head over one log cycle of the graph, in feet.

C-5.0 RECOVERY METHODS

Recovery data were analyzed using the Theis recovery method. This is a semilog analysis method similar to the Cooper–Jacob procedure.

In this method, residual drawdown is plotted on a semilog graph versus the ratio *t/t'*, where *t* is the time since pumping began and *t'* is the time since pumping stopped. A straight line of best fit is constructed through the data points and *T* is calculated from the slope of the line as follows:

$$T = \frac{264Q}{\Delta s}$$ **Equation C-10**

The recovery data are particularly useful compared with time-drawdown data. Because the pump is not running, spurious data responses associated with dynamic discharge rate fluctuations are eliminated. The result is that the data set is generally "smoother" and easier to analyze. This was of paramount importance in the R-38 pumping tests because variable current output from the electric generator induced discharge rate fluctuations.

C-6.0 SPECIFIC CAPACITY METHOD

The specific capacity of the pumped well can be used to obtain a lower-bound value of hydraulic conductivity. The hydraulic conductivity is computed using formulas that are based on the assumption that the pumped well is 100% efficient. The resulting hydraulic conductivity is the value required to sustain the observed specific capacity. If the actual well is less than 100% efficient, it follows that the actual hydraulic conductivity would have to be greater than calculated to compensate for well inefficiency. Thus, because the efficiency is unknown, the computed hydraulic conductivity value represents a lower bound. The actual conductivity is known to be greater than or equal to the computed value.

For fully penetrating wells, the Cooper–Jacob equation can be iterated to solve for the lower-bound hydraulic conductivity. However, the Cooper–Jacob equation (assuming full penetration) ignores the contribution to well yield from permeable sediments above and below the screened interval. To account for this contribution, it is necessary to use a computation algorithm that includes the effects of partial penetration. One such approach was introduced by Brons and Marting (1961, 098235) and augmented by Bradbury and Rothchild (1985, 098234).

Brons and Marting (1961, 098235) introduced a dimensionless drawdown correction factor, s_P, approximated by Bradbury and Rothschild as follows:

$$s_P = \frac{1-\frac{L}{b}}{\frac{L}{b}}\left[\ln\frac{b}{r_w} - 2.948 + 7.363\frac{L}{b} - 11.447\left(\frac{L}{b}\right)^2 + 4.675\left(\frac{L}{b}\right)^3\right]$$ **Equation C-11**

Where S_p = partial penetration correction, dimensionless,

L = well screen length, in feet,

b = aquifer thickness, in feet, and

r_w = radius of the pumping well, in feet.

In this equation, *L* is the well screen length, in feet. Incorporating the dimensionless drawdown parameter, the conductivity is obtained by iterating the following formula:

$$K = \frac{264Q}{sb}\left(\log\frac{0.3Tt}{r_w^2 S} + \frac{2s_P}{\ln 10}\right)$$ **Equation C-12**

Where K = hydraulic conductivity, in feet/day,

Q = flow rate, in gallons per minute,

T = transmissivity, in gallons per day per foot

T = time, in minutes,

S_p = partial penetration correction, dimensionless,

s = drawdown, in feet,

b = aquifer thickness, in feet,

r_w = radius of the pumping well, in feet, and

S = storage coefficient, dimensionless.

To apply this procedure, a storage coefficient value must be assigned. Confined conditions were assumed for R-38. Storage coefficient values for confined conditions can be expected to range from about 10–5 to 10–3 (Driscoll 1986, 104226). The calculation result is not particularly sensitive to the choice of storage coefficient value, so a rough estimate of the storage coefficient is generally adequate to support the calculations. An assumed value of 5 × 10–4 was used for R-38.

The analysis also requires assigning a value for the saturated aquifer thickness, b. For calculation purposes, the estimated aquifer thickness of 14 ft was used, equal to the identified thickness of the transitional zone.

Computing the lower-bound estimate of hydraulic conductivity can provide a useful frame of reference for evaluating the other pumping test calculations.

C-7.0 BACKGROUND DATA ANALYSIS

Background aquifer pressure data collected during the R-38 tests were plotted along with barometric pressure to determine the barometric effect on water levels.

Figure C-7.0-1 shows aquifer pressure data from R-38 along with barometric pressure data from TA-54 that have been corrected to equivalent barometric pressure at the water table in feet of water. The R-38 data are referred to in the figure as the “apparent hydrograph” because the measurements reflect the sum of water pressure and barometric pressure, having been recorded using a nonvented pressure transducer. The times of the pumping periods for the R-38 pumping tests are included in the figure for reference.

The background data collection period ran from 4:00 p.m. on December 13 to 8:00 a.m. on December 15. There was a clear signal shown in the data, with aquifer pressures declining for about 24 h and then rising for the duration of the background monitoring period before starting the 24-h pumping test. Note that beginning about a day earlier, the barometric pressure dropped dramatically and then rose again. Thus, the aquifer pressure response appeared to be a delayed, smoothed, and attenuated version of the barometric pressure signal.

The barometric pressure data were adjusted by reducing them by a barometric efficiency factor and adding a time delay. Further, to help smooth the modified data set, a rolling average was computed with 5 h of antecedent data. Figure C-7.0-2 shows the resulting comparison of the modified change in barometric pressure and the apparent hydrograph for R-38.

To optimize the curve fit, a barometric efficiency of 58% was used in the calculations along with a time delay of 16.5 h. Because 5 h of antecedent data were used in the computations, an average additional delay of 2.5 h was incorporated, for an average time lag of 19 h total. The general form of the two curves in Figure C-7.0-2 was similar, although the barometric pressure curve appeared “lumpy.”

To add more smoothing, the modified change in barometric pressure was recomputed using 8 h of antecedent data in the rolling average. Figure C-7.0-3 shows the resulting data plot for a time delay of 15 h (equivalent to 19-h total average delay, including the antecedent data).

Further improvement in curve smoothing was achieved by computing the rolling average of barometric pressure using 12 h of antecedent data. Figure C-7.0-4 shows the resulting data plot for a time delay of 13 h (equivalent to 19-h total average delay, including the antecedent data). The use of the 12-h rolling average successfully eliminated the lumpiness in the data plot. The resulting graph shows a satisfactory fit between the apparent hydrograph and the barometric pressure curve adjusted for a barometric efficiency of 58% and an effective average time delay of 19 h. The relationship shown in Figure C-7.0-4 was useful in correcting drawdown and recovery data, as described below.

C-8.0 R-38 DATA ANALYSIS

This section presents the data obtained from the R-38 pumping tests and the results of the analytical interpretations. Data are presented for trial 1, trial 2, and the 24-h constant-rate pumping test.

Trial 1

Trial 1 consisted of pumping R-38 for 30 min followed by 120 min of recovery. Figure C-8.0-1 shows a semilog plot of the trial 1 drawdown data. The initial discharge rate was 2.5 gpm. Midway through the test, the rate was increased to 5.8 gpm.

The initial data points on the graph showed exaggerated drawdown. This occurred because the pump had been lowered about 8 ft after filling the drop pipe. Thus, when pumping began, the top 8 ft of drop pipe was empty and the pump operated against only the vertical lift of about 810 ft and not the backpressure valve. This resulted in a pumping rate greater than 2.5 gpm briefly until the drop pipe and discharge pipe were refilled all the way to the backpressure valve. Once water reached the valve, the pressure against the pump increased and the rate settled in at 2.5 gpm.

The line of fit shown on the graph corresponding to a discharge rate of 5.8 gpm revealed a transmissivity of 3220 gpd/ft. Based on the assumed aquifer thickness of 14 ft, this made the hydraulic conductivity 230 gpd/ft^2, or 30.7 ft/d. Note that if more than 14 ft of formation contributed to the yield to the well, the corresponding calculated hydraulic conductivity would be proportionately less.

Figure C-8.0-2 shows the recovery data following pump shutoff. The transmissivity computed from the graph was 4490 gpd/ft, making the hydraulic conductivity 321 gpd/ft^2, or 42.9 ft/d.

The early data in Figure C-8.0-2 were not analyzed because of limited data density. The density of data collected for trial 2 and the 24-h test was greater, so early data analysis was deferred to those tests.

Trial 2

Trial 2 consisted of pumping R-38 for 60 min followed by 40 h of recovery. Figure C-8.0-3 shows a semilog plot of the trial 2 drawdown data. The initial measured discharge rate was 5.64 gpm. After about 10 min of pumping, the rate declined to 5.54 gpm, either because of a change in generator output or because of the change in pumping head that occurred as the elevated end of the discharge hose filled with water.

The early data in Figure C-8.0-3 showed exaggerated drawdown that was seen in trial 1, although the duration of the effect was an order of magnitude shorter. In trial 2, the entire drop pipe remained full before startup. However, a short segment of the horizontal discharge piping just ahead of the backpressure valve may have drained away through the discharge hose between tests, leaving a minor volume of piping to be refilled before pumped water reached the valve. This likely accounted for the erratic water-level response at early time. It is also possible that a minor volume of drop pipe water drained through leaky coupling joints downhole as sometimes occurs in these tests.

The first 10 min of data, corresponding to a discharge rate of 5.64 gpm yielded a calculated transmissivity of 3430 gpd/ft, making the hydraulic conductivity 245 gpd/ft^2, or 32.8 ft/d. The last half hour of the test, after the discharge rate had settled in at 5.54 gpm, supported a transmissivity determination of 4230 gpd/ft and hydraulic conductivity value of 302 gpd/ft^2, or 40.4 ft/d.

Figure C-8.0-4 shows a semilog plot of the recovery data from trial 2. Two distinct slopes were evident on the graph. The rapid data collection scheme enabled identifying the early data slope.

The early data (just a few seconds) supported a calculated transmissivity value of just 1300 gpd/ft. Dividing this value by the well screen length of 10 ft produced a hydraulic conductivity value of 130 gpd/ft^2, or 17.4 ft/d. This was substantially less than values obtained from other analyses.

There are several possible explanations for the observation of a lower hydraulic conductivity at early time. One possibility is sediments of lower permeability in the vicinity of the well screen compared with the aquifer at large. A second possibility is that the effective aquifer thickness is greater than 14 ft, which would make previous hydraulic conductivity values less than computed above and in better agreement with the early time result. Without better identification of permeable versus nonpermeable zones (from drilling observations and/or geophysics), it is not possible to determine if this is the case.

A final possibility is that the early data may have been affected by a storage phenomenon. When R-38 was developed, it was pumped at double-digit flow rates. It is possible that the pumping water level was pulled into the well screen just long enough to drain a minor amount of filter pack and trap a small amount of air in the filter pack behind the blank casing above the screen. Expansion and contraction of any trapped air in the system during drawdown and recovery would give a brief storagelike effect and create the appearance seen in Figure C-8.0-4.

Note that the early data were analyzed using the final measured discharge rate of 5.54 gpm. This is because the early recovery data respond according to the last discharge rate of the test. Subsequent data generally conform to the average pumping rate. For the trial 2 test, the average rate was 5.6 gpm.

The middle data in Figure C-8.0-4 supported a transmissivity determination of 4480 gpd/ft and a hydraulic conductivity of 320 gpd/ft^2, or 42.8 ft/d. This was in reasonable agreement with values obtained from trial 1.

The late data in Figure C-8.0-4 showed the effects of changes in barometric pressure. These data were not corrected and analyzed because the brevity of the trial test and short recovery time between trials 1 and 2 would have introduced errors into the analysis.

C-8.1 R-38 24-H Constant-Rate Pumping Test

R-38 was pumped continuously for 24 h from 8:00 a.m. on December 15 to 8:00 a.m. on December 16. Following pump shutoff, recovery data were recorded for 24 h until 8:00 a.m. on December 17.

Figure C-8.1-1 shows a semilog plot of the drawdown data recorded during the 24-h constant-rate pumping test. There were several points of interest revealed by the data.

First, the early data showed exaggerated drawdown associated with refilling the upper portion of the drop pipe that was air-lifted dry to prevent freezing overnight. Until the drop pipe was refilled to the backpressure valve, the pump operated against just the vertical lift of about 810 ft. This resulted in a greater discharge rate initially. Once water reached the valve, the rate declined to 5.7 gpm.

The duration of the greater discharge rate appeared to be between 0.07 and 0.08 min. According to the pump performance curve and pumping lift, the expected discharge rate during that time was about 20 gpm. Thus, around 1.5 gal. of water (20 × 0.075) would have been pumped before the drop pipe filled. This is the volume of about 10 ft of 2-in. Schedule 80 discharge pipe. This estimate agrees well with the typical length of pipe that would have been air-lifted dry to prevent freezing overnight (3 ft of pipe stickup plus an additional 7 ft below ground level).

After 20 min of pumping, there was a distinct change in discharge rate, from 5.7 to 5.45 gpm. This likely was attributable either to a change in the output characteristics of the electric generator used for the test or to the change in pumping head that occurred as the elevated end of the discharge hose filled with water. Note that the time it took for the pumping rate to decline was 20 min in the 24-h test versus 10 min in the trial 2 test (Figure C-8.0-3). In trial 2, a portion of the discharge hose still contained water that had been pumped during trial 1 and thus the hose filled more quickly, whereas the 24-h test began with an empty discharge hose that had been drained to prevent freezing overnight before the test. This observation is consistent with and tends to support the idea of changing head in the discharge hose as the cause of the rate reduction.

Finally, several hours into the test there was a noticeable increase in the slope of the drawdown graph. This could have been caused by a reduction in transmissivity of the formation at some distance from the well. Alternatively, it could indicate a linear boundary (limit to the aquifer) several hundred feet from the well. As described below, the late data showed a slope essentially double that of the middle data. Exact doubling of a drawdown slope is consistent with a linear boundary.

Data analyses were made for all segments of the drawdown graph: the early, high-discharge rate data; the two segments of middle data separated by the subtle discharge rate reduction; and the late data.

Figure C-8.1-2 shows an analysis of the early data captured while the pump filled the upper portion of the drop pipe at an estimated rate of 20 gpm. The transmissivity computed from the early data was 1200 gpd/ft, yielding a hydraulic conductivity value of 120 gpd/ft^2, or 16.0 ft/d. This result agreed well with computations made from the early recovery data from trial 2. As before, it could represent the hydraulic conductivity of the near well sediments or simply be an artifact of a minor storage effect.

Figure C-8.1-3 shows an analysis of the middle data collected before the discharge rate decline. The transmissivity computed from the line of fit on the graph was 3890 gpd/ft, yielding a hydraulic conductivity value of 278 gpd/ft^2, or 37.1 ft/d. This result was consistent with other analyses of middle data from R-38 pumping.

Figure C-8.1-4 shows the remaining drawdown data from R-38: the middle data following the pumping rate decline and the late data.

There was a subtle sinusoidal aspect to the plot, likely a reflection of response to barometric pressure changes. Therefore, before analysis, the data were corrected for barometric pressure changes using the relationship shown in Figure C-7.0-4. Figure C-8.1-5 shows the corrected drawdown data plot. The middle data supported a transmissivity calculation of 3290 gpd/ft, yielding a hydraulic conductivity value of 235 gpd/ft^2, or 31.4 ft/d. This result was in good agreement with previous calculations.

The late data showed a distinct slope change, yielding a transmissivity of 1800 gpd/ft and hydraulic conductivity value of 129 gpd/ft^2, or 17.2 ft/d. This could reflect actual formation properties some distance from the well or indicate the presence of a negative linear boundary or subcropping of the transitional zone some distance from the well.

The “corner” established by the intersection of the two straight lines in Figure C-8.1-5 occurred about 500 min after pumping began. The distance to a hypothetical negative boundary is related to this time factor by the following equation:

$$d = \frac{1}{2}\sqrt{\frac{0.3Tt}{S}}$$ **Equation C-13**

Where, *d* = distance to linear boundary, in feet,

T = transmissivity, in gallons per day per foot,

t = time of intersection of two lines of fit, in days, and

S = storage coefficient.

The distance, *d*, was evaluated using this equation for a transmissivity value of 3880 gpd/ft (the average ultimately determined from the bulk of the pumping test data), a pumping time of 0.347 d (500 min), and assumed storage coefficient values of 2×10^{-4} and 5×10^{-4}. The results were distance values of 710 and 450 ft, respectively. Given that the formations beneath the plateau dip distinctly and the transitional zone has limited submergence at R-38, it is not unreasonable that the updip edge of the transitional zone could truncate or become unsaturated some hundreds of feet from the well. It is also possible that the hydraulic response was caused by a fault or some other geologic or stratigraphic boundary consistent with limited lateral extent of the volcanic/sedimentary transitional zone. Thus, boundary conditions, rather than a lateral change in transmissivity, could well explain the late-time slope change observed in the time-drawdown graph.

Figure C-8.1-6 shows a semilog plot of the recovery data collected following the 24-h pumping test. The graph was consistent with previous results, showing a steep early slope, a flatter middle slope, and a steep late slope. An analysis was made of each segment of the curve.

Figure C-8.1-7 shows an expanded-scale plot of the early recovery data, within seconds of pump shutoff. The transmissivity calculated from the graph was 1400 gpd/ft, yielding a hydraulic conductivity value of 140 gpd/ft^2, or 18.7 ft/d. These results were consistent with previous analysis of early response data and may represent actual hydraulic conductivity of the near-well sediments or could be reflective of a small storage effect.

For the remaining analyses, the recovery data were corrected for the effects of changes in barometric pressure using the relationship shown in Figure C-7.0-4. Figure C-8.1-8 shows the resulting recovery graph of corrected data. These data were analyzed to determine formation characteristics.

Figure C-8.1-9 shows an expanded-scale plot of the middle and late recovery data. The transmissivity determined from the middle data was 4070 gpd/ft, yielding a hydraulic conductivity of 291 gpd/ft^2, or 38.9 ft/d. This result was consistent with previous analyses.

At late time, the slope essentially doubled, yielding a transmissivity of 1940 gpd/ft and a hydraulic conductivity value of 139 gpd/ft^2, or 18.5 ft/d. This result was consistent with what was obtained from analysis of the late drawdown data. The reduced transmissivity value at late time could represent properties of the sediments some hundreds of feet from the well or could reflect a boundary condition as discussed earlier.

C-8.2 Specific Capacity Data

Specific capacity data were used along with well geometry to estimate a lower-bound conductivity value for the formation at R-38 for comparison to the pumping test values. In addition to specific capacity, other input values used in the calculations included the estimated aquifer thickness of 14 ft, an estimated storage coefficient of 5×10^{-4} and a borehole radius of 0.51 ft. The calculations are somewhat insensitive to the assigned storage coefficient, so an estimate of this value was deemed adequate.

R-38 produced 5.45 gpm with a drawdown of 4.2 ft after 24 h of pumping for a specific capacity of 1.3 gpm/ft. Applying the Brons and Marting method (1961, 098235) to these inputs yielded a lower-bound hydraulic conductivity value for the screened interval of 178 gpd/ft^2, or 23.8 ft/d. This result was consistent with the hydraulic conductivity values obtained from the middle-time data.

C-8.3 Discussion

All of the pumping test data showed similar response in R-38: an early (seconds) steep slope gradually transitioning to a flatter middle slope (a few minutes to a few hours), changing again to a steep final slope. Table C-8.3-1 summarizes the results of the analytical calculations from the various portions of the time-drawdown and recovery curves for each of the tests.

The average early-time, middle-time and late-time hydraulic conductivity values computed from the tests were 17.4, 37.1 and 17.9 ft/d, respectively.

The best estimate of formation hydraulic conductivity is the middle-data average value of 37.1 ft/d.

The early time value of 17.4 ft/d either reflects the properties of a trivial volume of material adjacent to the well screen or is a manifestation of a tiny storage effect caused by a small quantity of air that may have been trapped in the filter pack during well development. On the other hand, if storage effects were not present, the low hydraulic conductivity value could be valid and might imply that the contiguous aquifer is more than 14 ft thick. Under this scenario, the middle-data hydraulic conductivity value would be lower than 37.1 ft/d by a ratio of 14 ft to the actual (unknown) thickness of the contiguous aquifer. For example, if a contiguous aquifer thickness of 30 ft were assumed, the average hydraulic conductivity computed from the middle data would be 17.3 ft/d, which would agree with the early-time value. There was no way to test or verify this idea. Taken at face value, and assuming a 14-ft-thick aquifer, the data tend to imply a formation hydraulic conductivity of 37.1 ft/d and a minor storage effect in the very early data. Nevertheless, there is a chance that the effective contiguous aquifer thickness could be greater than the 14-ft-thick transitional zone and that the actual hydraulic conductivity is about 17 ft/d. (Note: This idea would not be contradicted by the lower-bound hydraulic conductivity value computed from the specific capacity data. Assumption of a different aquifer thickness would change the lower-bound value. For example, in this case, assuming an aquifer thickness of 30 ft and applying the Brons and Marting method (1961, 098235) would yield a lower-bound hydraulic conductivity value of 17.2 ft/d, consistent with the early-time analysis. Thus, for the assumption of 30 ft of contiguous thickness for the hydraulic unit, the early data, middle data, and specific capacity estimate all produce similar hydraulic conductivity values, about 17 ft/d. Thus, the assumption of a thicker hydraulic unit may be valid, though not verifiable.)

The late-time doubling of the drawdown and recovery slopes indicated the presence of boundary conditions: either a reduction in transmissivity some distance from the well or a linear boundary (truncation of the aquifer), perhaps where the transitional zone becomes unsaturated or at the location of a fault or other geologic boundary. Calculations showed such a boundary to be approximately 450 to 710 ft from the pumped well for a realistic range of storage coefficient values. A doubling of the drawdown and recovery slopes is consistent with a linear boundary.

C-8.4 R-21 Response

The R-well nearest R-38 is R-21, located 1111 ft away. Data from this well were graphed to see if a response to pumping R-38 could be observed. Figure C-8.4-1 shows data from R-21 recorded during the R-38 pumping test. Barometric pressure data are shown along with the hydrograph for comparison purposes. Note that the two curves appeared similar. The scale of the barometric plot has been reversed, meaning that an increase in barometric pressure caused a drop in the water level in R-21. Because R-21 was monitored using a vented transducer, this relationship suggested high barometric efficiency. According to Figure C-8.4-1, most of the water-level change observed in R-21 was caused by change in barometric pressure. To discern whether the R-38 pumping test had an effect on R-21 water levels, it was necessary to correct the water-level data for the barometric pressure effects.

Figure C-8.4-2 shows a comparison of the R-21 hydrograph and a modified barometric pressure curve. The barometric pressure curve was modified to show 90% of the barometric pressure change using a 2-h rolling average of antecedent pressure data between 1 and 3 h before the corresponding water-level measurement. Thus, the modified barometric pressure curve was based on a barometric efficiency of 90%, an average lag time of 2 h, and smoothing using a 2-h rolling average. The resulting modified barometric pressure curve matched the hydrograph well, with no noticeable deviation of the hydrograph during the R-38 pumping test.

The hydrograph data were corrected for barometric pressure effects using the relationship from Figure C-8.4-1. Figure C-8.4-2 shows a plot of the original and corrected hydrographs. The corrected hydrograph showed a diurnal response having a magnitude of several hundredths of a foot. This probably was the effect of earth tides on the water-level data. Based on the corrected data shown in Figure C-8.4-2, no obvious response to pumping R-38 was evident. Any R-38 pumping effect was too small to be discerned from the corrected hydrograph.

To remove the diurnal hydraulic response from the hydrograph data, the data were manipulated using barometric and earth tide correction (BETCO) software, a more complex correction algorithm that uses regression deconvolution (Toll and Rasmussen 2007, 104799) to modify the data. Figure C-8.4-3 shows the resulting corrected hydrograph. A slight decline (a few hundredths of a foot) in the corrected water levels was seen during the first part of the 24-h pumping test, followed by a similar rise late in the test and following pump shutdown. These minor changes could be a combination of noise and pumping effects, although the fluctuations described were no greater than other fluctuations seen on the graph before and after the pumping and recovery test. Thus, the presence of a distinct response to pumping R-38 could not be concluded from the BETCO hydrograph.

The lack of a discernible response in R-21 to pumping R-38 was contradicted by water-level data collected during R-38 well construction in late November 2008. During construction, filter pack was washed into place around the well screen by flushing potable water and filter sand through a tremie pipe into the annulus around the well casing and screen. The water added to place the filter pack flowed into the aquifer, effectively constituting an injection test. Figure C-8.4-4 shows the hydrograph from this period along with the BETCO water-level data.

The hydrographs showed distinct water-level fluctuations, up to about 0.2 ft on November 15 and 16, 2008, and again on November 25 and 26, 2008. These dates corresponded to filter-packing operations during which water was added to R-38. During those 4 d, water was added to the well in volumes ranging from 1650 to 5800 gpd, averaging around 3000 gpd. On a given day, water typically was added in several individual events ranging from less than 15 min to more than an hour, interspersed with periods with no injection taking place. When active filter packing was occurring, the average injection rates ranged from less than 10 gpm to more than 30 gpm.

An attempt was made to simulate the R-21 water-level peaks caused by injection of water into R-38. Calculations were made using the Theis equation and the aquifer transmissivity of 3880 gpd/ft. Simulations were computed for a variety of storage coefficient values and numerous combinations of injection rates and durations. Figure C-8.4-5 shows a typical simulated water-level response in R-21.

The responses shown on the graph corresponded to assumed storage coefficient values of 10^{-4} and 5×10^{-4}. This specific example was based on injecting a total volume of 2500 gal. of water, with an average background rate of 4 gpm for 550 min followed by 30 gpm for 10 min. For the simulation shown in Figure C-8.4-5, it was not possible to reproduce the observed water-level peaks unless a very low storage coefficient value (around 10^{-4}) was used in the calculations. A moderate value, such as 5×10^{-4}, always resulted in simulated responses lower than observed. This was generally true for all simulations conducted, regardless of the flow rate pattern applied.

To compare with these results, the R-38 pumping test was simulated using the Theis equation (1934–1935, 098241) to create a distance-drawdown graph to see what the expected drawdown would be at R-21 at the end of the 24-h pumping test. Calculations were performed for the aquifer transmissivity of 3880 gpd/ft and a variety of storage coefficient values. Figure C-8.4-6 shows the results of the calculations for a few select storage coefficient values.

Note that for realistic storage coefficient values (10^{-4} and 5×10^{-4}), the predicted response in R-21 at the end of the R-38 pumping test was great enough (0.15 to 0.37 ft) that it could not have been missed in the corrected hydrographs shown in Figures C-8.4-2 and C-8.4-3. Only when the storage coefficient value was unreasonably large (e.g., greater than 0.001) did the computed drawdown at R-21 become small enough that it could be conceived of going undetected.

Normally, the results shown in Figure C-8.4-6 combined with the lack of an observable response in R-21 to the R-38 pumping test would imply either (1) hydraulic isolation of the two wells (by a fault or intervening aquitard, depending on the dip angle of the beds and relative elevations of the well screens) or (2) a larger storage coefficient, perhaps caused by minor leakage. However, if either of these conditions prevailed, the observed water-level responses in R-21 during R-38 well construction would have been impossible.

It should be pointed out that the calculations described here did not incorporate the presence of the negative boundary observed in the R-38 pumping test. This was because the distance and direction to the boundary could not be known with certainty. Nevertheless, the presence of a boundary would have the same effect in both sets of calculations (injection and pumping) and would not have altered the outcome of the analysis. In short, the observation of a response in R-21 during R-38 well construction and the lack of a response during the R-38 pumping test were contradictory. For example, injection of about 2000 gal. of water over a 15-h period on November 16 showed a clear response, whereas pumping nearly 8000 gal. of water over a 24-h period on December 15 and 16 showed no obvious response. There was no explanation for this apparent contradiction.

C-9.0 SUMMARY

Constant-rate pumping tests were conducted on R-38 in the north fork of Cañada del Buey within TA-54. The tests were conducted to gain an understanding of the hydraulic characteristics of the aquifer screened in R-38. Numerous observations and conclusions were drawn for the tests as summarized below.

1. Water-level data from R-38 showed a barometric efficiency of about 58%, with an average effective total lag time of about 19 h. Smoothing 12 h of data resulted in a good match between barometric pressure changes and aquifer pressure fluctuations.
2. Water-level data from R-21 showed a barometric efficiency of about 90%, with an average effective total lag time of about 2 h. Smoothing 2 h of data resulted in a good match between barometric pressure changes and aquifer pressure fluctuations.
3. None of the drawdown or recovery graphs showed the common flattening seen in most pumping tests on the plateau, generally associated with vertical expansion of the cone of depression and/or unconfined conditions. This suggested effective confinement of the permeable zone both above and below.
4. The data showed three distinct slopes on drawdown and recovery graphs.
5. The hydraulic conductivity value obtained from the early-time slope averaged 17.4 ft/d, which is in conflict with analysis of subsequent data. This suggested the possibility of (1) tighter sediments near the pumped well; (2) trapped air in the filter pack, causing a minor storage effect and an underestimation of hydraulic conductivity; or (3) a contiguous aquifer thickness greater than 14 ft (perhaps around 30 ft), resulting in agreement between the near-well and distal hydraulic conductivities. If trapped air was involved, it may have been introduced into the well during development when the discharge rates were greater than 10 gpm.
6. The middle data yielded an average hydraulic conductivity of 37.1 ft/d, tentatively the most realistic estimate. This value was in conflict with the early-time value and was based on the assumption of an aquifer thickness of 14 ft.
7. An actual aquifer thickness substantially greater than 14 ft would reduce the computed hydraulic conductivity below 37.1 ft/d and perhaps eliminate the contradiction of the early-time value. There was no way to test or verify this idea. The effective aquifer thickness would have to be discerned from the drilling observations and/or geophysical logs. In summary, the hydraulic conductivity is a minimum of 17 ft/d but is more likely 37 ft/d.
8. The late-time data showed, on average, a doubling of the drawdown and recovery slopes. An exact doubling of the transient slopes can be a telltale sign of a linear aquifer boundary, such as a fault, subcrop, or extension of the tilted aquifer into the unsaturated zone in the updip direction. The steeper slope also could indicate a generalized reduction in transmissivity some distance from the well.
9. If there is a linear boundary, calculations showed possible distances from the pumped well ranging from about 450 to 710 ft for assumed storage coefficient values of 5×10^{-4} to 2×10^{-4}, respectively.
10. Based on an aquifer thickness of 14 ft, specific capacity data yielded a lower-bound hydraulic conductivity estimate of 23.8 ft/d, consistent with the average middle-time value of 37.1 ft/d. As a first approximation, the well efficiency can be set equal to the ratio of the lower-bound and actual hydraulic conductivity values: 23.8/37.1 = 64%, a realistic value.
11. For an assumed hydraulic unit thickness of 30 ft, the early data, middle data, and specific capacity all produced consistent hydraulic conductivity estimates of just over 17 ft/d.

12. Analysis of R-21 water-level data showed no discernible response to the R-38 pumping test. In contradiction to this, water-level response was observed in R-21 due to water injection with filter pack placement during well construction. The lack of a pumping test response and the observation of an injection response could not be simulated using consistent aquifer coefficients. There was no obvious explanation for this unusual contradiction.

C-10 REFERENCES

The following list includes all documents cited in this appendix. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

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Toll, N.J., and T.C. Rasmussen, January–February 2007. "Removal of Barometric Pressure Effects and Earth Tides from Observed Water Levels," *Ground Water,* Vol. 45, No. 1, pp. 101–105. (Toll and Rasmussen 2007, 104799)

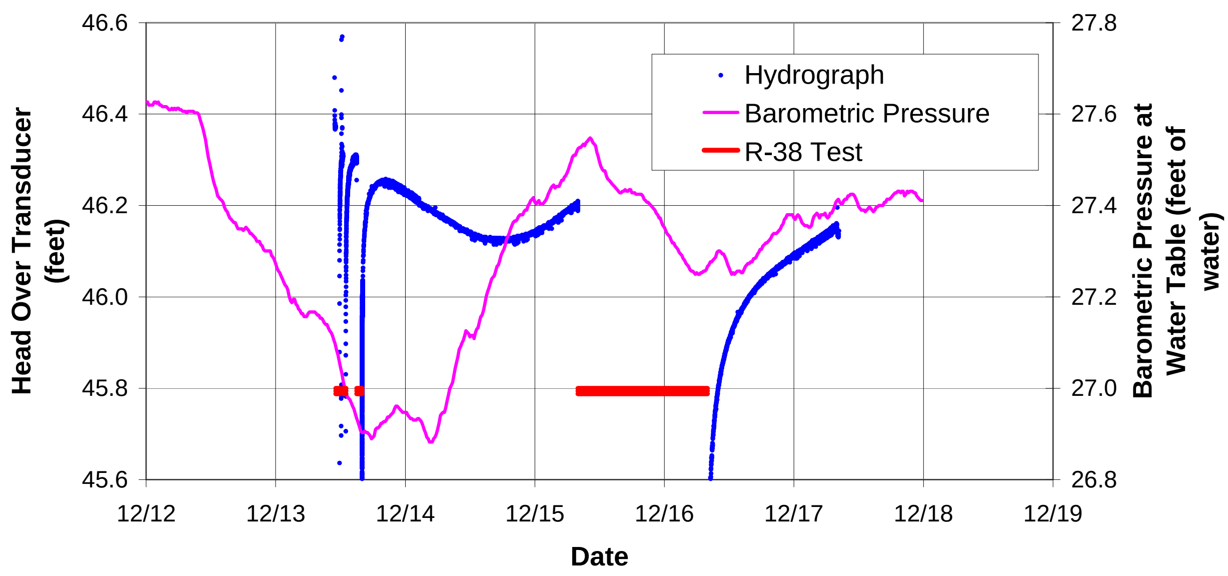

Figure C-7.0-1 Comparison of R-38 apparent hydrograph and adjusted TA-54 barometric pressure

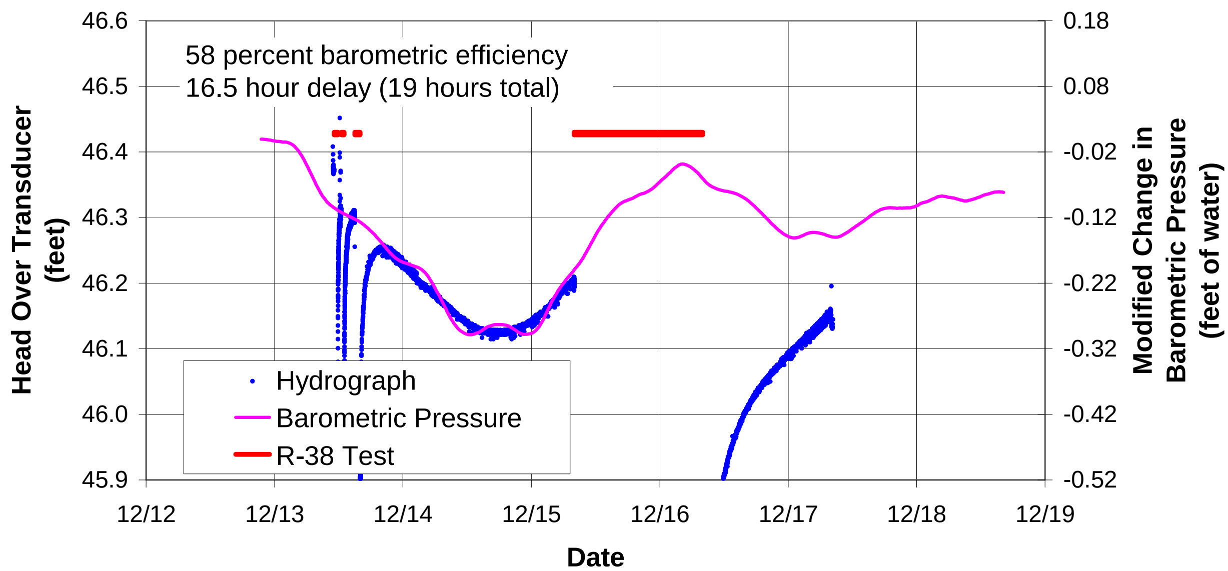

Figure C-7.0-2 R-38 apparent hydrograph and modified TA-54 barometric pressure: 5-h rolling average

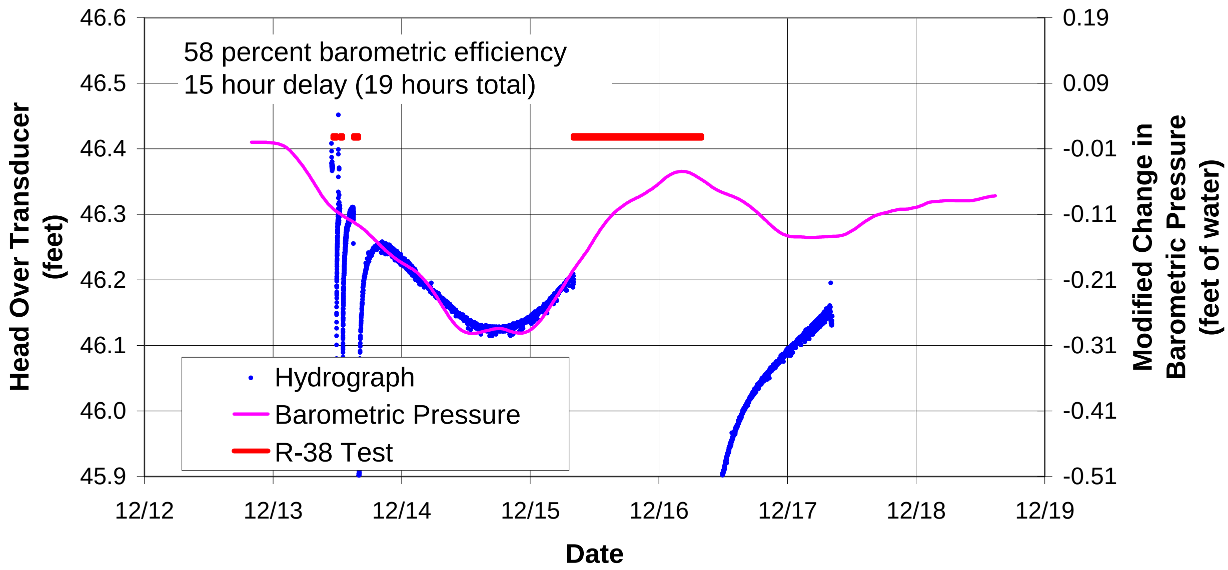

Figure C-7.0-3 R-38 apparent hydrograph and modified TA-54 barometric pressure: 8-h rolling pressure

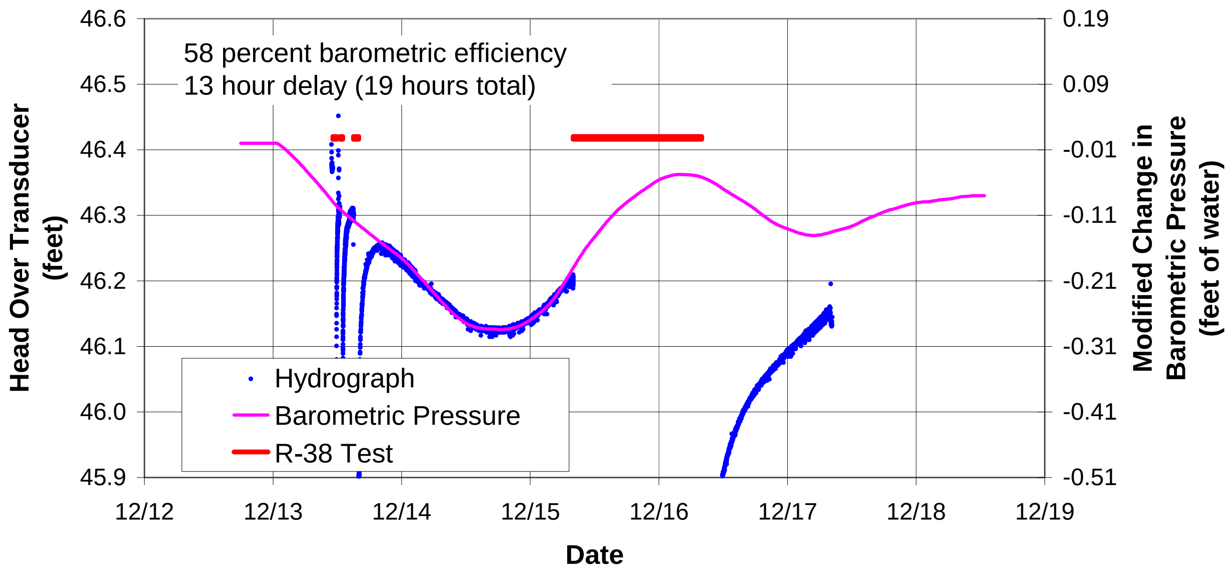

Figure C-7.0-4 R-38 apparent hydrograph and modified TA-54 barometric pressure: 12-h rolling average

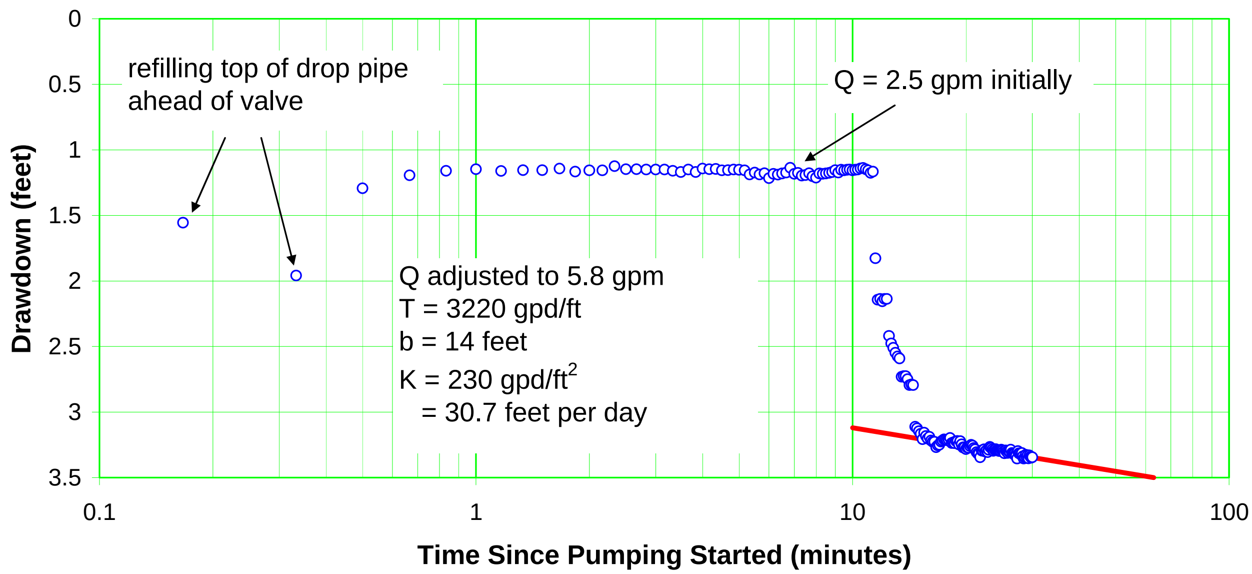

Figure C-8.0-1 Well R-38 trial 1 drawdown

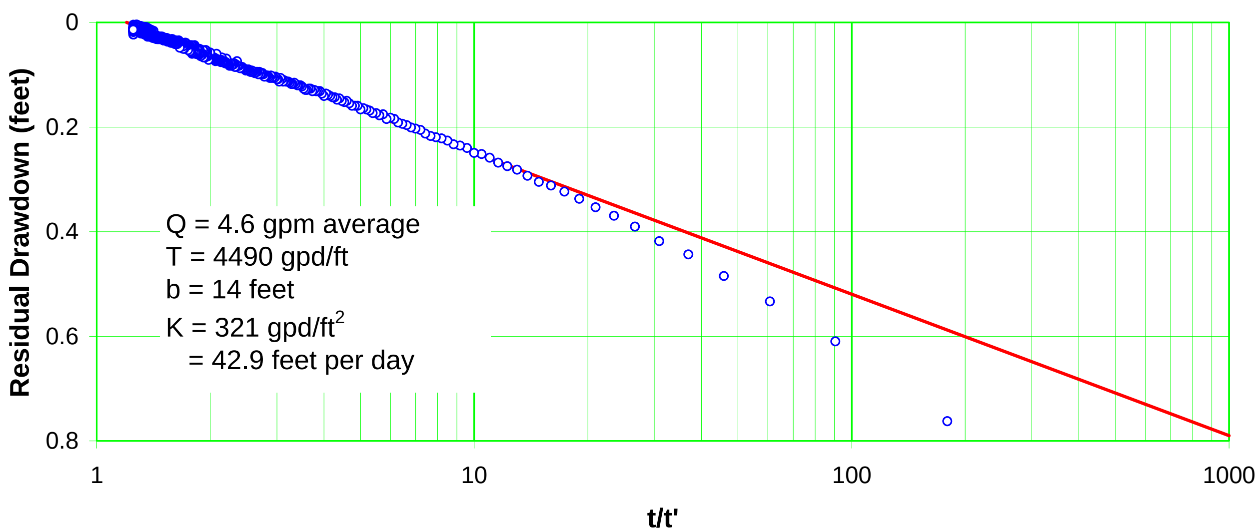

Figure C-8.0-2 Well R-38 trial 1 recovery

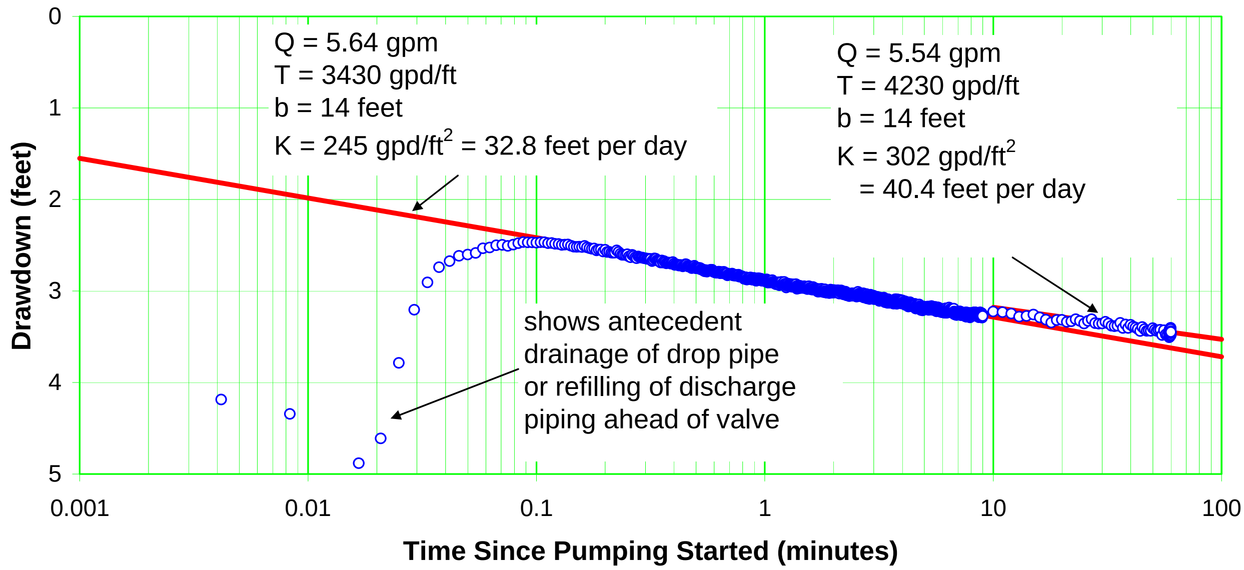

Figure C-8.0-3 Well R-38 trial 2 drawdown

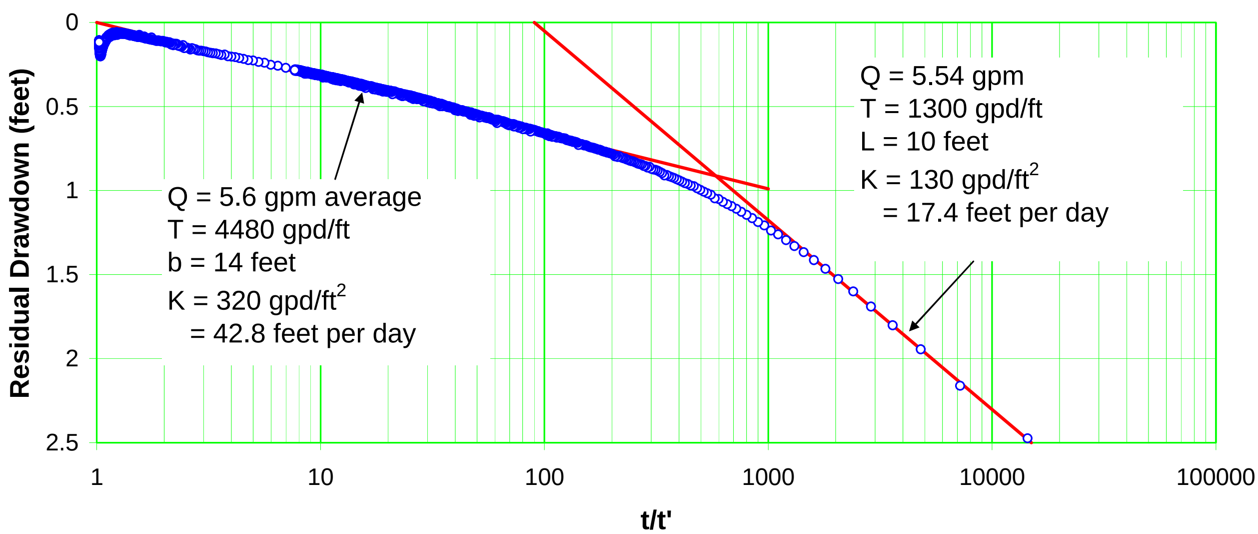

Figure C-8.0-4 Well R-38 trial 2 recovery

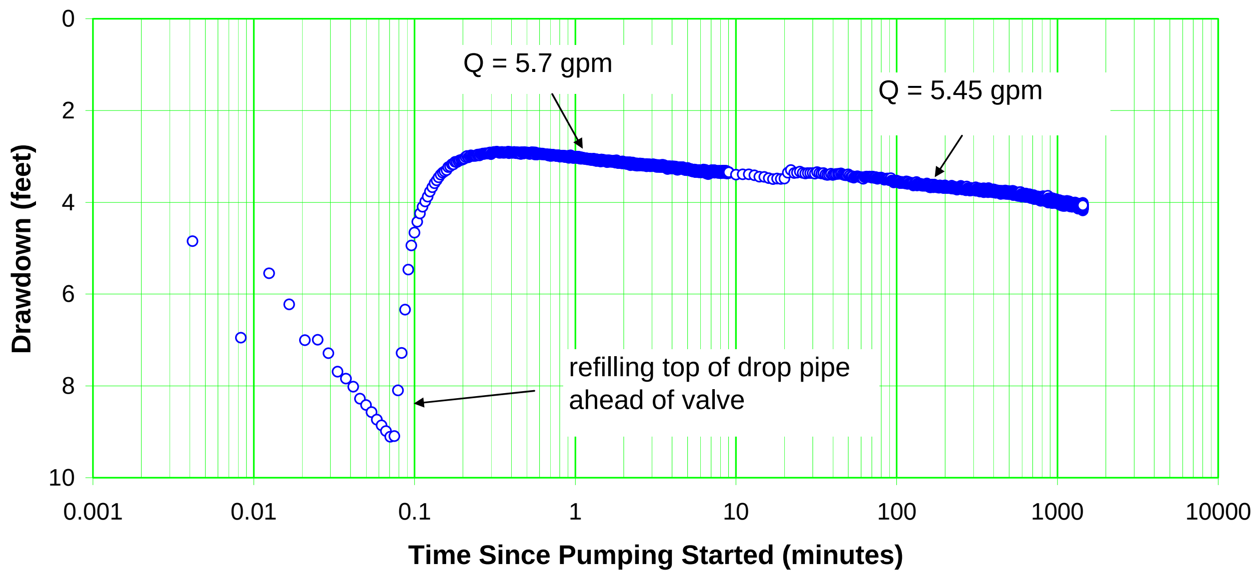

Figure C-8.1-1 Well R-38 drawdown

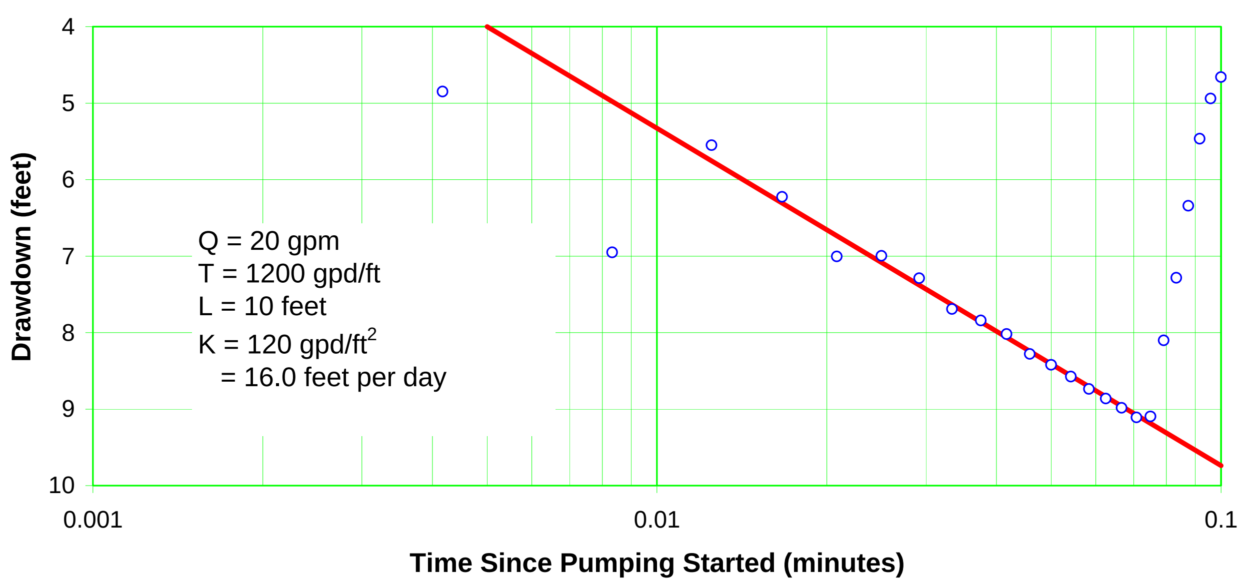

Figure C-8.1-2 Well R-38 drawdown: early data

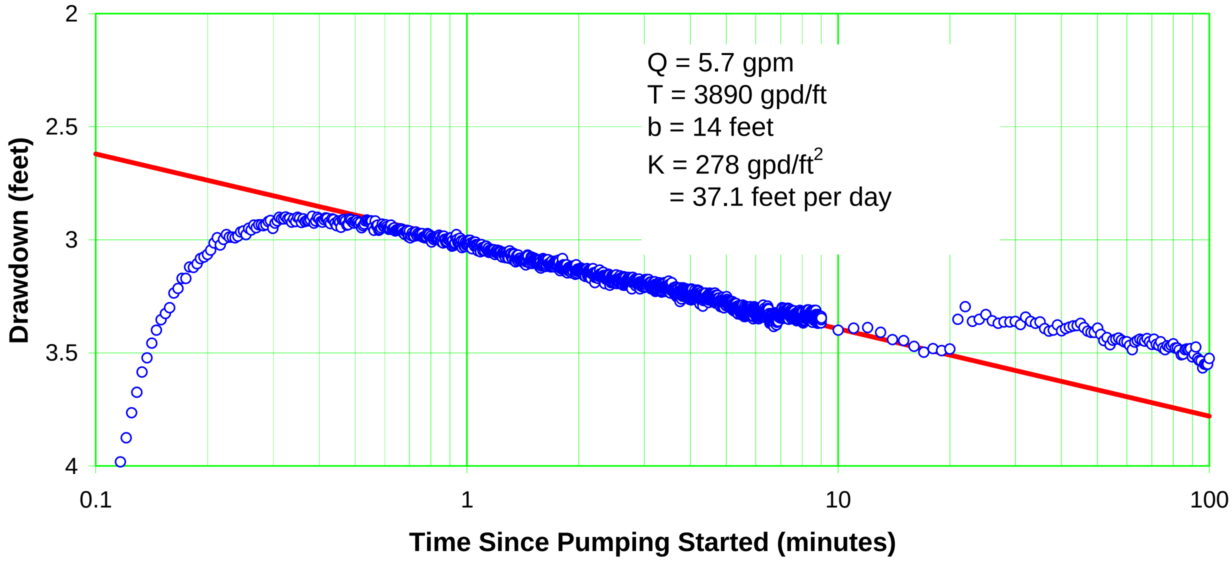

Figure C-8.1-3 Well R-38 drawdown: middle data

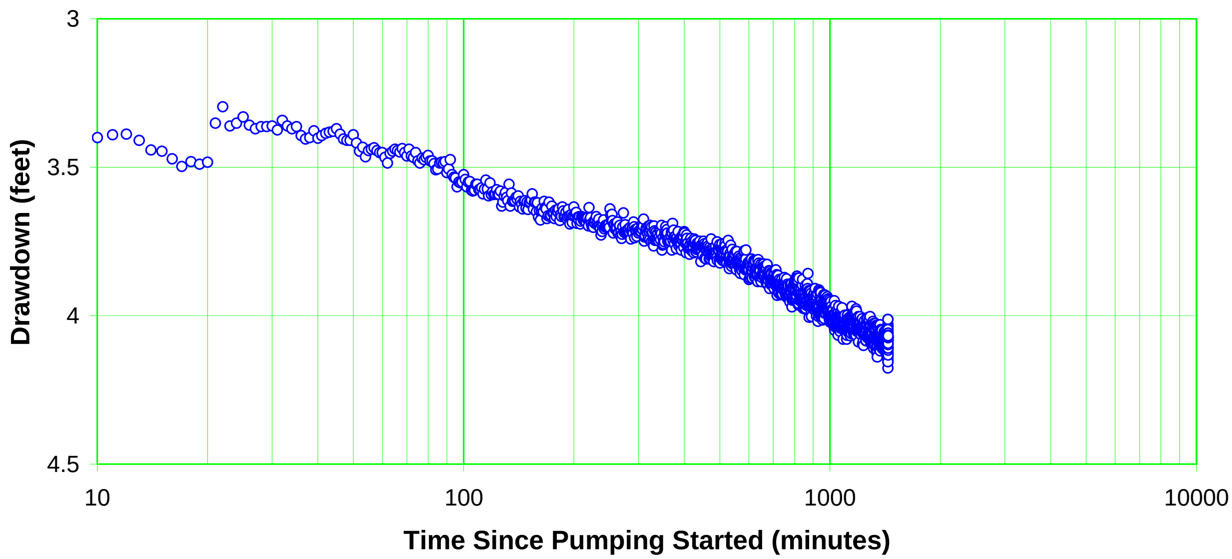

Figure C-8.1-4 Well R-38 drawdown: middle and late data

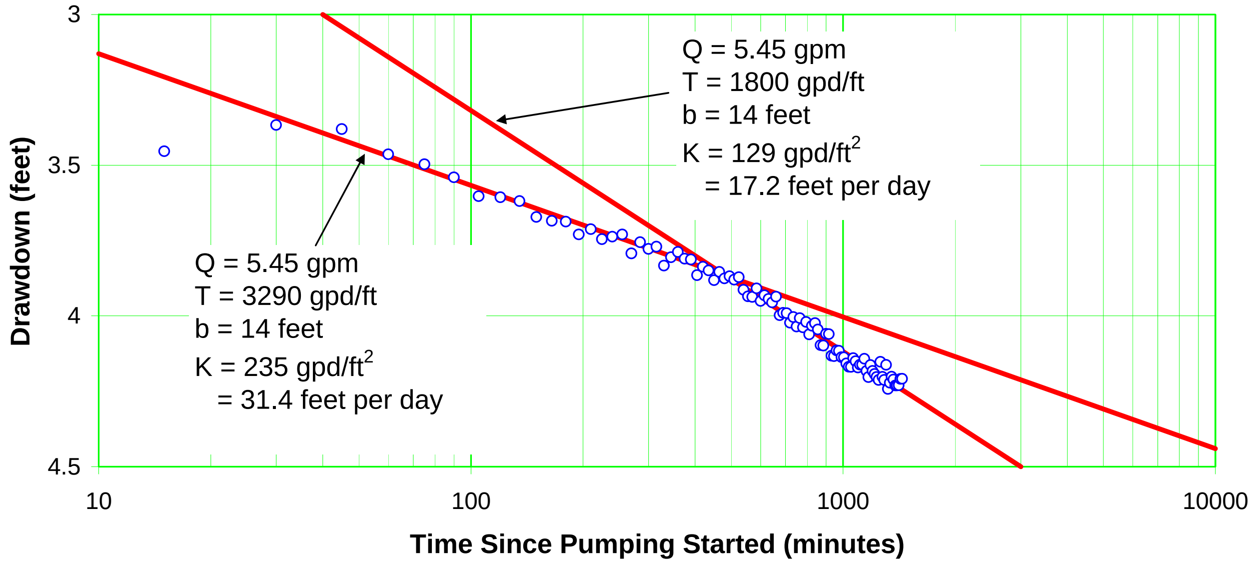

Figure C-8.1-5 Well R-38 corrected drawdown

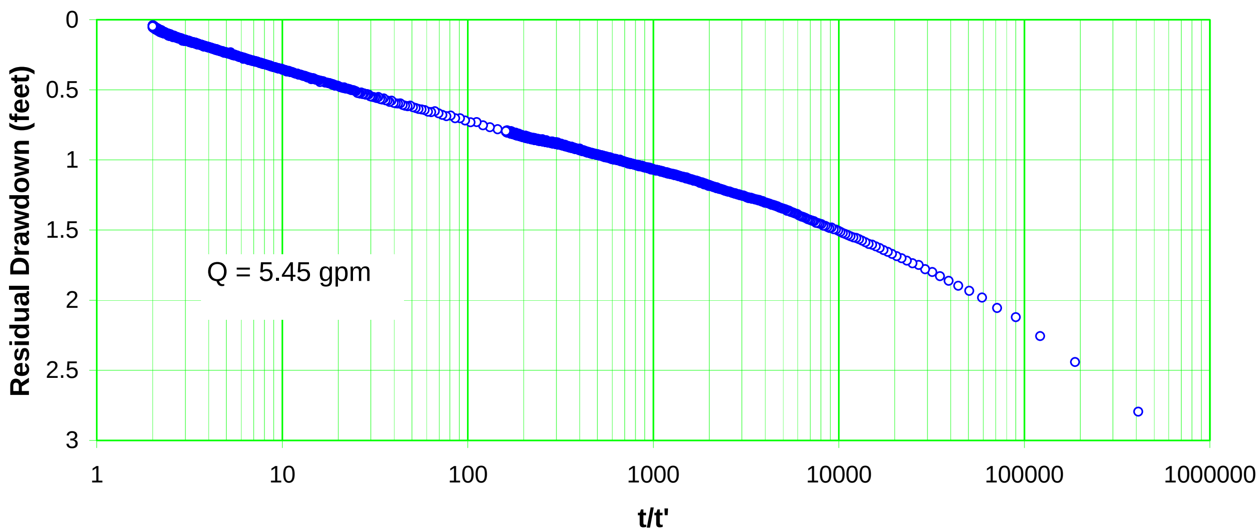

Figure C-8.1-6 Well R-38 recovery

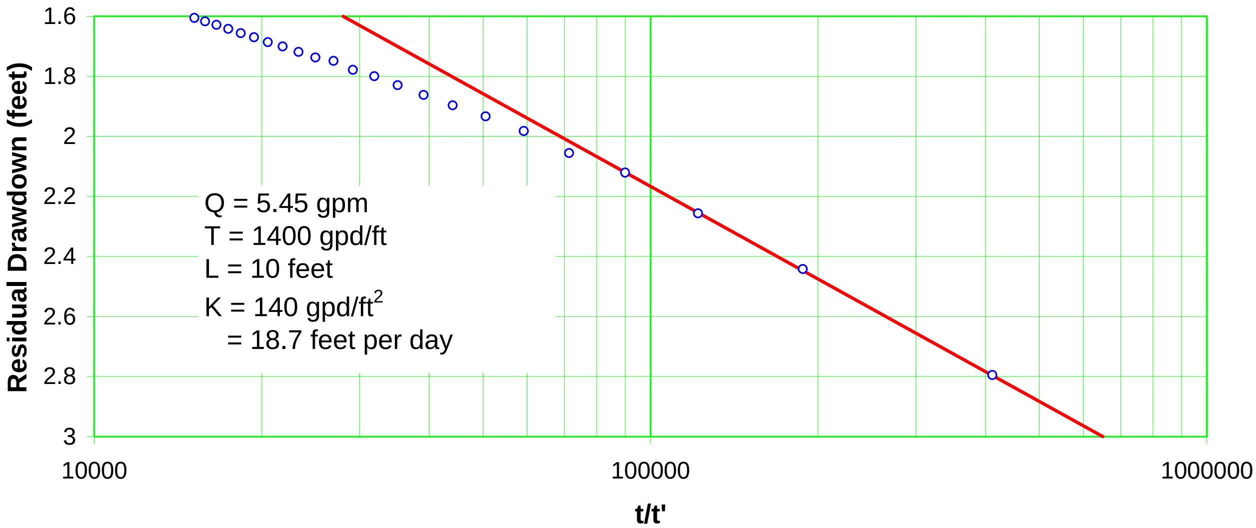

Figure C-8.1-7 Well R-38 recovery: early data

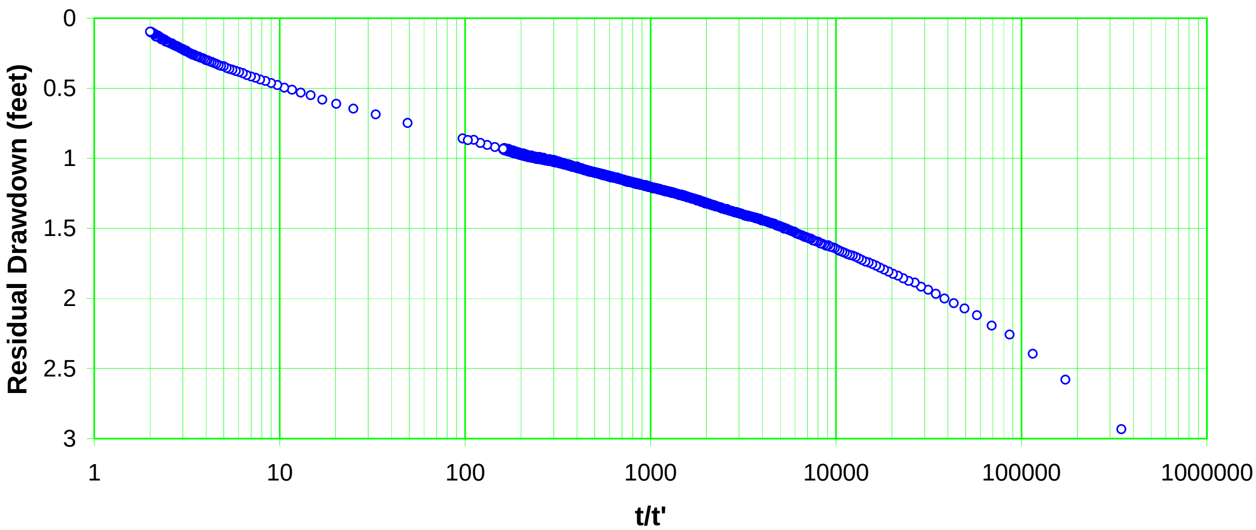

Figure C-8.1-8 Well R-38 corrected recovery

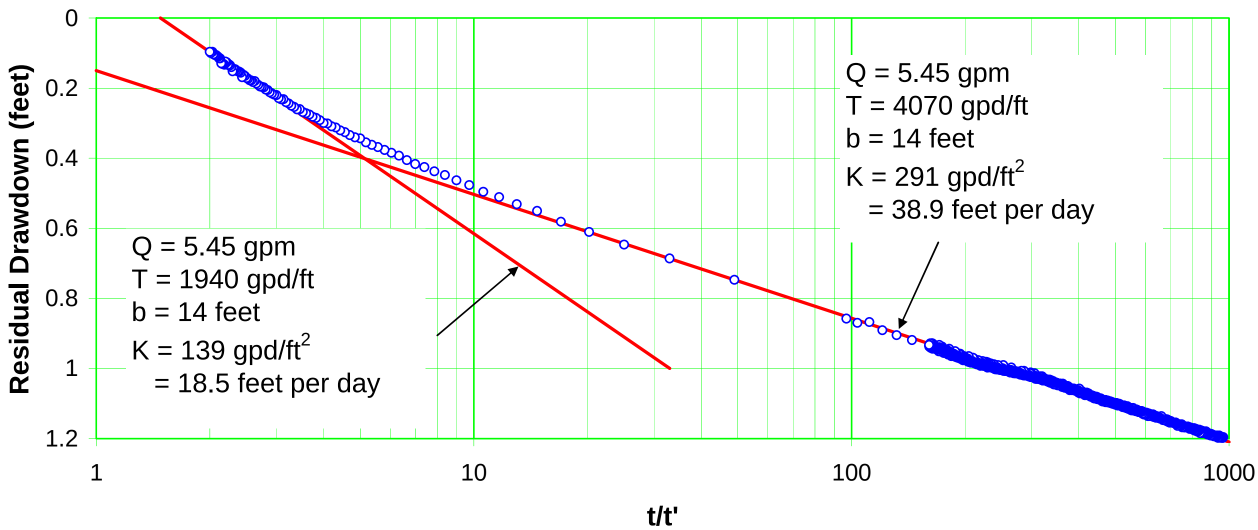

Figure C-8.1-9 Well R-38 corrected recovery: middle and late data analysis

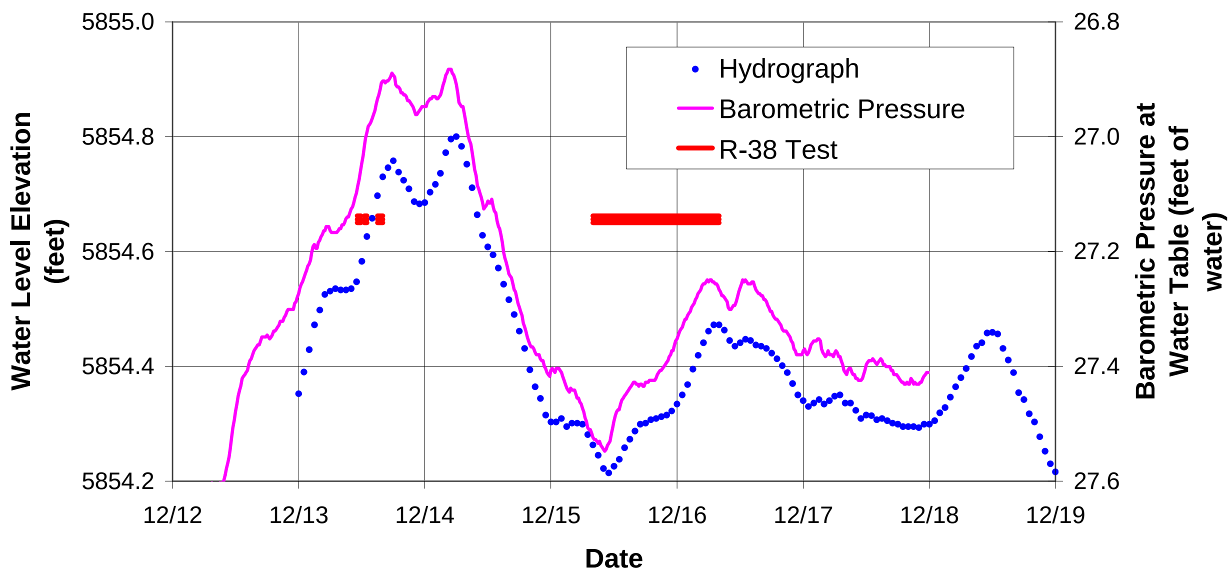

Figure C-8.4-1 Comparison of R-21 hydrograph and adjusted TA-54 barometric pressure

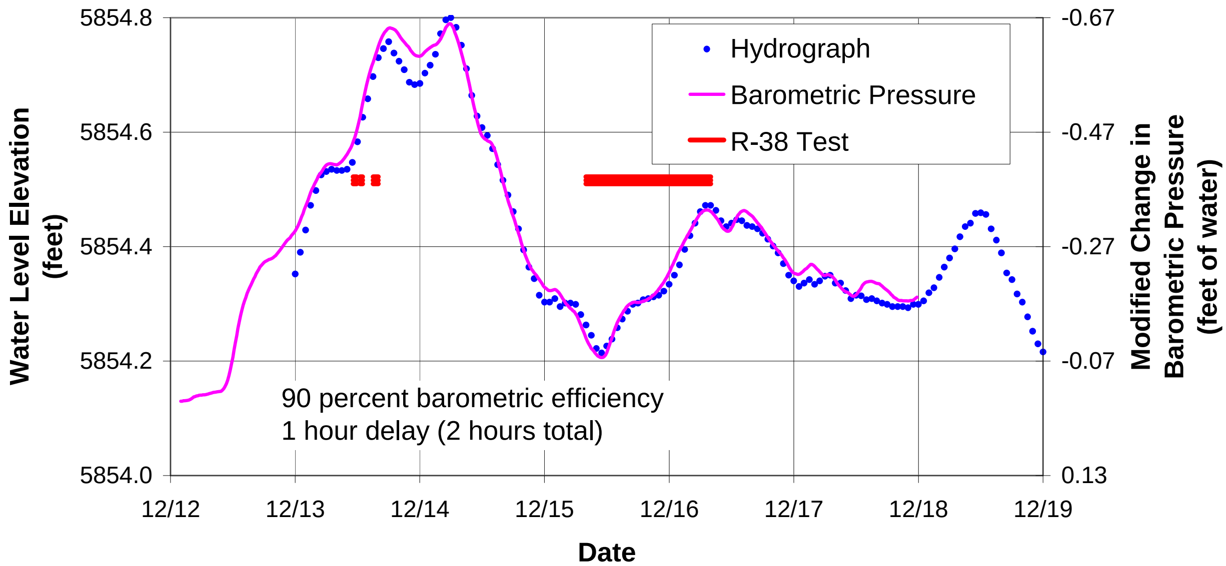

Figure C-8.4-2 R-21 hydrograph and modified TA-54 barometric pressure: 2-h rolling average

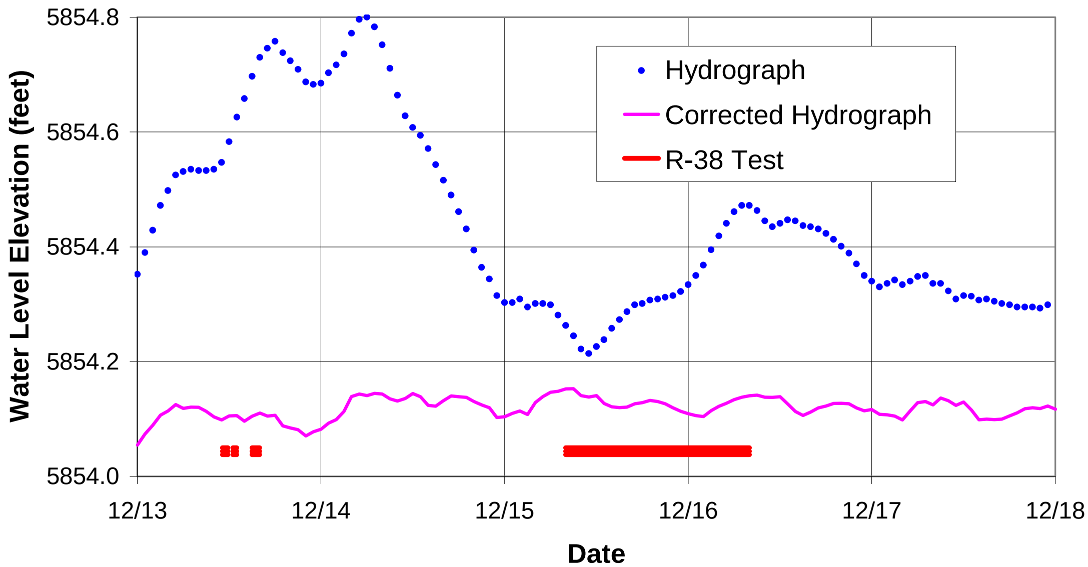

Figure C-8.4-2 R-21 original and corrected hydrographs

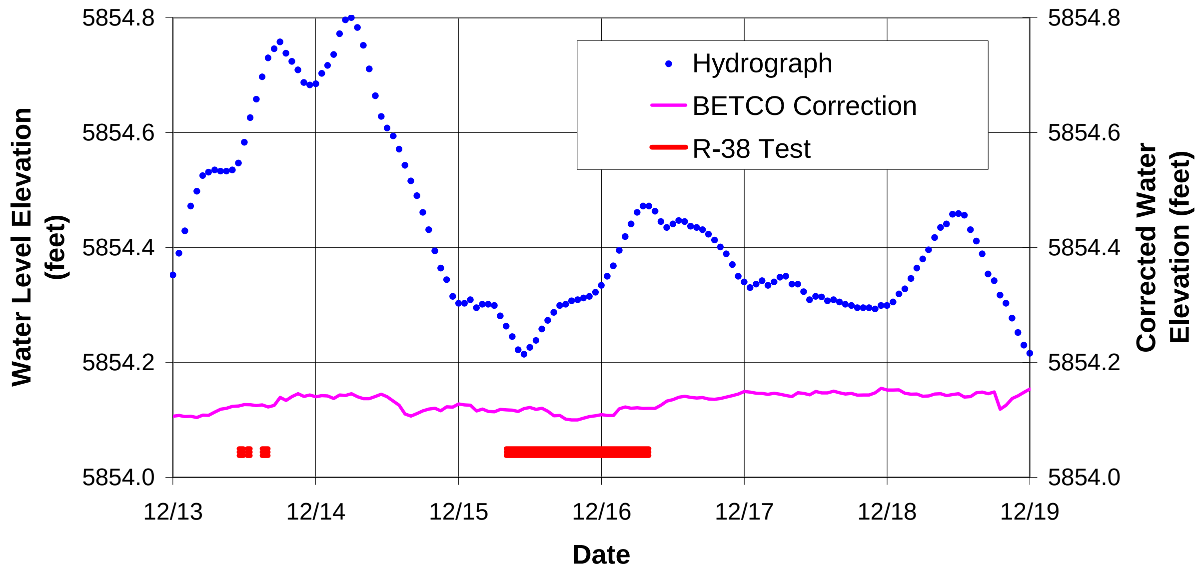

Figure C-8.4-3 Comparison of R-21 original hydrograph and BETCO

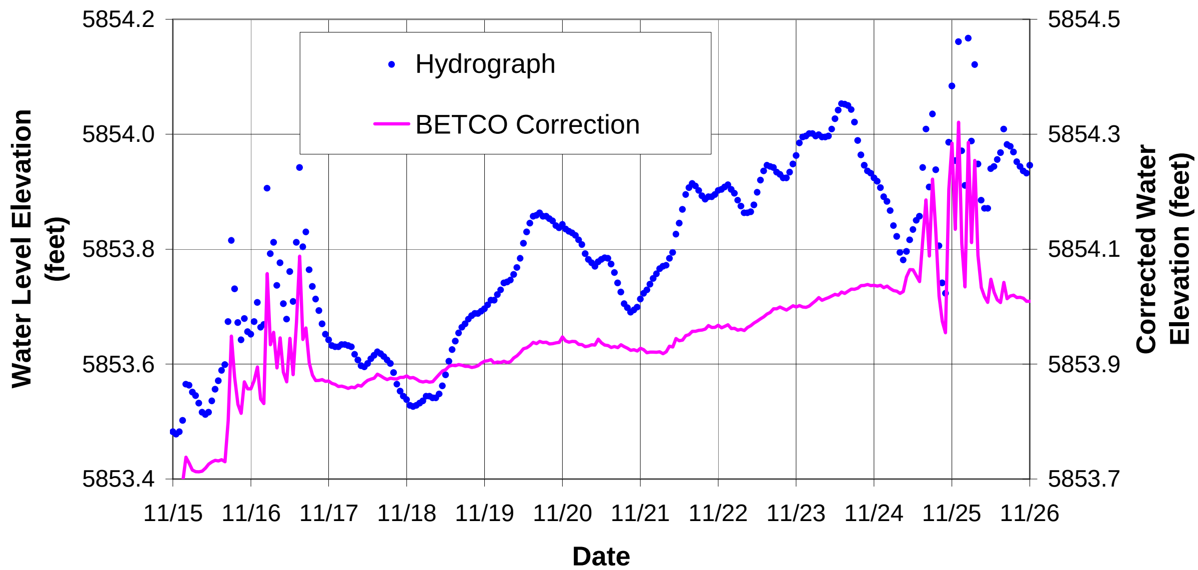

Figure C-8.4-4 Comparison of R-21 original hydrograph and BETCO during well construction

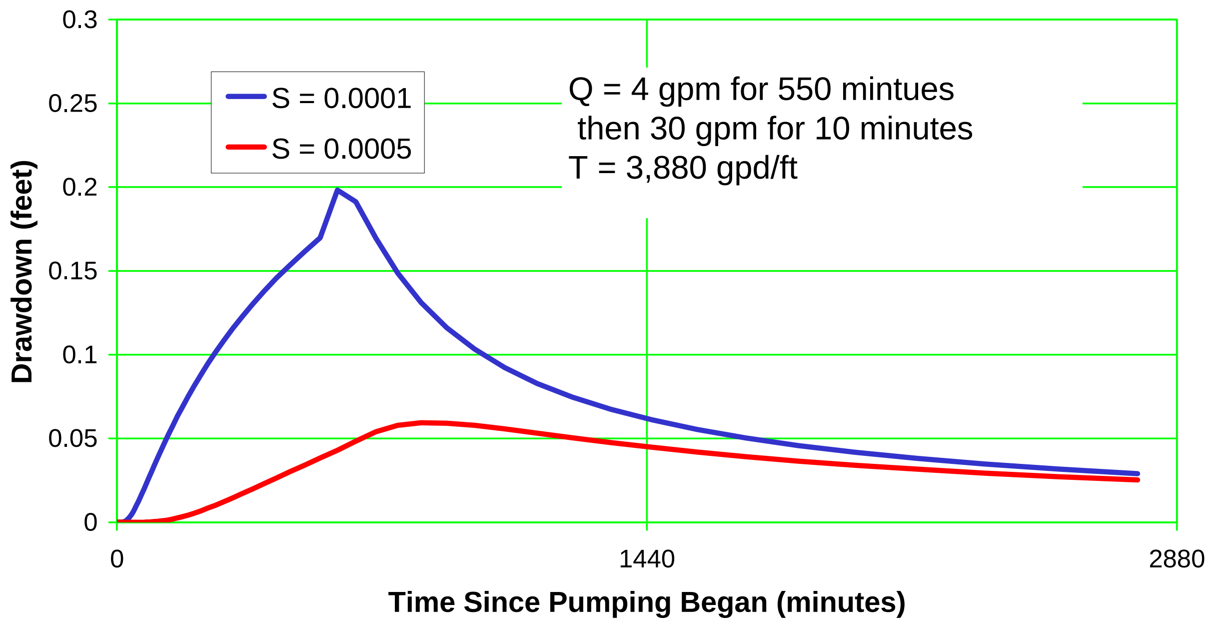

Figure C-8.4-5 Simulated pressure response in R-21 during construction of well R-38

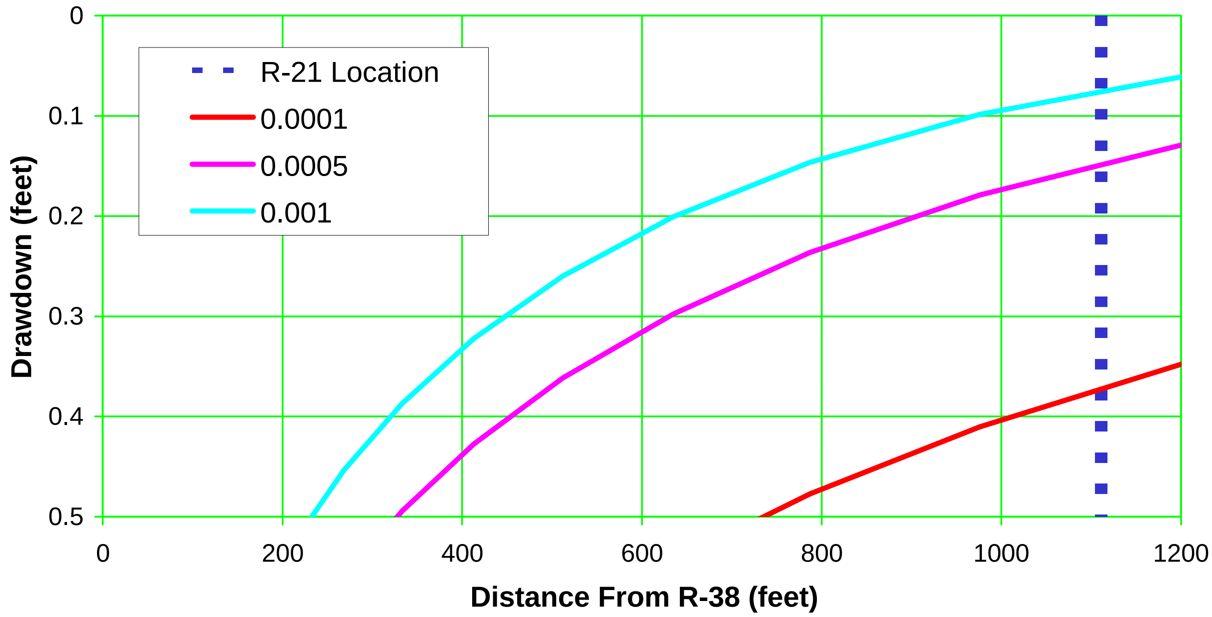

Figure C-8.4-6 Theoretical drawdown pumping R-38 at 5.45 gpm for 1 d with T= 380 gpd/ft

Table C-8.3-1
R-38 Pumping Test Results
Los Alamos National Laboratory Los Alamos, New Mexico

Analysis	Hydraulic Conductivity (ft/d)		
	Early Data	Middle Data	Late Data
Trial 1 Drawdown	na*	30.2	na
Trial 1 Recovery	na	42.9	na
Trial 2 Drawdown	na	32.8	na
	na	40.4	na
Trial 2 Recovery	17.4	42.8	na
24-H Drawdown	16.0	37.1	17.2
24-H Recovery	18.7	38.9	18.5
Average	17.4	37.1	17.9

* na = Not available.

Appendix D

Borehole Video (on DVD included with this document)

Appendix E

Schlumberger Geophysical Logging Report

Geophysical Logging Report

Schlumberger Water Services
February 2009

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1.0 SUMMARY

Geophysical logging was performed by Schlumberger in characterization well R-38 in November 2008 before well completion. The logging measurements were acquired from 40 to 891 ft below ground surface (bgs), when the borehole was open (uncased) from 758 to 891 ft (bottom of hole, as measured by the logs), drilled with a 11.875 inch (in.) diameter bit size, and cased contained approximately 12.6-in. inside diameter (I.D.) freestanding steel casing from ground surface to 758 ft.

The primary purpose of the geophysical logging was to characterize the geologic/hydrogeologic section intersected by the well, with emphasis on determining regional aquifer groundwater level, relative water saturation, moisture content, depths of permeable aquifer zones, and the stratigraphy and lithology of geologic units. A secondary purpose of the geophysical logging was to evaluate the borehole conditions, such as borehole diameter versus depth, deviation versus depth, and degree of drilling fluid invasion. These objectives were accomplished by measuring, nearly continuously, along the length of the well (1) total and effective water-filled porosity and pore-size distribution from which an estimate of hydraulic conductivity is made (in cased hole section only total water-filled porosity is available); (2) bulk electrical resistivity at multiple radial depths of investigation (open-hole section only); (3) spectral natural gamma ray, including potassium, thorium, and uranium concentrations; (4) bedding and fracture orientation, fracture aperture, and geologic texture (open-hole, water-filled section only); (5) borehole inclination and azimuth; and (6) borehole diameter.

The following Schlumberger geophysical logging tools were used in the project (Table 1.0-1).

Table 1.0-1
Geophysical Logging Tool, Technology, and Corresponding Derived Properties

Tool	Technology	Properties Derived
Combinable Magnetic Resonance tool (CMR*)	Magnetic resonance proton precession	Effective (moveable) versus bound water-filled porosity, estimated hydraulic conductivity and relative flow capacity versus depth
Accelerator Porosity Sonde (APS∗)	Epithermal and thermal neutron porosity, neutron capture cross section	Water/moisture content, lithologic variations
Array Induction Tool (AIT*)	Bulk electrical resistivity at multiple radial depths of investigation; spontaneous potential and borehole fluid resistivity	Stratigraphic delineation, relative permeability and water saturation from the borehole fluid invasion profile, clay content
Fullbore Formation Micro-Imager (FMI*)	Fully-oriented electrical resistivity imaging	Bedding, geologic texture and structure, discrete fracture characterization
Hostile Natural Gamma Spectroscopy (HNGS*) and gamma ray (GR)	Gross and spectral natural gamma ray, including potassium, thorium, and uranium concentrations	Formation matrix geochemistry, lithology and mineralogy
Power Positioning Tool (PPC*)	4-arm, high-precision caliper	Borehole diameter and ellipticity

∗ Mark of Schlumberger

Once the Terranear PMC well drilling project team provided Schlumberger final notification that R-38 was ready for geophysical well logging, the Schlumberger district in Farmington, New Mexico, mobilized a wireline logging truck, the appropriate wireline logging tools and associated equipment, and crew to the job site. Table 1.0-2 summarizes the geophysical logging runs performed in R-38.

Table 1.0-2
Geophysical Logging Services, Their Combined Tool Runs and Intervals Logged, as Performed by Schlumberger in Well R-38

Date of Logging	Run #	Tool 1 (bottom)	Tool 2 (top)	Tool 3	Depth Interval (ft bgs)
8-Nov-2008	1	CMR	HNGS	GR	760 - 884
	2	FMI	GR		760 - 891
	3	PPC	GR		40 – 885
	4	AIT	GR		760 – 879
	5	APS	GR		290 - 884

Preliminary results of these measurements were generated in the logging truck when the geophysical services were performed and are documented in field logs provided on-site. However, the measurements presented in the field results are not fully corrected for borehole conditions and are provided as separate, individual logs. The field results were reprocessed by Schlumberger to (1) correct/improve the measurements, as best as possible, for borehole/formation environmental conditions; (2) perform an integrated analysis of the log measurements so that they are all coherent and provide consistent hydrogeologic and geologic results; and (3) combine the logs in a single presentation, enabling integrated interpretation. The reprocessed log results provide better quantitative property estimates that are consistent for all applicable measurements, as well as estimates of properties that otherwise could not be reliably estimated from the single measurements alone (e.g., lithology).

The geophysical log measurements from well R-38 provide, overall, good quality results that are consistent with each other through most of the borehole. The quality of some measurements was degraded across intervals where the borehole contained large washouts and/or rugose hole, particularly in the uncased section across the intervals 811–822, 826–832, 861–866, 870–878, and 885–889 ft bgs. The measurements most affected by the adverse borehole conditions were ones that have a shallow depth of investigation and that require close contact to the borehole wall—the porosity measurements (particularly from the magnetic resonance tool). The greatest impact on the log processing was erroneously high water-filled porosity in the adverse borehole conditions—as estimated from the logs.

Also, in cased hole section of the borehole (above 758 ft) the existence, extent, and effect on the geophysical logs of a water or air-filled annulus between the casing and the borehole wall (voids behind the casing) are difficult to determine and thus there is uncertainty about how well some of the log measurements represent true geologic formation conditions (unaffected by drilling). The distance between the logging tool sensor and formation is unknown and thus difficult to account or correct for. The measurements most affected by voids behind the casing were ones that have a shallow depth of investigation and that require close contact to the uncased borehole wall—for the nonradioactive source logging suite employed in R-38 the APS neutron porosity measurements (bulk density, normally run in Los Alamos National laboratory [the Laboratory] cased holes was not run because it has a chemical radioactive source and the logging included the open-hole section). However, APS water-filled porosity measurements from different depths of investigation beyond the casing are consistent with each other, suggesting there are not significant voids behind the casing.

Through the integrated analysis and interpretation of all the logs, the individual shortcomings of the specific measurements are reduced. Thus, the results derived from integrated log analysis (e.g., the optimized water-filled porosity log) are the most robust single representation of the geophysical log measurements—providing a wealth of valuable high-resolution information on the geologic and hydrogeologic environment of the R-38 locale.

Important results from the processed geophysical logs in R-38 include the following.

1. The well standing water level in R-38 was 812 ft bgs at the time of logging and did not vary much between the different logging runs.

2. The processed logs indicate that the intersected geologic section is fully saturated with water from the bottom of the log borehole (889 ft bgs measured from the geophysical logs) to likely 812 ft bgs (depth of the borehole water level at the time of the logging), although the 10-ft zone directly beneath the top of the borehole water level was severely washed out and the geophysical logs do not measure true rock formation water saturation (instead measuring unrealistically high water content). The logs results indicate that there is possibly a lithologic boundary at 812 ft, with alluvium/fanglomerate lying below (as seen on the FMI electrical image) and more competent material above. Below 812 ft, the log-estimated water content and total porosity average about 30% of total rock/sediment volume in good borehole sections (below 860 ft it is very high, mostly above 50%, due to severe washouts). Above 812 ft, the water content is much lower, 5% increasing to 12% at 775 ft. The nonradioactive source open-hole logging suite does not provide a measurement of air-filled or total porosity, so a quantitative assessment of water saturation is not possible. These results suggest that the depth of the regional aquifer water level (depth at which there is full water saturation) is no higher than 812 ft and likely not much lower.

3. Above 812 ft bgs, which the processed logs definitely show to be within the vadose zone (above the top of the regional aquifer), the estimated water content varies from less than 5% of total rock/sediment volume to above 20% in a few zones, mostly remaining below 12%. The following zones have higher measured formation water content.

    - 730–755 ft, water content averages about 20%, with peaks as high as 32%. The integrated log analysis suggests this zone has higher silt/clay content than the surrounding section.

    - 600–635 ft, water content increases from 15% at the top to 35% at the bottom. This zone also appears to have elevated silt/clay content from the integrated log analysis.

    - 485–505 ft, water content varies from 10% to 20% at the bottom, with some indication of small amounts of fine-grained material from the integrated log analysis.

    - 355–400 ft, slightly elevated water content compared with the surrounding section, ranging from 10% to 13%, with no definitive indication of finer-grained material, although the uranium content is a little higher in this zone.

4. The predicted relative flow capacity profile generated from the integrated log analysis results suggests that the predominance of production/flow capacity in the saturated interval below 812 ft is from two zones at 872–890 ft (85% of total flow capacity) and 812–815 ft (15% of total flow capacity). However, these are severely washed out zones that are significantly biasing the permeability estimates (although it is quite possible these zones may be washed out from the drilling as a result of producing a lot of water). The FMI electrical image does show rounded gravels and cobbles in the intervals 812–821, 827–830, and possibly below 880 ft (image is hard to resolve due to severe washouts).

5. The geophysical log results clearly delineate that the saturated/water-filled section of the borehole consists of alluvium/fanglomerate ranging in grain size from gravel/cobble to sand, as seen on the processed FMI electrical image. Above the saturated/water-filled section (above 812 ft), where the FMI electrical imaging was unattainable because of lack of water in the borehole, the lithology is more difficult to discern from the logs. The open-hole section from 812 ft to the bottom of casing (758 ft) appears to be quite competent, suggesting possibly volcanic lava flows, but there is not a significant change in the spectral gamma-ray response that extends well into the unsaturated section up to 680 ft bgs. The integrated log analysis was performed assuming basalt or similar rock makeup from 812 ft up to the top of the porosity logged section at 295 ft, with several more silt/clay rich zones, as described above. The spectral gamma ray log response in the zone 225–240 ft is clearly characteristic of the Guaje Pumice Bed, with a large increase in thorium and uranium concentrations. Above this, the spectral gamma ray log response is characteristic of the volcanic tuff overlying the pumice bed and extending to the top of the log interval (60 ft bgs).

6. Interpreted planar bedding features across the electrically imaged interval 812 to 885 ft bgs have fairly widely varying dip azimuths (direction beds are dipping to), but the quadrants with highest frequency are to the northeast-southeast and secondarily to the north-northwest. Bedding feature dip angles (angle from horizontal) are mostly less than 15 degrees. No natural fractures were identified across this interval (except within a large rock “block” at 825 ft).

2.0 INTRODUCTION

Schlumberger performed geophysical logging services in characterization well R-38 in November 2008 before initial well completion. The purpose of these services was to acquire in situ measurements to help characterize the borehole, near-borehole, and abutting geologic formation environment. The primary objective of the geophysical logging was to provide in situ evaluation of formation properties (hydrogeology and geology) intersected by the well. This information was (and is) used by scientists, engineers, and project managers in the Los Alamos Characterization and Monitoring Well Project to design the well completion, better understand subsurface site conditions, and assist in overall decision-making.

The primary geophysical logging tools used by Schlumberger in well R-38 were the

- CMR tool, which measures the nuclear magnetic resonance response of the formation to evaluate total and effective water-filled porosity of the shallow formation and to estimate pore size distribution and in-situ hydraulic conductivity;
- APS, which measures volumetric water content of the formation to evaluate moist/porous zones;
- AIT, which measures formation electrical resistivity at five depths of investigation and borehole fluid resistivity to evaluate drilling fluid invasion into the formation (a qualitative indicator of permeability and water saturation), presence of moist zones far from the borehole wall, and presence of clay-rich zones;

- FMI tool, which measures electrical conductivity images of the borehole wall in fluid-filled open-hole and borehole diameter with a two-axis caliper to evaluate geologic bedding and fracturing, including strike and dip of these features and fracture apertures, and rock/sediment texture;

- General Purpose Inclinometry Tool (GPIT*), which measures borehole deviation and azimuth in open-hole to evaluate borehole position versus depth and to orient FMI images;

- NGS tool, which measures gross-natural gamma and spectral natural gamma-ray activity, including potassium, thorium, and uranium concentrations, to evaluate geology/lithology, particularly the amount of clay and potassium-bearing minerals; and

- PPC, which measures high-precision hole diameter and ellipticity.

In addition, calibrated gross GR was recorded with every service run for the purpose of correlating depths between the different logging runs. Table 2.0-1 summarizes the geophysical logging runs performed in R-38.

Table 2.0-1
Geophysical Logging Services, Their Combined Tool Runs and Intervals Logged, as Performed by Schlumberger in Borehole R-38

Date of Logging	Borehole Status	Run #	Tool 1	Tool 2	Tool 3	Depth Interval (ft bgs)
8-Nov-2008	Open hole below 761 ft; bit size of 11.875 in.; steel surface casing above 761 ft.; casing O.D. of 12.75 in.	1	CMR	HNGS	GR	760–884
		2	FMI	GR		760 –891
		3	PPC	GR		40–885
		4	AIT	GR		760 –879
		5	APS	GR		290–884

A more detailed description of these geophysical logging tools can be found on the Schlumberger website (http://www.hub.slb.com/index.cfm?id=id11618).

3.0 METHODOLOGY

This section describes the methods Schlumberger employed for geophysical logging of well R-38, including the following stages/tasks:

- measurement acquisition at the well site
- quality assessment of logs
- reprocessing of field data

3.1 Acquisition Procedure

Once the well drilling project team notified Schlumberger that R-38 was ready for geophysical well logging, the Schlumberger district in Farmington, New Mexico, mobilized a wireline logging truck, the appropriate wireline logging tools and associated equipment, and crew to the job site. Upon arriving at the Laboratory site, the crew completed site-entry paperwork and received a site-specific safety briefing.

After arriving at the well site, the crew proceeded to rig up the wireline logging system, including

1. parking and stabilizing the logging truck in a position relative to the borehole that is best for performing the surveys,
2. setting up a lower and an upper sheave wheel (the latter attached to, and hanging above, the borehole from the drilling rig/mast truck),
3. threading the wireline cable through the sheaves, and
4. attaching to the end of the cable the appropriate sonde(s) for the first run.

Next, prelogging checks and any required calibrations were performed on the logging sondes, and the tool string was lowered into the borehole. The tool string was lowered to the bottom of the borehole and brought up at the appropriate logging speed as measurements were made.

Any postlogging measurement checks were performed as part of log quality control (QC) and quality assurance. The tool string was cleaned as it was pulled out of the hole, separated, and disconnected.

The second tool string was attached to the cable for another logging run, followed by subsequent tool strings and logging runs. After the final logging run was completed, the cable and sheave wheels were rigged down.

Before departure, the logging engineer printed field logs and created a compact disc containing the field log data for on-site distribution and sent the data via satellite to the Schlumberger data storage center. The Schlumberger data processing center was alerted that the data were ready for postacquisition processing.

3.2 Log QC and Assessment

Schlumberger has a thorough set of procedures and protocols for ensuring that the geophysical logging measurements are of very high quality. This includes full calibration of tools when they are first built, regular recalibrations and tool measurement/maintenance checks, and real-time monitoring of log quality as measurements are made. Indeed, one of the primary responsibilities of the logging engineer is to ensure before and during acquisition that the log measurements meet prescribed quality criteria.

A tool-specific base calibration that directly relates the tool response to the physical measurement using the designed measurement principle is performed on all Schlumberger logging tools when first assembled in the engineering production centers. This is accomplished through a combination of computer modeling and controlled measurements in calibration models with known chemical and physical properties.

The base calibration for most Schlumberger tools is augmented through regular “master calibrations” typically performed every 1 to 6 mo in local Schlumberger shops (such as Farmington, New Mexico), depending on tool design. Master calibrations consist of controlled measurements using specially designed calibration tanks/jigs and internal calibration devices that are built into the tools, both with known physical properties. The measurements are used to fine-tune the tool’s calibration parameters and to verify that the measurements are valid.

In addition, on every logging job, before and after on-site “calibrations” are executed for most Schlumberger tools directly before/after lowering/removing the tool string from the borehole. For most tools, these represent a measurement verification instead of an actual calibration used to confirm the validity of the measurements directly before acquisition and to ensure that they have not drifted or been corrupted during the logging job.

All Schlumberger logging measurements have a number of associated depth-dependent QC logs and flags to assist with identifying and determining the magnitude of log quality problems. These QC logs are monitored in real-time by the logging engineer during acquisition and are used in the postacquisition processing of the logs to determine the best processing approach for optimizing the overall validity of the property estimates derived from the logs.

Additional information on specific tool calibration procedures can be found on the Schlumberger web page (http://www.hub.slb.com/index.cfm?id=id11618).

3.3 Processing Procedure

After the geophysical logging job was completed in the field and the data were archived, the data were downloaded to the Schlumberger processing center. There the data were processed in the following sequence: (1) the measurements were corrected for near-wellbore environmental conditions and the measurement field processing for certain tools (CMR) was redone using better processing algorithms and parameters, (2) the log curves from different logging runs were depth-matched and spliced, and (3) the near-wellbore substrate lithology/mineralogy and pore fluids were modeled through integrated log analysis. Separately, the FMI electrical image was processed to produce scaled and normalized high-resolution images that were interpreted to identify geologic features and compute fracture apertures. Afterwards, an integrated log montage was built to combine and compile all the processed log results.

3.3.1 Environmental Corrections and Raw Measurement Reprocessing

If required, the field log measurements were processed to correct for conditions in the well, including fluid type (water or air); presence of steel casing; and (to a much lesser extent) pressure, temperature, and fluid salinity. Basically, these environmental corrections entail subtracting from the measurement response the known influences of the set of prescribed borehole conditions. In R-38, the log measurements requiring these corrections are the APS porosity and NGS spectral gamma ray logs.

Two APS porosity measurements are available: one that measures thermal ("slow") neutrons, and one that measures epithermal ("fast") neutrons. Measurement of epithermal neutrons is required to make neutron porosity measurements in air-filled holes. In water- mud-filled holes, both the APS epithermal and thermal neutron measurements are valid, but the thermal neutron porosity has better statistical precision. Both epithermal and thermal neutron porosity measurements were made in R-38 because the borehole was partly water filled (below 812 ft during the APS logging) and partly air filled (above 812 ft during the logging). Epithermal neutron porosity was processed at the field site for borehole fluid type (air versus water) and other environmental conditions and didn't require any further processing. The thermal neutron porosity measurement was reprocessed for borehole conditions, although the results were very similar to the field logs. For further processing and analysis (e.g., integrated log analysis), the reprocessed thermal neutron porosity log was used.

The NGS spectral gamma ray is affected by the material (fluid, air, and casing) in the borehole because different types and amounts of these materials have different gamma ray shielding properties; the NGS measures incoming gamma rays emitted by radioactive elements in the formation surrounding the borehole. The processing algorithms try to correct for the damping influence of the borehole material. The NGS logs from R-38 were reprocessed to fully account for the environmental effects of the borehole fluid (water below 812 ft and air above) and hole size.

The measurements cannot be fully corrected for borehole washouts or rugosity because the specific characteristics (e.g., geometry) of these features are unknown and their effects on the measurements are often too significant to account for. Thus, the compromising effects of these conditions on the measurements should be accounted for in the interpretation of the log results.

3.3.2 Depth-Matching and Splicing

Once the logs were environmentally corrected for the conditions in the borehole and the raw measurement reprocessing was completed, the logs from different tool runs were depth-matched to each other using the FMI tool run as the base reference. Gross-gamma ray was used as the common correlation log measurement for depth-matching the different runs. The depth reference for all the processed logs in this report is ground surface; however, the depth reference for logs presented in the field are rotary table height (5.17 ft above ground surface).

3.3.3 Integrated Log Analysis

An integrated log analysis, using as many of the processed logs as possible, was performed to model the near-wellbore substrate lithology/mineralogy and pore fluids. This analysis was performed using the Elemental Log Analysis (ELAN∗) program (Mayer and Sibbit 1980, 103867; Quirein et al. 1986, 098043)—a petrophysical interpretation program designed for depth-by-depth quantitative formation evaluation from borehole geophysical logs. ELAN estimates the volumetric fractions of user-defined rock matrix and pore constituents at each depth based on the known log measurement responses to each individual constituent by itself[1]. ELAN requires an a priori specification of the volume components present within the formation, i.e., fluids, minerals, and rocks. For each component, the relevant response parameters for each measurement are also required. For example, if one assumes that quartz is a volume component within the formation and the bulk density tool is used, then the bulk density parameter for this mineral is well known to be 2.65 g/cc.

The logging tool measurements, volume components, and measurement response parameters used in the ELAN analysis for R-38 are provided in Table 3.3-1. The final results of the analysis—an optimized mineral-fluid volume model—are shown on the integrated log montage. In addition, the ELAN program provides a direct comparison of the modeled versus the actual measured geophysical logs, as well as a composite log of all of the key ELAN-derived results. To make best use of all the measurement data and to perform the analysis across as much of the well interval as possible (295 to 885 ft bgs, only the HNGS spectral natural gamma log was acquired above), as many of the processed logs as possible were included in the analysis, with less weighting applied to less robust logs. Not all of the tool measurements shown in Table 3.3-1 and the ELAN modeled versus measured log display are used for the entire interval analyzed, as not all the measurements are available, or of good quality, across certain sections of the borehole. To accommodate fewer tool measurements, certain model constituents are removed from the analysis in some intervals. Most notably, above 770 ft bgs capillary bound water had to be removed because no CMR measurement is available in the case hole section (CMR has the only measurement that is independently sensitive to bound water).

[∗]Mark of Schlumberger

[1]Mathematically this corresponds to an inverse problem: solving for constituent volume fractions from an (over)determined system of equations relating the measured log results to combinations of the tool measurement response to individual constituents.

The ELAN analysis was performed with as few constraints or prior assumptions as possible. A considerable effort was made to choose a set of minerals or mineral types for the model that is representative of Los Alamos area geology and its volcanic origins. For the ELAN analysis, the log interval from 295 to 812 ft bgs was assumed to basalt or other lava-like material, and a mineral suite considered representative of this, based on Laboratory cuttings mineral analysis, was used. The log interval 812 to 885 ft bgs was assumed to be in the Puye Formation, or fanglomerate/alluvium with similar composition, and a mineral suite considered representative of this geology, based on Laboratory cuttings mineral analysis, was used.

Initially, no prior assumption was made about water saturation—where the boundary between saturated and unsaturated zones lies (e.g., the depth to the top of the regional aquifer or perched zones)—in order to not bias where the analysis indicated full saturation was, even though there were no measurements in the open-hole logging suite specifically sensitive to air-filled or total porosity. Because of this, once the distinct change in water content at 912 ft was verified, an arbitrary total porosity was chosen for the full interval above. There is no way to objectively correct for the adverse effect on the log measurements from these borehole conditions; therefore the decision was made to perform the ELAN analysis so as to honor the log measurements. Accordingly, interpretations should be made from the ELAN results with the understanding that the mineral-fluid model represents a mathematically optimized solution that is not necessarily a physically accurate representation of the native geologic formation. Within this context, the ELAN model is a robust estimate of the bulk mineral-fluid composition that accounts for the combined response from all the geophysical measurements.

Table 3.3-1
Tool Measurements, Volumes, and Respective Parameters
Used in the R-38 ELAN Analysis

Volume / Tool Measurement	Air	Capillary Bound Water	Water	Hematite	Labradorite	Silica Glass, Cristo., Tridy.	Heavy Mafic Minerals	Augite	Montmorillinite	Orthoclase	Quartz
Epithermal neutron poro (ft^3/ft^3)	0	1.00	1.00	0.0556	-0.01	0.0	0.022	-0.01	0.5	-0.01	-0.05
Total CMR porosity (ft^3/ft^3)	0	1.0	1.0	0	0	0	0	0	0.5	0	0
CMR bound fluid volume (ft^3/ft^3)	0	1.0	0	0	0	0	0	0	0.5	0	0
Resistivity (ohm-m)[a]	Very high	9.76	4.88	Very high	Very high	Very high	Very high	Very high	Computed	Very high	Very high
Wet weight potassium (lbf/lbf)[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.003	0.004	0.12	0.0
Wet weight thorium (ppm)	0	0	0	0	1.75	2	4	13.5	24	5	0
Clay bound water volume (ft^3/ft^3)	0	0	0	0	0	0	0	0	0.5	0	0
Magnetic field variation (mT)[c]	0	0	0	10	0	0	2	0	0	0	0

gAPI = gamma ray API (American Petroleum Institute) standard unit

[a] ohm-m = Ohm × meters.

[b] lbf = Pounds force.

[c] mT = Millitesla.

4.0 RESULTS

Preliminary results from the wireline geophysical logging measurements acquired by Schlumberger in R-38 were generated in the logging truck at the time the geophysical services were performed and were documented in the field logs provided on-site. However, the measurements presented in the field results are not fully corrected for undesirable (from a measurement standpoint) borehole and geologic conditions and are provided as separate, individual logs. The field log results have been processed (1) to correct/improve the measurements, as best as possible, for borehole/formation environmental conditions, and (2) to depth-match the logs from different tool runs in the well. Additional logs were generated from integrated analysis of processed measured logs, providing valuable estimates of key geologic and hydrologic properties.

The processed log results are presented as continuous curves of the processed measurement versus depth and are displayed as (1) a one-page, compressed summary log display for selected directly related sets of measurements (see Figures 4.0-1, 4.0-2, and 4.0-3); and (2) an integrated log montage that contains all the key processed log curves, on depth and side by side. The summary log displays address specific characterization needs, such as moisture content, water saturation, and lithologic changes. The purpose of the integrated log montage is to present, side by side, all the most salient processed logs and log-derived models, depth-matched to each other, so that correlations and relationships between the logs can be identified.

Important results from the processed geophysical logs in R-38 are described below.

4.1 Well Fluid Level

The standing water level in R-38 was stable during the November 8, 2008, logging, remaining close to 812 ft bgs for all logging runs.

4.2 Regional Aquifer

The processed logs indicate that the intersected geologic section is fully saturated with water from the bottom of the log borehole (889 ft bgs measured from the geophysical logs) to likely 812 ft bgs (depth of the borehole water level at the time of the logging), although the ten foot zone directly beneath the top of the borehole water level was severely washed out and the geophysical logs do not measure true rock formation water saturation (instead measuring unrealistically high water content). The logs results indicate that there is possibly a lithologic boundary at 812 ft, with alluvium/fanglomerate lying below (as seen on the FMI electrical image) and more competent material above that could be acting as a hydrogeologic boundary. Below 812 ft the log estimated water content and total porosity[2] averages about 30% of total rock/sediment volume in good borehole sections (below 860 ft it is very high, mostly above 50%, due to severe washouts). Above 812 ft the water content is much lower, 5% increasing to 12% at 775 ft. The nonradioactive source open-hole logging suite does not provide a measurement of air-filled or total porosity, so a quantitative assessment of water saturation is not possible. These results suggest that the depth of the regional aquifer water level (depth at which there is full water saturation) is no higher than 812 ft and likely not much lower.

[2] Water-filled porosity (synonymous with volumetric water content) is defined in this report as the fraction of the total rock volume occupied by water. Total porosity is defined as fraction of the total rock volume occupied by water plus air, plus any other fluid or gas (nonsolid).

The predicted relative flow capacity profile generated from the integrated log analysis results suggests that the predominance of production/flow capacity in the saturated interval below 812 ft is from two zones at 872–890 ft (85% of total flow capacity) and 812–815 ft (15% of total flow capacity). However, these are severely washed out zones that are significantly biasing the permeability estimates (although it is quite possible these zones may be washed out from the drilling as a result of producing a lot of water). The FMI electrical image does show rounded gravels and cobbles in the intervals 812–821, 827–830, and possibly below 880 ft (image is hard to resolve because of severe washouts).

4.3 Vadose Zone Perched Water

Above 812 ft bgs, which the processed logs definitely show to be within the vadose zone (above the top of the regional aquifer), the estimated water content varies from less than 5% of total rock/sediment volume to above 20% in a few zones, mostly remaining below 12%. The following zones have higher measured formation water content.

- **730–755 ft bgs:** Water content averages about 20%, with peaks as high as 32%. The integrated log analysis suggests this zone has higher silt/clay content than the surrounding section.
- **600–635 ft bgs:** Water content increases from 15% at the top to 35% at the bottom. This zone also appears to have elevated silt/clay content from the integrated log analysis.
- **485–505 ft bgs:** Water content varies from 10% to 20% at the bottom, with some indication of small amounts of fine-grained material from the integrated log analysis.
- **355–400 ft bgs:** Slightly elevated water content compared with the surrounding section, ranging from 10% to 13%, with no definitive indication of finer-grained material, although the uranium content is a little higher in this zone.

4.4 Geology

The geophysical log results clearly delineate that the saturated/water-filled section of the borehole consists of alluvium/fanglomerate ranging in grain size from gravel/cobble to sand, as seen on the processed FMI electrical image. Above the saturated/water-filled section (above 812 ft), where the FMI electrical imaging was unattainable due to lack of water in the borehole, the lithology is more difficult to discern from the logs. The open-hole section from 812 ft to the bottom of casing (758 ft) appears to be quite competent, suggesting possibly volcanic lava flows, but there is not a significant change in the spectral gamma ray response that extends well into the unsaturated section up to 680 ft bgs. The integrated log analysis was performed assuming basalt or similar rock makeup from 812 ft up to the top of the porosity logged section at 295 ft, with several more silt/clay rich zones, as described above. The spectral gamma-ray log response in the zone 225–240 ft is clearly characteristic of the Guaje Pumice Bed, with a large increase in thorium and uranium concentrations. Above this the spectral gamma-ray log response is characteristic of the volcanic tuff overlying the pumice bed and extending to the top of the log interval (60 ft bgs).

Interpreted planar bedding features across the electrically imaged interval 812 to 885 ft bgs have fairly widely varying dip azimuths (direction beds are dipping to), but the quadrants with highest frequency at to the northeast to southeast and secondarily to the north-northwest. Bedding feature dip angles (angle from horizontal) are mostly less than 15 degrees. No natural fractures were identified across this interval (except within a large rock “block” at 825 ft).

4.5 Summary Logs

Three summary log displays have been generated for R-38 to highlight the key hydrogeologic and geologic information provided by the processed geophysical log results.

- Porosity summary log showing continuous hydrogeologic property logs, including total and moveable water content and water saturation,; highlights hydrologic information obtained from the integrated log results (Figure 4.0-1).
- Density and clay content summary showing a continuous logs of formation bulk density and estimated grain density, as well as photoelectric factor (sensitive to mineralogy) and estimated clay volume, highlights key geologic rock matrix information obtained from the log results (Figure 4.0-2).
- Spectral natural gamma ray and lithology summary showing a high vertical resolution, continuous volumetric analysis of formation mineral and pore fluid composition (based on an integrated analysis of the logs) and key lithologic/stratigraphic correlation logs from the spectral gamma ray measurement (concentrations of gamma-emitting elements) highlights the geologic lithology, stratigraphy, and correlation information obtained from the log results (Figure 4.0-3).

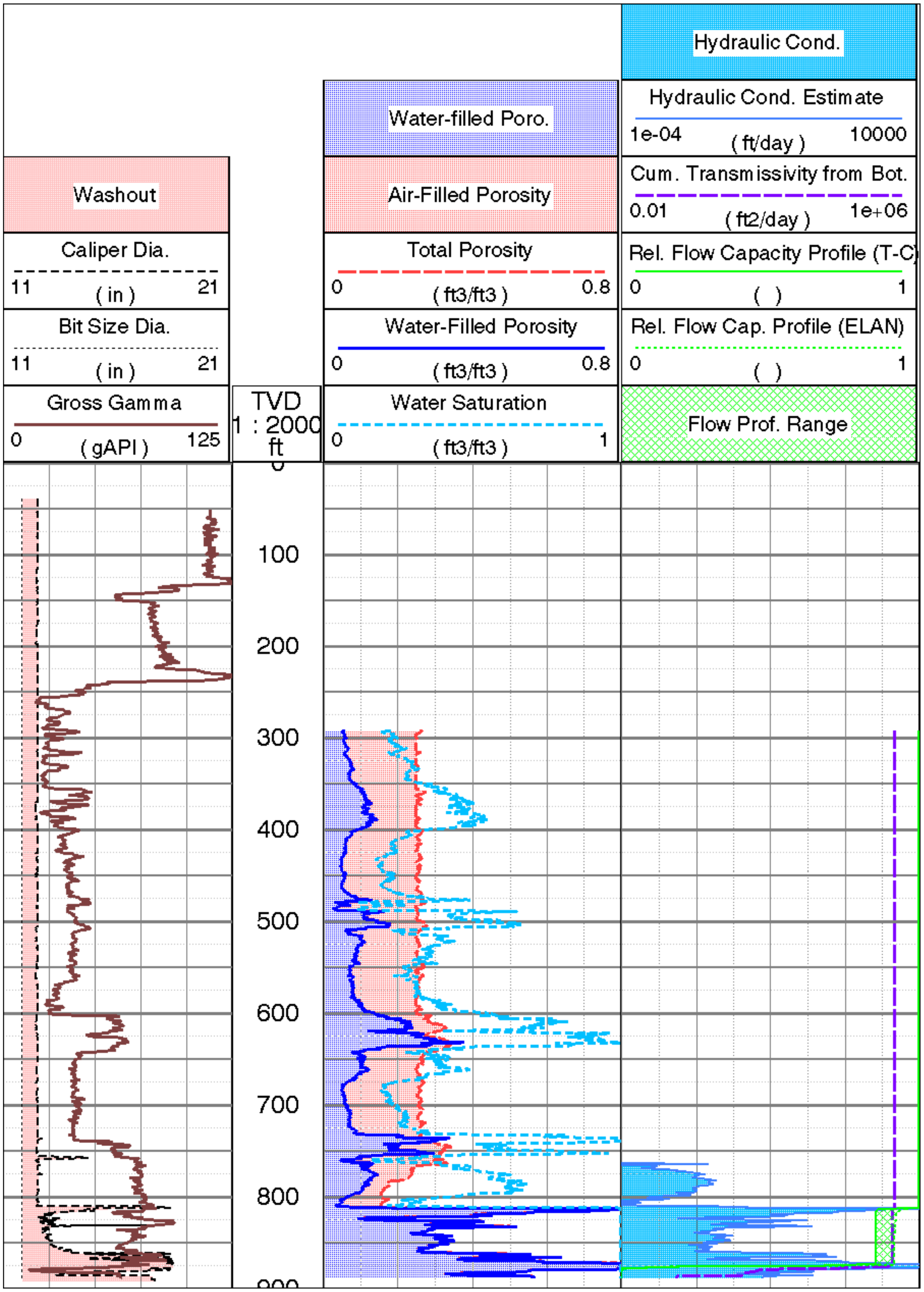

Figure 4.0-1 **Summary of porosity logs in R-38 borehole from processed geophysical logs, interval of 295 to 885 ft bgs, with caliper, gross gamma, water saturation, estimated relative flow capacity profile, hydraulic conductivity, and transmissivity logs also displayed. Porosity, water saturation, and hydraulic conductivity logs are derived from the ELAN integrated log analysis.**

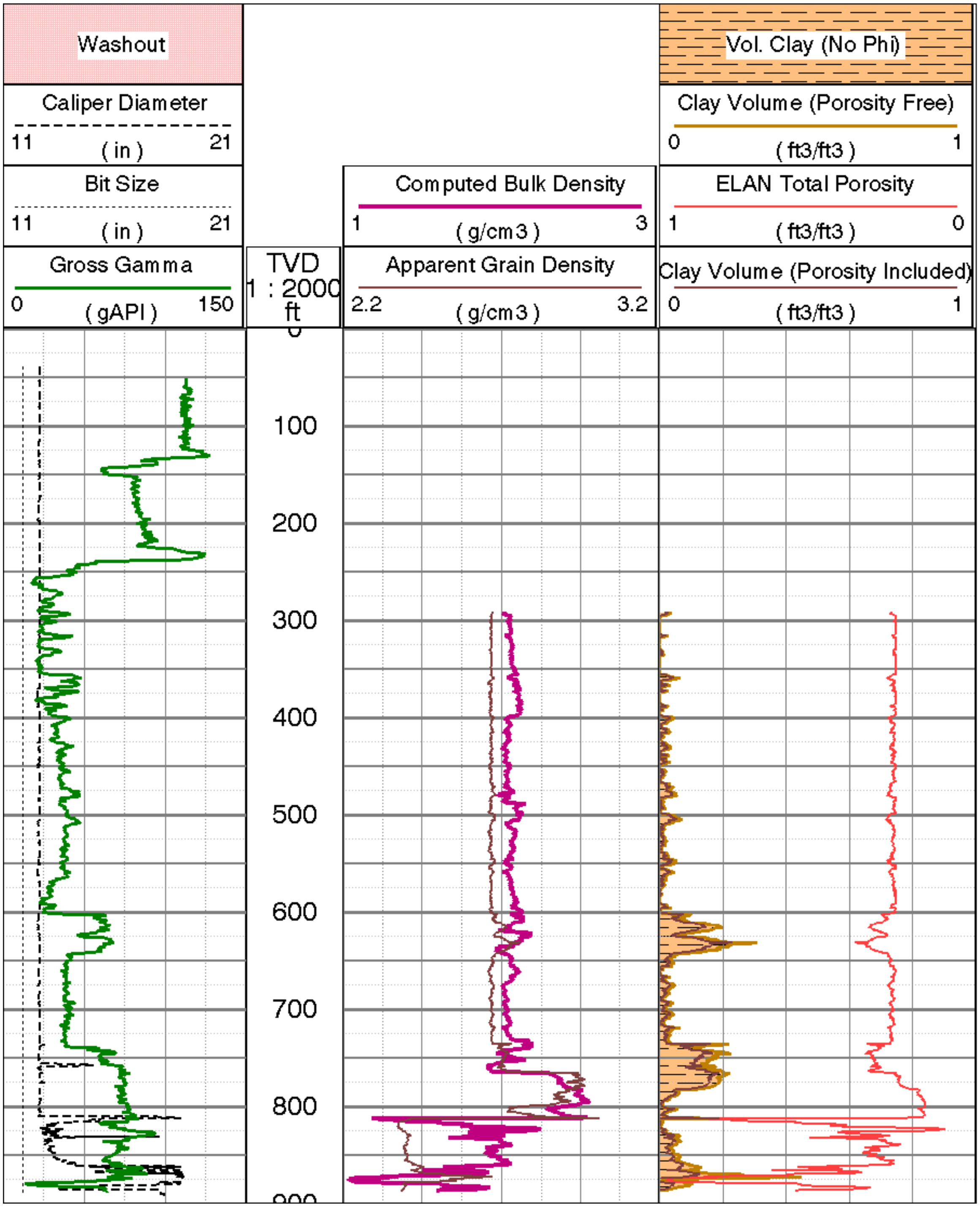

Figure 4.0-2 Summary of computed bulk density and volume clay logs in R-38 borehole from processed geophysical logs, interval of 295 to 885 ft bgs. Also shown are caliper, gross gamma, apparent grain density, and total porosity logs (the latter two derived from the ELAN analysis).

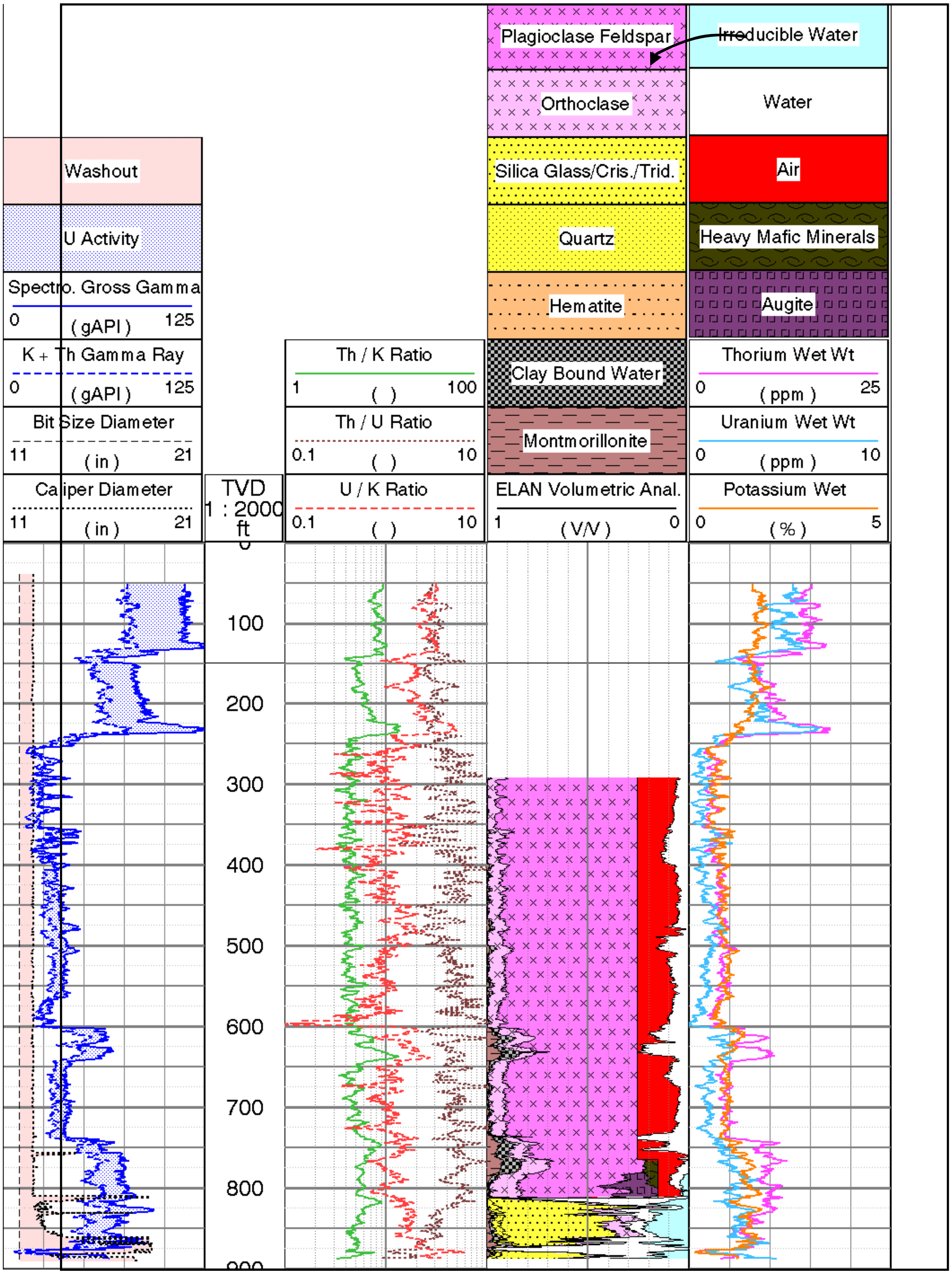

Figure 4.0-3 **Summary of spectral natural gamma ray logs and ELAN mineralogy/lithology and pore fluid model volumes derived from the ELAN integrated log analysis for R-38 borehole, interval 295 to 885 ft bgs. Caliper log is also shown.**

5.0 REFERENCES

The following list includes all documents cited in this appendix. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

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Quirein, J., S. Kimminau, J. LaVigne, J. Singer, and F. Wendel, June 9–13, 1986. “A Coherent Framework for Developing and Applying Multiple Formation Evaluation Models,” SPWLA 27th Annual Logging Symposium, June 9–13, 1986, Schlumberger Well Services, Houston, Texas. (Quirein et al. 1986, 098043)