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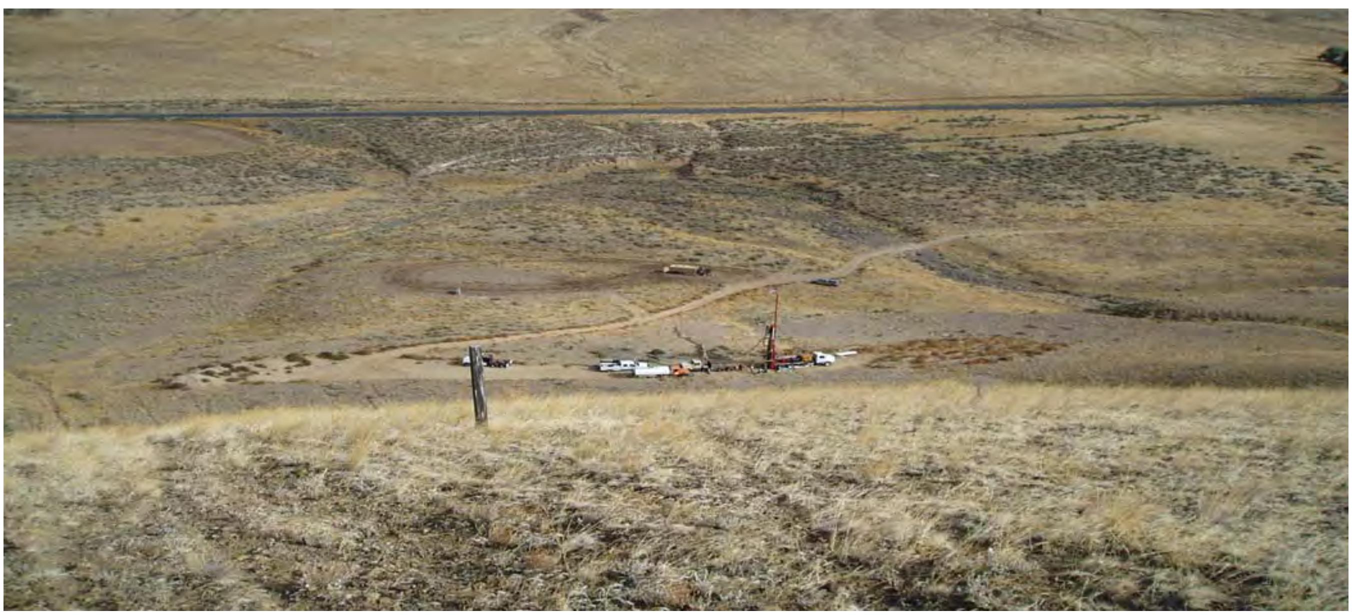
Managing Water in the West

Supplemental Report for Appraisal Assessment – Geology and Hydrogeology, Right Abutment, Black Rock Damsite

A component of
Yakima River Basin Water Storage Feasibility Study, Washington
Technical Series No. TS-YSS-18

Pacific Northwest Region



U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region

November 2007

Cover Photograph – View looking north from the upper right abutment of the proposed Black Rock dam at a Bureau of Reclamation drill crew set up on drill hole DH-06-1. Black Rock Damsite, Yakima River Basin Water Storage Feasibility Study, Washington – Bureau of Reclamation Photograph by K. Didricksen, March 2006.

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prepared by

Donnie N. Stelma, Geologist and Kayti Didricksen, Hydrogeologist
Under supervision of Richard A. Link, Regional Geologist

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Geology, Exploration & Instrumentation Group
Boise, Idaho

November 2007

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Preface

Congress directed the Secretary of the Interior, acting through the Bureau of Reclamation (Reclamation), to conduct a feasibility study of options for additional water storage for the Yakima River basin. Section 214 of the Act of February 20, 2003 (Public Law 108-7) contains this authorization and includes the provision "... with emphasis on the feasibility of storage of Columbia River water in the potential Black Rock reservoir and the benefit of additional storage to endangered and threatened fish, irrigated agriculture, and municipal water supply."

Reclamation initiated the *Yakima River Basin Water Storage Feasibility Study* (Storage Study) in May 2003. As guided by the authorization, the purpose of the Storage Study is to identify and examine the feasibility and acceptability of alternate projects by: (1) diversion of Columbia River water to the potential Black Rock reservoir for further water transfer to irrigation entities in the lower Yakima River basin as an exchange supply, thereby reducing irrigation demand on Yakima River water and improving Yakima Project stored water supplies, and (2) creation of additional storage within the Yakima River basin. In considering the benefits to be achieved, study objectives will be to modify Yakima Project flow management operations to most closely mimic the historic flow regime of a Yakima River system for fisheries, provide a more reliable supply for existing proratable water users, and provide additional supplies for future municipal demands.

Reclamation's Upper Columbia Area Office in Yakima, Washington, is managing and directing the Storage Study. Pursuant to the legislative directives, Reclamation has placed emphasis on Black Rock project study activities. These study activities are collectively referred to as the Black Rock Project Assessment (Assessment).

The Assessment has three primary objectives. First, it provides the emphasis directed by Federal and State legislation. Second, it builds upon prior work and studies to provide more information on the configuration and construction cost of the primary components of a Black Rock project. It examines legal and institutional considerations of water supply and use, and identifies areas where further study is needed. Third, it is a step forward in identifying the viability and feasibility of a Black Rock project.

This technical document, prepared by Reclamation's Pacific Northwest Regional Geology, Exploration & Instrumentation Group, Boise, Idaho, is a supplement to the assessment reporting on geologic investigations conducted at the Black Rock Damsite in 2003 and 2004.

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Summary and Conclusions

The Black Rock damsite was investigated by a private engineering consulting firm in 2002 and 2003. The study suggested that the right abutment bedrock at the damsite is highly fractured and permeable, and recommended further studies to determine the suitability of the right abutment for a dam foundation.

The ridges of the Yakima Fold Belt are generally asymmetrical, with the south limb gently inclined while the north limb is steeply folded with a thrust fault near the base of the fold. This configuration exists at the Black Rock damsite, which lies between the Yakima Ridge anticline on the north and Horsethief Mountain anticline on the south.

The current investigations were undertaken to obtain additional geologic and hydrogeologic data on Horsethief Mountain, which forms the right (south) abutment at the damsite. The specific location was chosen with the purpose of encountering a thrust fault mapped at the base of Horsethief Mountain, and to characterize the engineering and hydraulic properties of the basalt rock in and around the thrust fault zone. Two deep holes were drilled on the abutment slope. The first hole was drilled to obtain core samples and the second hole was drilled to perform hydraulic conductivity tests. The drilling and borehole testing program was initiated in December 2005 and continued until May 2006.

The rock recovered from the hanging wall (rock mass above the fault) and within the thrust fault zone is very fractured and broken from the folding and faulting activity. The fault zone consists of basaltic breccia composed of small angular clasts of pulverized rock in a weathered clayey sand matrix. The rock recovered from the footwall (rock mass below the fault) is considerably less fractured than the overlying folded and faulted rock.

Rock quality designation (RQD) is a measure of rock fracturing based on the lengths of core samples recovered. A sum of core samples equal to or exceeding 0.33 feet in length for each core run is divided by the total length of the core run. The values are expressed in percentages: Zero percent is the poorest quality (very intensely to intensely fractured) and 100 percent is the best quality (slightly fractured to unfractured). The weighted average RQD values for rock above the fault zone is 12 percent, the weighted average RQD within the fault zone is 7 percent, and the weighted average below the fault zone is 30 percent.

The question of reservoir leakage potential is multi-faceted due to lateral and vertical variation in hydrogeologic units across the site and the role of tectonic features on ground-water flow conditions. There are three primary leakage mechanisms: 1) leakage via the unconsolidated sediments underlying the reservoir; 2) vertical downward leakage into underlying basalts; and 3) leakage around the dam through the abutments. The intent of the 2004 Black Rock investigation program was to evaluate the leakage potential in the valley section of the reservoir and the 2006 program was to evaluate the south abutment conditions.

Various hydrologic test methods were used to assess the hydraulic properties of selected hydrogeologic units. The tests included slug tests, constant-head injection tests, and constant-rate pumping tests. Testing was performed in a total of six depth intervals within the unsaturated materials above the water table (vadose zone) and in six depth intervals within the unconfined and confined aquifers encountered at the site. The field test data were analyzed by Dr. Frank Spane of Pacific Northwest National Laboratory (PNNL) using various methods to determine hydraulic and storage properties (the report is located in Appendix A). The hydraulic and storage properties of an aquifer determine the potential transmission of reservoir seepage through the ground-water system.

Hydraulic conductivity values ranged from 0.42 to 3.77 ft/day in the fault breccia zone, 0.32 to 52.9 ft/day in the Pomona basalt, and 0.45 to 20.7 ft/day in the Umatilla basalt. These values were similar to K values reported from the Hanford site and to other reported values for Saddle Mountains basaltic intervals. These results were used as model input parameters, along with other available data, in a ground-water flow model that was developed to quantify seepage and hydrologic impacts from the potential Black Rock reservoir (Schmidt and others, 2007).

Introduction

Section 214 of the Act of February 20, 2003, P.L. 108-7, authorized the U.S. Department of the Interior, Bureau of Reclamation (Reclamation) to conduct a feasibility study of options for additional water storage in the Yakima River Basin with emphasis on the feasibility of storage of Columbia River water in the potential Black Rock Reservoir.

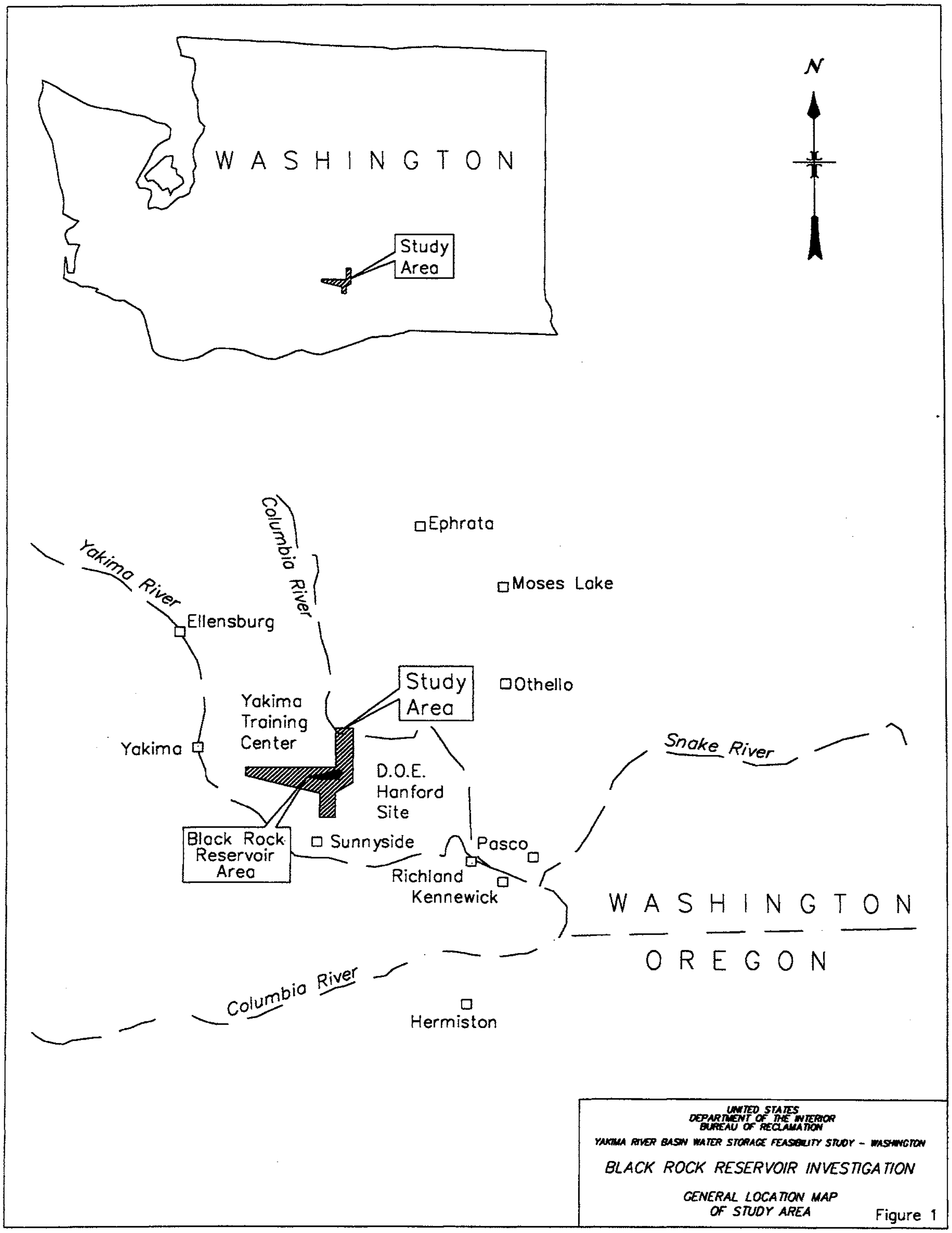
The Yakima River Basin Water Enhancement Project feasibility study conducted in the 1980's included possible storage by enlarging an existing reservoir or constructing an offstream reservoir within the Yakima River Basin. More recently, Washington Infrastructures Services, Inc. (WIS) investigated the Black Rock damsite in late 2002 and prepared a final report entitled, *Black Rock Reservoir Study – Initial Geotechnical Investigation*, dated January 2003. WIS completed the study for Benton County, Washington, which addressed pumping water from the Columbia River for storage in a proposed Black Rock reservoir. This water would then be made available for irrigation, instream flow enhancement, and municipal purposes in the Yakima River Basin. Water would be delivered to the Roza and/or the Sunnyside Canals in exchange for part or all of their Yakima River Basin water supply. The exchanged water could then be used for instream flow enhancement and/or for irrigation in dry years.

Purpose

This report summarizes the findings of the exploratory drilling program conducted at the Black Rock damsite from December 2005 to May 2006. The data collected were used to assess the suitability of the foundation at the site for the proposed embankment. The field program involved drilling to determine the engineering properties of the bedrock and performing hydrogeologic testing.

Location

The Black Rock Damsite is in the Black Rock Valley about 24 miles east of Yakima, Washington via State Highway 24 through the Moxee Valley in Section 12 and the N1/2 of Section 13, T.12 N., R. 23 E (refer to Figure 1).


WASHINGTON
Study Area
N
Columbia River
Ephrata
Yakima River
Moses Lake
Ellensburg
Study Area
Othello
Yakima Training Center
Yakima
Snake River
D.O.E. Hanford Site
Black Rock Reservoir Area
Sunnyside
Pasco
Richland
Kennewick
WASHINGTON
OREGON
Columbia River
Hermiston
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA RIVER BASIN WATER STORAGE FEASIBILITY STUDY – WASHINGTON
BLACK ROCK RESERVOIR INVESTIGATION
GENERAL LOCATION MAP
OF STUDY AREA
Figure 1

Previous Investigations

WIS investigated the Black Rock damsite in late 2002 and prepared a final report in 2003 (Washington Infrastructure Services, Inc., 2003). This investigation was funded by Benton County through a grant from the State of Washington. The investigation program consisted of completing geologic mapping, five test borings and nine test pits, water pressure testing, and a geophysical refraction survey. Two important conclusions were drawn from this investigation. First, the depth to bedrock in the main section of the damsite was considerably deeper than the 25 feet initially estimated, reaching depths as great as 216 feet in the maximum section. Also, the basaltic lava flows that form the bedrock at the site were considerably more fractured and broken than originally thought and rock quality was generally low. None of the borings intercepted the water table and no observation wells were installed at the site.

WIS also evaluated foundation material permeability in their 2003 report. Their initial evaluation identified intensely fractured bedrock in the right abutment area. Due to the condition of the rock, they were unable to complete the right abutment drill hole (DH-4) to the anticipated depth and did not conduct any permeability testing in that drill hole. They concluded that highly pervious zones are present and that additional permeability testing is needed.

Reclamation performed investigations at an alternate damsite west of the original site between December 2003 and May 2004 (Stelma, 2004). These investigations involved drilling five shallow holes to define the bedrock surface, and drilling one deep hole to confirm the stratigraphy of the deep foundation and a second deep hole for permeability testing. The exploratory drilling indicated that the depth to bedrock and overburden thickness at the alternate damsite was slightly greater than the original damsite. Based on that data, the original site was determined to be the preferred alignment and no further study of the alternate damsite was planned.

Current Investigation

The current investigation included drilling exploratory holes to characterize the right abutment bedrock and performing permeability testing at the damsite. Right-of-entry was obtained from the landowner, and a temporary access road and drill pad was constructed near the base of the right abutment slope by members of Reclamation's Pacific Northwest (PN) Regional Drill Crew (refer to Photograph No. 1).

Photograph No. 1. View looking southeast at Horsethief Mountain, which forms the south (right) abutment at the Black Rock damsite. Note access road and drill pad along the lower slope. The drill is set up on drill hole DH-05-1. Black Rock Damsite, Yakima River Basin Water Storage Feasibility Study, Washington – Bureau of Reclamation Photograph by D.N. Stelma, November 29, 2005.

PN Regional Drill Crew employees drilled two foundation borings. Core samples were obtained in the first drill hole (DH-05-1). The second drill hole (DH-06-1) was drilled to perform hydraulic conductivity testing. Coring was performed using an Ingersoll-Rand T-2 truck-mounted rotary drill, and the water test hole was drilled using a Foremost DR-12 dual-rotary truck-mounted drill, both with standard support equipment including air compressors and circulating pumps. Core samples of the bedrock were obtained using PQ [3.3-inch-inner-diameter (I.D.)] and HQ [2.5-inch-I.D.] wire-line coring systems with clear water and/or polymer as circulating fluids. The water test hole was drilled using a rock bit and down-the-hole-hammer, with air, water, and biodegradable foam additive to remove cuttings. Water for drilling and testing was procured from a privately owned water well located about 3 miles from the site. The water source is from the Wanapum aquifer and water quality samples were taken from this source to compare the chemistry of the drill fluid input water with the Saddle Mountains water encountered and tested in the abutment drill holes (refer to the *Hydrogeology* section for water quality data).

Eleven rock core samples were submitted to the Washington State University Geoanalytical Laboratory for geochemical analysis and three soil samples from the fault zone were submitted to Materials Testing and Inspection, Inc., Boise, Idaho, for gradation analysis. Test results are shown on geologic logs and the geochemical and gradation analyses data and results are included in Appendix B.

Various hydrologic test methods, including slug, constant-head injection, and constant-rate pumping tests, were used to assess the hydraulic properties of selected hydrogeologic units. Testing was performed in the unsaturated materials above the water table (vadose zone) and in the unconfined and confined aquifers encountered at the site. Hydraulic conductivity values from the tests were subsequently used in a ground-water model developed for the Black Rock site to estimate leakage from the potential reservoir (Schmidt and others, 2007). Additional information about the hydrologic testing is provided in the Hydrogeology section of this report, and in the letter report provided by Dr. Frank Spane of Pacific Northwest National Laboratory (PNNL) (located in Appendix A).

Regional Geology

A detailed description of the regional geology and seismicity is included in the report prepared in 2004 entitled, *Appraisal Assessment of Geology at a Potential Black Rock Damsite, A component of Yakima River Basin Water Storage Feasibility Study, Washington, Technical Services No.TS-YSS-5* (Stelma, 2004).

Site Geology

The right abutment of the proposed Black Rock damsite consists of the north limb of the Horesethief Mountain Anticline (refer to Drawing Nos. 33-100-3381 and -3473, both located in Appendix C). The upper foundation is composed of Quaternary loess and colluvium underlain by volcanic rocks of the Saddle Mountains and upper Wanapum Formations of the Columbia River Basalt Group. The Horsethief Mountain thrust fault underlying the northern edge of Horsethief Mountain was also encountered in the right abutment drill holes.

The geology and stratigraphy described here are based on exploratory drilling performed on the lower right abutment at the damsite, and from interpretations of foundation geology presented in Stelma (2004) and Washington Infrastructure Services, Inc. (2003). The alluvial units documented from drilling at the damsite include wind-blown loess (Qe) and colluvium (Qcg) deposits. These are underlain by the Saddle Mountains Basalt Formation, which includes the Pomona Basalt Member (Tp) and Umatilla Basalt Member (Tum). The long periods between eruptions allowed for the deposition of sediments between flows. The sediments are stratigraphically included in the Ellensburg Formation and at this site include only the Rattlesnake Ridge interbed (Trr). Although not encountered in these drill holes, the Priest Rapids Member (Tpr) of the Wanapum Basalt Formation and the Mabton sedimentary interbed (Tm) of the Ellensburg Formation are assumed to underlie the Saddle Mountains Formation at the core of the Horsethief Mountain anticline (refer to Drawing No. 33-100-3473). The geologic units encountered at the site are shown on the generalized stratigraphic section (refer to Figure 2) and described in the following narrative from youngest (recent) to oldest.

Quaternary Loessial Deposits (Qe)

Deposits of Holocene-age wind-blown loess blanket the site. The loess consists primarily of brown, dry to moist, fine sand and nonplastic silt. The loess was encountered during construction of the temporary access road and drill pad and in the upper 3 feet in drill holes DH-05-1 and DH-06-1 (refer to Drawing No. 33-100-3473).

Quaternary Colluvial Deposits (Qcg)

The colluvial deposits consist of loose, heterogeneous, coarse- to medium-grained sand with fines, gravel, cobbles, and boulders composed of basaltic detritus from local sources deposited at the foot of the slope by gravity. The unit is wedge shaped and appears to be from 60 to perhaps 100 feet thick at the base of Horsethief Mountain (refer to Drawing No. 13-100-3473).

Ringold Formation (Tr)

The Ringold Formation was not encountered in drill holes, but is known to be present in the valley portion of the foundation (refer to Drawing No. 13-100-3473). The Ringold Formation in the valley, based on earlier investigations, can be divided into three sections. The upper and lower sections are coarser-grained fluvial deposits with material ranging from poorly to well indurated sand and fines, to gravel and fines with cobbles. The base of the Ringold is characterized by a 10-foot-thick layer of cobbles. The middle section is finer-grained, consisting of well-indurated clayey sand with gravel.

Period	Epoch	Group	Formation	Member	Age (*)	Thickness (ft)	Graphic	Symbol
Quaternary	Recent		Loess		0.05–0.1	Appr. 60		Qe
	Pleistocene		Colluvium					Qcg
Tertiary	Miocene	Columbia River Basalt Group	Saddle Mountains	Pomona (upper)	12	Appr. 30		Tp
				Esquatzel/Umatilla	13	Appr. 136		Teq/Tum
			Horsethief Mountain Thrust Fault	Fault Breccia		Appr. 73		Tfb
			Saddle Mountains	Rattlesnake Ridge		Appr. 30		Trr
				Pomona	12	Appr. 90		Tp

Note: Drawing not to scale

Legend: Colluvium and Loess Deposits; Horsethief Mountain Thrust Fault; Sedimentary Interbeds; Columbia River Basalt Group Lava Flows

FIGURE 2 – GENERALIZED STRATIGRAPHY – LOWER RIGHT ABUTMENT – BLACK ROCK DAMSITE

Rattlesnake Ridge Interbed (Trr)

The Rattlesnake Ridge interbed is a member of the Ellensburg Formation and includes the sedimentary deposits that overlie the Pomona Basalt Member. The unit is composed of tuffaceous sandstone. The unit forms a short segment of the footwall beneath Horsethief Mountain thrust fault (refer to Drawing No. 33-100-3473). The unit was identified based on its stratigraphic position overlying the Pomona Basalt Member, which was confirmed based on geochemical analysis.

Pomona Basalt (Tp)

The Pomona Basalt forms the upper bedrock unit in the Black Rock valley and lower right abutment at the damsite. The basalt has reverse magnetic polarity and contains fine plagioclase crystals as indicated in hand samples. The Pomona Basalt was encountered above and below the Horsethief Mountain thrust fault. The upper basalt is extremely fractured and weathered, and is perhaps the remnant of a landslide at the base of Horsethief Mountain. The Pomona in the footwall beneath the Horsethief Mountain thrust fault is less fractured and weathered than the basalt above.

Selah Sedimentary Interbed (Ts)

The Selah interbed is a member of the Ellensburg Formation and is the sedimentary deposit between the Pomona and Esquatzel/Umatilla Basalt. The unit was not encountered between the basaltic units in the drill holes on the right abutment. The Selah interbed may be absent due to folding and uplift of the anticline at the time of interbed deposition. The interbed may have been removed by erosion during uplift of the anticline at the time of deposition.

Undifferentiated Esquatzel and Umatilla Basalt (Teq/Tum)

The Esquatzel Basalt overlies the Umatilla Basalt in the Black Rock valley. The two units have similar physical characteristics and normal magnetic polarity, and have been addressed as a single unit in previous reports. Geochemical data indicates the rock underlying the Pomona on the lower right abutment has Umatilla chemistry. The Esquatzel portion appears to be absent. It may have been eroded during folding and uplift of the anticline or the drill site is beyond the extent of the Esquatzel flow in this area. The Umatilla Basalt consists of gray to dark gray, hard, dense to slightly vesicular, fine-grained basalt.

Horsethief Mountain Anticline and Thrust Fault

The ridges of the Yakima Fold Belt are generally asymmetrical. The south limb is gently inclined while the north limb is steeply folded, and a thrust fault lies near the base of the north limb. This configuration exists at the Black Rock damsite, which is between the Yakima Ridge anticline on the north and Horsethief Mountain anticline on the south (refer to Drawing Nos. 33-100-3381 located in Appendix C).

The rock recovered above (hanging wall) and within the thrust fault zone is very fractured. The fault zone breccia (Tfb) consists of small angular clasts of pulverized rock in a clayey sand matrix. The matrix and coating on clasts consist of iron and manganese oxide, chlorite, and iron sulfide. The fault zone is at a low angle of inclination, and the thrust plane is at approximately 20 degrees (estimate) and is 72 feet thick (refer to Drawing No. 13-100-3473). The bedrock below the thrust fault (footwall) is considerably less fractured than the overlying folded and faulted rock, yet hydraulic conductivity (K) values are higher.

Engineering Geology

The Black Rock dam alignment was explored during a geologic investigation conducted in 2003 and the geologic conditions from that investigation are documented in the report by WIG (2003).

During the geologic investigation a single hole was drilled on the upper right abutment. Core samples were obtained and geochemical analyses were performed on two core samples. Poor weather conditions, highly fractured rock, loss of drill circulating fluid, and difficult drilling conditions prevented the drilling contractor from completing the drill hole and prevented conducting downhole permeability tests. The boring was abandoned after advancing to a depth of 115 feet.

Reclamation drilled two holes on the lower right abutment at the Black Rock damsite to determine physical and hydraulic properties of the bedrock. The first hole, designated DH-05-1, was drilled to provide a pilot sample hole for determining the stratigraphy and condition of the rock units and determine intervals for hydraulic conductivity testing. The second hole, designated DH-06-1, was drilled about 37 feet west of the first hole for downhole hydraulic conductivity tests (refer to Drawing 33-100-3381 for hole locations). For details refer to the geologic logs of drill holes DH-05-1 and DH-06-1 located in Appendix B. Also included in Appendix B are a summary of samples for geochemical testing and interpretation, geochemical test data, and gradation analysis data.

Rock quality designation (RQD) is a measure of rock fracturing based on the lengths of core samples recovered (Bureau of Reclamation, 1998). A sum of core samples equal to or exceeding 0.33 feet in length for each core run is divided by the total length of the core run. The values are expressed in percentages: Zero percent is the poorest quality (very intensely to intensely fractured) and 100 percent is the best quality (slightly fractured to unfractured). The length-weighted average RQD values for the bedrock units were calculated using the formula:

Sum [(RQD value) x (length)] / Total Thickness of Bedrock Unit

The range of RQD values and weighted average RQD values for individual bedrock units are presented in the following sections.

Washington Infrastructure Services, Inc. (WIS) Drill Hole DH-4

Exploration drill hole DH-4 was drilled on a prominent rock point about halfway between the base and the top of Horsethief Mountain, and about 100 feet north of the axis of the Horsethief Mountain anticline (refer to Drawing Nos. 33-100-3381 and -3473).

Continuous core samples were taken from the ground surface to the bottom of the hole at 115 feet. The following description is taken from the report by WIS (2003):

> The material was characterized by interbedded sandy, silty clay deposits and the presence of palagonite along fractures. Because of folding and faulting associated with the anticline, the unit was extremely fractured and in some cases rubble. Rock quality designation (RQD) was zero for all runs. The basalt in DH-4 is described as medium dark gray, moderately to severely weathered, highly fractured, with fractures being smooth to undulating, with iron-oxide staining and clay filled. Geochemical samples were taken at the ground surface and at 115 feet in the drill hole. Both had Umatilla chemistry. No water tests were performed in DH-4. Excessive water losses during drilling indicated highly pervious conditions that required casing and grouting during drilling such that water testing could not be performed.

Drill Hole DH-05-1

Drill hole DH-05-1 was drilled about 1,200 feet south of Washington State Highway 24, about 60 feet above the valley floor, on the lower south abutment along the proposed dam axis (refer to Drawing 33-100-3381). The specific location was chosen with the purpose of encountering the thrust fault mapped at the base of Horsethief Mountain, and to characterize the basaltic rock in and around the fault zone.

The exploration program originally called for a single drill hole to obtain representative core samples of the rock and to run hydrologic tests for estimating permeability. The boring was started using clear water as the circulating drill fluid, and several permeability tests were conducted in the upper basalt. In order to improve core recovery and improve drill fluid return, the circulating fluid was changed from water to a polymer-based drill mud. The core recovery improved, even though the rock quality remained poor, and the drillers were able to maintain a relatively high percentage of fluid return throughout most of the hole. Drill cuttings were sampled from the ground surface to 60.5 and from 77.8 to 151.0 feet. Core samples were attempted from 60.5 to 77.8 feet with poor or no recovery. Continuous core samples were obtained from 151.0 feet to the bottom of the hole at 401.4 feet.

The Black Rock valley floor and slopes of the surrounding hills are mantled with about 3.0 to 8.0 feet of wind-blown silt or loess (Qe). Loess samples from DH-05-1 are composed of sandy silt s(ML). High-pressure air was used to advance the casing in the loess. The resultant sample recovery was poor, but surface samples contained about 70 percent nonplastic fines and about 30 percent fine sand, with some organic material in the upper few feet.

The colluvium (Qcg) underlying the windblown silt was about 57.5 feet thick and was primarily coarse-grained gravel with medium- to coarse-grained sand and fines. Based on poor core recovery and drilling conditions, it was estimated that the colluvium also contained a considerable amount of cobble-sized (3- to 12-inch) material.

The upper bedrock unit on the lower slope of Horsethief Mountain is the Pomona Basalt Member (Tp) of the Saddle Mountains Basalt Formation. The north limb of the Horsethief Mountain anticline dips about 35 degrees, and the rock remaining on the slope has been fractured and broken from the folding activity. The Pomona Basalt encountered in DH-05-1 was extremely fractured, and relatively thin (31.5 feet thick). Based on mapping, the Pomona Basalt Member may be part of a rock slide mass, such as exists at Horsethief Point, rather than in-place rock (refer to Drawing Nos. 13-100-3381 and -3473). Recovery of the Pomona Basalt was poor. Four short core runs, between 60.5 and 77.8 feet, recovered only four feet of rock, consisting of basaltic cobbles with poorly graded gravel and silt. Geochemical analysis on a sample from 65.6 feet confirmed that the rock was Pomona Basalt.

The Selah Interbed (Ts) is a sedimentary unit that underlies the Pomona Basalt in the Black Rock valley. However, the unit was not encountered in the abutment drill holes. Because the Selah is absent, the contact between the Pomona Basalt

(Tp) and the underlying Esquatzel and Umatilla Basalt Member (Teq/Tum) was estimated at about 92 feet based partially on drill cuttings becoming slightly finer grained, indicating a possible flow contact, and partly on geochemical analysis on samples at 97.2, 117.0, and 136.5 feet in drill hole DH-06-1, which all had Umatilla chemistry.

The total thickness of the undifferentiated Esquatzel/Umatilla Basalt in drill hole DH-05-1 was 136.4 feet, which was about 60 feet less than the thickness in holes drilled in the Black Rock Valley. This may be from thinning of flows due to uplift and early formation of the fold, and later erosion and removal of the basaltic rock from the steep limb of the anticline. The poor condition of the rock prevented coring of the upper part of the unit. It was drilled to 151 feet using a rock bit and compressed air. From about 151.0 to 168.4, and from 174.4 to 184.5 feet, the rock consisted of black to dark gray and greenish black, vesicular, intensely to moderately weathered (W6), moderately hard (H4), very intensely fractured (FD9) basalt. From about 168.4 to 174.4 feet and 184.5 to 228.4 feet, the rock consisted of black to dark gray, dense, slightly weathered (W3), hard (H3), intensely to moderately fractured (FD8) basalt. RQD values from 151.0 to 228.4 feet (bottom of unit) ranged from 0 to 33 percent, with a weighted average of 12 percent. The fracture surfaces were randomly oriented and smooth and planar to rough and planar. Based on the lack of weathering on fracture surfaces and generally good drill fluid return, it would seem the joints were tight to slightly open in place. For details of RQD refer to the log for drill hole DH-05-1 located in Appendix B. Geochemical analysis on samples from 159.0, 171.5, and 219.3 feet confirmed the rock was Umatilla Basalt.

The Horsethief Mountain thrust fault was encountered in the drill hole between 228.4 to 301.1 feet. The contact between the Esquatzel/Umatilla Basalt (Teq/Tum) and the underlying fault zone was based on a change from predominantly fractured basalt to predominantly basaltic breccia. The rock consisted of black to greenish black, fine-grained basaltic fragments in a sand and clayey sand matrix. The fault zone was moderately (W5) to intensely weathered (W7) with abundant iron and manganese oxide and chlorite mineralization throughout, and the fragments were moderately hard (H4) to moderately soft (H5), and very intensely fractured (FD9). A block of relatively intact basalt was encountered from 250.9 to 273.0 feet within the fault zone. The block consisted of black to greenish black, dense, slightly weathered (W3), hard (H3), and intensely fractured (FD7) basalt. RQD values in the fault breccia were predominantly 0 percent, with a weighted average of 7 percent for the entire fault zone. For details of RQD refer to the log for drill hole DH-05-1 located in Appendix B. Geochemical analysis on a sample from 267 feet had Umatilla chemistry, indicating the fault in this area was composed of pulverized rock from the overlying basaltic member.

The lower contact of the fault zone was easily distinguishable based on a sharp change from basaltic breccia to tuffaceous sandstone. The sandstone was interpreted to be the Rattlesnake Ridge Interbed (Trr) of the Ellensburg Formation. The Rattlesnake Ridge Interbed is about 9.6 feet thick and is composed of fine-grained, well-indurated fine sand with silt and clay with scattered fragments of volcanic ash, pumice, and lithic fragments. The sandstone is moderately weathered (W6), moderately soft (H5), and moderately to slightly fractured (FD4). The RQD value of the sandstone is 92 percent. Once the unit was penetrated the water level in the hole raised about 112 feet, indicating that the sandstone interbed is a confining layer to the underlying Pomona Basalt aquifer.

The drill hole was terminated in the lower Pomona Basalt Member (Tp) at 401.1 feet. The Pomona Basalt below the fault zone is less fractured than the bedrock above the fault zone. The contact between the Rattlesnake Ridge Interbed and the Pomona is marked by a vesicular flow top with sediment mixed into the upper 2 to 4 feet of the underlying basalt. The rock from about 310.7 to 343.2 feet consisted of black and gray to greenish black, vesicular to slightly vesicular, moderately weathered (W5), moderately hard (H4), intensely fractured (FD7) basalt. The RQD for the interval ranged from 0 to 21 percent. The Pomona Basalt from 343.2 to 401.4 feet (bottom of hole) consisted of black and gray, dense, slightly weathered (W3), hard (H3), intensely to moderately fractured (FD6) basalt. RQD values ranged from 0 to 40 percent, with a weighted average of 23 percent. For details of RQD refer to the log for drill hole DH-05-1 located in Appendix B. Geochemical analysis on samples from 313, 347, and 389 feet confirmed the rock was Pomona Basalt.

Drill hole DH-05-1 was completed with a slotted-pipe piezometer. The original design planned for the piezometer to be isolated in the confined Pomona Basalt aquifer (refer to Figure 3a). This would allow the piezometer to support hydrologic characterization tests during the drilling and testing of companion hole DH-06-1. Due to complications during piezometric installation, the completion did not effectively isolate the monitoring zone in the confined aquifer. The surrounding sand pack material extended through the sedimentary interbed (confining layer) and into the overlying fault zone breccia (unconfined aquifer). This piezometric completion provided hydraulic communication between the two aquifer systems.

Recompletion of the piezometer took place in November 2006 (refer to Figure 3b). The original piezometer (PVC pipe) was backfilled with cement grout, then the drill hole was reamed with a 5-7/8-inch rockbit to a depth of 320 feet. The hole was backfilled with cement grout from 320 to 298 feet to seal off the Pomona Basalt aquifer and the Rattlesnake Ridge Interbed. A new 2-inch PVC piezometer was set to a depth of 295 feet. A sand pack was placed around the piezometer to a depth of 270 feet, then the remainder of the annulus to the surface was backfilled with cement grout. This piezometer is now monitoring the unconfined aquifer in the fault zone breccia. Additional information about monitored water levels in DH-05-1 is described in the *Hydrogeology* section, under *Long-term Monitoring*.

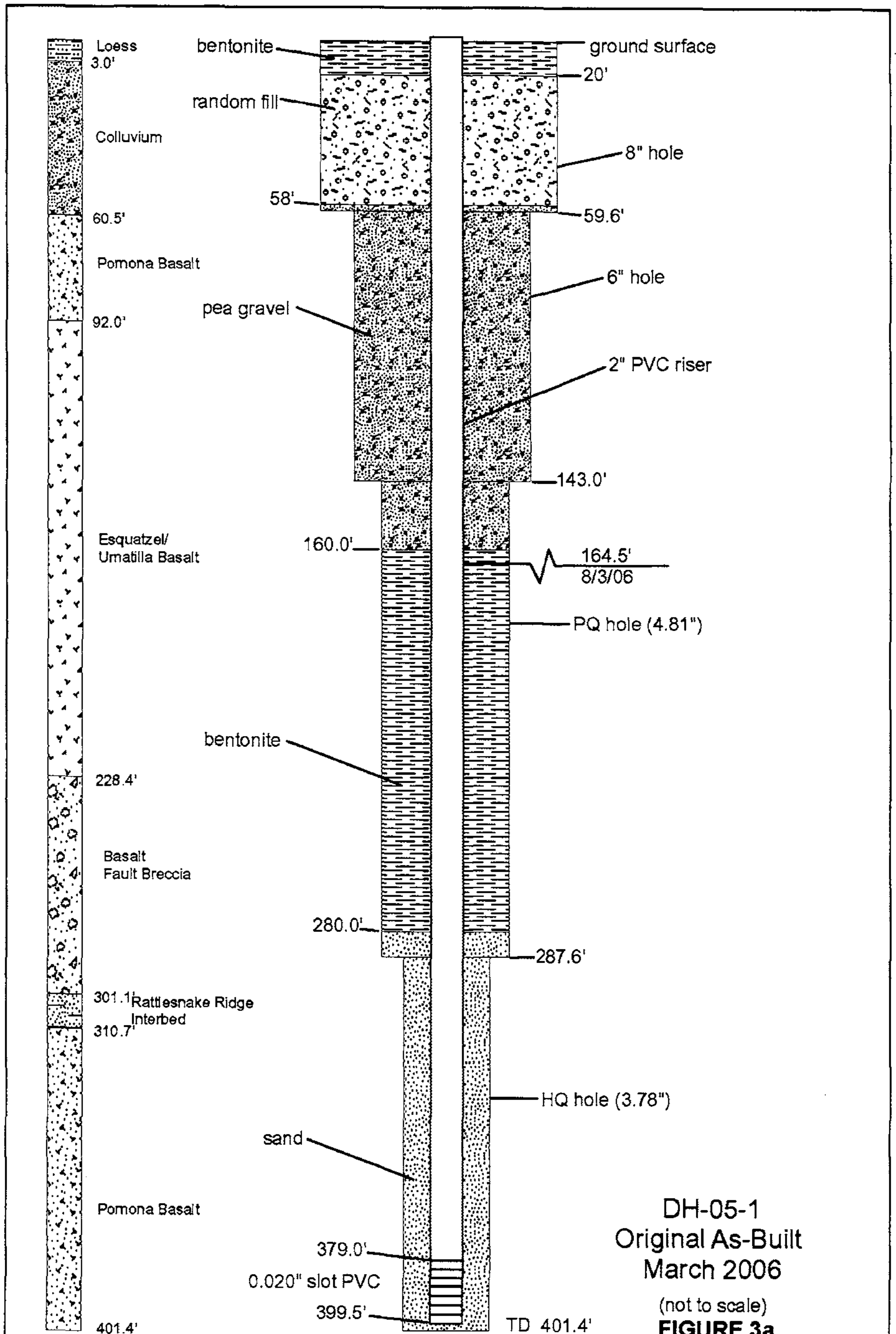


FIGURE 3a

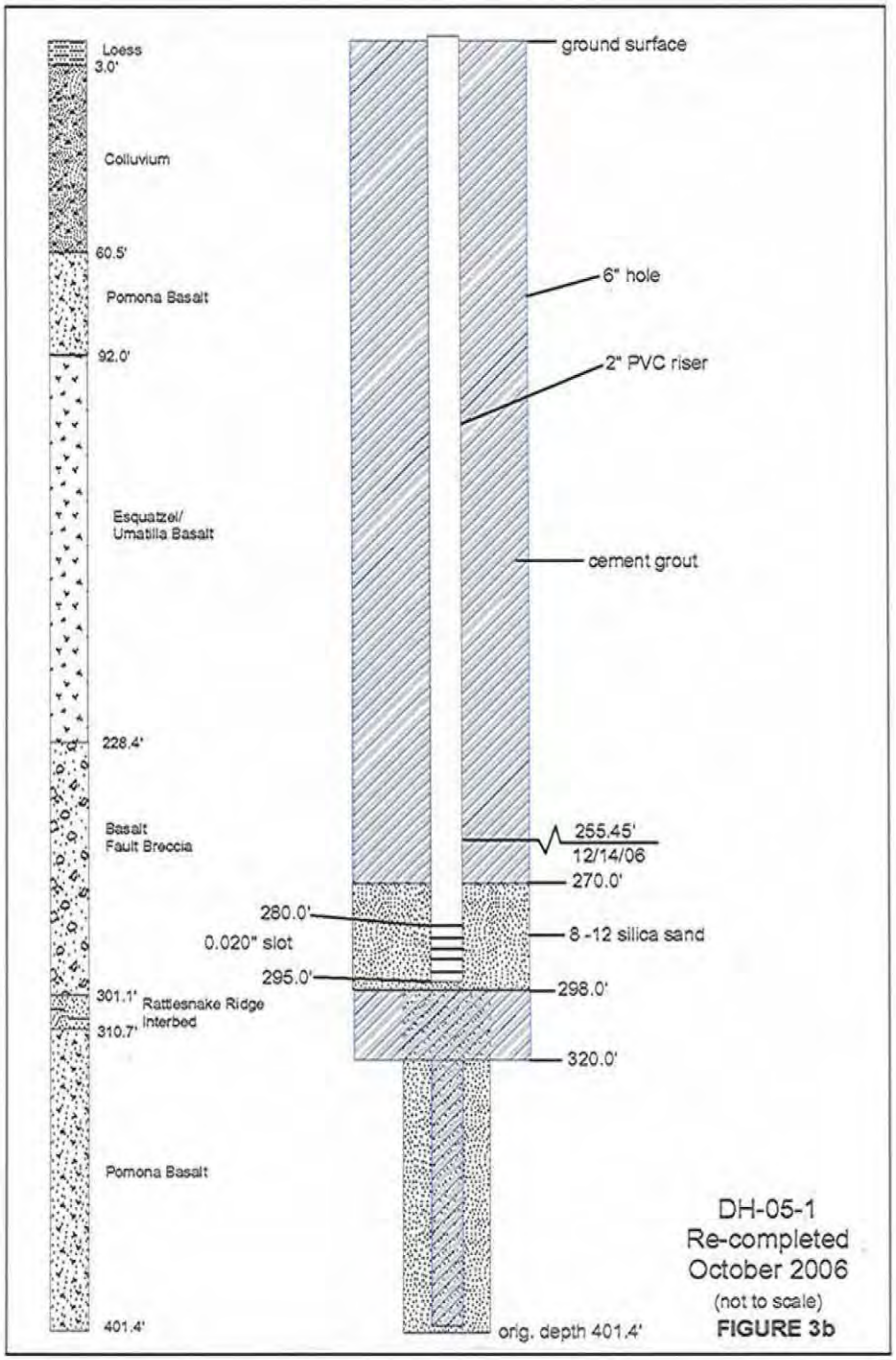

Loess
3.0'
Colluvium
60.5'
Pomona Basalt
92.0'
Esquatzel/
Umatilla Basalt
228.4'
Basalt
Fault Breccia
301.1' Rattlesnake Ridge
310.7' Interbed
Pomona Basalt
401.4'
ground surface
6" hole
2" PVC riser
cement grout
255.45'
12/14/06
270.0'
280.0'
0.020" slot
8 -12 silica sand
295.0'
298.0'
320.0'
orig. depth 401.4'
DH-05-1
Re-completed
October 2006
(not to scale)

FIGURE 3b

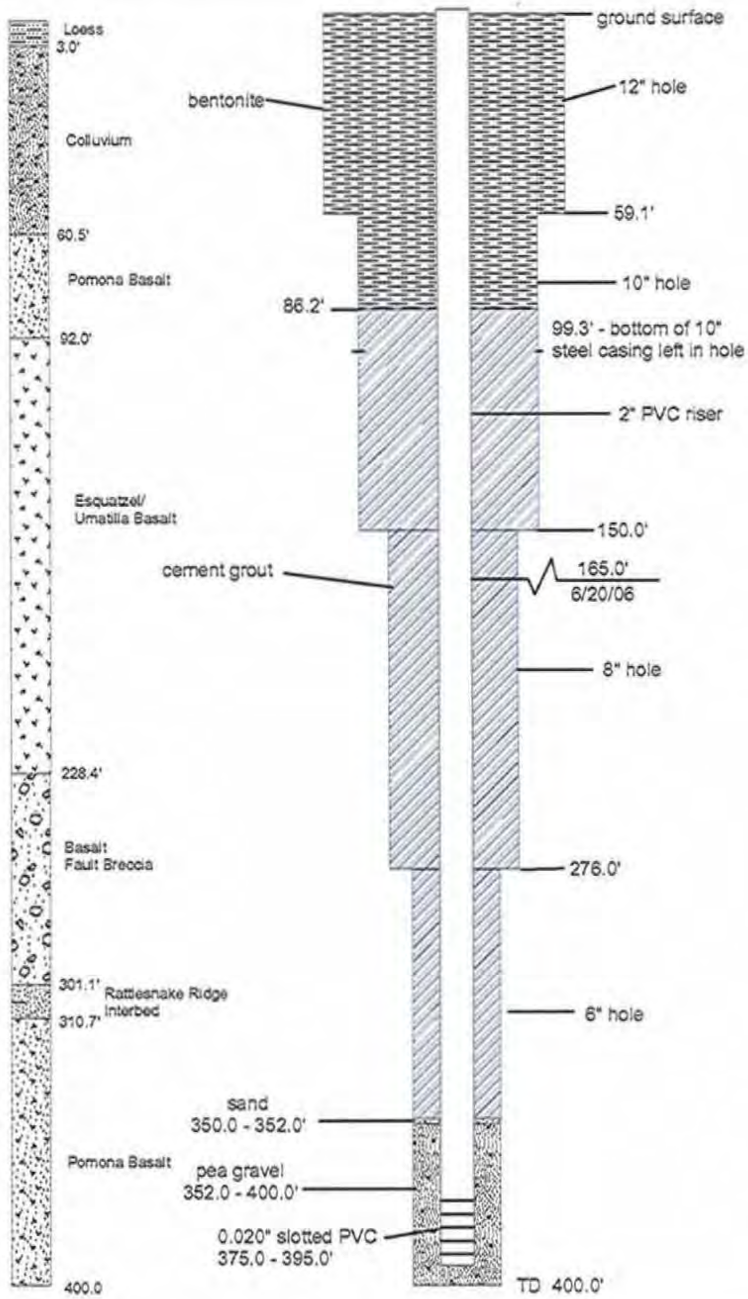
Drill Hole DH-06-1

Drill hole DH-06-1 was drilled with a rockbit and down-hole hammer, using air and foam to remove drill cuttings. The hole was located about 37 feet west of drill hole DH-05-1 and appeared to encounter the same stratigraphy and rock conditions as that hole. DH-06-1 was drilled to conduct hydrologic testing in specific zones that were chosen based on the drill core conditions and observed drill fluid losses in DH-05-1. Methods and results of the water tests are discussed in the *Hydrogeology* section of this report. Upon completion of water testing, a two-inch diameter PVC pipe piezometer was installed to monitor ground water and to perform borehole geophysical surveys (refer to Figure 4). A geologic log of the drill hole is included in Appendix B.

Hydrogeology

Hydrogeologic units are the aquifers and confining beds that compose the framework of the ground-water flow system. They are not always synonymous with the geologic unit divisions because in addition to stratigraphic position and composition, hydrogeologic units are defined by the material's hydraulic properties. Within basaltic formations, the primary water-bearing zones are generally limited to the flow tops (rubbly, vesicular areas) and interflow zones (contact zone between adjacent basaltic flows). The flow tops have relatively high lateral hydraulic conductivity, whereas the dense flow interiors have very low lateral conductivity but generally contain vertical cooling joints that could accommodate vertical ground-water movement. Vertical ground-water flow within the basalts is contingent on the connectivity of the fractures through the flows and the degree of infilling with secondary mineralization and clay. Other geologic conditions that could be conducive to vertical flow include basaltic flow margins and tectonic features. Where a basaltic flow thins or pinches out, sedimentary interbeds merge and are in hydraulic communication with each other.

Tectonic features (folds and faults) may impede ground-water flow or act as vertical flow pathways, depending on the physical characteristics of the feature. The degree to which these features affect ground-water flow depends on the age of the last movement on the fault, the size of the feature, severity of folding and fracturing of the rock, and the degree to which the fault zone has been altered and/or mineralized. Fault zone breccias are often highly altered (to clays) or exhibit secondary mineralization (silica, calcite, pyrite, zeolite) that cement the shattered rock and lower permeability. Yet younger, unaltered fault zones may provide preferential pathways for ground-water movement. Folding and faulting can affect ground-water conditions locally or on a regional scale.



DH-06-1
As-Built
May 2006
(not to scale)
FIGURE 4

Site Hydrogeology

The question of reservoir leakage is multi-faceted due to lateral and vertical variation in hydrogeologic units across the site and the role of tectonic features on ground-water flow conditions. There are three primary leakage mechanisms: 1) leakage via the unconsolidated sediments underlying the reservoir; 2) vertical downward leakage into underlying basalts; and 3) leakage around the dam through the abutments.

It was the intent of the Black Rock investigation program in 2004 to evaluate the leakage in the valley section of the reservoir and in 2006 to evaluate the south abutment conditions. The south abutment hydrogeology is significantly different from conditions in the valley. The basaltic units in the valley have a much shallower dip and are less fractured than basalts in the south abutment. In the valley, there is no unconfined aquifer system; the uppermost basaltic unit (Pomona Member of the Saddle Mountains Basalt) is unsaturated and has a low hydraulic conductivity, as indicated by hydrologic borehole tests (Didricksen, 2004). Below the Pomona, the Selah Interbed and flow top of the underlying Umatilla Basalt Member comprise a confined aquifer system. Testing in 2004 indicated vertical leakage through the Umatilla Basalt that hydraulically connects the Selah and Mabton interbeds (Didricksen, 2004).

The location of investigations on the lower right abutment of the proposed dam axis was chosen with the goal of encountering a mapped thrust fault at the base of Horsethief Mountain (Columbia Geotechnical Associates, 2004) and to characterize the basaltic rock in and around the fault zone. This location is important as it may represent a "worst case scenario" for both the condition of the foundation materials and for hydrologic leakage. A drilling and borehole testing program was initiated in December 2005 and continued until May 2006.

The original intent was to drill a single hole that would serve to obtain representative core samples and to conduct hydrologic tests to estimate permeability of the geologic units. The first hole, designated drill hole DH-05-1, was started using clear water as the circulating drill fluid and several permeability tests were run in the upper basalt, to a depth of 151 feet, all of which were in the unsaturated zone. In order to improve recovery of core samples and improve fluid return, the circulating fluid was switched to a polymer drill mud and occasional use of a drill fluid additive (Diamond Seal). The core recovery improved, even though the rock quality remained poor, and the drillers were able to maintain a relatively high percentage of fluid return through the remainder of the hole. However, several zones had complete loss of fluid, even with the addition of additives to the polymer drill mud. The use of the drill mud and sealant prevents an accurate measurement of ground-water level during drilling and may negatively affect the hydrologic test results. A companion borehole, designated drill hole DH-06-1, was drilled to collect representative water test data.

At the lower right abutment, an unconfined aquifer was encountered in the fault zone breccia in the Lower Umatilla Basalt. The static water level was about 268 feet below ground surface (elevation 1,008 MSL). The Rattlesnake Ridge sedimentary interbed underlies the fault zone breccia and is the confining layer that separates the unconfined aquifer from the underlying confined aquifer in the Pomona Basalt. The confined aquifer has a potentiometric level at about 166 feet below ground surface (elevation 1,110 MSL). Hydrologic tests were conducted at selected depths to characterize the hydraulic and storage properties. In addition, the hydrochemistry and hydraulic head relationship between the aquifers were monitored at the test location.

As discussed in the following narrative, the initial piezometric installation in DH-05-1 failed to isolate the riser within the Pomona Basalt confined aquifer (refer to Figure 3a). The piezometer was subsequently reinstalled in November 2006 in the unconfined aquifer in the fault zone breccia (refer to Figure 3b). Hydrologic tests conducted during drilling of DH-06-1 in May 2006 were impacted by the composite completion of nearby DH-05-1 and were partially re-run after the reinstallation in November 2006. The piezometer that was installed at the conclusion of drilling DH-06-1 monitors the confined aquifer of the Pomona Basalt (refer to Figure 4).

The field test data were analyzed by various methods to determine hydraulic and storage properties. Dr. Frank Spane, Pacific Northwest National Laboratory, was hired under an interagency agreement to provide analysis of the hydrologic data and his 2007 report is included in Appendix A. Long-term water level monitoring continues at the site and those data have also been reviewed and analyzed in Dr. Spane's report (Spane, 2007).

The hydraulic and storage properties of an aquifer determine the potential transmission of reservoir seepage through the ground-water system. A ground-water flow model has recently been developed by Reclamation (Schmidt and others, 2007) to estimate the length of time required to fill the reservoir with the available water supply, the amount and distribution of potential reservoir leakage, and to estimate the impacts that leakage could have on adjacent ground-water conditions at the Hanford Site. Model input included hydraulic property values obtained from the borehole field testing that is documented in this report

Hydrologic Borehole Testing – Intervals Tested and Methods Used

The primary technique to determine hydraulic conductivity is to perform a series of hydrologic borehole tests in which a stress is applied and the response data are compared to theoretical models of test responses.

Tests were conducted at selected intervals in the vadose (unsaturated) zone and the saturated zones of each well. The tests were conducted as the drill holes were advanced ("drill and test" procedure). Table 1 lists information about the tests conducted in DH-05-1 and Table 2 lists the tests conducted in DH-06-1.

Table 1 – Hydrologic tests in drill hole DH-05-1.

Type of Test	Depth of Test Interval (ft)	Geologic Unit	Hydrologic Zone	Date of Test
Constant-head injection	65.6–70.6	Pomona Basalt	Vadose zone	12/6/2005
Constant-head injection	73.6-77.8	Pomona Basalt	Vadose zone	12/7/2005
Constant-head injection	93-98	Esquatzel/Umatilla Basalt	Vadose zone	12/17/2005
Constant-head injection	113-119	Esquatzel/Umatilla Basalt	Vadose zone	12/17/2005
Constant-head injection	123-129	Esquatzel/Umatilla Basalt	Vadose zone	12/19/2005
Constant-head injection	133-151	Esquatzel/Umatilla Basalt	Vadose zone	12/19/2005
Constant-rate injection	269.2-287.4	Fault Zone Breccia	Unconfined aquifer	2/15/2006
Constant-rate injection	287.6-334.6	Pomona Basalt/Fault Zone Breccia Composite	Composite aquifers	2/21/2006
Pneumatic slug	379-399.5	Pomona Basalt	Confined aquifer	5/25/2006
Constant-head injection	280-295	Fault Zone Breccia	Unconfined aquifer	10/9/2006
Pneumatic slug	280-295	Fault Zone Breccia	Unconfined aquifer	10/25/06

Table 2 – Hydrologic tests in drill hole DH-06-1.

Type of Test	Depth of Test Interval (ft)	Geologic Unit	Hydrologic Zone	Date of Test
Constant-head injection, H = 166.56 ft	150-162.8	Esquatzel/Umatilla Basalt	Vadose zone	4/6/2006
Constant-head injection, H = 261.5 ft	150-162.8	Esquatzel/Umatilla Basalt	Vadose zone	4/7/2006
Constant-head injection, H = 149.25 ft	236-255.1	Fault Zone Breccia	Vadose zone	4/10/2006
Constant-head injection, H = 265.26 ft	236-255.1	Fault Zone Breccia	Vadose zone	4/11/2006
Constant-head injection, H = 270.4 ft	276-296	Fault Zone Breccia	Unconfined aquifer	4/19/2006
Constant-head injection, H = 435.31 ft	276-296	Fault Zone Breccia	Unconfined aquifer	4/20/2006
Step-drawdown pump test	311.8-400	Pomona Basalt	Confined aquifer	5/6 - 7/2006
Pneumatic slug tests	375-395	Pomona Basalt	Confined aquifer	5/25/2006
Pneumatic slug tests	375-395	Pomona Basalt	Confined aquifer	10/25/2006

Vadose Zone Testing

Methods

Constant-head injection tests were conducted in the unsaturated zone to estimate *in situ* saturated hydraulic conductivity. Performance of the tests generally followed procedures outlined in Reclamation's *Ground Water Manual* (Bureau of Reclamation, 1995). The steps were as follows:

1. Drill the borehole to a prescribed depth below the casing.

2. Remove the drilling tool assembly to provide an open borehole section.

3. Place a pressure transducer near the bottom of the borehole to monitor pressure response.

4. Rapidly fill the borehole/casing to the prescribed level (usually near the top of the casing).

5. Maintain a uniform level within the borehole and monitor the injection rates during the entire injection period.

6. Continue test until relatively uniform injection rates are established (i.e., pseudo-steady state conditions). Normally, constant-head injection testing was completed within two hours.

7. End injection and monitor pressure response during recovery of water level to pre-test condition.

Saturated Zone Testing

Methods

The fractured rock of the abutment site often precluded use of an inflatable packer to isolate the test zone. Instead, the bottom of the casing was grouted into the top of the test section to prevent the injected water from flowing around the outside of the casing. After the grout was allowed to cure, it was drilled through and the hole was advanced another 10 to 20 feet to open a test interval. The grout seal had to be competent enough to seal the casing during testing but not so strong that it could not be broken after the interval was tested so that the hole and casing could be advanced into deeper intervals. At times, the grout seal appeared to be competent but then failed during drilling of the open interval below the casing, which prevented isolation and testing of that zone.

Three test methods were used in the saturated zone: injection tests (constant rate and constant head); pneumatic slug tests; and pumping tests (variable rate step-drawdown and constant rate testing). The constant-head injection tests were conducted using the same methods as discussed for vadose zone testing. During testing of drill hole DH-06-1, however, some of the constant-head tests were conducted at two different stress levels to determine if the test results showed a dependence on the applied stress level. The first phase of the test maintained a constant head at the top of the open well casing (near ground level). The second phase of testing was conducted with a capped-well casing. A pressure gauge at the top of the casing monitored the pressure head that built up as water was injected. Constant-rate tests are similar except that the rate of injection is maintained constant while head changes are monitored with a transducer until they reach a quasi-steady-state level. After water injection ends, the water level is monitored during recovery to pretest levels.

Pneumatic slug tests were conducted at both drill holes after they were completed with 2-inch-diameter PVC piezometers (in May 2006 and repeated in November 2006 after recompletion of DH-05-1). The tests were conducted by introducing compressed air to the sealed wellhead to depress the water column to a prescribed level, maintaining that level for about 10 minutes, followed by a rapid release of the air pressure. The pressure response of the aquifer was monitored with a down-hole transducer. Slug tests are relatively rapid and easy to conduct so several tests, with varied applied pressures, were conducted.

A step-drawdown test and constant-rate pumping test were also conducted at DH-06-1 in the confined aquifer, following completion of drilling in the Pomona Basalt. A step-drawdown test was conducted prior to the constant-rate test to assess well performance and determine the optimal pumping rate for the constant-rate test. The test consisted of three pumping steps (rates of discharge) at 15.7 gallons per minute (gal/min), 31.2 gal/min, and 46.3 gal/min. Each of the first two discharge rates was maintained for about 95 minutes and the final step was extended and held at a constant rate for 912 minutes. The water level drawdown at the end of the test was about 9.9 feet.

Hydrologic Borehole Testing – Results

The analysis methods used to determine transmissivity (T), hydraulic conductivity (K), and storativity (S) are detailed by Dr. Spane in his June 2007 letter report to Reclamation that is included in Appendix A. Table 3, in this report, lists the best estimate value of K and S determined from the field testing.

Hydraulic conductivity values ranged from 0.42 to 3.77 ft/day in the fault breccia zone, 0.32 to 52.9 ft/day in the Pomona Basalt and 0.45 to 20.7 ft/day in the Umatilla Basalt. These values were similar to K values reported from the Hanford Site and to other reported values for Saddle Mountains Basalt intervals (Spane, 2007). It is important to remember the heterogeneity displayed in the basaltic flows. The range of K values listed in Table 3 demonstrates the variation of hydraulic properties that can exist within a single hydrogeologic unit. In addition, these values vary regionally as well, where the unit may have had a different amount of tectonic disturbance or conditions during basaltic emplacement.

Hydraulic Head Information

The original piezometric installation in DH-05-1 was intended to isolate the Pomona Basalt below the Rattlesnake Ridge Interbed and monitor the confined aquifer. Problems during the field installation resulted in a composite completion that combined the unconfined aquifer in the lower fault zone breccia with the interbed confining layer and the Pomona Basalt confined aquifer. This occurred because the sand pack that filled the annulus around the PVC riser pipe was installed too high and allowed hydraulic connection through this vertical pathway. The piezometer was recompleted in November 2006 and the isolated zone is now within the unconfined aquifer in the fault zone breccia. Figures 3a and 3b show the as-built completions before and after recompletion of the piezometer.

Transducers were installed in each of the boreholes after piezometric installation to monitor long-term water levels to detect seasonal variation or other stresses that affect site hydrologic conditions. After piezometer recompletion in DH-05-1, the water level was higher than expected for the unconfined aquifer and trended higher for about five months. However, in March 2007 the water level suddenly began a steep descent and is now leveling off near the expected static water elevation of the unconfined aquifer (refer to Figure 5).

The confined aquifer currently has a potentiometric surface elevation of about 1,109 ft MSL, which is about 100 feet higher than the water level of the unconfined aquifer (refer to Figure 5). The water level has been trending downwards. This trend may be due to seasonal variation or perhaps to other stresses. Future monitoring will continue and may help to explain the observed trends.

Table 3 - Best estimate of hydraulic conductivity and storativity values determined from borehole field tests (modified from Spane, 2007).

Test/Depth Interval (ft bgs)	Best Estimate Value		Basis/Comments
	Hydraulic Conductivity, $K_{h,}$[(a)] (ft/day)	Storativity (S)	
65.6 - 70.6 Upper Pomona Basalt	0.46	NA	DH-05-01 vadose zone test interval result
73.6 - 77.8 Upper Pomona Basalt	1.39	NA	DH-05-01 vadose zone test interval result
93 - 98 Umatilla Basalt	2.07	NA	DH-05-01 average vadose zone test interval result
113 - 119 Umatilla Basalt	5.43	NA	DH-05-01 average vadose zone test interval result
123 - 129 Umatilla Basalt	5.64	NA	DH-05-01 average vadose zone test interval result
133 - 150 Umatilla Basalt	0.45	NA	DH-05-01 adapted vadose zone test interval result
150 - 162.8 Umatilla Basalt	1.94	NA	DH-06-01 average vadose zone test interval result
236 - 255.1 Fault Zone Breccia	3.77	NA	DH-06-01 average vadose zone test interval result
269.2 - 276* Fault Zone Breccia	1.28*	4.5E-4	*Based on extension of de-superposition principle for overlapping test intervals from DH-05-01 and DH-06-01
276 - 296 Fault Zone Breccia	0.42	NA	Based on identical injection test results for DH-06-01 test interval

311.8 - 334.6 Pomona Basalt	0.32	4.0E-4	DH-05-01 average of test method results for test interval 319 - 334.6 ft extended to test interval 311.8 - 334.6 ft
334.6 - 375** Pomona Basalt	14.6	5.0E-5	**Based on desuperposition principle for encompassed test intervals from DH-05-01 and DH-06-01
375 - 395 Pomona Basalt	52.9	NA	DH-05-01 piezometer slug test results

(a) Assumed to be uniform within the test/depth interval.

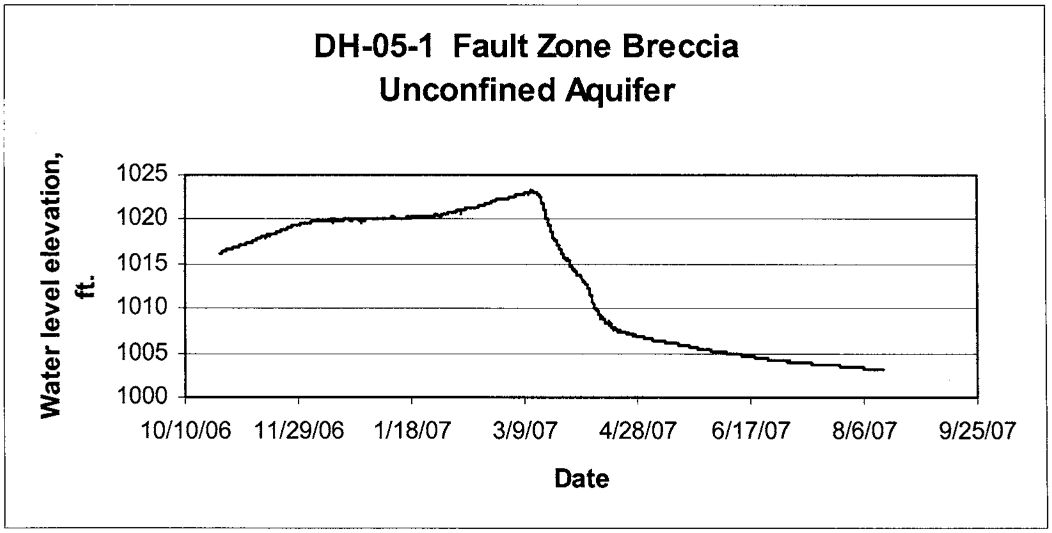
* See notes in Spane, 2007 letter report, Appendix A.

** See notes in Spane, 2007 letter report, Appendix A.

Hydrochemistry

Water samples were collected from DH-06-1 during each discharge step during the step-drawdown pumping test in the Pomona confined aquifer on May 6 and 7, 2006, see Table 4. The hydrochemistry remained constant throughout the pumping test. Water chemistry from the water supply well where the drill fluid and test injection water originated (open to the Wanapum Basalt Formation) was sampled on May 7, 2006 and the results are also listed in Table 4.

Concentrations of the major inorganic constituents in the confined aquifer at DH-06-01 are nearly identical to those sampled in 2004 at DH-04-2, completed in the uppermost basalt confined aquifer (Selah/Umatilla). In addition, the hydrochemistry from these two sites at Black Rock are very similar to major inorganic concentrations from the upper Saddle Mountains confined aquifer on the Hanford Site (Spane, 2007).



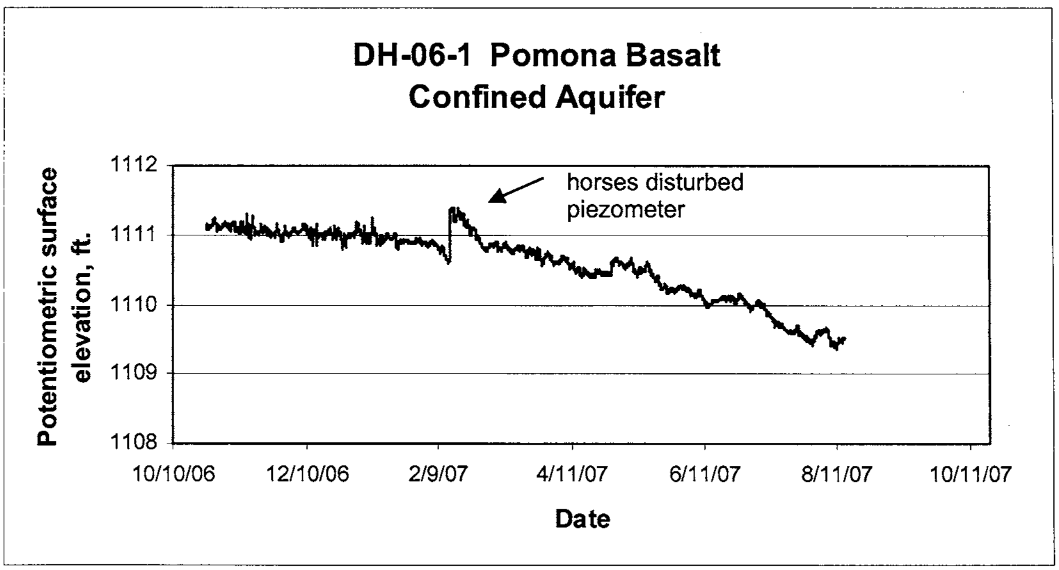


Figure 5. Hydrographs of drill hole DH-05-1 unconfined aquifer and drill hole DH-06-1 confined aquifer.

Table 4 - Physical properties and concentrations of dissolved constituents in drill hole DH-06-1 ground water.

Sample Date (Time, PST)	Hydrogeologic Unit	Physical Properties					Major Anions					Major Cations			
		Temp. C	Field pH SU	Specific conduc-tance uS/cm	Dissolved oxygen % saturated	Alkalinity mg/L as CaCO3 field/lab	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L	NO_3/ NO_2 mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L
5/6/06 (1107 hours)	Pomona Basalt Step 1 of step-drawdown test	-	-	-	-	--/116	142	16.9	3.7	ND	ND	12.5	4	23.6	11.5
5/6/06 (1240 hours)	Pomona Basalt Step 2 of step-drawdown test	16.9	8.4	282.9	35.7	113.1/116	142	16.6	3.7	ND	ND	12.5	4	24.2	11.4
5/6/06 (2007 hours)	Pomona Basalt Step 3 of step-drawdown test	-	-	-	-	117.9/116	142	16.4	3.7	ND	ND	12.6	4	24	11.4
5/6/06 (2030 hours)	Pomona Basalt Step 3 of step-drawdown test	15.4	8.14	288	-	--/117	143	16.5	3.7	ND	ND	12.5	4	24	11.4
5/7/06 (0358 hours)	Pomona Basalt end of pumping test	13.5	8.38	288.9	38.2	-	-	-	-	-	-	-	-	-	-
5/7/06 (1230 hours)	Wanapum Basalt (drill and test injection water)	24.1	8.13	285.5	27.1	--/144	175	<0.5	3	ND	ND	20	7	18	11.5

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Appendix A

Letter Report from Dr. Frank Spane

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Date July 10, 2007

To Kayti Didricksen

From Frank Spane

Subject The Black Rock Reservoir Study—Results of the Borehole Hydrologic Field Testing Characterization Program: At the Potential Damsite Southern Abutment Location

The following report provides the results for hydrologic characterization tests conducted primarily between December 2005 and June 2006 at corehole DH-05-01 and borehole DH-06-01. Additionally, hydrologic test results are also reported that were performed in December 2006 following re-completion of DH-05-01 as a piezometer within the overlying fault breccia zone. These two test boreholes are situated within the proposed damsite southern abutment location. For ease in referencing specific characterization elements of the testing program within the report, the following outline is provided:

REPORT OUTLINE

1. Executive Summary

To assess the hydrologic impact of the potential Black Rock Reservoir on local and surrounding areas, detailed hydrogeologic characterization of geologic units was conducted in the vicinity of the proposed damsite location during fiscal year (FY) and calendar year (CY) 2006. This investigation is a continuation of an earlier hydrogeologic assessment conducted during FY 2004 (Spane 2004) and presented in Didricksen (2004) that focused on hydrogeologic characterization of geologic units at a test site that would underlie the area of the proposed reservoir. Relevant hydrogeologic parameters for assessing the impact of the proposed reservoir project include 1) hydraulic and storage properties of vadose zone and aquifer systems, 2) vertical leakage between hydrogeologic units, and 3) hydrologic barriers (e.g., faults) to groundwater flow. Of particular importance is the potential leakage of surface water stored within the reservoir, which may alter existing local groundwater systems and adversely impact adjacent surface and groundwater-basin hydrologic conditions (e.g., Hanford Site). To assess the potential for leakage and impact on existing, underlying groundwater-flow systems, a borehole field-testing program has been designed by the U.S. Bureau of Reclamation to acquire detailed hydrogeologic characterization information pertaining to selected hydrogeologic units underlying and adjacent to the proposed reservoir location. This letter report presents the results for the second of a series of test boreholes that are planned as part of the detailed borehole field characterization program. The results relate to conditions obtained specifically at test borehole DH-06-01 and adjacent corehole DH-05-01, which are situated within the proposed damsite southern abutment location.

The active borehole field-testing program was conducted at corehole DH-05-01 and borehole DH-06-01 between December 2005 and May 2006. Corehole DH-05-01 was initially designed for completion as a piezometer to monitor hydrologic responses within the Pomona basalt confined aquifer and to support hydrologic characterization tests initiated during the drilling/testing at adjacent borehole DH-06-01 (located 38.4 ft from DH-05-01). Due to complications that occurred during the installation of the piezometer at DH-05-01, the well was not successfully completed to effectively isolate or restrict the piezometer monitoring zone to the underlying Pomona basalt confined-aquifer system. This initial piezometer completion (due to a misplaced sandpack installation within the borehole) provided a composite monitoring of the Pomona basalt confined aquifer and the overlying unconfined aquifer located within a thick basalt fault-zone breccia. These two aquifers are separated locally by the intervening low-permeability Rattlesnake Ridge interbed, which serves as a confining layer between the two aquifer systems. Because of the hydraulic communication afforded by the composite piezometer completion, DH-05-01 was subsequently re-completed on October 7, 2006, in the overlying unconfined aquifer within the fault-zone breccia above the Rattlesnake Ridge interbed confining layer.

Following hydrologic test characterizations conducted at borehole DH-06-01, the borehole was completed as a piezometer to provide long-term baseline monitoring of natural dynamic responses within the lower Pomona basalt confined-aquifer system at this location. With the re-completion of DH-05-01, the two monitoring-well facilities provide an opportunity to directly compare long-term baseline hydrologic responses exhibited within the two individual aquifers. Theoretically, the baseline response comparisons can be used to evaluate large-scale hydraulic communication between the two aquifer systems within the surrounding area. However, as discussed in this report, a comparison of baseline responses at the re-completed DH-05-01 and monitoring well DH-06-01 suggests that the re-completion of DH-05-01 was not completely effective in isolating the two aquifers with the new piezometer installation.

The principal characterization objectives for the test boreholes were to provide basic site-specific characterization information along the southern abutment location concerning the hydraulic/storage properties, hydrochemistry, and hydraulic head relationships of selected hydrogeologic units at this test location. Additionally, the assessment of the vertical communication/leakage between hydrogeologic units was to be evaluated, theoretically, by examining hydrologic responses at piezometer DH-05-01 during drilling and testing of borehole DH-06-01. The detailed field-testing program consisted of two sequential test phases that focused on different hydrologic characterization elements for hydrogeologic units beneath and in proximity to the proposed reservoir location. Phase 1 included determining the saturated hydraulic conductivity of selected vadose-zone (unsaturated zone) test intervals (i.e., above ~268 ft bgs; ~1,008-ft MSL). In total, eight vadose zone test/depth intervals were characterized ranging from depths of 66 to 255 ft bgs. Results from Phase 1 characterization activities indicated that, in total, the formations tested exhibited relatively low to moderately high hydraulic conductivities (0.45 to 20.7 ft/day), which generally fall within the range of values reported for these hydrogeologic units at the nearby Hanford Site.

Phase 2 of the borehole field-testing program included detailed characterization of the two-aquifer system present at the site: the unconfined aquifer within the fault zone breccia and the underlying confined-aquifer system within the underlying Pomona basalt. Because of borehole stability issues, the Rattlesnake Ridge interbed, which is believed to represent the principal confining layer separating the two aquifer systems, was not tested separately. Composite open borehole tests that included the Rattlesnake Ridge interbed at corehole DH-05-01, however, indicate a collectively low-permeability condition both for the interbed and for basalt and fault-zone sections immediately below and above the interbed, respectively. Detailed hydrologic characterization of the various test intervals utilized a suite of hydrologic test methods, including slug/slug interference, step-drawdown, constant-rate pumping, constant- pressure injection, and hydrochemical sampling. Salient findings and pertinent characterization information resulting from the Phase 2 testing and preliminary baseline monitoring results are provided below under summary categories of: site hydrogeology, hydraulic/storage properties, leakage characteristics and hydrologic boundaries, and hydrochemistry.

Site Hydrogeology

1) The following stratigraphic units were identified at the site, based on detailed core analysis provided by corehole DH-05-01:

a.	Quaternary loess deposits:	0 – 3.0 ft
b.	Quaternary colluvium:	3.0 – 60.5 ft
c.	Pomona basalt (Saddle Mountains Formation)	60.5 – 92.0 ft
d.	Undifferentiated Esquatzel/ Umatilla basalts:	92.0 – 228.4 ft
e.	Basalt fault zone breccia:	228.4 – 301.1 ft

f. Rattlesnake Ridge interbed: (Ellensburg Formation) 301.1 – 310.7 ft
g. Pomona basalt: (Saddle Mountains Formation) 310.7 > 400.0 ft

2) Two hydrogeologic features are of significance at the DH-05-01/DH-06-01 test site location:

- the Horse Thief Mountain thrust fault, which is embedded within and responsible for the fault zone breccia (depth: 228.4 to 301.1 ft)

- the Rattlesnake Ridge interbed, which serves as the primary confining layer separating an unconfined aquifer from the underlying Pomona basalt confined-aquifer system. The interbed may also have served as the thrust plane for faulting at this site.

3) The unconfined aquifer occurs within a relatively thick basalt fault-zone breccia that is situated directly above the Rattlesnake Ridge interbed. The unconfined aquifer conditions are supported by diagnostic derivative analysis plots, barometric response characteristics, and the relatively large head difference exhibited (~102 ft) in comparison to the underlying confined aquifer system. The hydraulic head conditions within the unconfined and underlying confined-aquifer systems during the active testing phase were approximately 1,008 and 1,110-ft MSL, respectively.

Hydraulic/Storage Properties

4) In total, six vadose zone test/depth intervals at corehole DH-05-1 and two vadose test intervals at borehole DH-06-1 were characterized between test depths of 65 and 255 ft bgs. The vadose zones tested exhibited relatively low to moderately high saturated hydraulic conductivities ranging between 0.45 to 20.7 ft/day. Saturated hydraulic conductivity ranges for specific hydrogeologic units determined for the test site include:

- Pomona basalt: 0.46 to 1.39 ft/day (two zones tested)
- undifferentiated Esquatzel/Umatilla basalt: 0.45 to 20.7 ft/day (five zones tested)
- basalt fault zone breccia: 3.77 ft/day (one zone tested).

Note: No vadose zone tests were conducted within the surficial sediments located above the basalt bedrock at this test site.

5) The range of saturated hydraulic conductivity for the basalt **vadose** zones at the test site location (0.45 to 20.7 ft/day) falls within the middle range reported for basalts within the Saddle Mountains Formation at the nearby Hanford Site/Pasco Basin (10^{-2} to 10^{3} ft/day), and the calculated geometric mean value of 2.31 ft/day for the seven basalt test intervals closely matches the median value of 2.4 ft/day reported regionally for this basalt formation, as presented in Reidel et al. (2002). Due to lack of comparative test information, it is not

known how the saturated-hydraulic-conductivity value for the basalt fault-zone breccia at the test site compares with other similar basalt tectonic features within the surrounding region. The vadose-zone test value for this tectonic feature (i.e., 3.77 ft/day), however, is similar to that expected for basalt flow tops/interflow zones and is only slightly higher than the geometric mean value of 2.31 ft/day determined for other basalt vadose-zone test intervals characterized at the site.

6) Hydrologic test characterization efforts for selected **groundwater** test zones at the site were hampered by a number of factors including:

   - the composite aquifer well completion at piezometer DH-05-1
   - lack of sealing integrity between well-casing strings and failure of cement seals during testing
   - short duration of some of the tests conducted.

7) In spite of these test complications, the groundwater hydraulic characterization test results at DH-05-1 and DH-06-1 provided a range of saturated hydraulic conductivity values for the basalt fault-zone breccia (K = 0.42 to 1.18 ft/day) that was lower than that determined for the more shallow, overlying vadose-zone test within this tectonic feature (i.e., 3.77 ft/day). The test/depth trend for hydraulic conductivity values for this tectonic feature suggests a decreasing value trend with depth at this test-site location.

8) The K estimates obtained for the Pomona basalt at DH-05-01/DH-06-01 serve as a basis for local and regional comparisons with previously reported Black Rock Reservoir test site results (Spane 2004) and values reported at the nearby Hanford Site, respectively. At the initial Black Rock test site (DH-04-01/DH-04-02), the Pomona basalt test intervals exhibited relatively low K characteristics (0.04 ft/day), while at the DH-05-01 and DH-06-01 test site, K values were over one to two orders-of magnitude higher, ranging between 0.32 to 52.9 ft/day. While the K estimates for the basalts at the DH-05-01/DH-06-01 test location fall within the range reported at the Hanford Site for similar Saddle Mountain basalt flow tops and interflow zones, the possibility of enhanced basalt permeability by past tectonic activity (i.e., ancillary fracturing associated with the local thrust fault) at the damsite abutment location is a possible explanation for the higher K values at this location. Additionally, it is interesting to note that K values for Pomona basalt test intervals were generally higher below the fault-zone breccia, within the footwall of the thrust-fault block, which geologically may be an area of more constrained stress/strain/fracturing within the basalts.

9) It is also interesting to note that analysis results obtained from testing a similar test/depth interval at DH-05-01 (269.2 to 287.4 ft) and DH-06-01 (276 to 296 ft) produced very similar K estimates for the overlapping test intervals (i.e., 0.73 vs. 0.42 ft/day). This is particularly relevant since the boreholes were drilled using different circulation drilling fluids (i.e., polymer drilling mud with sealant versus compressed air, water, and foam) and suggests a lack of a significant bias in K-estimate characterization due to drilling fluid effects for these two test examples.

Leakage Characteristics and Hydrologic Boundaries

Because of the test and completion complexities noted previously, detection of formational leakage and hydrologic boundaries was greatly limited. However, several observations can be noted:

10) No lateral hydrologic boundaries were noted for tests conducted solely within the unconfined aquifer. Because of the relative short duration of the tests and unconfined aquifer characteristics, the radius of investigation for boundary detection was ≤ 50 ft.

11) No cross-formational response due to leakage was detected at piezometer DH-05-1 during vadose-zone testing at nearby borehole DH-06-1.

12) Multi-well interference tests conducted in the confined aquifer within the Pomona basalt exhibited leakage effects; the exhibited leakage effects, however, are likely non-formational and attributable to the well-completion conditions imposed at piezometer DH-05-1.

Hydrochemistry

Groundwater samples collected from the Pomona basalt confined aquifer at DH-06-01 indicate nearly identical hydrochemical characteristics as displayed by groundwaters within the uppermost confined aquifer system at nearby test borehole DH-04-02. A comparative analysis of hydrochemical content suggests that the confined groundwaters at DH-06-01 and DH-04-02 are relatively youthful in character and do not display an evolved reactionary development. The hydrochemical and assumed isotopic content for this uppermost groundwater-flow system may be sufficiently different and distinguishable from Columbia River water. This difference may allow identification of reservoir-water leakage and it may be used to determine the vertical and lateral extent of reservoir recharge to the underlying groundwater system.

2. Background

The characterization of test boreholes DH-05-01 and DH-06-01 was designed to provide detailed hydrogeologic information along the proposed Black Rock dam southern abutment location. The site is located approximately 1 mile southeast of previous hydrogeologic studies conducted at test boreholes DH-04-01 and DH-04-02 (Figure 2.1). Results from the earlier field testing program are reported in Spane (2004) and also presented in Didricksen (2004). Detailed characterization activities conducted at test boreholes DH-05-01 and DH-06-01 include core analysis/description, borehole geophysics, hydraulic testing, and hydrochemical analysis. This report presents the detailed results obtained from the hydraulic field-testing characterization program and includes the preliminary hydrochemical analysis results obtained from groundwater samples collected at DH-06-01.

The major field testing program was conducted at DH-05-01 and DH-06-01 between December 2005 and May 2006 during the active borehole drilling phase. Additional hydrologic testing was performed following piezometer installation at each of the test boreholes. Corehole DH-05-01 was originally designed for completion as a piezometer to monitor hydrologic responses for the confined aquifer within the Pomona basalt and to support hydrologic characterization tests initiated during the drilling/testing at adjacent borehole DH-06-01 (located 38.4 ft from DH-05-01). This piezometer installation was completed on March 8, 2006. Due to complications that occurred during the completion process, the piezometer within DH-05-01 was not successfully installed to effectively isolate or restrict the piezometer monitoring zone to the underlying Pomona basalt confined aquifer. This lack of isolation was due to the misplacement of the sandpack across the confining layer (i.e., Rattlesnake Ridge interbed) providing hydraulic communication with the overlying unconfined aquifer system (Figure 2.2). This hydraulic communication between the two aquifer systems within DH-05-01 adversely impacted large-scale hydrologic testing activities at DH-06-01 when the borehole was advanced and testing was initiated within the underlying Pomona basalt (Section 6.2.2).

Because of the hydraulic communication afforded by the composite piezometer completion, DH-05-01 was re-completed on October 7, 2006, within the overlying unconfined aquifer in the fault-zone breccia above the Rattlesnake Ridge interbed confining layer (Figures 2.3 and 2.5). Difficulties in cementing the higher hydraulic head, upper Pomona basalt section within the borehole, however, occurred during the re-completion activities. The initial cement/grout slurry that was placed within the borehole migrated into the surrounding Pomona basalt and/or into the overlying fault zone breccia. Subsequent cementing activities appeared (at the time) to be successful, and the piezometer was re-completed within the fault-zone breccia with the well-screen placed at 280 to 295 ft. Hydrologic tests conducted within the DH-05-01 re-completed piezometer indicate that the piezometer test interval has lower-than-expected hydraulic property characteristics when compared to previously tested, over-lapping, test intervals conducted at DH-05-01 and DH-06-01 (Section 5.2.4). These lower hydraulic-property characteristics suggest that the piezometer re-completion activities may have adversely impacted the monitored fault-zone interval, possibly because of cement slurry migration or possibly mobilization (through re-drilling) of the bentonite-seal interval (160 to 280 ft; Figure 2.2) that was originally emplaced during the initial piezometer installation. Additionally, baseline monitoring of well water-levels within DH-05-01 following re-completion of the piezometer indicates that a small hydraulic connection still persists between the unconfined fault-zone breccia aquifer and underlying Pomona basalt confined aquifer within the piezometer/borehole installation (Section 4). This hydraulic connection has caused well water-levels to continuously rise within the re-completed DH-05-01 piezometer ~15 ft above previously determined static water-table conditions.

Following hydrologic test characterizations conducted at borehole DH-06-01, it was also completed as a piezometer on May 20, 2006, to provide long-term baseline monitoring of natural dynamic responses within the lower Pomona basalt confined aquifer system (Figure 2.4). With the re-completion of DH-05-01, the two monitoring-well facilities provide an opportunity to directly compare long-term baseline comparisons of hydrologic responses exhibited within the two individual aquifer systems at the damsite location. Theoretically, the baseline response comparisons can be used to evaluate large-scale hydraulic communication between the two aquifer systems within the surrounding area. The ~102 ft hydraulic head difference relationship exhibited between the two-aquifer systems is shown on the hydrogeologic schematic presented in Figure 2.5. As previously discussed, however, a comparison of baseline responses at the re-completed DH-05-01 and DH-06-01 piezometers indicates that the re-completion of DH-05-01 was not completely successful and effective in isolating the two aquifer systems at this location. Based on a review of the baseline response (Section 4), minor leakage/hydraulic communication appears to still exist within DH-05-01 and/or within the aquifer immediately surrounding the drilled borehole.

The static water-level elevation of ~1,110-ft MSL measured for the Pomona basalt confined aquifer system at the damsite borehole locations is consistent spatially with the ~1,155-ft MSL measured previously for the up-gradient, shallow confined aquifer system at DH-04-01 and DH-04-02, which are completed within the Selah and Mabton interbeds, respectively (Spane 2004). It is currently unknown whether the confined aquifer systems monitored at DH-04-01/DH-04-02 and the DH-05-01/DH-06-01 damsite location are hydrologically connected. No unconfined aquifer is present at the previously tested DH-04-01/DH-04-02 location for comparison purposes.

Site Geology

The following stratigraphic units were identified at the site, based on detailed core analysis provided by corehole DH-05-01:

a.	Quaternary loess deposits:	0	–	3.0	ft
b.	Quaternary colluvium:	3.0	–	60.5	ft
c.	Pomona basalt: (Saddle Mountains Formation)	60.5	–	92.0	ft
d.	Undifferentiated Esquatzel/ Umatilla basalts: (Saddle Mountains Formation)	92.0	–	228.4	ft
e.	Basalt fault breccia zone:	228.4	–	301.1	ft
f.	Rattlesnake Ridge interbed: (Ellensburg Formation)	301.1	–	310.7	ft
g.	Pomona basalt: (Saddle Mountains Formation)	310.7	>	400.0	ft

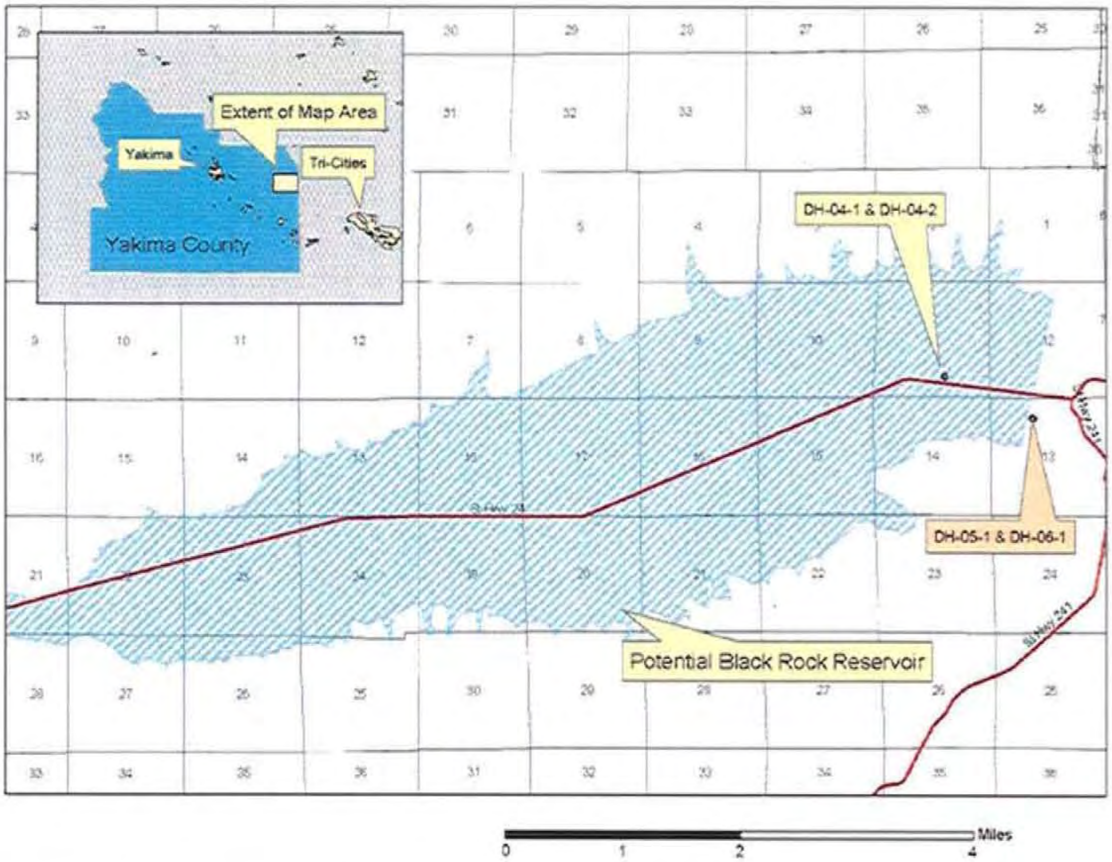


Figure 2.1. General Location Map of Test Site

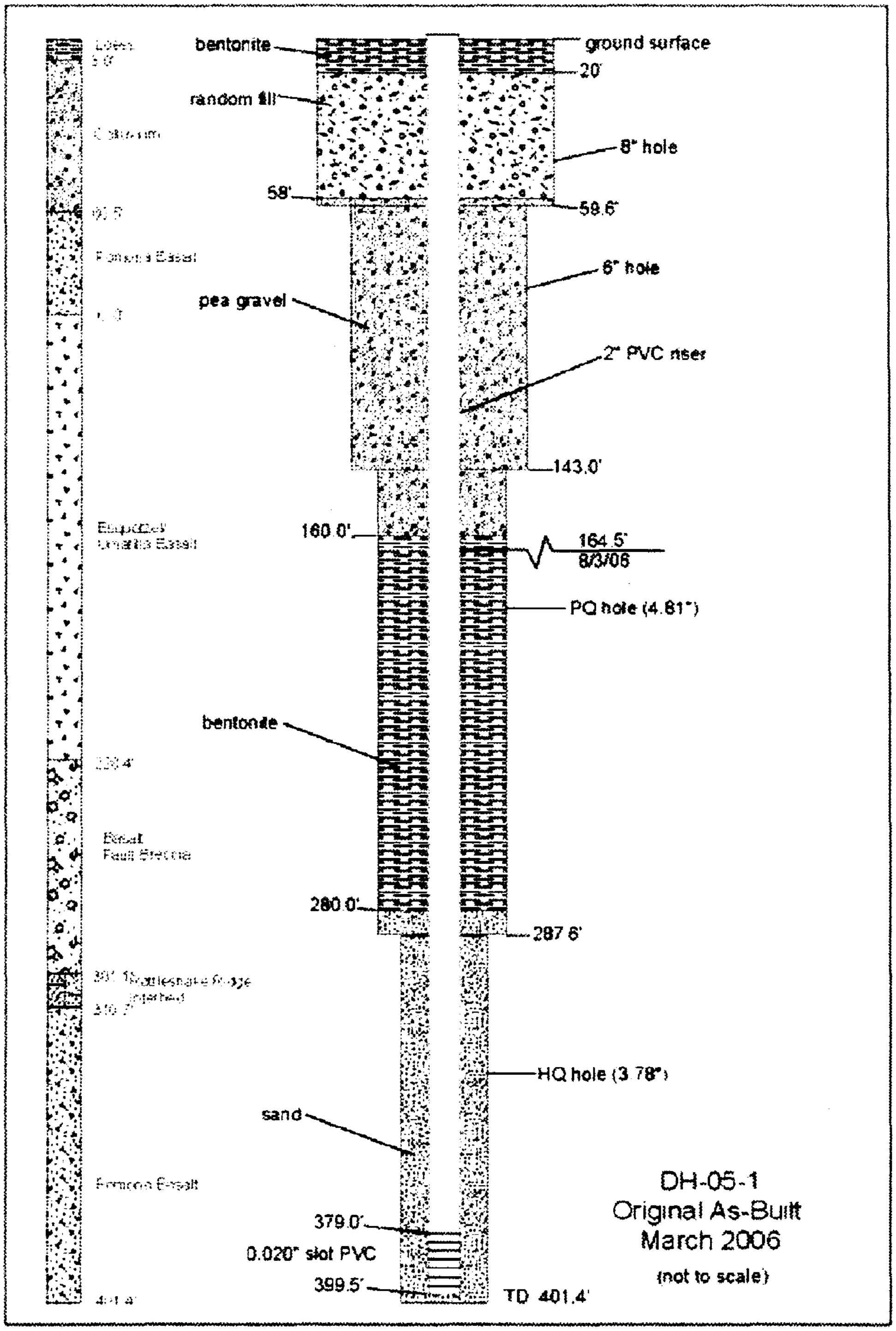


Figure 2.2. General Stratigraphy and Well As-Built for the Initial Piezometer Completion within DH-05-01

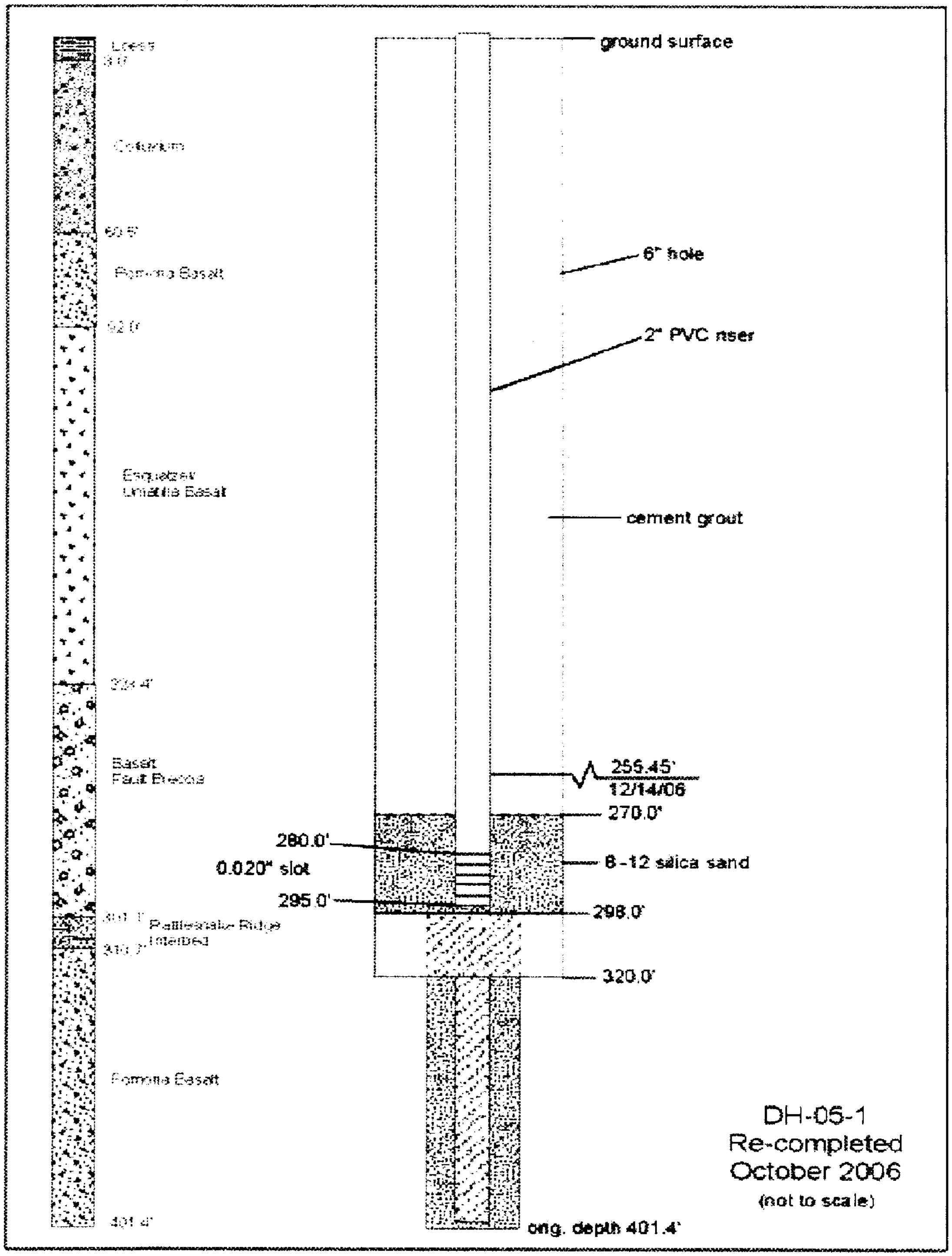


Figure 2.3. General Stratigraphy and Well As-Built for the Re-Completed Piezometer within DH-05-01

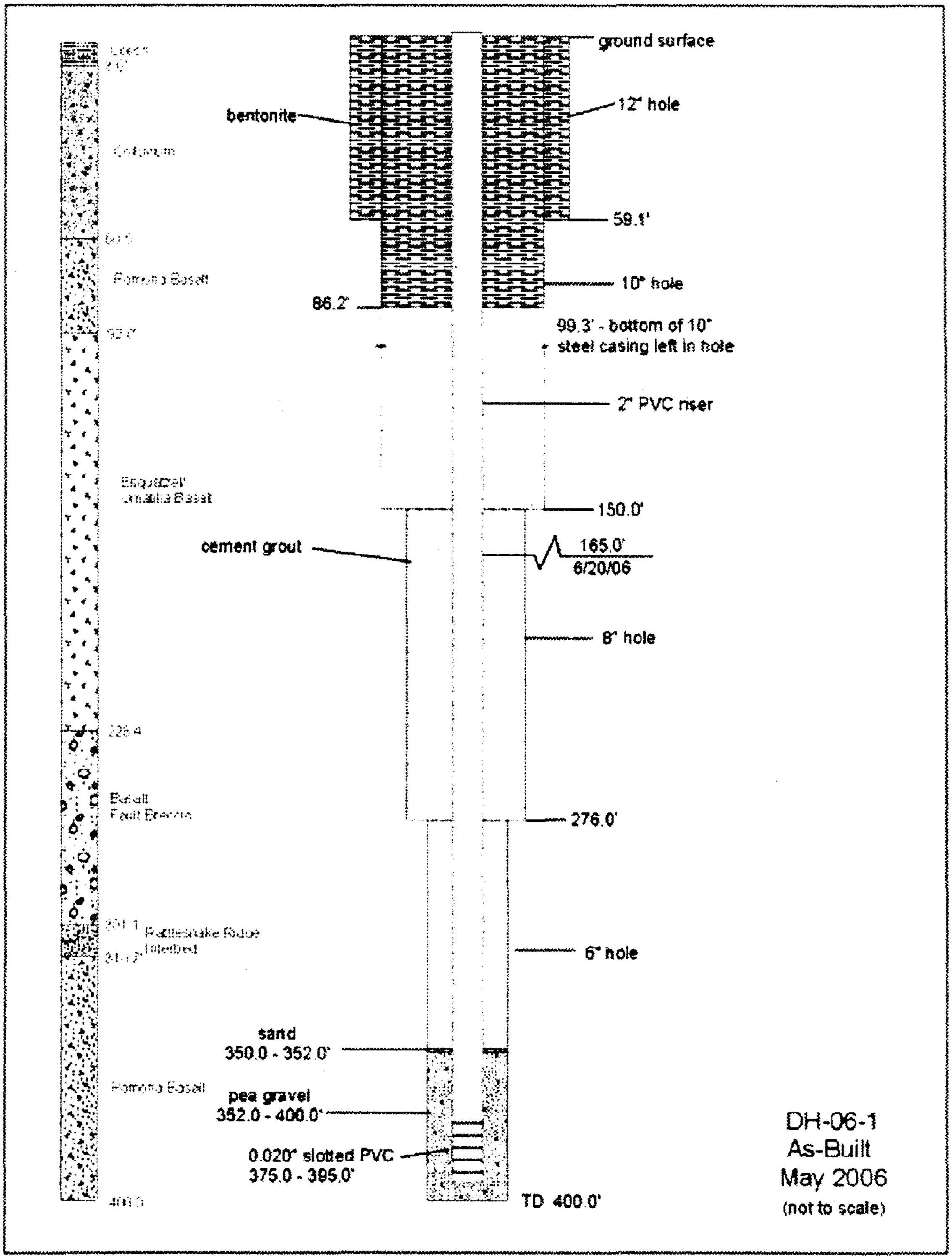


Figure 2.4. General Stratigraphy and Well As-Built for Piezometer Completion within DH-06-01

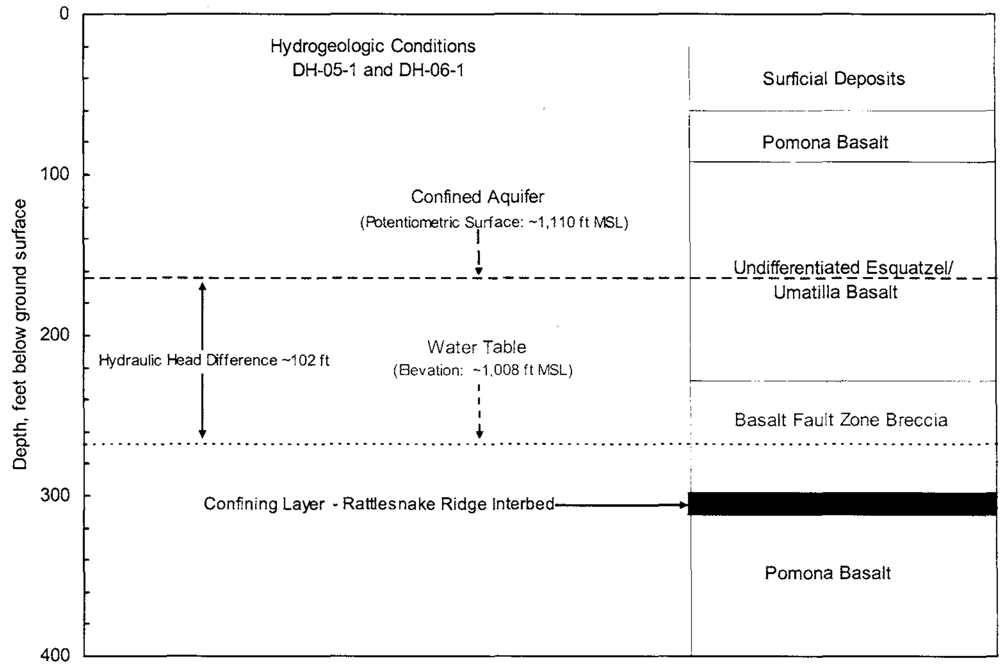


Figure 2.5. General Hydrogeologic Site Conditions

3. Hydrologic Test Characterization

The following provides a discussion of the detailed hydrologic field-testing program conducted at corehole DH-05-01 and borehole DH-06-01. The field-testing program follows the guidance and rationale originally presented in the response by Spane (2003) to the U.S. Bureau of Reclamation RFP for Hydrogeologic Services for the Potential Black Rock Dam and Reservoir Sites. The primary objectives of the field-testing program were to obtain detailed hydrogeologic characterization information pertaining to: hydraulic and storage properties of vadose zone and groundwater systems, vertical leakage between hydrogeologic units and hydrologic barriers (e.g., faults) to groundwater flow. Of particular importance is the potential leakage of surface water stored within the reservoir, which may alter existing local groundwater systems and adversely impact adjacent surface and groundwater-basin hydrologic conditions (e.g., Hanford Site). The following report sections describe pertinent aspects of test equipment and hydrologic test methods used to acquire the detailed hydrogeologic information during the borehole field testing program. The discussions in this section are taken largely from Spane (2004), which was also presented in Didricksen (2004).

3.1 Test Equipment

Hydrologic testing of vadose and groundwater zones within corehole DH-05-01 and borehole DH-06-01 was conducted primarily during borehole advancement. For groundwater test zone characterizations within DH-05-01, a modified Farwest Air-Longyear, Inc. inflatable wireline packer (model MD4.0) test system was employed. Salient features of the packer test system include: 1) an inflatable packer for isolating the test interval within the open borehole; 2) a pressure sensor transfer tube through the packer for monitoring below-packer/test interval response; and a 10-ft perforated pipe section mounted below the packer assembly. Appendix Figure A.1 provides a manufacturer diagram and description of the basic wireline inflatable packer system. Pictures of selected features of the packer test assembly utilized for testing in DH-05-01 are shown in Appendix Figures A.2 - A.3.

The submersible pump utilized for groundwater pumping tests performed in DH-06-01 was a 5 hp, Grundfos; model 40S15-50. In-Situ model PTX-261, 0-250 psi range pressure transducers were used during hydraulic testing at both test sites, while long-term baseline monitoring was performed using an Instrumentation Northwest, Inc., PT-2X, 0 - 15 psi range integrated pressure transducer and datalogger. An eight channel, Hermit 3000 datalogger was used to collect the readings from the pressure sensor systems, together with the site barometric pressure readings during the course of testing. Surface discharge and injection rates during testing were monitored with a 2-in. I.D., Master Meter, model MM7T in-line instantaneous/totalizer flow meter, and cross-checked using timed surface discharge measurements (i.e., using a calibrated 5-gallon bucket and 42-gallon barrel).

3.2 Test Methods

Field hydrologic test methods commonly have different scales-of-investigation (i.e., "radius of investigation") and exhibit varying degrees of resolution for various hydraulic/storage properties (see Table 3.1). The selection and sequence of characterization tests used, therefore, is of particular importance when designing a borehole hydrologic testing program. Standard single- and multi-well tests selected for use during the field borehole testing program included: slug, slug interference, step-drawdown, constant-rate/-head injection or constant-rate withdrawal (pumping) tests. To perform most of the identified hydrologic tests, a specific depth interval selected for detailed characterization was isolated within the borehole using the inflatable packer test system described in Section 3.1 or by setting of cemented well-casing strings, together with perforated pipe sections to maintain borehole stability during testing. Test formation response and zone isolation were assessed using downhole pressure probes that monitored test interval pressures during testing and imposed annulus zone stress applications. Analysis of the test interval pressure response during testing provided an average value for transmissivity, T, hydraulic conductivity, K, and storativity, S, for the isolated test intervals. In addition, monitoring test responses at nearby piezometer DH-05-01 (located ~38 ft from test borehole DH-06-01) provided the opportunity of obtaining intermediate-scale information for the monitored test interval during testing initiated at borehole DH-06-01.

The area-of-investigation (i.e., radius of investigation) for the various test methods is a function of: test duration, magnitude of stress imposed by the test, and test formation characteristics. Depending on these conditions, characteristics determined from specific test methods are expected to integrate formation property conditions ranging from ~1 to >500 ft from the test borehole location. In addition, certain hydrologic test methods are sensitive to detecting abrupt formational discontinuities or hydrologic boundaries (e.g., faults, stratigraphic pinch-outs) and for distinguishing between operative aquifer models (e.g., dual- vs. single-porosity systems, nonleaky vs. leaky conditions). Table 3.1 summarizes the attributes of the various test methods.

3.2.1 Vadose Zone Tests

Constant-head injection (gravity) tests were utilized as the only characterization method for estimating in-situ saturated hydraulic conductivity conditions within selected vadose zone test depth intervals at DH-05-01 and DH-06-01 during borehole advancement. The test procedure included drilling below an advanced borehole casing to a prescribed depth, which provided an open unsaturated borehole section for subsequent constant-head injection testing. Performance and analysis of the tests largely followed procedures outlined in the U.S. Bureau of Reclamation Earth Manual (USBR 1974, 1998) and Groundwater Manual (USBR 1977, 1995). The general vadose-zone test strategy included: installation of an in-borehole transducer near the bottom of the borehole; rapid filling of the open borehole and casing to a prescribed level (usually near land surface); maintaining the fluid level within the borehole to the prescribed level for the duration of the test; monitoring of the surface injection rates during the entire injection period, and continuing of the test until relatively uniform injection rates were established (i.e., pseudo-steady-state conditions).

The cited USBR references provide different equations for deep or shallow settings (i.e., to the "water table"), and whether the test borehole is open or partially cased. The first aquifer encountered was an unconfined aquifer system that occurs within the fault zone breccia (~268 to 301 ft bgs). Since dry, unsaturated conditions existed during the drilling and testing of the corehole and borehole to test depths of 268 ft, this unsaturated thickness value (or depth to a projected water table) was arbitrarily used for the purpose of selecting the appropriate shallow or deep water-table analysis method for the respective vadose zone tests. It should be noted that an uncertainty of ±10 to 15 ft in the depth to the static water table would not produce a significant error in the saturated hydraulic conductivity values (i.e., within ±5%).

As discussed in the USBR references, for deep water-table vadose zone test conditions (Zone 1, Method 1), the following equation would be used for calculating the saturated hydraulic conductivity for the open borehole test section, given the test system conditions employed at the test sites:

$$K_s = Q_s / (C_u r_w H) \tag{3.1}$$

where,

- Q_s = pseudo-steady-state constant-head injection
- C_u = saturated conductivity coefficient for deep water-table case
- r_w = radius of the open borehole test section
- H = imposed constant injection head above the bottom of the borehole test section

A value for C_u can be estimated from nomograph plots provided in the USBR references (e.g., USBR 1977, Figure 10-7) or calculated directly from the following equation presented in Stephens and Neuman (1983a):

$$C_u = 2\pi(2AH - A^2) / r_w \mathrm{H}[\sinh^{-1}(\mathrm{A}/\mathrm{r}_\mathrm{w}^2) - (A/H)] \tag{3.2}$$

For shallow water-table vadose zone test conditions (Zone 2, Method 1), the following equation was used for calculating the saturated hydraulic conductivity for the open borehole test section, which was indicated for the test system conditions exhibited at DH-06-01 for vadose zone depth interval 236 - 255 ft (Section 6.1.2):

$$K_s = 2Q_s / (C_s + 4)(rT_u) \tag{3.3}$$

where,

C_s = saturated conductivity coefficient for shallow water-table test case
T_u = vertical distance from water table to top of injection fluid-column level

$$C_s = 2\pi(A / r_w)/\ln(A/ r_w^2) \qquad (3.4)$$

Criteria for distinguishing between deep (Zone 1) and shallow (Zone 2) test conditions are based on the head/water-table aspect ratio, X, which is equal to H/T_u, and the water-table/test interval aspect ratio, T_u/A. These ratio parameters can then be utilized with the standard USBR nomograph plot shown in Figure 3.1 for distinguishing between deep and shallow water-table test conditions and identifying the appropriate analysis equations to use.

A number of previous papers have examined the appropriateness of these equations for calculating K_s under vadose-zone conditions (e.g., Stephens and Neuman 1983a, b, c). In most cases, the equations were considered appropriate if applied to applicable test site conditions. One assumption implied in all the discussed USBR constant-head equations is that the injection rates observed during the end of testing are reflective of steady-state injection conditions. As noted by others, this likely would require considerable test times to actually be achieved (e.g., days). For various soil-sediment types and permeability groups considered in studies presented Stephens and Neuman (1983c), injection rates attained 50 to 80% of steady-state values after ~2 hours of injection testing. This implies that vadose zone K_s estimates based on constant-head injection tests conducted using similar test durations, e.g., at DH-06-01, may over-estimate actual K_s conditions by a maximum factor of ≤2, due solely to not completely reaching steady-state injection rates. For this reason, all *"uniform"* injection rates, Q_s, observed near the end of constant-head injection testing at DH-06-01, and used in calculating K_s are referred to as *pseudo-steady-state* injection rates.

Another potential source of error for the damsite vadose zone tests is the fact that the constant-head injection levels utilized for some of the test intervals was significantly above the open borehole test interval (i.e., within the overlying borehole-cased section) and were commonly maintained at a level in proximity to or higher than land surface. This test procedure was implemented primarily to impose a maximum head on the vadose formations tested and for assessing any test stress dependence. Utilizing a higher injection head was considered to be more relevant for evaluating potential reservoir storage effects (i.e., leakage), and also facilitated easier performance of the test. Using an injection head level above the open borehole test interval, however, may impose some injection leakage to overlying unsaturated zones at and along the casing-borehole contact if an adequate seal is not maintained. While this possibility cannot be dismissed, the presence of a high percentage of fine-grained clays, silts, and tuffaceous sediments penetrated above the basalt formations suggest that a relatively "tight" seal was maintained when testing these vadose zone test intervals.

The previously discussed deep and shallow water-table analysis methods are not applicable for test cases where the test interval is either: at or below the water table, or in proximity to a low permeability barrier/test interval. For these vadose zone test interval conditions the use of the shallow (Zone 2) water-table equations 3.3 and 3.4 are invalid, due to the fact that flow from the injection borehole would be predominantly radial and not directed downward toward the water-table surface. For these test conditions, the radial-flow based Ziegler (1976) method is recommended.

$$T_s = (Q_s / H)[(1/2\pi)\ln(R/r_w)] \tag{3.5}$$

where,

R = radius of investigation for the constant-head injection test
T_s = saturated transmissivity equal to K_s/A

For moderately to highly transmissive test formations, the radius of investigation, R, is commonly taken as being equal to the open borehole test interval length, A. Investigations by Zeigler (1976) have shown, however, that T_s is relatively insensitive to R, with an order-of-magnitude variation producing a change of a factor of ≤1.5 in the calculated estimate of T_s. It should be noted that the Ziegler (1976) method was developed for radial-flow conditions for injection well test cases below the water table, and its applicability for vadose zone tests is not proven. For test conditions where vadose zone injection tests are predominantly radial (e.g., due to proximity to an underlying low-permeability layer) the USBR recommends utilizing a similarly-based, equation developed originally for saturated zone conditions (i.e., the Thiem equation). This equation, however, is based on steady-state, distance-drawdown/buildup conditions and requires use of observation wells completed at the same test/depth interval (which were not available at the Black Rock damsite test site). Although no vadose zone tests were analyzed using the Ziegler equation, it was used as a primary analysis method for the unconfined aquifer test after re-completion of the piezometer at DH-05-01. A more detailed discussion of the Ziegler (1976) method, particularly as it relates to injection tests conducted for characterizing basalts flows, is presented in Spane and Thorne (1985).

3.2.2 Groundwater Test Zones

The following is a general discussion of the various characterization and analytical methods utilized during the field borehole testing program of saturated test zones and is taken, in part, from Reidel et al. (2002). Table 3.1 lists hydrogeologic parameters and relative investigative scale for the various test methods used during testing of borehole DH-06-01 and piezometer DH-05-01. Pertinent and specific test information pertaining to actual testing performed, is presented in Section 5 and 6.

3.2.2.1 Slug and Slug Interference Tests

Because of their ease of implementation and relatively short duration, slug tests are commonly used to provide initial estimates of hydraulic properties (e.g., range and spatial/vertical distribution of hydraulic conductivity, K). Hydraulic properties determined using slug testing are representative of conditions relatively close to the borehole. For this reason, slug-test results are normally used to provide initial test interval hydraulic property characterization, and provide information that can be used in the design of subsequent hydrologic tests having greater areas of investigation.

Pneumatic slug (withdrawal) tests were conducted at both DH-05-01 and DH-06-01 after completing the boreholes with piezometer installations, following completion of borehole advancement. To conduct the pneumatic tests, regulated compressed air was administered to a sealed wellhead that was attached to the monitoring well or piezometer casing string to depress the fluid column within the well. Applied compressed air injection pressures and associated downhole pressure responses were monitored using pressure transducers that were installed within the well and piezometer. Applied compressed air injection pressures used during the pneumatic slug tests theoretically displaced (i.e., depressed) the well fluid column generally within the range of 3 to 15 ft. After the pressure within the monitored fluid column had stabilized (i.e., ~10 to 20 minutes) for a prescribed stress level, a slug withdrawal test was initiated by suddenly releasing the compressed gas used to depress the borehole fluid-column level. The test was initiated *instantaneously* by releasing the compressed gas from the piezometer casing column by opening a valve (e.g., ball valve) mounted on the attached surface wellhead, used to seal the piezometer casing system. Analysis of the recovery response provides an estimate of the test interval transmissivity (T), average hydraulic conductivity (K), and storativity (S). Estimates for storativity, however, are less certain, due to the test method's lower sensitivity to S. (Note: the effects of well skin, s_K, were not accounted for separately and were included within the estimate of S). The slug test responses were analyzed utilizing type-curve and deconvolution procedures discussed in Butler (1997) and Peres et al. (1989), respectively. These analysis procedures are applicable for over-damped or converted equivalent slug test responses. For these slug test response conditions, the slug test type-curves analyses presented in this report were generated using the Kansas Geological Survey (KGS) software program described in Liu and Butler (1995). For highly permeable slug test zones that exhibited oscillatory (under-damped) slug test response characteristics, the aforementioned over-damped analytical methods are not applicable and the High-K analysis method, presented in Butler (1997) and Butler and Garnett (2000) was utilized. This type of high permeability piezometer slug test response characteristics were exhibited for slug tests conducted within the Pomona basalt at both borehole locations (Section 5.2.3 and 6.2.3). A more detailed summary discussion of the performance and analysis of slug tests is presented in Spane and Newcomer (2004).

For slug interference tests, an observation well completed in the same test interval is required to monitor the surrounding pressure wave induced by the slug test initiated at a stress well location. This test configuration presented itself when testing was initiated at borehole DH-06-01 for the Pomona basalt depth interval 312 - 400 ft (Section 6.2.2), and following piezometer installation within the borehole. However, as noted in Section 2, the piezometer installation at DH-05-01 that was used to monitor the slug interference produced at DH-06-01 provided hydraulic communication within the piezometer installation to the overlying unconfined aquifer. Because of the high sensitivity of slug interference responses to leakage response effects (i.e., produced by the faulty piezometer installation) no quantitative analysis of the slug interference tests are presented in this report. Detailed descriptions of design, performance, and analysis of slug interference tests is provided in Novakowski (1989) and Spane (1992, 1996) and Spane et al. (1996).

3.2.2.2 Step-Drawdown Test

Step drawdown tests normally are conducted to assess well/aquifer loss performance, and for guidance in selecting the pumping rate for subsequent, longer duration, constant-rate pumping test. The test is conducted as a series of sequential, short-duration constant-rate pumping tests, with each step conducted of uniform duration (e.g., 1 to 2 hr) and at progressively higher pumping rates. A minimum of three steps is required, and ≥4 steps are preferred. The comparison of discharge, Q, and the drawdown/pumping rate ratio, s_w/Q, (i.e., drawdown/discharge) is plotted to assess well loss conditions. As denoted originally by Jacob (1946) and Rorabaugh (1953), an increasing s_w/Q vs. Q pattern is indicative of turbulent well loss conditions, while a constant relationship vs. Q indicates that all well losses are laminar in nature.

Jacob (1946) presented the following well loss/drawdown relationship used to assess well discharge performance:

$$s_w = BQ + CQ^2 \tag{3.6}$$

where,

BQ = laminar aquifer head loss

CQ^2 = turbulent well head loss

A linear regression slope fit through the step data provides coefficients for the head loss equation (3.6), with the intercept value equal to coefficient B and the slope equivalent to coefficient C. It should be noted that the laminar aquifer head loss, BQ, includes the effects of true formational aquifer characteristics (i.e., head loss due to hydraulic properties) and those attributable to well skin effects (i.e., damage associated with drilling/well construction process).

A single, extended step-drawdown test was conducted at test borehole DH-06-01 (Pomona basalt; test interval 312 - 400 ft. Results of this test are presented in Section 6.2.2.

3.2.2.3 Constant-Rate Pumping and Injection Tests

For constant-rate pumping (withdrawal) tests, formation water is withdrawn from the test interval and regulated to maintain a constant, uniform rate. (Note: constant-rate injection tests are performed in similar fashion, but instead of pumping water from the aquifer, water is injected at a constant rate. No further reference to constant-rate injection tests are presented in this section, however, the same procedures and analysis methods apply). For constant-rate tests, the pressure response within the test borehole is monitored during the active pumping phase and during the subsequent recovery period following termination of pumping. The analysis of the drawdown and recovery pressure response within the pumped test borehole (and for multi-well tests any nearby observation wells, e.g., piezometer DH-05-01) provides a means for estimating hydraulic properties of the reservoir tested, as well as for discerning formational and non-formational flow conditions (e.g., wellbore storage, skin effects, boundaries and leakage). Standard analytical methods used for the analysis of constant-rate tests include type-curve matching and straight-line methods.

Type-curve-matching methods are best applied to observation well data and not to pumping wells because of the additional head losses that occur at the pumped well. They can be used for pumped well analyses, however, if certain assumptions pertaining to well efficiency (i.e., well-skin effects = 0) or the test interval (e.g., S is known) are made. This is the approach taken for single-well pumping test analysis within the petroleum industry. Type-curve-matching methods commonly used in the analysis of pumping test responses include those described in Theis (1935), Hantush (1964), Novakowski (1990), and Moench (1997). Constant-rate pumping test type-curves presented in this report were generated using the WTAQ program described in Moench (1997).

For straight-line analysis methods, the rate of change of water levels within the well during drawdown and/or recovery is analyzed to estimate hydraulic properties. Because well effects are constant with time during constant-rate tests, straight-line methods can be used to analyze quantitatively the water-level response at both pumping and observation wells. The semilog, straight-line analysis techniques commonly used are based either on the Cooper and Jacob (1946) method (for drawdown analysis) or the Horner (1951) method for recovery analysis. It should be noted that the Horner method, which is commonly used in the petroleum industry, is identical to the Theis (1935) recovery method utilized in groundwater hydrology. These methods are theoretically restricted to the analysis of test responses from wells that fully penetrate nonleaky, homogeneous, isotropic, confined aquifers. Straight-line methods, however, may be applied under nonideal well and aquifer conditions if infinite-acting, radial flow conditions exist. Infinite-acting, radial flow conditions are indicated during testing when the change in pressure, at the point of observation, increases proportionately to the logarithm of time.

Log-log plots of water level versus time have traditionally been used for diagnostic purposes to examine pumping test drawdown data. More recently, the derivative of the water level or pressure has also been used as a diagnostic tool. Use of derivatives has been shown to improve significantly the diagnostic and quantitative analysis of various hydrologic test methods (Bourdet et al. 1989; Spane 1993; Spane and Wurstner 1993). The improvement in test analysis is attributed to the sensitivity of pressure derivatives to various test/formation conditions. Specific applications for which derivatives are particularly useful include the following:

- identifying formation-response characteristics (nonleaky or leaky; confined or unconfined aquifer) and boundary conditions (impermeable or constant head)

- assisting in the selection of the appropriate type-curve solution through combined type-curve/derivative plot matching

- determining when infinite-acting, radial flow conditions are established and, therefore, when straight-line analysis methods are applicable.

Figure 3.2 shows selected examples of log-log drawdown and derivative responses that are characteristic of some commonly encountered formation conditions. Spane (1993) provides a summary discussion on the use of standard and derivative-based analytical methods for constant-rate tests.

3.2.2.4 Constant-Head Injection Test

For this test, the water-level within the borehole/test system is raised in the test well and maintained at a relatively uniform level (constant head) for the duration of the test. This was accomplished for the re-completed piezometer at DH-05-01 (280 - 295 ft; Section 5.2.4) by filling and maintaining the fluid column to the top of the piezometer casing at land surface. The magnitude of the observed discharge for the given applied, constant head and its decline with time provides a means of determining the transmissivity, T, and to a lesser extent storativity, S, of the interval tested. The method used for analyzing this test is based on the solution presented originally by Jacob and Lohman (1952). Late-time, steady-state injection rates can also be analyzed using the equation relationship presented in Zeigler (1976), which is discussed in Section 3.2.1.

The fluid-level recovery within the borehole/test system following termination of the constant-head injection test can also be analyzed using the previously cited methods in Section 3.2.2.3 for constant-discharge pumping tests, provided that discharge does not vary significantly (e.g., ± 10%) over most of the test period (particularly the late-time pumping period). When discharge variation is significant, special procedures, e.g., superposition/multi-rate analysis methods (see Earlougher 1977 and Horne 1990) can be used to obtain reliable analytical results.

3.3 Leakage Response

Analysis of baseline pressure measurements monitored within piezometers installed at DH-05-01 and DH-06-01 provides the opportunity for assessing leakage or vertical hydraulic communication between hydrogeologic units and aquifer systems at this test site location. Specifically, leakage assessments can be determined from:

- Cross-formational response occurring during drilling of nearby borehole
- Cross-formation response during controlled multi-well hydrologic tests
- Diagnostic leakage response associated within the monitored hydrogeologic unit (single or multi-well tests)
- Lack of distinct differences in hydrochemistry and isotopic content
- Barometric leakage response pattern

Because of the faulty completions that occurred for the initial and re-completed piezometer installations at DH-05-01, natural formation leakage assessment was not possible. Man-induced leakage produced by the piezometer completions, however, was examined and reported within various sections of this report.

The first three identified leakage assessment methods are more commonly applied in hydrologic investigations, and are the primary methods utilized for assessing leakage at the first Black Rock Reservoir test site characterization that is reported in Spane (2004) and also presented in Didricksen (2004).

The presence of distinct differences in groundwater hydrochemistry and isotopic depth profile data has been cited in previous investigations (DOE 1988, Reidel et al. 2002) as a means of assessing a lack of vertical communication between hydrogeologic units. However, this method requires the use of numerous, closely spaced, vertical test/depth samples that were not available at this damsite test location (note: only one test/depth interval was collected from DH-06-01 for the Pomona basalt; Section 6.4).

The barometric-leakage response-pattern assessment is a developmental method, based on the extension of models presented in Rasmussen and Crawford (1997) and Spane (2002). Definitive barometric-response characteristics indicative of coupled or composite aquifer-system conditions were identified with this characterization technique and are reported in Section 4.2.3.

3.4 Hydrochemistry

Representative groundwater samples were collected during and near the end of the extended step-drawdown pumping test of the Pomona basalt (312 to 400 ft), for the primary purpose of comparing the background hydrochemical characteristics of the uppermost confined aquifer system at this damsite location with similar shallow confined aquifer depth intervals sampled earlier at the first reservoir-floor, field test site location (see Spane 2004, Didricksen 2004). This type of characterization would be particularly useful in the event that a reservoir is established at the site since surface water stored at the site will likely be distinctly different from existing basalt groundwater conditions. This distinct difference in Columbia River (and Yakima River) water, in comparison to basalt groundwaters, is discussed in Spane and Webber (1995). Establishing the background/baseline groundwater hydrochemical and isotopic content, therefore, would provide a powerful tool in establishing the degree and extent of reservoir leakage within the underlying and surrounding groundwater-flow systems.

For deep basalt test boreholes (e.g., >1,000 to 2,000 ft), comparing the hydrochemical and isotopic content for multiple discrete test/depth intervals has also proven very useful in the surrounding region for establishing the presence of either mixing or isolation for aquifer systems, as described in DOE (1988) and Reidel et al. (2002). However, because of the relative shallowness of the borehole investigation, this will likely not be a viable application at the Black Rock field test site.

Specific hydrochemical and isotopic parameters identified for establishing background groundwater conditions include major inorganics (bicarbonate/carbonate, sulfate, chloride, fluoride, nitrate, sodium, potassium, calcium, magnesium, silicon), pH, EH, alkalinity, specific conductance, temperature, selected trace elements/metals (e.g., iron, manganese, strontium, barium), selected stable isotopes (deuterium, oxygen-18, sulfur-34, carbon-13), and selected unstable isotopes (tritium, carbon-14). A brief discussion of the applications of these hydrochemical and isotopic parameters in basalt groundwater studies is provided in Spane and Webber (1995). Only major inorganics were analyzed for samples collected from DH-06-01 along with the following field-collection parameters: pH, specific conductance, alkalinity, and temperature. The results from these laboratory analyses are reported in Section 6.4.

Table 3.1. Summary of Hydrologic Test Methods Used for Test Site Characterization Investigations (modified from Reidel et al. 2002)

Test Method	Hydrologic Parameter[a]					Test Scale		
	T	K_h	K_D	S	L	Local	Intermed.	Large
Slug	√	√		x		√		
Slug Interference	√	√	x	√	√	√	√	
Constant-Rate Pumping/Injection – Drawdown & Recovery	√	√	√	√	√		√	√
Constant-Drawdown/Air-lift Pumping & Recovery	√	√	x	√	√		√	√

(a) Nomenclature
- T = test interval transmissivity
- K_h = equivalent hydraulic conductivity; equal to T divided by test interval length
- K_D = vertical anisotropy K_v/K_h
- S = storativity; dimensionless
- L = leakage response

Note: √ = provides quantitative information
x = only provides inferential/qualitative information

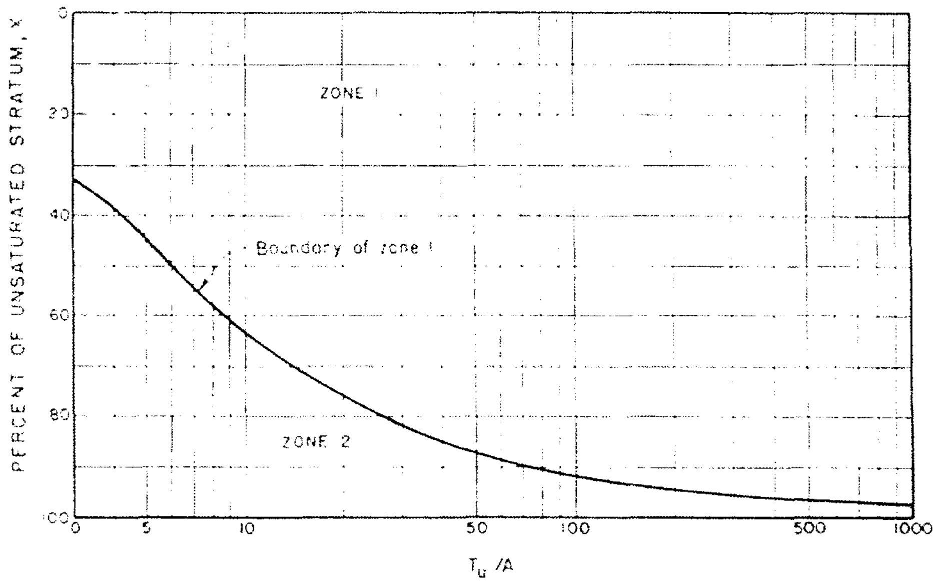


Figure 3.1. Determining Deep (Zone 1) or Shallow (Zone 2) Water-Table Vadose Zone Test Conditions (adapted from USBR 1974, Ground Water Manual)

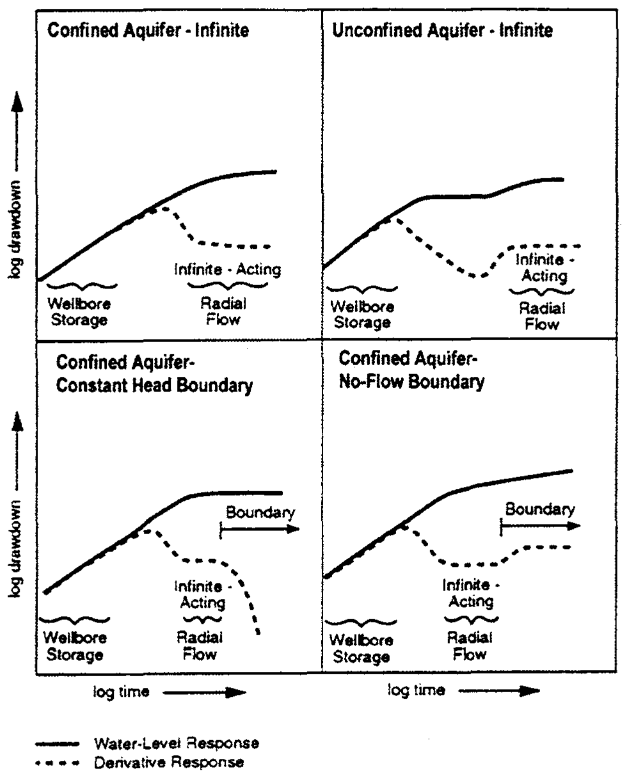


Figure 3.2. Characteristic Log-Log Drawdown and Drawdown Derivative Plots for Various Hydrogeologic Formation and Boundary Conditions (adapted from Spane and Wurstner 1993)

4. Baseline Monitoring

Long-term monitoring of well water-level responses provides information concerning the groundwater dynamics of monitored zones to seasonal/annual recharge event patterns. When examined across a monitor well network, baseline water-level measurements can be used to delineate groundwater-flow characteristics, including groundwater-flow patterns and flow velocity within and between aquifer systems. Water-level measurements collected within monitoring-well facilities (as part of baseline monitoring or during aquifer test characterizations), however, are subject to temporal external stress effects, which variably affect these well measurements. Naturally occurring external stresses impacting well water-levels include barometric pressure, Earth tides, and ocean and river-stage fluctuations. For the proposed Black Rock Reservoir location, barometric pressure and (to a lesser extent) Earth tides are the only external stresses that can exert a perceptible effect on well measurements.

Extended baseline monitoring was initiated at both piezometers within DH-05-01 and DH-06-01 following completion of active field testing (i.e., active drill-and-test phase) at the test site on May 20, 2006. The initial and re-completion of the piezometer within DH-05-01 first within the Pomona basalt confined aquifer (379 to 399.5 ft) and subsequently within the shallow fault zone breccia unconfined aquifer (280 to 295 ft) provided the opportunity to assess the groundwater dynamics within the two, uppermost aquifer systems at the southern abutment location. However, as noted in Section 2, the initial and subsequent piezometer installation at DH-05-01 did not fully isolate the two-aquifers within the borehole completion. As a result, the composite aquifer piezometer completions at DH-05-01 affected not only the baseline dynamics at DH-05-01, but adjacent DH-06-01. A discussion of the baseline monitoring results for DH-05-01 and DH-06-01 during the monitoring periods following initial and subsequent piezometer installations at DH-05-01 are provided in the following report sections.

4.1 Water-Level Dynamics

Figure 4.1 shows the water-level response dynamics for piezometers DH-05-01 and DH-06-01 over a 40-day monitoring period, from June 24 to August 2, 2006 (calendar days 175 to 215). The well water-level elevation hydrographs were developed by converting in-well pressure transducer readings, which were calibrated versus manual water-level measurements to account for instrument drift effects. Both piezometer well screens were completed within the Pomona basalt aquifer during this baseline monitoring period. As noted in Section 2, however, the sand-pack interval associated with the piezometer installation at DH-05-01 afforded hydraulic communication between the deeper Pomona basalt confined aquifer, with the unconfined aquifer system within the overlying fault zone breccia.

As shown in Figure 4.1, both monitoring sites exhibit subdued short-term, temporal response characteristics, which are associated primarily with natural barometric pressure stress effects (see Section 4.2). These temporal response characteristics are superimposed on longer-term trend behavior, which may be reflective of aquifer flow-system characteristics responding to natural factors (e.g., recharge/discharge cycles) or recovery from previous imposed activities (e.g., drilling, well completion, and/or tests) at the site. As mentioned above, the longer-term baseline response trend exhibited at piezometer DH-05-01 is believed reflective of a composite head equilibration trend produced by hydraulically connecting the two aquifer systems by the piezometer installation (Section 2). As shown in Figure 4.2, although similar short-term temporal response characteristics to barometric loading are displayed, different long-term trends are exhibited at both piezometer site locations for a 25-day period during the early phases of the monitoring period. Calculated water-level trends (calculated from linear-regression analysis) indicates -0.0071 ft/day for piezometer DH-05-01 and +0.0025 ft/day for monitor well DH-06-01 for this early 25-day measurement period (calendar days 180 to 205). The negative water-level trend exhibited at piezometer DH-05-01 is opposite in sign, in comparison to that observed at adjacent DH-06-01, and is consistent with a hydraulic communication between the confined aquifer and overlying (lower hydraulic head) unconfined aquifer provided within the DH-05-01 sandpack completion. Later during the baseline monitoring period (calendar days 204 to 215; Figure 4.1), similar and larger negative trends are exhibited at both piezometers. This parallel and increasing negative trend slope suggests that the radius of influence or a pressure cone of depression caused by the multiple-aquifer borehole connection was expanding surrounding the DH-05-01 piezometer site.

Figure 4.3 shows the water-level response dynamics for piezometers DH-05-01 and DH-06-01 over a 150-day monitoring period, from October 2, 2006, to March 1, 2007 (calendar days 275 to 425; CY 2006). As indicated in the figure, no continuous in-well monitoring was available during the first period of the baseline monitoring record, and only discrete water-level measurements were taken. The piezometer well-screened interval within DH-06-01 (375 to 395 ft) was the same as during the initial baseline monitoring period and was completed within the Pomona basalt confined aquifer. Due to the re-completion activities at DH-05-01, however, this piezometer well-screen section (280 to 295 ft) monitors, theoretically, only the unconfined aquifer system within the overlying fault-zone breccia. As previously discussed in Section 2, difficulties were experienced during the re-completion activities that may be attributed to the high head differences exhibited between the underlying, high-head confined aquifer and the overlying lower-head unconfined aquifer systems. The difficulties associated with the high differential head conditions within DH-05-01 may have compromised the hydraulic isolation between the two aquifer systems within the final piezometer re-completion installation.

Figure 4.3 indicates that on October 8, 2006 (a day after completion of the piezometer installation at DH-5-01), a water-level elevation of 1,008.3-ft MSL was observed within DH-05-01. This water-level elevation is similar to observed static water-level elevations (i.e., ~1,008-ft MSL) observed within the unconfined aquifer at both DH-05-01 and DH-06-01 during initial testing of the fault-zone breccia during advancement of the boreholes during drilling (Sections 5.2.1 and 6.2.1). Discrete well water-level measurements observed over the initial 2 months of the baseline monitoring period indicated a significant +12-ft increase over the initial 3-month period to a water-level elevation of 1,020.6-ft MSL measured on December 14, 2006 (calendar day 349). The water-levels within DH-05-01 have exhibited a continuing increasing pattern over the last 3 months of the monitoring period, however, at a significantly lower positive slope/trend rate. A well water-level elevation of 1,023.0-ft MSL was observed during the last day of monitoring period on February 28, 2007, which is ~15 ft higher than the previously determined, static water-table conditions.

Figures 4.4 and 4.5 show the well water-level response dynamics observed for piezometers DH-05-1 and DH-06-1 over a 25-day monitoring period, from January 1 to 25, 2007 (calendar days 1 to 26). The well water-level elevation hydrographs were developed by converting in-well pressure transducer readings, which were calibrated versus manual water-level measurements to account for instrument drift effects. As shown in the figures, both monitoring sites exhibit subdued short-term, temporal response characteristics that are associated primarily with natural barometric pressure stress effects (see Section 4.2). These temporal response characteristics are superimposed on background, longer-term trend behavior. As mentioned above, the longer-term baseline response exhibited at piezometer DH-05-01 is believed reflective of a composite head equilibration trend produced by the hydraulic connection of the two aquifer systems, by the piezometer installation (Section 2). Although similar short-term temporal response characteristics to barometric loading are displayed, different long-term trend slopes are exhibited at both piezometer site locations for this 25-day monitoring period during January 2007. Calculated water-level trend slopes (calculated from linear-regression analysis) indicates a 0.0111-ft/day trend for piezometer DH-05-01 and -0.0037-ft/day trend for monitor well DH-06-01 for this 25-day measurement period (calendar days 1 to 26). Generally, water-level elevations exhibit an inverse response relationship to barometric pressure fluctuations and trends for confined and deep unconfined aquifer systems. The temporal water-level response and negative water-level trend exhibited at piezometer DH-06-01 (Figure 4.5) is opposite to that exhibited by site barometric pressure fluctuations and is, therefore, consistent with this general barometric stress relationship. In contrast, although temporal water-level response characteristics at DH-05-01 exhibit a consistent inverse relationship with temporal barometric pressure fluctuations, the positive 0.0111-ft/day trend over the 25-day period is not. The increasing water-level elevation trend indicates an over-riding background hydrologic condition that exceeds the influence of the exhibited barometric pressure trend during this monitoring period. As noted above, this overriding background trend exhibited at DH-05-01 is believed associated with the hydraulic communication between the underlying higher head Pomona basalt confined aquifer with the overlying, lower hydraulic head fault zone breccia/unconfined aquifer system that is provided by the current piezometer re-completion.

4.2 Temporal Response Characteristics

The following report section pertains primarily to temporal response characteristics produced by barometric-pressure effects and is taken from Spane (1999, 2002) and also presented in Spane (2004) and Didricksen (2004). Earth-tide effects produce similar stress-related responses within wells, but are normally considerably less than those imposed by temporal barometric fluctuations. For this reason, only the effects of barometric pressure are discussed with any detail in this report. Pertinent discussions concerning the effects of Earth tides on aquifers and well water levels are provided in Bredehoeft (1967), Kanehiro and Narasimhan (1980), Van der Kamp and Gale (1983), and Hseih et al. (1988). The following report subsections analyze temporal response characteristics for both monitoring sites using several analysis procedures.

4.2.1 Spectral Analysis

Temporal-response characteristics exhibited within baseline monitoring data can be analyzed using frequency-domain methods to identify underlying influencing factors. Spectral analysis, based on fast Fourier transforms, is a common frequency technique for examining baseline monitoring records (see Spane 2002). Two baseline, 25-day monitoring periods were examined for spectral-analysis characterization: June 25–July 23, 2006 (calendar days 180–205; Figure 4.2), and January 1–26, 2007 (calendar days 1–26; Figures 4.4 and 4.5). The two baseline periods represent two separate monitoring periods in which piezometer DH-05-01 was initially completed within the deeper Pomona basalt confined aquifer, and secondly, re-completed within the shallow, unconfined aquifer in the overlying fault-zone breccia, respectively. To facilitate analysis, the long-term trend effects exhibited in the data record were first removed (i.e., de-trended data set), and data tapering was used to remove noise from the spectral plots. An example of the de-trended data set subjected to spectral analysis from the second baseline monitoring period is shown in Appendix Figure B.1.

Appendix Figures B.2 and B.3 show a comparison of the spectral analysis results for piezometers DH-05-01 and DH-06-01 versus the barometric-pressure spectra for the first and second baseline monitoring period, respectively. Several features in the spectral power plots are evident. First, both piezometers show a high correlation/association with the energy expressed within the barometric spectra, and secondly, more energy is exhibited with the first baseline monitoring period for frequencies centered on 12 and 24 hours (frequencies = 0.0833 and 0.0417 hr^{-1}, respectively). This is expected because of diurnal atmospheric heating/cooling and the associated barometric-pressure effects during the summer time period represented by the first baseline monitoring period.

Figure 4.6 (a) and (b) show a direct comparison of the water-level spectra for the first and second baseline monitoring period, respectively. Visual examination of the spectral patterns indicate a high correlation between the piezometer well-water levels (both in amplitude and phase), particularly for the first baseline monitoring period when both piezometers were completed within the Pomona basalt. Slightly more amplitude divergence is exhibited for the second baseline monitoring period, particularly for lower, longer duration barometric events. The greater divergence exhibited during the second baseline monitoring period is believed attributable to the observation location of the re-completed piezometer DH-05-01 within the lower permeability fault zone breccia section of the overlying unconfined aquifer system.

4.2.2 Barometric Response Model Analysis

As discussed in Spane (2004), barometric fluctuations represent an areal, blanket stress applied directly at land surface and to the open well water-level surface. The manner in which a well/aquifer system responds to changes in atmospheric pressure is variable and directly related to the degree of aquifer confinement and hydraulic/storage characteristics of the well/aquifer system. Rasmussen and Crawford (1997) identify three conceptual models that describe the response of water-level measurements in wells to barometric-pressure change. The models include an instantaneous well response within confined aquifers, a delayed well response within unconfined aquifers (because of the delayed transmission of barometric pressure through the vadose zone), and a delayed well response associated with well characteristics (i.e., wellbore storage and well-skin effects). Diagnostic plots for the three well-response models are shown in Appendix Figure B.4, which were developed from the multiple-regression convolution procedure initially described in Rasmussen and Crawford (1997). The plots show the time-lag dependence of each barometric response model associated with a unit step change in atmospheric pressure. As indicated, each barometric response model has a distinguishing pattern that can be used diagnostically for response-model identification. Spane (1999, 2002) extended these diagnostic plots to include composite responses that represent combined wellbore-storage together with either unconfined or confined aquifer models and open and closed-well systems.

As shown in Appendix Figure B.4, the diagnostic barometric response pattern for a perfectly confined or *nonleaky* confined aquifer model is distinguished by a constant well-response function for a step in pressure for all time lags. This constancy in barometric response is attributed to the lack of dependence on lagged barometric response (i.e., barometric effects are applied "instantaneously" both at the well and to the aquifer system). Of potential relevance to the field investigations conducted at the proposed Black Rock Reservoir would be the identification of leakage effects within barometric response models. Although it is not currently documented in scientific literature, *leaky* confined aquifer systems would be expected to deviate from the exhibited nonleaky response pattern as shown schematically in Appendix Figure B.5. For leaky confined systems, the response pattern would be expected to:

- initially coincide with the non-leaky horizontal pattern (i.e., no time-lag dependence)
- exhibit a transition pattern (i.e., time-lag dependence)
- finally exhibit a horizontal pattern representative of the total system barometric-efficiency characteristics (i.e., combined confined aquifer and confining layer leakage characteristics).

The final total system pattern would be expected to be either greater or *less than* the initial nonleaky pattern and be dependent on existing aquifer/aquitard BE characteristics and vertical hydraulic-head gradient conditions. Leakage would be exhibited by the transition pattern connecting the initial and final horizontal segments of the response pattern. Aquifer systems exhibiting higher leakage effects would be manifested by an earlier or faster expression of the transition leg that is reflective of a time-lag (leakage) dependence.

To examine the barometric response model characteristics, multiple-regression convolution techniques were applied to the de-trended 25-day data sets for the two baseline monitoring periods, following the procedure described in Rasmussen and Crawford (1997) and Spane (1999). The barometric response plots for the two piezometers during the two baseline monitoring periods are shown collectively for comparison purposes in Figure 4.7 (a) and (b), respectively. A number of distinct diagnostic features are evident in response plots for each baseline period.

For the first baseline monitoring period, Figure 4.7(a) suggests that the hydraulic connection afforded by the sand-pack installation at piezometer DH-05-01 with the overlying unconfined aquifer was relatively robust, with both piezometer barometric response plots exhibiting nearly identical and predominantly unconfined-aquifer response behavior. The time-lag dependence was completely resolved within 30 to 35 hours for both piezometer response plots.

For the second baseline monitoring period, Figure 4.7 (b) indicates several important diagnostic features (note: the extended horizontal scale). First, the early-time response characteristics for piezometer DH-05-01 indicate either a low hydraulic conductivity or damaged well-skin condition (see Spane 2002). This is consistent with the hydraulic property test results reported for this interval in Section 5.2.4. Additionally, after approximately 20 hours time-lag dependence, both monitored test intervals (i.e., DH-05-01 unconfined aquifer within the fault zone breccia and DH-06-01 in the Pomona basalt confined aquifer) respond identically and respond barometrically in unison. As indicated in the figure, after approximately 65 hours, the two aquifer systems appear "equilibrated," and no additional barometric time-lag dependence is exhibited (note: time lags extended to 200 hours, but not shown). The stabilized apparent barometric efficiency for the equilibrated region of the response plot is ~0.03.

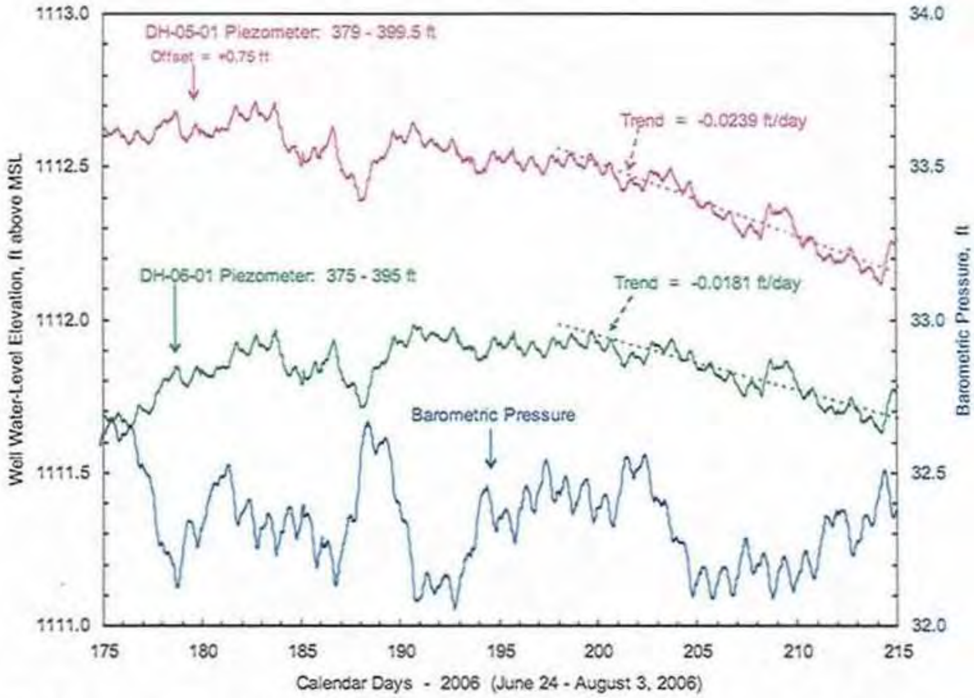


Figure 4.1. Comparison of Baseline Groundwater Dynamics Responses for Piezometers DH-05-01 and DH-06-01: June 24–August 3, 2006

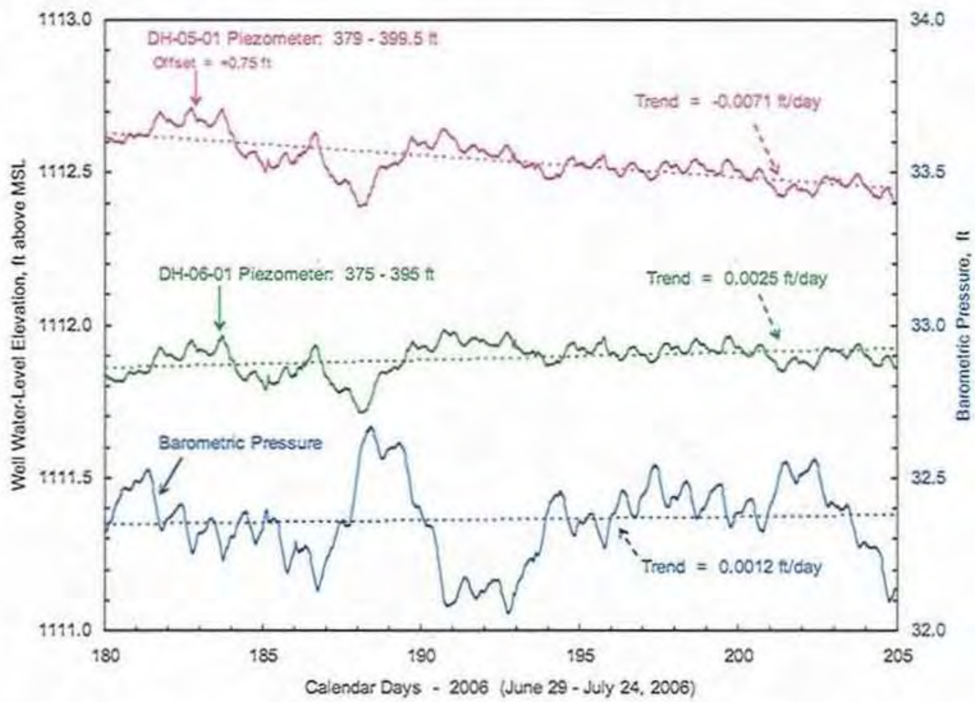


Figure 4.2. Comparison of Baseline Groundwater Dynamics Responses for Piezometers DH-05-01 and DH-06-01: June 29–July 24, 2006

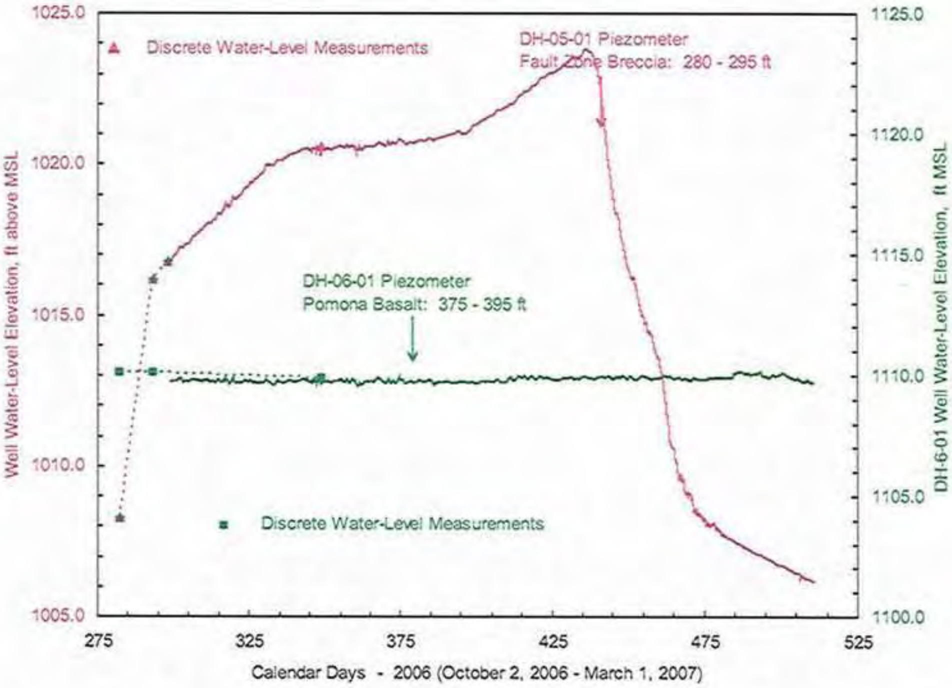


Figure 4.3. Comparison of Baseline Groundwater Dynamics Responses for Piezometers DH-05-01 and DH-06-01: Calendar Days 275 to 425 (CY 2006)

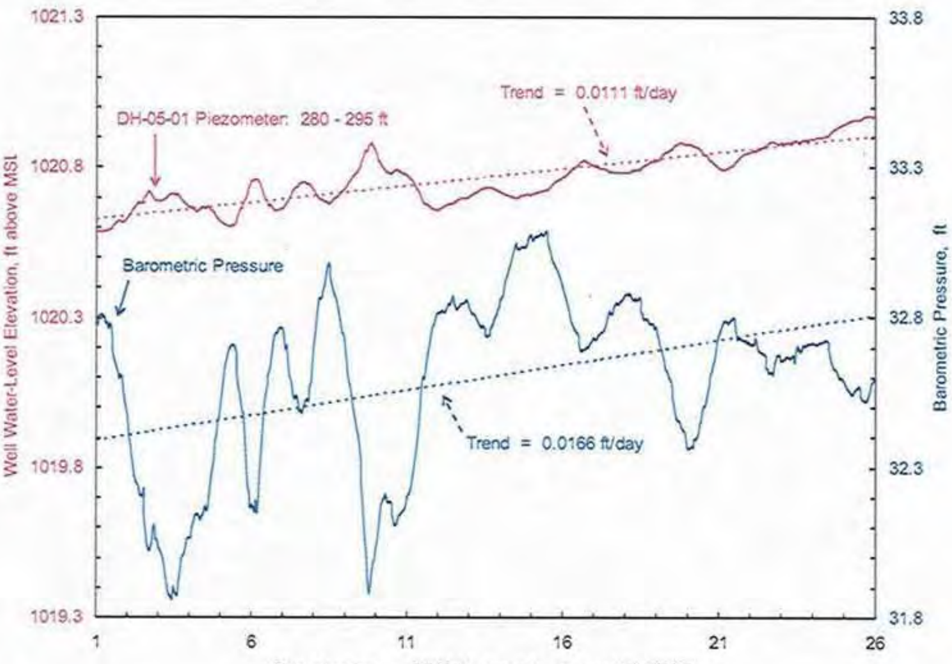


Figure 4.4. Comparison of DH-05-01 Water-Level Elevation and Barometric Pressure Response: Calendar Days 1 to 26 (CY 2007)

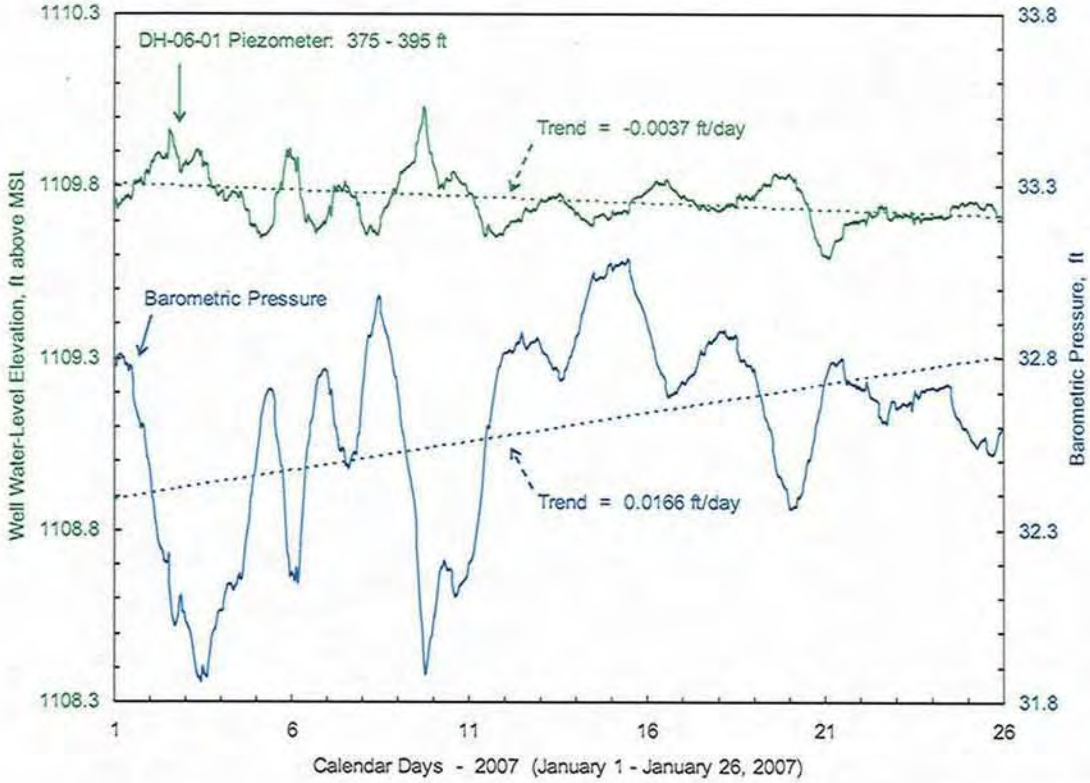
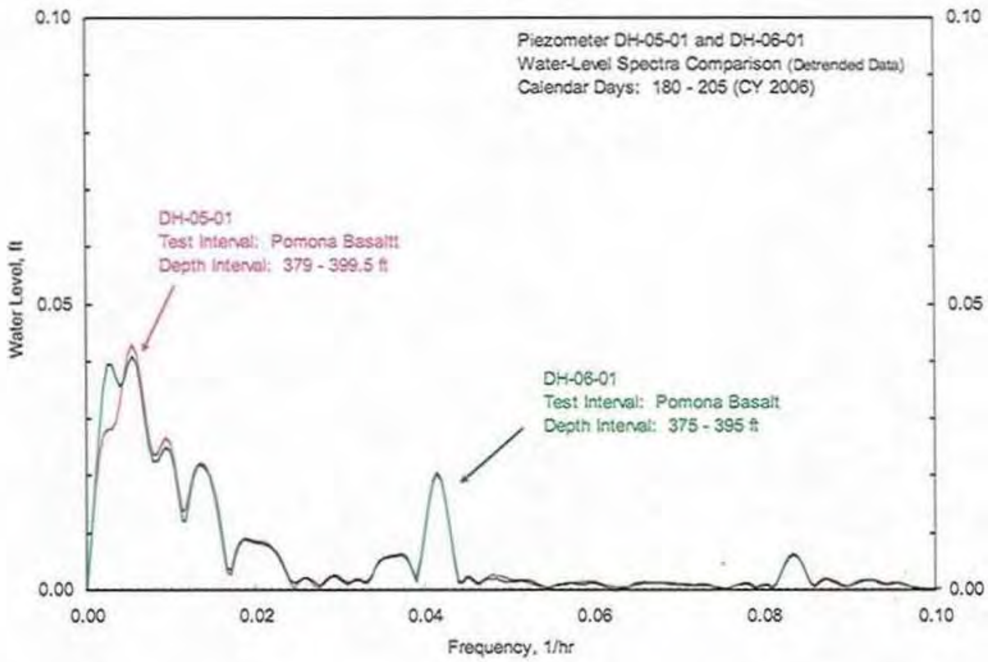


Figure 4.5. Comparison of DH-06-01 Water-Level Elevation and Barometric Pressure Response: Calendar Days 1 to 26 (CY 2007)

(a)



(b)

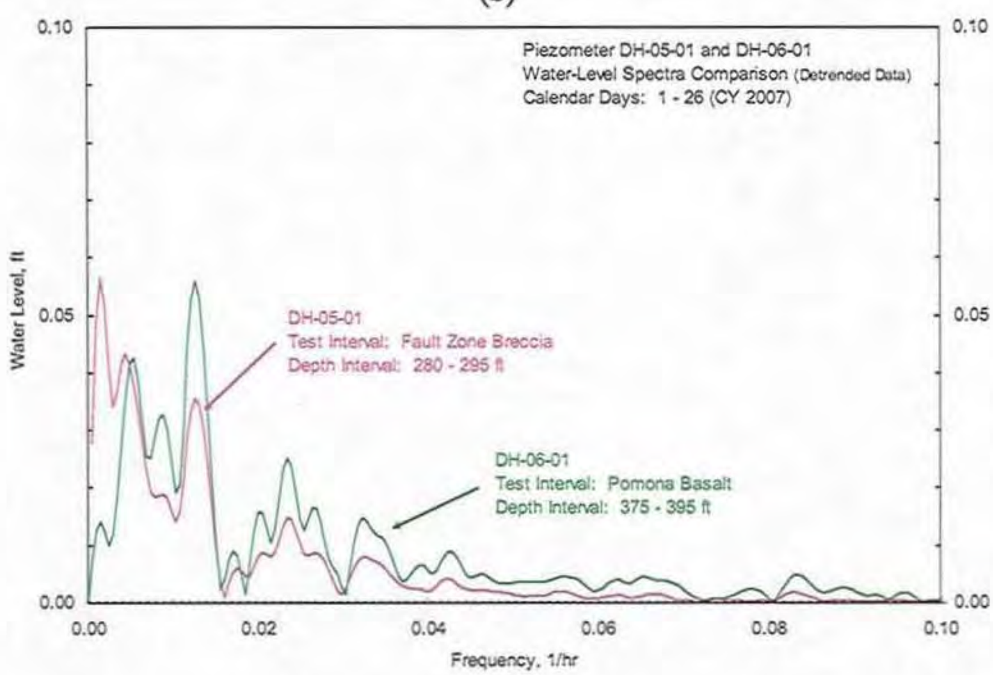
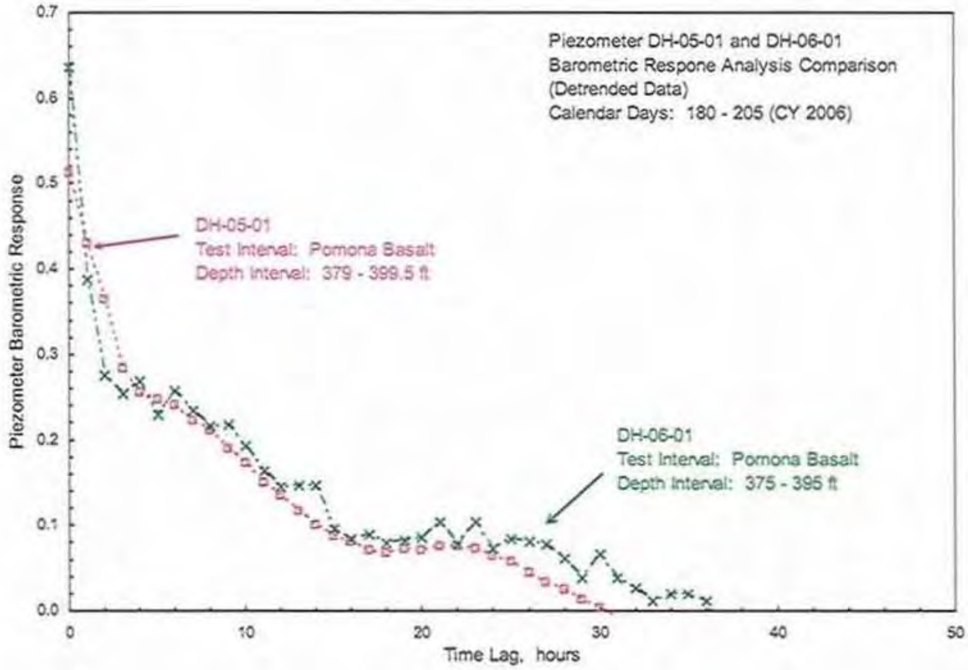


Figure 4.6. Comparison of Continuous Frequency Spectra for Well Water-Level Response for Piezometers DH-05-01 and DH-06-01 During the (a) First Baseline Monitoring Period and (b) Second Baseline Monitoring Period

(a)



(b)

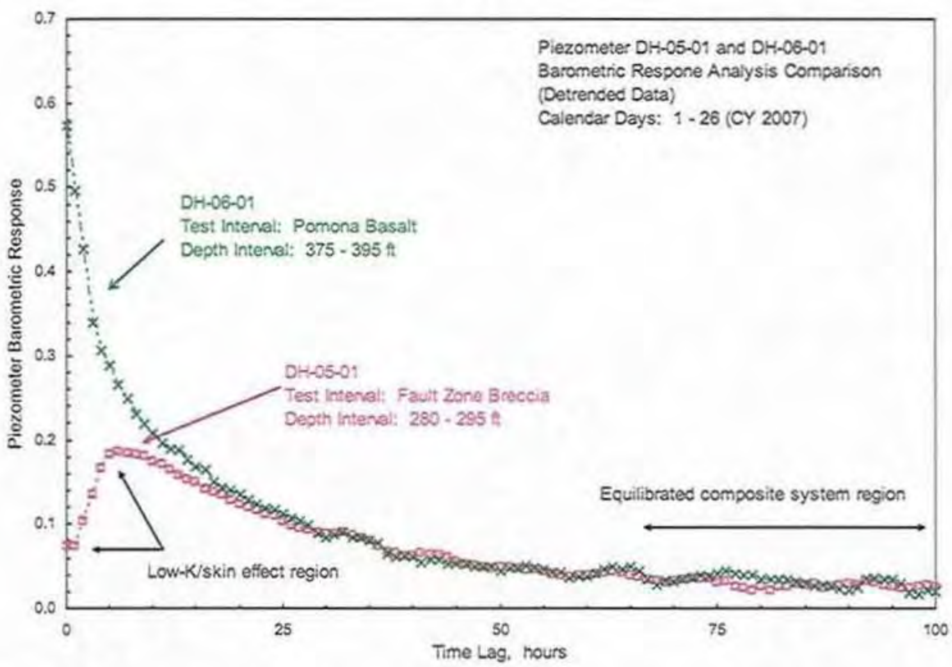


Figure 4.7. Barometric Response Plot Analysis for Well Water-Level Response for Piezometers DH-05-01 and DH-06-01 During the (a) First Baseline Monitoring Period and (b) Second Baseline Monitoring Period

5. Hydraulic Test Results: Borehole DH-05-01

In this section, a description of hydrologic tests and associated results for the various vadose-zone (unsaturated) and saturated-zone test intervals is provided. Tables 5.1 and 5.2 provide general test activity and information pertaining to borehole hydrologic characterization tests completed at DH-05-01 while the corehole was progressively drilled and tested between December 6, 2005 and February 22, 2006. Following completion of drilling activities, corehole DH-05-01 was initially completed as a piezometer within the Pomona basalt over the depth interval of 379 to 399.5 ft. However, after it was recognized that the piezometer original completion did not completely isolate the monitoring interval within the Pomona basalt confined aquifer system, remedial activities were initiated, and the corehole was subsequently re-completed as a piezometer monitoring the overlying unconfined aquifer over the depth interval 280 to 295 ft. Single-well tests were conducted within DH-05-01 within the original and re-completed piezometer installations on May 25 and October 9, 2006, respectively.

5.1 Vadose Zone Tests

Six vadose zone depth intervals were characterized for hydraulic property determination during the course of drilling DH-05-01 down to a depth of 151 ft. The vadose zone test results provide valuable hydrologic information concerning the permeability of geologic materials above the water table, which would be located along the south dam abutment of the proposed Black Rock Reservoir. The vadose zone tests were conducted using the constant-head injection-test method described in Section 3.2.1. Vadose zone test intervals within test borehole DH-05-01 were selected based on detailed geologic information obtained from visual core analysis performed in the field at the drill-site location.

Briefly stated, the vadose zone tests were conducted in open borehole sections of DH-05-01 that were core-drilled below the driven 6-in. drill casing. To initiate the test, the open corehole section was saturated by rapidly filling the corehole/casing system with freshwater to a selected depth from the top of the drill casing. Gravity injection flow rates required to maintain the level of water within the corehole (i.e., head above the bottom of the corehole) were monitored during the course of the injection-test period. Injection testing continued until injection rates became uniform with time, indicating the establishment of pseudo-steady-state conditions. Normally, constant head injection testing was completed within 2-hours. In-borehole pressures were monitored during testing with a pressure transducer datalogger system.

Saturated hydraulic conductivity values for the vadose zones tested were calculated using the analytical methods described in Section 3.2.1. The vadose zone hydraulic properties calculated fall within the reported range of hydraulic conductivity values determined for Saddle Mountain basalt units on the nearby Hanford Site. A summary of pertinent test information and analysis results obtained for the vadose zone tests are provided in Tables 5.1 and 5.2. Test descriptions and analytical results obtained for the individual vadose zone test intervals are presented below. Selected analysis figures for the vadose zone tests are presented in Appendix C.

5.1.1 Pomona Basalt: 65.6 to 70.6 ft

Hydrologic testing of this vadose zone test interval was accomplished by core drilling ~5 ft below the advanced PQ drilling rods (depth of 65.6 ft) to a corehole depth of 70.6 ft. At the time of testing, the 6-in. well casing was set at a depth of 60 ft. The coring was accomplished using clear water as the circulating drilling fluid. No core was recovered from this test section; however, the general geologic description for the unit tested indicates that the Pomona basalt at this location consists of black to gray, moderately hard to hard, mostly fine-grained, vesicular to dense, aphanitic basalt, and basalt breccia.

A pressure transducer was placed ~5 ft from the bottom of the corehole for the purpose of measuring downhole pressure buildup within the borehole during the constant-head injection test. A two-step, constant-head injection test was planned for this test interval. The first step of the injection test was initiated at 1023 hours, PST on December 6, 2005, by rapidly filling the corehole-casing system with freshwater to near the top of the test casing that extended a distance of ~4.6 ft above land surface, using a surface pump/water tank system. Injection rates during the first step were relatively uniform following the initial minutes of the test and averaged 2.0 gpm during the last 30 min of this injection step. This value was used as the pseudo-steady-state injection rate, Q_s. After 36 minutes into the test, the second step of the injection test was initiated by closing in the wellhead and increasing the injection rates in an attempt to increase the pressure-injection head. Comparison of injection-test results conducted at different injection pressures provides information that can be used for the purpose of assessing stress dependency. The injection pressure during the second step, however, could not be maintained at a uniform level, and the test was subsequently terminated at 1119 hours, PST, on December 6, 2005. A total of 150 gal of freshwater was estimated to have been injected into the test interval during the course of the test.

For the first injection step, downhole pressure readings remained relatively constant during the test and equate to a calculated average constant bottom test interval injection head, H, of 75.2 ft for the test. Based on these assigned values and the calculated test-relationship parameters X and T_u (listed in Table 5.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity for the first injection step, K_s, of 0.46 ft/day is indicated for this test interval. Pertinent test and analysis information for this vadose zone interval test are presented in Tables 5.1, 5.2, and Appendix Figure C.1. No hydraulic-property characterization is possible for the second injection step because of the lack of stability of pressures that is discussed above.

5.1.2 Pomona Basalt: 73.6 to 77.8 ft

Hydrologic testing of this vadose zone test interval was accomplished by core drilling ~5 ft below the advanced PQ drilling rods (depth of 73.6 ft), to a corehole depth of 77.8 ft. At the time of testing, the 6-in. casing was set at a depth of 60 ft. The coring was accomplished using clear water as the circulating drilling fluid. Only 45% of the core was recovered from this test section and is shown in Appendix Figure D.1. The general geologic description for this unit tested indicates that the Pomona basalt at this location consists of black to gray, moderately hard to hard, mostly fine-grained, vesicular to dense, aphanitic basalt, and basalt breccia.

A pressure transducer was placed ~6 ft from the bottom of the corehole for the purpose of measuring downhole pressure buildup within the borehole during the constant-head injection test. A single-step, constant-head injection test was planned for this test interval. The injection test was initiated at 1210 hours, PST on December 7, 2005, by rapidly filling the corehole-casing system with freshwater to a height ranging between 21 and 27 ft above the bottom of the corehole with a surface pump/water-tank system. Injection rates were variable during the first 20 minutes of the test, and this variability is reflective in fluctuations for pressure head evident during this initial period of the test (see Appendix Figure D.2). The injection flow rate was then fixed at ~1.5 gpm, and the downhole pressure head stabilized during the remaining 50 minutes of the injection. The final stabilized downhole pressure head of 22.3 ft was maintained during the last 20 minutes of the test. The injection test was subsequently terminated after 71 minutes at 1321 hours, PST, on December 7, 2005. A total of 95 gal of freshwater was estimated to have been injected into the test interval during the course of the test.

Based on the observed injection test conditions and the calculated test-relationship parameters X and T_u (listed in Table 5.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity, K_s, of 1.39 ft/day is indicated for this test interval. Pertinent test and analysis information for this vadose zone interval test is presented in Tables 5.1, 5.2 and Appendix Figure C.2.

5.1.3 Esquatzel/Umatilla Basalt: 93 to 98 ft

Hydrologic testing of this vadose zone test interval was accomplished by drilling 5-ft below the advanced 6-in. casing (set at 93 ft), to a borehole depth of 98 ft. The interval was not cored and was drilled using a rock bit with a 0.490-ft diameter. The drilling was accomplished using compressed air as the borehole circulating drilling fluid. The drilling assembly was then removed from the borehole, clearing the 5-ft open borehole interval for testing. The general geologic description for this unit tested indicates that the Esquatzel and Umatilla basalts at this location consist of black to gray, hard, mostly fine-grained dense basalt and basalt breccia.

Following removal of the drilling assembly, a pressure transducer was placed at a depth of 91.9 ft for measuring downhole pressure buildup within the borehole during the constant-head injection test. A single-step, constant-head injection test was planned for this test interval. The injection test was initiated at 1020 hours, PST, on December 17, 2005, by rapidly injecting freshwater into the borehole-casing system to a height ranging between 8 and 13 ft above the bottom of the borehole with a surface pump/water tank system. Injection rates were variable, ranging between 11.5 and 24 gpm during the first 10 minutes of the test. This variability is reflective in fluctuations for pressure head evident during this initial period of the test (see Appendix Figure D.3). The injection flow rate was controlled and set at ~14 gpm, and the downhole pressure head slowly stabilized during the remaining 40 minutes of the injection. The final stabilized downhole pressure head of 10.7 ft was maintained during the last 20 minutes of the test. The injection test was subsequently terminated after a total injection time of 50 minutes at 1110 hours, PST, on December 17, 2005. A total of 665 gal of freshwater was estimated to have been injected into the test interval during the course of the test.

Based on these assigned values and the calculated test relationship parameters X and T_u (listed in Table 5.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity range, K_s, of 17.1 to 24.2 ft/day is indicated for the test interval. This range in estimated hydraulic conductivity is reflective of the uncertainty associated with calculating the saturated conductivity coefficient, C_u, which is highly sensitive to low stress conditions. The listed best-estimate value for K_s of 20.7 ft/day represents the average of the calculated lower and upper range values. Pertinent test and analysis information for this vadose zone interval test is presented in Tables 5.1, 5.2, and Appendix Figure C.3.

5.1.4 Esquatzel/Umatilla Basalt: 113 to 119 ft

Hydrologic testing of this vadose zone test interval was accomplished by drilling 6-ft below the advanced 6-in. casing (set at 113 ft), to a borehole depth of 119 ft. The interval was not cored and was drilled using a rock bit with a 0.490-ft diameter. The drilling was accomplished using compressed air as the borehole circulating drilling fluid. The drilling assembly was then removed from the borehole, clearing the 6-ft open borehole interval for testing. The general geologic description for this unit tested indicates that the Esquatzel and Umatilla basalts at this location consists of black to gray, hard, mostly fine-grained dense basalt and basalt breccia.

Following removal of the drilling assembly, a pressure transducer was placed at a depth of 111.8 ft for measuring downhole pressure buildup within the borehole during the constant-head injection test. A single-step, constant-head injection test was planned for this test interval. The injection test was initiated at 1341 hours, PST, on December 17, 2005, by rapidly injecting freshwater into the borehole-casing system to a height ranging between 7 and 15 ft above the bottom of the borehole with a surface pump/water tank system. Injection rates were variable, ranging between 8.5 and 10.5 gpm during the first 9 minutes of the test. This variability is reflective in fluctuations for pressure head evident during this initial period of the test (see Appendix Figure D.4). The injection flow rate was lowered and controlled at a set value of ~4.1 gpm, and the downhole pressure head slowly stabilized during the remaining 30 minutes of the injection. The final stabilized downhole pressure head of 10.9 ft was maintained during the last 30 minutes of the test. The injection test was subsequently terminated after a total injection time of 40 minutes at 1421 hours, PST, on December 17, 2005. A total of 245 gal of freshwater was estimated to have been injected into the test interval during the course of the test.

Based on these assigned values and the calculated test-relationship parameters X and T_u (listed in Table 5.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity range, K_s, of 4.56 to 6.31 ft/day is indicated for the test interval. This range in estimated hydraulic conductivity is reflective of the uncertainty associated with calculating the saturated conductivity coefficient, C_u, which is highly sensitive to low-stress conditions. The listed best-estimate value for K_s of 5.43 ft/day represents the average of the calculated lower and upper range values. Pertinent test and analysis information for this vadose zone interval test is presented in Tables 5.1, 5.2, and Appendix Figure C.4.

5.1.5 Esquatzel/Umatilla Basalt: 123 to 129 ft

Hydrologic testing of this vadose zone test interval was accomplished by drilling 6-ft below the advanced 6-in. casing (set at 123 ft) to a borehole depth of 129 ft. The interval was not cored and was drilled using a rock bit with a 0.490-ft diameter. The drilling was accomplished using compressed air as the borehole circulating drilling fluid. The drilling assembly was then removed from the borehole, clearing the 6-ft open borehole interval for testing. The general geologic description for this unit tested indicates that the Esquatzel and Umatilla basalts at this location consist of black to gray, hard, mostly fine-grained dense basalt and basalt breccia.

Following removal of the drilling assembly, a pressure transducer was placed at a depth of 119.3 ft for measuring downhole pressure buildup within the borehole during the constant-head injection test. A single-step, constant-head injection test was planned for this test interval. The injection test was initiated at 1147 hours, PST, on December 19, 2005, by rapidly injecting freshwater into the borehole-casing system to a height ranging between 13 and 17 ft above the bottom of the borehole with a surface pump/water tank system. Injection rates were variable, initially starting at ~9.5 gpm and slowly lowering to 7.5 gpm during the first 10 minutes of the test. The injection flow rate was then lowered and controlled at a set value of ~7.1 gpm, and the downhole pressure head slowly stabilized during the remaining 40 minutes of the injection. The final stabilized downhole pressure head of 16.75 ft was maintained during the last 30 minutes of the test (see Appendix Figure C.5). The injection test was subsequently terminated after a total injection time of 53 minutes at 1240 hours, PST, on December 19, 2005. A total of 455 gal of freshwater was estimated to have been injected into the test interval during the course of the test.

Based on these assigned values and the calculated test relationship parameters X and T_u (listed in Table 5.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadosezone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity range, K_s, of 4.76 to 6.51 ft/day is indicated for the test interval. This range in estimated hydraulic conductivity is reflective of the uncertainty associated with calculating the saturated conductivity coefficient, C_u, which is highly sensitive to low-stress conditions. The listed best-estimate value for K_s of 5.64 ft/day represents the average of the calculated lower and upper range values. Pertinent test and analysis information for this vadose zone interval test is presented in Tables 5.1, 5.2, and Appendix Figure C.5.

5.1.6 Esquatzel/Umatilla Basalt: 133 to 151 ft

Hydrologic testing of this vadose zone test interval was accomplished by drilling 18 ft below the advanced 6-in. casing (set at 133 ft), to a borehole depth of 151 ft. The interval was not cored and was drilled using a rock bit with a 0.49-ft diameter. The drilling was accomplished using compressed air as the borehole circulating drilling fluid. The drilling assembly was then removed from the borehole, clearing the 18-ft open borehole interval for testing. The general geologic description for this unit tested indicates that the Esquatzel and Umatilla basalts at this location consist of black to gray, hard, mostly fine-grained dense basalt and basalt breccia.

Following removal of the drilling assembly, a pressure transducer was placed at a depth of 131.8 ft for measuring downhole pressure buildup within the borehole during the constant-head injection test. A single-step, constant-head injection test was planned for this test interval. The injection test was initiated at 1415 hours, PST, on December 19, 2005, by rapidly injecting freshwater into the borehole-casing system with a surface pump/water tank system. The initial injection rate of ~9.5 gpm produced a pressure transducer over-range (i.e., > 45 ft) during the first 15 minutes of the injection test. The injection rate was lowered to 2.2 gpm, which allowed the fluid column height above the bottom of the borehole to stabilize within the range of calibration of the transducer used. The downhole pressure head slowly stabilized at a value of 33.6 ft during the last 30 minutes of the injection (see Appendix Figure C.6). The injection test was subsequently terminated after a total injection time of 60 minutes at 1515 hours, PST, on December 19, 2005. A total of 240 gal of freshwater was estimated to have been injected into the test interval during the course of the test.

Based on these assigned values and the calculated test relationship parameters X and T_u (listed in Table 5.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity value, K_s, of 0.45 ft/day is indicated for the test interval. Pertinent test and analysis information for this vadose zone interval test is presented in Tables 5.1, 5.2, and Appendix Figure C.6.

5.2 Groundwater Test Zones

Two groundwater test zones (within the fault-zone breccia and a composite section of fault-zone breccia, Rattlesnake Ridge interbed, and Pomona basalt) were tested during the course of drilling DH-05-01 to a depth of 401 ft. The test results provide valuable hydrologic characterization information concerning the transmission, storage, and leakage characteristics of these hydrogeologic units in the vicinity of the proposed south abutment area. In addition to these tests performed during drilling, hydrologic tests were also conducted after drilling within the piezometer installation. As noted in Section 2 (Figure 2.2), the initial piezometer completion was adversely affected by the improper placement of sandpack materials within the borehole surrounding the piezometer. This improper sandpack installation afforded hydraulic communication between the underlying monitored Pomona basalt confined aquifer and the overlying unconfined aquifer that occurs within the fault-zone breccia. The groundwater test zones were conducted with a variety of test methods described in Section 3.2.2. Groundwater test intervals within DH-05-01 were selected based on detailed geologic information obtained from visual core analysis performed in the field at the drill site location.

Hydraulic conductivity values for the groundwater zones tested at DH-05-01 were calculated using the analytical methods described in Section 3.2.2. A summary of pertinent test information and analysis results obtained for the groundwater zones tested is provided in Table 5.1. Test descriptions and analytical results obtained for the individual groundwater-zone test intervals are presented below. Selected analysis figures for the tests are presented both in this section and in Appendix E.

5.2.1 Fault Zone Breccia: 269.2 to 287.4 ft

Hydrologic testing of this groundwater test interval was accomplished by core drilling to a depth of 287.4 ft, and the PQ drilling rods retracted to a depth of 269.2 ft, exposing an 18.2-ft corehole section for testing. At the time of testing, the 6-in. casing was set at a depth of 143 ft. The coring was accomplished using a polymer drilling mud with sealant as the circulating drilling fluid. Core recovery ranged between 95 to 100% over the test-interval section. Selected core pictures of the test interval are shown in Appendix Figures D.2A and 2B. The general geologic description of the unit tested is a fault-zone breccia that is moderately weathered at the top of the test section, which becomes more intensely altered with depth, with an adhering-clay to sandy-clay matrix.

To test this interval, the downhole packer/pressure probe test system was lowered within the borehole, and the packer was set inside the PQ drilling rods (due to open borehole stability concerns), at a depth of 269 ft. A 10-ft well screen was attached below the packer assembly. This theoretically isolated the test interval 269.2 to 287.4 ft for testing; however, the PQ drilling rods had been retracted ~18.2 ft (to a depth of 269.2 ft), and fluid by-pass around the drilling rods was possible. A static water level was not determined before testing; however, the projected recovery level following testing indicates a depth-to-water of 268 ft (elevation = 1008.2-ft MSL) for the test interval. This is consistent with an initial static depth-to-water of 267.8 ft measured on October 9, 2006, two days following re-completion of the piezometer in DH-05-01 within the fault-zone breccia.

A single-step, constant-rate injection test was initiated at 1250 hours, PST, on February 15, 2006, by injecting freshwater into the borehole-casing system with a surface pump/water tank system. Injection rates of ~17 gpm were observed during the initial minutes of the test, which were subsequently adjusted lower to an injection rate of 8.7 gpm within 5 minutes into the test. The injection rate averaged 8.76 gpm and varied less than 0.2 gpm from this value for the remainder of the test. The injection test was subsequently terminated after a total injection time of 191 minutes at 1601 hours, PST, on February 15, 2006. A total of 1,675 gal of freshwater was estimated to have been injected into the interval during testing.

Figure 5.1 shows the associated, downhole pressure response during and immediately following terminating the constant-rate injection test. As indicated in the figure, a significant temporary decline in pressure was observed 142 minutes into the test (at 913 minutes, February 15, 2006). The cause of this observed decline is not associated with a decrease in injection rate and is believed to be associated with a change in the test-interval conditions. A plausible explanation is that the increasing injection pressure (at ~ 100 ft of pressure head) produced a sudden fluid by-pass between the PQ drilling rods and the surrounding collapsed borehole wall. The fluid by-pass would increase the effective test interval length accepting the injection water and produce a momentary decline in pressure. The abrupt pressure build-up following the momentary decline also suggests that the fluid by-pass condition was temporary and that the borehole may have re-collapsed around the drilling rods.

In an effort to analyze the injection-test results for hydraulic-property characterization, the injection pressure head build-up data before the anomalous pressure change (i.e., at an elapsed time of 142 minutes) were the focus of the analysis. To analyze pressure build-up data, the pre-test, static formation pressure must be known. The formation pressure head was not measured before testing, but can be estimated by projecting (linear-regression) late-time recovery data to unity using a standard Horner (1951) recovery plot, as described in Earlougher (1977). Figure 5.2 shows the projected late-time recovery following termination of the injection test. As indicated, a projected static depth-to-water (converted from downhole pressure measurements) of 268.03 ft is indicated. This is equal to a hydraulic head value for the unconfined aquifer of 1008.07-ft MSL (based on a ground surface elevation of 1276.1-ft MSL). This water-table elevation is almost identical to the observed water-level elevation measured within DH-05-01 (i.e., 1,008.3-ft MSL) one day after re-completing the piezometer installation within the fault-zone breccia on October 7, 2006, as discussed in Sections 4 and 5.2.4.

Given the projected pre-test static head conditions, the initial 142 minutes of injection pressure build-up data were analyzed using two analytical methods. Because the test response is dominated by wellbore storage effects, standard straight-line solutions are not applicable. For an initial assessment, the build-up injection response was converted to an equivalent slug-test response and analyzed using slug-test-type curve methods described in Section 3.2.2.1. The convergence of pumping-test to equivalent slug-test responses is discussed in Peres (1989) and Spane (1996) and is useful for establishing bounds on storativity, S, and hydraulic conductivity, K, for the test interval examined. These initial slug-test analysis values were then applied and adjusted for calculated constant-rate pumping/injection-test-type curves (Section 3.2.2.3), which were used to match the observed build-up pressure-head data. Because of the flow variability exhibited during the initial minutes of the injection test, emphasis was placed only on matching the pumping/injection type curves to pressure build-up data after ~10 minutes into the test.

Two aquifer conditions were used in the analyses: full and partially penetrating aquifer scenarios. For the partially penetrating aquifer analysis, the base of the fault-zone breccia aquifer was assumed to be the top of the underlying Rattlesnake Ridge interbed at 301.1 ft. Given a static depth-to-water of ~268 ft, this yields an aquifer thickness, b, estimate of ~33 ft. This aquifer thickness was used for this analysis approach. For the full penetration aquifer analysis, the aquifer thickness was assumed to be equal to the open borehole section, i.e., 18.2 ft.

Figures 5.3 and 5.4 show examples of the converted slug test and injection build-up analyses, respectively, for the partially penetrating aquifer assumption. As indicated, a relatively close correspondence for average hydraulic conductivity (K = 0.59 and 0.78 ft/day) for the test interval was obtained for the two analytical methods. Table 5.1 lists the hydraulic parameter estimate results for T, K, and S for the two analytical methods under full and partially penetrating aquifer conditions. As indicated in the table, only T varied significantly, which is attributable to its direct association with aquifer thickness. For the converted equivalent slug-test analysis, K and S ranged between 0.78 and 0.84 ft/day, and 7.0E-4 and 8.0E-4, respectively. In comparison, for the injection type-curve analysis, K ranged between 0.59 and 0.63 ft/day, while a uniform value for S of 1E-3 was indicated for the two aquifer-analysis conditions. No skin effects, S_k, are assumed to occur during the test, and based on the S values from the analysis matches, no significant skin effects are believed operable during this test. Because of the short duration of the test, infinite-acting radial flow conditions were not reached and, therefore, a quantitative estimate for specific yield, S_y, is not attainable. However, the type-curve analysis applied suggests a bounding value for $S_y \geq 0.02$.

It should be noted that because of the adverse impact of the potential hydraulic by-pass observed during testing (i.e., at 142 min into the injection) as well as the impact of de-saturation of the vadose zone that was previously saturated during the injection test, no effort was attempted to analyze the recovery fall-off response data observed following termination of the injection test.

5.2.2 Pomona Basalt/Composite Zone: 319 to 334.6 ft/(287.6 to 334.6 ft)

Hydrologic testing of this groundwater test interval was accomplished by core drilling to a depth of 334.6 ft, and the HQ drilling rods retracted to a depth of 319 ft exposing a 15.6 ft open corehole section for testing. At the time of testing, a 4-in. casing was set at a depth of 287.6 ft. The coring was accomplished using a polymer drilling mud with sealant as the circulating drilling fluid. Core recovery ranged between 74 to 100% over the test-interval section. Core pictures of the test interval are shown in Appendix Figures D.3A through 3E. The general geologic description of the composite zone cored below the 4-in. casing includes: a fault zone breccia 287.4 to 301.1 ft, moderately to intensely weathered (Appendix Figures D3A and 3B); Rattlesnake Ridge interbed 301.1 to 310.7 ft, a moderately weathered/altered tuffaceous, fine-grained sedimentary unit (Appendix Figures 3B and 3C); and Pomona basalt 310.7 to 334.6 ft, vesicular, moderately weathered basalt (Appendix Figures D3C, 3D, and 3E). The composite cored section intersects two aquifer systems at the test site; the unconfined aquifer within the fault zone breccia, and a confined aquifer system within the underlying Pomona basalt. The Rattlesnake Ridge interbed serves as the principal confining layer between the two aquifer systems, which exhibits a significant hydraulic head difference of ~102 ft (i.e., unconfined aquifer = ~1008-ft MSL; confined aquifer = ~1110-ft MSL); see Figure 2.5).

To test this interval, the downhole packer/pressure probe test system was lowered within the borehole and the packer set inside the HQ drilling rods (due to open borehole stability concerns), at a depth of ~318 ft. A 10-ft well screen was attached below the packer assembly. This theoretically isolated the test interval between 319 and 334.6 ft for testing; however, the HQ drilling rods had been retracted ~15.6 ft (to a depth of 319 ft), and fluid by-pass around the drilling rods was possible. As will be discussed, there is evidence during the testing sequence that some minor hydraulic communication within the corehole existed between the open Pomona basalt test section and the overlying unconfined aquifer above the confining Rattlesnake Ridge interbed.

A single-step, constant-rate injection test was initiated at 1155 hours, PST on February 21, 2006, by injecting freshwater into the borehole-casing system utilizing a surface pump/water tank system. Injection rates of ~8 gpm were observed during the initial minutes of the test, which were subsequently adjusted lower to an injection rate of 4.6 gpm within 10 minutes into the test. The injection rate averaged 4.62 gpm and varied less than 0.1 gpm from this value for the remainder of the test. The injection test was subsequently terminated after a total injection time of 216 minutes at 1531 hours, PST on February 21, 2006. A total of 1,025 gal of freshwater were estimated to have been injected into the interval during testing.

Figure 5.5 shows the associated, downhole pressure response during, and immediately following terminating the constant-rate injection test. As indicated in the figure, injection pressures were relatively stable during the majority of the test. Figure 5.6 shows the fully recovered water-level elevation observed within the test interval with extended recovery time. As indicated, the recovered test interval water-level elevation following injection is ~6.5 ft lower (~1103.5-ft MSL) than observed for the isolated Pomona basalt confined aquifer system (~1110-ft MSL; Section 4). This observed lower-than-expected water level is reflective of the composite hydraulic head condition observed for this test zone. The composite head observed is a function of the higher hydraulic head within the confined aquifer, the lower hydraulic head within the overlying unconfined aquifer, and the *low* hydraulic connection between the two aquifer systems afforded by the HQ drilling rods and collapsed-formation contact boundary.

In an effort to analyze the injection-test results for hydraulic property characterization, both the observed pressure recovery data period and the active injection-test data were examined for possible characterization analysis. Figure 5.7 shows a diagnostic test data and data-derivative plot of pressure recovery following termination of the injection test. As shown, the majority of the early test data (which are more reflective of the open test interval/confined aquifer conditions) is dominated by wellbore storage effects, while the later recovery data are more representative of the combined composite aquifer test conditions. The complexity of the composite aquifer test conditions (hydraulic head differences and unknown hydraulic conductance of the wellbore connection between the two aquifers), makes analysis of this portion of the recovery data non-unique. Therefore, efforts were focused on analyzing the early-recovery test that is more representative of the open corehole test interval section (i.e., 319 to 334.6 ft).

Based on the diagnostic plot shown in Figure 5.7, recovery data before 20 minutes are considered applicable and primarily reflective of the open corehole test interval. As noted, the early recovery data are dominated by well-bore storage effects, which makes analysis using standard constant-rate pumping/injection type curves rather ambiguous. To facilitate analysis of the early-recovery test data, the recovery data were converted to an equivalent slug-test response and then analyzed using a standard slug-test-type curve and derivative plot methods described in Section 3.2.2.1. This is the same approach used and described previously for analyzing the constant-rate injection pressure build-up data within the overlying fault-zone breccia (269.2 to 287.4 ft).

Figure 5.8 shows the converted equivalent slug test data and data derivative and analysis plots. As indicated, a close match was obtained using the following parameter values for the test interval: transmissivity, T, = 4.4 ft^2/day; average hydraulic conductivity, K, = 0.28 ft/day; and storativity, S, = 4.8E-6. No skin effects, S_k, were assumed to occur, and based on the S-value analysis match, no significant skin effects are believed operable during this test. It should also be noted that the analysis is based on a fully penetrating aquifer test condition, which as shown for the previous fault-zone breccia test interval did not deviate appreciably from partially penetrating aquifer analysis conditions (i.e., for K and S).

As shown in Figure 5.5, the injection build-up pressure exhibited variability during the initial minutes of the injection, and after minor flow adjustments became rather steady for the majority of the test. This relative stability in injection pressure and lack of significant variation in injection flow rate for most of the test allows the opportunity to analyze the injection phase of the test as a constant-pressure injection test. Figure 5.9 shows the plot of observed injection flow rate and matched predicted injection rate versus time using the transient analytical method for constant-drawdown (head) tests presented in Jacob and Lohman (1952) and Lohman (1972). The matched flow-rate response plot is based on a calculated constant head value, ΔH, of 142.2 ft (Figure 5.5) above confined aquifer conditions, and the following hydrologic parameter values: T = 5.47 ft^2/day, K = 0.35 ft/day, and S = 8.0E-4. To demonstrate the sensitivity of the analysis to varying K, the simulated flow-rate response is also shown additionally for K values of 0.1 and 0.7 ft/day, with the remaining hydrologic parameters remaining fixed. As shown, the predicted response is highly sensitive to K.

For a qualitative comparison with the transient analysis result, a steady-state analysis for the constant-head test was also performed, using Equation 3.5. For the steady-state analysis, the following input values were used: Q_{avg} = 4.62 gpm; ΔH, = 142.2 ft; R = 100 ft (assumed);

r_w = 0.328 ft. Based on these input parameters, a calculated value for T and K of 6.42 ft^2/day and 0.41 ft/day were calculated, respectively. These steady-state derived estimates compare closely with the transient determined analysis results; however, they are not included in the test summary or best-estimate values because of the uncertainty of determining the radius of test investigation, R, and whether steady-state conditions were established during testing.

Table 5.1 lists pertinent hydraulic parameter estimate results for T, K, and S for the two test analysis methods applied for this test-interval characterization. It should be noted that because of the adverse impact of the hydraulic communication between the two aquifer systems observed during and following completion of the injection test, the hydraulic-property estimates assigned to the open corehole test section should be viewed with a moderate degree of uncertainty; however, the estimates are believed to provide conservative estimates for the analyzed hydrologic characterization parameters.

5.2.3 Pomona Basalt: 379 to 399.5 ft

Testing for this Pomona basalt depth interval (i.e., 379 to 399.5 ft) was conducted on May 25, 2006, after termination of drilling activities and piezometer completion installation (Section 2; Figure 2.2). At the time of the Pomona basalt piezometer tests at DH-05-01, nearby borehole DH-06-01 had been completed (on May 20, 2006) with a piezometer over a similar monitor depth interval (i.e., 375 to 395 ft). The geologic core description for this test interval indicates a slightly weathered, moderately to intensely fractured basalt section. As noted previously in Section 2, the piezometer completion did not completely isolate the monitoring interval within the Pomona basalt confined aquifer system, and a degree of hydraulic communication existed via the sandpack installation with the overlying unconfined aquifer system. The relatively high permeability of the monitored Pomona basalt interval (and relatively low permeability for the overlying unconfined aquifer) and relatively short-duration of the tests performed indicate that the hydraulic properties determined from the piezometer tests are largely reflective of the Pomona basalt confined aquifer system at this location.

Two pneumatic slug tests were conducted at piezometer DH-05-01 on May 25, 2006, by lowering the water column within the piezometer with compressed gas to depress the fluid-column level to the designed test stress levels. The actual stress level applied for each test was determined by comparing applied surface gauge pressures with observed downhole pressure-transducer readings that were projected to the time of test initiation. After the monitored fluid column was stabilized for ~10 minutes at the prescribed stress level (slug withdrawal test: SW #1 ~6.9 ft; SW #2 ~11.2 ft), a slug withdrawal test was initiated by suddenly releasing the compressed gas used to depress the borehole fluid-column level. The compressed gas was released from the piezometer casing by opening the valve (e.g., ball valve) mounted on the surface wellhead used to seal the casing system.

The first pneumatic slug withdrawal test was initiated at 1639 hours PDT on May 25, 2006, by opening the surface wellhead valves, which released the well-column compressed gas, allowing the test formation to recover to pre-test static conditions. The test recovery to pre-test static conditions was rapid, with full recovery occurring within 30 seconds of test initiation. Following recovery of the first slug withdrawal test, a second pneumatic test was performed by applying regulated compressed gas at a slightly higher injection pressure (~11.2 ft). The fluid-column depression phase lasted approximately 10 minutes, and the second slug withdrawal test was initiated at 1655 hours PDT. A nearly identical rapid-test-response recovery pattern was exhibited for the second slug-withdrawal test.

Figure 5.10 shows a diagnostic analysis plot of the slug-test response. As shown, a concave-downward response is indicated, which is indicative of critically damped slug-test conditions. For the test dimension relationships existing for this piezometer test, critically damped behavior implies moderately high test interval permeability conditions. The slug-recovery-test responses were analyzed using the High-K type-curve analysis approach that is discussed in Section 3.2.2.1.

Figure 5.11 shows the test response and analysis results for the second pneumatic slug-withdrawal test (SW #2). Because of the local-scale of this test, the test-analysis results are representative of the actual well-screened interval. As indicated, a transmissivity and hydraulic conductivity value of 215 ft^2/day and 10.5 ft/day were obtained, respectively, for this test analysis. These values were calculated from a projected test stress level, H_o, of 11.2 ft. Essentially identical results were obtained from test SW #1.

5.2.4 Fault Zone Breccia: 280 to 295 ft

In an attempt to remedy the multiple aquifer completion exhibited by the initial piezometer installation at DH-05-01, the original piezometer was cemented, and the borehole was re-drilled with a 5-7/8-in. rock bit to a depth of 320 ft. The drilling was accomplished using water and foam as the circulating drilling fluid. A cement grout seal was placed between 298 and 320 ft, which spans the confining layer represented by the Rattlesnake Ridge interbed. A 15-ft piezometer was installed between 280 and 295 ft, with a sandpack installation emplaced between 270 and 298 ft. A cement seal was placed between 270 ft and the land surface.

This re-completed piezometer provides baseline monitoring for the shallow unconfined aquifer. However, continuing long-term baseline monitoring for this piezometer completion indicates a slow but steady water-level increase from initial static conditions within the unconfined aquifer (Section 4.1). This steady increase suggests a small hydraulic communication within the wellbore and new piezometer completion installed at DH-05-01. Because this observed hydraulic connection between the two aquifer systems appears to be minor within DH-05-01, it is not expected to adversely impact the relatively short-duration hydrologic characterization tests used to obtain hydraulic property information within the fault-zone breccia.

Pneumatic slug tests and a constant-head injection test were conducted on the newly completed piezometer following culmination of installation activities on October 7, 2006. The hydraulic conductivity estimates for the piezometer fault zone breccia completion zone (i.e., 280 to 295 ft) are significantly lower than that calculated for an overlying, over-lapping fault-zone breccia test interval (i.e., 269.2 to 287.4 ft), as well as a similar test/depth interval characterized at the adjacent DH-06-01 (276 to 296 ft). This significant difference in hydraulic-property determination is believed attributable to cementing, re-drilling, and re-completion activities for the unconfined aquifer installation, which may have produced a reduction in formation permeability immediately surrounding the borehole, as discussed in Section 2.

The following describes the results for hydrologic tests conducted on the piezometer basalt fault-zone breccia test interval.

5.2.4.1 Constant-Head Injection Test

A constant-head injection test was conducted on October 9, 2006, within the newly re-completed piezometer within the fault-zone breccia. The water-level within the piezometer immediately before injection testing was 267.8 ft (1008.3-ft MSL), which is nearly identical to the projected 268.03 ft static water level obtained during testing within the fault-zone breccia during corehole advancement (Section 5.2.1). The test was performed in similar fashion as to other constant-head injection tests at the site by rapidly filling the piezometer to the top of the piezometer casing and measuring the injection flow rate periodically throughout the test duration. Because of battery failure issues within the datalogger system, no downhole pressures were measured within DH-05-01 during the course of the injection test. Recovery water-levels within the DH-05-01 piezometer were measured by hand using an electronic water-level depth sensor for 2.5 hours following termination of the injection test. A back-up pressure transducer system was used to monitor well-pressure responses during testing within the adjacent DH-06-01 piezometer, which is completed in the underlying Pomona basalt confined aquifer. No associated test responses were exhibited in DH-06-01 during the course of injection testing at the DH-05-01 piezometer.

The constant-head injection test was initiated at 0911 hours, PDT, on October 9, 2006, by injecting freshwater into the borehole-casing system with a surface pump/water tank system. Injection rates of >2 gpm were used during the initial 15 minutes of the test to fill-up the piezometer to the top of the casing. The injection rate was then adjusted manually during the course of the test to maintain a relatively constant hydraulic head condition within a few feet from the top of the piezometer. Injection rates were monitored periodically with an in-line flowmeter and were observed to steadily decline from 2.0 to 1.4 gpm during the injection test. The injection rate averaged 1.71 gpm for the entire injection period. The injection test was subsequently terminated after a total injection time of 262 minutes at 1332 hours, PDT, on October 25, 2006. A total of 445 gal of freshwater was estimated to have been injected into the test system during testing.

In an effort to analyze the injection-test results for hydraulic property characterization, both the active injection-rate test data and observed pressure recovery were examined for possible characterization analysis. Figure 5.12 shows the plot of observed injection flow rate and matched predicted injection rate versus time using the analytical method constant-drawdown (head) tests presented in Jacob and Lohman (1952) and Lohman (1972). The matched flow-rate response plot is based on a calculated constant head value, ΔH, of 268.4 ft above pre-test unconfined aquifer static conditions, and the following hydrologic parameter values: $T = 0.72$ ft^2/day, $K = 0.05$ ft/day, and $S = 1.0E\text{-}3$. To demonstrate the sensitivity of the analysis to varying K, the simulated flow-rate response is also shown additionally for K values of 0.04 and 0.06 ft^2/day with the remaining hydrologic parameters remaining fixed. As shown, the predicted response is highly sensitive to K.

Figure 5.13 shows a diagnostic test data and data-derivative plot of pressure recovery following termination of the injection test. As shown, almost all the early recovery test data are dominated by wellbore storage/well skin effects. Because of the dominance of these non-formational test conditions during the observed recovery period, analysis of the available recovery data would yield a non-unique solution using standard pumping/injection-test-type-curve methods. To facilitate analysis of the available recovery test data, the recovery data were converted to an equivalent slug-test response and then analyzed using standard slug-test-type curve and derivative plot methods described in Section 3.2.2.1. This is the same approach used and described previously for analyzing the constant-rate injection-pressure build-up data within the overlying fault-zone breccia (269.2 to 287.4 ft) and underlying Pomona basalt (319 to 334.6 ft).

Figure 5.14 shows the converted equivalent slug-test data and data-derivative and analysis plots. As indicated, a close match was obtained using the following parameter values for the test interval: transmissivity, T, = 0.54 ft^2/day; average hydraulic conductivity, K, = 0.04 ft/day; and storativity, S, = 6.8E-3. No skin effects, S_k, are assumed for the test. It should also be noted that the analysis is based on a fully penetrating aquifer test condition, which as shown for the previous fault-zone breccia test interval did not deviate appreciably from partially penetrating aquifer analysis conditions (i.e., for K and S).

Table 5.1 lists pertinent hydraulic parameter estimate results for T, K, and S for the two test analysis methods applied for this test interval characterization. As indicated, relatively comparable hydraulic property values were obtained for T and K using both methods. Slightly larger differences for storativity were exhibited for the test methods utilized. The S estimate obtained from the converted equivalent slug test method, however, may be considered to be more representative, given the relative insensitivity of the constant-drawdown/head analysis method to S.

5.2.4.2 Pneumatic Slug Tests

Two pneumatic slug tests were attempted on October 25, 2006, within the newly completed piezometer for the purpose of providing comparative hydraulic property estimates for the interval tested. The water level within the piezometer immediately before slug testing was 259.3 ft (1016.8-ft MSL), which indicates an 8.5-ft rise in water level within the piezometer from pre-test conditions observed before conducting the constant-head injection test on October 9, 2006. At the time of testing, it was uncertain whether the higher observed piezometer water level on October 25, 2006, was reflective of slow recovery following termination of injection testing on October 6 or due to an existing minor hydraulic communicative condition within the piezometer completion, connecting the unconfined aquifer with the underlying confined aquifer system. Subsequent baseline monitoring is highly suggestive of a low hydraulic communicative condition within the piezometer installation at DH-05-01 (Section 4).

The slug tests were performed in similar fashion as those conducted for the DH-05-01 Pomona basalt piezometer tests (Section 5.2.3). The pneumatic slug tests, however, proved to be unsuccessful because of the low-test-interval permeability conditions. As a consequence of the low-test-interval permeability, the fluid column was lowered only a small distance pneumatically within the piezometer during the active gas-injection phase, and consequently, steady-state conditions were not established prior to slug withdrawal initiation. Because of the lack of test-system stability and small fluid-column depressions, no quantitative hydraulic-property determinations were obtainable from these piezometer pneumatic tests.

5.3 Hydraulic Conductivity Depth Profile

Figure 5.15 shows a depth profile of the vertical distribution of hydraulic-conductivity values determined from hydraulic tests conducted at DH-05-01 as it relates to subsurface geologic conditions. Table 5.3 summarizes the hydraulic-property values shown in the figure and the basis for these estimates. As indicated in Table 5.3 and discussed in Section 5.2.4, the hydraulic-conductivity value for the re-completed piezometer test interval (i.e., 280 to 295 ft) is significantly lower than that calculated for the overlying, over-lapping fault-zone breccia test interval (i.e., 269.2 to 287.4 ft), and for a similar test/depth interval characterized at adjacent DH-06-01 (276 to 296 ft). This significant difference in hydraulic-property determination is believed attributable to cementing, re-drilling, and re-completion activities for the unconfined aquifer installation, which may have produced a reduction in formation permeability immediately surrounding the borehole. As a consequence, the hydraulic properties calculated for this test interval are considered to be non-representative of actual, surrounding formation conditions and are not used in developing the hydraulic-conductivity depth profile for this test site.

Table 5.1. Hydrologic Testing/Analysis Summary for Corehole DH-05-1 Test Zones

Test/ Depth Interval[(a)] ft bgs	Test Formation	Test Method	Hydraulic Properties			Comments
			T ft^2/d	K[(b)] ft/d	S	
65.6–70.6	Pomona Basalt	Constant-Head Injection (Zone 1 Method)	NA	0.46	NA	Vadose zone test
73.6–77.8	Pomona Basalt	Constant-Head Injection (Zone 1 Method)	NA	1.39	NA	Vadose zone test
93–98	Esquatzel/ Umatilla Basalt	Constant-Head Injection (Zone 1 Method)	NA	20.7 (17.1–24.2)	NA	Low-head vadose zone test; results indicate a moderately high permeability test interval; range shown reflective of uncertainty in C_u estimate.
113–119	Esquatzel/ Umatilla Basalt	Constant-Head Injection (Zone 1 Method)	NA	5.43 (4.56–6.31)	NA	Low-head vadose zone test; results indicate a moderate to high permeability test interval; range shown reflective of uncertainty in C_u estimate.
123–129	Esquatzel/ Umatilla Basalt	Constant-Head Injection (Zone 1 Method)	NA	5.64 (4.76–6.51)	NA	Low-head vadose zone test; results indicate a moderate to high permeability test interval; range shown reflective of uncertainty in C_u estimate.
133–151	Esquatzel/ Umatilla Basalt	Constant-Head Injection (Zone 1 Method)	NA	0.45	NA	Vadose zone test
269.2–287.4	Fault Zone Breccia	Converted Equivalent Slug Test Response: Type-Curve Analysis	15.2 (15.2–25.7	0.84 (0.78–0.84)	7.5E-4 (7.0E-4–8.0E-4)	Unconfined aquifer system; short-duration injection buildup test affected by partial corehole collapse or change in cement sealing conditions after ~142 min into the injection.

Table 5.1 (Cont.)

Test/ Depth Interval[a] ft bgs	Test Formation	Test Method	Hydraulic Properties T ft^2/d	K[b] ft/d	S	Comments
269.2–287.4	Fault Zone Breccia	Injection Test Buildup: Type-Curve Analysis (full and partial aquifer penetration)	11.5 (11.5–19.4)	0.63 (0.59–0.63)	1.0E-3 (S_y > 0.02)	Best-estimate value based on fully penetrating well analysis; values in parentheses provide range of fully and partially penetrating well solutions.
319–334.6 (287.6–34.6)	Pomona Basalt/ Composite Zone	Injection Test Converted to Equivalent Slug Test Response: Type-Curve Analysis	4.42	0.28	4.8E-6	Test results indicate a minor hydraulic communication within corehole during testing with overlying unconfined aquifer; analysis results assume insignificant contribution by overlying unconfined aquifer system; analysis results should be considered to be only qualitative estimates.
		Constant-Head Injection Test Type-Curve Transient Analysis	5.47	0.35	8.0E-4	
280–295*	Fault Zone Breccia	Injection Test Converted to Equivalent Slug Test Response: Type-Curve Analysis	0.54	0.04	6.8E-3	*Re-completed piezometer tests conducted within unconfined aquifer; test results appear to be impacted by cementing, piezometer re-completion activities and not considered representative of formational conditions.
		Constant-Head Injection Test Type-Curve Transient Analysis	0.72	0.05	1.0E-3	
379–399.5	Pomona Basalt	Pneumatic Slug Tests	215	10.5	NA	Confined aquifer system; interference tests may be affected by multiple-aquifer piezometer completion.

(a) **ft bgs**: feet below ground surface
(b) **K** = T/b; assumed contributing, b = test interval length except as noted
NA = not applicable or not applied

* Test results adversely impacted by cementing piezometer re-completion activities and are considered to not be representative of *in situ* formation conditions

Table 5.2. Pertinent Hydrologic Test and Analysis Information for Vadose Zone Test Intervals: Corehole DH-05-1

Test/ Depth Interval ft bgs	Test Formation	Constant Head Injection Test Parameters								K_s[(a)] ft/day
		r_w ft	A ft	H ft	X %	T_u ft	Q_s gpm	V_{tot} gal	C_u	
65.6–70.6	Pomona Basalt	0.201	5.0	75.2	27.5	272.6	2.0	150	55.5	0.46
73.6–77.8	Pomona Basalt	0.201	4.2	22.3	10.5	212.5	1.5	95	46.2	1.39
93–98	Esquatzel/ Umatilla Basalt	0.245	5.0	10.68*	5.9	180.7	13.93	665	42.3–60	20.7 (17.1–24.2)
113–119	Esquatzel/ Umatilla Basalt	0.245	6.0	10.93*	6.8	159.9	4.12	245	47.0–65	5.43 (4.56–6.31)
123–129	Esquatzel/ Umatilla Basalt	0.245	6.0	16.75*	10.8	155.8	7.10	455	51.2–70	5.64 (4.76–6.51)
133–151	Esquatzel/ Umatilla Basalt	0.245	18.0	33.55	22.3	150.6	2.2	240	115.3	0.45

(a) Results analyzed using the deep (Zone 1) water-table solutions
* Low-stress vadose zone tests; K estimate range is reflective of uncertainty in the calculated C_u values.

Nomenclature:

r_w = radius of open-borehole test section
A = length of open-borehole test section
H = imposed injection head above bottom of borehole test section
T_u = vertical distance from water table to top of fluid-column injection level; water-table depth = 268 ft bgs
X = H/T_u
Q_s = pseudo-steady-state injection flow rate
V_{tot} = total volume injected into borehole during injection test
C_u = saturated conductivity coefficient; Zone 1, Deep Water-Table Test Case
K_s = saturated hydraulic conductivity

Table 5.3. Test/Depth Hydraulic Conductivity Distribution Summary

Test/Depth Interval ft bgs	Best Estimate Value		Basis/Comments
	Hydraulic Conductivity, K_h,[(a)] ft/day)	Storativity, S	
65.6–70.6	0.46	NA	Vadose zone test result
73.6–77.8	1.39	NA	Vadose zone test result
93–98	20.7	NA	Average vadose zone test result
113–119	5.43	NA	Average vadose zone test result
123–129	5.64	NA	Average vadose zone test result
133–151	0.45	NA	Vadose zone test result
269.2–287.4	0.73	8.8E-4	Average of test-method results
280.–295*	0.05	3.9E-3	Average of piezometer test method results; representativeness of results is highly questionable due to re-drilling activities.*
319–334.6	0.32	4.0E-4	Average of test method results
379–399.5	10.5	NA	Pneumatic piezometer slug test results

(a) Assumed to be uniform within the test/depth interval .

* Test results believed to be non-representative of formation conditions due to cementing, re-drilling, and piezometer re-drilling activities; values not used for development of K vertical distribution at the site are listed just for comparison purposes.

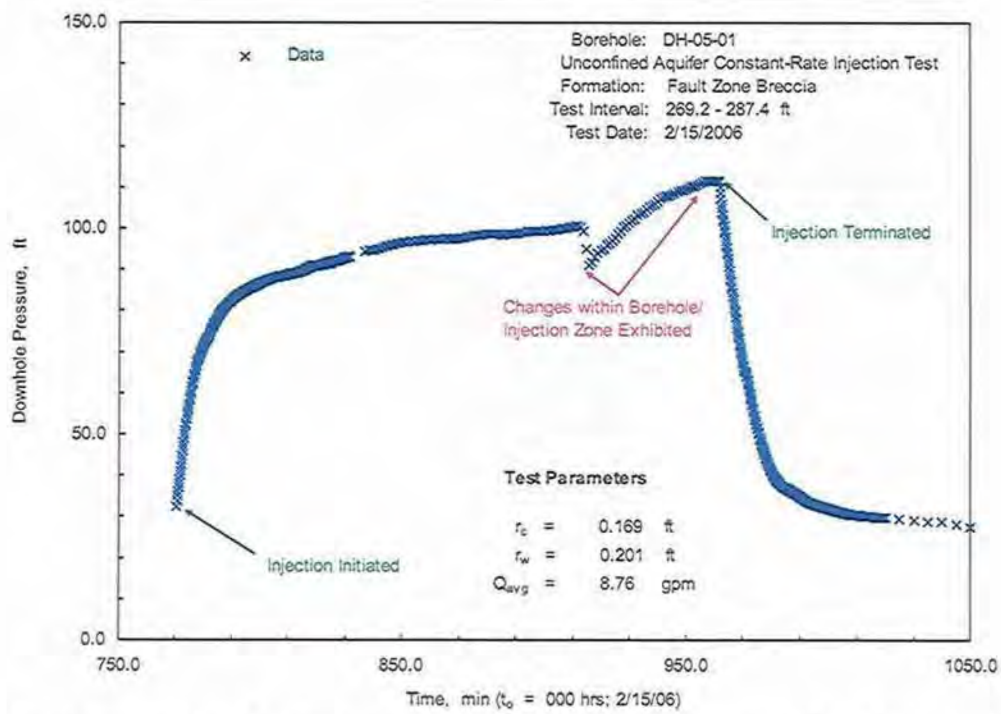


Figure 5.1. Pressure Head Response for DH-05-01, During Constant-Rate Injection Test: Fault-Zone Breccia; Test Interval 269.2 to 287.4 ft

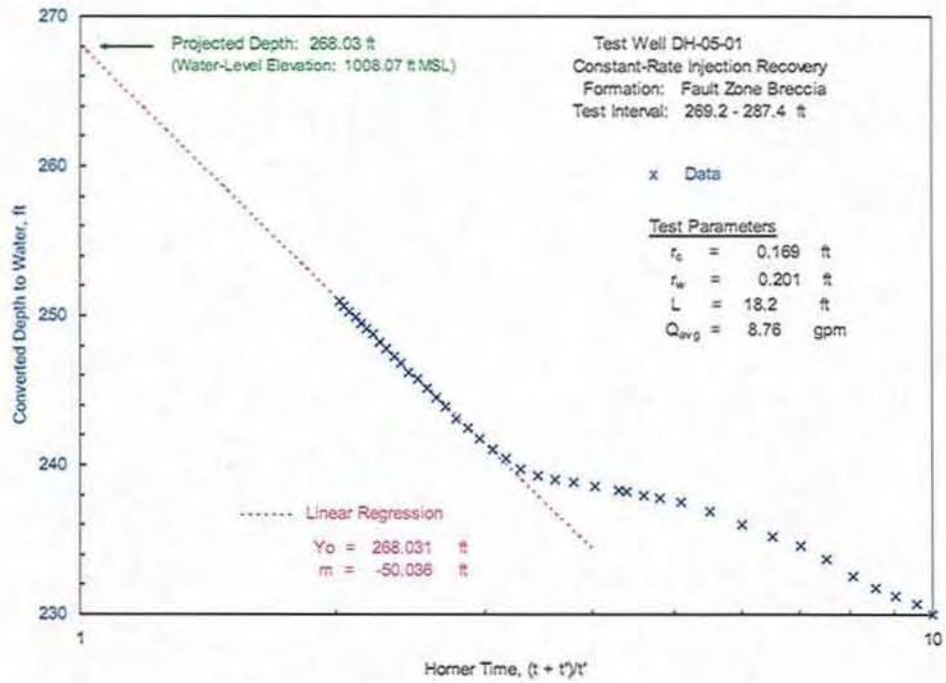


Figure 5.2. Horner Plot for DH-05-01 of Constant-Rate Injection Recovery: Fault-Zone Breccia; Test Interval 269.2 to 287.4 ft

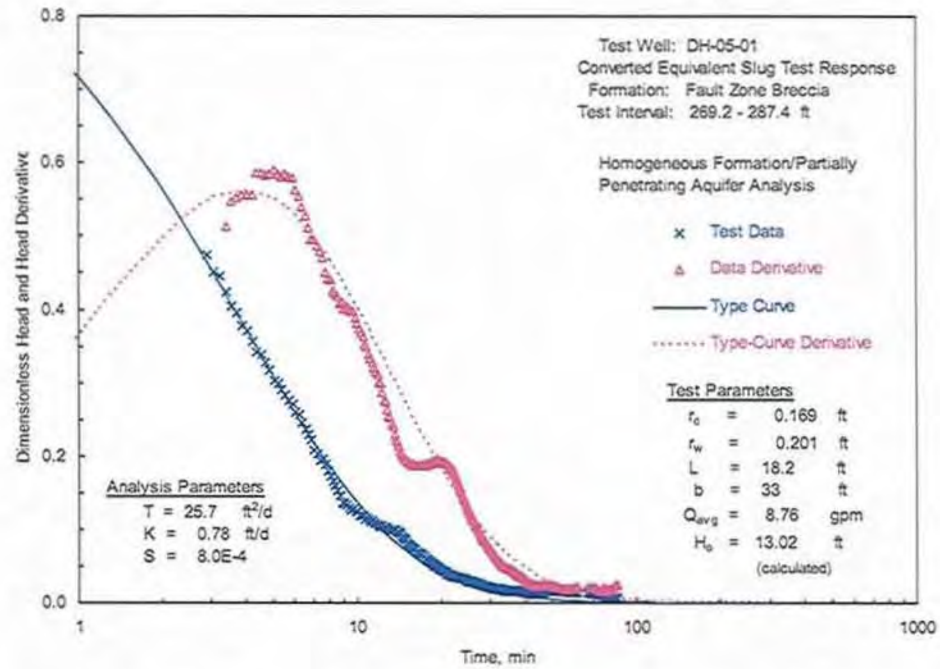


Figure 5.3. Converted Equivalent Slug Test Analysis for DH-05-01 of Constant-Rate Injection Test: Fault-Zone Breccia; Test Interval 269.2 to 287.4 ft

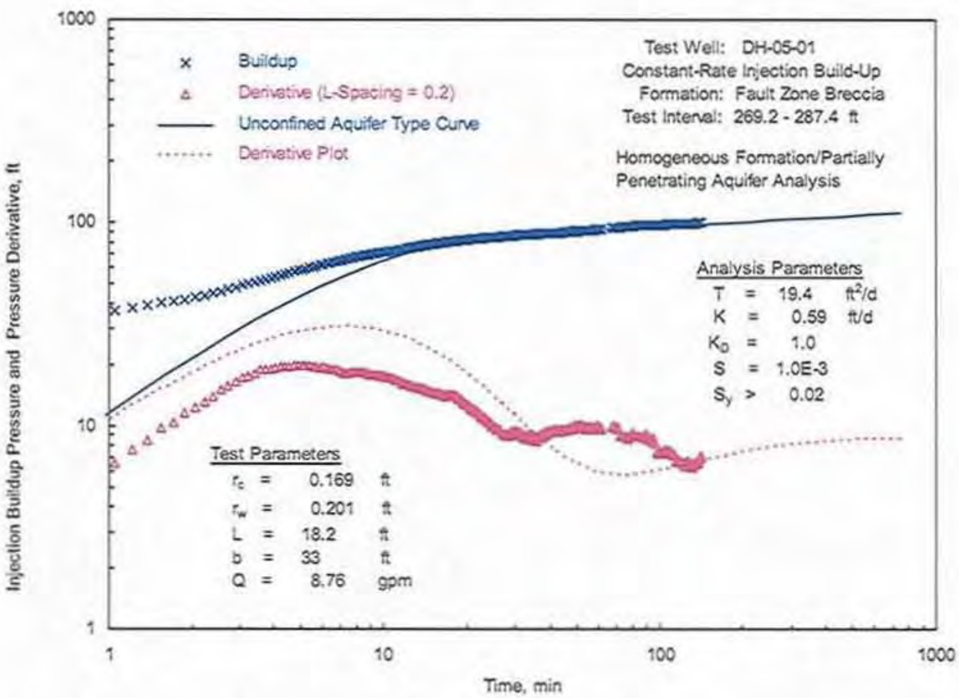


Figure 5.4. Type-Curve and Derivative Plot Analysis of Constant-Rate Injection Test: DH-05-01; Test Interval 269.2 to 287.4 ft

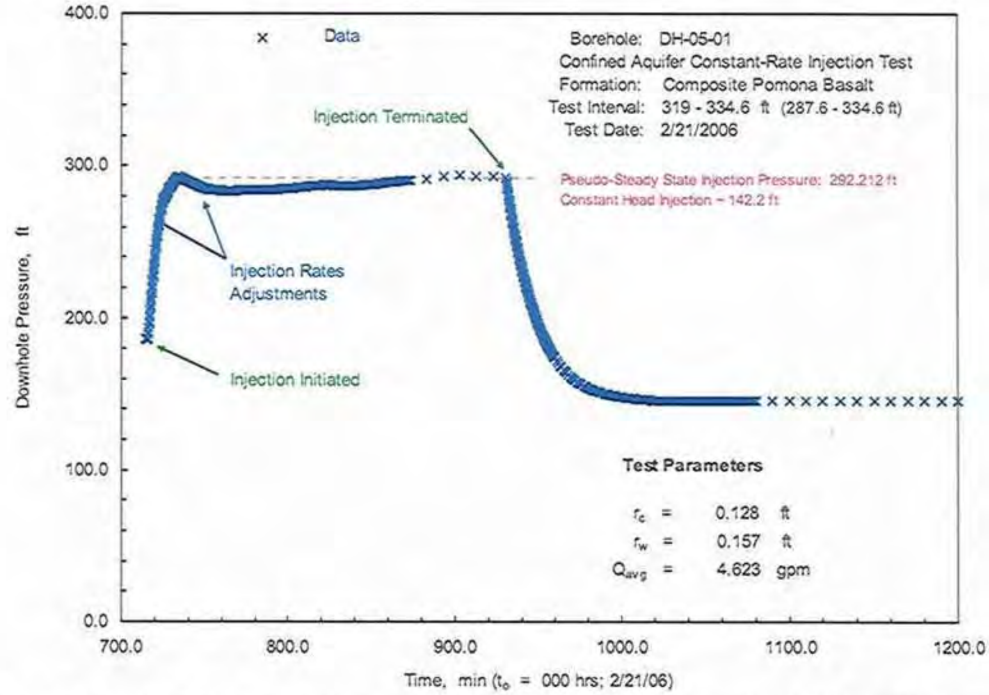


Figure 5.5. Pressure Head Response for DH-05-01, During Constant-Rate Injection Test: Pomona Basalt/Composite Zone; Test Interval 319 to 334.6 ft (287.6 to 334.6 ft)

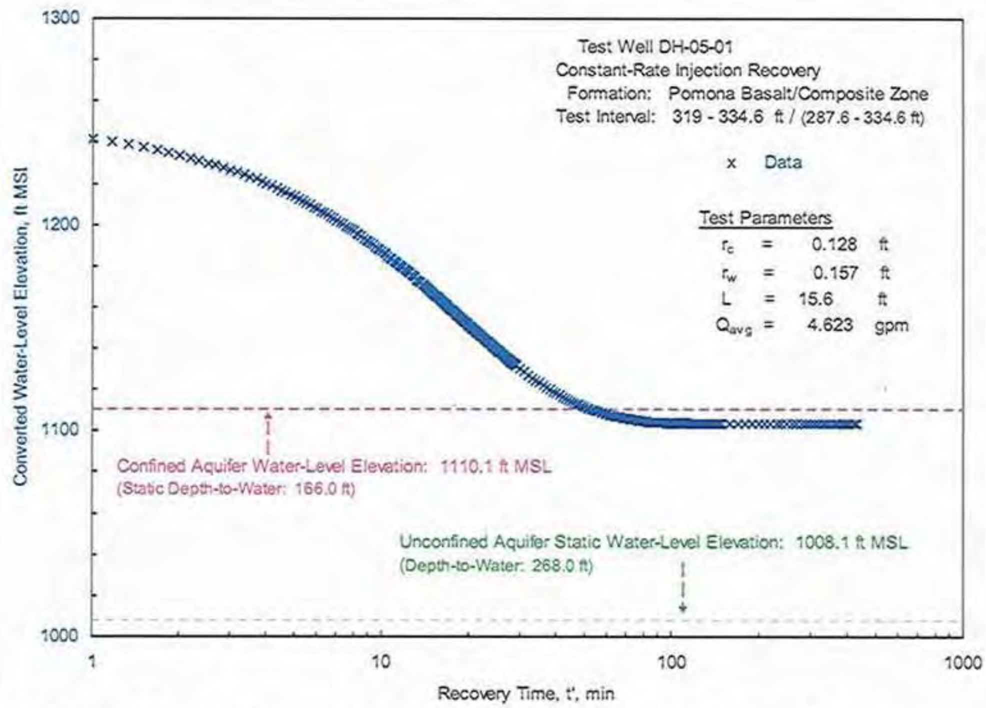


Figure 5.6. Water-Level Recovery Response for DH-05-01, Following Constant-Rate Injection Test: Pomona Basalt/Composite Zone; Test Interval 319 to 334.6 ft (287.6 to 334.6 ft)

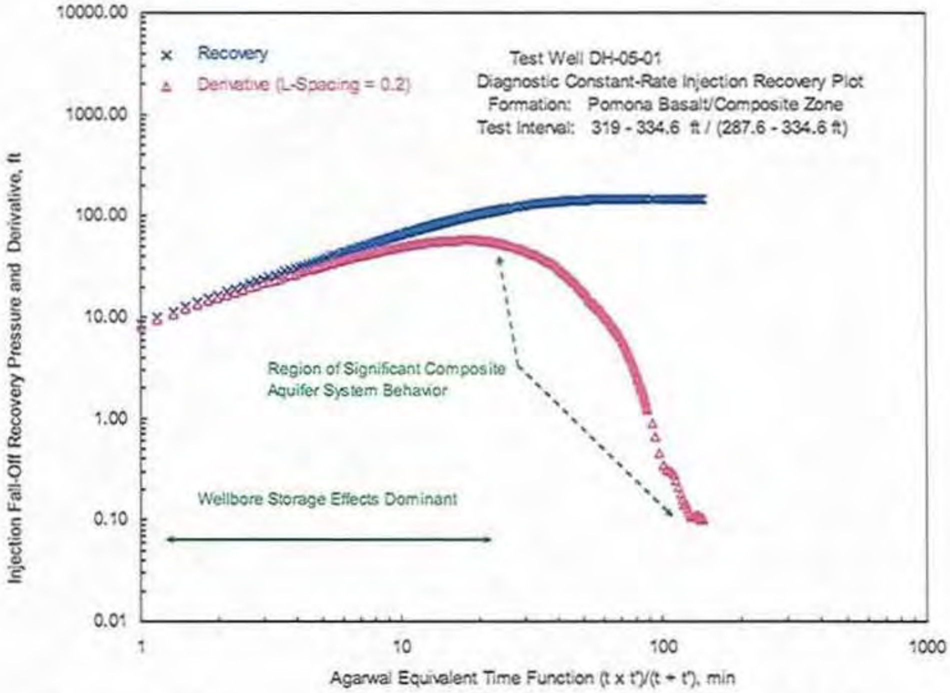


Figure 5.7. Diagnostic Constant-Rate Injection Recovery Plot, DH-05-01 Test: Pomona Basalt/Composite Zone; Test Interval 319 to 334.6 ft (287.6 to 334.6 ft)

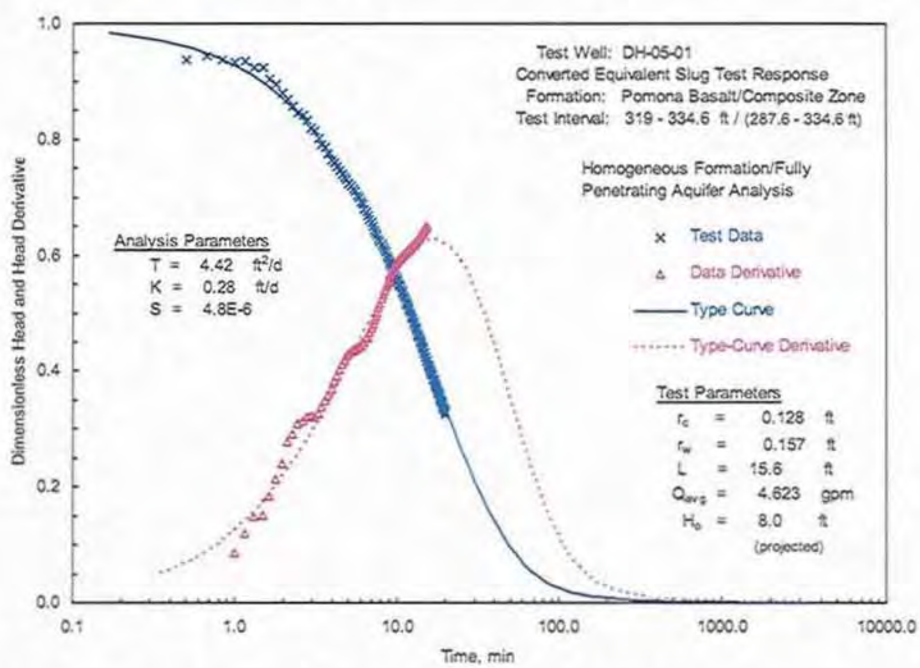


Figure 5.8. Converted Equivalent Slug Test Analysis for DH-05-01 of Constant-Rate Injection Test: Pomona Basalt/Composite Zone; Test Interval 319 to 334.6 ft (287.6 to 334.6 ft)

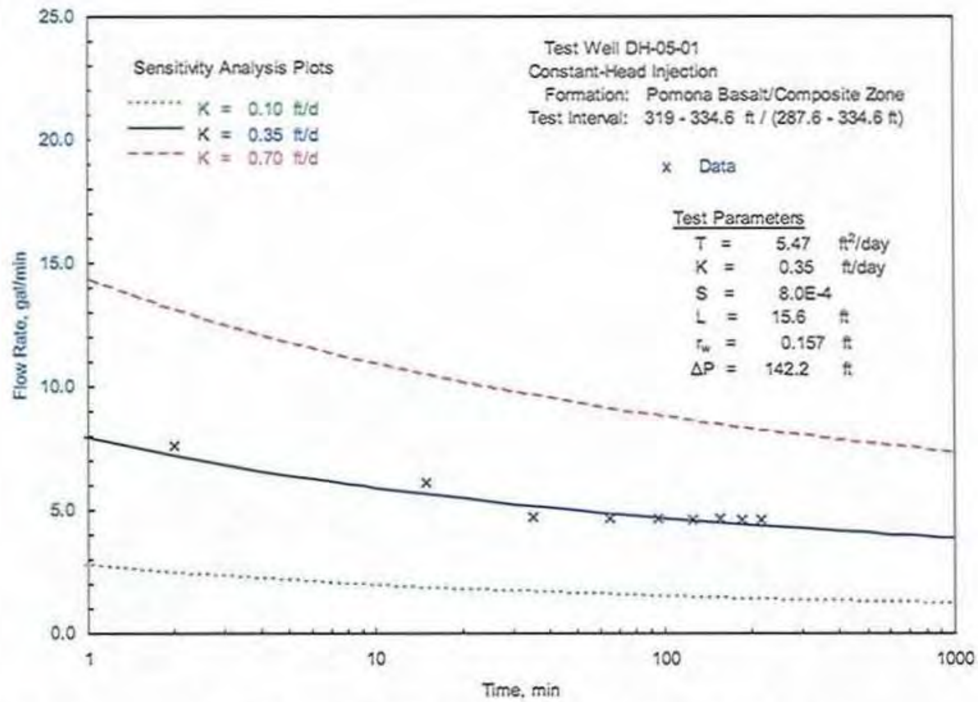


Figure 5.9. Constant-Head Injection Test Analysis for DH-05-01: Pomona Basalt/Composite Zone; Test Interval 319 to 334.6 ft (287.6 to 334.6 ft)

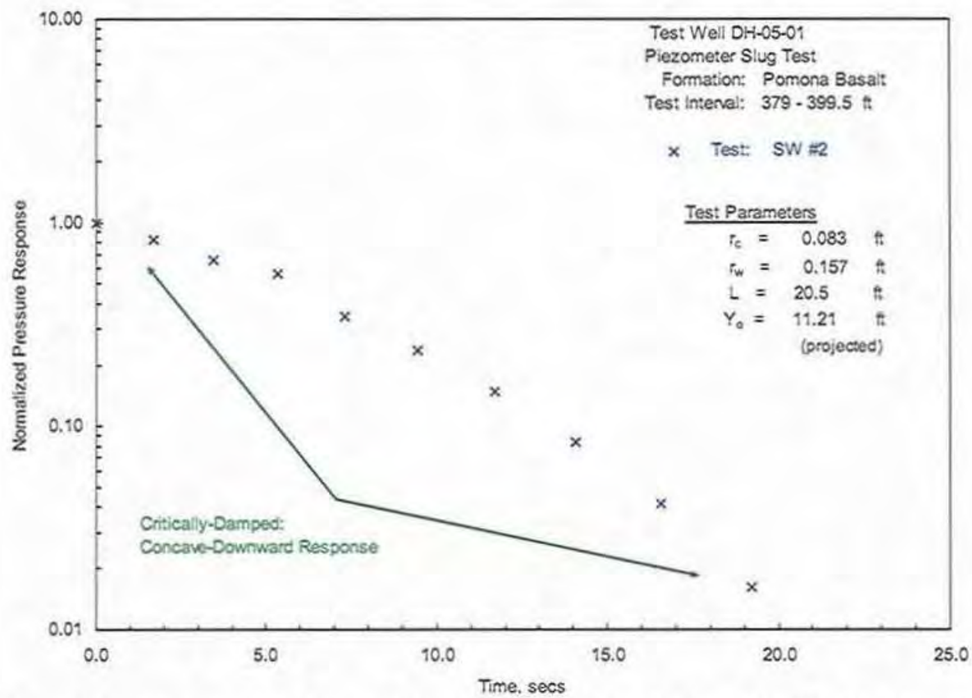


Figure 5.10. Diagnostic Plot Analysis for Piezometer DH-05-01, SW #2: Pomona Basalt; Test Interval 379 to 399.5 ft

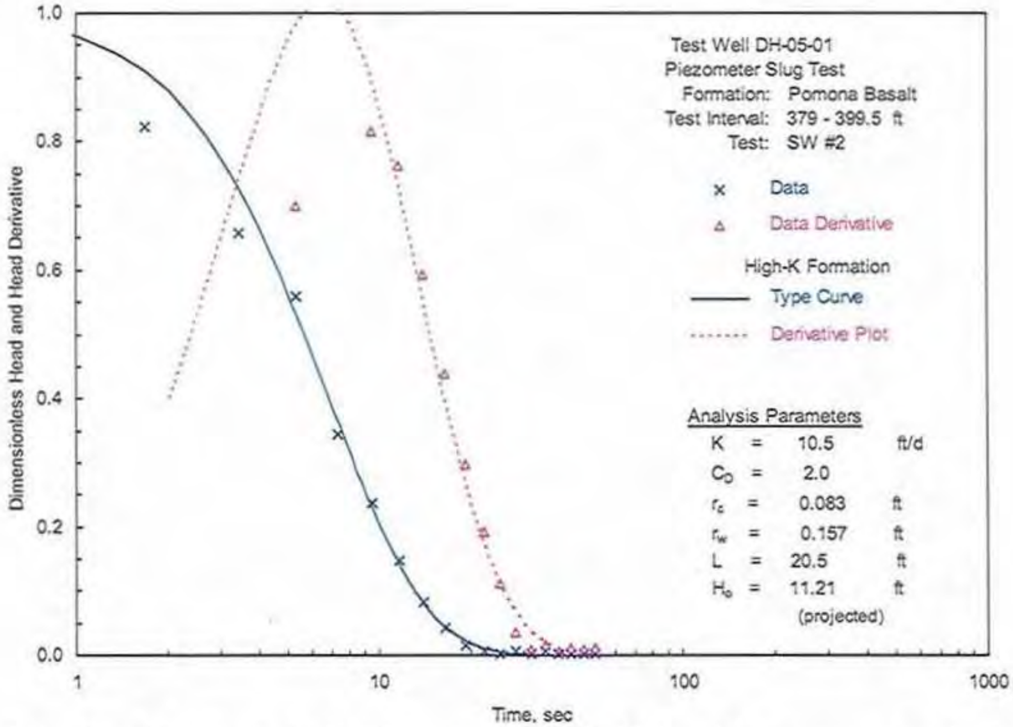


Figure 5.11. Slug Test Analysis for Piezometer DH-05-01, SW #2: Pomona Basalt; Test Interval 379 to 399.5 ft

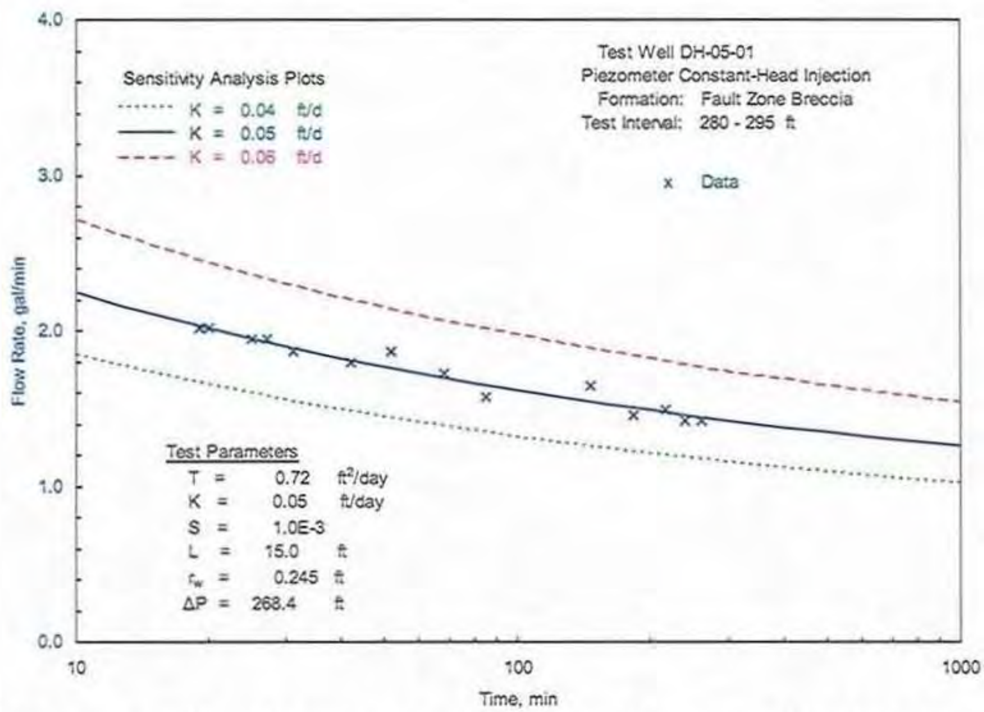


Figure 5.12. Constant-Head Injection Test Analysis for Piezometer DH-05-01: Fault Zone Breccia; Test Interval 280 to 295 ft

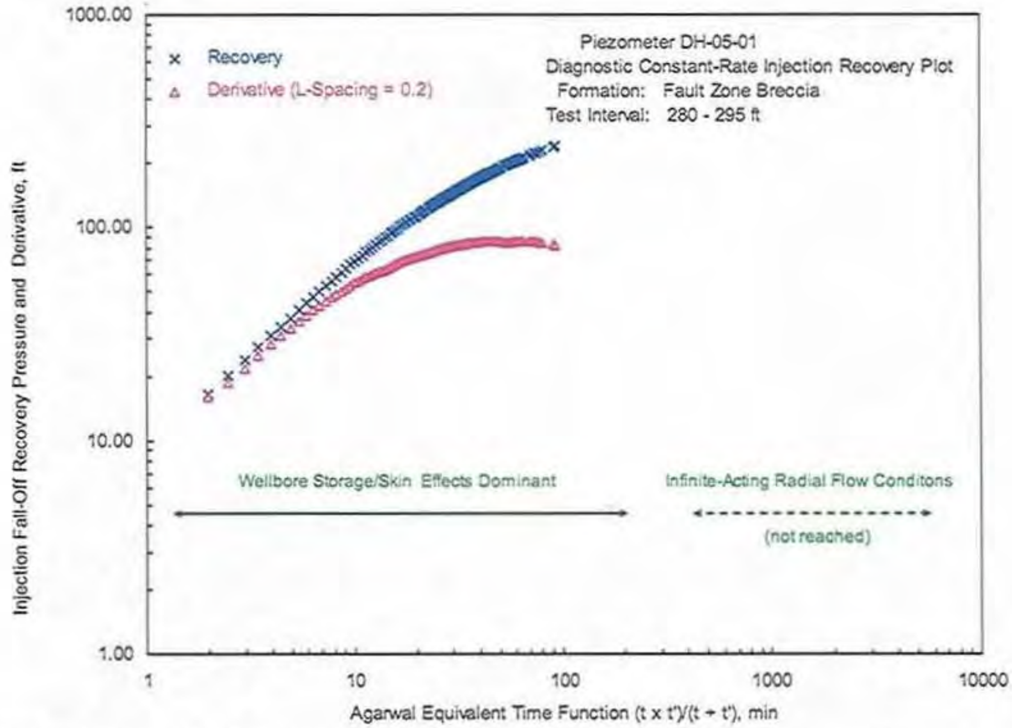


Figure 5.13. Diagnostic Constant-Head Injection Recovery Plot, Piezometer DH-05-01: Fault Zone Breccia; Test Interval 280 to 295 ft

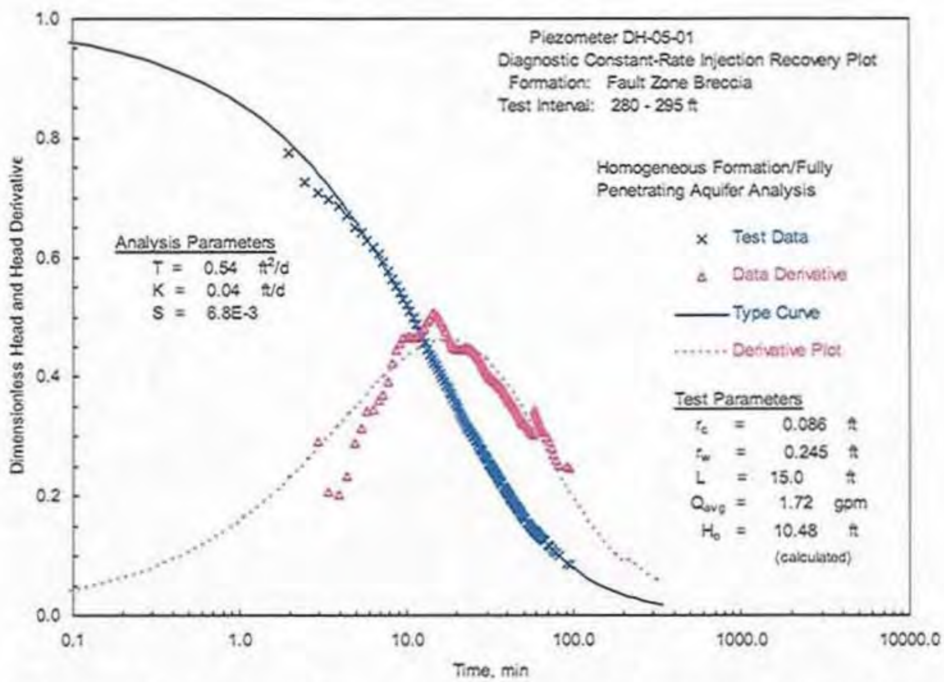


Figure 5.14. Converted Equivalent Slug Test Analysis for Piezometer DH-05-01 Constant-Head Injection Test: Fault Zone Breccia; Test Interval 280 to 295 ft

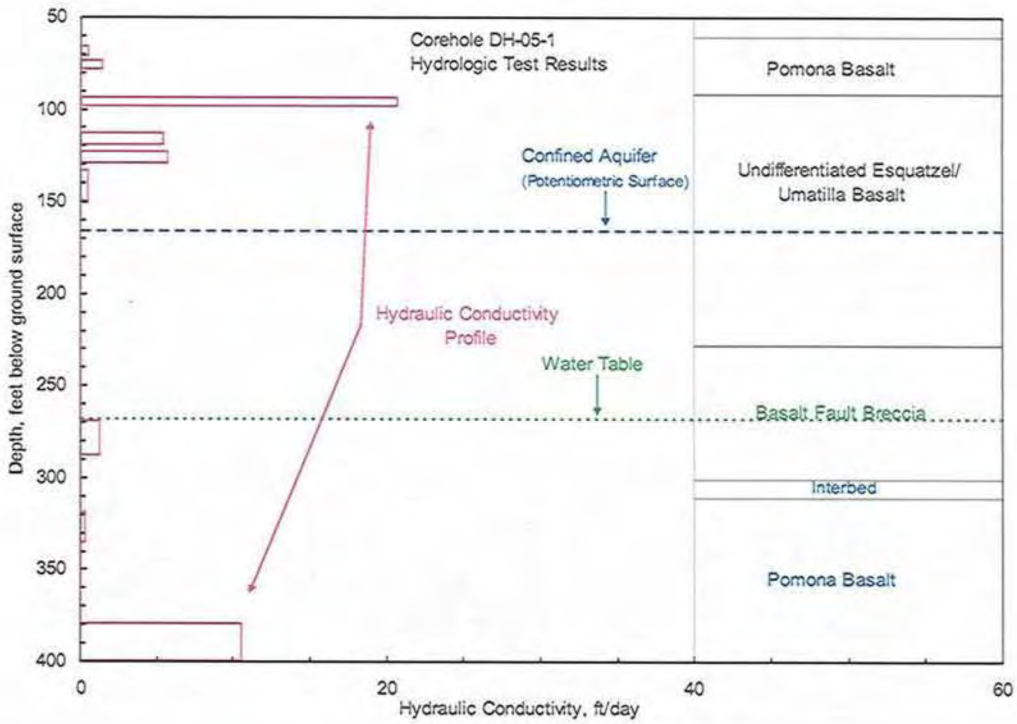


Figure 5.15. Hydraulic Conductivity Depth Profile: DH-05-01

6. Hydrologic Test Results: Borehole DH-06-01

In this section, a description of hydrologic tests and associated results for the various vadose zone (unsaturated) and saturated-zone test intervals is provided. Tables 6.1 and 6.2 provide general test activity and information pertaining to borehole hydrologic characterization tests completed at DH-06-01 while the borehole was progressively drilled and tested between April 6, 2006, and May 6, 2006. Following completion of drilling activities, borehole DH-06-01 was completed as a piezometer to provide long-term baseline monitoring of natural dynamic responses within the Pomona basalt confined aquifer system over the depth interval of 375 to 395 ft. Single-and multi-well piezometer tests were also conducted within DH-06-01, which also included the adjacent, original, and re-completed piezometer installations at DH-05-1 for tests conducted on May 25 and October 5, 2006, respectively.

6.1 Vadose Zone Tests

Two vadose zone depth intervals were characterized for hydraulic-property determination during the course of drilling DH-06-01 down to a depth of 255 ft. The vadose-zone test results provide valuable hydrologic information concerning the permeability of geologic materials above the water table, which would be located along the south abutment of the proposed Black Rock Reservoir. The vadose zone tests were conducted with the constant-head injection-test method described in Section 3.2.1. Vadose zone test intervals within test borehole DH-06-01 were selected based on detailed geologic information obtained by analyzing the core that was recovered from adjacent corehole DH-05-01.

Briefly stated, the vadose-zone tests were conducted in open-borehole sections of DH-06-01 that were drilled below the driven 8-in. weld-down casing. To initiate the test, the open borehole section was saturated by rapidly filling the borehole/casing system with freshwater to a prescribed and maintained depth level below the top of the drill casing. Gravity-injection flow rates required to maintain the level of water within the open borehole (i.e., below the top of casing) and/or pressurized, closed-system injection flow rates (i.e., for equivalent head levels above land surface) were monitored during the course of the injection-test period. Injection testing continued until injection rates became uniform with time, indicating the establishment of pseudo-steady-state conditions. Normally, constant-head injection testing was completed within 2 hours. In-borehole pressures were monitored during testing with a pressure transducer datalogger system. The pressure transducer was placed within a 1-in. stilling well that was installed within the 8-in. casing.

Pressure measurements were monitored within piezometer DH-05-01, which at the time of drilling and testing of DH-06-1 monitored the Pomona basalt over the depth interval 379 to 399.5 ft. The piezometer was monitored for the purpose of detecting potential cross-formational responses propagating through the confining layer represented by lower permeability zones within the fault zone breccia and Rattlesnake Ridge interbed. However, as noted previously, the initial piezometer completion at DH-05-01 had a sandpack placement above the designed depths, and this subsequently afforded hydraulic communication along the wellbore across the expected confining layers. No associated hydrologic leakage responses, however, were detected at piezometer DH-05-01.

Saturated hydraulic conductivity values for the vadose zones tested were calculated using the analytical methods described in Section 3.2.1. The vadose zone hydraulic properties calculated fall within the reported range of hydraulic conductivity values determined for Saddle Mountain basalt units on the nearby Hanford Site. A summary of pertinent test information and analysis results obtained for the vadose zone tests are provided in Tables 6.1 and 6.2. Test descriptions and analytical results obtained for the individual vadose zone test intervals are presented below. Selected analysis figures for the vadose zone tests are presented in Appendix C.

6.1.1 Esquatzel/Umatilla Basalt: 150 to 162.8 ft

Hydrologic testing of this vadose zone test interval was accomplished by drilling with a 9.5-in. rock bit to a borehole depth of 167.2 ft. At the time of testing, the 10-in. well casing was set (cement grouted) at a depth of 150 ft, and the borehole had collapsed to a depth of 162.8 ft. The drilling was accomplished using compressed air, water, and foam as the circulating drilling fluid. Core recovery ranged between 10 to 100% over the test-interval section at neighboring corehole DH-05-01. Selected core pictures of the test interval are shown in Appendix Figures D.4A and 4B. The general geologic description for the unit tested indicates that the Esquatzel/Umatilla basalt at this location consists of black to gray, hard, mostly fine-grained dense basalt and basalt breccia.

A pressure transducer was placed at a depth of 152.7 ft within the borehole for the purpose of measuring downhole pressure buildup during the constant-head injection testing. Two constant-head injection tests were planned for this test interval; one test was conducted at an injection head equivalent to filling the borehole to the top of the drilling casing (i.e., ~165 ft), and the second test was conducted at a higher injection-head pressure. The first injection test was initiated at 1209 hours, PDT, on April 5, 2006, by pumping freshwater into the borehole-casing system at a maximum injection rate of ~36 gpm. Because of the pervious nature of the open-borehole section and limiting transmission characteristics of the surface piping used, the pressure/fluid-column buildup within the borehole did not reach land surface within the first hour of injection. As a consequence, the first injection test was aborted at 1306 hours on April 5, 2006, and changes were made to the surface transmission-line characteristics (e.g., larger diameter flowmeter and piping) to enable larger injection rates to the borehole/test interval.

Following completion of the surface transmission-line system, a second injection test (Injection Test #2) was initiated at 0818 hours, PDT, on April 6, 2006, by pumping freshwater into the borehole-casing system at a injection rate ranging between 54 and 67 gpm during the first hour of injection. After 62 minutes into the injection test, the water within the borehole/casing system reached the top of the test casing that extended a distance of ~4.2 ft above the land surface. The pseudo-steady-state injection rates for the remainder of the test averaged 54.35 gpm to maintain the injection head at the top of the test casing. Injection Test #2 was terminated after 195.5 minutes at 1133 hours PDT on April 6, 2006. A total of 11,165 gal of freshwater was estimated to have been injected into the borehole/test interval during the course of the test.

Based on these assigned values, the calculated test-relationship parameters X and T_u (listed in Table 6.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose-zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity, K_s, of 2.04 ft/day is indicated for the test interval. Pertinent test and analysis information for this vadose zone interval injection test is presented in Tables 6.1, 6.2, and Appendix Figure C.7.

Following overnight recovery of Injection Test #2, a third injection test (Injection Test #3) was initiated at 1240 hours, PDT, on April 7, 2006, by pumping freshwater into the borehole-casing system at an injection rate of ~86 gpm during the first 12 minutes of injection. After 12 minutes into the injection test, the water within the borehole had reached the top of the test casing, and the wellhead was closed in to enable maintenance of higher injection pressures (i.e., >165 ft). The pseudo-steady-state injection rate for the remainder of the test averaged 77.52 gpm, which supported a relatively stabilized injection head 261.5 ft above the borehole bottom (i.e., +98.7 ft above land surface). Injection Test #3 was terminated after 127.3 minutes at 1447 hours PDT on April 7, 2006. A total of 10,340 gal of freshwater was estimated to have been injected into the borehole/test interval during the course of the test.

Based on these assigned values, the calculated test-relationship parameters X and T_u (listed in Table 6.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose-zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity, K_s, of 1.84 ft/day is indicated for the test interval. This is only ~10% lower than the K estimate derived from the previous lower injection head test #2, but may suggest a slight stress dependence in hydraulic properties at the damsite location. Pertinent test and analysis information for this vadose zone interval injection test are presented in Tables 6.1, 6.2, and Appendix Figure C.8.

6.1.2 Fault Zone Breccia: 236 to 255.1 ft

Hydrologic testing of this vadose zone test interval was accomplished by drilling with a 7.875-in. rock bit to a borehole depth of 256.5 ft. At the time of testing, the 8-in. weld-down casing was set at a depth of 236 ft, and the borehole had collapsed to a depth of 255.1 ft. The drilling was accomplished using compressed air, water, and foam as the circulating drilling fluid. Core recovery ranged between 79 to 100% over the test-interval section at neighboring corehole DH-05-01. Selected core pictures of the test interval are shown in Appendix Figures D.5A and 5B. The general geologic description of the unit tested is a slightly weathered fault-zone breccia that is intensely fractured in sections.

A pressure transducer was placed at a depth of 234.8 ft within the borehole for the purpose of measuring downhole pressure buildup during the constant-head injection testing. Two constant-head injection tests were planned for this test interval; one test was conducted at an injection head equivalent to filling the borehole to the top of the drilling casing (i.e., ~260 ft), and the second test was conducted at a higher injection head pressure. The first injection test (Injection Test #1) was initiated at 1359 hours, PDT, on April 10, 2006, by pumping freshwater into the borehole-casing system at injection rates ranging between 43 and 68 gpm. After ~28 min of injection, the fluid-column build-up was near the top of the surface casing, and injection flow rates were lowered repeatedly to maintain the fluid column near land surface. However, due to an insufficient water-supply on hand for the elevated injection rate, the injection rate was adjusted lower to ~47 gpm for the remainder of the test. In response to this lowering of injection rate, the fluid-column lowered and achieved pseudo-steady-state equilibrium conditions (i.e., 149.25 ft above the bottom of the borehole) over the last 50 minutes of the injection test. The first injection test was terminated after 122.1 minutes at 1601 hours on April 10, 2006. A total of 5,555 gal of freshwater was estimated to have been injected into the borehole/test interval during the course of the test.

Based on these assigned values, the calculated test-relationship parameters X and T_u (listed in Table 6.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a shallow water-table (Zone 2) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for shallow water-table conditions, a calculated saturated hydraulic conductivity, K_s, of 3.66 ft/day is indicated for the test interval for Test #1. Pertinent test and analysis information for this vadose zone interval injection test is presented in Tables 6.1, 6.2, and Appendix Figure C.9.

Following overnight recovery for Injection Test #1, a second injection test (Injection Test #2) was initiated at 1207 hours, PDT, on April 11, 2006, by pumping freshwater into the borehole-casing system at a nearly constant injection rate of ~85 gpm. After 62 minutes into the injection test, the water within the borehole/casing system reached the top of the test casing that extended a distance of ~4.2 ft above land surface. The wellhead was closed in at the surface, and the injection head increased and achieved pseudo-steady-state conditions at 265.26 ft above the borehole bottom during the last 40 minutes of the injection test. The pseudo-steady-state injection rates during the last 40 minutes of the injection test averaged 85.629 gpm. Injection Test #2 was terminated after 143.75 minutes at 1431 hours PDT on April 10, 2006. A total of 12,255 gal of freshwater was estimated to have been injected into the borehole/test interval during the course of the test.

Based on these assigned values, the calculated test-relationship parameters X and T_u (listed in Table 6.2), and using criteria presented in Section 3.2.1 (Figure 3.1), the injection test can be categorized as a deep water-table (Zone 1) vadose zone test case. Using the appropriate equations listed in Section 3.2.1 for deep water-table conditions, a calculated saturated hydraulic conductivity, K_s, of 3.87 ft/day is indicated for the test interval. Pertinent test and analysis information for this vadose zone interval injection test is presented in Tables 6.1, 6.2, and Appendix Figure C.10.

6.2 Groundwater Test Zones

Two groundwater test zones (within the fault-zone breccia and a large composite section of Pomona basalt beneath the fault) were tested during the course of drilling DH-06-01 to a depth of 400 ft. Together with information collected from neighboring corehole DH-05-01, the DH-06-01 test results provide valuable hydrologic characterization information concerning the transmission, storage, and leakage characteristics of these hydrogeologic units in the vicinity of the proposed south abutment area. In addition to these tests performed during drilling, hydrologic tests were also conducted after drilling within the piezometer installation.

The groundwater test zones within DH-06-01 were conducted with a variety of test methods described in Section 3.2.2. Groundwater test intervals within DH-06-01 were selected based on detailed geologic information obtained from drill cuttings from DH-06-01 and analysis of a core recovered from nearby DH-05-01. Unlike DH-05-01, groundwater tests conducted within DH-06-01 were performed without the use of a packer/screen test assembly. The testing of open drilled borehole sections was accomplished through casing that was either set through advancement and/or cement grouting. This test strategy assumes that the overlying casing adequately seals and isolates the open borehole test section from the overlying cased-off formation section. Based on observed test conditions, test-interval isolation was not always maintained.

During groundwater tests conducted during the active drilling phase of DH-06-01, pressure measurements were monitored within nearby piezometer DH-05-01 that (at the time of drilling of DH-06-01) monitored a section of Pomona basalt over the depth interval 379 to 399.5 ft. As noted in Section 2 (Figure 2.2), the initial piezometer completion at neighboring DH-05-01 was adversely affected by the improper placement of sandpack materials within the borehole surrounding the piezometer. This improper sandpack installation afforded hydraulic communication between the underlying monitored Pomona basalt confined aquifer and the overlying unconfined aquifer that occurs within the fault-zone breccia. This hydraulic communication significantly impacts the reliability of multi-well tests conducted between the two test-well locations.

Hydraulic conductivity values for the groundwater zones tested at DH-06-01 were calculated using the analytical methods described in Section 3.2.2. A summary of pertinent test information and analysis results obtained for the groundwater zones tested are provided in Table 5.1. Test descriptions and analytical results obtained for the individual vadose zone test intervals are presented below. Selected analysis figures for the tests are presented both in this section and in Appendix E.

6.2.1 Fault-Zone Breccia: 276 to 296 ft

Hydrologic testing of this groundwater test interval was accomplished by drilling with a 7.875-in. rock bit to a borehole depth of 296 ft. At the time of testing, the 8-in. weld-down casing was set at a depth of 276 ft and had a cement casing seal between 271 and 276 ft. The drilling was accomplished using compressed air, water, and foam as the circulating drilling fluid. Core recovery ranged between 74 to 100% over the test-interval section at neighboring corehole DH-05-01. Selected core pictures of the test interval are shown in Appendix Figures D.2A and 2B. The general geologic description of the unit tested is a fault-zone breccia that is moderately to intensely weathered and which becomes more intensely altered with depth, with adhering clay to a sandy-clay matrix.

Two constant-head injection tests were planned for this test interval; one test was conducted at an injection head equivalent to filling the borehole to the top of the drilling casing (i.e., ~272 ft above static water-table conditions), and the second test was conducted at a higher injection head pressure. The objective of conducting two injection tests at two different injection pressures was to evaluate any hydraulic-property stress dependence. The first injection test (Injection Test #1) was initiated at 1249 hours, PDT, on April 19, 2006, by pumping freshwater into the borehole-casing system at an injection rate of ~83 gpm. A pressure transducer was placed at a depth of 285.0 ft within the borehole for the purpose measuring downhole pressure buildup during the constant-head injection testing. After ~10 min of injection, the fluid-column build-up was near the top of the surface casing, and the injection flow rate was lowered to ~18 gpm to maintain the fluid column at the top of the casing (TOC = +4.0 ft above land surface). The flow rate for the remainder of the test was stable and averaged 18.03 gpm during this period of the test. The first injection test was terminated after 130.5 minutes, at 1459 hours, on April 19, 2006. A total of 3,115 gal of freshwater was estimated to have been injected into the borehole/test interval during the course of the test.

Figure 6.1 shows the associated, downhole pressure response during and immediately following terminating the constant-rate injection test. As indicated in the figure, after the initial 10 minutes to fill the casing to land surface, the downhole pressure remained essentially constant for the duration of injection testing. To analyze the injection-test results for hydraulic-property characterization, the static hydraulic-head conditions in the unconfined aquifer within the fault-zone breccia must be known. For this analysis, the static water-level-depth of 268.0 ft (hydraulic head = 1008.1-ft MSL), as determined from testing in neighboring DH-05-01 was used as a consistent static condition for unconfined aquifer tests at DH-06-01. This static water-level value is based on both observed equilibrated values and projected test-recovery responses. Slightly deeper water-level depths were measured in DH-06-01 with an observed recovery water level of 269.8 ft measured following extended, incomplete recovery from Injection Test #2. The deeper water-level measurements observed within DH-06-01 are believed to be *apparent* and may be attributable to greater borehole deviation effects incurred at the site due to the air-rotary/hammer drilling technique employed in drilling DH-06-01. As an example, a 7° borehole deviation from vertical would indicate a 2.25 ft deeper water-level measurement. Borehole-deviation effects would be accentuated by dipping geologic contacts, which are prevalent at this test-site location. For this reason, the static conditions obtained from corehole DH-05-01 are believed to be more representative of static hydraulic head conditions within the unconfined aquifer and are consequently used in the analysis of unconfined aquifer tests conducted in DH-06-01.

Because of the uniformity of observed pressure-head conditions during injection testing (Figure 6.1) and a relatively constant-injection rate during the test, the steady-state analysis for constant-head injection tests (Equation 3.5) was employed for this test. The following input values were used for the steady-state analysis: Q_{avg} = 18.03 gpm; ΔH, = 270.40 ft; R = 20.2 ft (calculated); r_w = 0.328 ft. The area of investigation, R, was calculated based on the calculated volume of water injected into the test interval during the active injection phase (2,393 gal) and an assumed unconfined aquifer specific yield/effective porosity of 0.25. As noted in Section 3, the steady-state solution (Equation 3.5) is relatively insensitive to uncertainties associated with R. Based on these input parameters, a value for T and K of 8.42 ft^2/day and 0.42 ft/day were calculated, respectively.

Following overnight recovery for Injection Test #1, a second injection test (Injection Test #2) was initiated at 0900 hours, PDT, on April 20, 2006, by pumping freshwater into the borehole-casing system at a nearly constant injection rate of ~83 gpm. A pressure transducer was placed at a depth of 281.8 ft within the borehole for the purpose of measuring downhole pressure buildup during the constant-head injection testing. After 10 minutes into the injection test, the water within the borehole/casing system reached the top of the test casing that extended a distance of ~4.0 ft above land surface. The wellhead was then closed in at the surface and the injection rate lowered to ~29 gpm in attempt to maintain a uniform injection-head condition. The borehole pressure conditions achieved pseudo-steady state conditions at 449.11 ft during the next 70 minutes of the injection test. As shown in Figure 6.2, after ~82 minutes into the injection test, the borehole pressure dropped rapidly, and injection rates were increased to ~50 gpm in an attempt to re-establish the previously maintained borehole pressure. This sudden drop in borehole pressure and adjusted increase in injection rates is indicative of failure of the 5-ft casing cement seal (i.e., between 271 and 276 ft) and subsequent by-pass to the overlying formations. Injection Test #2 was terminated after 140.2 minutes at 1120 hours PDT on April 20, 2006. A total of 5,510 gal of freshwater was estimated to have been injected into the borehole/test interval during the course of the entire test.

In an attempt to analyze the Injection Test #2 results, the pseudo-steady-state conditions that were established immediately before the loss of the casing cement seal were analyzed using the same steady-state constant-head test method employed for test #1. The following input values were for the steady-state analysis of test #2: Q_{avg} = 29.97 gpm; ΔH = 435.31 ft; R = 19.6 ft (calculated); r_w = 0.328 ft. The area of investigation, R, was calculated based on the calculated volume of water injected into the test interval during this portion of the active injection phase (2,246 gal) and an assumed unconfined aquifer specific yield/effective porosity of 0.25. Based on these input parameters, essentially identical values for T and K of 8.33 ft^2/day and 0.42 ft/day were calculated, respectively, for test #2. The nearly identical hydraulic-property estimates calculated under two significantly different test stress conditions (test #1 = ΔH_i = 270.40 ft; test #2 = ΔH_i = 435.31 ft) indicates a lack of stress dependence for the unconfined aquifer system at this test location.

It is interesting to note the relative correspondence in K estimates at DH-06-01 and DH-05-01 for similar, overlapping fault-zone breccia test intervals. At DH-05-01, an average K estimate of 0.73 ft/day was calculated for the fault-zone breccia zone of 269.2 to 287.4 ft (Section 5.2.1) in comparison to the K value of 0.42 ft/day calculated at DH-06-01 for the test interval 276 to 296 ft.

Figure 6.3 shows the recovery response following termination of Injection Test #1. The diagnostic plot indicates a test response that initially is dominated by wellbore storage effects, which is followed by recovery derivative response characteristics that are suggestive of leakage conditions. The likely cause for the leakage response condition during recovery is around the basal casing cement seal, which was observed to fail during the subsequent Injection Test #2. Because of these observed diagnostic test conditions and the close corroboration of the constant-head injection-test results, no attempt was made to analyze the recovery test data.

6.2.2 Composite Pomona Basalt: 311.8 to 400 ft

Following completion of testing interval 276 to 296 ft, efforts were implemented within DH-06-01 to isolate the unconfined aquifer from drilling and testing of the underlying Rattlesnake Ridge interbed and Pomona basalt confined-aquifer system. The 6-in. weld-down casing was advanced and set with a cement seal at a depth of 301.2 ft at the top of the Rattlesnake Ridge interbed/confining layer. The borehole was advanced by drilling with a 5.875-in. rock bit through the interbed to a depth of 311.8 ft. During drilling of the interbed, the cement seal around the bottom of the 6-in. drill casing was broken, and the interbed interval (confining layer) could not be isolated or tested. Another attempt at isolating the top of the underlying Pomona basalt by grouting around the bottom of the 6-in. drill casing was also unsuccessful due to failure of the grout seal. The total borehole depth of 400 ft was reached on May 3, 2006, with the 6-in. drill casing set (with no cement seal) at a depth of 311.8 ft. The drilling was accomplished using compressed air, water, and foam as the circulating drilling fluid. Core recovery ranged between 40 to 100% over the test-interval section at neighboring corehole DH-05-01. Selected core pictures of the test interval are shown in Appendix Figures D.3(C), D.3(D), D.3(E), and D.6(A) through D.6(E). The general geologic description of the composite Pomona basalt unit tested is a moderately to slightly weathered, moderately to intensely fractured aphanitic basalt.

A three-stage, step-drawdown test was planned for this composite test interval. The last step was designed to be extended for a protracted period, and the recovery was monitored to determine hydraulic and storage properties of the Pomona basalt test interval and well-loss conditions for the test. Test responses were planned to be monitored at nearby piezometer DH-05-01, which (at this time) was completed within the lower Pomona basalt interval (i.e., 379 to 399.5 ft). To facilitate the performance of the step-drawdown test, a 5-HP Grundfos submersible pump was set at a depth of 299.7 ft (intake = 297.6 ft) within the well casing. A 0 to 250 psi pressure probe was installed at a depth of 275 ft within a 1-in. stilling-well pipe to monitor associated drawdown responses during the step-drawdown test. Test-pressure responses for test DH-06-01 and piezometer DH-05-01 were stored on an In-Situ Hermit Model 3000 datalogger system. Surface discharge rates were measured periodically with an in-line instantaneous/totalizer flowmeter and checked with discrete volumetric/time measurements at the end of the discharge line (i.e., 42-gal bucket). The pumped water was conveyed by hoses a distance of approximately 100 ft north from test well DH-06-01 and allowed to discharge freely to the land surface and into the ephemeral drainage located in proximity to the site. Temperature, pH, EC, dissolved oxygen (DO), alkalinity, and Eh were analyzed periodically in the field from discrete surface discharge samples, during the course of testing. Additionally, water samples were collected near the end of each step for detailed analysis for major inorganic species.

The hydrologic test equipment installation and pre-test system checks were performed the day prior to formal step-drawdown testing on May 5, 2006. A pre-test static water-level depth of 165.45 ft (1,110.65-ft MSL) was observed immediately before starting the step-drawdown test. The first step of the step-drawdown test was initiated at 0936 hours, PDT, May 6, 2006, and was maintained at an average discharge rate of 15.74 gpm for 94 min. The observed drawdown at the end of the first step was 2.475 ft, with a calculated $\Delta s_w/Q$ ratio = 0.157 ft/gpm. The second drawdown step was conducted for 96 minutes at an average discharge rate of 31.16 gpm. The observed drawdown at the end of the second step was 5.742 ft, with a calculated $\Delta s_w/Q$ ratio = 0.105 ft/gpm. The third injection step was initiated at 1248 hours and was maintained at a pumping rate of 46.23 gpm over the initial 96 minutes into the step. The observed drawdown at the end of the third step was 9.482 ft, with a calculated $\Delta s_w/Q$ ratio = 0.081 ft/gpm. The third step was extended for a total step-duration of 912 minutes and was terminated at 0400 hours, on May 7, 2006. The average discharge rate for the extended third step was 46.29 gpm. The observed drawdown at the end of the test was 9.87 ft with a calculated $\Delta s_w/Q$ ratio = 0.089 ft/gpm for the extended period.

Figures 6.4 and 6.5 show the associated downhole pressure response observed during the step-drawdown test and a well-loss plot from conducted steps within DH-06-01. It should be noted that the pressure transducer used in adjacent piezometer DH-05-01 malfunctioned and exhibited erratic readings during the step-drawdown test conducted in DH-06-01 and therefore was not used in the test analysis of this composite Pomona basalt zone.

The decreasing well loss ($\Delta s_w/Q$) vs. Q trend exhibited in Figure 6.5 is anomalous to a standard increasing trend plot for most natural test-formation conditions and is believed attributable to increased leakage around the cement casing seal in DH-06-01 at the higher pumping rates and possibly to the previously discussed multiple aquifer completion present at piezometer DH-05-01.

Because of the increasing significance of leakage on observed drawdown pressure responses with an increasing pumping rate, the lower stress Step 1 drawdown pattern was examined for possible characterization property analysis. Figure 6.6 shows the drawdown and drawdown derivative plot observed at DH-06-01 during Step 1 of the step-drawdown, together with the matched constant-rate pumping-test-type curve matching analysis solution. As indicated in the figure, the pumping-test-type-curve analysis indicated a reasonable match to the observed drawdown data using a T and S value of 1,655 ft^2/day and 5.0E-5, respectively. For the composite Pomona basalt test interval thickness of 88.2 ft, an average K value of 18.8 ft/day is indicated. As shown in Figure 6.6, leakage effects become recognizable on the highly sensitive derivative plot after ~20 minutes into the test. In spite of seal leakage in the Step 1 drawdown response, sufficient test data and analysis correspondence are demonstrable to support the hydraulic-property characterization analysis for this test interval.

6.2.3 Pomona Basalt: 375 to 395 ft

Testing for this Pomona basalt depth interval (i.e., 375 to 395 ft) was conducted on May 25, 2006, after termination of drilling activities and piezometer installation (Section 2; Figure 2.4) were completed on May 20, 2006. At the time of testing the piezometer at DH-06-01, the piezometer at nearby DH-05-01 was completed over a similar monitor depth interval (i.e., 379 to 399.5 ft). The geologic core description for this test interval indicates a slightly weathered, moderately to intensely fractured basalt section. As noted previously in Sections 2 and 5, the piezometer completion at DH-05-01 did not completely isolate the monitoring interval within the Pomona basalt confined aquifer system, and a degree of hydraulic communication existed via the sandpack installation with the overlying unconfined aquifer system. The relatively high permeability of the monitored Pomona basalt interval (and relatively low permeability for the overlying unconfined aquifer), and relatively short-duration of the slug tests performed, however, indicate that the local-scale hydraulic properties determined from the piezometer tests are largely reflective of the Pomona basalt confined aquifer system at this location.

Two pneumatic slug tests were conducted at piezometer DH-06-01 on May 25, 2006, between 1527 and 1556 hours by lowering the water column within the piezometer using compressed gas to depress the fluid-column level to the designed test stress levels. After the monitored fluid column was stabilized for ~10 minutes at the prescribed stress level, a slug-withdrawal test was initiated by suddenly releasing the compressed gas used to depress the borehole fluid-column level. The compressed gas was released from the piezometer casing by opening a valve (e.g., ball valve) mounted on the surface wellhead used to seal the casing system. Both pneumatic slug tests conducted at DH-06-01 exhibited oscillatory (under-damped) slug-test response behavior. This type of slug-test response is indicative of moderate to high permeability test-interval conditions. The pressure transducer depth setting in DH-06-01 was at ~270 ft, or ~104 ft below the water level within the piezometer. For quantitative analysis of slug tests exhibiting under-damped behavior, the pressure sensor must be located near the top of the fluid column. Because of this monitoring deficiency, quantitative analysis of the two pneumatic slug tests was not performed. Analytical results of pneumatic slug tests conducted at nearby piezometer DH-05-01 on May 25, 2006, did not have this measurement constraint and are reported in Section 5.2.3.

A series of six pneumatic slug tests within piezometer DH-06-01 were repeated on October 25, 2006, following the re-completion of the adjacent DH-05-01 piezometer within the overlying unconfined aquifer located in the fault-zone breccia (Figure 2.3). The pneumatic slug tests were conducted in similar fashion to earlier pneumatic piezometer slug tests conducted within DH-06-01, with the exception that the pressure sensor was placed at two different fluid-column depths during testing (i.e., 2 and 270 ft from the top of the fluid-column surface). Compressed gas pressures ranging between 1.2 and 6.5 ft were used to depress fluid levels for slug-test initiation. All slug-test responses exhibited similar oscillatory (under-damped) response behavior, although the deeper sensor location test responses exhibited slightly more attenuated response characteristics. For the purpose of test interval hydraulic characterization, slug-test analysis was limited to the two pneumatic tests performed with the pressure sensor at the shallowest fluid-column depth (i.e., SW #3 and #4).

Figure 6.7 shows a diagnostic analysis plot of the slug-test response. As shown, an oscillatory (under-damped) test response is indicated. For the test dimension relationships existing for this piezometer test, under-damped behavior implies moderately high test-interval permeability conditions. The slug-recovery test responses were analyzed with the High-K type-curve analysis approach that is discussed in Section 3.2.2.1. Figure 6.7 shows the test response and analysis results for pneumatic slug withdrawal test #4. Because of the local-scale of this test, the test analysis results are representative of the actual well-screened interval. As indicated, a transmissivity and hydraulic conductivity value of 1,058 ft^2/day and 52.9 ft/day were obtained, respectively, for this test analysis. These values were calculated from an observed test stress level, H_o, of 2.36 ft. Essentially identical results were obtained from test SW #3.

6.3 Hydraulic Conductivity Depth Profile

Figure 6.8 shows a depth profile of the vertical distribution of hydraulic-conductivity values determined from hydraulic tests conducted at DH-06-01 as it relates to subsurface geologic conditions. Table 6.3 summarizes the hydraulic-property values shown in the figure and the basis for these estimates. As indicated in Table 6.3, the hydraulic conductivity for the depth interval 311.8 to 375 ft was determined based on the principle of de-superposition, which, generally stated, indicates that within linear-based groundwater systems (e.g., confined aquifers), the overall composite transmissivity of a large test interval is the summation of hydraulic conductivity times the thickness of its contributing parts. If a test section is a subset of an overall larger test interval, its transmissivity can be subtracted from the encompassing, larger test section, and the residual transmissivity is assigned to the encompassing interval. To determine the average hydraulic conductivity, K, for the depth interval 311.8 to 375 ft, the transmissivity calculated for the depth interval 375to-395 ft (1058 ft^2/day) was subtracted from the composite Pomona basalt test interval 311.8 to 400 ft transmissivity (1,655 ft^2/day). The residual transmissivity of 597 ft^2/day was then divided by the remaining test-interval thickness (i.e., 63.2 ft) to calculate an average residual hydraulic conductivity of 9.45 ft/day. This calculated average residual K value was assigned to the 311.8- to 375-ft depth interval.

6.4 Hydrochemical Results

As discussed in Section 6.2.2, groundwater samples were collected for detailed hydrochemical analysis either during or at the end of each step of the three-stage, step-drawdown pumping test conducted at DH-06-01 between May 6 and 7, 2006. The samples collected during the step-drawdown pumping test are representative of the confined-aquifer system within a composite Pomona basalt section (depth: 311.8 to 400 ft). As noted in Section 6.2.2, evidence of casing/cement seal leakage was evident during the test, which may have provided hydraulic communication between the confined and overlying unconfined aquifer systems. Because of the significant hydraulic-head differences exhibited between the two aquifer systems, however, groundwater sampled during the course of the step-drawdown test is believed to be reflective of basalt confined-aquifer system conditions. The unconfined aquifer was not sampled at either the DH-05-01 or DH-06-01 test sites.

Appendix Table E.1 shows a comparison of the major inorganic dissolved-solids constituents within samples collected for the various stages of the step-drawdown. As indicated in the figure, the major hydrochemistry remained uniform during the course of the entire step-drawdown test.

Appendix Table E.2 shows a comparison of the major inorganic constituents within the confined aquifer at DH-06-01, with the uppermost basalt confined aquifer (Selah/Esquatzel) sampled previously at nearby test well DH-04-02 (Figure 2.1). As shown, nearly identical concentration levels are exhibited for the two shallow confined-aquifer systems at DH-06-01 and DH-04-02. For comparison purposes, hydrochemical results for the Selah confined-aquifer system from test wells/boreholes on the Hanford Site are also presented. Examination of Appendix Table E.2 indicates that groundwater for the upper Saddle Mountains Basalt confined-aquifer system at these two Black Rock Reservoir locations generally exhibit major inorganic hydrochemical concentration levels that fall within the range reported for the Selah interbed on the Hanford Site. The only hydrochemical exceptions are the slightly lower concentration level for sodium (Na) and potassium (K), and the slightly higher concentration value for calcium (Ca) that is exhibited for the DH-06-01 and DH-04-02 shallow confined groundwater.

Figure 6.9 shows a tri-linear hydrochemical plot comparison of groundwater for the two upper Saddle Mountains Basalt confined-aquifer sites (note: DH-06-01 and DH-04-02 are coincident with the "red circle" plotting location in the figure) within the Black Rock Reservoir region, as they relate to hydrochemical results and trends for groundwaters within the upper Saddle Mountains Basalt at the Hanford Site and surrounding Pasco Basin. As shown in Figure 6.9, the Black Rock Reservoir region upper confined-aquifer groundwater samples possess similar hydrochemical characteristics as displayed by groundwaters within the upper Saddle Mountains Basalt at the Hanford Site and surrounding Pasco Basin, as presented in DOE (1988) and Spane and Webber (1995). A comparative analysis of hydrochemical content suggests that the DH-06-01 (and DH-04-02) groundwaters are relatively youthful in character and do not display an evolved reactionary development. This would be expected for basalt groundwaters within predominant recharge region locations. As noted previously in Spane (2004), the hydrochemical and assumed isotopic content for this uppermost, confined groundwater-flow system may be sufficiently different and distinguishable from Columbia River water. This difference may allow identification of reservoir water leakage and determine the vertical and lateral extent of reservoir recharge to the underlying groundwater flow systems.

Table 6.1. Hydrologic Testing/Analysis Summary for Corehole DH-06-1 Test Zones

Test/ Depth Interval[(a)] ft bgs	Test Formation	Test Method	Hydraulic Properties			Comments
			T ft^2/d	K[(b)] ft/d	S	
150–162.8	Esquatzel/ Umatilla Basalt	Constant-Head Injection (Zone 1 Method)	NA	1.94	NA	Average of vadose zone tests; slight stress dependence exhibited.
236–255.1	Fault Zone Breccia	Constant-Head Injection (Zone 2 Method)	NA	3.77	NA	Average of vadose zone tests; slight stress dependence exhibited.
276–296	Fault Zone Breccia	Constant-Head Injection Test #1 Steady-state Analysis	8.42	0.42	NA	Unconfined aquifer test; very stable test conditions.
		Constant-Head Injection Test #2 Steady-state Analysis	8.33	0.42	NA	Unconfined aquifer test; data analyzed before loss casing cement seal.
311.8–400	Composite Pomona Basalt	Step-Drawdown Transient Analysis (Step 1)	1,655	18.8	5.0E-5	Confined aquifer system; tests affected by failure of annular cement seal between casing strings and multiple-aquifer piezometer completion at DH-05-01; analysis based on Step 1 drawdown analysis, which is least impacted by seal leakage.
375–395	Pomona Basalt	Pneumatic Slug Test Analysis	1,058	52.9	NA (C_D = 0.425)	High-K analysis of oscillatory pneumatic slug tests with shallow pressure fluid-column depth.

(a) **ft bgs**: feet below ground surface
(b) **K** = T/b; assumed contributing, b, = test interval length except as noted
NA = not applicable or not applied
C_D = well slug test response damping parameter; dimensionless

Table 6.2. Pertinent Hydrologic Test and Analysis Information for Vadose Zone Test Intervals: Corehole DH-06-1

Test/ Depth Interval ft bgs	Test Formation	Test (Date)	Constant Head Injection Test Parameters								
			r_w ft	A ft	H ft	X %	T_u ft	Q_s gpm	V_{tot} gal	C_u or C_s	K_s[(a)] ft/day
150–162.8	Esquatzel/ Umatilla Basalt	#2 (4/6/06)	0.396	12.8	166.56	61.2	272.2	54.35	11,165	77.83	2.04
		#3 (4/7/06)	0.396	12.8	261.50	68.6	381.0	77.52	10,340	78.52	1.84
236–255.1	Basalt Fault Breccia	#1 (4/10/06)	0.328	19.1	149.25	92.0	162.15	47.05	5,555	90.02	3.66
		#2 (4/11/06)	0.328	19.1	265.26	95.3	278.3	85.63	12,255	90.02	3.87

(a) Results analyzed using either the deep (Zone 1) or shallow (Zone 2) water-table solutions.

Nomenclature:

r_w = radius of open borehole test section
A = length of open borehole test section
H = imposed injection head above bottom of borehole test section
T_u = vertical distance from water table to top of fluid-column injection level; water table depth = 268 ft bgs
X = H/T_u
Q = pseudo-steady-state injection flow rate
V_{tot} = total volume injected into borehole during injection test
C_u = saturated conductivity coefficient; Zone 1, Deep Water-Table Test Case
C_s = saturated conductivity coefficient; Zone 2, Shallow Water-Table Test Case
K_s = saturated hydraulic conductivity

Table 6.3. Test/Depth Hydraulic Conductivity Distribution Summary

Test/Depth Interval ft bgs	Best Estimate Value		Basis/Comments
	Hydraulic Conductivity, K_h,[(a)] ft/day)	Storativity, S	
150–162.8	1.94	NA	Average of vadose zone test results
236–255.1	3.77	NA	Vadose zone test result
276–296	0.42	NA	Identical steady-state analysis results for unconfined aquifer tests
311.8–375*	9.45*	5.0E-5	Determined by subtracting the transmissivity value for piezometer zone (375–395 ft) from test zone 311.8–400 ft and assigning residual to depth interval 311.8–375 ft
375–395	52.9	NA	Average of piezometer test method results

(a) Assumed to be uniform within the test/depth interval .

* Based on principle of de-superposition by subtracting the transmissivity value for piezometer zone (375–395 ft) from test zone 311.8–400 ft and assigning residual to depth interval 311.8–375 ft ; $T_3 = T_1 - T_2 = 1655–1058 = 597$ ft²/day ; $K_3 = T_3/63.2$ ft = 9.45 ft/day.

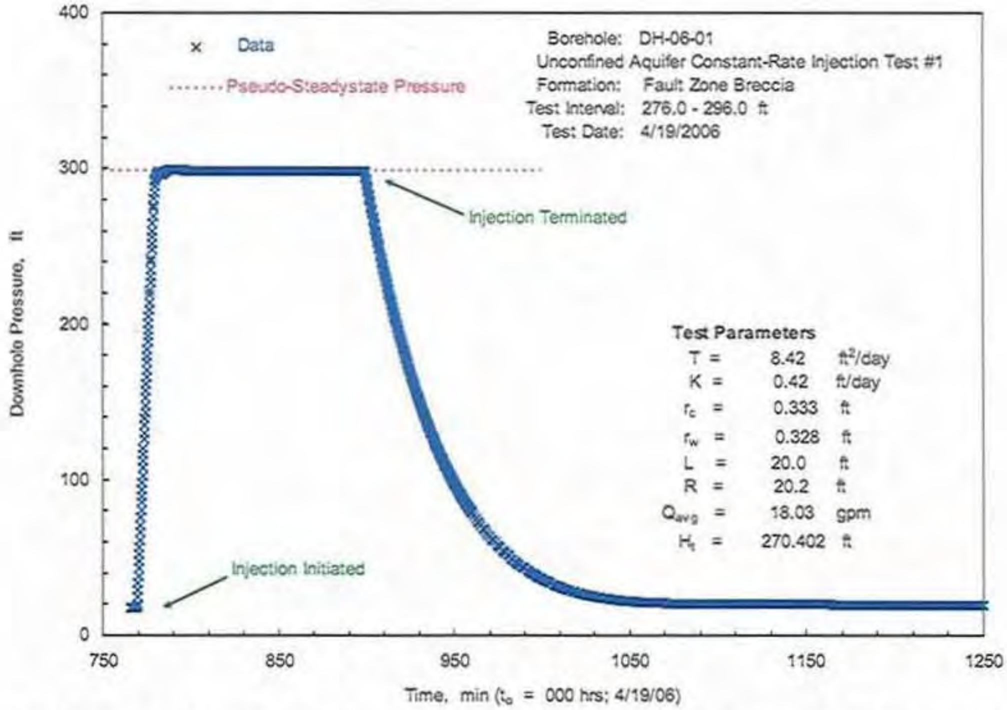


Figure 6.1. Pressure Head Response for DH-06-01, During Constant-Head Injection Test #1: Fault-Zone Breccia; Test Interval 276 to 296 ft

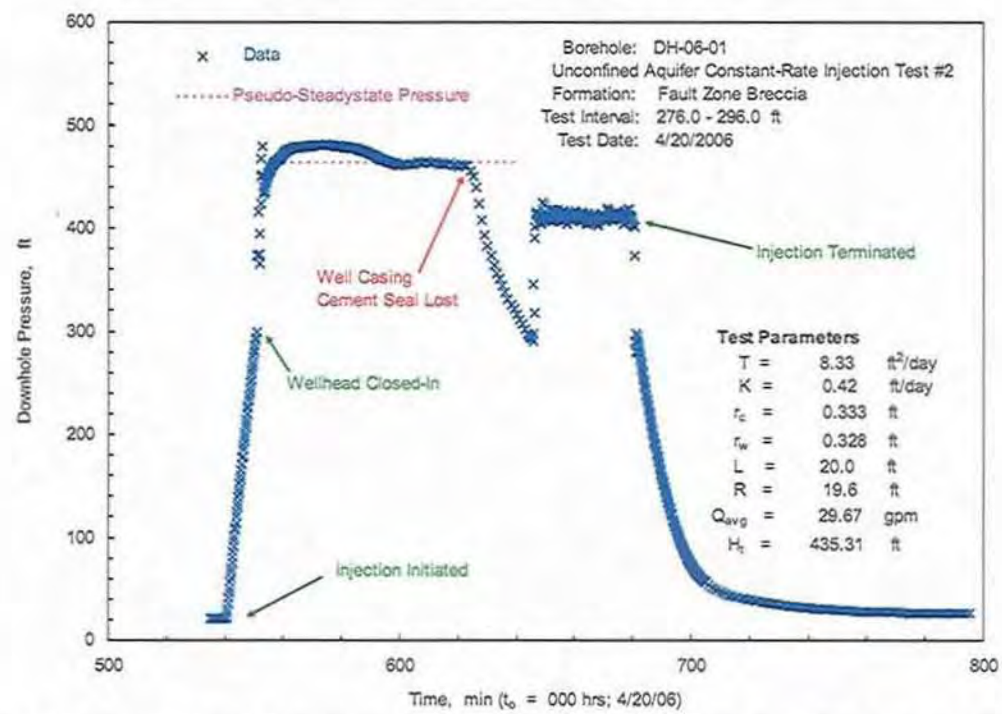


Figure 6.2. Pressure Head Response for DH-06-01, During Constant-Head Injection Test #2: Fault-Zone Breccia; Test Interval 276 to 296 ft

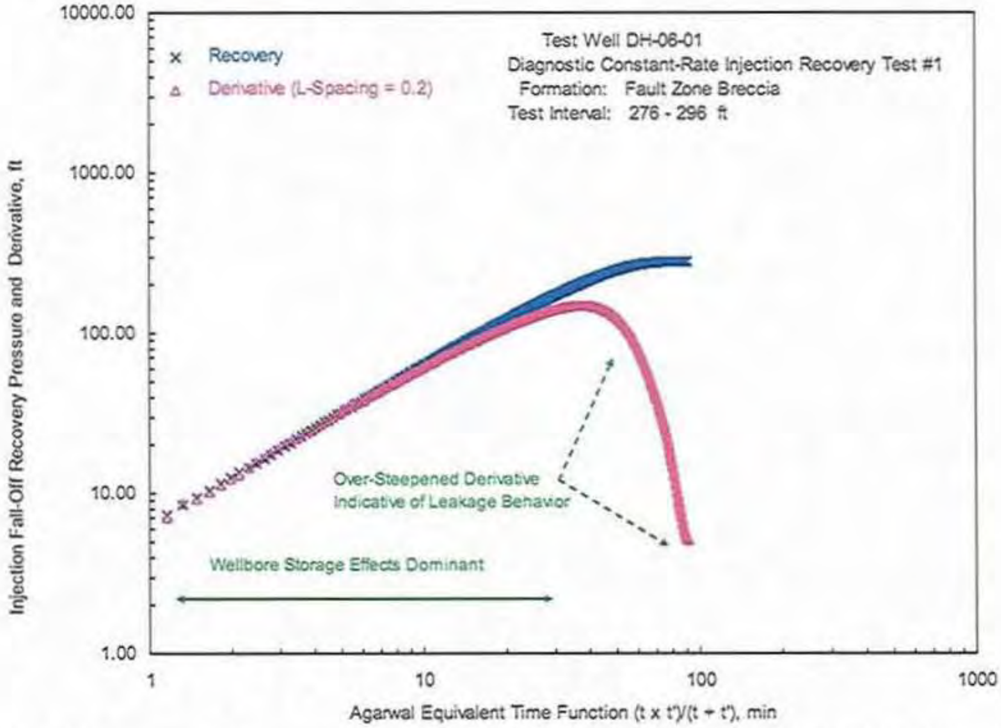


Figure 6.3. Diagnostic Constant-Head Injection Test #1 Recovery Plot, DH-06-01: Fault-Zone Breccia; Test Interval 276 to 296 ft

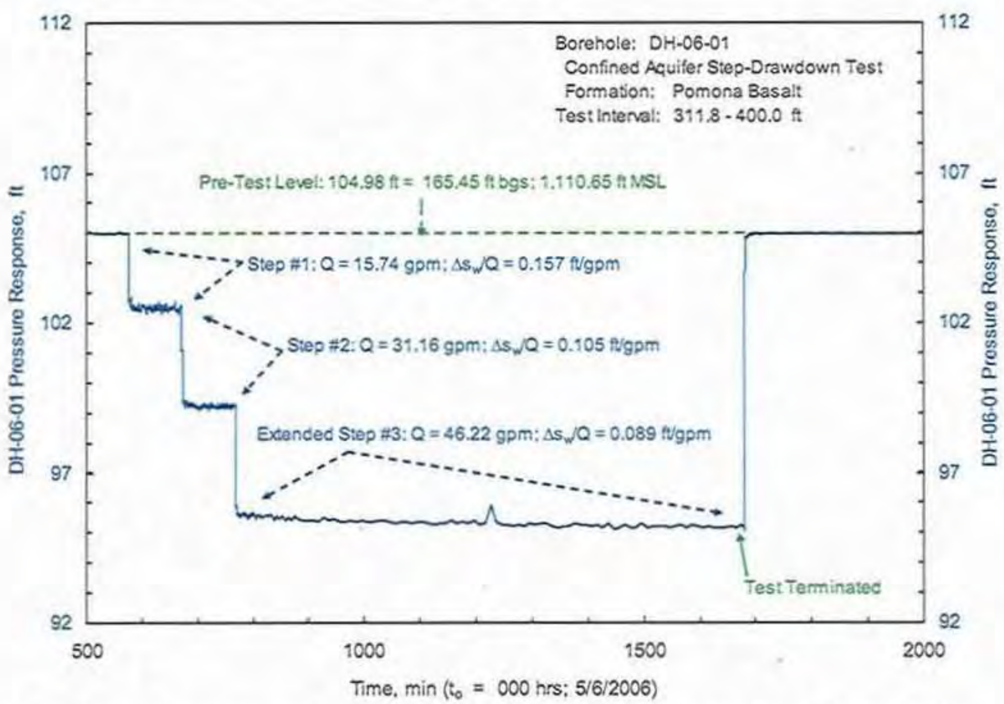


Figure 6.4. Observe Pressure Response During Step-Drawdown Test, DH-06-01: Composite Pomona Basalt; Test Interval 311.8 to 400 ft

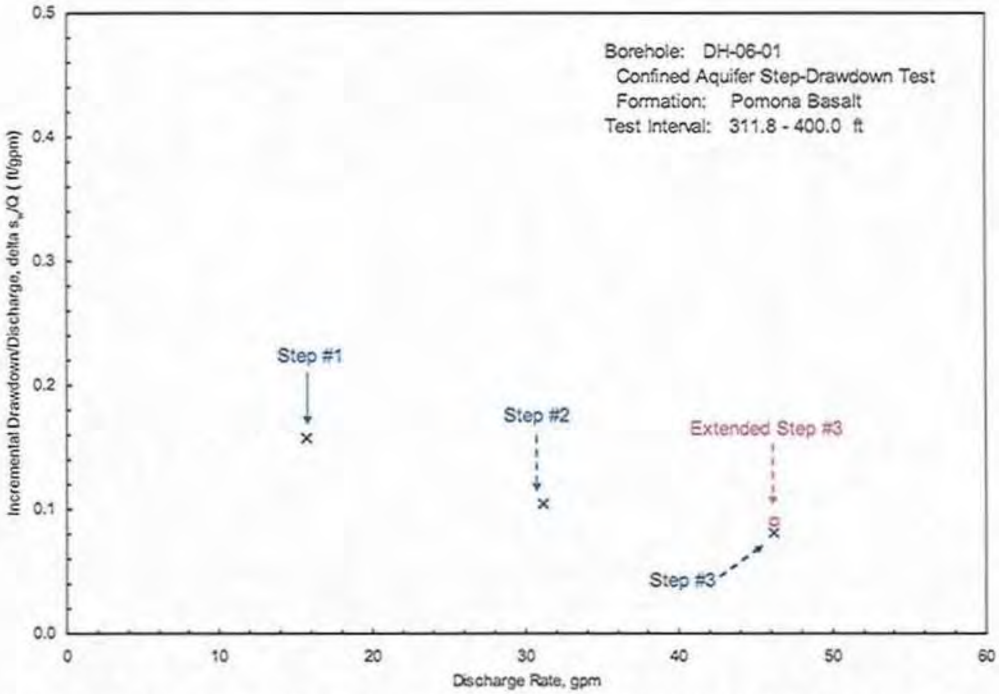


Figure 6.5. Step-Drawdown Test, Well-Loss Analysis, DH-06-01: Composite Pomona Basalt; Test Interval 311.8 to 400 ft

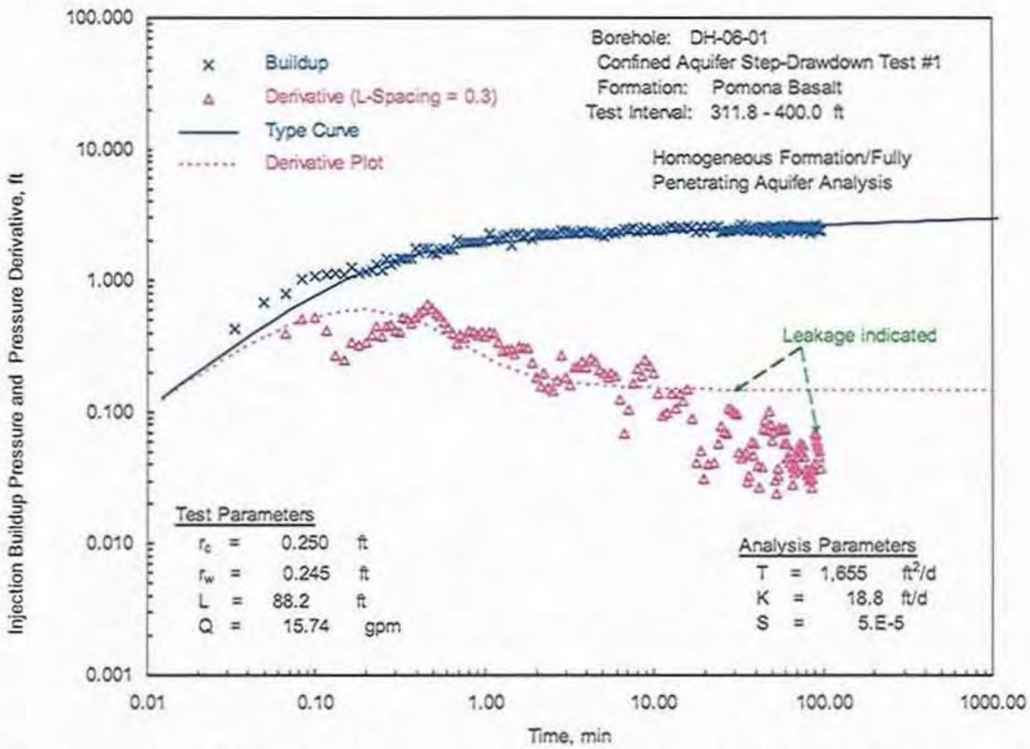


Figure 6.6. Type-Curve and Derivative Plot Analysis of DH-06-01 Step-Drawdown Test (Step 1): Composite Pomona Basalt; Test Interval 311.8 to 400 ft

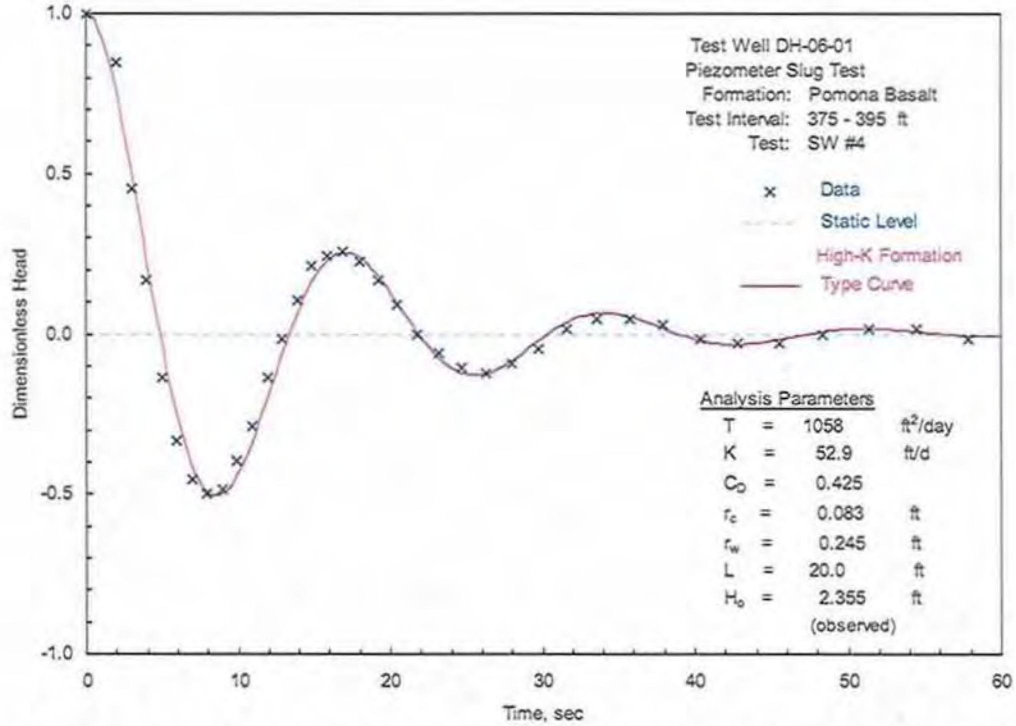


Figure 6.7. Slug Test Analysis for Piezometer DH-06-01, SW #4: Pomona Basalt; Test Interval 375 to 395 ft

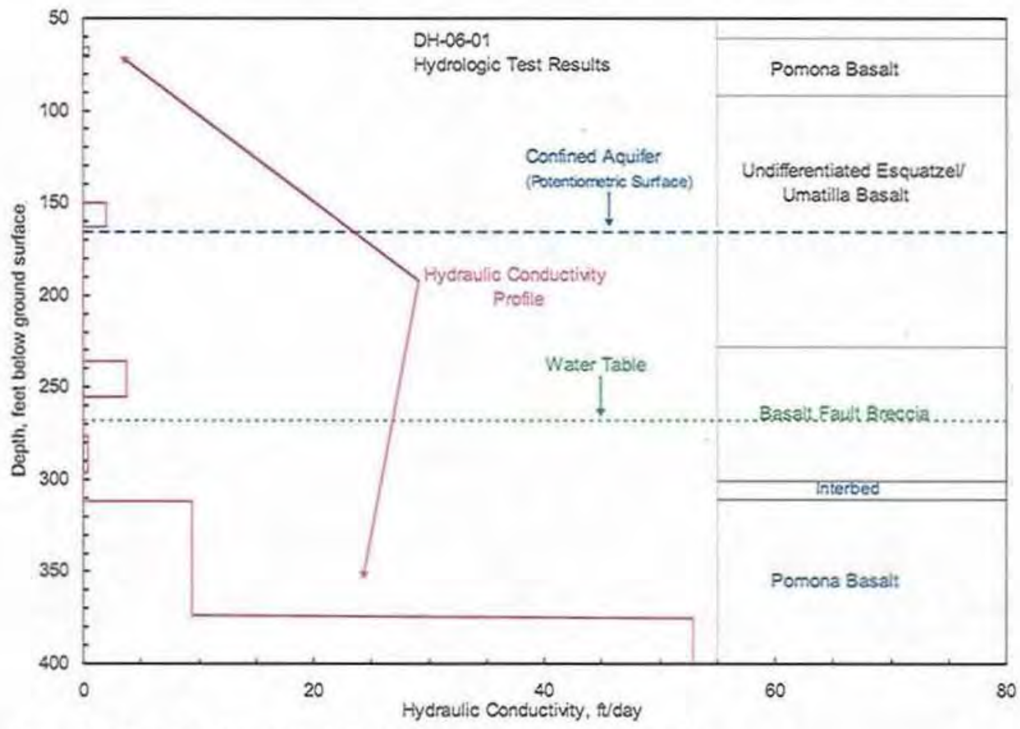


Figure 6.8. Hydraulic Conductivity Depth Profile: DH-06-01

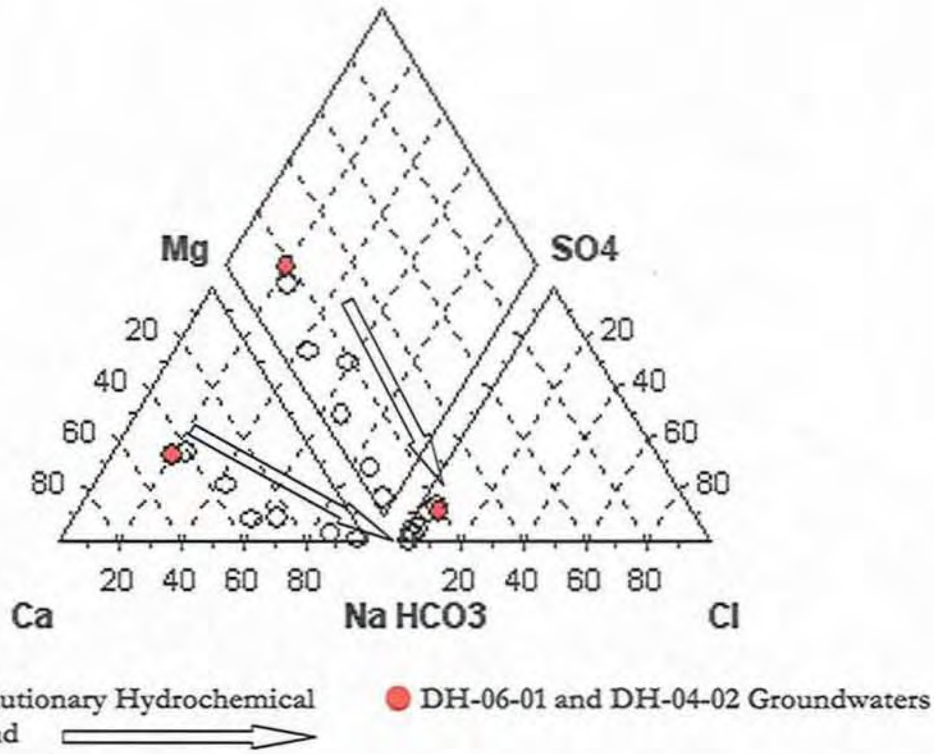


Figure 6.9. Tri-linear Plot Showing the Relationship of DH-06-01 (Pomona Basalt) and DH-04-02 (Selah Interbed) Confined Aquifer Groundwaters (both plotting within Red Circle), in Comparison to Hanford Site Upper-Saddle Mountains Basalt Groundwaters

7. Conclusions and Recommendations

To assess the potential hydrologic impact of the proposed Black Rock Reservoir on local and surrounding areas, detailed hydrologic testing is being conducted at selected test borehole locations. This report is the second of several planned USBR hydrogeologic borehole characterization test investigations and was designed to provide detailed hydrogeologic information specific to the proposed southern abutment location. In total, eight vadose-zone intervals and seven groundwater test/depth zone intervals were successfully characterized down to depths of 400 ft below land surface (land surface = 1276.1-ft MSL). The principal characterization objectives for the borehole testing program were to provide basic site-specific characterization information concerning the hydraulic/storage properties, hydrochemistry, and hydraulic head relationships of selected hydrogeologic units at this test site location. Additionally, assessment of the vertical communication/leakage between hydrogeologic units was to be assessed by examining hydrologic responses at piezometer DH-05-01 during drilling and testing of borehole DH-06-01. However, the multi-aquifer installation of the initial piezometer in DH-05-01 (i.e., 379 to 399.5 ft) diminished the ability to assess cross-formational leakage effects. Salient findings and pertinent characterization information resulting from the borehole test characterization are provided below.

Geologically, the test site is underlain (with increasing depth) by 60.5 ft of unconsolidated Quaternary sediments; 31.5 ft of Pomona basalt; 136.4 ft of undifferentiated Esquatzel and Umatilla basalts; 72.7 ft of basalt fault-zone breccia; 10.6 ft of Rattlesnake Ridge interbed; and 89.3 ft of Pomona basalt (not fully penetrated). Two hydrogeologic features are of significance at the damsite location: 1) the Horse Thief Mountain thrust fault, which is embedded within and responsible for the fault-zone breccia (depth: 228.4 to 301.1 ft); and 2) the Rattlesnake Ridge interbed (depth: 301.1 to 310.7 ft), which serves as the primary confining layer separating the unconfined aquifer within the fault-zone breccia from the underlying Pomona basalt confined aquifer. The hydraulic head difference between the two aquifer systems was approximately 102 ft, with the unconfined water-level elevation at ~1,008-ft MSL, and the underlying basalt confined-aquifer potentiometric elevation equal to ~1,110-ft MSL.

Hydraulic test results (Sections 5 and 6) were combined to develop a partial, hydraulic conductivity, K, depth profile below the test site location. Figure 7.1 shows the calculated vertical profile based on hydraulic conductivity measurements obtained and combined from test boreholes DH-05-01 and DH-06-01. The basis for the K-depth profile is summarized in Table 7.1. It is interesting to note that analysis results obtained from testing a similar test/depth interval at DH-05-01 (269.2 to 287.4 ft), which was drilled with polymer drilling mud with sealant, and DH-06-01 (276 to 296), which was drilled using compressed air, water, and foam as the circulating drilling fluid, produced very similar K estimates for the overlapping test intervals (i.e., 0.73 vs. 0.42 ft/day). This relative correspondence in K estimates suggests a lack of a significant bias in K estimate characterization, due to drilling-fluid effects for these two test examples.

A comparison of K estimate results obtained for hydrogeologic units tested at DH-05-01 and DH-06-01, with the previous Black Rock Reservoir test site results (DH-04-01 and DH-04-02) and values reported at the nearby Hanford Site are presented in Table 7.2. Of interest are the K estimates obtained for the Pomona basalt. At the initial Black Rock test site (DH-04-01/ DH-04-02), the Pomona basalt test intervals exhibited relatively low K characteristics (0.04 ft/day), while at DH-05-01 and DH-06-01 test-site K values were more than one to two orders-of-magnitude higher, ranging from 0.32 to 52.9 ft/day. While the K estimates for the basalts at the DH-05-01 and DH-06-01 test location fall within the range reported at the Hanford Site for similar Saddle Mountain basalt flow tops and interflow zones, the possibility of enhanced basalt permeability by past tectonic activity (i.e., ancillary fracturing associated with the local thrust fault) at the damsite abutment location is a possible explanation for the higher K values. Additionally, it is interesting to note that K values for Pomona basalt test intervals were generally higher below the fault-zone breccia within the footwall of the thrust fault block, which geologically may be an area of more constrained stress/strain/fracturing within the basalts.

Monitored hydrologic responses within the initial piezometer completed in DH-05-01 during testing and drilling of neighboring borehole DH-06-01 could not be used quantitatively to assess cross-formational leakage between the unconfined and confined aquifer systems. This is due to an error in sandpack placement within the initial piezometer installation, which provided direct hydraulic communication between the two aquifer systems. Subsequent re-completion of the piezometer within DH-05-01 in the unconfined aquifer provides an opportunity to monitor the aquifer dynamic responses and possible hydraulic communication between the two aquifer systems, separately. Barometric-response analysis and long-term baseline monitoring responses for the piezometers monitoring the unconfined and confined aquifer systems at the damsite location, however, indicate that a degree of hydraulic communication still exists within the borehole section (and/or the immediately surrounding borehole/formation contact region). The long-term baseline response within piezometer DH-05-01 will likely continue to trend upward and reach a composite hydraulic head that is between the static water levels exhibited for the unconfined aquifer (i.e., ~268 ft; 1008-ft MSL) and confined aquifer (~166 ft; 1110-ft MSL). The equilibrated, composite system hydraulic head predicted for DH-05-01 would be a function of the head difference and transmissivities of the two aquifer systems and the degree-of hydraulic connection (i.e., permeability) provided by the borehole between the two monitored aquifers.

Groundwater samples collected from the Pomona basalt confined aquifer at DH-06-01 indicate nearly identical hydrochemical characteristics as displayed by groundwaters within the uppermost confined-aquifer system at nearby test borehole DH-04-02. A comparative analysis of hydrochemical content suggests that the confined groundwaters at DH-06-01 and DH-04-02 are relatively youthful in character and do not display an evolved reactionary development. The hydrochemical and assumed isotopic content for this uppermost, groundwater-flow system may be sufficiently different and distinguishable from Columbia River water. This difference may allow identification of reservoir-water leakage and be used to determine the vertical and lateral extent of reservoir recharge to the underlying groundwater system.

Based on the results obtained from the initial two-field testing-program investigations, the following general recommendations are provided for subsequent borehole, hydrogeologic site characterizations.

1. All borehole characterization sites should have an initial corehole for detailed geologic and borehole geophysical characterization of the site. Following characterization, the corehole should be completed as a piezometer to allow detailed hydrologic test analysis and leakage assessment. The corehole piezometer should monitor the uppermost confined-aquifer system underlying the site. If air-lift pumping is used to develop the piezometer installation, the air-lift injecting pipe (conductor pipe) should be located a minimum of 20 ft above the piezometer screened interval.

2. Following completion of drilling and testing activities, the adjacent hydrologic test characterization borehole should be completed as a piezometer either in the overlying unconfined aquifer or deeper confined aquifer system. This will afford monitoring of two separate aquifers at the test site and provide an opportunity to assess long-term hydraulic communication response characteristics of the two systems.

3. The corehole (prior to piezometer installation) and adjacent test borehole should have borehole declination/deviation surveys conducted to provide accurate lateral distance assessments for the test-interval depths.

4. For borehole test characterization sites located within the proposed reservoir boundary, the following additional vadose zone characterization tests may be considered:
    a) continuous test profiling throughout the vadose zone (e.g., 5 to 10 ft test sections
    b) laboratory permeability tests of selected core samples
    c) *in situ* air-injection permeability test.

5. Complementing or as a replacement of some of the recommended vadose-zone tests, a sealed vadose zone piezometer monitoring the bottom/base of the sediments overlying the uppermost basalt flow will provide a bulk vertical hydraulic diffusivity (K_v/S_s) for all vadose zone units from land surface to the point of measurement. This is realized by monitoring barometric-pressure transmission from land surface to the point of measurement for an extended monitoring period (e.g., 2 to 4 weeks).

6. Based on inferential results from the initial two borehole site characterizations, several hydrogeologic units appear locally to function as hydrologic barriers to vertical groundwater flow (e.g., at DH-05-01/DH-06-01 = Rattlesnake Ridge interbed; at DH-04-01/DH-04-02 = Pomona basalt). Subsequent test-site characterizations should include efforts to characterize the hydraulic conductivity and sealing characteristics of any apparent low-permeability unit that may significantly impact vertical groundwater flow.

7. A packer/probe test system with an attached, high-strength, perforated tail-end section should be considered for routinely testing test intervals during borehole advancement, particularly for unstable borehole test sections. Open borehole tests within stable borehole sections conducted with an overlying, cement-sealed casing have proven successful; however, the time required for curing the cement seal may be more costly than using the packer/probe test system.

It should be noted that the first two recommendations were attempted for this site-characterization location. As noted in the report, however, some difficulties were encountered during the DH-05-01 corehole piezometer completion, which limited monitoring activities during the characterization period. Efforts were also made to test the Rattlesnake Ridge interbed confining layer (Recommendation 6); however, borehole stability and drill-casing sealing problems caused these attempts to be unsuccessful. In addition, the use of a packer/probe test system (Recommendation 7) proved to be unsuccessful in testing the Pomona basalt below the Rattlesnake Ridge interbed confining layer. This was largely attributable to the highly fractured condition of the Pomona basalt over this test/depth interval. Despite the lack of success of several of these recommended characterization activities at the proposed south dam abutment location, it is still advised to implement these recommendations at subsequent borehole, hydrogeologic site characterizations.

Table 7.1. Test/Depth Hydraulic Conductivity Distribution Summary

Test/Depth Interval ft bgs	Best Estimate Value		Basis/Comments
	Hydraulic Conductivity, K_h,[(a)] ft/day)	Storativity, S	
65.6–70.6	0.46	NA	DH-05-01 vadose zone test interval result
73.6–77.8	1.39	NA	DH-05-01 vadose zone test interval result
93–98	20.7	NA	DH-05-01 average vadose zone test interval result
113–119	5.43	NA	DH-05-01 average vadose zone test interval result
123–129	5.64	NA	DH-05-01 average vadose zone test interval result
133–150	0.45	NA	DH-05-01 adapted vadose zone test interval result
150–162.8	1.94	NA	DH-06-01 average vadose zone test interval result
236–255.1	3.77	NA	DH-06-01 average vadose zone test interval result
269.2–276*	1.28*	4.5E-4	*Based on extension of de-superposition principle for overlapping test intervals from DH-05-01 and DH-06-01
276–296	0.42	NA	Based on identical injection-test results for DH-06-01 test interval
311.8–334.6	0.32	4.0E-4	DH-05-01 average of test method results for test interval 319–334.6 ft extended to test interval 311.8–334.6 ft
334.6–375**	14.6	5.0E-5	**Based on de-superposition principle for encompassed test intervals from DH-05-01 and DH-06-01
375–395	52.9	NA	DH-05-01 piezometer slug test results

(a) Assumed to be uniform within the test/depth interval.

* Based on extension of de-superposition principle for overlapping test intervals. Determined by subtracting the overlapping transmissivity section value for DH-06-01 Zone (276-296 ft) from DH-05-01 test zone 269.2-287.4 ft and assigning residual to depth interval 269.2–276 ft ; $T_3 = T_1 - T_2 = 13.47 – 4.79 = 8.68$ ft²/day ; $K_3 = T_3/6.8$ ft = 1.28 ft/day

** Determined by subtracting the transmissivity value for DH-06-01 Zone (T_1 @ 276-296 ft) and DH-05-01 Zone (T_2 @ 311.8–334.6 ft) from DH-6 Zone (T_3 @ 311.8–400 ft) and assigning residual to depth interval 334.6 -375 ft ; $T_4 = T_3 - T_2 - T_1 = 1655 – 1058 - 7.3 = 589.7$ ft²/day ; $K_4 = T_4/10.8$ ft = 14.6 ft/day

Table 7.2. Hydrogeologic Unit Hydraulic Conductivity Property Summary/Comparison

Hydrogeologic Unit	Hydraulic Conductivity Range, ft/day		
	DH-05-01 & DH-06-01	DH-04-01 & DH-04-02	Hanford Site Geometric Mean/(Range)
Quaternary Surficial Sediments	NT	0.85	0.2–2.20)[a]
Ringold Formation	NP	2.64	8.43[b] (0.05–210)
Rattlesnake Ridge Interbed	NT	0.8	2.36[c] (0.06–25.6)
Pomona Basalt	0.46–1.39 (above fault zone)	0.04	$(10^{-2}–10^{3})$[d]
	0.32–52.9 (below fault zone)		
Undifferentiated Fault Zones	0.42–3.77	NP	NP
Selah Interbed	NP	2.7	2.36[c] (0.06–25.6)
Undifferentiated Esquatzel/Umatilla Basalts	0.45–20.7	NT	$(10^{-2}–10^{3})$[d]

(a) Saturated hydraulic conductivity estimates determined from laboratory permeability core tests for the Early Palouse soils and fine-grained sequence within the Hanford Formation, as reported in Connelly et al. (1992).
(b) Results for 38 Ringold Formation test sites within the central Hanford Site, as reported in Spane et al. (2001a, 2001b, 2002, 2003) and Spane and Newcomer (2004).
(c) Results for 22 Rattlesnake Ridge interbed test sites within the Hanford Site, as reported in Spane and Vermeul (1994) and Spane and Webber (1995).
(d) Results for Saddle Mountains Basalt flow tops and interflow zones, as reported in DOE (1988).

NT: Encountered but not tested during drilling

NP: Not present or encountered during drilling

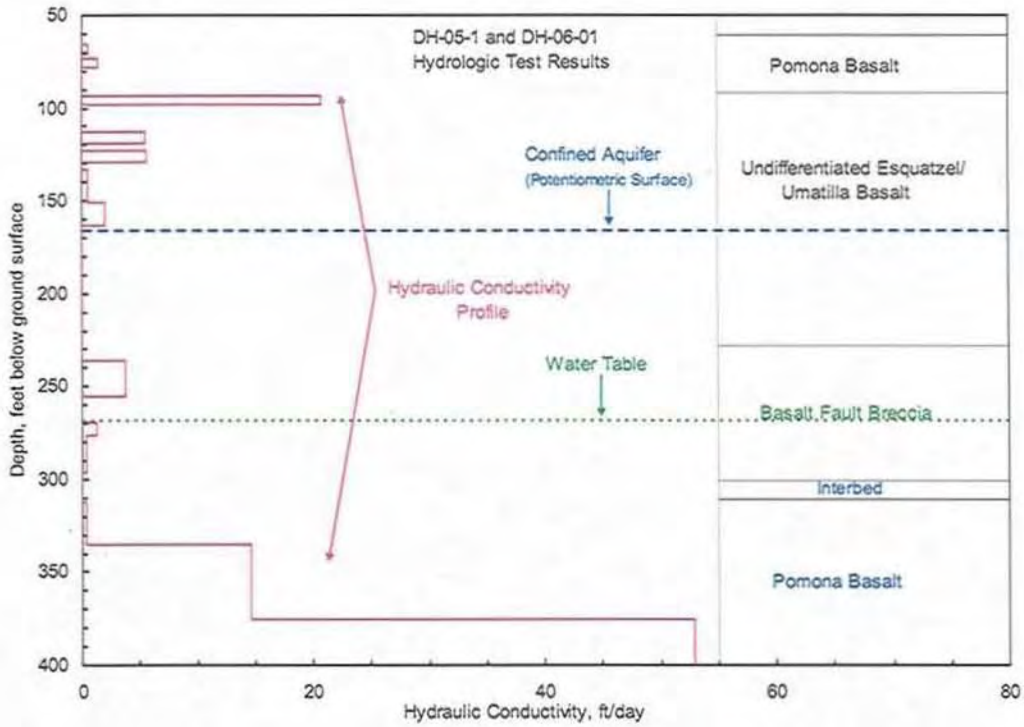


Figure 7.1. Hydraulic Conductivity Depth Profile for DH-05-01 and DH-06-01 Test Site

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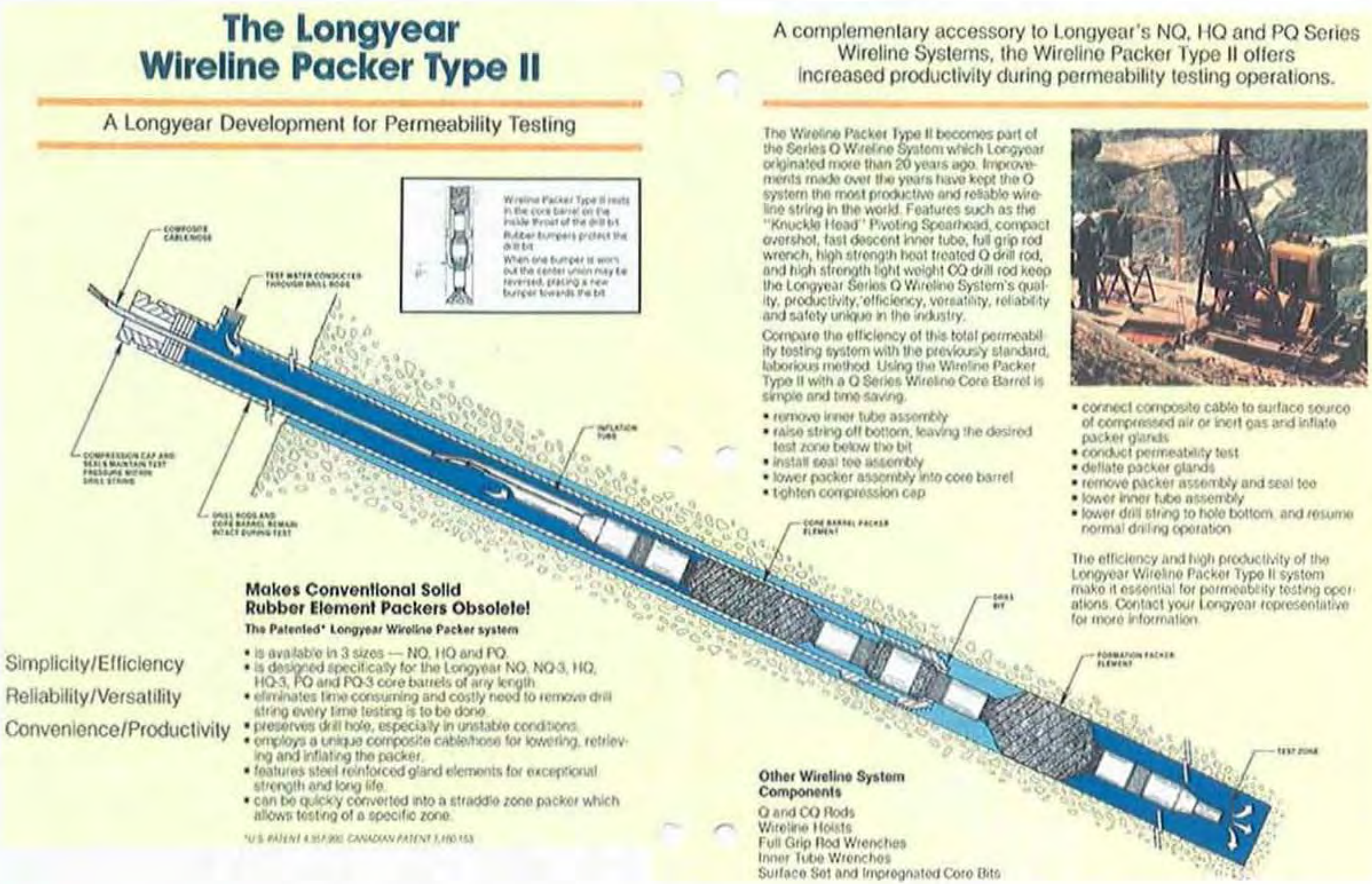
APPENDIX A

Test Equipment Pictures

A.1 Manufacturer General Description of Farwest Air-Longyear Wireline Packer Test System Used in Corehole DH-05-01

A.2 Inflatable Packer Test Equipment Assembly

A.3 Close-Up of Transducer Line and PTE Connection Assembly



The Longyear Wireline Packer Type II

A Longyear Development for Permeability Testing

A complementary accessory to Longyear's NQ, HQ and PQ Series Wireline Systems, the Wireline Packer Type II offers increased productivity during permeability testing operations.

The Wireline Packer Type II becomes part of the Series Q Wireline System which Longyear originated more than 20 years ago. Improvements made over the years have kept the Q system the most productive and reliable wireline string in the world. Features such as the "Knuckle Head" Pivoting Spearhead, compact overshot, fast descent inner tube, full grip rod wrench, high strength heat treated Q drill rod, and high strength light weight CQ drill rod keep the Longyear Series Q Wireline System's quality, productivity, efficiency, versatility, reliability and safety unique in the industry.

Compare the efficiency of this total permeability testing system with the previously standard, laborious method. Using the Wireline Packer Type II with a Q Series Wireline Core Barrel is simple and time saving.

- remove inner tube assembly
- raise string off bottom, leaving the desired test zone below the bit
- install seal tee assembly
- lower packer assembly into core barrel
- tighten compression cap
- connect composite cable to surface source of compressed air or inert gas and inflate packer glands
- conduct permeability test
- deflate packer glands
- remove packer assembly and seal tee
- lower inner tube assembly
- lower drill string to hole bottom, and resume normal drilling operation

The efficiency and high productivity of the Longyear Wireline Packer Type II system make it essential for permeability testing operations. Contact your Longyear representative for more information.

Simplicity/Efficiency
Reliability/Versatility
Convenience/Productivity

Makes Conventional Solid Rubber Element Packers Obsolete!

The Patented* Longyear Wireline Packer system

- is available in 3 sizes — NQ, HQ and PQ.
- is designed specifically for the Longyear NQ, NQ-3, HQ, HQ-3, PQ and PQ-3 core barrels of any length.
- eliminates time consuming and costly need to remove drill string every time testing is to be done.
- preserves drill hole, especially in unstable conditions.
- employs a unique composite cable/hose for lowering, retrieving and inflating the packer.
- features steel reinforced gland elements for exceptional strength and long life.
- can be quickly converted into a straddle zone packer which allows testing of a specific zone.

*U.S. PATENT 4,357,900 CANADIAN PATENT 1,160,153

Other Wireline System Components

Q and CQ Rods
Wireline Hoists
Full Grip Rod Wrenches
Inner Tube Wrenches
Surface Set and Impregnated Core Bits

Figure A.1. Manufacturer General Description of Farwest Air-Longyear Wireline Packer Test System Used in Corehole DH-05-01

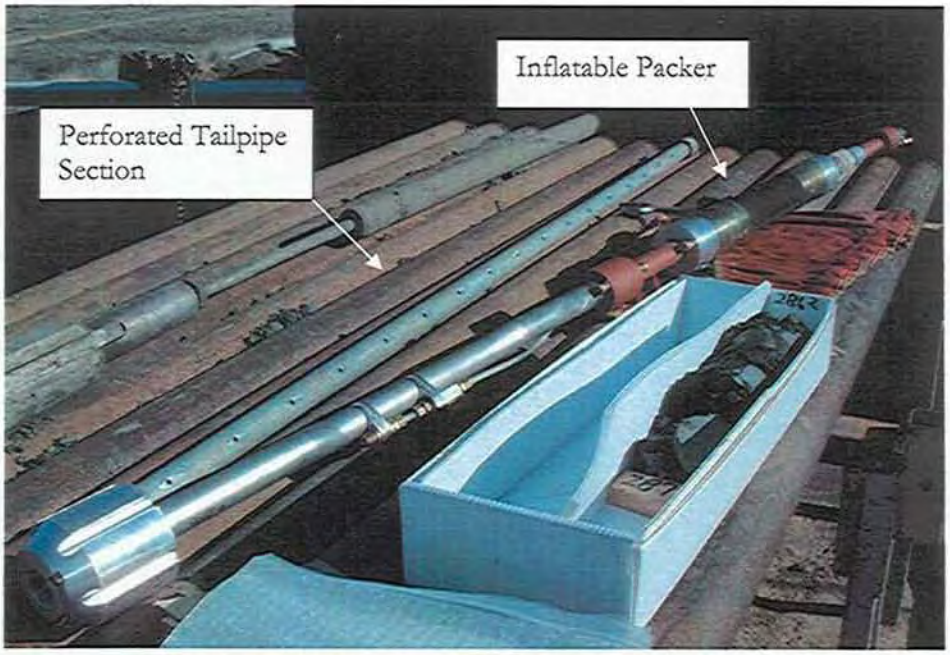


Figure A.2. Inflatable Packer Test Equipment Assembly

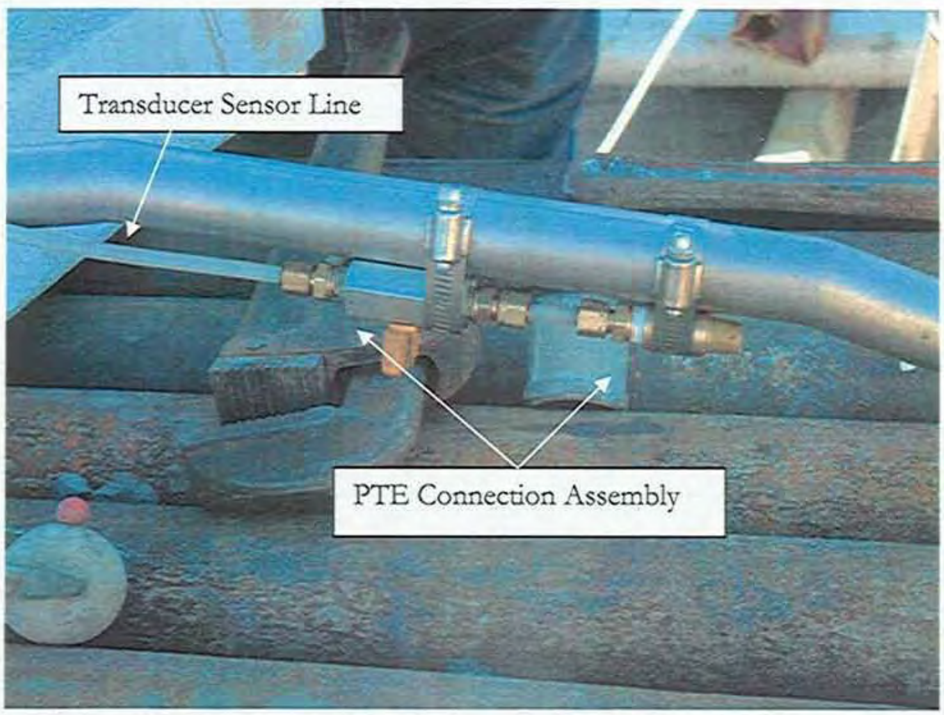


Figure A.3. Close-Up of Transducer Sensor Line and PTE Connection Assembly

APPENDIX B

Miscellaneous Baseline Monitoring/Barometric Analysis Plots

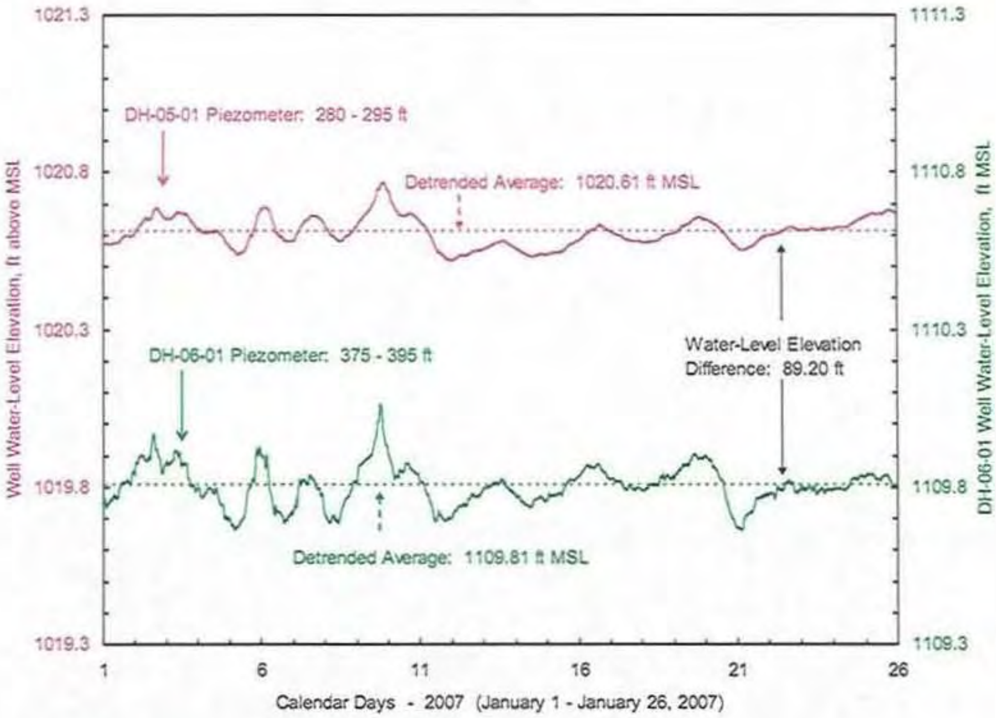


Figure B.1. A Comparison of De-Trended Data for Baseline Monitoring Period January 1–25, 2007, Piezometers DH-05-01 and DH-06-01

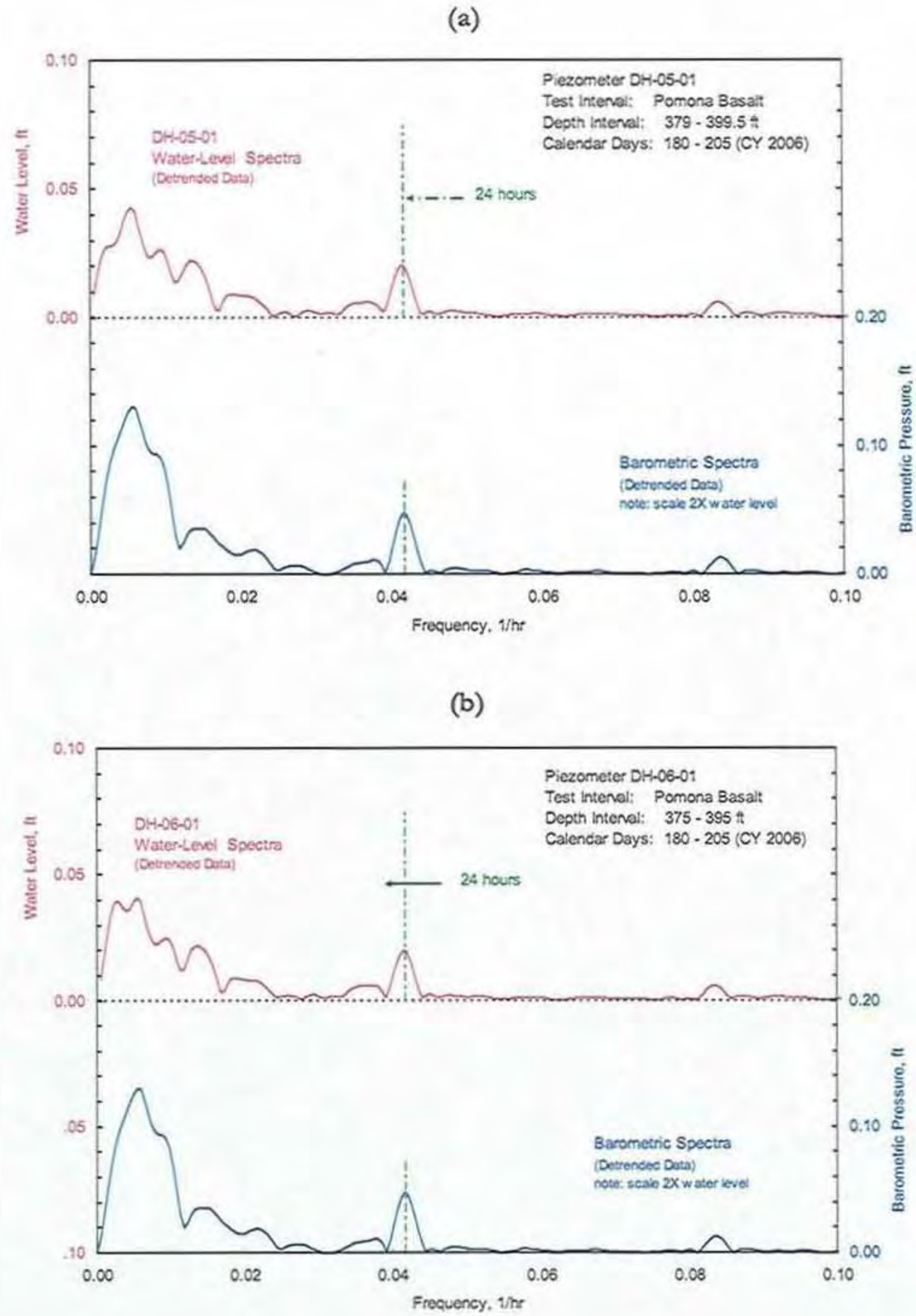
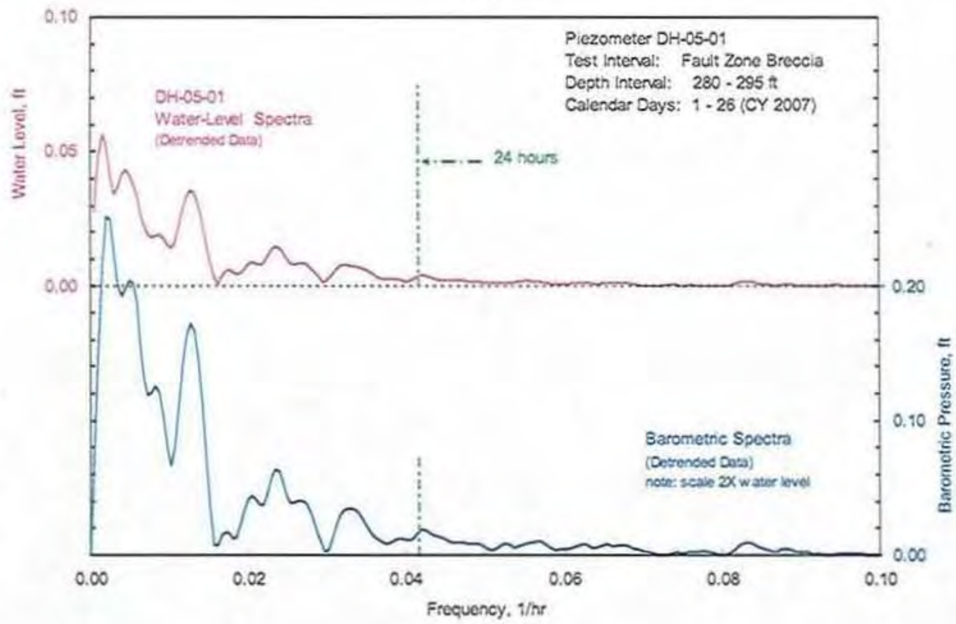


Figure B.2. Comparison of Continuous Frequency Spectra for Barometric Pressure and Well Water-Level Response for First Baseline Monitoring Period at: (a) Piezometer DH-05-01 and (b) Piezometer DH-06-01

(a)



(b)

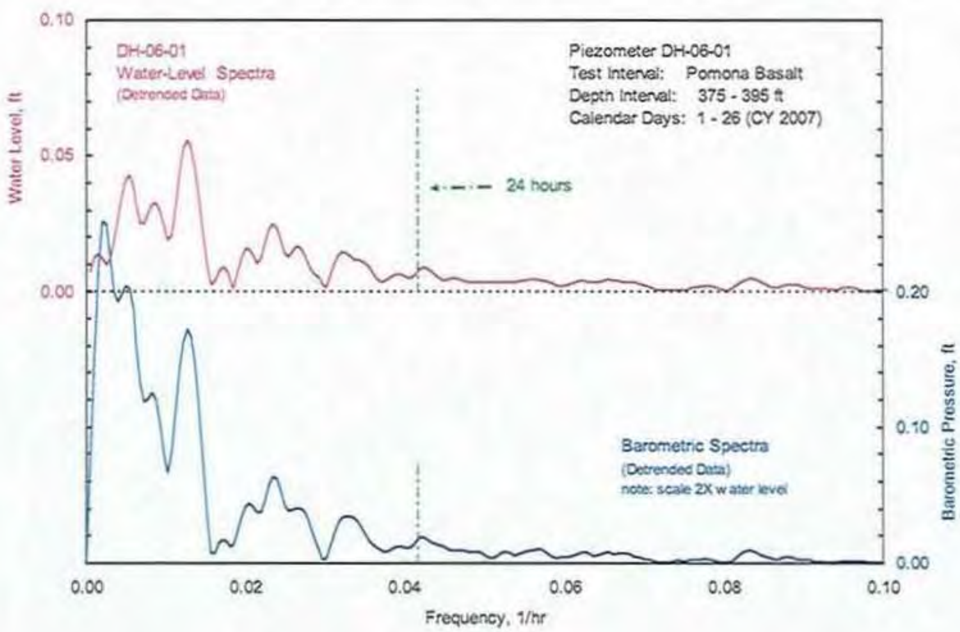


Figure B.3. Comparison of Continuous Frequency Spectra for Barometric Pressure and Well Water-Level Response for Second Baseline Monitoring Period at: (a) Piezometer DH-05-01 and (b) Piezometer DH-06-01

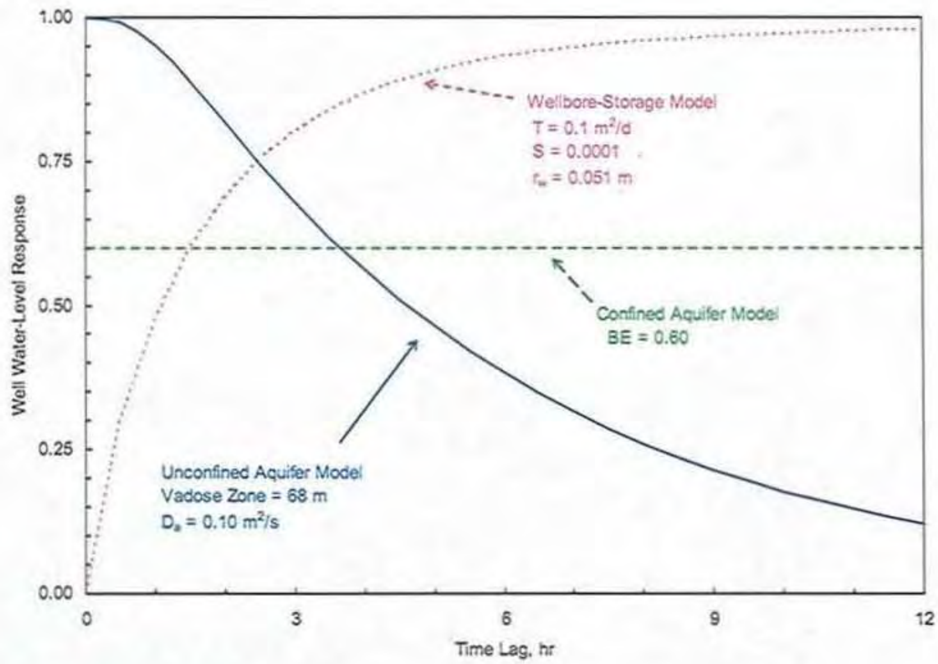


Figure B.4. Well Barometric Pressure Response Models (from Spane 1999)

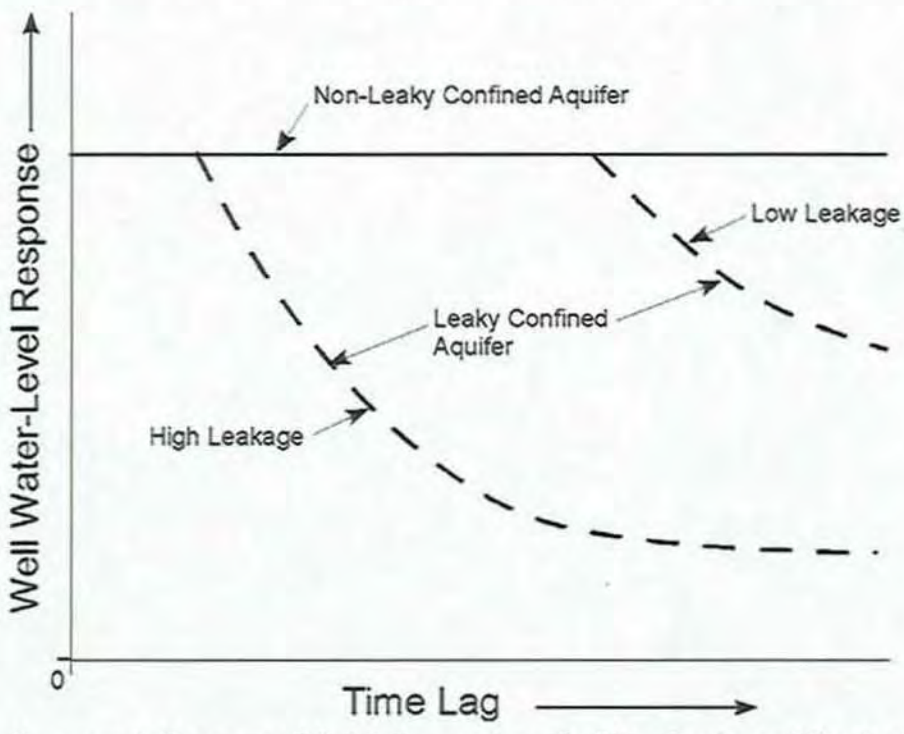


Figure B.5. Barometric Response Model Comparison for Non-Leaky and Leaky Confined Aquifer Conditions

APPENDIX C

Vadose Zone Test Analysis Plots

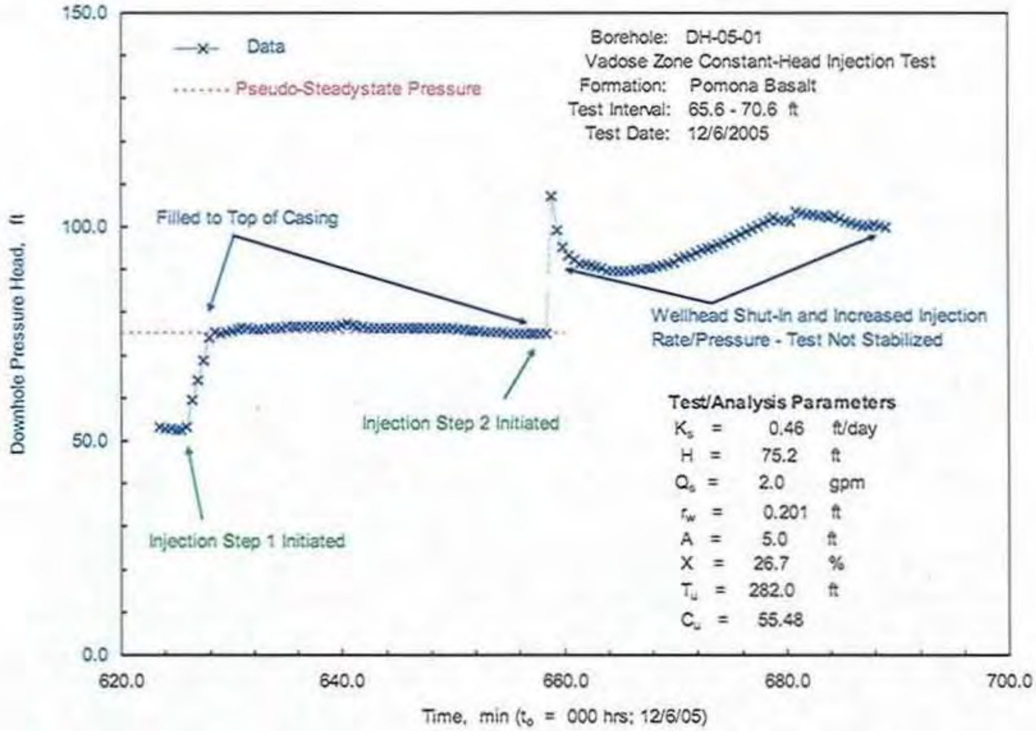


Figure C.1. Constant-Head Injection Test Results for DH-05-01, Vadose Zone: 65.6 to 70.6 ft

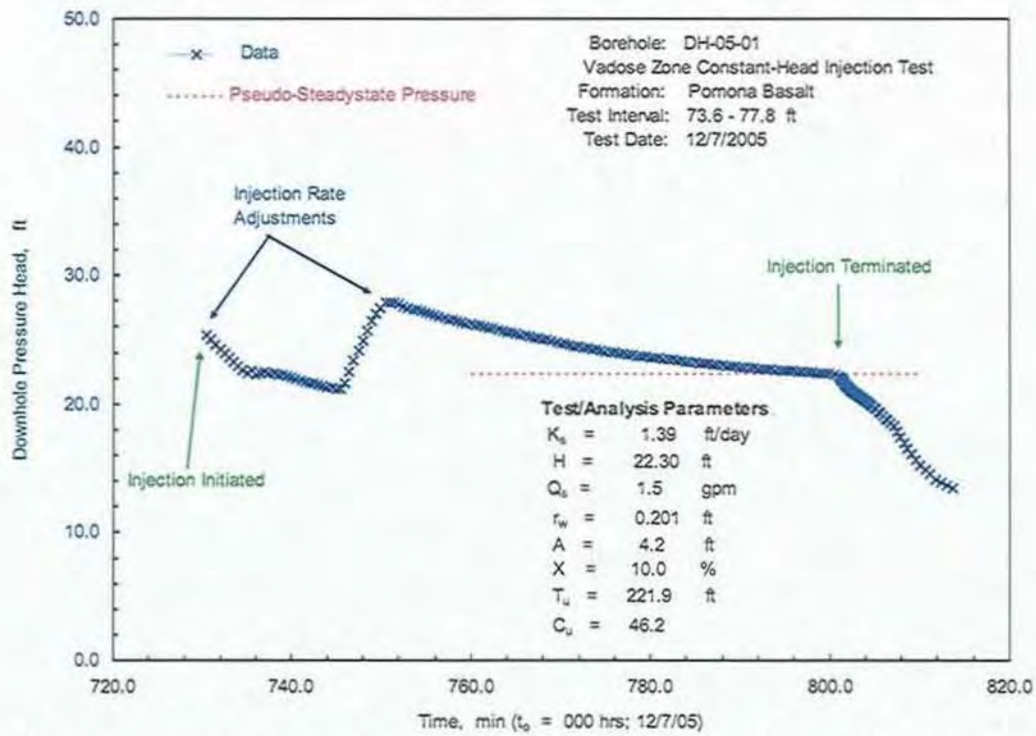


Figure C.2. Constant-Head Injection Test Results for DH-05-01 Vadose Zone: 73.6 to 77.8 ft

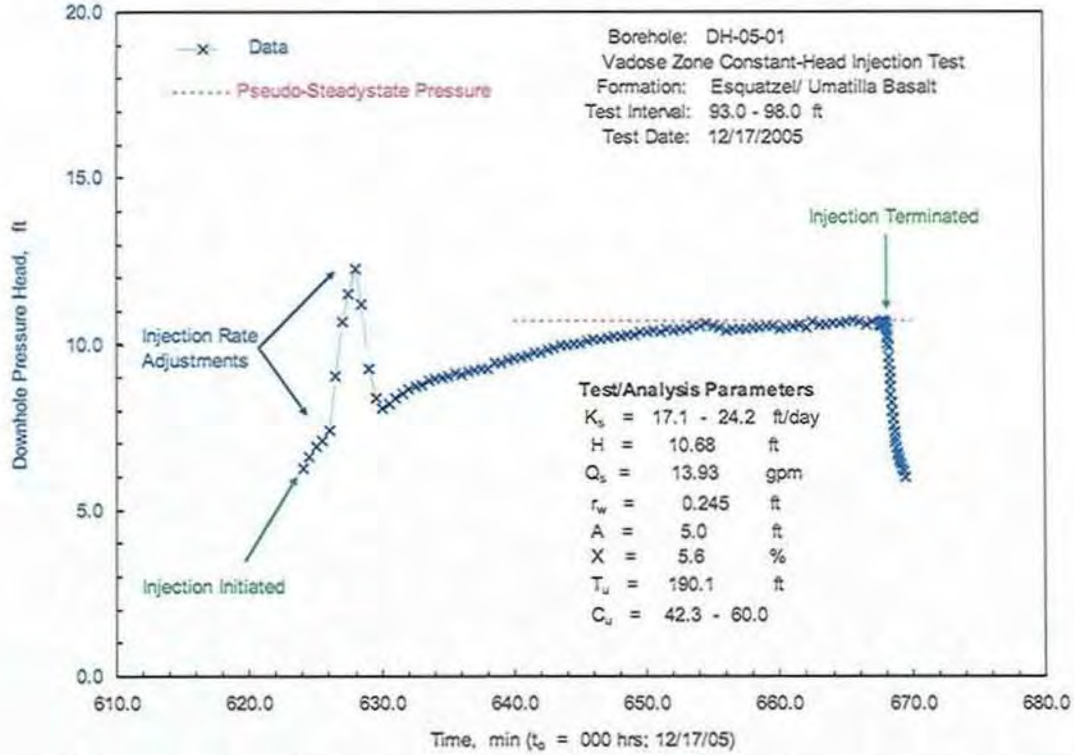


Figure C.3. Constant-Head Injection Test Results For DH-05-01 Vadose Zone: 93 to 98 ft

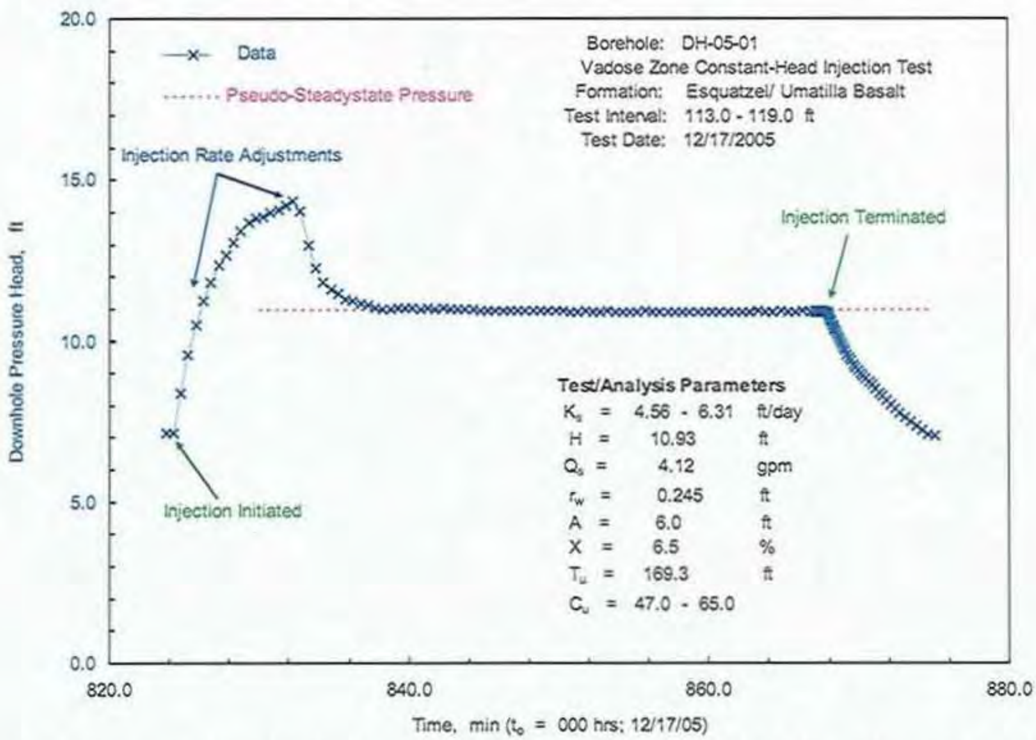


Figure C.4. Constant-Head Injection Test Results for DH-05-01 Vadose Zone: 113 to 119 ft

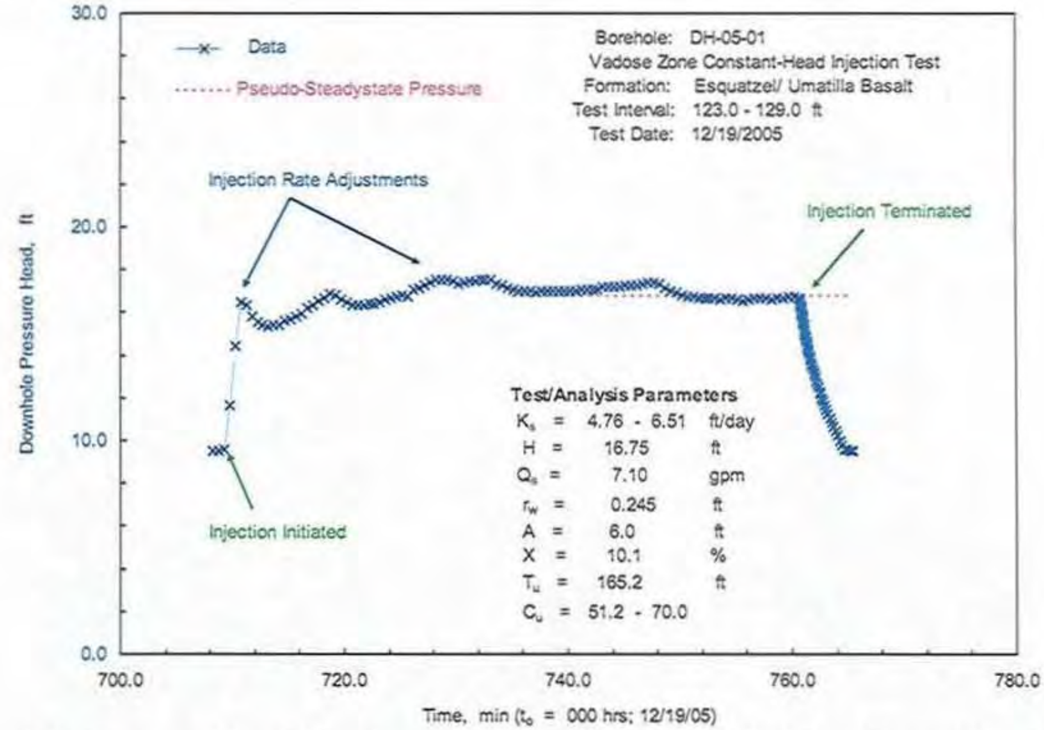


Figure C.5. Constant-Head Injection Test Results for DH-05-01 Vadose Zone: 123 to 129 ft

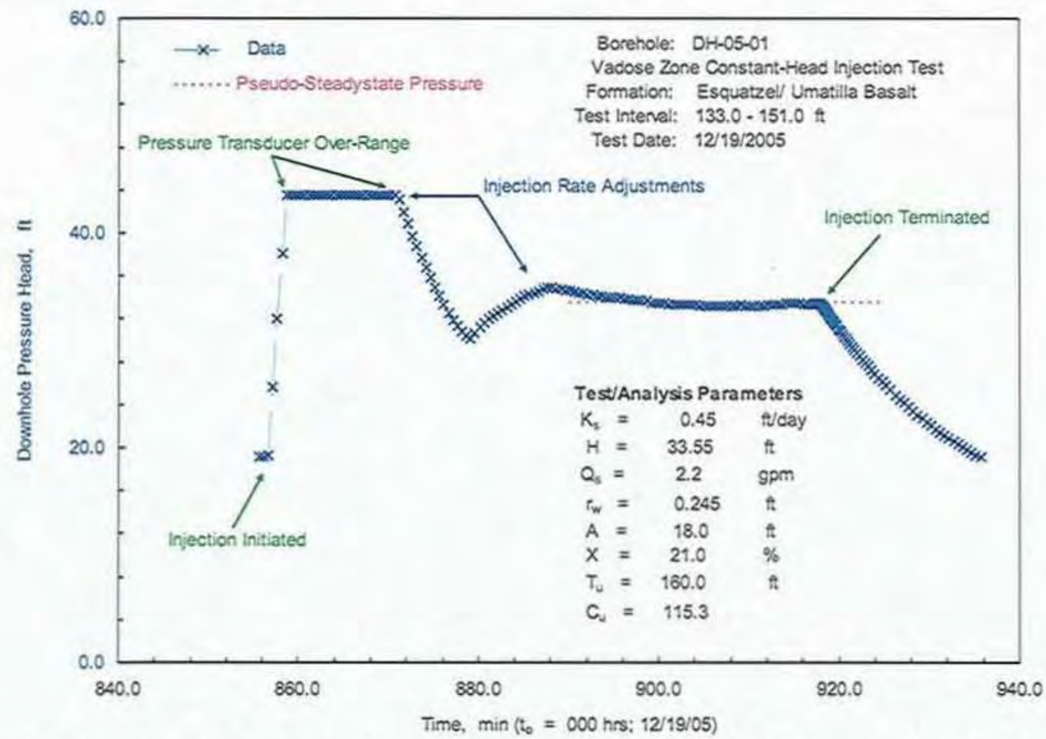


Figure C.6. Constant-Head Injection Test Results for DH-05-01 Vadose Zone: 133 to 151 ft

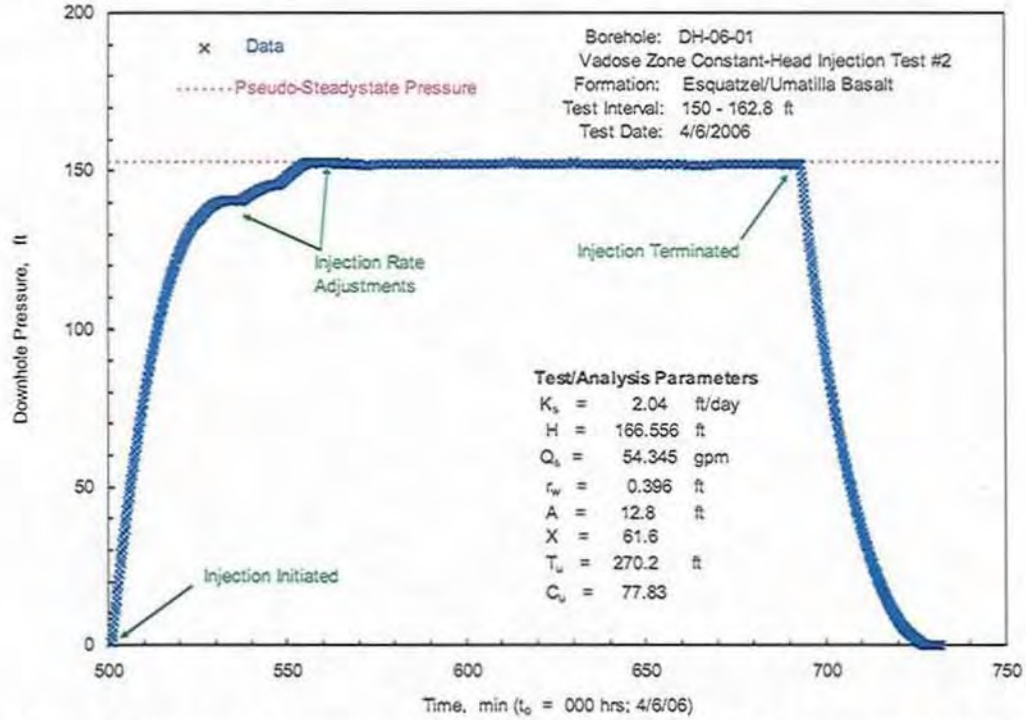


Figure C.7. Constant-Head Injection Test Results for DH-06-01, Injection Test Vadose Zone: 150 to 162.8 ft; Injection Test #2

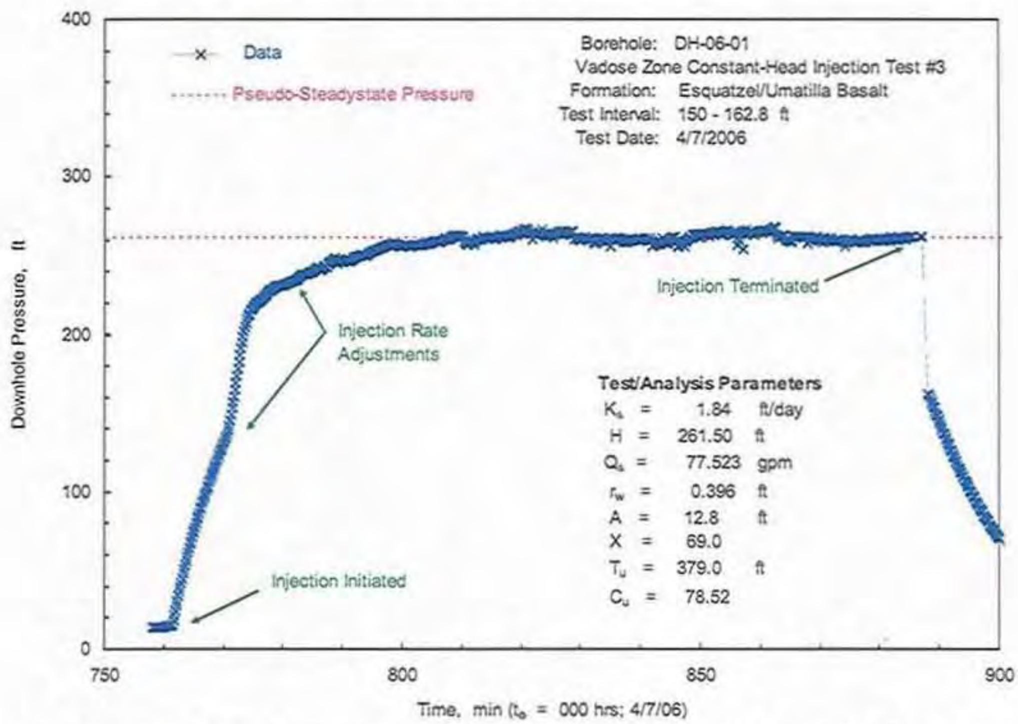


Figure C.8. Constant-Head Injection Test Results for DH-06-01, Injection Test Vadose Zone: 150 to 162.8 ft; Injection Test #3

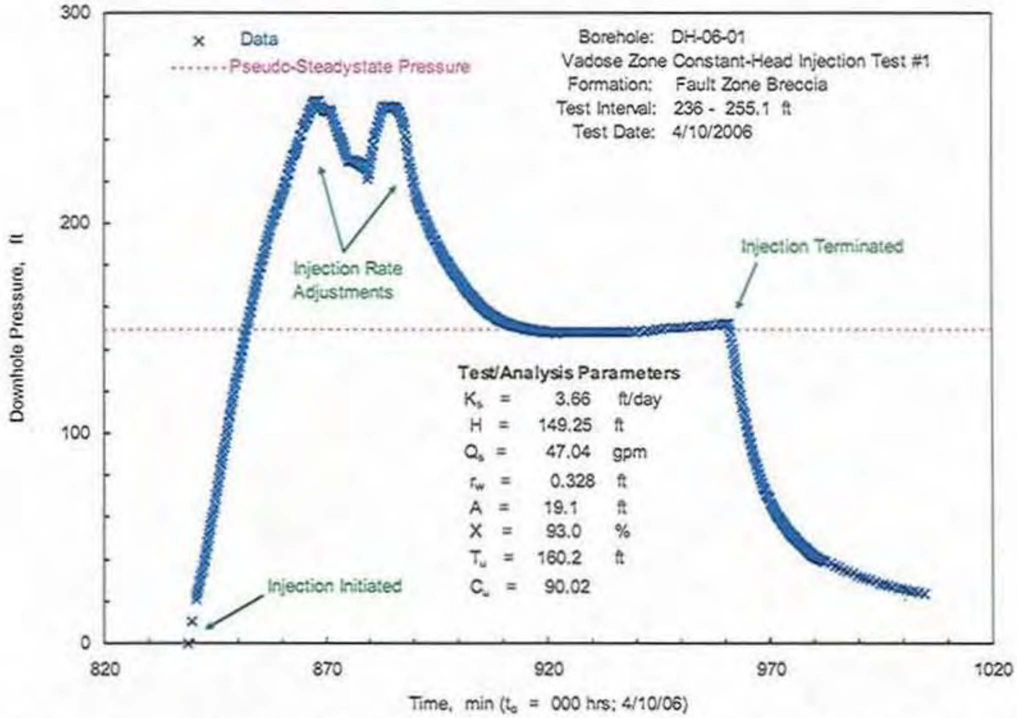


Figure C.9. Constant-Head Injection Test Results for DH-06-01, Injection Test Vadose Zone: 236 to 255.1 ft; Injection Test #1

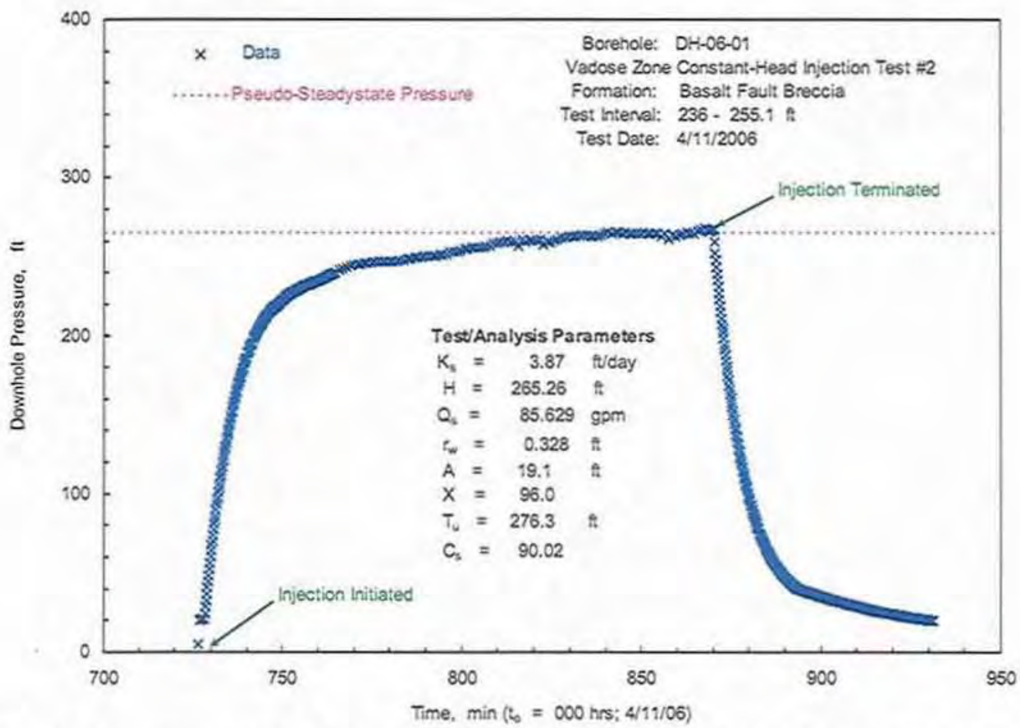


Figure C.10. Constant-Head Injection Test Results for DH-06-01, Injection Test Vadose Zone: 236 to 255.1 ft; Injection Test #2

APPENDIX D

Core Pictures for Selected Test Zone Intervals

D.1 Core Pictures for DH-05-01, Vadose Test Zone: 73.6 to 77.8 ft

D.2 Selected Core Pictures for DH-05-01 Groundwater Test Zone: 269.2 to 287.4 ft

D.3 Selected Core Pictures for DH-05-01 Groundwater Test Zone: 287.6 to 334.6 ft

D.4 DH-05-01 Core Pictures for DH-06-01, Vadose Test Zone: 150 to 162.8 ft

D.5 DH-05-01 Core Pictures for DH-06-01, Vadose Test Zone: 236 to 255.1 ft

D.6 Selected DH-05-01 Core Pictures for DH-06-01 Groundwater Test Zone: 311.8 to 400 ft

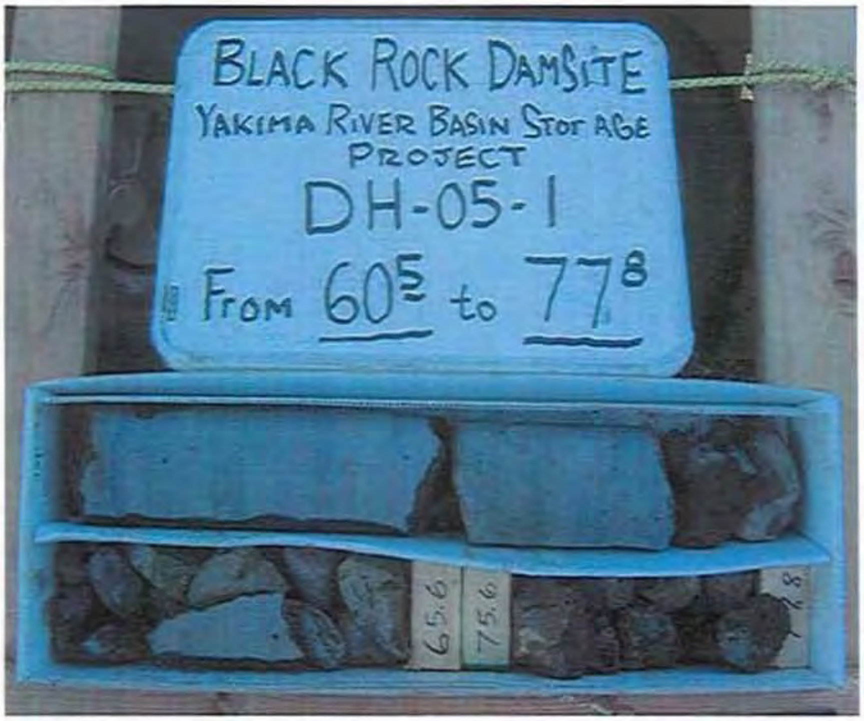


Figure D.1. Core Pictures For DH-05-01, Vadose Test Zone: 73.6 to 77.8 ft

Figure D.2(A). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 269.2 to 287.4 ft

Figure D.2(B). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 269.2 to 287.4 ft

BLACK ROCK DAMSITE
DH–5-1 287.6 - 297.8

Figure D.3(A). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 287.6 to 334.6 ft

BLACK ROCK DAMSITE
DH--05-1 297.8 - 307.5

Figure D.3(B). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 287.6 to 334.6 ft

BLACK ROCK DAMSITE
DH--05-1 307.5 - 317.5

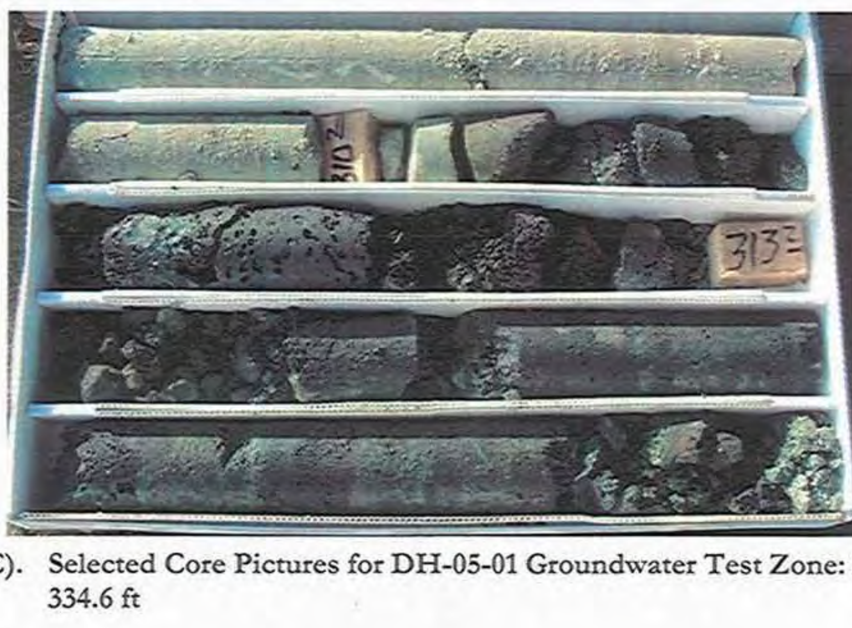


Figure D.3(C). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 287.6 to 334.6 ft

BLACK ROCK DAMSITE
DH--05-1 317.5 - 326.6

Figure D.3(D). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 287.6 to 334.6 ft

BLACK ROCK DAMSITE
DH--05-1 326.6 - 335.3

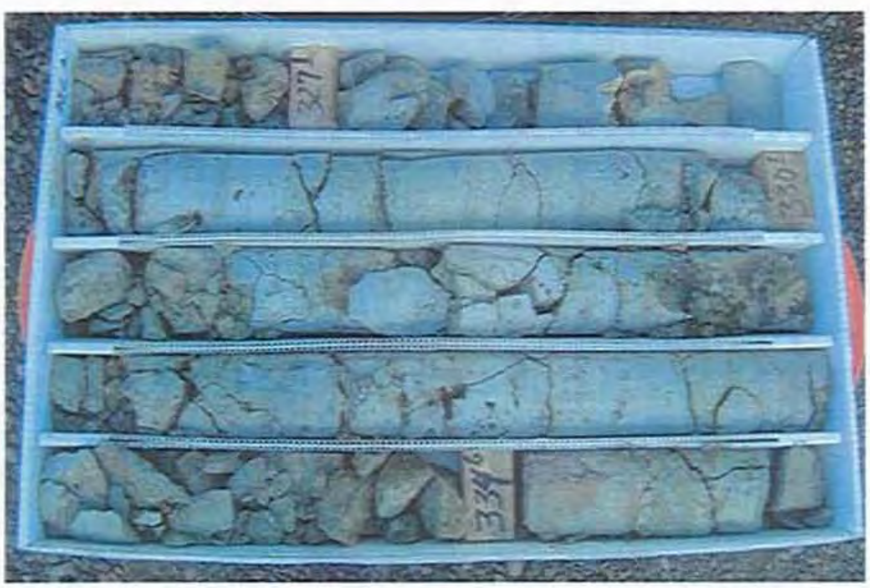


Figure D.3(E). Selected Core Pictures for DH-05-01 Groundwater Test Zone: 287.6 to 334.6 ft

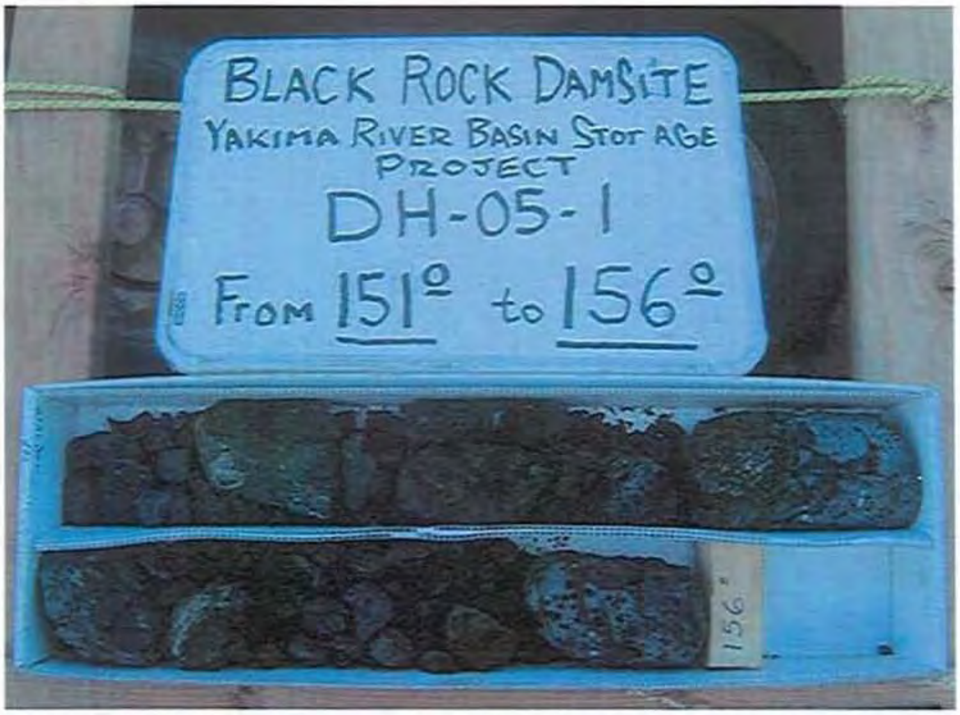


Figure D.4(A). DH-05-01 Core Pictures for DH-06-01, Vadose Test Zone: 150 to 162.8 ft

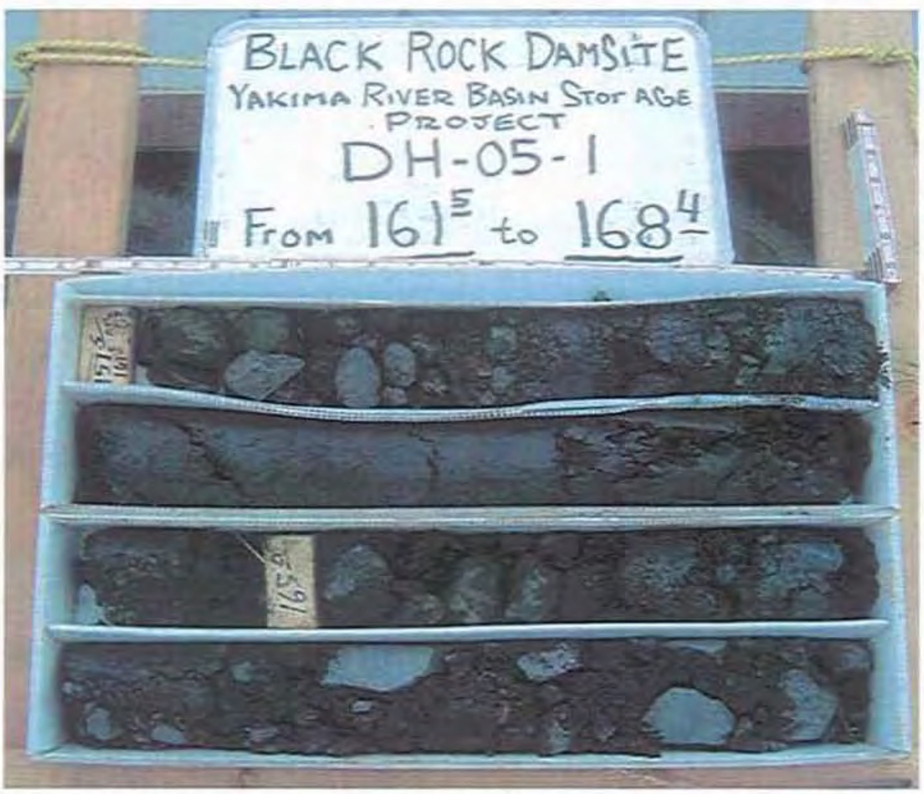


Figure D.4(B). DH-05-01 Core Pictures For DH-06-01, Vadose Test Zone: 150 to 162.8 ft

Figure D.5(A). DH-05-01 Core Pictures for DH-06-01, Vadose Test Zone: 236 to 251.1 ft

Figure D.5(B). DH-05-01 Core Pictures For DH-06-01, Vadose Test Zone: 236 to 255.1 ft

BLACK ROCK DAMSITE
DH--05-1 335.3 - 346.0

Figure D.6(A). Selected DH-05-01 Core Pictures for DH-06-01 Groundwater Test Zone: 311.8 to 400 ft

BLACK ROCK DAMSITE
DH--05-1   354.5 - 363.4

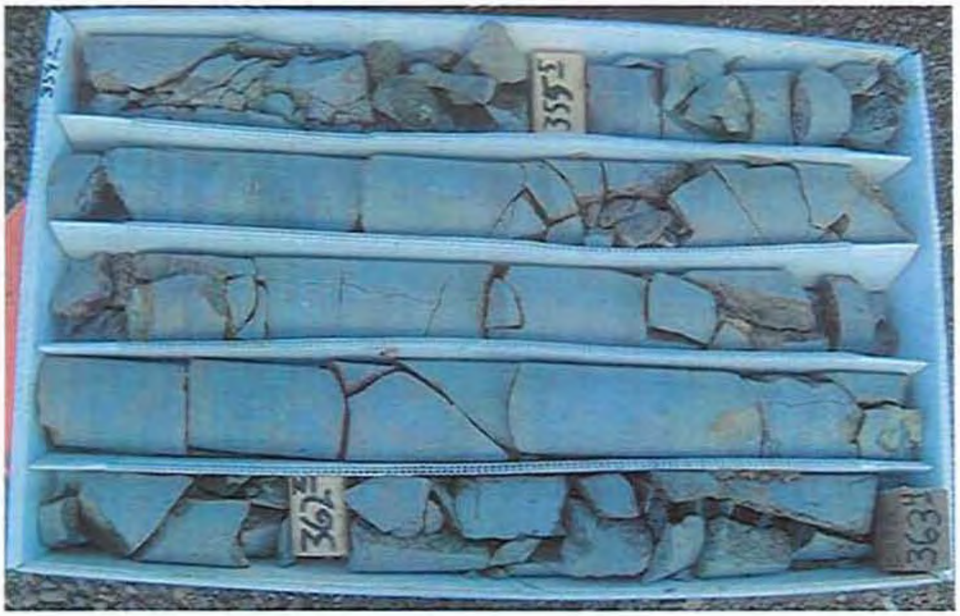


Figure D.6(B). Selected DH-05-01 Core Pictures for DH-06-01 Groundwater Test Zone: 311.8 to 400 ft

BLACK ROCK DAMSITE
DH--05-1   372.2 - 381.1

Figure D.6(C). Selected DH-05-01 Core Pictures for DH-06-01 Groundwater Test Zone: 311.8 to 400 ft

BLACK ROCK DAMSITE
DH--05-1 381.1 - 390.2

Figure D.6(D). Selected DH-05-01 Core Pictures for DH-06-01 Groundwater Test Zone: 311.8 to 400 ft

BLACK ROCK DAMSITE
DH--05-1 390.2 - 399.6

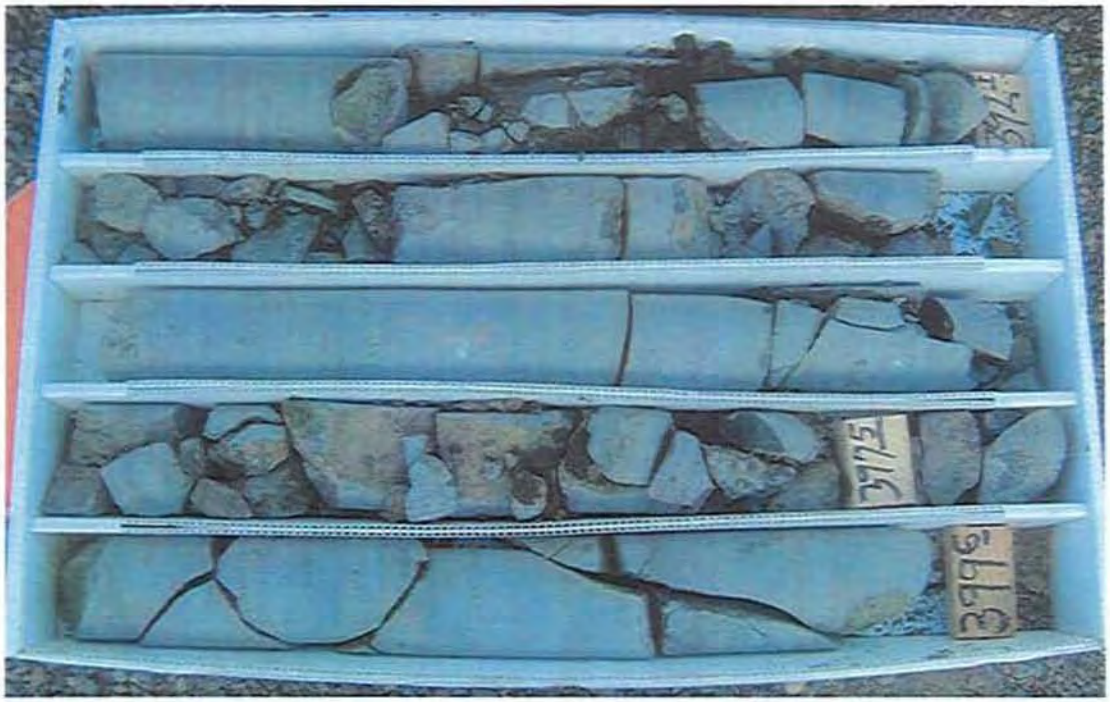


Figure D.6(E). Selected DH-05-01 Core Pictures for DH-06-01 Groundwater Test Zone: 311.8 to 400 ft

APPENDIX E

Hydrochemical Data

Table E.1. Dissolved Major Inorganic Constituents for Groundwater-Samples Collected from DH-06-01 Step-Drawdown Test

Sample Date (Time, PST)	Stage of Step-Drawdown Test	Major Anions					Major Cations			
		HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L	NO_3/NO_2 mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L
5/6/2006 (1107 hours)	Step 1	142	16.9	3.7	ND	ND	12.5	4.0	23.6	11.5
5/6/2006 (1240 hours)	Step 2	142	16.6	3.7	ND	ND	12.5	4.0	24.2	11.4
5/6/2006 (2007 hours)	Step 3	142	16.4	3.7	ND	ND	12.6	4.0	24	11.4
5/6/2006 (2030 hours)	Step 3	143	16.5	3.7	ND	ND	12.5	4.0	24	11.4

ND Not Determined

Table E.2. Dissolved Major Inorganic Constituents in DH-06-01 Confined Aquifer Groundwater

Sample Date (Time, PST)	Hydro geologic Unit	Major Anions					Major Cations			
		HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L	NO_3/NO_2 mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L
DH-06-01 5/6/2006	Pomona	143	16.5	3.7	ND	ND	12.5	4.0	24	11.4
DH-04-02 5/13/04 (1053)	Composite Selah/ Esquatzel	145	16.6	6.9	0.37	1.46	12.8	4.1	26.1	11.9
Hanford Site* (1979-1981)	Selah	132 - 210	1.2 - 19.1	1.5 - 5.0	0.03 - 0.90	<0.5 - 2.7	16.8 - 78.4	6.4 - 12.0	2.4 - 25.3	0.4 - 13.5

ND Not Determined

*Note: Hanford Site results obtained from hydrochemical data reported in Early et al. (1986).

Appendix B

Geologic Logs of Drill Holes, Core Photographs, and Borehole Geophysical Logs

Laboratory Data

Geologic Log of Drill Hole No. DH-05-1
(Lower Right Abutment – Foundation Samples)

Photographs of Core – 60.5 to 77.8 feet and 151.0 to 401.4 feet
Borehole Geophysical Log

GEOLOGIC LOG OF DRILL HOLE NO. DH-05-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 11/17/05 FINISHED: 3/8/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 162.9 (1113.18) 3/5/06

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,490.4 E 1,794,496.6
TOTAL DEPTH: 401.4
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.1
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Stelma/Didricksen
REVIEWED BY: Doug Bennett

Depth interval	% RECOVERY	FIELD CLASSIFICATION	GEOLOGIC UNIT
0.0-3.0	0	ML	Qe
3.0-60.5	0	(GP-GM)sc	Qcg
60.5-65.6	51		Tp
65.6-75.6	0		Tp
75.6-77.8	45		Tp
77.8-92.0	0		Tp
92.0-96.0	0		
96.0-98.0	90		

Column headings: NOTES; DEPTH; % RECOVERY; SPT; ENGINEERING PROPERTIES (WEATHERING, HARDNESS, FRACTURE DENSITY, RQD); FIELD CLASSIFICATION; LAB CLASSIFICATION; GEOLOGIC UNIT; GRAPHIC; HOLE COMPLETION; CLASSIFICATION AND PHYSICAL CONDITION

NOTES

All elevations measured from ground surface and are same as driller reported.

PURPOSE OF HOLE:
To determine foundation stratigraphy and rock fracturing characteristics for hydrogeologic testing.

DRILL SETUP:
Setup on a hillside drill pad located on the lower right abutment along the original Black Rock dam axis approximately 1200 feet south of Washington State Highway 24.

DRILLING EQUIPMENT:
Truck mounted Ingersoll-Rand T-2 rotary drill.

DRILLER:
Chris Peterson

DRILLING METHODS:
0.0-51.0': Advanced 8-inch casing using a top drive hammer with a 7-7/8" rockbit and compressed air to remove cuttings.

51.0-60.5': Advanced 6-inch casing using a top drive hammer with a 5-7/8" rockbit and water to remove cuttings.

60.5-77.8': Advanced hole with PQ wireline core barrel (3.336" I.D.) and diamond bit using clear water as circulating fluid. Pulled PQ and 6" casing, advanced 8" casing to 63.4' using a top drive hammer with a 7-7/8" rockbit and compressed air to remove cuttings. Installed 6" casing through 8" casing and continued drilling and driving.

77.8-139.5': Advanced 6-inch using top drive hammer with a 5-7/8" rockbit and compressed air to remove cuttings.

139.5-151.0': Advanced hole with a 5-7/8" rockbit and compressed air to

CLASSIFICATION AND PHYSICAL CONDITION

0.0-3.0': **QUATERNARY LOESS DEPOSITS (Qe).** Surficial deposits of silt with lesser amounts of clay, composed primarily of wind-blown silt with small amounts of fine sand. Description is based on drilling conditions and and cuttings returned.

3.0-60.5': **QUATERNARY COLLUVIUM (Qcg).** Unconsolidated gravel, sand and cobbles with silt and clay. Descriptions are based on drilling conditions and cuttings returned.

3.0-47': SAND, SILT AND GRAVEL. Description are based on drilling conditions and cuttings returned.

47.0-51.0': SAND AND SILT. Description are based on drilling conditions and cuttings returned.

51.0-60.5': GRAVEL, SAND, AND FINES WITH COBBLES. Description are based on drilling conditions and cuttings returned.

60.5-92.0': **POMONA MEMBER (Tp)** of the Saddle Mountains Basalt Formation, Miocene Columbia River Basalt Group (CRBG). Black to gray, moderately hard to hard, mostly fine grained, vesicular to dense aphanitic basalt and basalt breccia. Descriptions are based on drilling conditions, cuttings returned, and PQ-size core samples.

60.5 to 77.8': BASALT COBBLES WITH POORLY GRADED GRAVEL AND SILT: TOTAL SAMPLE (BY VOLUME): About 10% 3- to 5-inch hard, subangular cobbles; about 50% 5- to 12-inch hard, subangular cobbles; remainder minus 3 inch; clasts composed of basalt.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 65.6'. Pomona Member (Tp) chemistry.

MINUS 3-INCH FRACTION (BY MASS): About 90% mostly coarse, hard, subangular gravel; about 10% nonplastic fines.

HYDRAULIC CONDUCTIVITY OF INTERVAL 65.6-70.6': 0.45 feet/day.

HYDRAULIC CONDUCTIVITY OF INTERVAL 73.6-77.8': 1.39 feet/day.

77.8-92.0': BASALT SAND AND GRAVEL. Description based on drilling conditions and cuttings returned.

92.0-228.4': **UMATILLA MEMBER (Tum)** of the Saddle Mountains Basalt Formation, Miocene Columbia River Basalt Group (CRBG. Black to gray, hard, mostly fine grained dense basalt and basalt breccia. Descriptions are based on PQ- and HQ-size core samples.

92.0-98.0': BASALT SAND, GRAVEL AND FINES. Description based on drilling conditions and cuttings

COMMENTS: Samples were logged in the field using Designation USBR 5005-86, "Procedures for Determining Unified Soil Classification (Visual Method)."

Center column descriptors are defined in the Reclamation Engineering Geology Field Manual, Volume 1, Second Edition, distributed February 1999.

Cs = Casing Sz = Size of Casing I.D. = Inside Diameter O.D. = Outside diameter

Geologic unit descriptions, stratigraphy and geochemistry interpretation based partially on information presented in the following reports:

"Black Rock Reservoir Study, Initial Geotechnical Investigation", Prepared for Benton County Sustainable Development by Washington Infrastructures Services, Inc., Dated January 2003.

"Geologic Investigation Black Rock Dam, Alternate Dam Site, Yakima County, Washington, Prepared for U.S. Bureau of Reclamation by Columbia Geotechnical Associates, Inc., Dated February 12, 2004.

"Chemical Discrimination of Columbia River Basalt Flows", P.R. Hooper, Department of Geology, Washington State University, Dated June 14, 2000.

GEOLOGIC LOG OF DRILL HOLE NO. DH-05-1

FEATURE: Black Rock Alternate Damsite
PROJECT: Yakima R. Basin Water Storage Feas. Study
STATE: Washington
LOCATION: South of Washington State Highway 24
COORDINATES: N 437,490.4 E 1,794,496.6
GROUND ELEVATION: 1276.1
BEGUN: 11/17/05 FINISHED: 3/8/06
TOTAL DEPTH: 401.4
ANGLE FROM HORIZONTAL: AZIMUTH:
DEPTH AND ELEV OF WATER
DEPTH TO BEDROCK: 60.5
HOLE LOGGED BY: Stelma/Didricksen
LEVEL AND DATE MEASURED: 162.9 (1113.18) 3/5/06
REVIEWED BY: Doug Bennett

NOTES

remove cuttings.

151.0-161.5': Advanced hole with PQ wireline core barrel (3.336" I.D.) and diamond bit using clear water as circulating fluid. Reamed hole with 5-7/8" rockbit to 156.0' and installed 6-inch using top drive hammer to 143.0' (refusal).

161.5-218.5': Advanced hole with PQ wireline core barrel (3.336" I.D.) and diamond bit using polymer (EZ Mud) as circulating fluid and Diamond Seal to enhance fluid return.

218.5-222.9': Advanced hole with PQ wireline core barrel (3.336" I.D.) and diamond bit using clear water as circulating fluid. Flushed hole and tremied 60 gallons of calcium sealant through drill rods, estimated to fill bottom 81.0' of hole. Actually filled bottom 40', up to 185.6' due to losses. Reamed hole with PQ wireline core barrel to 222.9'.

222.9-287.4': Advanced hole with PQ wireline core barrel (3.336" I.D.) and diamond bit using polymer (EZ Mud) as circulating fluid and Diamond Seal to enhance fluid return.

287.4-401.4: Pulled PQ and installed 4" casing to 287.4'. Advanced hole with HQ wireline core barrel (2.50" I.D.) and diamond bit using polymer (EZ Mud) as circulating fluid and Diamond Seal to enhance fluid return.

DRILLING CONDITIONS:
0.0-301.1': Slow and rough, frequent blocking (core barrel).

301.1-310.7': Slow and smooth, frequent blocking (core barrel).

310.7-401.4': Slow and rough, frequent blocking (core barrel).

CASING RECORD:

2005 Date	Cs Sz	Depth Hole	Depth Cs
11/22	6"	14.0'	14.0'
11/29	8"	38.0'	38.0'
11/30	8"	51.0'	41.0'
12/02	8"	61.0'	41.0'
12/03	8"	61.0'	41.0'
12/05	6"	65.0'	60.0'

LOG COLUMNS (DEPTH 101–219)

DEPTH scale: 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, 200, 205, 210, 215

% RECOVERY (top to bottom): 0, 90, 0, 67, 0, 54, 10, 100, 92, 100, 92, 83, 27, 95, 97, 80, 100, 100, 100, 100, 100, 100, 100, 100, 100, 100, 100

ENGINEERING PROPERTIES:
- WEATHERING (top to bottom): W6, W3, W6, W3
- HARDNESS (top to bottom): H4, H3
- FRACTURE DENSITY (top to bottom): FD9, FD8, FD9, FD8
- RQD (top to bottom): 26, 0, 33, 0, 13, 23, 10, 0, 22

FIELD CLASSIFICATION: Basalt

GEOLOGIC UNIT: Tum

CLASSIFICATION AND PHYSICAL CONDITION

returned.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 97.2'. Umatilla Member (Tum) chemistry (drive sample from companion hole DH-06-1).

HYDRAULIC CONDUCTIVITY OF INTERVAL 93.0-98.0': 20.7 feet/day.

98.0-103.0': BASALT SAND AND GRAVEL. Description based on drilling conditions and cuttings returned.

103.0-108.0': BASALT SAND, GRAVEL AND FINES. Description based on drilling conditions and cuttings returned.

108.0-113.0': BASALT SAND, GRAVEL AND COBBLES. Description based on drilling conditions and cuttings returned.

113.0-140.0': BASALT SAND, GRAVEL AND FINES. Description based on drilling conditions and cuttings returned.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 117.0'. Umatilla Member (Tum) chemistry (drive sample from companion hole DH-06-1).

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 136.5'. Umatilla Member (Tum) chemistry (drive sample from companion hole DH-06-1).

HYDRAULIC CONDUCTIVITY OF INTERVAL 113.0-119.0': 5.43 feet/day.

HYDRAULIC CONDUCTIVITY OF INTERVAL 123.0-129.0': 5.64 feet/day.

140.0-143.0': BASALT GRAVEL AND COBBLES. Description based on drilling conditions and cuttings returned.

143.0-151.0': BASALT. Description is based on drilling conditions and cuttings returned.

HYDRAULIC CONDUCTIVITY OF INTERVAL 133.0-151.0': 0.45 feet/day.

151.0-157.5': BASALT. Black to dark gray, fine grained, vesicular basalt. Vesicles comprise about 20% of the rock. Intensely to Moderately Weathered (W6). Extensive oxidation (iron and manganese) throughout body of rock, blackish-green to light green (chlorite) coating on fractures surfaces and filling vesicles. Moderately Hard (H4). Core fragments can be broken with moderate hammer blow. Very Intensely Fractured (FD9). Core recovered in lengths from fragments to 0.4', mostly mostly as fragments. Joints dip about 50 degrees, surfaces are rough and planar.

157.5-161.5': BASALT. Description is based on drilling conditions and cuttings returned.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 159.0'. Umatilla Member (Tum) chemistry.

161.5-168.4': BASALT. Black to dark gray, fine grained, vesicular basalt fragments in a sand and clayey sand matrix. Vesicles comprise about 20% of the rock portion. Intensely to Moderately Weathered (W6). Extensive oxidation (iron and manganese) throughout body of rock, blackish-green to light green (chlorite) coating on

GEOLOGIC LOG OF DRILL HOLE NO. DH-05-1

FEATURE: Black Rock Alternate Damsite
PROJECT: Yakima R. Basin Water Storage Feas. Study
STATE: Washington
LOCATION: South of Washington State Highway 24
COORDINATES: N 437,490.4 E 1,794,496.6
GROUND ELEVATION: 1276.1
BEGUN: 11/17/05 FINISHED: 3/8/06
TOTAL DEPTH: 401.4
ANGLE FROM HORIZONTAL: AZIMUTH:
DEPTH AND ELEV OF WATER
DEPTH TO BEDROCK: 60.5
HOLE LOGGED BY: Stelma/Didricksen
LEVEL AND DATE MEASURED: 162.9 (1113.18) 3/5/06
REVIEWED BY: Doug Bennett

NOTES

12/06 6" 75.0' 60.0'
12/07 6" 77.8' 60.0'
12/14 8" 77.8' 59.6'
12/16 6" 98.0' 93.0'
12/17 6" 119.0' 113.0'
12/19 6" 151.0' 133.0'
12/20 6" 156.0' 139.5'
12/21 6" 156.0' 143.6'

2006 Cs Depth Depth
Date Sz Hole Cs

01/18 6" 161.5' 143.0'
01/19 6" 170.0' 143.0'
01/20 6" 180.0' 143.0'
01/21 6" 189.7' 143.0'
01/23 6" 199.4' 143.0'
01/24 6" 209.2' 143.0'
01/25 6" 218.5' 143.0'
02/01 6" 222.9' 143.0'
02/02 6" 222.9' 143.0'
02/03 6" 231.9' 143.0'
02/04 6" 243.3' 143.0'
02/05 6" 254.2' 143.0'
02/06 6" 264.8' 143.0'
02/07 6" 275.8' 143.0'
02/08 6" 287.4' 143.0'
02/16 4" 287.6' 287.6'
02/17 4" 294.2' 287.6'
02/18 4" 300.1' 287.6'
02/19 4" 322.0' 287.6'
02/20 4" 334.6' 287.6'
02/22 4" 343.2' 287.6'
03/01 4" 352.0' 287.6'
03/02 4" 368.7' 287.6'
03/03 4" 388.2' 287.6'
03/04 4" 401.4' 287.6'

FLUID COLOR:
0.0-51.0': Tan (air).
51.0-60.5': Tan (water).
60.5-65.6': Gray (water).
65.5-129.0': Brown (air).
129.0-151.0': Black (air).
151.0-156.0': No return.
156.0-161.5': Black (water).
161.5-300.1': Black (polymer - ez mud and diamond seal).
300.1-401.4': Gray (polymer - ez mud and diamond seal).

FLUID RETURN:
0.0-51.0': Drilled w/ air.
51.0-60.5': 70%
60.5-77.8': 25%
77.8-151.0': Drilled w/ air.
151.0-156.0': 0%
156.0-191.7': 90%
191.7-209.2': 70%
209.2-211.0': 50%
211.0-215.0': 20%
215.0-217.1': 50%
217.1-218.5': 60%
218.5-222.9': 50%
222.9-227.0': 70%
227.0-230.0': 60%
230.0-231.9': 1%
231.9-236.0': 50%
236.0-239.2': 60%
239.2-243.3': 80%
243.3-247.6': 60%
247.6-254.2': 70%
254.2-256.6': 60%
256.6-271.6': 70%
271.6-275.8': 60%
275.8-278.8': 70%

LOG COLUMNS (DEPTH 220–337)

Column	Values (top to bottom)
DEPTH	220, 225, 230, 235, 240, 245, 250, 255, 260, 265, 270, 275, 280, 285, 290, 295, 300, 305, 310, 315, 320, 325, 330, 335
% RECOVERY	91, 100, 100, 100, 93, 100, 90, 83, 100, 79, 94, 96, 100, 92, 93, 57, 98, 95, 100, 100, 100, 74, 93, 100, 67, 95, 95, 100, 100, 96, 100, 100, 100
SPT	
WEATHERING	W7, W3, W5, W6, W5
HARDNESS	H4, H5, H4, H5, H4
FRACTURE DENSITY	FD9, FD7, FD9, FD3, FD7
RQD	16, 0, 41, 20, 0, 16, 92, 21
FIELD CLASSIFICATION	Breccia, GM, Breccia, GMs, Breccia, GMs, Breccia, Sandstone
LAB CLASSIFICATION	
GEOLOGIC UNIT	Tfb, Trr

CLASSIFICATION AND PHYSICAL CONDITION

fractures surfaces, infilling vesicles, and forms clayey sand matrix . Moderately Hard (H4). Core fragments can be broken with moderate hammer blow. Very Intensely Fractured (FD9). Core recovered in lengths from fragments to 0.4', mostly mostly as fragments.

168.4-174.4': BASALT. Black to dark gray, fine grained, dense basalt. Slightly Weathered (W3). Extensive oxidation and alteration (iron and manganese) limited to joint surfaces. Hard (H3). Core breaks with heavy hammer blow. Intensely to Moderately Fractured (FD6). Core recovered ranges from fragments to 0.6', mostly as fragments. Joints dip from 45 to 70 degrees, surfaces are rough and planar.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 171.5'. Umatilla Member (Tum) chemistry.

174.4-184.5': BASALT. Black to greenish black, fine grained, vesicular basalt fragments in a sand and clayey sand matrix. Vesicles comprise about 20% of the rock portion. Intensely to Moderately Weathered (W6). Extensive oxidation (iron and manganese) throughout body of rock, blackish-green to light green (chlorite) coating on fractures surfaces, infilling vesicles, and forms clayey sand matrix, traces of iron sulfide (pyrite). Hard (H3). Core fragments can be broken with heavy hammer blow. Very Intensely Fractured (FD9). Core recovered in lengths mostly as chips and fragments.

184.5-228.4': BASALT. Black, fine grained, dense basalt. Slightly Weathered (W3). Oxidation and alteration (iron and manganese) limited to joint surfaces, traces of iron sulfide (pyrite). Hard (H3). Core breaks with heavy hammer blow. Very Intensely to Intensely Fractured (FD8). Core recovered ranges from fragments to 0.6', mostly recovered as fragments. Joints dip angles are predominantly 45 and 70 degrees with occassional vertical fracture surfaces, surfaces are generally smooth and planar.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 219.3'. Umatilla Member (Tum) chemistry.

228.4-301.1': **FAULT BRECCIA (Tfb).** Brecciated zone associated with the Horsethief Mountain Thrust Fault. Black to greenish black basalt breccia. Descriptions are based on PQ- and HQ-size core samples.

228.4-239.6': BASALT BRECCIA. Black to greenish black, fine grained basalt fragments in a sand and clayey sand matrix. Intensely Weathered (W7). Extensive oxidation (iron and manganese) throughout body of rock, blackish-green to light green (chlorite) coating on fractures surfaces and forms clayey sand matrix, abundant iron sulfide (pyrite). Moderately Hard (H4). Core fragments can be broken with moderate hammer blow. Very Intensely Fractured (FD9). Core recovered in lengths mostly as chips and fragments.

LABORATORY TEST DATA ON SAMPLE FROM INTERVAL 235.0-236.0': 70.0% gravel, 10.0% sand, 20.0% fines; LL=NP, PI=NP. Laboratory classification of sample is Silty Gravel (GM).

239.6-250.9': BASALT. Black to greenish black, fine grained, dense basalt. Slightly Weathered (W3). Oxidation and alteration (iron and

GEOLOGIC LOG OF DRILL HOLE NO. DH-05-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 11/17/05 FINISHED: 3/8/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 162.9 (1113.18) 3/5/06

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,490.4 E 1,794,496.6
TOTAL DEPTH: 401.4
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.1
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Stelma/Didricksen
REVIEWED BY: Doug Bennett

NOTES

278.8-287.4': 80%
287.4-294.2': 90%
294.2-294.6': 70%
294.6-295.8': 80%
295.8-300.1': 20%
300.1-310.2': 95%
310.2-313.2': 50%
313.2-322.0': 80%
322.0-327.1': 20%
327.1-330.0': 70%
330.0-352.0': 60%
352.0-388.2': 90%
388.2-392.1': 70%
392.1-401.4': 0% to 5%

WATER LEVEL DURING DRILLING:
(Drill fluid level from ground surface at start of shift)

2005

Date	Fluid Level
11/29	Dry
11/30	Dry
12/02	Dry
12/03	Dry
12/05	Dry
12/06	Dry
12/07	Dry
12/14	Dry
12/16	Dry
12/17	Dry
12/19	Dry
12/20	Dry
12/21	131.3'

2006

Date	Fluid Level
01/18	Dry
01/19	94.3'
01/20	34.6'
01/21	26.7'
01/23	38.8'
01/24	153.0'
01/25	196.3'
02/01	Dry
02/02	Dry
02/03	200.2'
02/04	223.8'
02/05	147.2'
02/06	172.1'
02/07	86.0'
02/08	132.7'
02/16	260.0'
02/17	249.3'
02/18	244.3'
02/19	254.4'
02/20	121.8'
02/21	164.2'
02/22	172.4'
03/01	163.1'
03/02	161.8'
03/03	162.7'
03/04	163.3'

WATER LEVEL AFTER DRILLING:

2006

Date	Fluid Level
03/05	162.9'
03/06	162.8'
03/07	162.8'
03/08	163.0'

DRILLING TIME:

Drilling: 400 hrs.

LOG

DEPTH	% RECOVERY	SPT	WEATHERING	HARDNESS	FRACTURE DENSITY	RQD	FIELD CLASSIFICATION	LAB CLASSIFICATION	GEOLOGIC UNIT	GRAPHIC	HOLE COMPLETION
340						0					
	40										
345	100					14					
350	100					33					
355	100					0	Basalt		Tp		
360	100					22					
365	97					30					
370	100		W3	H3	FD6						
375	100										
380						40					
385	100										
390	100					15					
395	83					24					
400	100										

BOTTOM OF HOLE

CLASSIFICATION AND PHYSICAL CONDITION

manganese) throughout, blackish-green (chlorite) coating on fractures surfaces. Moderately Hard (H4). Core fragments break with moderate hammer blow. Intensely Fractured (FD7). Core recovered ranges from fragments to 0.6', mostly recovered as fragments.

250.9-273.0': BASALT. Black to greenish black, fine grained, dense basalt. Moderately Weathered (W5). Oxidation and alteration (iron and manganese) throughout, blackish-green (chlorite) coating on fractures surfaces, abundant iron sulfide. Moderately Soft (H5). Core fragments break with moderate manual pressure. Very Intensely Fractured (FD7). Core recovered mostly as fragments.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 267.0'. Umatilla Member (Tum) chemistry.

LABORATORY TEST DATA ON SAMPLE FROM INTERVAL 265.0-266.0': 56.0% gravel, 28.1% sand, 15.9% fines; LL=NP, PI=NP. Laboratory classification of sample is Silty Gravel with Sand (GM)s.

HYDRAULIC CONDUCTIVITY OF INTERVAL 269.2-287.4': 1.32 feet/day (variations in values depending on analysis method used).

273.0-301.1': BASALT BRECCIA. Black to greenish black, fine grained basalt fragments in a sand and clayey sand matrix. Moderately to Intensely Weathered (W6). Oxidation (iron and manganese) throughout body of rock, blackish-green to light green (chlorite) coating on fractures surfaces and forms clayey sand matrix. Moderately Hard (H4). Core fragments can be broken with moderate hammer blow. Very Intensely Fractured (FD9). Core recovered in lengths mostly as chips and fragments.

LABORATORY TEST DATA ON SAMPLE FROM INTERVAL 293.0-294.2': 53.0% gravel, 29.0% sand, 18.0% fines; LL=NP, PI=NP. Laboratory classification of sample is Silty Gravel with Sand (GM)s.

301.1-310.7': **TERTIARY RATTLESNAKE RIDGE MEMBER (Trr)** of the Miocene Ellensburg Formation. Well indurated tuffaceous fine sand with silt and clay. Description based on PQ-size core sample.

301.1-310.7': SANDSTONE (TUFFACEOUS). Fine grained, greenish gray, homogeneous, well indurated fine-sand with silt and clay. Particles consist of volcanic ash, pumice and lithic fragments. Moderately Weathered (W6). Some minerals altered to clay due to partial solutioning of fine-grained volcanic fragments. Moderately Soft (H5). Core can be grooved by knife with moderate to heavy pressure. Moderately to Slightly Fractured (FD4). Core recovered in lengths from 0.3' to 3.0', mostly in lengths about 1.5' to 2.0', the joint surfaces are mostly smooth and planar.

310.7-401.4': **POMONA MEMBER (Tp)** of the Saddle Mountains Basalt Formation, Miocene Columbia River Basalt Group (CRBG). Black to gray, moderately hard to hard, mostly fine grained, vesicular to dense aphanitic basalt. Descriptions are based on drilling conditions, cuttings returned, and HQ- size core samples.

310.7-343.2': BASALT. Black and gray to greenish black, fine grained, vesicular to slightly basalt. Sharp contact with overlying sediment. Moderately Weathered (W5). Oxidation and alteration (iron and

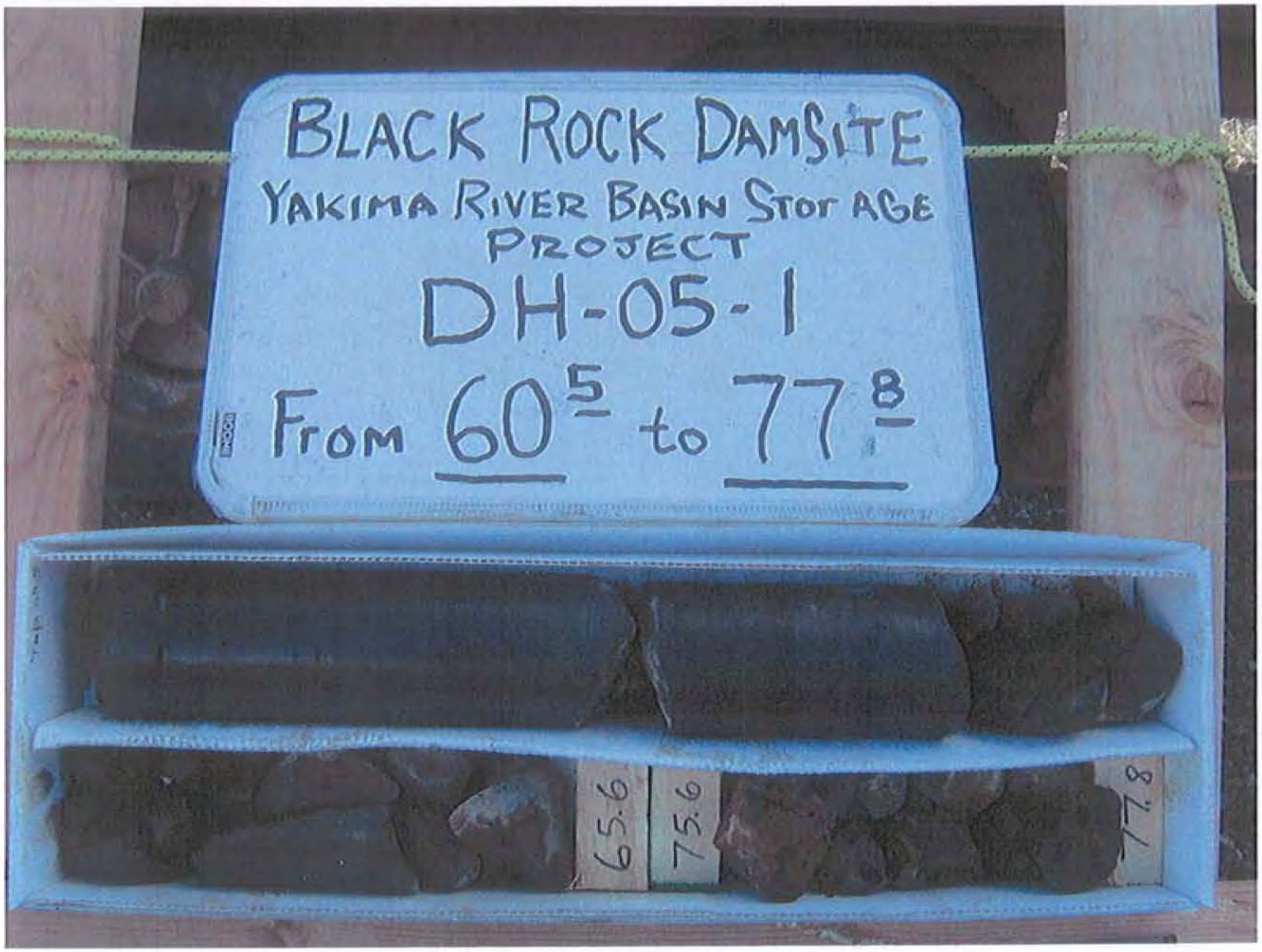
GEOLOGIC LOG OF DRILL HOLE NO. DH-05-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 11/17/05 FINISHED: 3/8/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 162.9 (1113.18) 3/5/06

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,490.4 E 1,794,496.6
TOTAL DEPTH: 401.4
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.1
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Stelma/Didricksen
REVIEWED BY: Doug Bennett

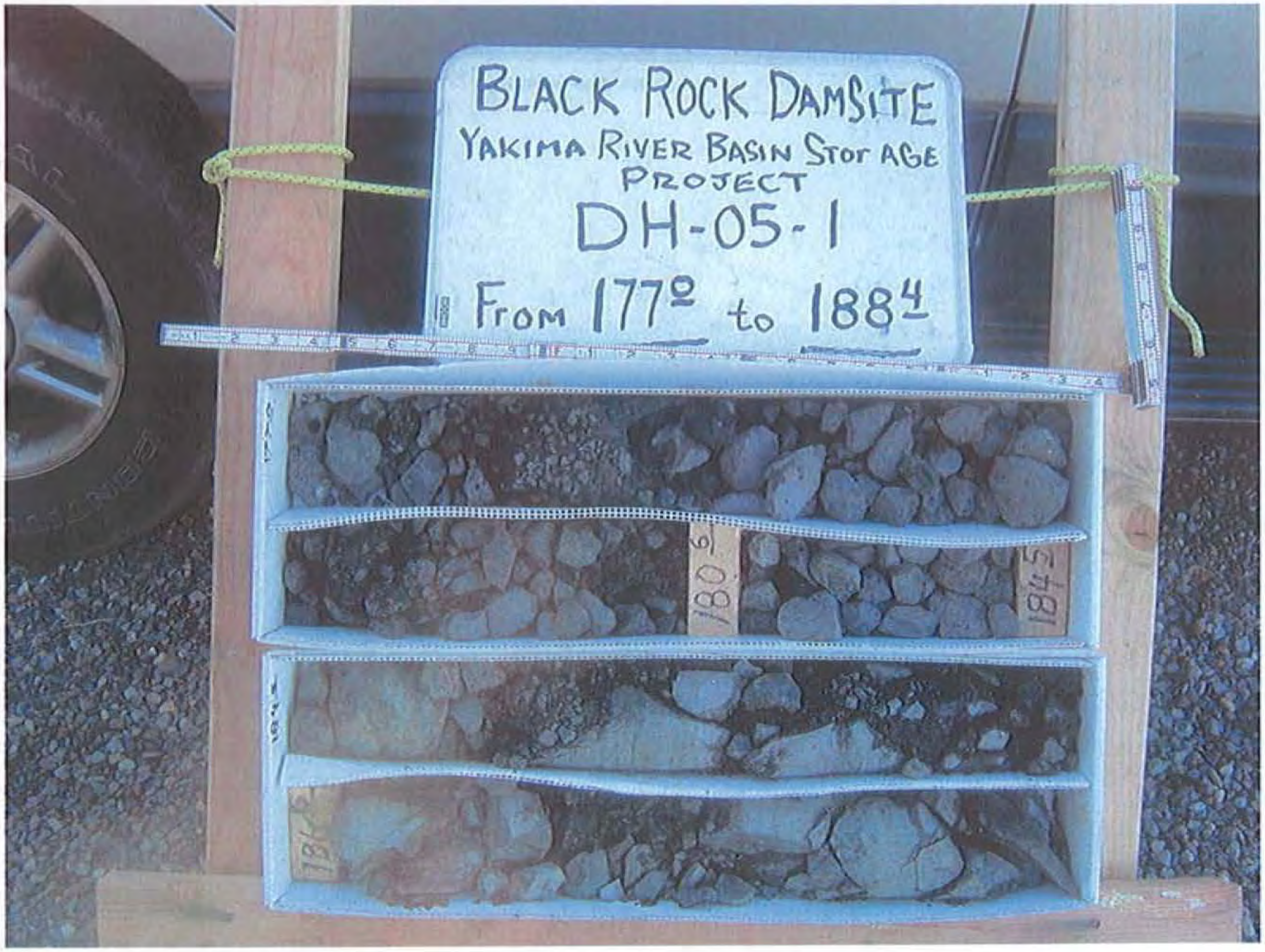
NOTES	DEPTH	% RECOVERY	SPT	ENGINEERING PROPERTIES: WEATHERING	HARDNESS	FRACTURE DENSITY	RQD	FIELD CLASSIFICATION	LAB CLASSIFICATION	GEOLOGIC UNIT	GRAPHIC	HOLE COMPLETION	CLASSIFICATION AND PHYSICAL CONDITION
Moving: 15 hrs. Down: 14 hrs. (Travel time not included) HOLE COMPLETION: 0.0-270.0': Cement grout. 270.0-298.0': Filter sand and slotted pipe with 2" diameter pvc riser. 298.0-401.4': cement grout.													manganese) throughout, blackish-green (chlorite) coating on fractures surfaces, abundant iron sulfide and palagonite. Moderately Hard (H4). Core can be scratched with knife with moderate manual pressure. Intensely Fractured (FD7). Core recovered mostly in lengths less than 0.4'. LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 313.0'. Pomona Member (Tp) chemistry. HYDRAULIC CONDUCTIVITY OF INTERVAL 287.6-334.6': 0.09-0.11 feet/day. 343.2-401.4': BASALT. Black to gray, fine grained, dense basalt. Slightly Weathered (W3). Oxidation and alteration is limited to fracture surfaces. Hard (H3). Core breaks with heavy hammer blow. Intensely to Moderately Fractured (FD6). Core recovered in lengths from fragments to 1.0', mostly less than 0.4', the joint surfaces are mostly smooth and planar to irregular. Numerous joints were weakly healed with clorite and clay. Fracfure angles are mostly horizontal with scattered continuous vertical joints. LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 347.0'. Pomona Member (Tp) chemistry. LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 398.0'. Pomona Member (Tp) chemistry. HYDRAULIC CONDUCTIVITY OF INTERVAL 379.0-399.5': 10.6 feet/day. 401.4': BOTTOM OF HOLE.

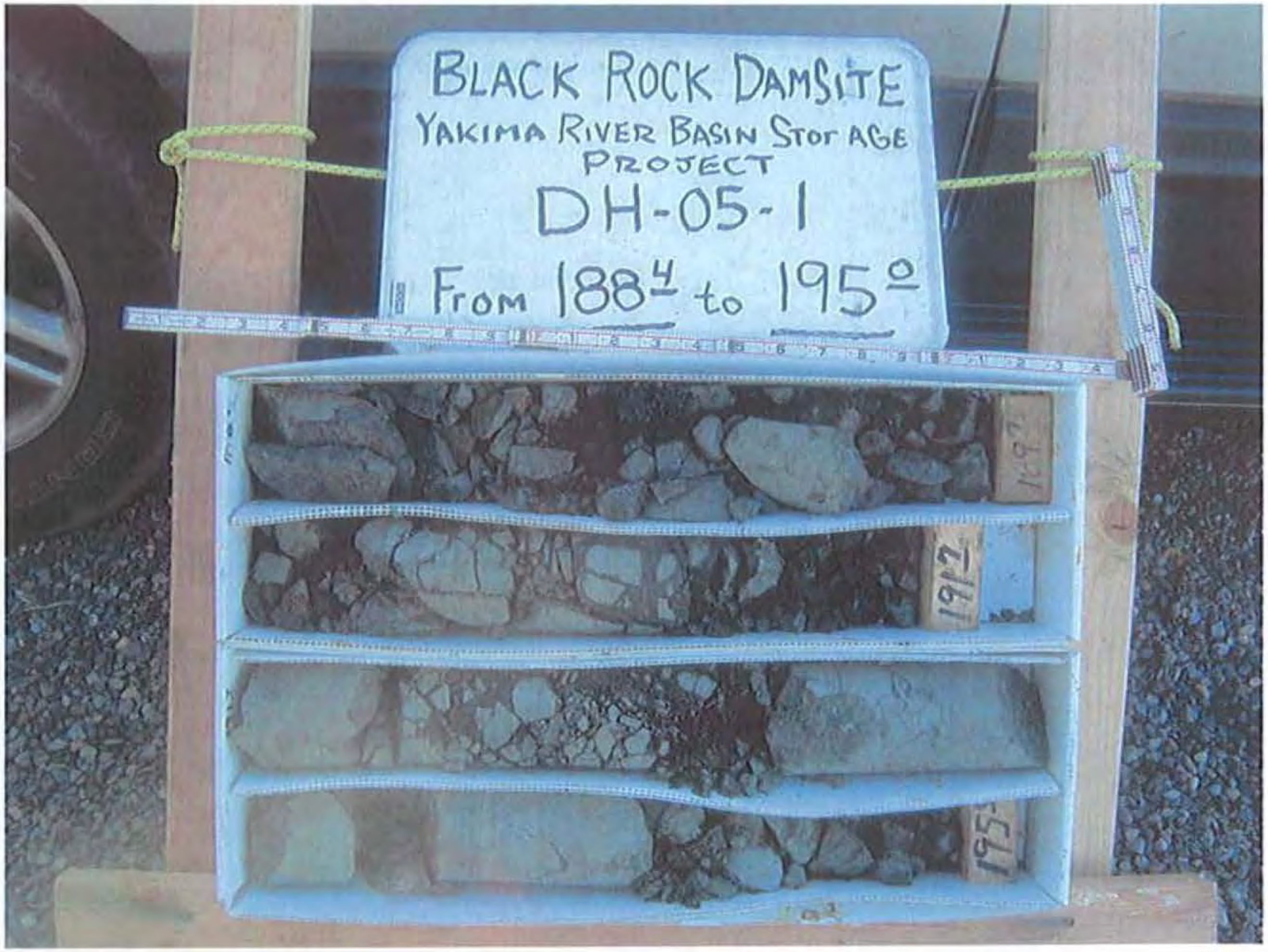

BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 60.5 to 77.8
65.6
75.6
77.8

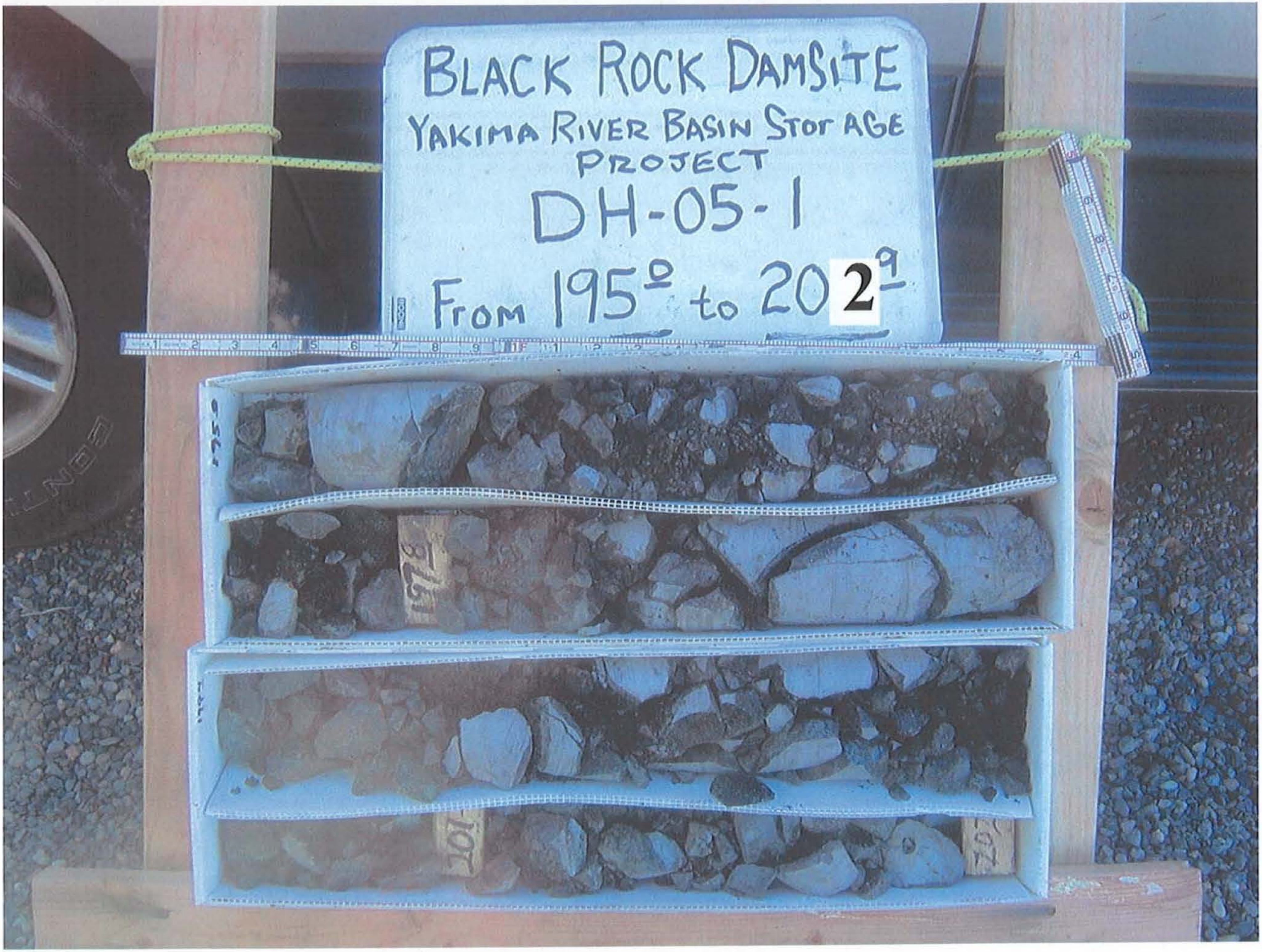

BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STOR AGE PROJECT
DH-05-1
From 151º to 156º
156'

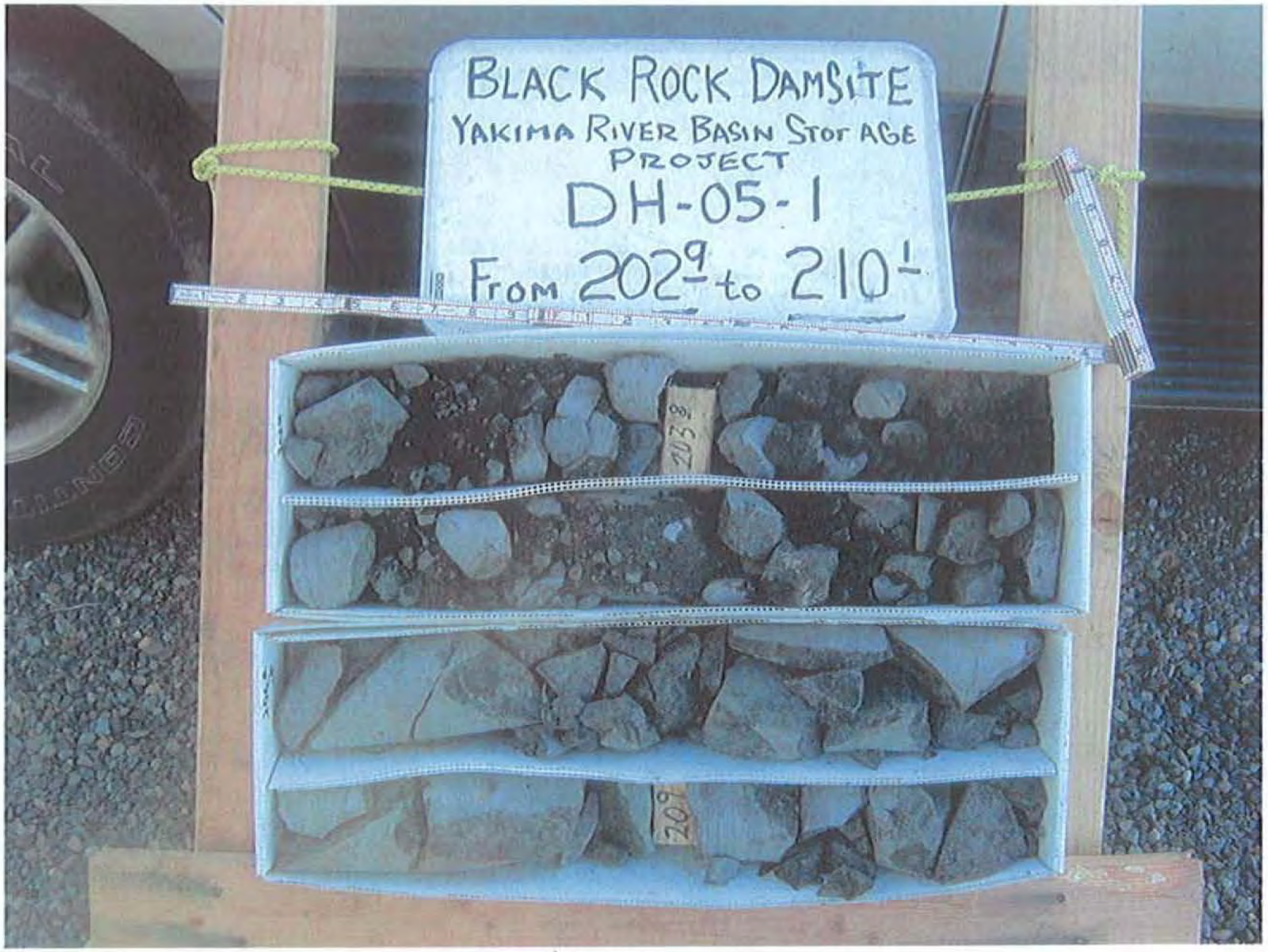

BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 161.5 to 168.4

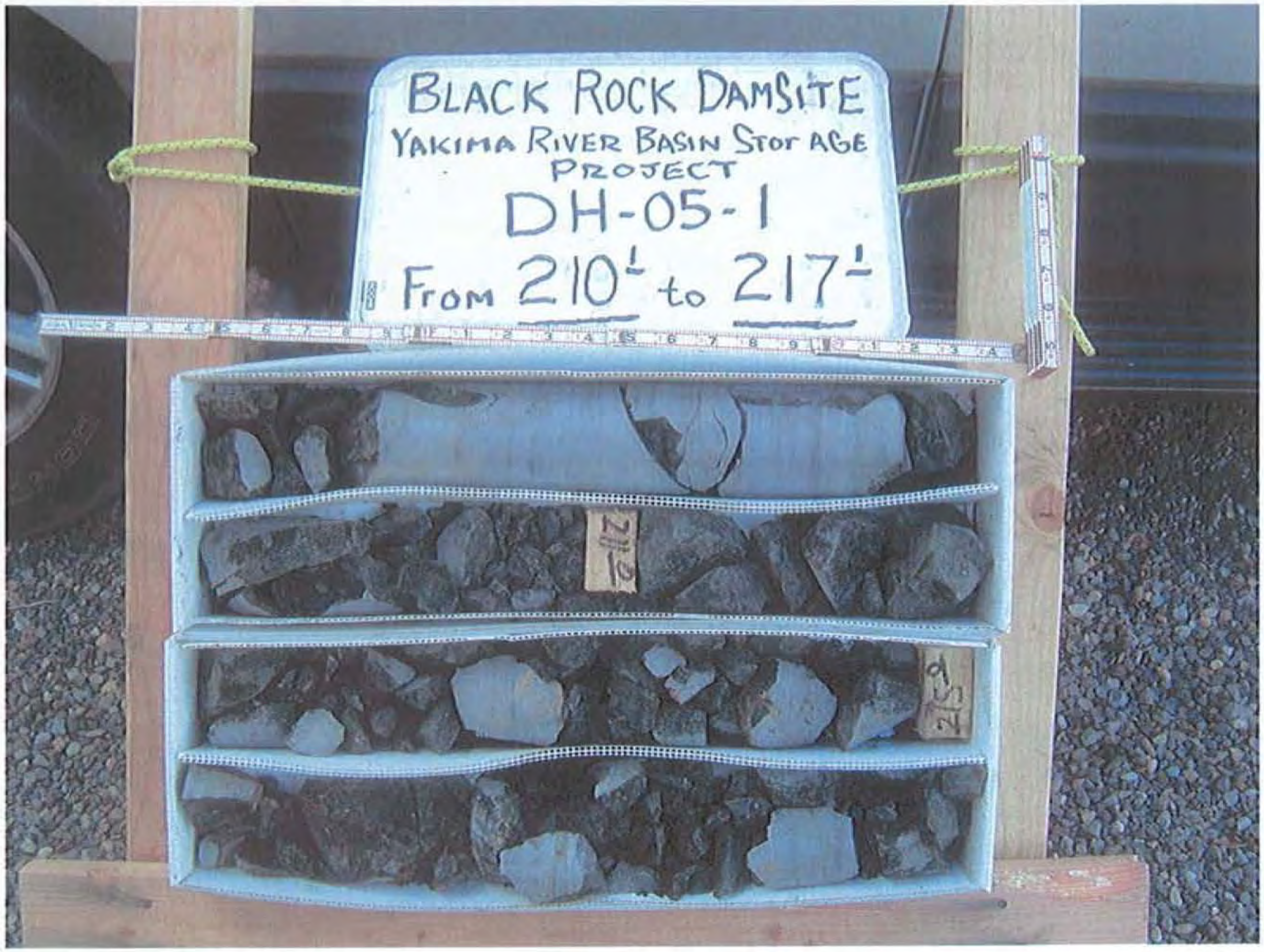

BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STOrAGE
PROJECT
DH-05-1
From 168⁴ to 177⁰
170⁰¹

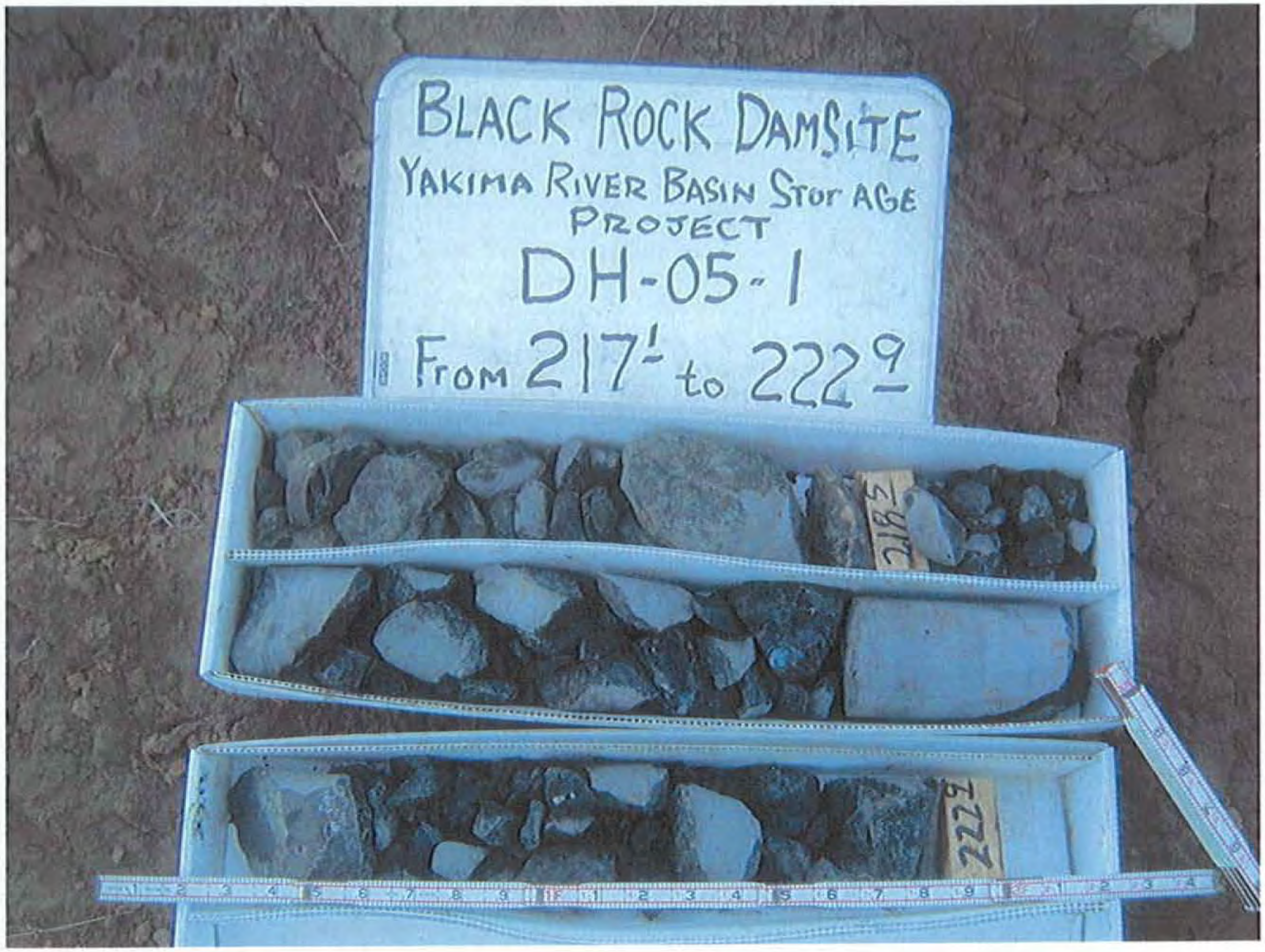

BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STOrAGE
PROJECT
DH-05-1
From 177.0 to 188.4
180.6
184.5


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE PROJECT
DH-05-1
From 188.4 to 195.0
1912


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 195.0 to 202.9

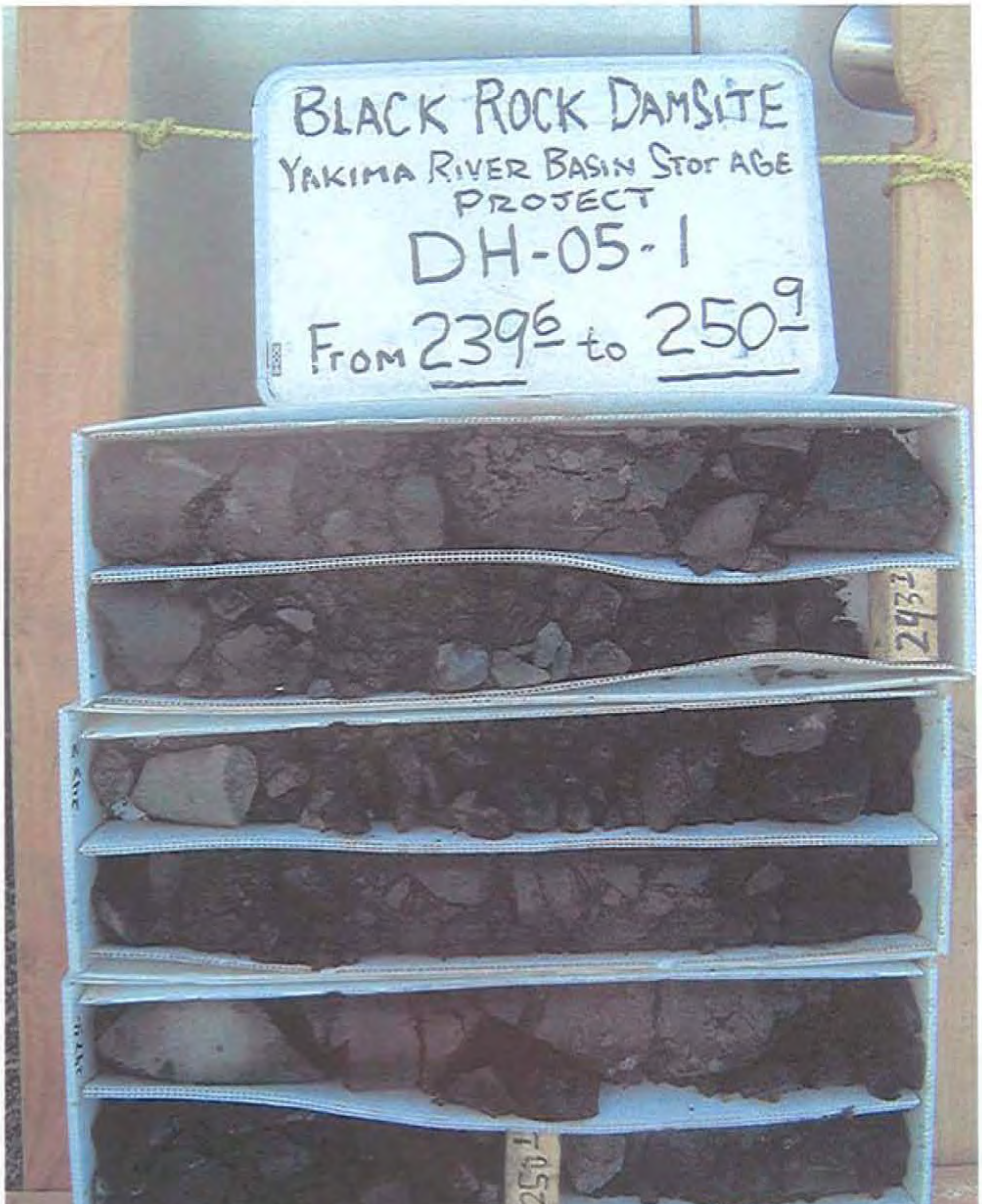

BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE PROJECT
DH-05-1
From 202.9 to 210.1
203.8
209


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE PROJECT
DH-05-1
From 210± to 217±


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 217.1 to 222.9
218.5
222.9


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 222.9 to 228.4'


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 228.4 to 239.6


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE PROJECT
DH-05-1
FROM 239.6 to 250.9


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE PROJECT
DH-05-1
From 250.9 to 262.0


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE
PROJECT
DH-05-1
From 262.0 to 273.0


BLACK ROCK DAMSITE
YAKIMA RIVER BASIN STORAGE PROJECT
DH-05-1
From 273.0 to 279.7

BLACK ROCK DAMSITE

DH-05-1   279.7 - 287.6


BLACK
ROCK

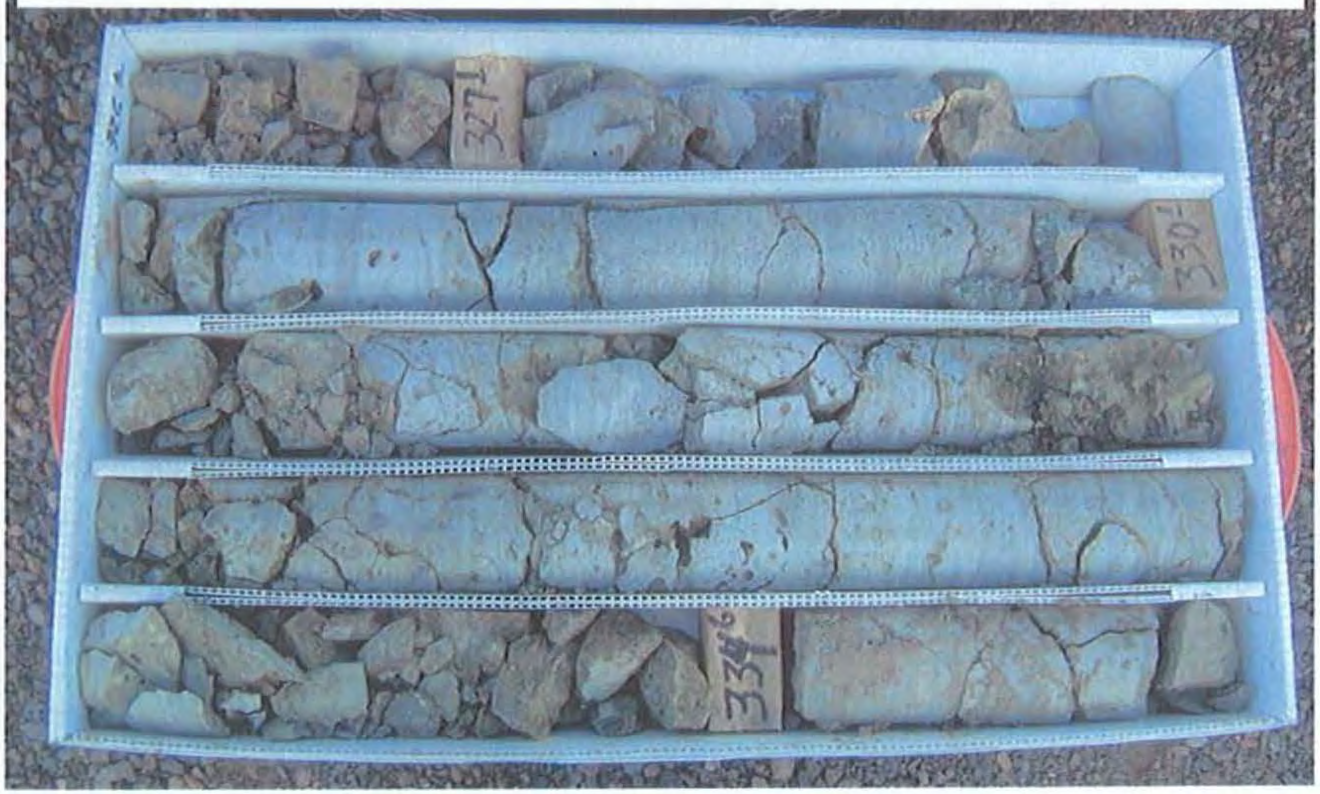
BLACK ROCK DAMSITE
DH--5-1   287.6 - 297.8

BLACK ROCK DAMSITE
DH--05-1   297.8 - 307.5

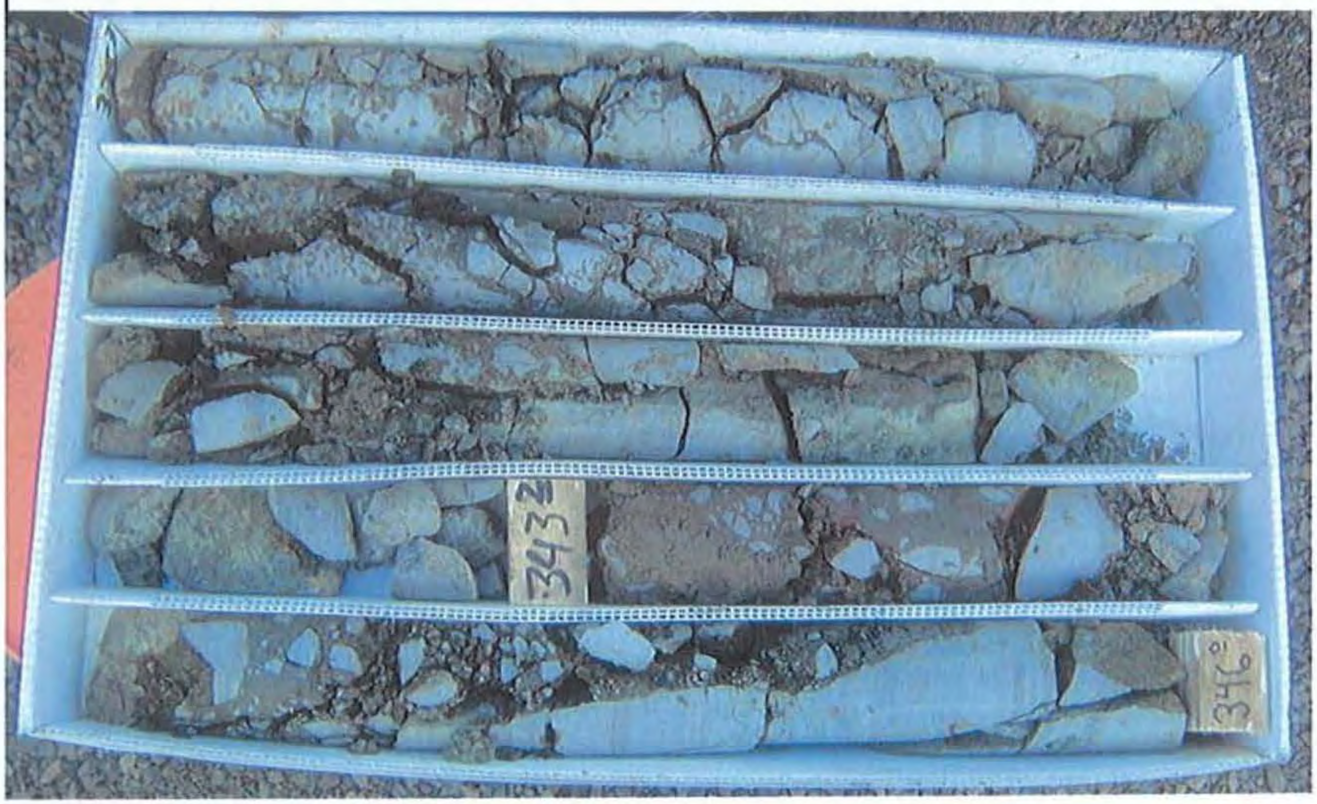
BLACK ROCK DAMSITE
DH--05-1 307.5 - 317.5

BLACK ROCK DAMSITE
DH--05-1 317.5 - 326.6

BLACK ROCK DAMSITE
DH--05-1   326.6 - 335.3



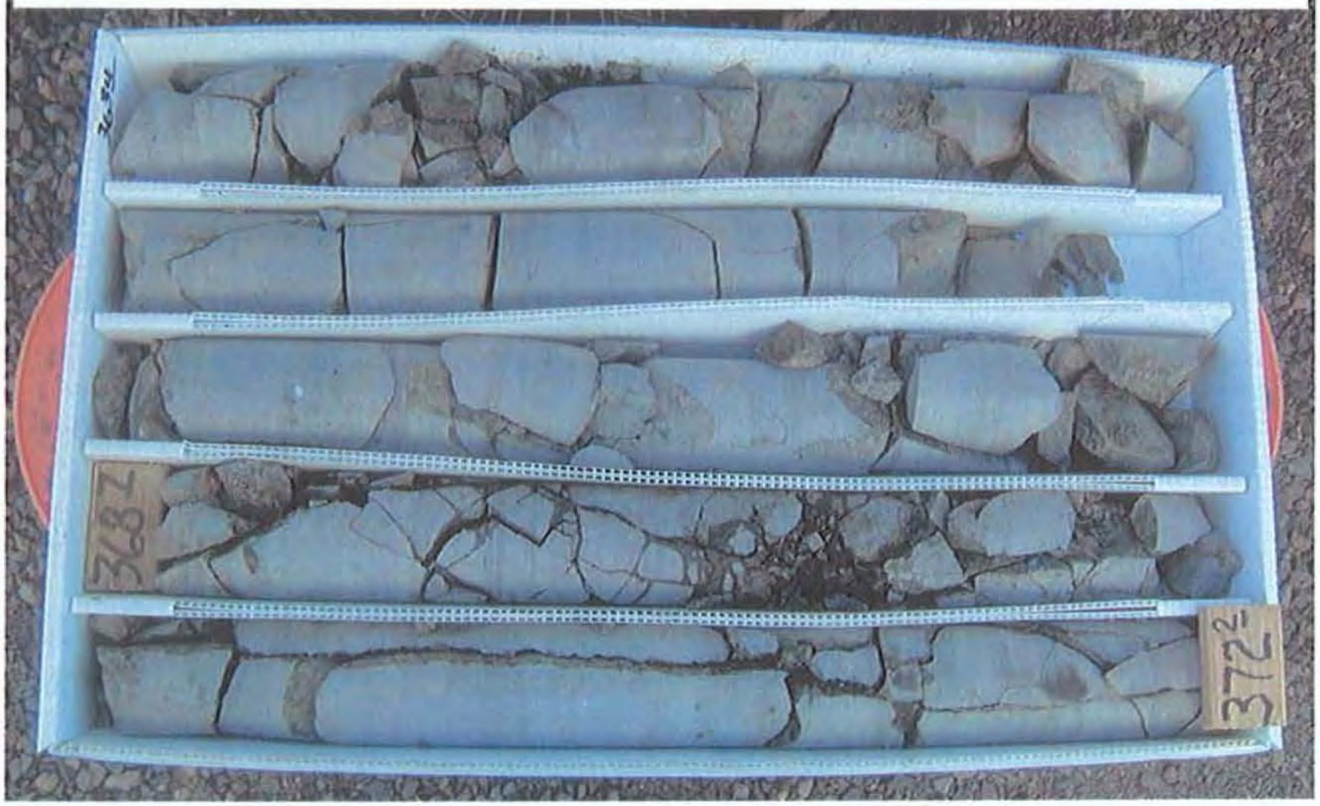
BLACK ROCK DAMSITE
DH--05-1   335.3 - 346.0



BLACK ROCK DAMSITE
DH--05-1   346.0 - 354.5

BLACK ROCK DAMSITE
DH--05-1   354.5 - 363.4

BLACK ROCK DAMSITE
DH--05-1   363.4 - 372.2

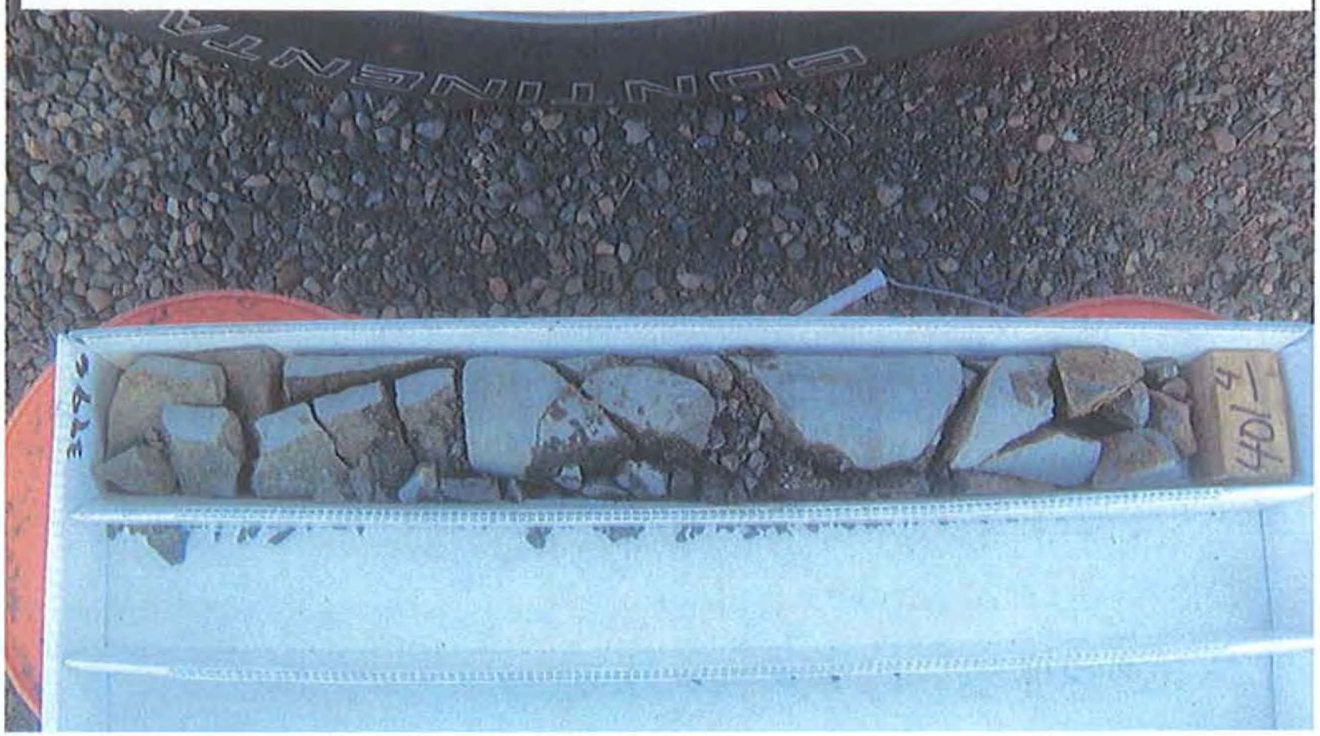


BLACK ROCK DAMSITE
DH--05-1   372.2 - 381.1

BLACK ROCK DAMSITE
DH--05-1   381.1 - 390.2

BLACK ROCK DAMSITE
DH--05-1   390.2 - 399.6

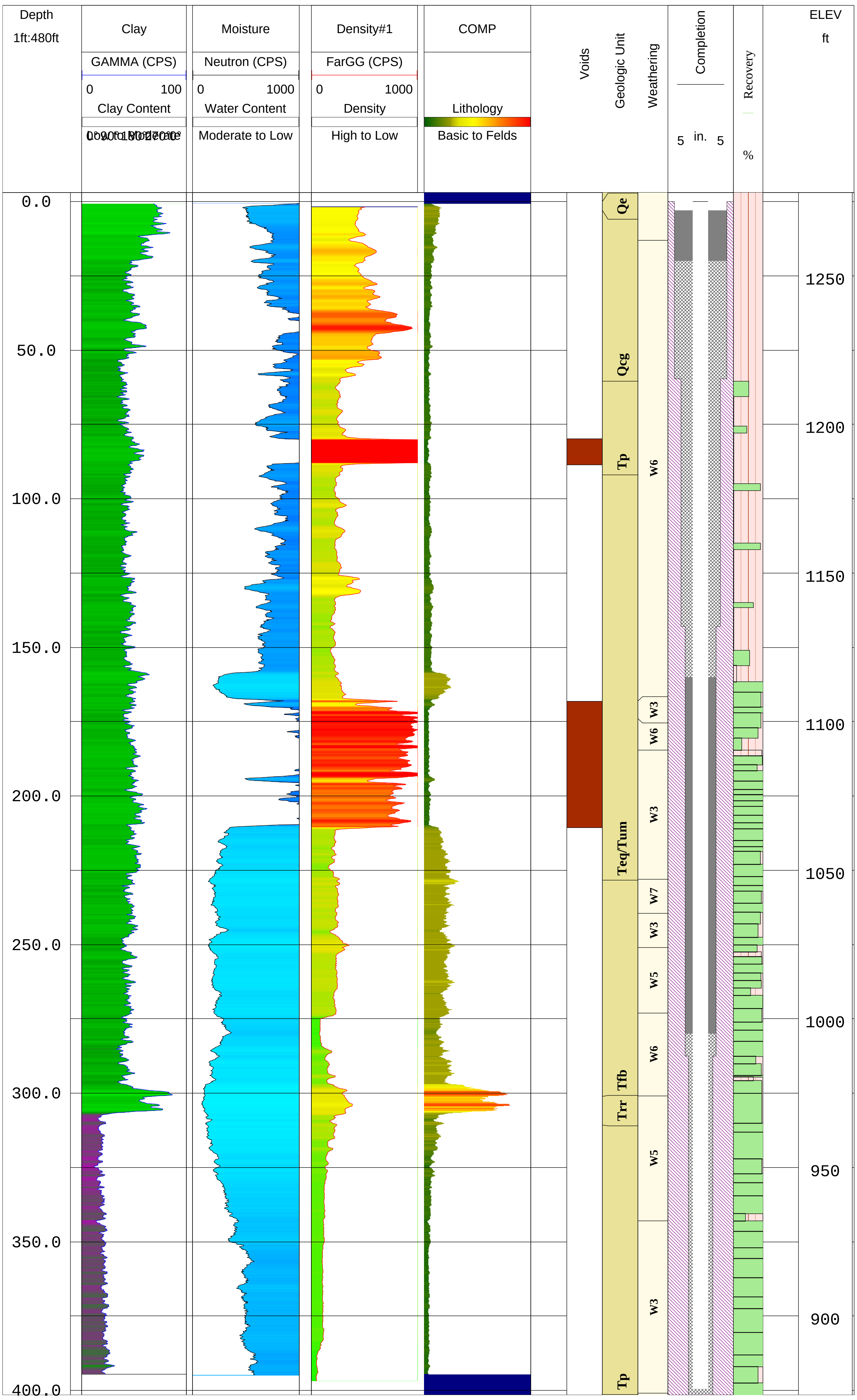
BLACK ROCK DAMSITE
DH--05-1   399.6 - 401.4



RECLAMATION

BOREHOLE GEOPHYSICAL LOGS

Project	Black Rock	Surface Elev.	1276.1
Feature		Location	DRAFT PLOT
Hole No.	DH05-01	Northing	
		Easting	
Total Depth Logged		Logged By/ Date	



Geologic Log of Drill Hole No. DH-06-1
(Lower Right Abutment – Water Test Borehole)

Borehole Geophysical Log

GEOLOGIC LOG OF DRILL HOLE NO. DH-06-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 3/23/06 FINISHED: 5/20/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 165.5 (1110.50) 5/5/-6

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,498.0 E 1,794,459.0
TOTAL DEPTH: 400.0
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.0
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Didricksen/Stelma
REVIEWED BY: Doug Bennett

NOTES	DEPTH	% RECOVERY	SPT	ENGINEERING PROPERTIES: WEATHERING	HARDNESS	FRACTURE DENSITY	RQD	FIELD CLASSIFICATION	LAB CLASSIFICATION	GEOLOGIC UNIT	GRAPHIC	HOLE COMPLETION	CLASSIFICATION AND PHYSICAL CONDITION
	0–3.0	0						ML		Qe			
	3.0–60.5	0						(GP-GM)sc		Qcg			
	60.5–92.0	0								Tp			
	92.0–	90											

NOTES

All elevations measured from ground surface and are same as driller reported.

PURPOSE OF HOLE:
To perform hydrogeologic testing.

DRILL SETUP:
Setup on a hillside drill pad located on the lower right abutment along the original Black Rock dam axis about 37 feet west of DH-05-1, and approximately 1200 feet south of Washington State Highway 24.

DRILLING EQUIPMENT:
Foremost DR-12 truck mounted dual-rotary drill.

DRILLER:
Ben Horton and Steve Scrivner

DRILLING METHODS:

0.0-60.1': Advanced 12-inch weld-down casing using a down-the-hole hammer with a 11-1/4" rockbit, and compressed air with water and foam (biodegradable foaming agent) to remove cuttings.

60.1-150.0': Advanced 10-inch weld-down casing using a down-the-hole hammer with a 9-7/8" rockbit, and compressed air with water and foam to remove cuttings.
Took drive samples (maxi-sampler) from 95.2-97.2', 115.0-117.0' and 135.0-136.5'.
Placed a grout seal from 145.0-150.0' for pressure water testing.

150.0-167.2': Drilled open-hole with a 9-1/2" rockbit using a down-the-hole hammer with compressed air with water and foam to remove cuttings. Hole caved to 162.8'. Performed water test.

167.2-236.0': Advanced 8-inch weld-down casing

CLASSIFICATION AND PHYSICAL CONDITION

0.0-3.0': **QUATERNARY LOESS DEPOSITS (Qe).** Surficial deposits of silt with lesser amounts of clay, composed primarily of wind-blown silt with small amounts of fine sand. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1.

3.0-60.5': **QUATERNARY COLLUVIUM (Qcg).** Unconsolidated gravel, sand and cobbles with silt and clay. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1.

60.5-92.0': **POMONA MEMBER (Tp)** of the Saddle Mountains Basalt Formation, Miocene Columbia River Basalt Group (CRBG). Black to gray, moderately hard to hard, mostly fine grained, vesicular to dense aphanitic basalt and basalt breccia. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1.

92.0-228.4': **UMATILLA MEMBER (Tum)** of the Saddle Mountains Basalt Formation, Miocene Columbia River Basalt Group (CRBG. Black to gray, hard, mostly fine grained dense basalt and basalt breccia. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1, and geochemical analysis of the following samples.

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 97.2'. Umatilla Member (Tum) chemistry (drive sample).

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 117.0'. Umatilla Member (Tum) chemistry (drive sample).

LABORATORY SAMPLE FOR GEOCHEMICAL ANALYSIS FROM 136.5'. Umatilla Member (Tum) chemistry (drive sample).

HYDRAULIC CONDUCTIVITY OF INTERVAL 150.0-162.8': 1.94 feet/day.

228.4-301.1': **FAULT BRECCIA (Tfb)** Brecciated zone associated with the Horsethief Mountain Thrust Fault. Black to greenish black basalt breccia. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1.

HYDRAULIC CONDUCTIVITY OF INTERVAL 236.0-255.1': 3.57 feet/day.

HYDRAULIC CONDUCTIVITY OF INTERVAL 276.0-296.0': 3.20 feet/day (variations in values depending on analysis method used).

301.1-310.7': **TERTIARY RATTLESNAKE RIDGE MEMBER (Trr)** of the Miocene Ellensburg Formation. Well indurated tuffaceous fine sand with silt and clay. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1.

310.7-400.0': **POMONA MEMBER (Tp)** of the Saddle Mountains Basalt Formation, Miocene Columbia River Basalt Group (CRBG). Black to gray, moderately

COMMENTS: Samples were logged in the field using Designation USBR 5005-86, "Procedures for Determining Unified Soil Classification (Visual Method)."

Center column descriptors are defined in the Reclamation Engineering Geology Field Manual, Volume 1, Second Edition, distributed February 1999.

Cs = Casing Sz = Size of Casing I.D. = Inside Diameter O.D. = Outside diameter

Geologic unit descriptions, stratigraphy and geochemistry interpretation based partially on information presented in the following reports:

"Black Rock Reservoir Study, Initial Geotechnical Investigation", Prepared for Benton County Sustainable Development by Washington Infrastructures Services, Inc., Dated January 2003.

"Geologic Investigation Black Rock Dam, Alternate Dam Site, Yakima County, Washington, Prepared for U.S. Bureau of Reclamation by Columbia Geotechnical Associates, Inc., Dated February 12, 2004.

"Chemical Discrimination of Columbia River Basalt Flows", P.R. Hooper, Department of Geology, Washington State University, Dated June 14, 2000.

GEOLOGIC LOG OF DRILL HOLE NO. DH-06-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 3/23/06 FINISHED: 5/20/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 165.5 (1110.50) 5/5/-6

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,498.0 E 1,794,459.0
TOTAL DEPTH: 400.0
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.0
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Didricksen/Stelma
REVIEWED BY: Doug Bennett

NOTES	DEPTH	% RECOVERY	SPT	WEATHERING	HARDNESS	FRACTURE DENSITY	RQD	FIELD CLASSIFICATION	LAB CLASSIFICATION	GEOLOGIC UNIT	GRAPHIC	HOLE COMPLETION	CLASSIFICATION AND PHYSICAL CONDITION
	105	0											
	110												
	115	90											
	120												
	125	0											
	130												
	135	67											
	140												
	145							Basalt					
	150												
	155												
	160												
	165												
	170												
	175												
	180												
	185									Tum			
	190												
	195												
	200												
	205												
	210												
	215												

NOTES:

using a down-the-hole hammer with a 7-7/8" rockbit, and compressed air with water and foam to remove cuttings.
Placed a grout seal from 231.1-236.0 for pressure water testing.

236.0-256.5': Drilled open-hole with a 7-7/8" rockbit using a down-the-hole hammer and compressed air with water and foam to remove cuttings. Hole caved to 255.1'. Performed water test.

256.5-276.0': Advanced 8-inch weld-down casing using a down-the-hole hammer with a 7-7/8" rockbit, and compressed air with water and foam to remove cuttings.
Placed a grout seal from 271.0-276.0' for pressure water testing.

276.0-296.0': Drilled open-hole with a 7-7/8" rockbit using a down-the-hole hammer and compressed air with water and foam to remove cuttings. Performed water test.

296.0-301.2': Advanced 8-inch weld-down casing using a down-the-hole hammer with a 5-7/8" rockbit, and compressed air with water and foam to remove cuttings.

Placed a grout seal from 295.0-301.2' for pressure water testing.

301.2-311.8': Drilled open-hole with a 5-7/8" rockbit using a down-the-hole hammer and compressed air with water and foam to remove cuttings.

Broke grout seal between 8" and 6" casing during drilling, did not perform water test. Re-grouted seal from 295.0-311.8'

311.8-336.0': Drilled open-hole with a 5-7/8" rockbit using a down-the-hole hammer with compressed air and foam to remove cuttings. Broke grout seal between 8" and 6" casing during drilling, did not perform water test.

336.0-400.0': Drilled open-hole with a 5-7/8" rockbit using a

CLASSIFICATION AND PHYSICAL CONDITION:

hard to hard, mostly fine grained, vesicular to dense aphanitic basalt. Description is based on drill cuttings and core sample logged in companion drill hole DH-05-1.

HYDRAULIC CONDUCTIVITY OF INTERVAL 311.8-400.0': 25.0-26.0 feet/day (variations in values depending on analysis method used).

400.0': BOTTOM OF HOLE.

GEOLOGIC LOG OF DRILL HOLE NO. DH-06-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 3/23/06 FINISHED: 5/20/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 165.5 (1110.50) 5/5/-6

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,498.0 E 1,794,459.0
TOTAL DEPTH: 400.0
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.0
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Didricksen/Stelma
REVIEWED BY: Doug Bennett

NOTES	DEPTH	% RECOVERY	SPT	WEATHERING	HARDNESS	FRACTURE DENSITY	RQD	FIELD CLASSIFICATION	LAB CLASSIFICATION	GEOLOGIC UNIT	GRAPHIC	HOLE COMPLETION	CLASSIFICATION AND PHYSICAL CONDITION
down-the-hole hammer and compressed air with water and foam to remove cuttings. Performed water test.	220–229												
DRILLING CONDITIONS: 0.0-162.7': Fast and slightly rough. 162.7-256.0': Fast and smooth to slightly rough. 256.0-275.0': Slow and slightly rough. 275.0-311.8': Fast and slightly rough. 311.8-400.0': Slow, hard and slightly rough to rough. CASING RECORD: 2006 Cs Depth Depth Date Sz Hole Cs ------------------------ 03/23 12" 39.5' 39.5' 03/24 12" 59.1' 59.1' 03/25 10" 60.1' 60.1' 03/26 10" 97.2' 95.0' 03/27 10" 117.0' 115.0' 03/28 10" 150.0' 150.0' 04/05 10" 167.2' 167.2' 04/09 8" 236.0' 236.0' 04/10 8" 256.5' 256.5' 04/12 8" 276.0' 276.0' 04/19 8" 296.0' 296.0' 04/23 6" 301.2' 301.2' 04/24 6" 311.8' 311.8' 05/03 6" 400.0' 400.0' 05/04 6" 400.0' 336.0' FLUID COLOR: 0.0-60.1': Brown (air) 60.1-95.1': Brownish black (air/water/foam). 95.1-295.0': Dark gray (air/water/foam). 295.0-308.0': Light green (air/water/foam). 308.0-311.8': Greenish black (air/water/foam). 311.8-400.0': Black (air/water/foam).	229–302	0						Breccia		Tfb			
FLUID RETURN: 0.0-400.0': Drilled w/ air, and air, foam and water mix, estimated 100% return.	302–311							Sandstone		Trr			
WATER LEVEL DURING DRILLING: (Drill fluid level from ground surface at start of shift) 2006 Date Fluid Level 03/24 Dry 03/25 Dry 03/26 Dry 03/27 Dry 03/28 Dry 04/05 Dry 04/09 Dry 04/10 Dry 04/11 Dry 04/19 281.0'	311–338												

GEOLOGIC LOG OF DRILL HOLE NO. DH-06-1

FEATURE: Black Rock Alternate Damsite
LOCATION: South of Washington State Highway 24
BEGUN: 3/23/06 FINISHED: 5/20/06
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 165.5 (1110.50) 5/5/-6

PROJECT: Yakima R. Basin Water Storage Feas. Study
COORDINATES: N 437,498.0 E 1,794,459.0
TOTAL DEPTH: 400.0
DEPTH TO BEDROCK: 60.5

STATE: Washington
GROUND ELEVATION: 1276.0
ANGLE FROM HORIZONTAL: AZIMUTH:
HOLE LOGGED BY: Didricksen/Stelma
REVIEWED BY: Doug Bennett

NOTES	DEPTH	% RECOVERY	SPT	ENGINEERING PROPERTIES: WEATHERING	HARDNESS	FRACTURE DENSITY	RQD	FIELD CLASSIFICATION	LAB CLASSIFICATION	GEOLOGIC UNIT	GRAPHIC	HOLE COMPLETION	CLASSIFICATION AND PHYSICAL CONDITION
04/23 266.3' 04/25 236.4' 04/26 223.8' 05/03 215.5' 05/04 165.2' 05/05 165.4' 05/06 165.4' 05/07 165.4' 05/08 165.8' 05/09 165.3' 05/17 176.2' 05/18 152.8' WATER LEVEL AFTER DRILLING: 2006 Date Fluid Level Not reported DRILLING TIME: Drilling: 200 hrs. Moving: 6 hrs. Down: 4 hrs. Pump Tests: 105 hrs. (Travel time not included) HOLE COMPLETION: 0.0-86.2': Bentonite surface seal. 86.2-236.0': Grout seal. 236.0-350.0': Cal-seal and cement. 350.0-400.0': Pea gravel and filter sand. 375.0-395.0': Slotted pipe (.020") with 2" diameter pvc riser and filter sand. Note: Extracted about 50.7-feet of 10-inch weld-down casing when the casing became lodged in the hole, about 99.3-feet of casing was left in the drill hole.	340 345 350 355 360 365 370 375 380 385 390 395 400							Basalt		Tp			

BOTTOM OF HOLE

RECLAMATION

BOREHOLE GEOPHYSICAL LOGS

Project Black Rock

Surface Elev. 1276.0

Feature

Location DRAFT PLOT

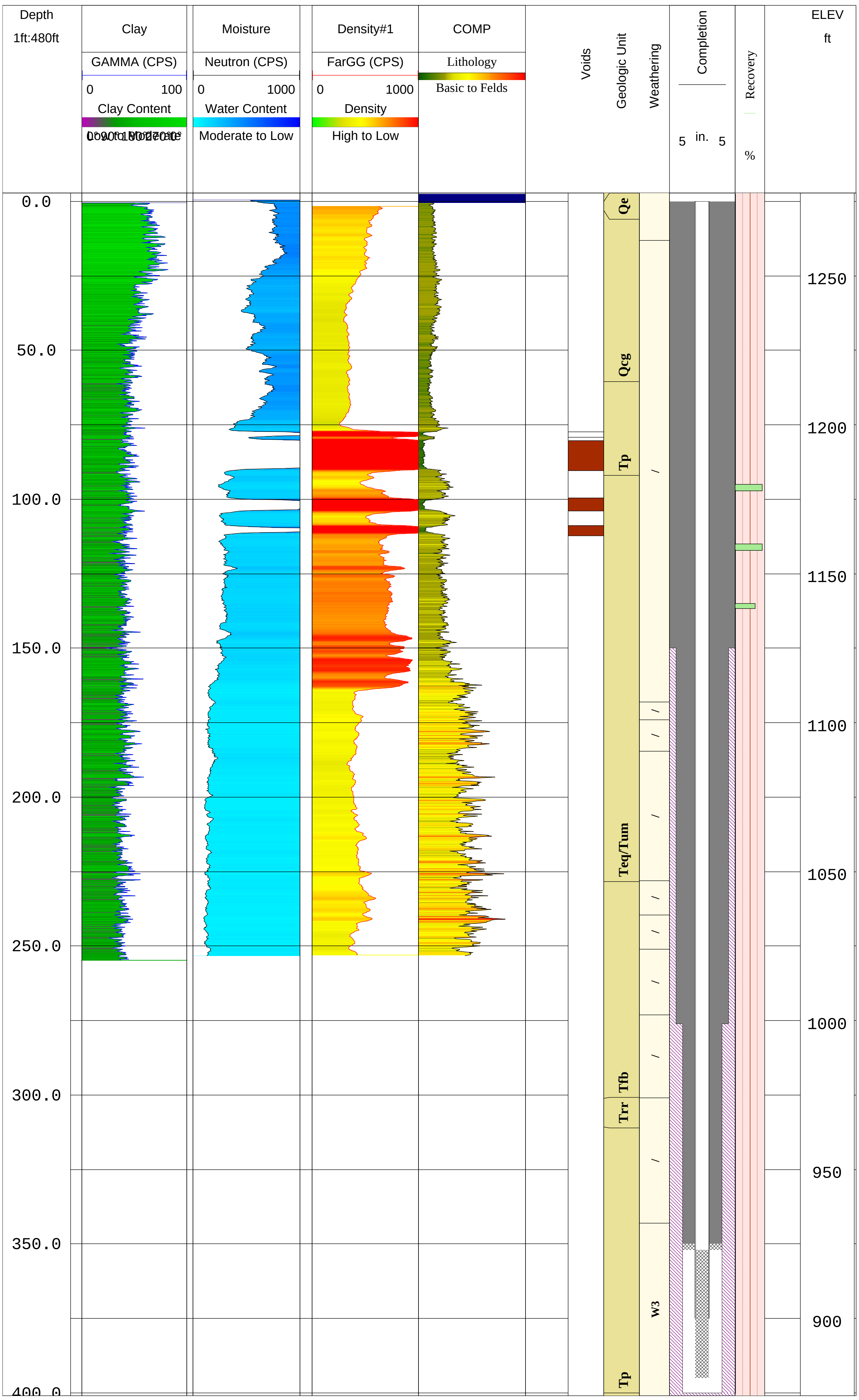
Hole No. **DH06-01**

Northing

Easting

Total Depth Logged 253.9

Logged By/ Date



Results of Geochemical and Gradation Analysis

Summary of Samples for Geochemical Testing and Interpretation
Geochemical Test Data
Gradation Test Data

SUMMARY OF SAMPLES FOR GEOCHEMICAL TESTING – BLACK ROCK DAMSITE, WASHINGTON
MAY 2006

Sample No.	Drill Hole	Location (T,R,S)	*Depth (ft.)	Sample Type	**Geologic Unit
DID-DH-05-1-1	DH-05-1	T12N, R23E, Sec 13	65.6	Rock Core	Pomona
DID-DH-05-1-2	DH-05-1	T12N, R23E, Sec 13	159.0	Rock Core	Umatilla
DID-DH-05-1-3	DH-05-1	T12N, R23E, Sec 13	171.5	Rock Core	Umatilla
DID-DH-05-1-4	DH-05-1	T12N, R23E, Sec 13	219.3	Rock Core	Umatilla
DID-DH-05-1-5	DH-05-1	T12N, R23E, Sec 13	267.0	Rock Core	Umatilla
DID-DH-05-1-6	DH-05-1	T12N, R23E, Sec 13	313.0	Rock Core	Pomona
DID-DH-05-1-7	DH-05-1	T12N, R23E, Sec 13	347.0	Rock Core	Pomona
DID-DH-05-1-8	DH-05-1	T12N, R23E, Sec 13	389.0	Rock Core	Pomona
DID-DH-06-1-1	DH-06-1	T12N, R23E, Sec 13	97.2	Rock Fragments (drive sample)	Umatilla
DID-DH-06-1-2	DH-06-1	T12N, R23E, Sec 13	117.0	Rock Fragments (drive sample)	Umatilla
DID-DH-06-1-3	DH-06-1	T12N, R23E, Sec 13	136.5	Rock Fragments (drive sample)	Umatilla

*Depth from ground surface to bottom of core sample tested.
**Geologic unit based on sample identification using information from: Hooper, P.R., 2000, Chemical discrimination of Columbia River Basalt Flows, Geochemistry, Geophysics Geosystems, Journal of Earth Sciences, Volume 1, Paper 2000GC000040, published by the American Geophysical Union.

GEOCHEMICAL TEST RESULTS ON SAMPLES FROM DRILL HOLES

AT BLACK ROCK DAMSITE - MAY 2006

	DID DH 05-1-1	DID DH 05-1-2	DID DH 05-1-3	DID DH 05-1-4	DID DH 05-1-5	DID DH 05-1-6	DID DH 05-1-7	DID DH 05-1-8	DID DH 06-1-1	DID DH 06-1-2	DID DH 06-1-3
Date	7-Mar-06	7-Mar-06	7-Mar-06	7-Mar-06	7-Mar-06	8-Mar-06	8-Mar-06	8-Mar-06	8-May-06	8-May-06	8-May-06
Unnormalized Major Elements (Weight %):											
SiO2	52.17	54.03	53.43	53.98	54.10	50.99	51.78	52.27	51.81	52.17	51.92
TiO2	1.659	3.054	2.933	2.764	2.738	1.635	1.663	1.680	3.142	3.038	2.996
Al2O3	14.72	13.80	13.42	13.57	13.85	14.70	14.65	14.86	13.93	13.52	13.41
FeO*	10.73	10.33	12.13	11.65	10.99	10.55	10.45	10.71	9.94	9.99	10.06
MnO	0.181	0.106	0.198	0.195	0.160	0.192	0.178	0.184	0.102	0.159	0.166
MgO	6.59	1.71	2.99	2.63	1.89	5.48	5.76	6.22	1.73	2.49	2.58
CaO	10.67	4.94	6.55	6.36	5.25	10.70	10.68	10.79	5.08	6.79	6.74
Na2O	2.37	3.37	3.09	2.99	3.47	2.24	2.34	2.36	3.36	2.89	2.97
K2O	0.69	2.59	2.73	3.08	2.83	0.38	0.60	0.65	2.43	2.57	2.41
P2O5	0.229	0.910	0.848	0.924	0.983	0.240	0.224	0.230	0.940	0.828	0.840
Sum	100.02	94.85	98.33	98.15	96.27	97.10	98.32	99.95	92.46	94.43	94.09
Normalized Major Elements (Weight %):											
SiO2	52.17	56.97	54.34	55.00	56.20	52.51	52.66	52.30	56.03	55.24	55.18
TiO2	1.658	3.219	2.983	2.816	2.844	1.684	1.692	1.681	3.398	3.217	3.184
Al2O3	14.71	14.55	13.65	13.83	14.38	15.13	14.90	14.86	15.07	14.31	14.25
FeO*	10.73	10.89	12.34	11.87	11.42	10.86	10.63	10.72	10.75	10.58	10.69
MnO	0.181	0.111	0.202	0.198	0.166	0.198	0.181	0.184	0.110	0.168	0.176
MgO	6.59	1.80	3.04	2.68	1.97	5.65	5.86	6.22	1.88	2.63	2.75
CaO	10.67	5.21	6.66	6.48	5.46	11.02	10.86	10.79	5.49	7.19	7.17
Na2O	2.37	3.56	3.14	3.05	3.61	2.31	2.38	2.36	3.63	3.06	3.16
K2O	0.69	2.73	2.78	3.14	2.94	0.39	0.61	0.65	2.62	2.72	2.56
P2O5	0.229	0.960	0.862	0.942	1.021	0.248	0.228	0.230	1.016	0.876	0.893
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Unnormalized Trace Elements (ppm):											
Ni	46	5	8	7	5	48	43	46	10	12	10
Cr	100	1	2	2	1	105	99	105	4	3	5
Sc	38	27	29	27	27	37	36	37	29	29	28
V	279	217	218	185	187	277	285	284	227	243	234
Ba	521	3207	3075	3354	3473	243	381	465	3133	3028	3234
Rb	18	48	46	51	55	9	13	15	42	51	47
Sr	235	294	275	277	276	233	235	237	294	285	289
Zr	136	477	474	498	515	134	136	138	473	459	461
Y	31	47	48	50	49	32	31	31	44	46	45
Nb	12.6	21.9	21.5	22.0	22.5	12.1	12.4	12.3	22.1	22.2	22.2
Ga	19	21	21	21	21	18	18	19	21	22	21
Cu	52	9	14	9	8	44	48	48	8	8	10
Zn	93	111	129	136	129	91	94	95	119	134	131
Pb	5	11	9	11	12	4	4	4	12	10	10
La	17	47	45	46	49	17	15	17	44	43	45
Ce	38	94	93	97	103	37	33	36	96	96	94
Th	3	7	7	6	7	1	2	3	6	6	6
Nd	21	47	50	52	56	22	20	18	49	49	51
sum tr.	1664	4691	4565	4851	4994	1362	1504	1610	4633	4545	4743
in %	0.17	0.47	0.46	0.49	0.50	0.14	0.15	0.16	0.46	0.45	0.47
sum m+tr	100.18	95.32	98.79	98.64	96.77	97.24	98.47	100.11	92.93	94.89	94.56
M+Toxides	100.23	95.40	98.87	98.72	96.85	97.28	98.51	100.16	93.01	94.97	94.65
Cr2O3	145.7	1.5	3.5	3.5	1.6	153.9	144.1	153.3	5.4	4.4	7.2
Sc2O3	58.3	40.6	43.7	41.7	41.4	56.4	54.9	56.4	43.9	44.6	42.2
V2O3	410.9	318.6	321.1	272.3	274.5	407.1	419.3	418.1	334.1	357.0	344.1
BaO	581.1	3580.9	3433.6	3744.5	3877.4	271.3	424.9	519.4	3498.0	3380.9	3611.1
Rb2O	19.5	52.2	49.8	55.8	60.0	9.5	14.5	16.7	46.4	55.2	51.4
SrO	278.0	347.8	325.0	327.5	326.0	275.5	277.9	280.5	347.2	337.5	341.4
ZrO2	185.8	651.5	647.7	680.0	702.9	183.5	186.1	188.3	645.5	626.9	629.2
Y2O3	39.6	59.4	61.1	63.2	62.2	40.4	39.0	39.0	56.4	58.2	57.1
Nb2O5	18.0	31.3	30.8	31.5	32.2	17.3	17.7	17.6	31.6	31.8	31.8
Ga2O3	26.1	27.6	27.7	28.6	28.8	23.5	24.7	25.5	28.2	29.2	28.0
CuO	64.6	11.6	17.5	11.3	10.3	55.6	60.6	60.3	9.8	9.8	12.4
ZnO	115.9	138.8	161.9	169.8	162.1	113.3	118.0	118.6	148.5	168.0	164.6
PbO	5.3	11.8	9.6	12.1	12.5	3.9	3.9	4.4	12.7	11.0	10.9
La2O3	19.8	55.6	52.7	54.1	57.9	19.8	17.0	19.9	52.1	50.3	53.0
CeO2	46.5	115.4	114.6	118.9	126.0	45.1	40.4	43.6	118.3	117.9	115.8
ThO2	2.8	7.4	8.2	7.1	7.2	1.3	1.7	3.0	6.8	6.5	6.7
Nd2O3	25.0	55.2	58.7	60.9	64.7	26.0	23.4	21.0	57.0	56.7	58.9
U2O3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
sum tr.	2102	5514	5377	5691	5854	1764	1923	2044	5454	5361	5578
in %	0.21	0.55	0.54	0.57	0.59	0.18	0.19	0.20	0.55	0.54	0.56

WSU GeoAnalytical Laboratory *Analyses by XRF*

MATERIALS TESTING & INSPECTION

SIEVE ANALYSIS

DATE: SEPTEMBER 20, 2006

\\SERVER\REPORTS\BOISE\2006 REPORTS\1000-1199\861050L\S5419.DOC

❑ Environmental Services ❑ Geotechnical Engineering ❑ Construction Materials Testing ❑ Special Inspections

«FirstName» «LastName»
«Company»
«Address1»
«City», «State» «PostalCode»

Project: Black Rock Dam
Test Date: July 31, 2006

As requested MTI has performed sieve analysis testing on the sample referenced below. The testing was performed in accordance with current Bureau of Reclamation standards. The results obtained in our laboratory were as follows:

Source:	DH-05-1							
Sample ID:	5419							
Sampling and Preparation:	ASTM D75:	X	AASHTO T2:		AASHTO T87:		ASTM D421:	X
Test Standard:	ASTM C117:	X	AASHTO T11:		ASTM D1140:		ASTM D5444:	
	ASTM C136:	X	AASHTO T27:		ASTM D422:		AASHTO T88:	

Sieve Size	Percent Passing		
	235.0 - 236.0	265.0 – 266.0	293.0 – 294.2
3"	100	100	100
1.5"	70	89	83
¾"	54	75	70
3/8"	38	57	57
#4	30	44	47
#8	26	35	40
#10	26	33	38
#16	24	29	35
#30	23	25	30
#40	22	23	28
#50	21	21	26
#100	20	18	22
#200	20.0	15.9	18.0
1 Minute	20.0	15.8	18.0
4 Minute	18.7	15.5	17.6
19 Minute	16.9	14.3	16.8
60 Minute	12.3	11.6	12.1
435 Minute	8.0	7.4	7.6
1545 Minute	2.3	1.8	2.0
Atterberg Limits	Non-Plastic	Non-Plastic	Non-Plastic

If you have any questions concerning this report (Document2), please call on us at **(208) 376-4748**.
Respectfully submitted,
MATERIALS TESTING & INSPECTION INC.

Brandon Huff C.E.T.
Laboratory Manager
Original signed copy to client:

2791 S. Victory View Way, Boise ID 83709 • 208 376-4748 • Fax 208 322-6515
E-Mail mti@mti-id.com • http://www.mti-id.com

Appendix C

Drawings

5 | 4 | 3 | 2 | 1

GENERAL GEOLOGIC LEGEND

Quaternary Units

Qe — Quaternary Loess Deposits (Qe). Deposits of Holocene age wind–blown loess blanket the site. The loess consists primarily of brown, dry to moist, non–plastic silt and fine sand.

Qcg — Quaternary Colluvium Deposits (Qcg). The colluvium deposits consist of undifferentiated medium to coarse–grained sand with fines, gravel, cobbles and boulders composed of basaltic detritus from local sources.

Qh — Quaternary Alluvium Deposits (Qh). The alluvium deposits consist of undifferentiated medium to coarse–grained sand with fines, gravel, cobbles and boulders composed of basaltic detritus from local sources.

Landslide — Landslide. Landslide debris of unknown age and composition, includes deposits on the northwest and east slopes of Horsethief Mountain, and Horsethief Point.

Tertiary Units

Tr — Ringold Formation (Tr). The Ringold is a fluviolacustrine deposit composed of a poorly to well–indurated, subrounded basalt sand, gravel and cobble size clasts in a matrix of fines and silty sand.

Tfb — Fault Breccia (Tfb). Basalt breccia associated with the Horsethief Mountain Thrust Fault. The fault material consists of angular, hard, sand– to boulder–size inclusions of black to greenish–black, slightly to intensely weathered, hard fine–grained dense basalt in a clayey sand matrix. Alteration products include iron and manganese oxide on rock surfaces, and abundant matrix forming blackish–green to light green chlorite.

Ellensburg Formation.

Tem — Elephant Mountain Member (Tem). The Elephant Mountain member consists of medium to fine grained basalt. The member was not encountered in test borings at the alternate dam site, but was logged in drill holes the original dam site, refer to WIS (2003) for detailed description.

Trr — Rattlesnake Ridge Member (Trr). The Rattlesnake Ridge member also includes the sedimentary deposits between the Elephant Mountain Basalt and the Pomona Basalt. The unit is composed of fluvial gravel, sand, and cobbles with intensely weathered basalt fragments and tuffaceous silt and clay.

Columbia River Basalt Group – Saddle Mountains Basalt Formation.

Tp — Pomona Member (Tp). The Pomona member underlies the valley and the north abutment at the damsite, the basalt has reverse magnetic polarity, is generally black to gray, fine grained, slightly weathered, hard and intensely to moderately fractured, dense basalt with fine plagioclase crystals. The Pomona flow is invasive into the underlying Selah interbed, the upper portion of the flow includes glassy vesicular basalt with inclusions of fine sediment, which is referred to as a peperite.

Ellensburg Formation.

Ts — Selah Sedimentary Interbed (Ts). The Selah Interbed is a sedimentary unit composed of tuffaceous siltstone and claystone. The Selah sediments are reddish orange to black, well indurated clay to medium sand –sized lithic fragments composed of pumice, ash and chert.

Columbia River Basalt Group – Saddle Mountains Basalt Formation.

Teq/Tum — Esquatzel and Umatilla Members (Teq/Tum). The Esquatzel member is an intercanyon flow that filled ancestral Columbia River channels, sometimes overflowing the channel and pouring out into the floodplain.The Esquatzel member overlies the Umatilla member, and it is difficult to distinguish between the two flows, due to similar characteristics the two members are addressed as a single unit. The flows consist of gray to dark gray, fresh to slightly weathered, hard, moderately to slightly fractured, dense to slightly vesicular, fine–grained basalt. Both basalt have normal magnetic polarity.

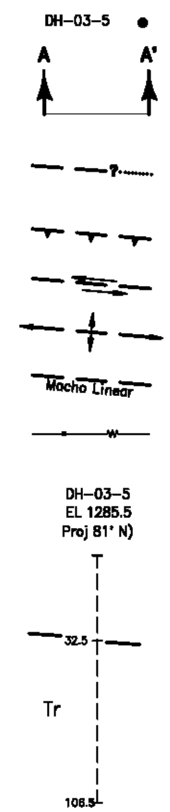
Ellensburg Formation.

Tm — Mabton Sedimentary Interbed (Tm). The Mabton Interbed is a thick sequence of light green to brown, moderately soft tuffaceous siltstone, sandstone and claystone. The Mabton sediments are light green to dark brown, well indurated, intensely weathered clay silt and sand–size fragments. Traces of black charcoal fragments noted. The interbed represents an extended time period of deposition between eruptions.

Columbia River Basalt Group – Wanapum Basalt Formation

Tpr — Priest Rapids Basalt Member (Tpr). The Priest Rapids Member is distinguished by its coarse–grained texture and reverse magnetic polarity. The flows consist of black to dark gray, slightly weathered, hard, intensely to moderately fractured, fine–grained to porphyritic vesicular basalt.

GENERAL GEOLOGIC EXPLANATION



- Drill hole location, designation and number.
- Location and designation of geologic section.
- Geologic contact. Dashed where approximate, queried where inferred, dotted where concealed.
- Thrust Fault (plan view), dashed where approximate, arrows toward direction of footwall movement.
- Thrust Fault (section view), dashed where approximate, arrows toward direction of movement.
- Anticline, dashed where approximate.
- Photographic Linear, dashed where approximate.
- Overhead power line.
- Drill hole designation.
  Elevation of ground surface at collar of drill hole.
  Distance and direction of projection (if projected).
- Stick log of drill hole. Dashed when projected more than ten feet to the section.
- Depth to geologic contact.
- Geologic unit.
- Total depth of drill hole.

GENERAL GEOLOGIC NOTES

1. The Unified Soil Classification System, Designation USBR 5005–86, "Procedure for Determining Unified Soil Classification (Visual Method)"; Designation USBR 5000–86, Procedure for Determining Unified Soil Classification (Laboratory Method)" were used in describing earth materials sampled in exploratory drill holes.

2. Descriptive terms appearing on geologic logs describe the physical characteristics of materials and conform to standard definitions as given in "Engineering Geology Field Manual, Volume I, 2nd Edition" (USBR, 1998) and "Volume II, 2nd Edition" (USBR, 2001).

3. General Geologic Explanation, Legend and Notes to accompany dwgs: 33–100–3381 through –3384, and 33–100–3473.

REV NO		
1	2006–6–23 100–T.E.E.	ADDED "FAULT BRECCIA", ADDED Qcg TO GENERAL GEOLOGIC LEGEND, ADDED THRUST FAULT SYMBOL AND DEFINITION TO EXPLANATION, AND CHANGED NOTES AS NEEDED.

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA RIVER BASIN WATER STORAGE FEASIBILITY STUDY – WASHINGTON

BLACK ROCK DAMSITE

GENERAL GEOLOGIC LEGEND, EXPLANATION AND NOTES

GEOLOGY: STELMA / DIDRICKSEN — CHECKED: DS
DRAWN: T.ENGLAND — TECH. APPR.: [signature]
APPROVED: [signature]
PEER REVIEWER – REGIONAL GEOLOGIST

CAD SYSTEM ACAD 2004 — geo\blackrock\dwgs\33–100–3380
BOISE, IDAHO — SHEET 1 OF 1 — 2004, JUNE 15 — 33–100–3380

Official Use Only/SENSITIVE

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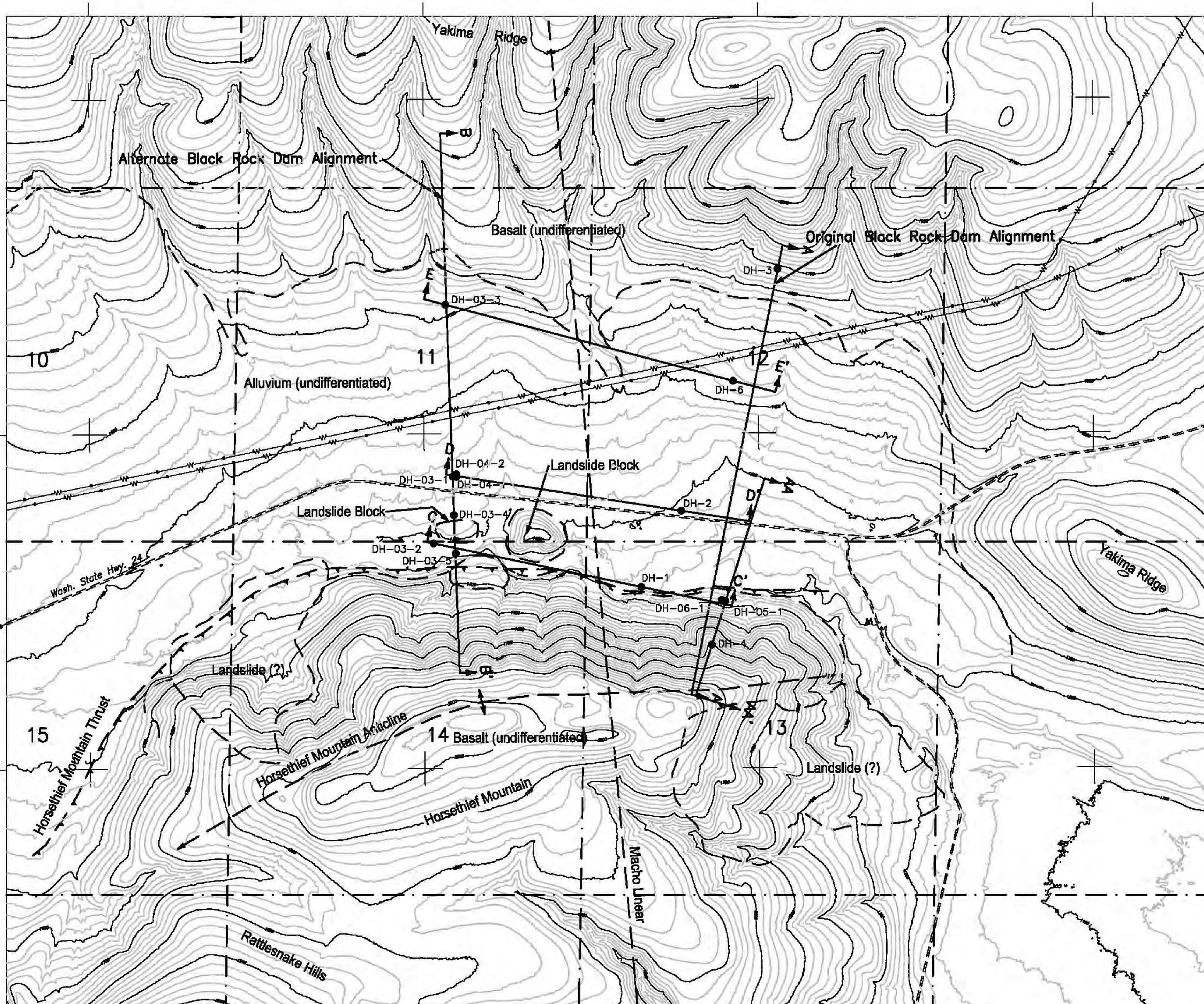

Notes:

1 General surface geology and tectonic features from report titled "Black Rock Reservoir, Initial Geotechnical Investigation, Prepared for Benton County Sustainable Development by Washington Infrastructures Services, Inc., Dated January 2003."

2 Locations and stick-log information for drill holes DH-1, DH-2, DH-3, DH-4 and DH-6 from from report titled "Black Rock Reservoir, Initial Geotechnical Investigation, Prepared for Benton County Sustainable Development by Washington Infrastructures Services, Inc., Dated January 2003."

3. For Geologic Sections refer to Drawing 33-100-3382, -3383 and -3384, and 33-100-3473.

4. For Geologic Explantion, Legend and Notes refer to Drawing 33-100-3380.

REV NO		
1	2006-6-23 100-TEE/DNS	ADDED EXPLORATORY DRILL HOLES DH-05-1 AND DH-06-1, GEOLOGIC SECTION AA - AA' AND CHANGED NOTES AS NEEDED.

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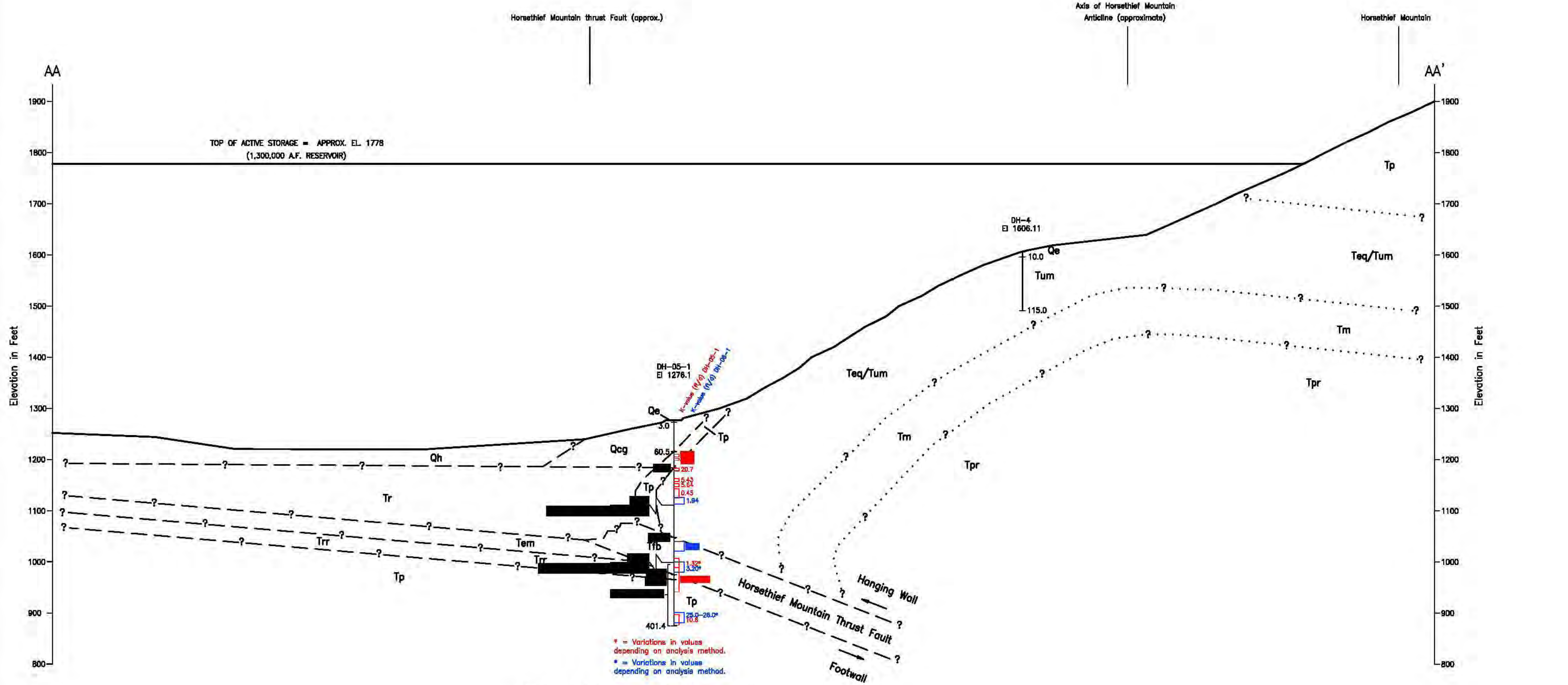
YAKIMA RIVER BASIN WATER STORAGE FEASIBILITY STUDY – WASHINGTON

BLACK ROCK DAM SITE

GEOLOGIC PLAN MAP, LOCATIONS OF EXPLORATIONS AND SECTIONS

GEOLOGY STELMA / DIDRICKSEN CHECKED DS
DRAWN T.ENGLAND TECH. APPR. Douglas J. B[illegible]
APPROVED Richard A. L[illegible]
PEER REVIEWER – REGIONAL GEOLOGIST

CAD SYSTEM ACAD 2004 | geo\blackrock\dwgs\33-100-3381
BOISE, IDAHO SHEET 1 OF 1 2004, JUNE 15 | **33-100-3381**



Black Rock Damsite – Right Abutment

100 0 100 200 300
SCALE OF FEET

Notes:

1. General geology and tectonic features from report titled "Black Rock Reservoir, Initial Geotechnical Investigation, Prepared for Benton County Sustainable Development by Washington Infrastructures Services, Inc., dated January 2003."

2. For location of Geologic Section refer to Drawing 33-100-3381.

3. For General Geologic Explantion, Legend and Notes refer to Drawing 33-100-3380.

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BLACK ROCK DAMSITE
RIGHT ABUTMENT
GEOLOGIC SECTION AA–AA'

GEOLOGY STELMA, DIDRICKSEN — CHECKED [signature]
DRAWN D.STELMA, T.ENGLAND — TECH. APPR. [signature]
APPROVED [signature]
PEER REVIEWER – REGIONAL GEOLOGIST

CAD SYSTEM ACAD 2006 | geo\blackrock\dwgs\33-100-3473
BOISE, IDAHO SHEET 1 OF 1 2007, OCTOBER 25 | 33-100-3473

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D C B A

WEATHERING

FRESH (W1): Body of rock is not oxidized or discolored; fracture surfaces are not oxidized or discolored*; no separation of grain boundaries; no change of texture and no solutioning. Hammer rings when crystalline rocks are struck.

SLIGHTLY WEATHERED TO FRESH (W2):**

SLIGHTLY WEATHERED (W3): Discoloration or oxidation is limited to surface of, or short distance from fractures; some feldspar crystals are dull; fracture surfaces have minor to complete discoloration or oxidation; no visible separation of grain boundaries; texture preserved and minor leaching of soluble minerals may be present. Hammer rings when crystalline rocks are struck, body of rock is not weakened by weathering.

MODERATELY TO SLIGHTLY WEATHERED (W4):**

MODERATELY WEATHERED (W5): Discoloration or oxidation extends from fractures, usually throughout body of rock; ferromagnesian minerals are "rusty", feldspar crystals are "cloudy"; all fracture surfaces are discolored or oxidized; partial opening of grain boundaries visible; texture generally preserved, but soluble minerals may be mostly leached. Hammer does not ring when rock is struck, body of rock is slightly weakened.

INTENSELY TO MODERATELY WEATHERED (W6):**

INTENSELY WEATHERED (W7): Body of rock is discolored or oxidized throughout; all feldspars and ferromagnesian minerals are altered to clay to some extent. All fracture surfaces are discolored or oxidized, and friable; partial separation of grain boundaries, rock is friable; in situ disaggregation of granitics common in semi-arid regions; texture altered and leaching of soluble minerals may be complete. Rock has dull sound when struck with hammer; rock is weakened, usually can be broken with moderate to heavy manual pressure or by light hammer blow without reference to planes of weakness.

VERY INTENSELY WEATHERED (W8):**

DECOMPOSED (W9): Body of rock is discolored or oxidized throughout, but resistant minerals such as quartz may be unaltered; all feldspars and ferromagnesian minerals are completely altered to clay; complete separation of grain boundaries (disaggregated), partial or complete remnant rock structure may be preserved, but resembles a soil.

NOTE: Weathering categories are established primarily for crystalline rocks and those with ferromagnesian minerals, weathering in various sedimentary rocks will not always fit the categories established – weathering categories may be modified for particular site conditions or alteration such as hydrothermal alteration. Where modified criteria are established, they should be identified and described.

* Characteristics of fracture surfaces do not include directional weathering along shears or faults and their associated fracture zones; for example a shear that carries weathering to great depths in a fresh rock mass would not require the whole rock mass to be classified as weathered.

** Combination descriptors are used when equal distribution of both weathering characteristics are present over significant intervals or where characteristics noted are "in between" the diagnostic characteristics.

DURABILITY INDEX

DURABILITY DESCRIPTOR	DESCRIPTIVE CRITERIA
DIØ	Rock specimen or exposure remains intact with no deleterious cracking after exposure longer than 1 year.
DI1	Rock specimen or exposure develops hairline cracking on surfaces within 1 month, but no disaggregation within 1 year of exposure.
DI2	Rock specimen or exposure develops hairline cracking on surfaces within 1 week, and/or disaggregation within 1 month of exposure.
DI3	Specimen or exposure may develop hairline cracks in 1 day and displays pronounced separation of bedding and/or disaggregation within 1 week of exposure.
DI4	Specimen or exposure displays pronounced cracking and disaggregation within 1 day (24 hours) of exposure. Generally ravels and degrades to small fragments.

COLOR

The Munsell color system (Geologic Society of America Rock Color Chart) should be used. This system defines wet color by its hue, value, and chroma. Color symbols used (i.e., 5 YR 5/6 may be included).

SEDIMENTARY AND PYROCLASTIC ROCK PARTICLE SIZES

Size in mm	Sedimentary Rounded, subrounded, subangular		Pyroclastic	
	Particle or fragment	Lithified product	Fragment	Lithified product
	Boulder	Boulder conglomerate	Block[(a)] or Bomb[(b)]	Volcanic[(a)] breccia or Volcanic[(b)] agglomerate
256	Cobble	Cobble conglomerate		
64	Pebble	Pebble conglomerate	Lapilli	Lapillistone and Lapilli tuff
4	Granule	Granule conglomerate		
2	Very coarse sand	Sandstone (Very coarse, coarse, medium, fine, or very fine)	Coarse ash	Coarse tuff
1	Coarse sand			
0.5	Medium sand			
0.25	Fine sand			
0.125	Very fine sand			
0.0625	Silt	Siltstone/ Shale	Fine ash	Fine tuff
0.00391	Clay	Claystone Shale		

(a) Broken from previous igneous rock, block shaped (angular to subangular).
(b) Solidified from plastic material while in flight, rounded clasts.

IGNEOUS AND METAMORPHIC ROCK TEXTURE

TEXTURE DESCRIPTOR	AVERAGE GRAIN DIAMETER
VERY COARSE GRAINED OR PEGMATITIC	>10 mm [>3/8 in]
COARSE GRAINED	5–10 mm [3/16 –3/8 in]
MEDIUM GRAINED	1–5 mm [1/32 –3/16 in]
FINE GRAINED	0.1–1 mm [0.004 – 1/32 in]
APHANITIC (Cannot be seen with the unaided eye)	<0.1 mm [<0.004 in]

ADDITIONAL TEXTURAL ADJECTIVES

PIT (pitted) – pinhole to 0.03 ft [3/8 in] (<1 to 10 mm) openings.

VUG (vuggy) – Small openings (usually lined with crystals) ranging in diameter from 0.03 ft [3/8 in] to 0.33 ft [4 in] (10 to 100 mm).

CAVITY – An opening larger than 0.33 ft [4 in] (100 mm), size descriptions are required, and adjectives such as small, large, etc., may be used.

HONEYCOMBED – If numerous enough that only thin walls separate individual pits or vugs, this term further describes the preceding nomenclature to indicate cell-like form.

VESICLE (vesicular) – Small openings in volcanic rocks of variable shape and size formed by entrapped gas bubbles during solidification.

BEDDING FOLIATION OR FLOW TEXTURE

DESCRIPTORS	THICKNESS/SPACING
MASSIVE	Greater than 10 ft (>3 m)
VERY THICKLY (bedded, foliated or banded)	3 to 10 ft (1 to 3 m)
THICKLY	1 to 3 ft (300 mm to 1 m)
MODERATELY	0.3 to 1 ft (100 to 300 mm)
THINLY	0.1 to 0.3 ft (30 to 100 mm)
VERY THINLY	0.03 [3/8 in] to 0.1 ft (10 to 30 mm)
LAMINATED (Intensely foliated or banded)	Less than 0.03 ft [3/8 in] (<10 mm)

BEDROCK HARDNESS/STRENGTH

EXTREMELY HARD (H1): Core, fragment or exposure cannot be scratched with knife or sharp pick; can only be chipped with repeated heavy hammer blows.

VERY HARD (H2): Cannot be scratched with knife or sharp pick. Core or fragment breaks with repeated heavy hammer blows.

HARD (H3): Can be scratched with knife or sharp pick with difficulty (heavy pressure). Heavy hammer blow required to break specimen.

MODERATELY HARD (H4): Can be scratched with knife or sharp pick with light or moderate pressure. Core or fragment breaks with moderate hammer blow.

MODERATELY SOFT (H5): Can be grooved 1/16 inch (2 mm) deep by knife or sharp pick with moderate or heavy pressure. Core or fragment breaks with light hammer blow or heavy manual pressure.

SOFT (H6): Can be grooved or gouged easily by knife or sharp pick with light pressure, can be scratched with fingernail. Breaks with light to moderate manual pressure.

VERY SOFT (H7): Can be readily indented, grooved or gouged with fingernail, or carved with a knife. Breaks with light manual pressure.

Any bedrock unit softer than H7, Very Soft, is to be described using USBR 5005-86 (visual classification of soils) consistency characteristics.

REV NO		
1	3-8-00 D – P. M. R.	CONVERTED ORIGINAL DRAWING 40-D-6493 TO ACAD, CHANGED DWG. NO., MINOR REVISIONS.

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

GEOLOGY FOR DESIGN & SPECIFICATIONS

STANDARD DESCRIPTORS AND DESCRIPTIVE CRITERIA FOR ROCK

GEOLOGY NOMENCLATURE COMMITTEE CHECKED CHUCK SULLIVAN
DRAWN MARSHALL MONSON TECH. APPROVAL PETER M. ROHRER
APPROVED MARK McKEOWN
PEER REVIEWER

CADD SYSTEM	CADD FILENAME	DATE AND TIME PLOTTED
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DENVER, COLORADO	MARCH 8, 2000	40-D-7022

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DISCONTINUITY TERMINOLOGY

DISCONTINUITY – A collective term used for all structural breaks in geologic materials which usually are unhealed and have zero or low tensile strength. Discontinuities also may be healed and exhibit high tensile strength. Discontinuities comprise fractures (including joints), planes of weakness, shears/faults, and shear/fault zones. Contacts between various units also may be considered discontinuities.

FRACTURE – A term used to describe any natural break in geologic material excluding shears and shear zones. Additional fracture terminology is provided below.

SHEAR – A structural break where differential movement has taken place along a surface or zone of failure by shear; characterized by striations, slickensides, gouge, breccia, mylonite, or any combination of these. Often direction, amount of displacement, and continuity may not be known because of limited exposures or observations.

FAULT – A shear with significant continuity which can be correlated between observations; occurs over a significant portion of a given site, foundation area, or region; or is a segment of a fault or fault zone defined in the literature. The designation of a shear as a fault or fault zone is a site-specific determination.

SHEAR/FAULT ZONE – A shear that is expressed in relative terms of width. The zone may consist of gouge, breccia, or many related faults or shears together with fractured and crushed rock between the shears and faults, or any combination of these. In the literature many fault zones simply are referred to as faults.

SHEAR-/FAULT-DISTURBED ZONE – An associated zone of fractures and/or folds adjacent to a shear or shear zone where the country rock has been subjected to only minor cataclastic action and may be mineralized. If adjacent to a fault or fault zone, the term is fault-disturbed zone. Occurrence, orientation, and areal extent of these phenomena depend upon depth of burial (pressure and temperature) during shearing, brittleness of materials, and the stress envelope.

FRACTURE TERMINOLOGY

EXAMPLES SHOWN FOR CORE, BUT APPLICABLE TO ANY OBSERVATION

JOINT (JT) – A relatively planar fracture along which there has been little or no shearing displacement.

FOLIATION JOINT (FJ) OR BEDDING JOINT (BJ) – a relatively planar fracture which is parallel to foliation or bedding along which there has been little or no shearing displacement.

BEDDING PLANE SEPARATION – A separation along bedding after extraction or exposure due to stress relief or slaking.

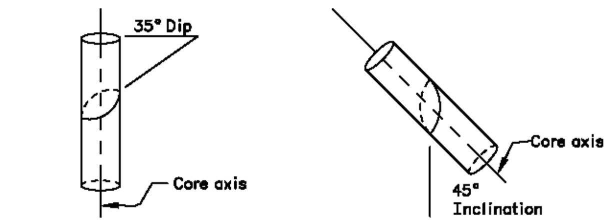
INCIPIENT JOINT (IJ) OR INCIPIENT FRACTURE (IF) – A joint or fracture which does not continue through the specimen or at least is not seen with the naked eye. However, when the specimen is wetted, and then allowed to dry, the joint or fracture trace is evident. When core is broken, it breaks along an existing plane.

RANDOM FRACTURE (RF) – A natural break which does not belong to a joint set, and which exhibits a generally rough, very irregular, nonplanar surface.

MECHANICAL BREAK (MB) – A break due to drilling, blasting, or handling. Mechanical breaks parallel to bedding or foliation are called Bedding Breaks (BB) or Foliation Breaks (FB), respectively. Recognizing mechanical breaks may be difficult. The absence of oxidation, staining, or mineral fillings, and often a hackly or irregular surface are clues for recognition.

FRACTURE ZONE (FZ) – Numerous, very closely spaced intersecting fractures. Often fragmented core cannot be fitted together.

METHOD OF MEASURING DIP OF PLANAR DISCONTINUITIES, FOLIATION, AND BEDDING IN CORE



1. Vertical hole – true dip is measured and reported.

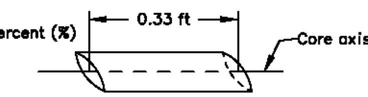
2. Angle hole – true dip usually not known; angle is measured from core axis and is called inclination.

ROCK QUALITY DESIGNATION (RQD)

EXAMPLE SHOWN FOR CORE, BUT APPLICABLE TO ANY LINEAR OBSERVATION

$$RQD = \frac{\text{Sum of length of solid core pieces} > 0.33 \text{ ft [4 in] (100 mm) long}}{\text{Length of the run in feet (mm)}} \times 100$$

Expressed as percent (%)



FRACTURE FREQUENCY

FRACTURE FREQUENCY – The number of natural fractures occurring within a base length or core run. The number of fractures is divided by the length and is reported as fractures per foot or fractures per meter. Expressed as 3/m or 6/ft.

FRACTURE DENSITY

FRACTURE DENSITY – Based on the spacing of all natural fractures in an exposure or core recovery lengths in boreholes; excludes mechanical breaks, shears, and shear zones; however, shear-disturbed zones (fracturing outside the shear) are included. Descriptors for fracture density apply to all rock exposures such as tunnel walls, dozer trenches, outcrops, or foundation cut slopes and inverts, as well as boreholes. Descriptive criteria presented below are based on borehole cores where lengths are measured along the core axis. For other exposures the criterium is distance measured between fractures (size of blocks).

UNFRACTURED (FD0): No fractures.

VERY SLIGHTLY FRACTURED (FD1): Core recovered mostly in lengths greater than 3 feet (1 m).

SLIGHTLY TO VERY SLIGHTLY FRACTURED (FD2) *

SLIGHTLY FRACTURED (FD3): Core recovered mostly in lengths from 1 to 3 feet (300 to 1000 mm) with few scattered lengths less than 1 foot (300 mm) or greater than 3 feet (1000 mm).

MODERATELY TO SLIGHTLY FRACTURED (FD4) *

MODERATELY FRACTURED (FD5): Core recovered mostly in 0.3- to 1.0-foot (100- to 300-mm) lengths with most lengths about 0.6 foot (200 mm).

INTENSELY TO MODERATELY FRACTURED (FD6) *

INTENSELY FRACTURED (FD7): Lengths average from 0.1 to 0.3 foot (30 to 100 mm) with scattered fragmented intervals. Core recovered mostly in lengths less than 0.3 foot (100 mm).

VERY INTENSELY TO INTENSELY FRACTURED (FD8) *

VERY INTENSELY FRACTURED (FD9): Core recovered mostly as chips and fragments with a few scattered short core lengths.

* Combinations of fracture densities (e.g., Very Intensely to Intensely Fractured or Moderately to Slightly Fractured) are used where equal distribution of both fracture density characteristics are present over a significant interval or exposure, or where characteristics are "in between" the descriptor definitions.

FRACTURE SPACING

JOINT SET, OR FRACTURE SPACING DESCRIPTOR	TRUE SPACING
EXTREMELY WIDELY SPACED (SP1)	Greater than 10 ft (>3 m)
VERY WIDELY SPACED (SP2)	3 to 10 ft (1 to 3 m)
WIDELY SPACED (SP3)	1 to 3 ft (300 mm to 1 m)
MODERATELY SPACED (SP4)	0.3 to 1 m (100 to 300 mm)
CLOSELY SPACED (SP5)	0.1 to 0.3 ft (30 to 100 mm)
VERY CLOSELY SPACED (SP6)	less than 0.1 ft (<30 mm)

FRACTURE CONTINUITY

CONTINUITY DESCRIPTOR	DISCONTINUITY LENGTH
DISCONTINUOUS (C1)	Less than 3 ft (<1 m)
SLIGHTLY CONTINUOUS (C2)	3 to 10 ft (1 to 3 m)
MODERATELY CONTINUOUS (C3)	10 to 30 ft (3 to 10 m)
HIGHLY CONTINUOUS (C4)	30 to 100 ft (10 to 30 m)
VERY CONTINUOUS (C5)	Greater than 100 ft (>30 m)

FRACTURE ENDS (JOINT SURVEYS)

FRACTURE ENDS DESCRIPTOR	DESCRIPTIVE CRITERIA
E0	Zero ends leave the exposure (both ends can be seen).
E1	One end of the fracture terminates in the exposure (one end can be seen).
E2	Neither fracture end terminates in the exposure (neither end can be seen).

FRACTURE OPENNESS OR FILLING THICKNESS

FILLING THICKNESS DESCRIPTOR	THICKNESS/OPENNESS	OPENNESS DESCRIPTOR
CLEAN (T0)	No film or coating.	
	No visible separation.	TIGHT (O0)
VERY THIN (T1)	Less than 0.003 ft [1/32 in] (<1 mm).	SLIGHTLY OPEN (O1)
MODERATELY THIN (T2)	0.003 to 0.01 ft [1/32 to 1/8 in] (1 to 3 mm).	MODERATELY OPEN (O2)
THIN (T3)	0.01 to 0.03 ft [1/8 to 3/8 in] (3 to 10 mm).	OPEN (O3)
MODERATELY THICK (T4)	0.03 ft [3/8 in] to 0.1 ft (10 to 30 mm).	MODERATELY WIDE (O4)
THICK (T5)	Greater than 0.1 ft (>30 mm). Actual thickness or openings recorded.	WIDE (O5)

FRACTURE MOISTURE CONDITIONS

MOISTURE DESCRIPTOR	DESCRIPTIVE CRITERIA
M1	The fracture is dry. It is tight or filling (where present) is of sufficient density or composition to impede waterflow. Waterflow along the fracture does not appear possible.
M2	The fracture is dry with no evidence of previous waterflow. Waterflow appears possible.
M3	The fracture is dry, but shows evidence of waterflow such as staining, leaching and/or vegetation.
M4	The fracture or filling (where present) is damp, but no free water is present.
M5	The fracture shows seepage. It is wet with occasional drops of water.
M6	The fracture emits a continuous flow (estimate flow rate) under low pressure. Filling materials (where present) may show signs of leaching or piping.
M7	The fracture emits a continuous flow (estimate flow rate) under moderate to high pressure. Water is squirting and/or filling material (where present) may be substantially washed out.

FRACTURE ROUGHNESS

Refers to small-scale asperities of surfaces, not large-scale undulations or waviness.

STEPPED (R1): Near-normal steps and ridges occur on the fracture surface.
ROUGH (R2): Large, angular asperities can be seen.
MODERATELY ROUGH (R3): Asperities are clearly visible and fracture surface feels abrasive.
SLIGHTLY ROUGH (R4): Small asperities on the fracture surface are visible and can be felt.
SMOOTH (R5): No asperities, smooth to the touch.
POLISHED (R6): Extremely smooth and shiny.

FRACTURE SURFACE AND/OR FILLING ALTERATION AND HARDNESS

Descriptors for weathering or alteration of fracture surfaces and fracture fillings (excluding soil materials) are the same as those used for weathering and alteration of rock.

Descriptors for hardness/strength of fillings and/or fracture surfaces are the same as those presented for hardness of rock and consistency of soils.

DISCONTINUITY HEALING

TOTALLY HEALED (HL1) – All fragments bonded, discontinuity is completely healed or recemented to a degree at least as hard as surrounding rock.

MODERATELY HEALED (HL3) – Greater than 50 percent of fractured or sheared material, discontinuity surfaces or filling is healed or recemented; and/or strength of healing agent is less hard than surrounding rock.

PARTLY HEALED (HL5) – Less than 50 percent of fractured or sheared material, discontinuity surface or filling is healed or recemented.

NOT HEALED (HL6) – Discontinuity surface, fractured zone, sheared material or filling is not healed or recemented, rock fragments or filling (if present) held in place by their own angularity and/or cohesiveness.

SHEAR/FAULT DESCRIPTORS

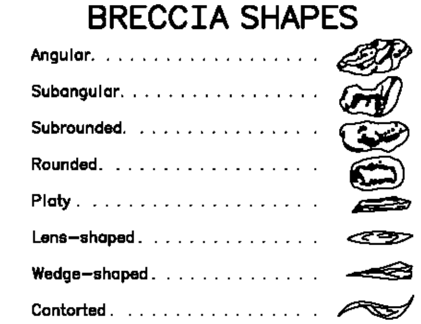
SHEAR/FAULT GOUGE CONSISTENCY

DESCRIPTOR	DESCRIPTIVE CRITERIA (Similar to consistency of soils)
VERY HARD	Gouge cannot be broken with finger pressure; cannot be indented with fingernail.
HARD	Gouge can be broken with firm finger pressure; can be indented with fingernail; cannot be indented with thumb.
FIRM	Gouge can be easily crumbled; can be indented with thumb 1 to 5 mm.
SOFT	Gouge can be easily molded; can be penetrated with thumb 5 to 25 mm.
VERY SOFT	Gouge can be penetrated with thumb more than 25 mm.

SHEAR/FAULT MOISTURE DESCRIPTORS

The apparent moisture content of gouge is described as WET (visible free water); MOIST (damp, but no visible water); and DRY (absence of moisture, dusty, dry to the touch). Moisture descriptors M1 through M7 may be used to describe the shear or shear zone.

BRECCIA SHAPES



REV NO	DATE	DESCRIPTION
1	3-8-00 D - P. M. R.	CONVERTED ORIGINAL DRAWING 40-D-6499 TO ACAD, CHANGED DWG. NO., MINOR REVISIONS.

ALWAYS THINK SAFETY

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GEOLOGY FOR DESIGN & SPECIFICATIONS

STANDARD DESCRIPTORS AND DESCRIPTIVE CRITERIA FOR DISCONTINUITIES

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DRAWN MARSHALL MONSON TECH. APPROVAL PETER M. ROHRER
APPROVED MARK McKEOWN PEER REVIEWER

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