Nye County Early Warning Drilling Program
Phase VI Drilling Report

NWRPO-2010-03

FINAL

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DISCLAIMER

EXECUTIVE SUMMARY

Introduction

This report describes the methods and results of Phase VI of the Nye County Early Warning Drilling Program (EWDP), performed as part of the Nye County Nuclear Waste Repository Project Office (NWRPO) Independent Scientific Investigations Program (ISIP). The ISIP was funded by a cooperative agreement with the U.S. Department of Energy (DOE) to support the evaluation of a high-level nuclear waste repository at Yucca Mountain, Nevada. Goals of the EWDP include a better definition of the potential risks of repository activities on Nye County drinking water supplies and the design of a groundwater monitoring network along potential flow paths between Yucca Mountain and populated areas of southern Nye County. A better understanding of the hydrogeologic flow system in this region is a necessary first step in achieving these goals and has been the primary focus of the EWDP to date.

Phase VI activities were conducted from June 2008 through July 2009 and involved drilling a deep borehole to 1,860 feet (ft) below ground surface, geologic sampling, testing, geophysical logging; and well completion. The primary technical objectives for constructing a Phase VI piezometer include:

- Help fill data gaps in hydrogeology in northern Amargosa Desert along the eastern margin of the Fortymile Wash drainage.
- Collect cuttings samples and run borehole geophysical logs to 1,860 ft.
- Conduct step-drawdown and 48-hour constant discharge tests to evaluate the hydrologic characteristics and water production potential of the well.
- Conduct isolated-zone packer tests to determine the hydrologic characteristics and production potential of each screened interval.
- Provide water chemistry data in each screened interval

All EWDP borehole names have a formal “NC-EWDP-” prefix; in this report the names will be given by number only. Phase VI boreholes were drilled at Site 4 where two boreholes (4PA and 4PB) had been previously drilled in NWRPO’s Phase II activities. Both boreholes were completed as piezometer wells to support Nye County’s groundwater monitoring program and were designed to provide a better understanding of the hydrogeologic flow system in this region.

The first attempt to drill a borehole in Phase VI (4PC) was unsuccessful due to bad borehole conditions and drilling equipment failure. The borehole was abandoned and plugged-back to surface and the replacement borehole 4PD was drilled and completed approximately 20 ft to the east of the abandoned borehole.

Drilling

The drilling methods employed in Phase VI included: air-rotary reverse circulation (AR-RC) drilling and mud-rotary conventional circulation (MR-CC) drilling. At 4PC, AR-RC methods were used to sample and advance the borehole. The borehole became unstable at 460 ft and consequently borehole abandonment operations were conducted. The drill rig was then moved over to a “new” spot approximately 20 ft east of the abandoned well and the replacement well 4PD was drilled and sampled using MR-CC.

AR-RC methods have been shown in previous EWDP Phases (NWRPO, 2003; NWRPO, 2005 and NWRPO 2009) to yield drill cuttings samples from unsaturated alluvium with reasonably representative coarse (sand plus gravel) and fine (silt plus clay) fractions. Samples from MR-CC are recognized as being the least representative of in situ conditions. Samples were collected at 10-ft intervals from the water table downward (from 320 ft below ground surface (bgs)) and processed into three splits: one for archive to the DOE Sample Management Facility (SMF), one for laboratory sieve analysis, and one for field logging. Data collected from laboratory testing was limited to sieve analysis as it is recognized that the fine component of the formation is lost to the mud-based drilling fluid. These sieve data were used only for the selection of screen aperture size and sand pack gradation and sizing.

Geologic Logging

Geologic logs indicate that alluvium and valley-fill units penetrated during Phase VI were composed predominantly of volcanic rock, the only exception was within the interval of 920 to 1,320 ft at 4PD where clasts derived from sedimentary units, including sandstone, siltstone, claystone, and quartzite, comprised up to 60% of the clasts in the samples. Non-alluvium was not penetrated in 4PC as the borehole was not advanced past 460 ft and all samples collected were composed of alluvial and valley-fill material. At 4PD samples were not collected above 320 ft due to the fact that there was no need to duplicate unsaturated zone samples already collected and logged in this interval at 4PC. The non-alluvium contact at 4PD was intersected at 1,760 ft; depositional units below this contact consisted of ash-flow tuff, although intervals of basalt lava flows, sandstone, older and cemented alluvium occur between 1,400 and 1,760 ft.

The observed water contents of unsaturated alluvium drill cuttings from 4PC above 340 ft were all artificially wet due to the use of injection water during the advancement of the borehole. Below 340 ft the borehole began producing water as saturated sediments were penetrated. At 4PD all drill cuttings from the unsaturated zone were artificially wet due to the use of drilling fluids used to circulate the drill cuttings to surface and condition borehole walls.

Cementation in drill cuttings of alluvium from 4PC ranged from none to weak from 0 to 185 ft, none to weak to moderate from 185 to 410 ft, and strong from 410 to 460 ft. Cementation observed in drill cuttings of alluvium from 4PD varied from none to weak to moderate from 320 ft (beginning sample point) to 620 ft. From 620 to 640 ft the alluvium becomes strongly cemented and hard. From 640 to 1,070 ft the interval is weak to moderately cemented. From 1,070 to 1,110 ft layers of strongly cemented and thinly bedded (laminated) sandstone, siltstone, and claystone were observed. The remainder of the alluvial section from 1,110 to 1,400 ft was strongly cemented.

Hydrochloric acid (HCl) reaction for different sample intervals ranged from none to strong in Phase VI boreholes. Since alluvium penetrated in Phase VI boreholes does not contain carbonate rocks, HCl reaction indicates the presence of calcite, a potential cementing agent. However, the lack of visual evidence of cementation in alluvium suggests that calcite does not play a significant role in cementation. A similar conclusion regarding calcite as a cementing agent was reached in Phase IV and Phase V boreholes (NWRPO, 2005) and (NWRPO, 2009) respectively.

Drilling penetration rates varied from less than 0.1 ft per minute (fpm) to greater than 1 fpm. At 4PC the drilling rates were fairly consistent and generally greater than 0.8 fpm, however, lower drilling rates occurred in the intervals where the hole was unstable and thus created difficult drilling conditions or in intervals where sediments contained high clay content resulting in problems with bit plugging. At 4PD drilling rates in the alluvium were similarly impacted by sediments with high clay content or within unstable borehole intervals, however, the lowest drilling rates (0.09 to 0.2 fpm) occurred within the harder non-alluvium units below 1,400 ft.

Water production rates were not measured in Phase VI boreholes during drilling due to the use of water injection or bentonite mud circulation to facilitate the advancement of the boreholes.

Laboratory Test Results on Drill Cuttings

Well borehole 4PD was drilled with MR-CC, therefore the alluvial drill cuttings samples are not representative of in situ sediments. The samples are biased toward the coarse fraction and considered disturbed. Cutting samples collected by the NWRPO are generally tested in the lab in an effort to measure the physical, textural, and hydraulic properties of the materials. However, because of bias introduced by mud-rotary drilling methods, samples from 4PD were not subjected to an extensive laboratory testing program.

Cuttings samples collected from a nearby borehole (4PB) drilled during Phase II on the same site using reverse circulation hammer (Becker) drilling methods as well as samples collected using AR-RC methods from 4PC from 0 to 455 ft, prior to borehole abandonment, are considered reasonably representative of in situ conditions. Borehole 4PB is approximately 40 ft east of 4PD and was drilled and sampled to 850 ft. Borehole 4PC is approximately 20 ft west of 4PD and was drilled and sampled to 460 ft. Archived samples from 4PB, along with samples collected from 4PC were tested to determine particle size distribution (PSD) and clay content (hydrometer) in the NWRPO laboratory in August 2008.

Due to the proximity of these boreholes, a close agreement of textural properties was expected. Laboratory data demonstrated that the sediments are consistent, if allowances are made for textural differences due to lateral facies changes and slight differences in the depth to stratigraphic contacts due to the dip of the depositional units, and by extrapolation they are assumed to be consistent with sediments underlying 4PD.

From ground surface to 850 ft, wet sieve and hydrometer data for 4PB and 4PC were used to determine particle size distribution (relative percentages of gravel, sand, silt, and clay) and sediment layering. Reliable sieve data were not available for sediments below 850 ft. Visual comparison of PSD data curves from 4PB and 4PD above 850 ft indicate large sample bias resulting from drilling and sampling of mud-rotary cuttings. This comparison illustrated that 4PD mud-rotary samples are not representative of in situ conditions, as recognized in previous EWDP investigations. For this reason 4PD PSD data was not used for sediment texture and layering analysis.

Summary of Lithologic Logging Results

Boreholes 4PC and 4PD

The geology at Site 4 consists of a relatively thick (about 400 ft) Quaternary and older alluvial sequence overlying Tertiary valley-fill sediments including older alluvium and basalt lava flows of Miocene age which in turn are presumed to overly Middle Miocene volcanic rocks of the Timber Mountain Group. The valley-fill sediments exhibit a more fine-grained texture than the overlying alluvial sequences encountered in EWDP boreholes further west in Fortymile Wash and may reflect the presence of an older sequence of sediments deposited in fluvial, paludal and lacustrine environments near the Gravity Fault. Similar sediments were encountered at depth in boreholes at sites 5 and 23, to the east and north respectively.

Well NC-EWDP-4PD is a 1,850 ft well with 6 screened zones. The two lowermost zones are completed in well-indurated ash-flow tuffs and hard basalt lava flows and the upper four zones are longer intervals in unconsolidated clayey to gravel-rich valley-fill sediments.

Borehole Geophysical Logging Results

Borehole geophysical logs were used for lithologic characterization and stratigraphic correlations. For the most part, only qualitative interpretations of rock properties were made from the logs. Significant findings include the following:

- Increasing amounts of fines in formation materials usually correlate with increasing natural gamma counts, decreasing formation resistivity values, increasing density values, and decreasing neutron porosity log counts (increasing water filled porosity).
- In 4PD, increasing amounts clay correlate with all of the above, except increasing natural gamma counts. In this case, natural gamma counts may decrease (rather than increase) as a result of a decrease in the concentration of gamma emitters due to the diagenesis of the formation.
- In alluvium, increasing natural gamma curves and peaks in density and neutron porosity curves correspond to clean well-graded sand and/or gravel that produces clean water. These sand and/or gravel units can serve as preferential flow paths.
- In volcanic units, formation resistivity logs are useful for identifying ash-flow tuffs and basalt flows, and therefore useful for stratigraphic correlation. Higher resistivity values correlate well with denser rocks identified in the geological cuttings described at the site and lower resistivity values correlate with nonwelded rocks.
- Basalt flows exhibit lower natural gamma counts and higher density values than alluvium.
- In 4PD, fluid resistivity and fluid temperature logs could be used to identify discrete intervals where groundwater flows into or out of the wellbore. In several cases, formation resistivity, density, and neutron porosity logs supported identification of water movement into/out of the borehole.
- In alluvial units in 4PD, large peaks in caliper logs resulted from washout zones and corresponding decreases in natural gamma, density, resistivity, and neutron porosity log values.

- Density and neutron porosity responses can be due to different clay contents, degree of cementation, grading of clasts, washout zones, and/or fractures.
- Sonic velocity curves are variable, reflecting the density of the formation. Low velocities can possibly indicate a decrease in water saturation in the sediments. Increasing sonic velocities suggest a pervasive cement or that a denser clastic material may be present.

Recommendations

- When contracting AR-RC drilling work, add a contract clause requiring a minimum of 10 years "behind the controls" experience for drilling rig operator.
- Always include a deviation clause (including 'dog-leg') for MR-CC well borehole drilling contracts.
- Do not conduct particle size distribution analysis (wet sieve analysis) on MR-CC samples as the bias introduced by the drilling method eliminates any interpretive value of the analysis.
- Continue recording field estimates of major particle size fractions in alluvium and valley-fill (unconsolidated) on drill cuttings logging forms. These data are proving very useful in characterizing the textural layering in the sediments downgradient from Yucca Mountain.
- Continue running natural gamma, caliper, formation resistivity, density, neutron porosity, sonic, fluid temperature, and fluid resistivity geophysical logs.

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FIGURES

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ACRONYMS

AR-RC	air-rotary reverse circulation
ASTM	American Society for Testing and Materials
ATC	Alluvial Testing Complex or Alluvial Tracer Complex
bgs	below ground surface
DOE	U.S. Department Of Energy
DR-CA	dual-rotary casing-advance
EWDP	Early Warning Drilling Program
fpm	feet per minute
FM-RC	flooded-mud reverse circulation
ft	feet
GLS	Geophysical Logging Services
gpm	gallons per minute
HCl	hydrochloric acid
ISIP	Independent Scientific Investigations Program
LANL	Los Alamos National Laboratory
LCM	lost circulation material
MR-CC	mud-rotary conventional circulation
NTS	Nevada Test Site
NWRPO	Nuclear Waste Repository Project Office
OD	outside diameter
OTV	optical televiewer
PSD	particle size distribution
PVHA	Probabilistic Volcanic Hazard Analysis
QA	quality assurance
QARC	Quality Assurance Records Center
RID	record index designator
SMF	Sample Management Facility
SP	spontaneous potential or self potential
TD	total depth
TP	technical procedure
TPN	test plan
USCS	Unified Soil Classification System
USGS	U.S. Geological Survey
VDL	Variable Density Log
WP	work plan
YMP	Yucca Mountain Project

1.0 INTRODUCTION

This report describes activities performed during Phase VI of the Early Warning Drilling Program (EWDP), which include borehole drilling; geologic sampling, testing, and logging; and well completion. Phase VI field work began in June 2008 and continued through July 2009. These activities were performed as part of the Nye County Nuclear NWRPO ISIP, which was funded by a cooperative agreement with the U.S. Department of Energy Yucca Mountain Project (DOE YMP) to support the evaluation of a high-level nuclear waste repository at Yucca Mountain, Nevada.

1.1 Program Background

The Yucca Mountain repository is located within Nye County. Because Nye County retains limited local jurisdiction over this site, the county has rights of participation, funding, and onsite representation in YMP policies and activities. Nye County began to exercise these rights in 1987 by creating the NWRPO. The major goals of the NWRPO are to provide an independent evaluation and review of activities and policies related to the transport, disposal, and storage of nuclear waste within Nye County, and to supplement federal studies about potential impacts of the repository.

The ISIP was initiated in 1994 with a technical grant from DOE YMP to provide an independent evaluation of selected site characterization and repository design and performance issues potentially affecting human health, safety, and the environment in southern Nye County. Since 1994, several additional grants and cooperative agreements have been obtained from DOE YMP to continue the ISIP.

The EWDP is a subregional-scale hydrogeologic study and monitoring program designed to help protect Nye County water supply interests. The program focuses primarily on the region between the Yucca Mountain repository and populated areas of the Town of Amargosa, referred to as Amargosa Valley in this report, in southern Nye County. The closest Amargosa Valley community to Yucca Mountain is Lathrop Wells, which is approximately 12 miles southeast of Yucca Mountain and downgradient along potential groundwater flow paths. Figure 1.1-1 shows the location of these areas, as well as the Nevada Test Site (NTS), areas of private land ownership, and the principal population centers within southern Nye County.

A major Nye County concern is whether future Yucca Mountain nuclear waste management activities have the potential to impact the groundwater and surface water supplies within the Amargosa Valley and, in turn, human health and the environment. Although Amargosa Valley is sparsely populated and largely undeveloped, significant economic development and population growth will likely occur as a result of the YMP. Amargosa Valley also contains important sensitive natural environments and habitats, including Ash Meadows National Wildlife Refuge, Devils Hole, the Amargosa River, and various springs and associated wetlands.

The first five phases of the EWDP, conducted October 1998 through April 2006, and were funded by cooperative agreements with DOE YMP. Selected results from Phases I through V are found on the NWRPO website (NWRPO, 2010). In addition, an overview of Phases I and II can be found in the NWRPO report for fiscal years 1996 through 2001 (NWRPO, 2001).

Finally, details of Phase III, Phase IV, and Phase V methods and results are found in three NWRPO technical reports (NWRPO 2003, NWRPO 2005, and NWRPO 2009). These technical report documents can also be found on the NWRPO website.

1.2 Program Objectives and Activities

The overall objectives of the EWDP include the following:

- A better definition of the potential risk to Amargosa Valley drinking water supplies from high-level nuclear waste handling and disposal at the Yucca Mountain repository
- The design of an appropriate "early warning" groundwater monitoring network between the repository and present and future populations in the Amargosa Valley area

A better understanding of the hydrogeologic system is a necessary first step toward achieving these objectives and has been the focus of all EWDP phases to date.

Before initiating the EWDP, an evaluation of existing hydrogeologic data revealed a significant data gap in the region downgradient from Yucca Mountain, including part of southern Jackass Flats, southern Crater Flat, western Rock Valley, and the northern Amargosa Desert. In short, there were few or no subsurface hydrogeologic data for these areas. The EWDP has targeted basic hydrogeologic data deficiencies in this region and continues to study the origin of spring deposits; geologic and hydraulic properties of valley-fill sediments; groundwater depths, gradients, and flow patterns; and baseline water chemistry.

Specific objectives of the EWDP include determining the following:

- Flow and transport parameters needed to refine and reduce uncertainty in groundwater and performance assessment models that incorporate groundwater modeling results
- Baseline water chemistry and water level data, and the capability to monitor trends in these data in strategically placed boreholes over time

- A better understanding of the hydraulic properties of the tuff/alluvium interface, the nature and continuity of alluvial textural layers, the hydrogeologic units underlying the alluvium, and hydraulic gradients within and between units.

Phases I and II, completed in 2000 and 2001, respectively, provided hydrogeologic and baseline water chemistry data for the region south of the repository and along U.S. Highway 95, which traverses the northern edge of Amargosa Valley.

Phase III, completed in 2002, focused on filling data gaps for the region along the lower reaches of Fortymile Wash within and outside the NTS. Work in the region outside the NTS included establishing further testing and monitoring capabilities at the Alluvial Testing Complex (ATC) (Site 19) located just west of the present day braided channel area of Fortymile Wash approximately a mile north of Highway 95. The ATC was established for cooperative studies conducted by the DOE YMP; U.S. Geological Survey (USGS); Los Alamos National Laboratory (LANL); University of Nevada, Las Vegas; and Nye County to characterize the hydraulic and transport properties of the saturated alluvium near the southwestern boundary of the NTS.

Phase IV, completed in August 2003, targeted southerly flow paths from Yucca Mountain in the drainage immediately to the west of Fortymile Wash, named Flat Tire flat in NWRPO (2005), and along the western edge of Fortymile Wash. In addition, it included a sonic corehole at Site 19.

Phase V activities were concluded in April 2006 and involved constructing 6 boreholes, 5 of which were completed as piezometers to help fill data gaps in hydrogeology along the southeastern edge of Crater Flat and in the area south of Highway 95 in the general area of Fortymile Wash, and to support on-going groundwater tracer testing in both alluvium and fractured tuff. Phase V activities included borehole drilling, drill cuttings and core collection, geologic logging and laboratory testing of selected samples, borehole geophysical logging, completion of single-screen and multiple string (i.e., nested) piezometers, water chemistry and water level monitoring, and limited aquifer testing.

Phase VI activities were concluded in July 2009 and involved drilling two boreholes and constructing one multiple-screen monitor well.

The primary technical objectives for drilling and construction of Phase VI piezometers include: 1) collect cuttings samples and run borehole geophysical logs to 1,860 ft; 2) conduct step-drawdown and 48-hour constant discharge tests to evaluate the hydrologic characteristics and water production potential of the well; 3) conduct isolated-zone packer tests to determine the hydrologic characteristics and production potential of each screened interval; 4) provide water chemistry data in each screened interval.

This report focuses on the scope, methods, and results of these Phase VI activities, with the exception of water chemistry and water level monitoring, which will be described in future Nye County technical reports.

1.3 Location of Phase VI Boreholes

The locations of the two Phase VI boreholes are shown on Figure 1.1-1 their coordinates are given in Table 1.3-1. All EWDP borehole names have an “NC-EWDP-” prefix; in this report the names will be given by number only. The two Phase VI boreholes are listed as follows with the “P” in each number standing for a piezometer, which is defined in this report as a small diameter monitor well with a screen length generally less than 250 ft.

- 4PC
- 4PD

Due to unstable borehole conditions in 4PC at approximately 460 ft bgs, it was necessary to abandon this borehole, and as a result it could not be completed as a water table piezometer. Well 4PD was constructed as a replacement for 4PC.

The deep Phase VI piezometer (4PD) was constructed in a location where relatively shallow piezometers (4PA and 4PB) had previously been constructed; 4PD is located about 1 mile south of the southern boundary of the Nevada Test Site and about 2.5 miles east of the present day main channel of the lower portion of Fortymile Wash. Access to the well site is along Lathrop Wells Gate 510 Road and is about 0.8 miles north of Highway 95.

1.4 Pre-Phase VI Knowledge

1.4.1 Geologic Setting

Boreholes 4PC and 4PD are located in northern Amargosa Desert, in southern Jackass Flats, and along the eastern margin of lower Fortymile Wash. This wash is the major topographic drainage system for Jackass Flats, the eastern side of Yucca Mountain, and the upland region of the southwestern corner of the NTS.

The Phase VI boreholes 4PC and 4PD were drilled at the existing site of Phase II boreholes 4PA and 4PB which is along the eastern margin of the Fortymile Wash, approximately 3 miles west of the Stripped Hills, and less than 1 mile north of the Highway 95. The site is approximately 2 miles north of the Highway 95 fault, a roughly east-west trending buried fault that restricts ground water flow in the north-south direction and supports higher heads to the north. Past EWDP drilling and testing has found that flow in the alluvial aquifer is not homogeneous, but rather complex, reflecting the environment of deposition of the sediments. The boreholes and piezometers at Site 4 provide significant new data on the geologic and hydrologic characteristics of the alluvial and valley-fill aquifers along the eastern margin of Fortymile Wash and have contributed to NWRPO's effort to construct reasonably detailed lithologic logs, stratigraphic correlations through the valley-fill of Fortymile Wash. In addition, the data collected from Phase VI boreholes serves to complete an east-west transect through Fortymile Wash extending from the southern Windy Wash area on the west to the Striped Hills on the east. The Site 4 location is also significant due to its close proximity (approximately 2 miles west) to a large-scale north-south gravity gradient that has long been recognized and interpreted as a buried normal fault (i.e., the "Gravity" Fault).

The geology at Site 4 consists of a relatively thin (about 400 ft) Quaternary and older alluvial sequence overlying Tertiary valley-fill sediments including older alluvium and basalt lava flows of Miocene age which in turn are presumed to overly Middle Miocene volcanic rocks of the Timber Mountain Group. The valley-fill sediments exhibit a more fine-grained texture than the alluvial sequences encountered in EWDP boreholes further west in Fortymile Wash and may reflect the presence of an older sequence of sediments deposited in fluvial, paludal and lacustrine environments near the Gravity Fault. Similar sediments were encountered at depth in boreholes at sites 5 and 23, to the east and north respectively.

Well NC-EWDP-4PD is a 1,850 ft well with 6 screened zones. The two lowermost zones are completed in well-indurated ash-flow tuffs and hard basalt lava flows and the upper four zones are longer intervals in unconsolidated clayey to gravel-rich valley-fill and alluvial sediments.

Previous drilling in the southern Jackass Flat area by Nye County includes boreholes and wells developed at sites 5 and 23 (Figure 1.3-1). At site 5, in EWDP Phase I, the well borehole NC-

EWDP-5S was drilled a depth of 1,200 ft using AR-RC methods. Summary logs indicate an upper section of relatively coarse alluvial sediments (SW-SM and GW) to 240 ft with a base of GC from 240 to 265. Underlying the coarse alluvial materials are finer clay-rich sediments (SC, GC, CL, SW-SC) with lesser interbedded sand-rich units (SW). It is interpreted, that the clay-rich sediments represent older valley-fill sediments prior to alluvial deposition above 265 ft.

At site 23, in EWDP Phase III, the well borehole NC-EWDP-23P was drilled to a depth of 1340 ft using AR-RC methods. As at site 5, an upper section of coarse alluvium (SW-SM) from surface to 450 ft is underlain by clay-rich sediments (SC) to 1,200 ft. Below 1200 ft and to total depth (TD), SW-SM predominates. A layer of basaltic boulders was encountered at 1,320 to 1,325 ft.

Both boreholes (5S and 23P) have a similar overall stratigraphy that includes an upper section of coarse alluvial deposits similar to boreholes in the Fortymile Wash section (24P, 29P, 19D, 2DB) and the intermediate distant borehole at NC-EWDP-Washburn- 1x. It is apparent that east of Fortymile Wash (see Alluvial Cross Section Record Index Designator (RID) 5613, also in NWRPO 2003), that below this upper layer of coarse alluvium is a series of clay-rich sediments to depths beyond 1200 ft, without the intersection of a “bedrock” unit. The exact age and depositional environment of this lower clay-rich sequence is problematic, since no easily datable unit exists within the sequence. As part of the YMP Probabilistic Volcanic Hazard Analysis (PVHA) analysis, dating of the basalt in 23P at approximately 10 Ma from the 1,320 ft interval provides a bound on the ages represented.

It has been recognized that additional work east of Fortymile Wash was warranted to understand the valley-fill and alluvial sequences present. Site 4, with the existing shallow holes (4PA, 4PB), could provide data on the deeper stratigraphic relationships.

Locations of the Phase VI boreholes with respect to surface geology are shown on a recent geologic map of the Yucca Mountain area by Potter and others (2002), which describes local stratigraphy and faults (Figure 1.4-1).

1.4.2.1 Gravity Data

A regional gravity study of the area performed by the USGS (Blakely and Ponce, 2001) identified several gravity anomalies within the Death Valley ground-water model area reflecting various rock types, deep sedimentary basins, and linear geologic features such as faults. The thick accumulation of quaternary alluvial deposits and older valley-fill sediments encountered at Site 4 play an important role in the saturated-zone hydrology of the eastern Fortymile Wash and Jackass Flat areas.

The work of Blakely and Ponce (2001) further shows a north-south-trending gravity gradient between low and moderate depths to basement on the east side of Fortymile Wash. This feature, which has long been recognized (Winograd and Thordarson, 1975) and is interpreted to be a buried normal fault, has been termed the Gravity Fault. All Phase IV, V, and VI boreholes are located west of the Gravity Fault on the down-dropped side.

1.4.2.2 Aeromagnetic Survey

An airborne magnetic survey was also performed by the USGS (Blakely et al., 2000) to identify younger volcanic rocks, which are more magnetic than other rock types. Three deep-seated east-west trending magnetic gradients (signatures) were identified between the south end of the repository and Highway 95; and a prominent magnetic lineament coincident with the north-south trending gravity gradient passing through Jackass Flat was also identified. Figures showing these gravity and magnetic lineaments are presented in NWRPO (2005).

The most prominent magnetic feature revealed by the magnetic survey in Jackass flats is a broad linear positive anomaly that trends northeast and extends from the central area of Jackass Flats southward to the northern boundary of Amargosa Desert. This anomaly is interpreted to represent buried Miocene basalt. Nye County's drill hole 23P near the south end of the anomaly intersected a 33 ft-thick basalt at a depth of 1312 ft. Geochronologic work conducted by USGS has dated the basalt at 9.5 Ma (PVHA, 2007).

In addition, the Blakely et al. (2000) survey identified magnetic anomalies (areas of high magnetic values) that were interpreted as potential basalt flows in lower Fortymile Wash. An even more detailed airborne magnetic survey of smaller aerial extent was completed by DOE YMP over the Yucca Mountain Region in 2005 (Kelley, 2005). In late 2005 and 2006 the DOE YMP drilled and sampled a number of the magnetic anomalies that were potential buried basalt flows.

1.4.3 Groundwater Flow System and Phase VI Borehole Locations

The groundwater flow system in the Yucca Mountain/Amargosa Desert area is generally characterized by flow from north to south (Winograd and Thordarson, 1975). A potentiometric surface map of the area is shown on Figure 1.4-2 (DOE, 2003). The map shows a relatively steep potentiometric gradient north and west of Yucca Mountain as well as south of Yucca Mountain along Highway 95 and between Crater Flat and the basin to the east (Flat Tire Flat).

1.5 Hydrogeologic Objectives of Phase VI Boreholes

Phase VI boreholes were sited to collect hydrogeologic information downgradient of Yucca Mountain, in both volcanic rocks and alluvium between Yucca Mountain and Amargosa Valley. Specifically, hydrogeologic objectives for Phase VI include the following:

- Determine the stratigraphy and role of valley-fill units including potential basalt flows and on groundwater levels and chemistry in 4PD.
- Drill, sample, log, instrument, and complete a deep monitor well to provide geologic and hydrologic information below 850 ft, and to serve as a pumping well during future large-scale pump tests.
- Provide future monitoring points for water levels and water chemistry along the eastern margin of Fortymile Wash.

1.6 Quality Assurance Plans and Procedures

The NWRPO Quality Assurance (QA) Program Plan and quality administrative procedures outline QA management procedures for the collection and documentation of scientific data. These documents help to ensure that NWRPO scientific investigations provide valid data that are useful to Nye County and other potential users associated with the YMP. The U.S. Nuclear Regulatory Commission evaluated the Quality Assurance Program Plan in 1999 and issued a conditional acceptance statement (Reamer, 1999, personal communication).

Table 1.6-1 lists the specific work plans (WPs), technical procedures (TPs), and test plans (TPNs) pertinent to Phase VI. The WPs included in this table outline technical objectives and describe methods and procedures for accomplishing these objectives (e.g., scopes of work). In addition, WPs reference applicable TPs, which in turn provide detailed instructions for performing routine technical activities or tasks. TPNs document technical objectives and detailed instructions for one-of-a-kind technical activities. Some deviations from these WPs, TPs, and TPNs were found to be necessary due to conditions encountered in the field. Major deviations were documented on field change approval forms filed in the NWRPO Quality Assurance Records Center (QARC). In general, these deviations did not affect the achievement of project objectives and goals.

1.7 Report Organization

Section 1.0 of this report provides pertinent background information and describes the purpose and scope of EWDP Phase VI activities. Section 2.0 summarizes field drilling, sampling, logging, and laboratory testing methods and procedures. Section 3.0 describes well completion and development. Section 4.0 presents the results of geologic logging, Section 5.0 the results of laboratory testing, and Section 6.0 the results of geophysical and lithologic logging and geologic cross-section interpretations. Section 7.0 summarizes major findings and recommendations.

2.0 DRILLING, CORING, SAMPLING, LOGGING, AND TESTING

This section describes Phase VI drilling, sampling, geologic logging, laboratory testing, and geophysical logging methods. Further details about these methods can be found in the QA documents listed in Table 1.6-1. The NWRPO Geoscience Manager was responsible for program oversight and approval of procedural and scope changes necessitated by field conditions or findings. NWRPO field staff and contract geologists and technicians, referred to as NWRPO personnel in this report, were responsible for recording site management information, equipment calibrations, general observations, and progress notes in scientific field notebooks. Field forms were used by NWRPO personnel to record key drilling, sampling, and well completion data, including, but not limited to, depth control, geologic logging, and chain of custody. Completed forms and scientific notebooks are on file at the QARC.

2.1 Drilling

Under NWRPO oversight, drilling was conducted by drilling contractors responsible for 1) implementation of the drilling scope of work, 2) compliance with all applicable permit conditions and regulations, and 3) compliance with both industry-standard work practices specified in contract documents and the site-specific NWRPO health and safety plan. All contract documents are on file at the QARC.

Drilling methods for Phase VI boreholes were based on a number of objectives, including the ability of the methods to:

- Yield drill cuttings as representative as possible of in situ formation rock
- Minimize disturbance of the formation rock
- Achieve target depths
- Provide a borehole suitable for open-hole geophysical logging
- Yield a borehole suitable for multiple-screen piezometer well completion

These objectives were previously used to select the drilling methods used in Phases III, IV, and V. The methods employed in Phase VI included: AR-RC drilling and MR-CC to sample and advance the boreholes and to enlarge and case open hole sections where required. The AR-RC drilling method was used to advance 4PC, but unstable borehole conditions at 460 ft and a detached casing shoe resulted in the decision to abandon the borehole. The drill rig was relocated approximately 20 ft to the east and the replacement well 4PD was drilled using MR-CC in an effort to avoid the problems encountered in 4PC.

The target depth for 4PD was achieved and the borehole was drilled to a TD of 1,850 ft, however drilling problems limited the 4PC borehole to a depth of 460 ft.

2.1.1 Overview of Methods

This section provides background information on Phase VI drilling methods including AR-RC drilling and MR-CC drilling. As mentioned previously, the Phase VI wells used both of these methods to meet the drilling objectives.

2.1.1.1 AR-RC Methods

AR-RC methods are commonly used in mineral exploration and are described in detail in NWRPO (2003) and (2005). These reports include a detailed discussion of drilling and drilling-related impacts that can potentially disturb the representativeness of drill cuttings and formation material. AR-RC methods are believed to provide reasonably representative drill cuttings for geologic logging from most formations, with the exception of saturated alluvium producing significant amounts of water. In this report the term “alluvium” refers to unconsolidated rock and “non-alluvium” to consolidated rock.

The NWRPO required that AR-RC method use compressed air exclusively as the drilling fluid. Generally, compressed air minimizes the disturbance to formation rock permeability and water chemistry. However, air often erodes borehole walls and can create caving conditions, especially in the unsaturated zone. In these cases, drilling mud (i.e., sodium bentonite and/or polymers and/or foamers) was used to stabilize the walls of AR-RC drilled boreholes. The method involved halting drilling, injecting drilling fluid using conventional circulation, and drying the borehole walls with compressed air before continuing the advancement of the borehole. At 4PC this borehole conditioning method allowed AR-RC drilling to proceed to a depth of 320 ft bgs before borehole conditions necessitated the use of flooding the annulus of the borehole with bentonite mud during drilling. The use of organic drilling fluids and additives, including foams and polymers was minimized to the extent possible. No lost circulation materials (LCM) were used in Phase VI drilling.

In unsaturated alluvium, AR-RC generally produces drill cuttings where the total percent of fine particle sizes (silt plus clay) and the total percent of coarse particle sizes (sand plus gravel) are not significantly altered from in situ conditions. However, the method generally significantly reduces the gravel fraction and increases the sand fraction percentages compared to in situ conditions, while the percentages of silt and clay generally remain similar to in situ conditions (NWRPO, 2003).

2.1.1.2 MR-CC Methods

MR-CC methods are commonly used in water and oil and gas well drilling. The method employs a drilling fluid consisting of a bentonite mud mixture that is pumped and circulated down the inside of the drill pipe to the drill bit. During borehole advancement, cuttings from the bit are brought to surface between the borehole wall and the outside of the drill pipe. This method provides for stable borehole conditions in unconsolidated formations, however bentonite mud “cake” coats the borehole wall and must be removed within water production zones with well development methods. Also, intervals of lost circulation can occur, that slow or halt drilling and consume mud products. High yield fractures and porous formation can be plugged with the bentonitic drilling fluid that will reduce the yield of the formations.

2.1.2 Details of Drilling Methods and Equipment by Borehole

Prior to discussing specifics for each borehole, it is important to note that for both Phase VI boreholes, NWRPO personnel and drilling contractors maintained depth control during drilling by measuring/recording drill string and down-hole bit assembly lengths and, where practicable, depth sounding.

Surface casing was necessary in both Phase VI boreholes to prevent caving of relatively unstable near-surface sediments, maintain annular borehole air pressure while drilling the remaining portion of each borehole, and provide a surface-well seal for later installation of a multiple-screen piezometer.

2.1.2.1 Borehole 4PC

Borehole 4PC was drilled by Drill Tech, Inc. of Chino Valley, Arizona, using a Schramm T685W drill rig, 4-1/2 -inch-diameter dual-wall drill pipe, and several down-hole bit assemblies, as summarized in Table 2.1-1.

The upper 60 ft of 4PC was drilled and sampled using AR-RC methods with a 5-1/2 -inch bit. The borehole was then reamed using conventional air-foam methods with a 12-1/4 -inch reamer bit to 60 ft bgs, over-reamed from 60 to 64.1 ft, and cased with an 8.625-inch outer diameter (OD) surface casing, which in turn was grouted in place from 62.3 ft bgs to the ground surface.

With a surface casing in place, AR-RC drilling was continued with a 6-1/2 inch tricone long-tooth bit using open-hole methods to a depth of 320 ft bgs. The open-hole section was drilled in weakly-consolidated to unconsolidated alluvium with intervals containing high clay content that eventually resulted in borehole stability issues, bit plugging, and circulation problems. At 320 ft the decision was made to use a different type of bit and a different drilling method in an effort to overcome borehole problems. The hole was cased from surface to 320 ft with 6.625-inch OD casing to facilitate drilling deeper. From 320 ft AR-RC methods modified by flooding the annular space with drilling mud (bentonite) was used. This part of the borehole was drilled with a 5.5 inch tricone button bit, and enabled the driller to advance the borehole to 460 ft. At 460 ft progress was again stopped due to flowing sands and bit plugging problems. While attempting to remove the casing, and again modify the drilling method, the casing shoe bit detached from the casing, became lodged in the borehole, and the decision was made to abandon the borehole.

The 4PC borehole was abandoned on July 10, 2008 by back-filling the borehole with 20% by weight bentonite, emplaced using a tremmie line, and capping the abandonment with approximately 20 ft of Portland grout. The 8-inch surface casing was cut down to slightly below ground level and a 6-inch nail was set in the grout plug at original ground level.

2.1.2.2 Borehole 4PD

Subsequent to abandoning 4PC, the drill rig was moved approximately 20 ft east, and drilling of a replacement borehole (4PD) began using mud-rotary methods. Drilling of borehole 4PD began on July 12, 2008. This borehole was drilled to a TD of 1,860 ft using conventional-circulation mud rotary methods. The borehole was completed as an 8-inch multiple-screen monitor well with screens from 317.6 to 397.9 ft, 498 to 638.8 ft, 738.9 to 999.9 ft, 1,059.9 to 1,260.5 ft, 1,480.5 to 1,550.6 ft, and 1,780.8 to 1,851.2 ft.

The upper 20 ft of 4PD was drilled and sampled with a 12-7/8 inch diameter tricone button bit and 5-3/8 inch API drill pipe. An 8.625-inch O.D. surface casing was set at 20 ft and grouted to surface. The pilot borehole was drilled and sampled from 20 ft to 123 ft with a 7-7/8 inch tricone button bit and 6 collar joints. The first two collar joints above the drill bit were 5-3/8 inch outside diameter and the last four collars were 5 inch outside diameter. From 123 ft to 1,300 ft the borehole was advanced with regular 4-1/2 inch API drill pipe above the collar joints and drilling progressed at an average rate of about 0.5 ft/min.

At about 1,300 ft the sediments became very clay-rich and drilling progressed slowly with drilling rates on the order of 0.1 to 0.2 ft/min. At 1,470 ft the decision was made to trip-out the button bit and replace it with a 7-7/8 inch milltooth bit for faster advancement through clayey sediments. From 1,470 ft drilling and sampling was completed with the milltooth bit to a TD of 1,846.6 ft. After achieving TD, the drill string was removed from the borehole and the hole was geophysically logged. Following logging, the borehole was reamed from ground surface to 100 ft with a 21-1/2 inch reaming bit. After installing and grouting a 16 inch surface casing to 100 ft, the remainder of the hole from 100 ft to 1,860 ft was opened-up with a 15 inch reamer bit. Geophysical logging (caliper log only) was again conducted, followed by well completion activities.

Following well completion, the well screens and sand packs were developed using both dual-wall swab airlift method and submersible pump swab methods. Following well development activities, well aquifer testing was conducted including both composite-zone and isolated-zone aquifer tests. The composite well testing in conjunction with spinner logging was started on February 23, 2009, and final isolated zone test of screen #1 was concluded on June 30, 2009. Water quality samples were collected from each screen during aquifer testing activities.

2.2 Geologic Sampling

Drill cuttings were collected using AR-RC methods at 4PC and MR-CC methods at 4PD for continuous field geologic logging and laboratory testing from both boreholes.

Geologic sampling and sample handling methods conformed to the applicable WPs, TPs, and TPNs listed in Table 1-6.1 Exceptions to these methods are described in geologic log form comments and/or scientific field notebooks. Sampling related processes that may have disturbed samples further from in situ conditions and affected geologic logging descriptions and/or laboratory testing are also described in Sections 4.0 through 6.0.

2.2.1 Drill Cuttings

Table 2.2-1 summarizes the number of drill cuttings samples, sample splits, and the number and types of laboratory tests conducted on drill cuttings from Phase VI boreholes. Except as noted in Table 2.2-1 footnotes, continuous drill cuttings were collected at 5.0 -foot intervals at 4PC in alluvium and 10 -foot intervals at 4PD in both alluvium and non-alluvium. A total of 97 drill cuttings samples were collected in the alluvial sediments at 4PC. At 4PD, 144 alluvial samples and 11 non-alluvial samples were collected. With the addition of splits prepared for the NWRPO and DOE YMP, approximately 500 cuttings samples were packaged, labeled, and handled.

At 4PC drill cuttings produced by reverse circulation methods were collected at the ground surface in a cyclone separator. The entire alluvial sample from a particular depth interval was collected in 5-gallon buckets. In the saturated portion of the borehole where significant amounts of water were produced during drilling, an Anaconda rotating wet splitter was attached beneath the cyclone separator to reduce the sample volume from a sample depth interval to a manageable number of 5-gallon buckets. The solid phase in the buckets was homogenized and subsampled over 5-foot depth intervals, except as noted in Table 2.2-1.

At 4PD, saturated-zone samples collected from mud-rotary drilling methods were collected from “shale shakers” – a contained mud system with fine shaker screens that collect the majority of cuttings possible, given the drilling method. Variables such as borehole lag time, shaker lag for both coarse and fine screens were tested and computed to minimize the known inadequacies of alluvial mud-rotary samples. The samples were collected at 10 ft intervals from the water table downward (320 ft) in galvanized 10-gallon tubs and homogenized in an effort to collect a representative sample. Two different mixing methods were employed. From 320 ft to 690 ft the cuttings were emptied onto a tarpaulin, mixed, and subsampled by the cone and quarter method. This method of sampling proved to be very difficult and labor intensive due to the large volume and weight of drill cuttings collected from the shaker screens, from 690 ft to the TD of the borehole a cement mixer was used to facilitate ease and efficiency of homogenizing the drill cuttings.

All samples from both 4PC and 4PD were processed into three splits: the first NWRPO split was collected for archival at the DOE YMP (SMF); the second NWRPO split was subsampled for field logging and the preparation of chip trays for future reference; the third NWRPO split was designated for NWRPO laboratory testing. A fourth split was collected onsite by DOE YMP personnel. Both NWRPO and DOE YMP splits sent to the SMF were sealed in olefin bags; splits for laboratory testing were sealed in double plastic bags. All samples were labeled with appropriate identification and shipped to their destinations under chain-of-custody.

2.3 Geologic Logging

Geologic logging procedures are described in TP-8.0. Geologic logging data on drill cuttings collected from Phase VI boreholes were recorded on the Alluvium and Non-Alluvium Drill Cuttings Logging Forms (Figures 2.3-1 and 2.3-2, respectively).

Procedures for geologic logging of alluvial samples are based on the visual-manual logging methods described in American Society for Testing and Materials (ASTM) D 2488-93. The alluvium logging form records soil classification parameters, many of which are related to flow and transport properties of alluvial sediments. These parameters include color, moisture, PSD, cementation, hydrochloric acid (HCl) reaction, and other soil characteristics.

The non-alluvium logging form records parameters that support the identification of lithostratigraphic units, including color; moisture content in the unsaturated zone; rock unit; weathering; structure; matrix porosity; and color, size, and volume of phenocrysts and clasts. Since most rock units in the vicinity of Yucca Mountain are volcanic tuffs, additional descriptive tuff parameters include mode of deposition, degree of welding, and alteration. In addition, both alluvium and non-alluvium logging forms include entry fields for sample bulk-density-related measurements, rates of drilling, and water production; however, density related measurements and water production were not tracked in Phase VI boreholes due to the impact that injection water and drilling fluids have on these parameters.

The Alluvium Drill Cuttings Logging Form however, was used for recording the properties of the sediments that are not affected by mud-rotary drilling methods such as color, grain shape, cementation, sediment reaction to HCl, major rock type represented in the gravel clasts, and plasticity where available. Plasticity is not always reliable because of the plasticity introduced into the samples as a result of bentonitic drilling fluids. Therefore, plasticity estimates are only reliable when natural formation clays are preserved. Drilling rate, as recorded on the logging forms, was also used to help distinguish units that drill slowly (i.e., soft clayey units) from more competent "hardrock" units that drill much faster.

Field estimates of PSD in alluvial samples were used to estimate gross textural variability over the sample interval. Since these were field estimates, they were not used for quantitative purposes; instead, laboratory PSD measurements were used where quantitative data were required. In general, field logging observations were valuable for qualitatively identifying trends in logged flow related parameters in the saturated zone versus depth to support the location of well screens; as well as identify trends in color, clay content, and cementation that may indicate the presence of low permeability intervals that may in part control flow in the saturated zone. Trends in several of these logged parameters are described in Section 4.0. Also, since field estimates of PSD were determined over each drilled interval and laboratory measurements of PSD were determined for selected intervals, field estimates that are reasonably accurate fill in data gaps between lab measurements. Due to the impact of drilling with injection water and drilling fluids, Phase VI sieve data was only used for selecting screen aperture size and sand pack grading.

2.4 Hydraulic Parameter Laboratory Testing

The number and type of hydraulic parameter related laboratory tests conducted on geologic samples collected during Phase VI are summarized for drill cuttings in Table 2.2-1. Tests were conducted on selected interval drill cuttings from Phase VI boreholes as well as archived cutting samples from the nearby Phase II borehole 4PB to facilitate screen aperture selection and sand pack gradation. Tests were not conducted on saturated non-alluvial samples. All laboratory tests were conducted in accordance with industry standard methods (Table 2.4-1).

2.5 Borehole Geophysical Logging

The primary geophysical logging contractor, Geophysical Logging Services (GLS) of Prescott, Arizona, was responsible for conducting downhole logging in the 4PD borehole and well in accordance with industry-standard procedures (ASTM, 1995; API, 1997). Century Geophysical Corporation (Century) of Tulsa, Oklahoma was also contracted to conduct limited and specialized logging in borehole 4PD and Jet West Geophysical Services of Farmington, New Mexico was contracted to conduct specialized completion logging and perforation services in 4PD.

Descriptions of methods, specifications, and quality controls used during geophysical logging are presented in WP-6.0 and TP-11.0 (Table 1.6-1).

2.5.1 Description of Borehole Geophysical Logs

Table 2.5-1 summarizes the types, properties measured, and applications of the geophysical logs performed in Phase VI. Most of these logs were also run in EWDP Phase III, IV, and V boreholes. A number of these logs measure similar or related parameters and have similar applications. These logs are run together in the same borehole to increase the level of confidence identified in logging data trends. Individual logs are discussed in relation to major categories of use or application in the following section.

2.5.1.1 Lithology Identification and Correlation

Gamma, density, moisture, sonic, spectral gamma, spontaneous potential (SP), fluid resistivity, formation-related resistivity (i.e., R8, R16, R32, or R64), and optical televiewer (OTV) logs can help identify and confirm formation contacts and properties in areas where sample recovery is poor, lithologic units are similar or indistinct, or where bedded lithologic units are thinner than the geologic sample interval. For example, density, neutron, and sonic log outputs are related to formation and/or layer porosity, which may vary between lithologic units.

Gamma logs help identify clay layers and indicate the natural changes in the gross radioactivity between differing volcanic and valley-fill units. Spectral gamma logs can be used to ascertain relative amounts of potassium, thorium, and uranium to aid in lithology identifications. Spectral gamma log data were obtained in 4PD.

Formation-related resistivity logs can indicate areas of increased welding in volcanic units, and also respond to the presence of clays. In addition, fluid resistivity, formation-related resistivity, and spontaneous potential log outputs may vary between formations and/or layers within a formation and can be used to identify and evaluate contacts between subsurface geologic units, thinly bedded sequences, and vertical facies changes in sedimentary sequences.

Caliper logs provide borehole diameter data necessary for the interpretation of many of the logs. For example, log responses to washout zones (i.e., intervals of borehole with significantly larger diameters) can be separated from actual responses to changes in formation and/or borehole fluid parameters. In addition, changes in borehole diameter are often related to lithology changes, especially contacts between unconsolidated and consolidated material.

2.5.1.2 Water Production Zone Identification

Several geophysical logs can provide information about water transmitting zones. For example, temperature (fluid temperature and differential temperature) logs can detect changes in subsurface temperature gradients at groundwater production zones (e.g., inflow from fractures). Fluid and formation resistivity logs can in some cases identify changes in salinity and total dissolved solids in water from different production zones. Formation resistivity logs can also potentially identify differences in groundwater chemistry at different distances outward from the borehole. Spontaneous potential logs can in some cases identify differences in borehole and formation fluid composition. Formation porosity information, which may be related to aquifer production, can be obtained from density, neutron moisture, and sonic logs.

2.5.1.3 Well Installation Support and Use

A number of logs provide valuable information that can be used for well design, installation, verification, and use. Caliper logs yield borehole diameter data, which are useful for the design and placement of well screens and sampling ports. Deviation logs provide information about the locations of notable borehole deviations from vertical (e.g., doglegs) that may complicate the completion process. Borehole deviation data are also necessary to provide accurate elevations of geologic contacts, screened intervals, and water table and piezometric surfaces. Following well installation, gamma and density logs can also help confirm the location and integrity of bentonite seals and well-screen sand packs in completed wells.

2.5.2 Suites of Borehole Geophysical Logs

Table 2.5-2 summarizes the three suites of geophysical logs used in 4PD. Open-hole geophysical logs were run by GLS in the open, uncased borehole, where borehole stability was good and the drill pipe or casing could be removed before logging. Century Geophysical ran drill string logs including density and neutron tools using a radioactive sourced tool inside 5-1/2 inch logging casing (used to protect the saturated zone from the radioactive source). Jet West ran drill string logs including a gauge ring, collar locator, sonic, and freepoint tools in an effort to free the stuck tremmie pipe. Jet West also ran perforation tools and cutting tools with collar locator tools to perforate and cut the completion tremmie at specific depths. After the completion of the well casing string with sandpacks and seals, well-completion logs were run by GLS inside the well casing.

The open-hole geophysical log suite included formation resistivity, fluid resistivity and temperature, spontaneous potential, caliper, sonic, natural and spectral gamma. Temperature and fluid resistivity logs are typically run downhole in the first tool run to capture undisturbed temperature and salinity gradients in the water or drilling fluid column.

The well-completion suite included gamma, fluid resistivity, fluid temperature, caliper, sonic, deviation, and optical logs. This suite of logs was run in the 4PD well following completion with well casing and screen.

3.0 WELL COMPLETION, DEVELOPMENT AND TESTING

Well completion, development and well testing for Phase VI was conducted by drilling contractors under oversight by the NWRPO in accordance with applicable QA drilling and well construction plans (Table 1.6-1), except where deviations from these plans were necessitated by field conditions and/or findings.

3.1 Well Completion

Borehole 4PC was abandoned in accordance with Nevada Administrative Code 534.420, and therefore was not completed as a well.

Well 4PD was completed as a multiple-screened single-cased borehole with 6 screens in accordance with permit requirements and the Nevada Revised Statutes (i.e., NRS 534.60). The well casing string consists of 8 inch (8.625-inch outside diameter; 8.125-inch inside diameter, 0.250-inch wall thickness) API 5lb carbon steel. Blanks and screen joints are 20 ft nominal lengths and rated at 35,000 psi minimum yield. Screen joints have welding collars on the uphole end and are square on the downhole end. Screened casing joints have 0.050-inch slot openings consisting of downward facing corrugated louver-shaped apertures.

Screened intervals are from 317.6 to 397.9 ft, 498 to 638.8 ft, 738.9 to 999.9 ft, 1,059.9 to 1,260.5 ft, 1,480.5 to 1,550.6 ft, and 1,780.8 to 1,851.2 ft. Screen intervals were selected based on geologic logging, geophysical logging, and laboratory PSD test data. The two lowermost zones are completed in well-indurated ash-flow tuffs and hard basalt lava flows and the upper four zones are longer interval zones in unconsolidated clayey to gravel-rich valley-fill sediments and alluvium.

Three sand make-up tubes were welded to the side of the 8-inch well casing to allow for maintaining the sandpack levels in screen zones 2, 3, and 4. The make-up tubes are attached from 0 to 496.5 ft to service screen 2, 0 to 737.2 ft to service screen 3, and 0 to 1,058 ft to service screen 4. The tubes are nominal 20 ft lengths of 1-1/4 inch schedule 40 coupled steel.

Figure 3.1-1shows the multiple-screen completion in 4PD. Table 1.3-1 summarizes completion data, including open-hole water levels, screened and sandpacked intervals, and formation units adjacent to these intervals. Table 3.1-1 contains reference point elevations (i.e., top of casing and ground surface) for water level measurements, as well as initial water level measurements. Depth data in Tables 1.3-1 and 3.1-1 have not been corrected for borehole deviation.

Emplacement of completion materials at 4PD required an unorthodox approach due to complications resulting from the presence of large deviations in borehole alignment (“dog-legs”). At approximately 314 ft a dog-leg was severe enough to pin the 2-7/8 inch steel tremmie line against the borehole sidewall when 8-inch well casing with sand make-up tubes was run into the borehole and beside the tremmie line. With the tremmie line stuck, it would not be possible to lift the tremmie above the level of completion materials during emplacement operations; therefore, an alternative method was necessary to emplace sand packs and screen grout seals.

The tremmie line was perforated in place at strategic locations above each screen section of the well casing and completion materials were pumped through the perforations. This was accomplished by utilizing a downhole perforating tool to puncture the tremmie pipe with 3/8 inch holes (spaced at 4 holes per foot over a length of about 4 ft) and then utilizing shaped explosive charges to separate the perforations into larger and more transmissive openings.

After emplacing completion materials for screens 6 through 2 in this manner, the tremmie line was cut using a chemical cutting tool at the 314 ft free-point (point above which the tremmie was not stuck). Screen 1 and the remaining upper section of the well was then completed in the "normal" manner by emplacing completion materials in lifts with the tremmie. The length of tremmie line below the free-point cut at 314 ft remains within the completion materials.

Sand packs around the piezometer screens consisted of washed 8/12 mesh Colorado silica sand tremmied to within 1 to 2 ft of the specified target depths, which were generally 5 to 10 ft above and below well screens. Pumped water was used to carry the sand through the tremmie to its target depth. Bentonite grout seals consisting of at least 30% by weight of solids were emplaced as slurry using a tremmie pipe. Sand packs were emplaced to the target depths using a tremmie pipe and a centrifugal pump, whereas grout seals were emplaced as slurry using a tremmie pipe and a diaphragm or piston grout pump (positive displacement pumps). Generally for the dry completion materials (sand and Ben-Sand), water was initially pumped through the tremmie pipe at approximately 25 to 50 gallons per minute (gpm), followed by the addition of dry completion materials to the water stream via an open "tee" connection on the water intake side of the centifugal pump. Grout slurry materials were first mixed on surface in tubs to the proper consistency and pumped down the tremmie line with diaphragm or piston grout pumps.

Figure 3.1-2 shows the wellhead protection diagram for well 4PD. The surface completion of well 4PD includes a locking cap at the top of the 8-inch casing. A plate is welded between the 8-inch well casing and the 16-inch surface casing with the sand make-up tubes passing through. The sand tubes have threaded caps installed. For further protection, an approximately 4- by 4-foot by 8-inch-thick concrete pad was set around the surface casing. The wellhead is labeled with the well name in the concrete pad. The well was surveyed by a registered Nevada surveyor for location and elevation data according to QA standards (Table 1.3-1).

3.2 Well Development

As a result of drilling with MR-CC methods for well NC-EWDP-4PD, post completion well development was required to remove the bentonite mud cake from the borehole walls and develop a filter pack in the sandpacked intervals. Two development methods were employed to assure complete development of the sandpack and adjacent formation at the well screened intervals. Shortly after well completion, preliminary development was conducted using dual-wall drill string and a reverse circulation swab. After preliminary development removed the bulk of the drilling fluids from the completion, secondary development was conducted using a 6-inch pump/swab assembly.

The second phase of development occurred over a 5-week period. Each screened zone was pumped, surged, swabbed, and treated with clay dispersants. After these development activities, water quality improved and water in each screen zone was sampled. Field parameters (i.e., pH and electrical conductivity) were monitored in the discharged water to determine when the water quality became stable, at which time samples were collected.

3.3 Well Testing

A pumping test program was conducted at well NC-EWDP-4PD to determine aquifer parameters for each screened interval, or zone, in the well. The testing program consisted of conventional pumping tests and spinner log surveys. An initial composite test was conducted by pumping the well with all screened intervals open to flow. Spinner surveys were conducted both under static conditions and while the well was being pumped with all zones open to flow. Zonal testing was conducted by setting packers across individual screened intervals. Water levels in the pumping well and in available observation wells were monitored with pressure transducers or by manual measurements.

Preliminary analysis of spinner surveys with all zones open to flow indicates that the majority of flow occurs in the sands and gravels in the upper four zones; however, significantly flow still occurs in the basalt and sand and gravel in Zone 5 and the ash flow tuff in Zone 6. This is confirmed in the individual zonal testing analyses which indicate very high transmissivities in the upper four zones and significant transmissivity in Zones 5 and 6. A detailed report on the well testing and analysis at NC EWDP-4PD is being prepared under separate cover.

4.0 GEOLOGIC SAMPLE LOGGING

The results of field geologic logging activities on drill cuttings are presented in this section. Because 4PD was drilled with conventional mud-rotary methods, the unconsolidated formation drill cuttings (alluvial and valley-fill sediments) collected are not representative of in-situ sediments. In general, mud drilling methods tend to bias the particle size distribution of the sediments sampled toward the coarse fraction as a result of the drilling fluid removing the finer fractions. As discussed above, it was necessary to compile geologic data from two nearby boreholes (4PB and 4PC) located on the same well site in order to construct depth to contacts in alluvial and valley-fill profiles and describe the sediments adequately. Boreholes 4PB and 4PC were drilled with reverse circulation drilling methods which yield drill cuttings that are considered to be better representations of in situ formation.

4.1 Geologic Logging of Drill Cuttings

Examples of geologic logging data from drill cuttings, and descriptions of their limitations, trends, correlations, and significance, are presented in this section. Where appropriate, the possible bias that drilling methods and sample handling procedures introduce into geologic logging data and the ability of such data to accurately characterize in situ formation conditions and properties are described.

Examples of geologic logging forms for alluvial and non-alluvial drill cuttings are presented on Figures 2.3-1 and 2.3-2, respectively. As discussed in Section 2.3, alluvium logging forms primarily record soil classification parameters, many of which are related to flow and transport properties of alluvial sediments. The non-alluvium logging forms primarily record lithology-related parameters to support identification of lithostratigraphic units. Both forms also include rates of drilling. Due to the impact of wet drilling methods, sample density measurements, moisture content of drill cuttings, and water production were not monitored.

4.1.1 Data Censoring

All geologic logging and drilling data on the logging forms for 4PD are biased toward the coarse fraction due to mud-rotary drilling methods. For this reason the alluvium from this borehole, including particle size distribution and Unified Soil Classification System (USCS) group symbol recorded on the Alluvium Drill Cuttings Logging Form were censored (Table 4.1-1).

4.1.2 Geologic Logging and Drilling Depth Profiles

Depth profiles of selected geologic logging and drilling data that illustrate important trends with depth are presented in this section. Examples of depth profiles for both alluvial and non-alluvial portions of the boreholes are presented, where applicable. Geologic logging parameter data for sample intervals of alluvial drill cuttings include field estimates of cementation and HCl reaction; and for non-alluvial drill cuttings include HCl reaction and the degree of welding in tuff, if present. Drilling data are limited to measured drilling rates.

The criteria used to describe geologic logging parameters are qualitative or semi-quantitative at best, and are subject to human error and inconsistency. Therefore, trends in these parameters are considered approximations of in situ conditions. At the same time, geologic descriptions are useful for identifying drilling impacts and relative changes in hydrogeologic parameters with depth for both drill cuttings and the formation rock.

Finally, geologic logs from Phase III, IV, and V boreholes indicate that alluvial drill cuttings are composed of nearly 100% volcanic rock, and non-alluvial drill cuttings are composed primarily of volcanic rock or sediment derived from volcanic rocks. Similar observations have been made in Phase VI boreholes with the exception of a 400 ft interval in 4PD from 920 to 1,320 ft where a large contribution of clasts collected from drill cuttings are derived from sedimentary sources. These rock types include sandstone, siltstone, claystone, and quartzite.

4.1.2.1 Cementation and Hydrochloric Acid Reaction Depth Profiles

It is very difficult to identify degrees of cementation in drill cuttings. The drilling method, equipment, specific technique used by the driller, and related drilling rates can potentially affect evidence of cementation. However, the presence of cemented sand grains and thick grain coatings of calcium carbonate were observed in Phase VI drill cuttings indicating that cementation occurs within the alluvial and valley-fill materials of Fortymile Wash. As recorded on the Alluvium Drill Cuttings Logging Form, these cementation indicators first appear in 4PC at about 185 ft bgs and persist throughout the entire borehole in thin intervals suggesting that cementation is layered within the sedimentary deposits and may reflect the environment at the time of deposition.

As noted above, 4PD samples were not collected above 320 ft because there was no need to duplicate unsaturated zone samples already collected at 4PC; however, indicators of cementation in drill cuttings from the alluvial and valley-fill section at 4PD (320 to 1,400 ft) suggest that varying degrees of cementation continue to occur throughout the entire sequence. From 320 to 740 ft, thick layers of weakly cemented intervals alternated with thin layers of moderate and strong intervals. A relatively thick interval from 740 to 1,340 ft contains fragments of strongly cemented sand grains that were preserved in the drill cuttings that are up to 15 mm in size, and clasts of tuff appear throughout this interval with thick grain coatings up to 5 mm. From 1,340 to 1,400 ft, cement is recorded as being moderate.

HCl reaction is more easily observed than cementation and the reaction for different sample intervals ranged from none to strong in Phase VI boreholes. HCl reaction indicates the presence of calcium carbonate, a potential cementing agent; however, the lack of correlation discovered in Phase V boreholes (NWRPO, 2009) between HCl reaction and cementation seems to indicate that calcium carbonate does not play a major role in cementation. A similar lack of correlation between HCl reaction and cementation was observed in Phase IV boreholes (NWRPO, 2005).

A comparison of HCl reactions in the 2 boreholes drilled at Site 4 in Phase II (4PA and 4PB) shows that from ground surface to about 255 ft bgs, there is a strong correlation in HCl profiles. From ground surface to 125 ft both profiles show varying degrees of reaction from none, to weak, to strong and from 125 to 255 ft no HCl reactions were observed in drill cuttings from either borehole. Below 255 ft, no direct correlation can be made between 4PA and 4PB HCl profiles. A comparison of 4PA and 4PB with Phase VI borehole 4PC shows that 4PC has a similar near surface profile down to 190 ft with varying degrees of reaction to 125 ft bgs and no reaction from 125 ft to 190 ft. From 190 ft to the bottom of the borehole at 460 ft, 4PC drill cuttings show a much stronger reaction to HCl than either 4PA or 4PB.

A comparison between 4PC and 4PD, both drilled during Phase VI and within 20 ft of each other, can only be made in the sampled interval common to both (320 to 460 ft). HCl reactions throughout this short interval are strong for both boreholes. Below 460 ft the HCl profile of alluvial sediments at 4PD shows a predominantly strong reaction and is in sharp contrast to the profile at 4PB (the only other borehole at Site 4 that is deeper than 500 ft), which shows predominantly weak reactions below 500 ft. Finally, the non-alluvial units in 4PD were as follows: basalt from 1,400 to 1,430 ft shows a strong reaction; sandstone from 1,430 to 1,490 ft shows a strong reaction; basalt from 1,490 to 1,540 ft shows a weak reaction; older alluvium from 1,540 to 1,775 ft shows a strong reaction; and the ash-flow tuff from 1,775 to 1,860 ft shows no reaction.

Finally, it is interesting to note that in contrast to the general lack of a direct correlation of HCl reactions between Site 4 boreholes, a good correlation was observed between HCl reactions in sets of boreholes drilled on the same sites in Phases III, IV, and V (NWRPO, 2009). HCl reaction in Phase III borehole 22SA and Phase V borehole 22PC, located approximately 60 ft apart, show a good correlation, Phase IV borehole 24P (NWRPO, 2005) and Phase V borehole 24PB, separated approximately 150 ft from each other, also show a good correlation.

4.1.2.3 Drilling Rate Depth Profiles

Numerous formation- and drilling-related factors affected drilling rates in boreholes or portions of boreholes drilled using AR-RC and MR-CC methods. Drilling parameters include drill bit and drill casing diameters and types, drill bit weights, drilling fluids used, air pressures and flow velocities, and rotation rates. For the purpose of discussing drilling rates herein, it is assumed that drilling parameters remain approximately constant within a particular borehole, and that variations in drilling rates are due primarily to differing rock and sedimentary properties and the decrease in drilling efficiency with increasing penetration depth.

At 4PC reverse circulation drilling methods were employed and the drilling rates were fairly consistent and generally greater than 0.8 fpm in the granular sands and gravels; however, drilling rates were impacted in the granular sections of the upper part of the borehole as a result of unconsolidated alluvial sediments sloughing from the borehole walls and forming a “boot” above the bit and effectively burying the bit. Deeper in the borehole lower drilling rates in the range of 0.1 to 0.3 fpm occurred in the clayey intervals beginning at about 410 ft bgs. The clayey sediments had a tendency to “ball-up” and plug the ports of the tricone rock bit and the center tube of the dual wall drill pipe, inhibiting circulation and the removal of drill cuttings from the borehole. Further complications resulted in the difficulty of stabilizing borehole intervals that contained layers of loose “flowing sands”. These sediments are composed of well-sorted sand with no silt or clay fractions to act as a binder to effectively hold the material in place.

At 4PD, mud-rotary methods were employed in an effort to minimize the difficulties encountered at 4PC with unstable borehole walls; however, drilling rates in the alluvium were similarly impacted by sediments with high clay content. From ground surface to 1,470 ft the borehole was advanced using a tricone button bit. The lowest drilling rates (0.09 to 0.2 fpm) occurred while trying to drill through the very hard upper basalt lava flow from 1,400 to 1,430 ft. More than 12 hours of drilling time were required to penetrate this 30 ft section of hard basalt. In the sandstone unit beneath the basalt drilling rates were once again impacted by clayey materials. Finally, at 1,470 ft the button bit was replaced with a mill-tooth bit which proved to be more effective in the clayey intervals. With the mill-tooth bit installed, drilling rates improved dramatically and the remainder of the borehole was advanced at drilling rates ranging from 0.2 to 1.1 fpm.

5.0 LABORATORY TEST RESULTS

The results of laboratory data collection activities for drill cuttings samples are described in this section.

5.1 Laboratory Tests of Drill Cuttings

Because 4PD was drilled with conventional mud-rotary methods, the unconsolidated formation drill cuttings (alluvial and valley-fill) collected are not representative of in situ sediments. The samples are biased toward the coarse fraction and considered disturbed from in situ conditions. For this reason the alluvium from this borehole, including the particle size distribution, were censored (Table 4.1-1). However, archived samples from 4PB, drilled with reverse circulation methods during Phase II on the same site, are considered reasonably representative of in situ conditions.

Borehole 4PB is approximately 40 ft east of 4PD and was drilled and sampled to 850 ft in January 2000. Archived samples from 4PB were tested (PSD and hydrometer) in the NWRPO laboratory in August 2008 during Phase VI drilling operations. Samples from 4PC, which is approximately 20 ft west of 4PD and was drilled to 460 ft, were also tested (PSD and hydrometer) in October 2008. Laboratory data show a close agreement of textural properties between 4PB and 4PC, as would be expected for boreholes in close proximity to each other. From ground surface to 850 ft, wet sieve and hydrometer data for 4PB and 4PC were relied upon to determine particle size distribution (relative percentages of gravel, sand, silt, and clay) and sediment layering used for the construction of summary lithologic logs. Reliable sieve data were not available for sediments below 850 ft.

Visual comparisons of PSD data curves from 4PB and 4PD above 850 ft indicate large sample bias resulting from drilling and sampling of mud-rotary cuttings (Figure 5.1-1). The comparison illustrated that 4PD mud-rotary samples are not representative of in situ conditions, as recognized in previous EWDP investigations. Rotary drilling pulverizes coarser components into finer particles and the in situ fines (silt and clay) are carried away in the drilling mud. For these reasons, 4PD PSD data were not used for sediment texture and layering analysis.

5.1.1 Particle Size Distribution Data from Alluvium and Valley-Fill

The following assumes that the PSDs of alluvial and valley-fill drill cuttings produced by AR-RC drilling methods are reasonably representative of in situ formation PSDs and that geologic field logging of drill cuttings produced by mud-rotary drilling methods can be relied upon for recognizing gross textural changes in the sediments that were encountered in 4PD. Evidence for this assumption was presented in NWRPO (2003 and 2005). Evidence that unsaturated zone drill cuttings produced by dual-rotary casing advance (DR-CA) methods may also have the potential to be reasonably representative of in situ conditions is presented below.

5.1.1.1 Spatial Trends in Particle Size Distribution Data

The geology at Site 4 consists of a relatively thick (about 390 ft) upper sequence of Quaternary alluvium overlying Tertiary valley-fill sediments, basalt flows and older valley-fill sediments. The valley-fill sediments exhibit a more fine-grained texture than is encountered in EWDP boreholes further west in Fortymile Wash and may reflect a transition to a deltaic environment near the Gravity Fault. Previous work conducted in NWRPO's Phase III drilling program (NWRPO,2003) showed the alluvial drill cuttings in two boreholes at Site 19 (19IM1A and 19IM2A), which is located west of the main Fortymile Wash channel, to be comprised only of granular materials (gravel, sand, and silt sized particles). These boreholes intersected alluvial materials to 820 ft bgs and were stopped in a distinctive weakly welded tuff also intersected in 4PD.

At 4PC, clayey sediments (including true "fat" clays) were encountered at 415 ft and were found to occur in thin layers throughout the remainder of the borehole. It was these clayey units that were responsible in part for difficult drilling conditions and the failed attempt to advance the borehole using AR-RC drilling methods. Borehole 4PD also intersected much finer-grained materials than were encountered at Site 19, however due to the poor recovery of the fines component using MR-CC, the sieve data do not reflect as clearly the higher fines content.

6.0 BOREHOLE LITHOLOGY

Summary lithologic and borehole geophysical logs are presented and discussed in this section.

6.1 Summary Lithologic Logs

A summary lithologic log from Phase VI borehole 4PD is presented as Figure 6.1-1. The alluvial and valley-fill section of the borehole is subdivided into major textural groups using the USCS group name classification system based on particle size percentages criteria, estimated plasticity determined on drill cuttings collected in the field, and the following laboratory tests on drill cuttings: percentages of major particle size fractions determined by wet sieve analyses; and percentages of clay by hydrometer methods. ASTM procedures for generating these laboratory data are listed in Table 2.4-1. The summary lithologic log for alluvium and valley-fill units also make use of both geologic and geophysical logging data.

The underlying volcanic rocks (non-alluvium) are subdivided based on lithology. These rocks are described in summary lithologic logs primarily using the lithologic related parameters recorded on non-alluvium logging forms for drill cuttings. An example form is presented in Figure 2.3-2 and non-alluvium forms for all boreholes are included with alluvium forms at the QARC. Borehole geophysical logs are also used to help identify and confirm contacts primarily between non-alluvium rock units and/or between alluvium and non-alluvium rocks. These logs are described in Section 6.2, and were especially useful where geologic contacts were located within 5 ft and 10 ft sample intervals, where samples were not collected, or the sample quality was poor.

This section will briefly describe the location of the Phase VI drill site including known nearby faults and surface outcrops and drainages. For Phase VI boreholes, the text will provide a narrative description of the summary lithologic logs.

6.1.1 Boreholes 4PC and 4PD

Phase VI boreholes 4PC and 4PD are located in northern Amargosa Desert, within southern Jackass Flats, along the eastern margin of lower Fortymile Wash. This wash is the major topographic drainage system for Jackass Flats, the eastern side of Yucca Mountain, and the upland region of the southwestern corner of the NTS. Site 4 is approximately 2 miles north of the Highway 95 fault (as proposed in NWRPO 2009) (Figure 6.1-2), a northwest trending buried fault that restricts flow in the north-south direction and supports higher heads to the north and approximately 2 miles west of a large-scale north-south gravity gradient that has long been recognized and interpreted as a buried normal fault.

Borehole 4PC penetrated a layered sequence of sandy alluvium and clayey valley-fill from ground surface to 460 ft bgs. The borehole was abandoned at 460 ft due to unstable borehole walls and drilling equipment failure. The sediments intersected prior to abandonment consisted of alternating layers generally ranging from 5 to 20 ft thick but as thick as 30 to 70 ft in places, of well-graded sand (SW), poorly graded sand (SP), and well-graded sand with silt (SW-SM) down to 415 ft. From 415 ft to the bottom of the borehole at 460 ft, sandy lean clays (SC) interbedded with more granular and poorly graded silty sands (SP) grade down into true fat clays (CH) that are interbedded with well-graded silty sands (SW-SM). The gravel components of these sediments are all volcanic in origin and consisted of both welded and non-welded tuff clasts derived from the volcanic rocks of the Southwestern Nevada Volcanic Field. Because 4PC was abandoned and replaced with 4PD, no summary lithologic log was produced for 4PC.

Because borehole 4PD was drilled with mud-rotary methods, the Alluvium Drill Cuttings Logging Form was only used for determining properties of the sediment that are not affected by mud-rotary drilling methods such as color, grain shape, cementation, sediment reaction to HCl, major rock types represented in the gravel clasts, and plasticity where available. The summary lithologic log for 4PD (Figure 6.1-1) was developed from several data sources. Nearby boreholes 4PA and 4PB (drilled to 500 and 850 ft bgs [respectively] on the same site using reverse circulation methods) produced drill cuttings that are considered to be reasonably representative of in situ conditions.

Geologic field logs and laboratory test data from archived samples collected at 4PA and 4PB were relied upon for alluvial textural analysis in the Summary Lithologic Log for 4PD down to 850 ft. Below 850 ft, where particle size data is not available from the lab, no attempt was made to assign USCS group symbols to sediments and only general descriptions of sediments are shown. Geophysical logs were also relied upon, especially below 850 ft, to identify textural changes in the alluvium. Gamma, resistivity, density, and sonic logs all show recognizable signatures and have spatial trends that allow the assignment of depth intervals to fine and coarse textures within the alluvial deposits.

Borehole 4PD penetrated a layered sequence of alluvium from ground surface to 390 ft. These units consisted of coarse well-graded gravelly and sandy layers with silt (GW-GM and SW-SM) grading downward to more clay-rich coarse units consisting of well-graded gravelly and sandy layers with clay (GW-GC and SW-SC). From 390 to 1,110 ft, the alluvial materials become clayey and consist of lean clays (CL), clayey sands (SC), well-graded gravels with clay (GW-GC), well-graded sand with clay (SW-SC), and sandy clay with gravels (CL). These clay-rich units below 390 ft are interpreted as valley-fill sediments.

From 1,110 to 1,400 ft the sediments become more granular and consist of layered gravelly sands and silty sand layers, silty sand with gravel, and at the base of the sequence from 1,355 to 1,400 ft the sands and gravels are well cemented. The rock types represented by gravel clasts within the sediments are all volcanic tuff from ground surface to 970 ft. From 970 to 1,265 ft clast types include volcanic tuff, siltstone, sandstone, and quartzite. From 1,265 to 1,355 ft gravel clasts are all volcanic tuffs. The gravel clasts in the cemented unit at the base from 1,355 to 1,400 ft are predominantly basalt with fewer tuff clasts. Gravel clast shapes throughout the sediments are rounded to angular.

The sequence is underlain by a thin basalt flow from 1,400 to 1,430 ft. The basalt flow is reddish brown in color with abundant white feldspar crystals. The basalt is vesicular, fractured, and has a glassy groundmass. The top and bottom of the basalt display the greatest degree of weathering. The basalt also contains traces of zeolitic mineral coatings.

Underlying the basalt is a well-cemented sandstone unit from 1,430 to 1,490 ft. The sand grains within the sandstone are well sorted, well rounded, and composed predominantly of dark reddish brown basaltic grains. The sandstone is interpreted as an epiclastic unit deposited between basaltic flow horizons and accumulating within depressions on the surface of the underlying basalt flow.

From 1,490 to 1,540 ft another basalt flow is present. The basalt is reddish brown and is similar to the basalt described above. The lower basalt flow has a thicker flow core and a well-developed flow breccia at the bottom.

Underlying the lower basalt, from 1,540 to 1,775 ft, is a sequence of older unconsolidated alluvial sediments composed of well-graded sand with clay and gravel grading into clayey sand. The unit is a fining-downward sequence with the clayey sand appearing at 1,630 ft and persisting to the bottom of the unit. Gravels within the unit are composed of roughly equal proportions of non-welded volcanic tuff clasts and welded tuff clasts. The welded clasts are angular and the non-welded clasts are distinctly rounded.

Finally, the last unit penetrated is an ash-flow tuff from 1,775 to 1,860 ft, which is the TD of the borehole. The tuff is pale yellow to very pale brown, soft, weakly to nonwelded, devitrified, and contains distinctive white pumice. The upper contact with valley-fill sediments is sharp. The tuff unit is believed to be the same unit intersected in boreholes 19D1, 19IM1A, and 19IM2A, located approximately 3 miles to the northwest, just west of the main Fortymile Wash channel.

6.1.2 Major Correlations

Near-surface alluvial units penetrated in 4PD are the same as those encountered in other EWDP wells in the general vicinity. Below 390 ft, the clay-rich units encountered are similar only to units intersected in boreholes 5S, 5SB and 23P. No EWDP boreholes west of 4PD intersect similar clay-rich valley-fill units. The tuff unit intersected below 1,775 ft in 4PD is correlative with a tuff unit intersected in 19D1, 19IM1A and 19IM2A at approximately 825 ft.

6.2 Borehole Geophysical Logs

Geophysical logs run in Phase VI boreholes are classified into three logging suites: drill-string, open-hole, and well completion (Table 2.5-2). Selected logs from the GLS open-hole suite and/or the Century drill-string suite run in borehole 4PD are presented on Plate 1. In addition, this plate includes lithologic units, selected descriptive lithologic details, and borehole diameters illustrated in well completion diagrams. Correlations between lithologic log data and the responses of the borehole geophysical logs will be described for borehole 4PD in the following sections.

Several logging tools produced inconsistent or unreasonable results. These logs were not used in interpretations and have been censored (Table 6.2-1).

Drill-string and open-hole logs were run in exploratory boreholes drilled primarily with air; only very small amounts of bentonite, bentonite with polymer, and several synthetic-based drilling fluids were used to maintain stable borehole conditions during drilling, geophysical logging, and subsequent well completion activities). The exception is 33P, where large amounts of polymer were used during drilling. However, the borehole was circulated with phosphate-free dispersant and airlifted prior to geophysical logging and well completion.

Responses of both drill-string and open-hole logs to changes in formation conditions are likely affected only to a small degree by the relatively small amounts of bentonite and other drilling additives used to condition the boreholes. For example, the use of these drilling additives to condition the boreholes did not prevent the GLS open-hole suite from providing useful information such as water table location, water production zones, and confirmation of alluvium/tuff and other stratigraphic contacts, where present.

Several geophysical logs are considered to have meaningful responses only when run below the water table. These include formation resistivity, spontaneous potential (SP), sonic, fluid temperature, and fluid resistivity logs. Other logs, (i.e., induction resistivity [run only in 13P], natural gamma, compensated density, and compensated neutron) show meaningful qualitative responses in the unsaturated zone as well.

In addition to impacts from drilling fluids, responses of the Century drill-string suite are likely influenced by the size, type, and configuration of steel drill casing. For example, density logs run inside multiple steel casings have significantly higher responses than logs run only in drill pipe. In spite of this influence, logs in the drill-string suite clearly show the location of the water table, zones that may be producing or taking water, changes in water-filled porosity, changes in formation density, changes in textural properties, and the contacts between most lithologic units.

Although the well-completion suite helps to confirm the location and integrity of sandpacks placed across the well screens and bentonite seals above and below each sandpack, it shows few, if any, trends related to formation properties and/or water producing zones. As a result, these logs will not be discussed in this report, but may be viewed on the NWRPO website (NWRPO, 2010) or at the QARC.

6.2.1 Geophysical Log Signatures and Interpretations for 4PD

Geophysical logs and lithologic log data from 4PD are displayed on Plate 1.

Well-Graded Sand with Gravel Interbedded with Well-Graded Sand with Silt and Gravel (0-165 ft bgs)

This alluvial unit is characterized by relatively steady natural gamma and neutron counts. Short- and long-spaced compensated density (density) values increase near the middle portion of the unit, indicating an increase in the amount of fines through this section. Near the base of the unit, at approximately 120 ft, density values decrease, indicating a decrease in the amount of fines in the unit. Geophysical log responses from 0 to approximately 50 ft bgs are likely due to the effects of the surface casing (to 20 ft), and the larger borehole diameter (i.e., “washout”) directly below the surface casing (from 20 to 50 ft). It must be noted that the differential temperature log responses are not representative when the tool is above the water table.

Well-Graded Gravel with Silt and Sand Grading into Well-Graded sand with Silt and Gravel (165-255 ft bgs)

Gamma logs over this interval display similar responses as the overlying unit. Neutron log responses are fairly steady. Density log responses show little character, with the exception of the interval from about 210 to 225 ft, where increased density counts correspond to an increase in fines content. This increase in fines content is logged (from 4PC) as persisting to 245 ft; however, the summary lithologic log for 4PB (drilled to 850 ft using reverse-circulation methods) shows an interval with increased clay content from 215 to 220 ft.

Well-Graded Gravel with Silt and Sand (255-305 ft bgs)

The gamma logs over this unit show similar character to those from the overlying unit. Neutron logs still show little character. An increase in the density log is observed from about 270 to 290 ft; this corresponds to a sample with relatively high fines content from 275 to 280 ft. However, this is a single sample, and there is no other explanation in the cuttings log for the elevated character of the density log.

Well-Graded Gravel with Clay and Sand Interbedded with Well-Graded Sand with Clay and Gravel (305-390 ft bgs)

Gamma logs decrease slightly at the top of the unit with an abrupt decrease at approximately 320 ft corresponding approximately with the water table. Resistivity and density values show a slight decrease with depth, probably indicting a fining downward below approximately 340 ft, and more erratic resistivity and density values, above 340 ft represent variably interbedded coarser materials. The basal contact is marked by a sharp spike in density values with a corresponding decrease in resistivity. This contact may represent an unconformity between oldest alluvium and the top of Miocene valley-fill units. Neutron log values are fairly steady throughout unit. An abrupt positive delta temperature response at approximately 360 ft is likely related to water table variations. Self Potential (SP) log curves indicate flat increasing values, without substantial deviations below the indicated water table at approximately 325 ft, Sonic velocity curves indicate highly variable low velocities possibly as a result of less than full water saturation of the sediments to a depth of approximately 370 ft, below which sonic velocity data appears more uniform.

Sandy Lean Clay with Gravel and Clayey Sand (390-515 ft bgs)

Top of unit is marked by an abrupt decrease in gamma counts (as seen in clayey units in earlier EWDP drilling; Phase IV and V), with a corresponding decrease in resistivity. Log curves are variables and “noisy” through the upper sub-units, probably indicating coarser clastic material interbedded with lower gamma clays. The basal unit (from approximately 480 to 515 ft) displays a progressive increase in gamma counts, probably the gradational contact to the coarser unit below. Density values show a slight decrease from the overlying unit, below the distinct density spike at the presumed unconformity. Density also has an increase with depth as the unit becomes more coarse-grained toward the base as a result of the higher component of clastic sands and gravels. Neutron values are steady though the middle and basal sections of the unit with a broad valley (low) in the upper section corresponding to the dense tuffaceous clayey section. The basal section from 490 to 515 ft is gradational with the underlying gravelly units, showing an increase in resistivity with depth and corresponding increase in density values and gamma log counts. Differential temperature log values indicate positive anomalies at base of the upper clayey unit, and the top of the lower gradational unit, presumably at coarser and more permeable clastic beds. The SP curve is flat with little character except in the middle sandy clay units where minor negative deflections occur probably as a result of interbedding between clays and sands. Sonic velocity curves are variable reflecting the interbedded nature of the unit with slight velocity increase toward the base as a result of coarser or dense material. Variable density log (VDL) plots of near and far receiver (two right-most geophysical plots) illustrate the four sub-units described in the lithology column. The upper tuffaceous clay-rich unit displays low velocities with chaotic late-time sine waves; the upper middle sandy clay unit displays more consistent higher velocities with more organized late sine waves transitioning to the lower middle unit with more variable velocity including a distinct high velocity peak (gravel) and more disorganized late sine waves; and the basal unit with consistent higher velocities and organized late sine waves indicating the well bedded nature. Caliper data indicate substantial wash out zones developed in the upper clay-rich (altered tuff) unit. Smaller wash out zones also occur in the lower units, probably in coarser poorly-graded clastic beds.

Well-Graded Gravel with Clay and Sand Grading into Well-Graded Sand with Clay and Gravel (515-660 ft bgs)

This fluvial valley-fill unit comprises a general fining downward sequence of well graded material. Gamma log curves reflect a general decrease in counts with depth as the unit fines with depth. Resistivity log curves are higher (than overlying unit) representing coarser grained units with fresh water. The curves generally decrease with depth, except for two distinct peaks at approximately 570 and 610 ft. Density values are highly variable in the approximate upper two-thirds of the unit and relatively flat in the lower third indicating a coarse interbedding of coarser and finer materials in the upper section and more consistent finer materials in the lower section. Neutron curves also have a similar character to the density curves, with a “noisy” upper two thirds and a lower third marked by a sharp decrease in counts and less noisy character. The change in density and neutron curves occurs at approximately 610-615 ft, where substantial deflections in the differential temperature log occur, suggesting a potential flow zone at or above this interval. The SP curve also has a trend toward lower voltages with an inflection point roughly centered in the middle of the unit at approximately 580 ft. Sonic velocity curves are noisy throughout the unit, with the largest changes in the lower third of the unit. VDL logs are relatively consistent in the upper two-thirds of the unit, and more variable in the lower one-third with the change occurring at a velocity maximum at approximately 610 ft. VDL curves show a general decrease in velocities in the lower third of the unit, with more organized sine waves, indicating finer bedding and fining of the sediments (aquiclude). Caliper logs show that the unit stays in gauge except the lowest approximately 20 ft of the unit that is very slightly washed-out.

Clayey Sand with Interbeds of Sandy Lean Clay (660-740 ft bgs)

Relatively thin unit of clay-rich sediments with indistinct low gamma log response. Resistivity is also very low with little character except a slight increase toward the base of the unit. Density log data is low with little or no character, all suggesting a homogenous unit, perhaps a reworked tuff as described in the lithology. The neutron log curve is also flat with only very minor inflections probably as a result of sandy beds within the clay-rich unit. Differential temperature log data shows only small changes indicating little water is moving within the unit. The SP curve has several small inflections with a gradual decreasing trend. Sonic velocity data is generally low (compared with coarser units) with several positive peaks. VDL logs also show low velocities with well organized late sine wave patterns indicating a well bedded clay-rich unit. Caliper log indicates that the unit is competent and stays in gauge.

Sand with Clay and Gravel Interbedded with Gravelly Sand and Clayey Sand (740-1,110 ft bgs)

Very thick sequence of sandy and clayey sediments with low flat gamma log response. Resistivity log is marginally higher than the clay-rich unit above contains two major sections, an upper section from 740 to 880 ft forming a valley centered at 800 ft, and a lower section of consistent moderate resistivity. The resistivity curves gently decrease toward the base of the lower section. The density log curve is flat through the upper section (as defined above by resistivity) with slight increase in density with depth. Below approximately 970 ft, the density curve has more character with several broad low amplitude peaks and valleys that may correspond to changes in gravel lithology and possibly cementation. Neutron log data is flat with little or no character, however, the differential temperature log has several substantial inflections indicating in-flow and out-flow points within the open borehole from 900 to 970 and 1,050 ft to 1,110 ft. The SP log has a large inflection at approximately 875 ft that probably represent in flow of fresh water into the mud-filled borehole. Otherwise, the SP log is flat, with minor valleys in the upper 100 ft of the unit and a slight increase with depth. Fluid resistivity also has a major inflection at approximately 875 ft as seen in the SP log. Sonic log velocities are moderately high with less abrupt fluctuations than overlying units. VDL log data indicates a relatively consistent bedding of finer sediments with few coarse intervals. Caliper log indicates that the unit is competent and stays in gauge.

Layered Sequence of Gravelly Sand with Sandy and Silty Layers (1,110 to 1,265 ft bgs)
Layered sequence of relatively coarse sediments interbedded with finer grained layered units. Distinct increase in gamma counts at both upper and lower contacts suggests a unique provenance for the sediments or gravel clasts. Gamma log trace has more variation than other units suggesting coarser bedding especially in the upper one-half of the unit. Resistivity of the unit is generally higher than both underlying and overlying units and shows more variability, especially in the uppermost 50 ft, indicating coarser clastic unit with fresh water. Variation in formation resistivity decreases below 1,160 ft. Density log values are similar to surrounding units but show much greater viability especially below approximately 1,160 ft, possibly a result of formation cementation of primary porosity. Neutron log data shows little variation except for a few small peaks that roughly correlate with differential temperature anomalies. Differential temperature curves have three distinct peaks at approximately 1,140 ft, 1,205 ft, and 1,220 ft indicating potential out-flow zones from the unit. SP logs are generally flat through the unit with a broad slope change or inflection at approximately 1,150 ft. Sonic velocity logs has several valleys (lows) probably indicating zones of less cementation or possibly secondary porosity, these lows however do not corresponds to apparent out-flow zones identified in the differential temperature log. VDL log data show that the unit is coarse grained with disorganized early sine waves and moderate velocity indicating only weak or incomplete cementation. Caliper log indicates that the unit is competent and stays in gauge.

Silty Sand with Gravel (1,265-1,355 ft bgs)
Thin unit of predominantly fine grained sediments.

Note: Lower contact of unit is based on the presence of basaltic clast gravel bed at 1,355 ft. Geophysically, the base of this unit is more likely at approximately 1,335 ft. This geophysical description will cover the interval from 1,265 to 1,335 ft only. The interval from 1,335 to 1,355 ft will be described in the underlying unit.

Gamma logs have similar response as overlying coarser sediment, with slight decrease at the contact. Resistivity logs indicate that the upper one-third of the unit has low resistivity, probably indicating clay-rich material. The lower two-thirds of the unit has moderate resistivities that is consistent with silty sand. Density logs are variable throughout unit, again possibly indicating changes in cementation. Neutron logs and differential temperature log are generally flat indicating that little water is associated or moving through the unit. SP logs are generally flat with slight decrease through the unit. At the upper contact, there is a weak deflection in the SP log suggesting different waters between the two units and possibly higher total dissolved solids in this unit. Sonic velocity data shows moderate velocities that are generally flat except for a peak at approximately 1,320 ft where resistivity also peaks indicating a coarse bed of gravelly material. VDL logs indicate well bedded fine grained sediments. Caliper log indicates that the unit is competent and stays in gauge.

Well-Cemented Sand and Gravel (1,355-1,400 ft bgs)
Gamma logs shift downward at 1,335 ft, probably reflecting a different provenance for this unit from the overlying units. Resistivity logs have moderate resistivity and are variable indicating some fresh water, probably in less cemented beds or fractures as shown in the neutron logs. Density logs decrease substantially through the unit to the base at the contact with the basalt. Neutron logs have several distinct peaks that correspond to peaks in resistivity indicating the presence of fresh water in either beds or fractures. Differential temperature logs show little character. The SP curve is flat with two very minor inflections. Sonic velocity increases in this unit and is more consistent than overlying unit suggesting a pervasive cement or denser clastic material. VDL logs indicate a coarser dense sediment with little bedding based on the disorganized early sine waves. Caliper log indicates that the unit is competent and stays in gauge.

Basalt Lava Flow (1,400-1,430 ft bgs)
Upper basalt lava flow. Gamma log curve shows little change from overlying and underlying sandy sedimentary units. Flow has moderate resistivities that increase toward the base, as does the density curve, probably indicating a dense base with flow-fragmented top. Neutron log has a distinct peak at the top, presumably within the brecciated flow top, and generally increases toward the base. Differential temperature log curve is flat with little character. SP log curve is flat, but has a small inflection at the contact with the overlying sediments. Sonic logs indicate that the basalt is dense, has moderate velocities, except the flow-fragmented top of the unit that has a distinct velocity low. VDL logs show a dense high velocity pattern with little character except the distinct narrow velocity low at the top of the basalt flow. Caliper log indicates that the flow is fractured and washes out slightly.

Sandstone (1,430-1,490 ft bgs)
Clayey well-cemented interflow volcaniclastic sandstone. Unit has similar gamma response to overlying basalt flow and sediments. Resistivity values are moderate and variable, probably reflecting variation in clay content. Density log values increase substantially with depth probably indicating dense cementation of primary porosity. Neutron log curve is elevated with little character. Differential temperature log shows moderate anomaly toward base of the unit. SP curve has little character, but steepens in slope within the unit. Sonic velocity data indicates dense and consistent high velocity unit, similar to density log results. VDL logs indicate a well bedded dense fine-grained sedimentary rock. Caliper log indicates that the unit is competent and stays in gauge.

Basalt Lava Flow (1,490-1,540 ft bgs)

Lower basalt lava flow. Gamma log shows little change from overlying unit, and is consistent from 1,335 to 1,540 ft indicating that the basalt flows, interflow sandstone and overlying sands and gravels are genetically related, probably with a disconformity at the base and top of the 1,335 to 1,540 ft interval. Resistivity values are moderate and increase toward the base, as do the density values similarly to the upper basalt flow, indicating a dense flow core with flow-fragmented top. Abrupt decrease in density between 1,535 and 1,540 ft at the base of the flow unit probably represents and flow breccias bottom. Neutron logs are noisy and decrease toward the middle of the unit, where the log reverse trend and sharply spikes toward the base, suggesting fractures and flow bottom breccias with water. Temperature differential logs have a broad spike near the middle of the unit, again indicating water outflow zone potentially from fractures in the flow. SP log curve is flat, but slope increases progressively toward base probably related to the inflection in the underlying unit. Sonic velocity logs indicate probable fractures within the dense high velocity lavas. VDL logs indicate that the fractures likely extend laterally into the flow. Caliper log data show that the unit is slightly out-of-gauge, especially toward the base, possibly indicating fracturing or friable character of the lava flow.

Well-Graded Sand with Clay and Gravel Grading into Clayey Sand (1,540-1,775 ft)

Thick sequence of undifferentiated and unconsolidated sediments. Gamma log shifts sharply at contact with overlying basalt flow confirming the interpretation of a disconformity and paleosol development at the top of the unit. Gamma logs are noisy, probably indicating the bedded nature of the unit. Resistivity logs indicate moderate resistivities with a general decrease with depth related to the general fining with depth observed in the lithologic logging. Several valleys in the resistivity are likely related to clay-rich beds in the sediments. Density log data indicate that the unit has lower density than the basaltic interval above and similar or lower density than the unconsolidated sediments above the basalts. Several spikes in the density log may reflect more cemented intervals within the unit. Neutron log curves are relatively flat compared with the overlying basalt interval. Differential temperature log is discontinuous due to separate logging runs, but has two broad spikes in the central section of the unit, possibly indicating out-flow zones. SP curves are also discontinuous, but show an inversion near the top of the unit, indicating a change in total dissolved solids of the waters between the overlying basalt and this unit. The SP curve elsewhere in the unit is flat. Sonic velocity data indicate a homogeneous low velocity unit with slight variations probably reflecting changes in grain size in beds. VDL logs indicate that the sediments are well bedded and homogeneous. Caliper logs indicate that unit is competent and in gauge.

Ash-Flow Tuff (1,775 to 1,860 ft bgs T.D.)

Non-welded felsic tuff similar or same as tuff at site 19 (825 to 1,245 ft). Gamma logs shift distinctly upward in tuff unit. Resistivity logs shift to moderate to high resistivities, probably due to water-filled porosity in tuff matrix. Density log decreases within low density non-welded tuff. Neutron log decrease slightly below contact with overlying sediments. Differential temperature log is flat except for weak positive anomaly at approximately 1,805 ft. SP log curve is flat, except for a spike at approximately 1,830 ft, probably due to material in borehole. Sonic velocity log shows low velocities with some variation, possibly due to crude bedding at the top of the unit or fractures. VDL logs show some potential layering of tuff. Caliper logs indicate that the unit is competent and stays in-gauge.

7.0 FINDINGS AND RECOMMENDATIONS

This section summarizes major findings from Phase VI drilling, logging, and testing of geologic deposits at site 4PD.

7.1 Major Findings

7.1.1 Drilling, Coring, and Well Construction

MR-CC drilling methods used to drill borehole 4PD did provide a large diameter, stable borehole for the installation of a multiple screen piezometer to 1,850 ft bgs. However, borehole deviation created substantial problems during well completion activities. As a result of bentonite mud cake on the borehole walls, well development required more resources than anticipated.

Borehole development methods (both initial reverse-circulation swabbing and later pump swabbing) adequately removed drilling fluids and developed the filter pack within the sandpacked intervals. Isolated zone testing using a packer assembly provided additional well development.

7.1.2 Geologic Logging

Geologic logs indicate that alluvium penetrated during Phase VI was composed solely of volcanic rocks. Valley-fill units below 390 ft are also composed of volcanic rocks, and include intervals of interbedded clay, silt, sand, and gravel to 1,400 ft. From 1,400 to1,540 ft, a sequence of basalt and sandstone was encountered. The bedrock unit penetrated in borehole 4PD is a nonwelded tuff believed to be the same unit encountered in boreholes 19D1, 19IM1A, and 19IM2A.

Data Censoring

Alluvium logging data from borehole 4PD were censored from 350 to 1,770 ft (the entire alluvial interval sampled) due to the bias toward the coarse fraction introduced by the MR-CC drilling method.

Alluvial Drill Cuttings

Findings regarding PSD data from geologic logging will be discussed below in relation to results from laboratory tests on drill cuttings (Section 7.1.3).

7.1.3 Laboratory Tests on Drill Cuttings

Because 4PD was drilled with conventional mud-rotary methods, the unconsolidated formation drill cuttings (alluvial and valley-fill) collected are not representative of in situ sediments. The samples are biased toward the coarse fraction and considered disturbed from in situ conditions. For this reason, alluvium logging data from this borehole, including the particle size distribution, were censored. However, archived samples from 4PB, drilled with reverse circulation methods during Phase II on the same site, are considered reasonably representative of in situ conditions.

Archived samples from 4PB were tested (PSD and hydrometer) in the NWRPO laboratory in August 2008 during Phase VI drilling operations. Samples from 4PC, which is approximately 20 ft west of 4PD and was drilled to 460 ft, were also tested (PSD and hydrometer) in October 2008. Laboratory data show a close agreement of textural properties between 4PB and 4PC, as would be expected for boreholes in close proximity to each other. From ground surface to 850 ft, wet sieve and hydrometer data for 4PB and 4PC were relied upon to determine particle size distribution (relative percentages of gravel, sand, silt, and clay) and sediment layering used for the construction of summary lithologic logs. Reliable sieve data were not available for sediments below 850 ft.

Visual comparisons of PSD data curves from 4PB and 4PD above 850 ft indicate large sample bias resulting from drilling and sampling of mud-rotary cuttings. The comparison illustrated that 4PD mud-rotary samples are not representative of in situ conditions, as recognized in previous EWDP investigations. Rotary drilling pulverizes coarser components into finer particles and the in situ fines (silt and clay) are carried away in the drilling mud. For these reasons, 4PD PSD data were not used for sediment texture and layering analysis.

Spatial Trends in PSDs of Alluvium Drill Cuttings

The geology at Site 4 consists of a relatively thick (about 390 ft) upper sequence of Quaternary alluvium overlying Tertiary valley-fill sediments, basalt flows and older valley-fill sediments. The valley-fill sediments exhibit a more fine-grained texture than is encountered in EWDP boreholes further west in Fortymile Wash and may reflect a transition to a deltaic environment near the Gravity Fault. Previous work conducted in NWRPO's Phase III drilling program (NWRPO,2003) showed the alluvial drill cuttings in two boreholes at Site 19 (19IM1A and 19IM2A), which is located west of the main Fortymile Wash channel, to be comprised only of granular materials (gravel, sand, and silt sized particles). These boreholes intersected alluvial materials to 820 ft bgs and were stopped in a distinctive weakly welded tuff also intersected in 4PD.

At 4PC, clayey sediments (including true "fat" clays) were encountered at 415 ft and were found to occur in thin layers throughout the remainder of the borehole. It was these clayey units that were responsible in part for difficult drilling conditions and the failed attempt to advance the borehole using AR-RC drilling methods. Borehole 4PD also intersected much finer-grained materials than were encountered at Site 19, however due to the poor recovery of the fines component using MR-CC, the sieve data do not reflect as clearly the higher fines content.

Data Censoring

As stated above, all alluvium data from 4PD were censored due to the bias introduced by the MR-CC drilling method.

7.1.4 Summary Lithology Logs

Borehole 4PC

Borehole 4PC penetrated a layered sequence of sandy alluvium and clayey valley-fill from ground surface to 460 ft bgs. The borehole was abandoned at 460 ft due to unstable borehole walls and drilling equipment failure.

The sediments intersected prior to abandonment consisted of alternating layers generally ranging from 5 to 20 ft thick (but as thick as 30 to 70 ft in places), of well-graded sand (SW), poorly graded sand (SP), and well-graded sand with silt (SW-SM) down to 415 ft. From 415 ft to the bottom of the borehole at 460 ft, sandy lean clays (SC) interbedded with more granular and poorly graded silty sands (SP) grade down into true fat clays (CH) that are interbedded with well-graded silty sands (SW-SM). The gravel components of these sediments are all volcanic in origin and consisted of both welded and non-welded tuff clasts.

Borehole 4PD

Because borehole 4PD was drilled with mud-rotary methods, samples were biased toward the coarse fraction and are considered disturbed from in situ conditions. Geologic field logs and laboratory test data from archived samples collected at nearby boreholes 4PA and 4PB were relied upon for alluvial textural analysis in the Summary Lithologic Log for 4PD down to 850 ft. Below 850 ft, geophysical logs were relied upon to identify textural changes in the alluvium.

Borehole 4PD penetrated a layered sequence of alluvium from ground surface to 390 ft. These units consisted of coarse well-graded gravelly and sandy layers with silt (GW-GM and SW-SM) grading downward to more clay-rich coarse units consisting of well-graded gravelly and sandy layers with clay (GW-GC and SW-SC). From 390 to 1,110 ft, the alluvial materials become clayey and consist of lean clays (CL), clayey sands (SC), well-graded gravels with clay (GW-GC), well-graded sand with clay (SW-SC), and sandy clay with gravels (CL). These clay-rich units below 390 ft are interpreted as valley-fill sediments.

From 1,110 to 1,400 ft the sediments become more granular and consist of layered gravelly sands and silty sand layers, silty sand with gravel, and at the base of the sequence from 1,355 to 1400 ft the sands and gravels are well cemented. The rock types represented by gravel clasts within the sediments are all volcanic tuff from ground surface to 970 ft. From 970 to 1,265 ft clast types include volcanic tuff, siltstone, sandstone, and quartzite. From 1,265 to 1,355 ft gravel clasts are all volcanic tuffs. The gravel clasts in the cemented unit at the base from 1,355 to 1,400 ft are predominantly basalt with fewer tuff clasts. Gravel clast shapes throughout the sediments are rounded to angular.

The sequence is underlain by a thin basalt flow from 1,400 to 1,430 ft. The basalt flow is reddish brown in color with abundant white feldspar crystals. The basalt is vesicular, fractured, and has a glassy groundmass. The top and bottom of the basalt display the greatest degree of weathering. The basalt also contains traces of zeolitic mineral coatings.

Underlying the basalt is a well-cemented sandstone unit from 1,430 to 1,490 ft. The sand grains within the sandstone are well sorted, well rounded, and composed predominantly of dark reddish brown basaltic grains. The sandstone is interpreted as an epiclastic unit deposited between basaltic flow horizons and accumulating within depressions on the surface of the underlying basalt flow.

From 1,490 to 1,540 ft another basalt flow is present. The basalt is reddish brown and is similar to the basalt described above. The lower basalt flow has a thicker flow core and a well-developed flow breccia at the bottom.

Underlying the lower basalt, from 1,540 to 1,775 ft, is a sequence of older unconsolidated alluvial sediments composed of well-graded sand with clay and gravel grading into clayey sand. The unit is a fining-downward sequence with the clayey sand appearing at 1,630 ft and persisting to the bottom of the unit. Gravels within the unit are composed of roughly equal proportions of non-welded volcanic tuff clasts and welded tuff clasts. The welded clasts are angular and the non-welded clasts are distinctly rounded.

Finally, the last unit penetrated is an ash-flow tuff from 1,775 to 1,860 ft, which is the TD of the borehole. The tuff is pale yellow to very pale brown, soft, weakly to nonwelded, devitrified, and contains distinctive white pumice. The upper contact with valley-fill sediments is sharp. The tuff unit is believed to be the same unit intersected in boreholes 19D1, 19IM1A, and 19IM2A, located approximately 3 miles to the northwest, just west of the main Fortymile Wash channel.

7.1.5 Borehole Geophysical Logging

Borehole geophysical logs were used for lithologic characterization and stratigraphic correlations. For the most part, only qualitative interpretations of rock properties were made from the logs. Significant findings include the following.

- Increasing amounts of fines in formation materials usually correlate with increasing natural gamma counts, decreasing formation resistivity values, increasing density values, and decreasing neutron porosity log counts (increasing water filled porosity).
- In 4PD, increasing amounts clay correlate with all of the above, except increasing natural gamma counts. In this case, natural gamma counts may decrease (rather than increase) as a result of a decrease in the concentration of gamma emitters due to the diagenesis of the formation.
- In alluvium, increasing natural gamma curves and peaks in density and neutron porosity curves correspond to clean well-graded sand and/or gravel that produces clean water. These sand and/or gravel units can serve as preferential flow paths.
- In volcanic units, formation resistivity logs are useful for identifying ash-flow tuffs and basalt flows, and therefore useful for stratigraphic correlation. Higher resistivity values correlate well with denser rocks identified in the geological cuttings described at the site and lower resistivity values correlate with nonwelded rocks.
- Basalt flows exhibit lower natural gamma counts and higher density values than alluvium.
- In 4PD, fluid resistivity and fluid temperature logs could be used to identify discrete intervals where groundwater flows into or out of the wellbore. In several cases, formation resistivity, density, and neutron porosity logs supported identification of water movement into/out of the borehole.

- In alluvial units in 4PD, large peaks in caliper logs resulted from washout zones and corresponding decreases in natural gamma, density, resistivity, and neutron porosity log values.
- Density and neutron porosity responses can be due to different clay contents, degree of cementation, grading of clasts, washout zones, and/or fractures.
- Sonic velocity curves are variable, reflecting the density of the formation. Low velocities can possibly indicate a decrease in water saturation in the sediments. Increasing sonic velocities suggest a pervasive cement or that a denser clastic material may be present.

7.2 Recommendations

- When contracting AR-RC drilling work, add a contract clause requiring a minimum of 10 years “behind the controls” experience for drilling rig operator.
- Always include a deviation clause (including ‘dog-leg’) for MR-CC well borehole drilling contracts.
- Do not conduct particle size distribution analysis (wet sieve analysis) on MR-CC samples as the bias introduced by the drilling method eliminates any interpretive value of the analysis.
- Continue recording field estimates of major particle size fractions in alluvium and valley-fill (unconsolidated) on drill cuttings logging forms. These data are proving very useful in characterizing the textural layering in the sediments downgradient from Yucca Mountain.
- Continue running natural gamma, caliper, formation resistivity, density, neutron porosity, sonic, fluid temperature, and fluid resistivity geophysical logs.

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