City of Pasco, Washington

Hydrogeologic Feasibility Assessment

Aquifer Storage and Recovery Feasibility Study

December 29, 2020

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Abbreviations and Acronyms

afy	acre-feet per year
ASR	Aquifer Storage and Recovery
bgs	below ground surface
b	cumulative thickness of the interflow zones
BG	billion gallons
$CaCO_3$	calcium carbonate
cm	centimeters
City	City of Pasco, Washington
CRBG	Columbia River Basalt Group
cfs	cubic feet per second
E	East
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management
FFWA	Family Farm Water Act
FCWCB	Franklin County Water Conservancy Board
gpd/foot	gallons per day per foot
gpm	gallons per minute
Golder	Golder Associates, Inc.
GSI	GSI Water Solutions, Inc.
h	available buildup
I	interstate
ID	identification
INTERA	INTERA, Inc.
K	hydraulic conductivity
Kh	horizontal hydraulic conductivity
Kv	vertical hydraulic conductivity
MCL	maximum contaminant level
µS/cm	microSiemens per centimeter
mg/L	milligrams per liter
mg/L-N	milligrams per liter as nitrogen
mgd	million gallons per day
MG	million gallons
Ma	million years ago
maf	million acre-feet
M&I	municipal and industrial
MSA	Murray, Smith, and Associates, Inc.
Murraysmith	Murraysmith, Inc.
m.y.	millions of years before present
NAD27	North American Datum of 1927
ne	effective porosity
OCR	Office of the Columbia River
Off-season	November through March
Peak-season	May through September
Q	flow rate
Qa	maximum annual production volume
Qi	maximum instantaneous flow rate
QCWR	Quad City Water Right

Quad Cities	Cities of Kennewick, Pasco, Richland, and West Richland
R	Range
RAW	Rattlesnake-Wallula alignment
RH2	RH2 Engineering, Inc.
ROE	Record of Examination
SMB	Saddle Mountains Basalt
s.u.	standard units
SR	state route
S	storativity
SMCL	secondary maximum contaminant level
SCBID	South Columbia Basin Irrigation District
t	pumping time
T	Township
T	transmissivity
TDS	total dissolved solids
UGA	Urban Growth Area
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USDOE	United States Department of Energy
USGS	United States Geological Survey
V	volume
WTP	Water Treatment Plant
WB	Wanapum Basalt
WAC	Washington Administrative Code
WPWTP	West Pasco Water Treatment Plant

Executive Summary

This report presents findings from a reconnaissance-level investigation of the hydrogeologic feasibility of developing an Aquifer Storage and Recovery (ASR) program for the City of Pasco (City). This investigation is being conducted to evaluate the feasibility of using ASR to optimize the use of existing water rights, and to create a sustainable and resilient supply option that allows the City to meet peak demands and future demand projections for their potable and irrigation systems.

ASR is a water management tool that municipalities throughout Washington and Oregon use to help manage and optimize their water supply resources. The concept for a City ASR program would include withdrawing water from existing supply sources during the winter months, injecting and storing that water in an aquifer system beneath the City using a well or series of wells, and recovering the stored water from those same wells to meet summer demands. This would allow the City to augment peak-season demand needs and help meet projected demand shortfalls without increasing permitted withdrawals from the Columbia River during the low-flow summer months.

The primary aquifer units evaluated for ASR storage included the suprabasalt sediments (i.e., alluvial sand and gravel) and the underlying basalt sheet flows of the Columbia River Basalt Group. Groundwater in the suprabasalt aquifer is unconfined and in direct hydraulic connection with the Columbia River. Groundwater is considered confined in the basalt aquifer system within the Study Area. Low storage capacity and recovery volume potential precludes the suprabasalt aquifer from being targeted as a potential ASR storage zone.

The vast majority of the operational ASR systems in the Pacific Northwest are hosted by CRBG aquifers, including the cities of Kennewick, Walla Walla and Pendleton. The Umatilla Member of the Saddle Mountains Basalt and the Roza and Frenchman Springs Members of the Wanapum Basalt have been identified as potential target aquifer storage zones for a Pasco ASR program. The available storage capacity is estimated at 13,300 acre-feet, or roughly 4,300 million gallons (MG), though could vary depending on the actual hydrogeologic characteristics of the storage zones beneath the candidate ASR development sites. No groundwater quality concerns were identified for these target basalt storage zones.

The City's potable water system is projected to have a slight source capacity deficiency in 2036 of approximately 145 gallons per minute (gpm) (0.2 million gallons per day, mgd) based on the system's total capacity, and a capacity deficiency of approximately 2,245 gpm (3.2 mgd) based on the system's firm capacity (summarized in **Table 1-1**).

The City's irrigation system is estimated to have a 2036 supply deficiency of approximately 5,548 gpm (7.9 mgd) based on the system's total capacity, and approximately 8,548 gpm (12.3 mgd) based on the system's firm capacity (summarized in **Table 1-2**).

Both systems combined are projected to have a 2036 peak season total capacity shortfall of 5,693 gpm (8.1 mgd) and 2036 peak season firm capacity shortfall of 10,793 gpm (15.5 mgd). During the 153-day peak demand season (May through September), this equates to a total capacity shortfall of 1,255 million gallons (MG) and firm capacity shortfall of approximately 2,370 MG.

The estimated storage capacity of the target basalt storage zones underlying Pasco is estimated to be greater than the total predicted shortfall for the potable and irrigation systems. The estimated basalt storage capacity is estimated to range between 110 and 10,800 MG, based on a range of aquifer hydraulic characteristics. Using observations from the City of Kennewick's ASR system, the storage capacity of the basalt aquifer system underlying Pasco is estimated at 4,300 MG.

The surplus capacity available for ASR supply during the off-season (November through March) is limited to 8.4 mgd from the City's West Pasco Water Treatment Plant (WPWTP). The City's potable water system does have access to the interruptible portion of the Quad Cities water right during the off-season months via their West Pasco and Butterfield Intakes when instream flow provisions on the Columbia River are met. Based on the number of days that water is historically available (uninterrupted) for withdrawal under the Quad Cities water right, an estimated total of 1,025 MG would be available as ASR supply for aquifer recharge during the off-season months. No water quality limitations are anticipated to reduce the off-season capacity estimate from the WPWTP for ASR supply.

Some loss of source water stored in the target aquifer storage zone(s) is likely and will limit full recovery of the volume of water recharged by an estimated 10 percent. This means that of the 1,025 MG estimated to be available for ASR supply from the potable system, only an estimated 922 MG will be available for recovery. The estimated 922 MG is enough to cover the entire projected shortfall for the potable system, but only a portion (432 MG, or 23 percent) of the projected shortfall for the irrigation system. As a result, additional sources of water would be needed to meet the peak-season shortfall remaining for the irrigation system, either as additional recharge source water from the Butterfield WTP or in combination with municipal and industrial water potentially available from the U.S. Bureau of Reclamation/South Columbia Basin Irrigation District to offset the projected irrigation demands. The Butterfield WTP was not considered as a source for ASR supply because it is distant from the irrigation system and distant from most future growth and demand in the potable system.

Preferred locations within the Study Area where ASR could help address future demand growth for the potable and irrigation systems have been identified in the northwest portion of the Study Area. Findings suggest that the hydrogeologic conditions beneath this portion of the Study Area are favorable. Hydrogeologic conditions along the Columbia River or in the eastern portion of the City however, are less favorable.

A conceptual ASR wellfield design was developed to accept a maximum recharge rate of 8.4 mgd for these preferred locations. Because source water available for ASR supply is interruptible during the off-season, the ASR wellfield must be designed and capable of recharging water at the maximum rate of 8.4 mgd (approximately 6,000 gpm) when it becomes available. This would require an estimated four ASR wells designed to recharge at 1,500 gpm each. Two ASR well pairs could be located at one site and two at another. Each pair would consist of one ASR well completed in the Umatilla Member of the Saddle Mountains Basalt and one in the Roza or Frenchman Springs Members of the Wanapum Basalt. The actual number and configuration of the ASR wells will depend on site-specific aquifer characteristics determined as part of a future work phases should the City decide to pursue an ASR program.

Data gaps identified as part of this work are summarized in the last section of this report. The data gaps pertain mostly to geologic and hydrogeologic data and groundwater quality data. The primary geologic and hydrogeologic data gaps consist of geologic characterization data, site-specific aquifer hydraulic characteristics, groundwater levels, and storage zone capacities. Though basalt groundwater quality in the Kennewick area is within the regional range reported for the regional basalt system, there are no site-specific native groundwater quality data available for the potential target storage zones in the Pasco area.

Given the general lack of specific data on the target CRBG storage zones in the Study Area, a drilling and testing program would be needed to further assess ASR feasibility at a potential candidate development site. The primary purpose of drilling and testing would be to fill site-specific data gaps regarding the geologic conditions, aquifer hydraulic characteristics, groundwater levels, groundwater quality, and geochemical characteristics of potential aquifer storage zones. A drilling and testing program is recommended to obtain this information through supplemental investigations.

SECTION 1: **Introduction**

The City of Pasco (City) is conducting an aquifer storage and recovery (ASR) feasibility study to evaluate the feasibility of using ASR to optimize the use of existing water rights, and to create a sustainable and resilient supply option that enables the City to meet peak demands and future demand projections. Meeting these demands is challenging, as the City is constrained by the legal and/or physical availability of alternative water supply source options. Challenges like these are not unique, and are increasingly driving water utilities, planners and resource managers towards diversifying their supplies and using integrated approaches to meet current and future water needs.

ASR is a proven water management tool that municipalities and agricultural operations in the Pacific Northwest use to manage and optimize their water supply resources. Municipalities throughout Washington and Oregon have been developing and using ASR systems to realign water supply availability with seasonal demand patterns, reduce or defer costly infrastructure expansion, optimize the use of existing water rights, and improve system resilience, with many successful applications in Eastern Washington and Oregon (e.g., cities of Kennewick and Walla Walla, Washington and cities of Pendleton and Baker City, Oregon). Because the City shares similar circumstances to several other ASR users in the region, ASR is a promising option for helping the City bridge the disconnect between water right deficiencies during peak-use months and excess permitted water right capacity during the low demand season, without expanding the use of sources during the dry low-flow summer and fall seasons.

1.1 Purpose and Scope

The purpose of this study is to evaluate the feasibility of using and storing off-season water available from the Columbia River and the shallow alluvial aquifer system in groundwater storage zones beneath the City for use during the high-demand period. This feasibility study is a reconnaissance-level investigation based entirely on existing and available information. Future work will be needed to help address data gaps and uncertainties to improve aquifer storage capacity estimates and better assess overall feasibility.

The City entered into a grant agreement (Agreement No. WROCR-1921-Pasco-00015) with the Washington State Department of Ecology (Ecology) Office of the Columbia River (OCR) to complete the ASR feasibility study. The Agreement outlined a phased approach for completing the study and defined four tasks:

- **Task 1: Project Administration/Management** – This task is reserved for City staff to administer the project.
- **Task 2: Hydrogeologic Feasibility Assessment** – Identify locations and characteristics of potential groundwater storage zones beneath the City that may be suitable for ASR (*focus of this report*).
- **Task 3: Source Option Analysis** – Evaluate when, where, and how much source water is available for ASR recharge, considering legal and physical water availability and water system conveyance and treatment constraints.
- **Task 4: Initial Feasibility Study Report** – Synthesize results from Tasks 2 and 3 to rank and prioritize various ASR development options. Results from this report will be the basis for assessing whether source water availability and the hydrogeological setting in the Pasco area suggest that ASR may be feasible.

This report summarizes the geologic framework components used to develop a conceptual hydrogeologic model of the Pasco area (Task 2 – Hydrogeologic Feasibility Assessment). The conceptual model identifies locations and characteristics of potential groundwater storage zones beneath the City that may be suitable for ASR, and provides estimates of aquifer storage capacities and conceptual ASR well/wellfield designs.

This report also includes a preliminary summary of (1) where, when, and how much storage capacity is needed to meet current and future demands for the City's potable and irrigation systems and (2) potential source water options for ASR recharge. This information is used in conjunction with the conceptual hydrogeologic model to begin to narrow the focus of the feasibility study on areas within the City that may be more favorable for ASR. A more detailed discussion of these latter topics will be presented under separate cover prepared as part of Task 3 – Source Option Analysis (RH2, in preparation).

1.2 Geographic Setting

The City of Pasco is located at the southern margin of Franklin County and is one of four cities that make up the Quad-City[1] area of southeast Washington (**Figure 1-1**). The Columbia River forms the City's western and southern boundaries, while the Snake River and its conflux with the Columbia River border the City to the east. To the north, the City transitions from an urban setting to extensive agricultural land. The area north of the City is sometimes referred to as the Pasco Greenbelt (Brown, 1979) because of widespread irrigation and farming. Land surface elevations generally rise gradually from low-lying areas south along the Columbia River (350-390 feet NAD27)[2] to agricultural areas north (500-525 feet NAD27).

1.2.1 Study Area

The project study area is located in the southern portion of the Pasco Basin, a south-central sub-basin of the intermontane Columbia Basin, and includes the City of Pasco and future urban growth area (**Figure 1-2**). The eastern extent of the approximately 60 square mile study area (Study Area) is bounded partially by the Snake River and includes the City's Process Water Reuse Facility and Farm Circles, while the southern and western extents are bounded by the Columbia River. The northern border encompasses the City's recently adopted 20-year urban growth area and immediate surrounding areas.

1.3 Water Systems and Supply Needs

The City supplies its ratepayers with potable water sourced from two Columbia River surface diversions and water treatment plants. The City also operates a separate non-potable water system to serve water to customers for irrigating residential landscaping, parks, and sports fields.

1.3.1 Potable System

The City's potable water system is sourced by two Columbia River diversions and water treatment plants (WTP): Butterfield Intake and West Pasco Intake (**Figure 1-2**). The current potable water system has a total physical capacity of approximately 34 mgd and existing firm capacity of approximately 30 million gallons per day (mgd), if one membrane filter at the Butterfield WTP is out of service. The City is currently designing improvements at the West Pasco WTP (WPWTP) to provide a total capacity of 18 mgd and firm capacity of between 12 and 15 mgd. The City also is currently implementing improvements at the Butterfield WTP to supply projected future demands. All combined, these improvements will increase the total firm capacity of the system from 30 mgd to between 45 and 48 mgd and provide a total physical capacity of approximately 52 mgd.

The current water system service area covers over 19,000 acres, and includes areas within City limits and some unincorporated areas within Franklin County. The future service area, including the City's 20-year urban growth area (UGA), is approximately 25,600 acres (Murraysmith, 2019).

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[1] The Quad-Cities are made up of Kennewick, Pasco, Richland, and West Richland

[2] North American Datum of 1927

The City's projected year 2036 potable water system demands are assumed to include both infill demands and the demands projected in the UGA expansion area. With completion of the capacity expansions at the two WTPs and anticipated future population growth, the potable water system is projected to have a source capacity deficiency by year 2036 of approximately 145 gallons per minute (gpm) (0.2 mgd) based on the system's total capacity, and a capacity deficiency of approximately 2,245 gpm (3.2 mgd) based on the system's firm capacity (**Table 1-1**). The firm capacity estimate assumes that the high service pump or a membrane train in the West Pasco WTP is out of service.

Table 1-1. 2036 Peak Season Potable System Supply Capacity Summary

Description	Total Capacity (gpm)	Firm Capacity (gpm)
Source Capacity		
Existing Source Capacity	22,800	20,700
Additional WPWTP Capacity	8,333	8,333
Total Source Capacity	**31,133**	**29,033**
Demands		
Maximum Day Demand (MDD)	29,056	29,056
UGA Expansion Area MDD	2,222	2,222
Total Demands	**31,278**	**31,278**
Surplus (or Deficient) Source Capacity		
Surplus (or Deficient) Source Capacity	**(145)**	**(2,245)**

Adapted from RH2 (in preparation)

1.3.2 Irrigation System

The City owns and operates an irrigation water system separate from the potable system. The irrigation system is supplied by groundwater from 11 wells and surface water pumped from the Columbia River Intake, located near the I-182 bridge (**Figure 1-2**). The City's irrigation wells range between 135 and 245 feet deep and are completed in an unconfined alluvial aquifer consisting mainly of sand and gravel (i.e., suprabasalt aquifer). The reported production capacities of the wells range between 450 and 2,500 gpm. Surface water from the Columbia River is pumped directly to the irrigation distribution system via a river intake and booster station. The City uses the irrigation system annually from April through October to avoid using treated drinking water as a source for irrigation. Source water for the irrigation system is not treated or disinfected.

The irrigation system has an approximate total supply capacity of 17,750 gpm (25.5 mgd) and current demands are approximately equal to the system capacity. The existing firm capacity of the system is 14,750 gpm (21.2 mgd) if the Columbia River Intake source is out of service. The City has identified source improvements and related water right adjustments that potentially could increase the system's total and firm capacity by 6,000 gpm (8.6 mgd) in the future.

Growth within the irrigation system is anticipated to take place as infill within the existing irrigation system footprint, with an estimated 907 gpm (1.3 mgd) of infill demand growth anticipated prior to year 2036. Additional demand growth is anticipated within the City's UGA expansion area in the northwestern portion of the City. A portion of the UGA expansion area is located at higher elevations and will likely require additional booster station facilities and/or storage facilities. Because no additional storage facilities are currently planned in the UGA expansion area, future irrigation system supply facilities must be capable of meeting the peak-hour demand needs in the UGA expansion area. Based on a capacity evaluation conducted by RH2 Engineering, Inc. (in preparation), the irrigation system is estimated to have a 2036 supply deficiency of approximately 5,548 gpm (7.9 mgd) based on the system's existing total capacity, and approximately 8,548 gpm (12.3 mgd) based on the system's existing firm capacity (**Table 1-2**). The firm capacity estimate assumes that the 3,000 gpm Columbia River Intake source is out of service.

Table 1-2. 2036 Peak Season Irrigation System Supply Capacity Summary

Description	Total Capacity (gpm)	Firm Capacity (gpm)
Source Capacity		
Existing Source Capacity	17,750	14,750
Additional Intake Pumping Capacity	5,400	5,400
Additional Groundwater Pumping Capacity	600	600
Total Source Capacity	**23,750**	**20,750**
Demands		
MDD	15,090	15,090
Infill Demand Projection (MDD)(1)	907	907
Expansion Area (PHD)(1)	13,301	13,301
Total Demands	**29,298**	**29,298**
Surplus (or Deficient) Source Capacity		
Surplus (or Deficient) Source Capacity	**(5,548)**	**(8,548)**

Adapted from RH2 (in preparation). (1) Existing system storage is slightly deficient for existing demands. If no additional storage is constructed, peak hour demand (PHD) is recommended to be considered future demand projections, or a reduction in service pressures will occur in system during PHD events.

The Franklin County Irrigation District also serves non-potable water to a large portion of the area south of I-182 and west of SR 395. Irrigation demands outside of these irrigation system service areas are met by the potable water system.

1.4 Recharge Objective

The primary recharge objective for a City of Pasco ASR program is to realign supply availability with peak-season (May through September) potable and irrigation demand needs by seasonal storage and recovery of water. The ASR concept would withdraw water from the Columbia River (and/or possibly wells in hydraulic connection with the river) using the City's existing infrastructure and treatment facilities during the off-season winter months, store it in an aquifer system beneath the City, and recover the stored water to augment peak-season demands. This would allow the City to supplement peak-season demand needs and help meet projected demand shortfalls without increasing permitted withdrawals from the Columbia River during the low-flow summer months, allowing more efficient use of existing water rights. Environmental and economic benefits from such a program would:

- Reduce environmental effects of surface water diversions during periods of high demand by shifting water withdrawals from the Columbia River from the summer months when flows in the river are at their lowest to the winter months when flows are highest
- Optimize the City's potable and irrigation supply system infrastructure without having to make costly improvements to existing supply sources and treatment plants to meet all of the projected peak-season demand shortfalls
- Reduce or eliminate costs associated with mitigating impacts to the Columbia River from usage of the Quad City Water Right during periods of low instream flows

SECTION 2: **Hydrogeologic Framework**

This section summarizes key features of the hydrogeologic framework of the Study Area that are relevant to assessing the feasibility of ASR for the City. The content of this section is excerpted and condensed from a more detailed summary prepared for the project by INTERA (Tolan, 2020). The reader is encouraged to review the INTERA technical memorandum, provided in **Attachment A**, for details and citations that form the basis for the following hydrogeologic framework summary.

2.1 Hydrogeologic Setting

The Study Area is located within the Pasco Basin, a topographic and structural low located near the eastern edge of the Yakima Fold Belt structural sub-province within the Columbia River Flood Basalt Province. The Pasco Basin is geologically defined by the following features (**Figure 2-1A**):

- On the west by the northwest-trending anticlinal folds and faults that define the Rattlesnake-Wallula alignment (RAW) (**Figures 2-1A** and **2-1B**).
- On the north by the east-west-trending portion of the Saddle Mountains, which is a Yakima Fold Belt anticlinal ridge.
- On the east by the combination of the westward-dipping Palouse Slope-Jackass anticline/monocline and the north-northwest-trending Columbia River Basalt Group (CRBG) dike swarm (**Figure 2-1B**).

The bedrock geology of the Pasco Basin (**Figure 2-2**) is dominated by the flood-basalt flows of the middle-to-late Miocene CRBG and the interbedded sediments of the Ellensburg Formation. The CRBG flows are overlain by suprabasalt sediments, including the late Miocene-Pliocene sediments of the Ringold Formation, the Quaternary-age Hanford formation, and Holocene-age sediments (**Figure 2-2**). The CRBG (and interbedded Ellensburg Formation sediments), Ringold Formation and Hanford Formation are major hydrostratigraphic units (**Figure 2-2**) that host significant aquifers and serve as important sources of groundwater throughout much of this region. The nature and distribution of each of these stratigraphic units are summarized in more detail in the following section.

2.2 Pasco Basin Hydrostratigraphy

The geologic characteristics of the stratigraphic units (**Figure 2-2**) beneath the greater Pasco area are summarized in the following subsections. Collectively, these units form a general three-dimensional framework of the aquifers that they may host beneath the greater Pasco area. The primary stratigraphic units for the purposes of this ASR feasibility study can be divided into two main types: “suprabasalt sediments” and the underlying basalt sheet flows of the CRBG. Two geologic cross sections were developed through the north Pasco area of interest to illustrate the general relationships and thicknesses of each of these units within the Study Area. The cross sections were developed from isopach maps of the stratigraphic units within the Pasco Basin, developed by studies completed for the Columbia Basin Groundwater Management Area (Tolan et al., 2007). The locations and orientations of the cross sections are shown on **Figure 2-3**, and cross sections A – A’ and B – B’ are shown on **Figures 2-4** and **2-5**. **Figure 2-3** shows also preferred ASR recharge and recovery areas (A-D) based on anticipated growth demands for the City’s potable and irrigation systems (see Section 3.0 and **Figure 3-1**).

2.2.1 Suprabasalt Sediments

The term “suprabasalt sediments” is used to collectively identify all of the sediment deposits that overlie the CRBG to the ground surface. In the greater Pasco Basin area these sediments can be subdivided, from youngest to oldest, into Holocene (or “recent”) deposits, Hanford formation, and Ringold Formation (**Figure 2-2**).

2.2.1.1 Holocene Deposits

In the greater Pasco area, Holocene sediments dominantly consist of relatively unconsolidated, wind-deposited silt (i.e., loess) and sand (active and stabilized sand dunes) that unconformably overlie the Hanford formation. In the greater Pasco area these Holocene deposits can range from less than 2 feet to greater than 15 feet thick and typically do not host any groundwater. Consequently, the Holocene sediments are not considered a potential ASR storage zone and will not be discussed in any further detail for the purposes of this report.

2.2.1.2 Hanford Formation

The informally named Hanford formation (**Figures 2-4** and **2-5**) consists of unconsolidated deposits of silt, sand, and gravel that were deposited in the Pasco Basin by a series of cataclysmic flood events (i.e., Missoula Floods or Bretz Floods) due to failures of large, glacial ice-dammed lakes from around 1.6 million years until about 13,000 years ago.

The Study Area lies within several of the main channel floodwater pathways. As a result of this, the Hanford formation sediments that were deposited throughout this area are predominately unconsolidated, massive to bedded, open framework, coarse gravel and sand, with only very minor amounts of silt present. Subsurface mapping of the thickness of the Hanford formation in the greater Pasco area indicate that these deposits can collectively range in thickness from approximately 40 to 300 feet or more (**Figures 2-4** and **2-5**).

The Hanford formation deposits within the Pasco Basin often comprise a large portion of the vadose zone (unsaturated interval between the ground surface and water table), but proximal to the Columbia and Snake Rivers and within cataclysmic flood channels, can host a significant portion of the unconfined (“water table”) aquifer. High-capacity water wells completed in the unconfined aquifer hosted by the coarse gravel and sand deposits of the Hanford formation are reported to have yields between approximately 1,000 and 3,000 gpm. The City’s irrigation supply wells are completed in the Hanford formation.

2.2.1.3 Ringold Formation

In the greater Pasco Basin region, the Ringold Formation (**Figure 2-2**) consists of interbedded, unconsolidated to cemented, clay, silt, sand, and gravel deposited by rivers, and within lakes, associated with the ancestral Columbia River system from about 10.5 to 2.6 million years ago (m.y.). As a result of the cataclysmic flood erosion, the preserved thickness of the Ringold Formation is highly variable within the Pasco Basin. Two of three informally-designated members of the Ringold Formation have been removed from the Study Area by cataclysmic flood erosion, leaving only poorly-consolidated to well-cemented river (fluvial) gravel deposits with minor interbedded sand and overbank (silt and clay) deposits inferred to belong to the Wooded Island member. The thickness of the Ringold Formation beneath the Study Area is highly variable, ranging from absent to greater than 200 feet (**Figures 2-4** and **2-5**).

Along with the Hanford formation, the Wooded Island member of the Ringold Formation in much of the Study Area also hosts the suprabasalt unconfined aquifer. It commonly has however, a significantly lower permeability than the overlying Hanford formation flood sediments, with well yields of normally a few hundreds of gallons per minute (Brown, 1979).

2.2.2 CRBG and Ellensburg Formation Interbeds

As noted above, the CRBG and associated sediment interbeds of the Ellensburg Formation, host confined aquifers that may be suitable ASR storage zones. The vast majority of the operational ASR systems in the Pacific Northwest are hosted by CRBG aquifers, including the cities of Kennewick, Walla Walla and Pendleton. The City of Yakima has developed an ASR system in sediments of the upper Ellensburg Formation, which is essentially equivalent to, but far thicker than, the Ringold Formation in the Pasco Basin.

2.2.2.1 CRBG Hydrogeology

The CRBG consists of more than 350 continental flood basalt sheet flows that cover a 77,220 square miles portion of Washington, Oregon, and western Idaho (**Figure 2-1A**). The maximum thickness of the CRBG is inferred to occur beneath Pasco Basin area where it is estimated to be greater than 10,000 feet-thick. The following sections provide a brief, general overview of the nature and physical characteristics CRBG and its importance in understanding CRBG hydrogeology and aquifer systems.

2.2.2.2 Physical Features of CRBG Flows

The CRBG consists of a regionally extensive series of thick sheet flows (**Figure 2-6**) that display a distinct three-part internal structure consisting of a flow top, a dense interior, and a flow bottom (**Figure 2-7**). All three of these types of intraflow structures play important roles in defining CRBG aquifers and aquitards (confining layers) within the CRBG aquifer system. The physical and hydraulic properties of the flow top, in combination with the overlying flow bottom (and any Ellensburg Formation sediment that might be present) is termed the “interflow zone” (**Figure 2-7**) and are typically hosts for water-bearing (aquifer) zones, while the dense flow interiors act as aquitards that limit vertical flow between interflow zones within the CRBG aquifer system. The characteristics of the flow top and flow bottom that form an interflow zone determine the hydraulic characteristics of these potential ASR storage zones, including hydraulic conductivity and transmissivity (hydraulic conductivity multiplied by the thickness).

Flow Tops

Flow tops range between two basic end-members: a simple *vesicular flow top* and a *flow top breccia* (**Figure 2-7**). A vesicular flow top (e.g., tops of flows 1 and 2 in **Figure 2-7**) commonly consists of glassy to fine-grained basalt that displays a rapid increase in the density of vesicles (i.e., solidified gas bubbles) towards the top of the flow. Simple vesicular flow tops may have low-to-moderate permeability and may only be a few feet thick, resulting in limited transmissivity. In contrast, a flow top breccia consists of angular fragments of basaltic rubble that lies above a zone of non-fragmented, vesicular basalt (top of flow 3 in **Figure 2-7**). Flow top breccias can be very thick (over half the flow thickness to more than 100 feet-thick) and laterally extensive (Tolan et al, 2009). Flow top breccias host some of the most highly-productive aquifers in the CRBG.

Flow Bottoms

The physical characteristics of CRBG flow bottoms (**Figure 2-7**) are largely dependent on the environmental conditions the molten basalt lava encountered as it was emplaced (Tolan et al., 2009). If the advancing CRBG lava encountered relatively dry ground, a simple <u>*flow bottom*</u> (flows 2 and 3 in **Figure 2-7**) results that commonly consists of a narrow, <2-foot-thick zone of sparsely vesicular, glassy to very fine-grained basalt (base of flows 2 and 3 in **Figure 2-7**). Simple flow bottoms are very common within the CRBG, and provide only limited contribution to the transmissivity of an interflow zone.

If advancing CRBG lava encountered water (e.g., lakes, rivers, and/or areas of water-saturated, unconsolidated sediments), a *pillow lava complex* (base of flow 1 in **Figure 2-7**) would be created as the molten lava flowed into the water. A pillow complex consists of elongate to spherical lobes of basalt (pillows) set in a matrix of glassy basalt fragments. Pillow complexes may be thick and host highly transmissive and productive aquifers.

Dense Flow Interior

CRBG dense flow interiors typically consist of massive basalt that is characterized by typically non-vesicular, glassy to crystalline basalt that contains numerous contraction joints (termed “cooling joints”). While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be typically 77 to >99 percent filled with secondary minerals (clay, silica, zeolite) and void spaces that do occur are typically not interconnected. The presence of pervasive secondary minerals filling the cooling joints accounts for the very low hydraulic conductivity values (“K” on **Figure 2-7**) measured within CRBG flow dense interiors and explains why the interiors of CRBG flows act as aquitards within CRBG aquifer systems.

Lateral Variations of Intraflow Structures

The nature and thickness of intraflow structures within a flow often vary laterally throughout the flow’s extent. These lateral variations often occur gradually, but in some cases can occur very abruptly. Lateral changes to the nature of flow tops and flow bottoms affect the hydraulic characteristics of CRBG-hosted aquifers by (e.g., increased/decreased transmissivity). The presence of interbedded sediments can either enhance (e.g., sandstone and conglomerate) or inhibit (e.g., mudstone and paleosols) groundwater storage and movement within this zone. As previously discussed, thick flow top breccias are known to abruptly end with a much thinner normal flow top taking its place (Tolan, 2020). The same is true for flow bottom features (e.g., pillow complexes) that can abruptly end or transition to a simpler flow bottom. These intraflow structure facies changes can result in radical changes of the hydraulic properties and behavior of individual CRBG aquifers being pumped by wells.

2.2.2.3 CRBG and Ellensburg Formation Members

The primary focus of this ASR feasibility assessment is on the uppermost portion of the CRBG confined aquifer system beneath the Study Area, consisting of the Saddle Mountains and Wanapum Basalts (**Figure 2-2**). Suitable storage aquifers also may be present within the deeper basalt flows of the Grande Ronde Basalt. The Grande Ronde Basalt however, is considered a lower priority target option for this study because of poor water quality conditions and deep well completions compared to shallower comparable CRBG aquifers. Developing an ASR storage zone in the Grande Ronde would be substantially more expensive because of the greater well drilling and seal depths required (>2,000 feet) and potential need to condition the aquifer to mitigate the presence of warm and mineralized water commonly found in the Grande Ronde aquifers in the Columbia Basin.

Figures 2-4 and **2-5** present two geologic cross-sections through the Study Area that depict our interpretation of the subsurface CRBG geology based on the best available geologic and hydrogeologic information summarized in **Attachment A**. The following sections provide a brief description of the CRBG and Ellensburg Formation units, from youngest to oldest, depicted in the geologic cross-sections.

Ice Harbor Member, Saddle Mountains Basalt

The 8.5 million years ago (Ma) Ice Harbor Member (**Figure 2-2**) represents the youngest CRBG unit in the area and may consist of a total of two to four sheet flows. The thickness in the Study Area is estimated to range from 100 to >150 feet (**Figures 2-4** and **2-5**). Where more than one Ice Harbor Member flow is present, water supply wells that penetrate these interflow zones indicate that they do produce groundwater.

Groundwater yields however, are commonly low, ranging from 20 to 50 gpm. The Ice Harbor Member is unlikely to have suitable hydraulic characteristics to target as an ASR storage aquifer.

Levey Member, Ellensburg Formation

The Levey Member of the Ellensburg Formation (or "Levey interbed") is defined as sediments found between the 8.5 Ma Ice Harbor Member and 10.5 Ma Elephant Mountain Member of the CRBG (**Figure 2-2**). In the Pasco area the Levey sediments consist of 10 to 20 feet of semi-indurated silt, clay, and fine sand. Due to the relatively thin thickness of this unit in the Study Area, it is not depicted between the Ice Harbor and Elephant Mountain Members on **Figures 2-4** and **2-5**. The Levey Member beneath the Pasco area does not have suitable thickness and hydraulic characteristics to target as an ASR storage aquifer.

Elephant Mountain Member, Saddle Mountains Basalt

The 10.5 Ma Elephant Mountain Member typically consists of two units, each represented by a single flow in the Pasco area (**Figure 2-2**). The total thickness in the Study Area is variable, ranging in thickness from 90 to 140 feet (**Figures 2-4** and **2-5**). Groundwater yields from Elephant Mountain Member interflow zones are highly dependent on the type of flow top/flow bottom intraflow structures that are present at the particular well location. Where the interflow zones consist of simple vesicular flow tops/flow bottoms, the groundwater yield is often lower than 50 gpm. Where either a flow top breccia and/or basal pillow complex is present however, groundwater yields can range from 100 to greater than 300 gpm. While the Elephant Mountain Member is potentially more productive than the overlying Ice Harbor Member, the potential for encountering suitable hydraulic characteristics to target it as an ASR storage aquifer is low.

Rattlesnake Ridge Member, Ellensburg Formation

The Rattlesnake Ridge Member of the Ellensburg Formation (or "Rattlesnake Ridge interbed") is defined as sediments found between the Elephant Mountain Member and 11.8 Ma Pomona Member of the CRBG (**Figure 2-2**). In the Study Area, the Rattlesnake Ridge interbed is inferred to consist of a very thin deposit (1 to 5 feet thick) of semi-indurated silt, clay, and possibly fine-sand. (**Figures 2-4** and **2-5**). Due to the relatively thin thickness of this unit in the Study Area, it is not depicted between the Elephant Mountain and Pomona Members on **Figures 2-4** and **2-5**. The Rattlesnake Ridge Member does not have suitable hydraulic characteristics to target as an ASR storage aquifer.

Pomona Member, Saddle Mountains Basalt

The 11.8 Ma Pomona Member (**Figure 2-2**) typically consists of a single flow within the Pasco Basin, but can locally consist of two flow-lobes that together collectively define a single sheet flow. The thickness of the Pomona Member in the Pasco Basin is variable ranging from 120 to 150 feet (**Figures 2-34**and **2-5**).

Like the Elephant Mountain Member, groundwater yields from Pomona Member interflow zones are highly dependent on the type of flow top/flow bottom intraflow structures that are present at the well location. In the Pasco Basin area, where Pomona Member interflow zones consist of simple vesicular flow tops/flow bottoms, groundwater yields are often less than 30 gpm. Where a flow top breccia and/or basal pillow complex is present however, groundwater yields can be greater than 100 gpm. Similar to the Elephant Mountain Member, the potential for encountering suitable hydraulic characteristics in the Pomona Member to target it as an ASR storage aquifer is relatively low.

Selah Member, Ellensburg Formation

The Selah Member of the Ellensburg Formation (or "Selah interbed") is defined in the Study Area as sediments found between the Pomona Member and older Esquatzel Member of the CRBG, or between the

Pomona and Umatilla members where the Esquatzel Member is missing (**Figure 2-2**). In the Study Area, the Selah interbed likely consists of semi-indurated silt/clay and sand and may be capped by consolidated volcanic ash (tuff). The thickness of the Selah interbed in the Study Area likely ranges from 30 to 60 feet (**Figures 2-4** and **2-5**). The Selah Member is unlikely to have suitable hydraulic characteristics to target as an ASR storage aquifer, and may have the characteristics of a confining unit.

Esquatzel Member, Saddle Mountains Basalt

The Esquatzel Member (**Figure 2-2**) typically consists of a single sheet flow in the Pasco Basin area. The Esquatzel Member is mainly confined to the northern and western portions of the Pasco Basin. Where present, the thickness of the Esquatzel Member within Pasco Basin is variable, ranging from less than 50 feet to over 100 feet. Based on the geologic log for the Welch's well (Tolan, 2020; **Appendix A** of **Attachment A**), the Esquatzel Member may not be present within the southern portion of the Study Area, but the southern margin of the flow potentially could be present in the northern-most part of the Study Area. Therefore, the Esquatzel Member has not been depicted on **Figures 2-4** and **2-5**. There is no specific information available on potential groundwater yields from the Esquatzel Member in the Pasco Basin area. The limited distribution of the Esquatzel flow however, suggests that its potential for ASR storage within the Study Area is low.

Cold Creek Member, Ellensburg Formation

The Cold Creek Member of the Ellensburg Formation (or "Cold Creek interbed") is defined in the Pasco Basin area as sediments found between the Esquatzel Member and the 13.0 Ma Umatilla Member of the CRBG (**Figures 2-2**). Where the Esquatzel Member (or Asotin Member) is absent, the sediments between the Pomona and Umatilla Members are defined as the Selah Member of the Ellensburg Formation. In the Pasco Basin area the Cold Creek interbed typically consists of semi-indurated silt/clay and ranges from absent to >70 feet thick. The Cold Creek Member does not have suitable hydraulic characteristics to target as an ASR storage aquifer.

Umatilla Member, Saddle Mountains Basalt

The 13.0 Ma Umatilla Member in the Pasco Basin area typically consists of two units (**Figure 2-2**) that are each represented by a single sheet flow. Based on the geologic log for the Welch's well (Tolan, 2020; **Appendix A** of **Attachment A**), both Umatilla units are likely present beneath the Study Area. Total thickness of the Umatilla Member is variable, ranging from 40 to more than 270 feet thick within the Pasco Basin area. The thickness of the Umatilla Member beneath the Study Area is inferred to range from as low as approximately 40 in the eastern portion of the Study Area to as high as 280 feet in the western portion (**Figures 2-4** and **2-5**).

In the portions of the Pasco Basin area where Umatilla Member interflow zones consist of simple vesicular flow tops/flow bottoms, the groundwater yield from these zones are often less than 50 gpm. Where a flow top, or flow bottom, breccia zones are present however, groundwater yields can be many times greater. The ability of flow breccia zones to produce high groundwater yields is clearly documented in the Welch's well, which was drilled in 1981 (Tolan, 2020; **Appendix A** of **Attachment A**). Based on the geologist and driller's logs, the Welch's well penetrated an interflow zone within the Umatilla Member that consisted of a flow bottom breccia/flow top breccia that was approximately 50 feet thick and capable of very high groundwater yields (tested at 1,390 gpm with 100 feet of drawdown), indicating that the Umatilla Member is a good candidate to evaluate as a target aquifer for ASR.

Mabton Member, Ellensburg Formation

The Mabton Member of the Ellensburg Formation (or “Mabton interbed”) is defined as sediments found between the Umatilla Member and the top of the Wanapum Basalt (**Figure 2-2**). Few wells in the Pasco Basin area have been drilled deep enough to penetrate the Mabton interbed. Based on the limited data from this area, the Mabton interbed appears to consist of semi-indurated silt, sand, and tuffs with inferred thicknesses in the Study Area ranging from 30 feet to 50 feet (**Figures 2-4** and **2-5**). The Mabton Member is unlikely to have suitable hydraulic characteristics to target as an ASR storage aquifer. Groundwater in the underlying Wanapum Basalt is considered confined and isolated from the overlying Saddle Mountains Basalt by the Mabton interbed. The Mabton interbed is understood to be present throughout much of the region.

Priest Rapids Member, Wanapum Basalt

The 14.5 Ma Priest Rapids Member (**Figure 2-2**) consists of two units in the Pasco Basin, the Lolo (younger) and the Rosalia (older), each represented by a single sheet flow. There is however, no direct subsurface information on the Priest Rapids Member beneath the Study Area, and the only information regarding its potential characteristics comes from geologically logged deep wells to the west (City of Kennewick ASR wells; Tolan, 2020; **Appendix A** of **Attachment A**) and northwest (Hanford Site well DDH-3, DC-15, DB-1, and DB-2; Tolan, 2020; **Appendix A** of **Attachment A**). The geologic logs from these deep wells suggest that only the younger Lolo flow is likely present beneath the Study Area. The thickness of the Lolo flow beneath the Study Area is estimated to range from as low as 40 in the eastern portion of the Study Area to as high as 175 feet in the western portion (**Figures 2-4** and **2-5**). The Lolo flow may have either a thin (less than 10 feet thick) flow top breccia or thin simple vesicular flow top, and a thin vesicular flow bottom.

There is no specific information available on potential groundwater yields from the Priest Rapids Member in the Pasco Basin area. Based on the inferred characteristics of the Lolo flow’s intraflow structures and interflow zones likely present, it is likely that this member have low to intermediate range (20 to 200 gpm) groundwater yields, and the potential for developing an ASR system within the Study Area using it is low.

Quincy Member, Ellensburg Formation

The Quincy Member of the Ellensburg Formation (or “Quincy interbed”) is defined as sediments found between the bottom of the Priest Rapids Member and the top of the Roza Member (**Figure 2-4** and **2-5**). Few wells in and adjacent to Pasco have been drilled deep enough to penetrate the Quincy interbed (see Tolan, 2020; **Attachment A**). Based on the limited data from this area, the Quincy interbed appears to consist of semi-indurated silt, clay, and diatomite, with minor beds of fine sand. Thickness of the Quincy interbed the Study Area could be highly variable, potentially ranging from less than 5 feet to more than 20 feet thick (**Figures 2-4** and **2-5**). The Quincy Member does not have suitable hydraulic characteristics to target as an ASR storage aquifer.

Roza Member, Wanapum Basalt

In the greater Pasco Basin area, the 14.9 Ma Roza Member (**Figure 2-2**) can consist of up to three sheet flows. The southern margin of the Roza Member is inferred to lie south of the Study Area and follows roughly along the track of the modern-day Snake River. As noted above for Priest Rapids Member however, there is no direct subsurface information on the Roza Member beneath the Study Area. The only information on the Roza Member comes from geologically logged deep wells to the northwest (Tolan, 2020; **Attachment A**). The geologic logs from these deep wells suggest that at least one Roza flow is likely present beneath the Study Area. This Roza flow may have either a thin (less than 10 feet thick) simple vesicular flow top or possibly a 30- to 50-foot thick flow top breccia, a well-developed columnar-blocky jointed dense interior, and a thin vesicular flow bottom. The thickness of the Roza flow varies within Pasco Basin due to pre-existing topography. Beneath the Study Area, the thickness of the Roza flow is estimated to potentially range between 100 and 175 feet (**Figures 2-4** and **2-5**).

There is no specific information available on potential groundwater yields from the Roza Member in the Pasco Basin area. If the Roza flow beneath the Study Area however, does possess a 30- to 50-foot thick flow top breccia, this interflow zone might be capable of very high groundwater yields (greater than 1,000 gpm), rendering the Roza flow as a potentially good candidate to evaluate for ASR.

Squaw Creek Member, Ellensburg Formation

The Squaw Creek Member of the Ellensburg Formation (or “Squaw Creek interbed”) is defined as sediments found between the bottom of the Roza Member and the top of the Frenchman Springs Member (**Figure 2-2**). Few wells in and adjacent to the Pasco area have been drilled deep enough to penetrate the Squaw Creek interbed (see Tolan, 2020; **Attachment A**). Based on the limited data from this area, the Squaw Creek interbed appears to consist of semi-indurated silt, clay, and diatomite and is likely very thin, potentially ranging in between an estimated 0 to less than 2 feet thick in the Study Area, and is not depicted on **Figures 2-4** or **2-5**. The Squaw Creek interbed is considered unsuitable for further consideration as an ASR storage aquifer.

Frenchman Springs Member, Wanapum Basalt

In the greater Pasco Basin area, the 15.0 to 15.4 Ma Frenchman Springs Member (**Figure 2-2**) consists of between 9 to 14 sheet flows that has been subdivided into five separate units. All five of the Frenchman Springs Member subunits (**Figure 2-2**) are inferred to be present beneath the Study Area. As noted for all of the other Wanapum Basalt members however, there is no direct subsurface information on the Frenchman Springs Member beneath the Study Area. The only information on the complete Frenchman Springs Member section comes from geologically logged deep wells to the northwest (Tolan, 2020; **Appendix A** of **Attachment A**). The geologic logs from these two deep Hanford Site wells suggest that more than half of the Frenchman Springs Member flows present in each well have flow top breccias that comprise from 10 to more than 40 percent of the individual flow thickness, and typically have a thin vesicular flow bottom. Beneath the Study Area, the total thickness of the Frenchman Springs Member is estimated to range between 700 and 800 feet (**Figures 2-4** and **2-5**).

There is limited specific information available on potential groundwater yields from the Frenchman Springs Member in the Pasco Basin area. The potential for the presence of multiple flow top breccias within the Frenchman Springs Member section beneath Study Area however, does suggest that one or more of these interflow zones might be capable of very high groundwater yields (1,000 – 3,000 gpm). The ASR storage zone in the City of Kennewick’s ASR well consists primarily of flowtop breccia in the shallower flows of the Frenchman Springs Member and is capable of recharging at rates greater than 1,600 gpm and pumping at greater than 2,000 gpm, indicating that the interflow zones within the Frenchman Springs Member are high priority candidates to evaluate for ASR in the Study Area.

Vantage Member, Ellensburg Formation

The Vantage Member of the Ellensburg Formation (or “Vantage interbed”) is defined as sediments found between the bottom of the Wanapum Basalt (Frenchman Springs Member) and the top of the Grande Ronde Basalt (**Figure 2-2**). Based on the limited data from this area, the Vantage interbed appears to consist of semi-indurated clay and paleosol (i.e., deeply weathered basaltic soil) developed on top of the uppermost Grande Ronde Basalt flow. The Vantage interbed is likely very thin in the Study Area, potentially ranging in thickness from 0 to less than 2 feet, and is not depicted on **Figures 2-4** or **2-5**). The unit is considered unsuitable for additional consideration as an ASR storage aquifer.

Grande Ronde Basalt

The 16 – 15.6 Ma Grande Ronde Basalt is the thickest and most voluminous of the major CRBG formations, consisting of at least 125 flows in 25 formal and informal members, with a total thickness exceeding 10,000 feet in the greater Pasco Basin area (Reidel and Tolan, 2013). The top of the uppermost member (Sentinel Bluffs Member) of the Grande Ronde Basalt is inferred to be approximately 1,500 – 2,200 feet below ground surface in the Study Area (**Figure 2-2**) (**Figures 2-4** and **2-5**).

The upper members of the Grande Ronde Basalt host productive aquifers that are important water supply sources for irrigation and municipal purposes north of the Pasco Basin, and south in the Umatilla Basin, Oregon. As noted for the Wanapum Basalt however, there is no direct subsurface information for the Grande Ronde Basalt beneath the Study Area. The only information on the upper Grande Ronde comes from geologically logged deep wells at the Hanford Site to the northwest (Tolan, 2020; **Attachment A**). In general, interflow zones within the Grande Ronde Basalt tested at the Hanford Site have exhibited a wide range of hydraulic conductivities, similar to those in the overlying Wanapum and Saddle Mountains interflow zones. Groundwater quality in the Grande Ronde also tends to be warmer and more geochemically evolved than the shallower units, with higher mineral content. In the Cold Creek syncline northwest of Pasco, the Umtanum Member of the Grande Ronde Basalt exhibits a >100-foot thick flow top breccia that was highly productive (>2,000 gpm), but when pump-tested produced toxic, non-potable groundwater (Terry Tolan, INTERA, Inc., personal communication, December 2020). Poor water quality concerns and greater well completion depths render development of an ASR system using Grande Ronde Basalt-hosted aquifers more costly than development of comparably-productive and better water quality aquifers in the shallower basalt units. Therefore, the Grande Ronde Basalt is a lower priority target for ASR, and the remainder of this document will focus on the Wanapum and lower Saddle Mountains Basalt Formations.

2.3 Groundwater Flow System

The geologic units described in Section 2.2 comprise three main aquifer units of interest for this feasibility study, corresponding to the two upper multi-aquifer basalt formations (Saddle Mountains and Wanapum Basalts) and the overlying suprabasalt sediments. The basalt flows (and interbeds) that make up the regional aquifer system of the Columbia Basin, are present under mostly confined conditions within the Study Area. The suprabasalt sediment aquifer consists of the catastrophic flood sediments of the Hanford formation and older Ringold conglomerate facies (Wooded Island member, where present), which host a shallow, unconfined sedimentary aquifer present throughout the Pasco Basin and within the Study Area. The remainder of Section 2.3 summarizes the distribution, general hydrogeological characteristics and properties relevant to ASR feasibility.

2.3.1 Hydrogeologic and Physical Boundaries

This section describes the hydrogeologic and physical boundaries of the suprabasalt sediments and CRBG aquifer system based on published reports and geologic mapping of the Pasco Basin and surrounding area.

2.3.1.1 Suprabasalt Sediments

The suprabasalt sediment aquifer is widespread throughout the Pasco Basin, though its regional interconnection is limited by lateral barriers formed by basalt uplands. Within the Study Area, the flood sediments of the Hanford formation are present across its entirety at thicknesses of between 40 and 300 feet, whereas the presence and thickness of Ringold Formation sediments are variable. The collective thickness of the suprabasalt sediments in the Study Area ranges from less than 50 to greater than 300 feet **Figures 2-4** and **2-5**). The thickness of the suprabasalt sediments in the Study Area is a relatively uniform in an east-west direction across the northern part of the Study Area (**Figure 2-4**), although the thickness of the higher permeability Hanford formation flood sediments varies because of the presence of erosional channels in the Ringold (Figure 2-4). The suprabasalt sediments thin somewhat in a southern direction from the plateau north of I-182 towards the Columbia River primarily because of thinning of the Hanford formation flood sediments (**Figure 2-5**). The suprabasalt sediment aquifer in the Study Area is in direct hydraulic connection with Columbia River.

2.3.1.2 CRBG Aquifers

The Saddle Mountains and Wanapum Basalt aquifer systems are present beneath the entire Pasco Basin and Study Area. There are several processes that can modify the specific and overall hydraulic characteristics and behavior of CRBG aquifers and aquitards. These include tectonic fracturing forming faults/tectonic joints, folding, and the presence of CRBG feeder dikes. Understanding their impact is critically important to accurately interpreting boundary conditions of CRBG aquifer systems in any specific locality. The presence and potential significance of these features to the boundaries of the CRBG aquifers in the vicinity of Pasco and the Study Area are summarized below.

Faults and Tectonic Joints

The presence of faults that transect the CRBG can impact both lateral and vertical groundwater movement within the CRBG aquifers. Faults have been found to impact the CRBG groundwater system in several ways. They can (1) form barriers to the lateral movement of groundwater and a series of faults can create hydrologically isolated areas (i.e., compartments), (2) faults and tectonic joints can provide a potential vertical pathway (of varying lengths) for vertical groundwater movement allowing otherwise confined CRBG aquifers to be in direct hydraulic communication, and (3) they can expose interflow zones creating local opportunities for CRBG aquifer recharge and/or discharge. The most relevant and important of these fault-induced impacts with regards to the Study Area is the presence of major faults associated with the RAW. The Umtanum Ridge extension and Saddle Mountains form the respective western and northern hydrogeologic boundaries of the Pasco Basin (**Figure 2-1**). The southeastern extension of the Yakima Ridge anticline and inferred fault(s) (part of the RAW; **Figure 2-1**) lies within western boundary of the Study Area (**Figure 2-1**). The Yakima Ridge fault, along with other parallel faults associated with the RAW, likely form a hydrogeologic barrier that inhibits CRBG aquifer groundwater from moving from the Study Area to the west and southwest. Major faults associated with the Saddle Mountains, and possibly associated with the eastward extension of Umtanum Ridge (**Figure 2-1**), serve a similar function.

Folding

Several groundwater investigations in the Columbia Plateau area have noted that folds (primarily anticlinal and monoclinal folds) affect the occurrence and movement of groundwater through CRBG aquifers. In many cases, folds have been identified as groundwater barriers or impediments that either block or restrict lateral groundwater movement through the CRBG aquifer system. The process of folding the CRBG can affect the hydraulic characteristics of interflow zones by shearing and destroying the mechanically weaker interflow zones, which impacts the original hydraulic characteristics of interflow zones, reducing or even destroying the permeability of these features.

With regards to the Study Area, this process may play a minor role along the eastern boundary of the Pasco Basin/Palouse Slope (**Figure 2-1**), which was originally defined by the southwest-dipping, north-northwest-trending monoclinal fold. The presence of Ice Harbor Member (Saddle Mountains Basalt) and Frenchman Springs Member (Wanapum Basalt) feeder dikes however, probably have a far greater hydrogeologic impact on the CRBG aquifer system and are discussed in the next section.

CRBG Feeder Dikes

As indicated on **Figure 2-1**, the eastern boundary of the Pasco Basin is in part defined by the presence of multiple CRBG dikes. These dikes once served as long, linear, vertical conduits that supplied the magma to the ground surface that produced individual basalt flows belonging to both the older Frenchman Springs Member of the Wanapum Basalt and the younger Ice Harbor Member of the Saddle Mountains Basalt (**Figure 2-2**). Surface geologic mapping of the eastern boundary area (and aeromagnetic survey mapping of the area clearly shows the extent of these north-northwest-trending CRBG feeder dikes along the eastern side of the Study Area.

In the case of the Ice Harbor Member dikes, these dikes essential form vertical sheet walls composed of dense basalt through all CRBG flows present beneath the Ice Harbor Member, playing a primary role in forming the eastern hydrogeologic boundary to the Pasco Basin and Study Area.

2.3.2 Hydraulic Properties

This section summarizes the hydraulic characteristics of the suprabasalt sediments and CRBG aquifers. The information presented in this section is based on published reports and available hydrogeologic data.

2.3.2.1 Suprabasalt Sediments

The Wooded Island member of the Ringold Formation sediments is highly cemented and its permeability is relatively low (Tolan, 2020, **Attachment A**). Because the Hanford formation flood sediments are considerably more permeable and thicker than the Ringold sediments, the flood sediments account for the bulk of groundwater flow within the suprabasalt sediment aquifer. Ranges of hydraulic properties for the suprabasalt sediments are presented below.

Hydraulic Conductivity and Transmissivity

Hydraulic conductivities of the coarse-grained (i.e., sand and gravel) Hanford formation flood sediments are significantly greater than those of the Ringold sediments, principally because of the presence of porosity-filling cementation in the Ringold sediments. Published hydraulic conductivities for the Ringold gravels range from 0.003 feet/day to 13 feet/day, whereas the hydraulic conductivities of coarse-grained flood sediments range from 20 feet/day to >10,000 feet/day. The overall transmissivity of the suprabasalt sediment aquifer is in large part controlled by the saturated thickness of the flood sediments and proportion of the aquifer comprised of coarse-grained (sand and gravel) Hanford formation flood sediments. Transmissivities of the suprabasalt sediment aquifer in the vicinity of the Study Area estimated by Brown (1979) are reported to range from 10,000 gallons per day per foot (gpd/foot) to >1,000,000 gpd/foot. The areas with higher transmissivities commonly define buried erosional channels filled with thicker saturated sequences of Hanford formation flood sediments within the Study Area.

Specific Yield

The specific yield of the suprabasalt sediments is defined as the volume of water that will drain by gravity from a unit volume of aquifer material, also known as drainable porosity. The specific yield of an unconfined aquifer is equivalent to or less than the effective porosity. Published values for the specific yield of the coarse-grained facies of the Hanford formation range from 0.1 (10 percent) to 0.4 (40 percent), with a median of 0.25. The specific yield of the Ringold is significantly less, on the range of 0.05 to 0.1.

2.3.2.2 CRBG

The available data on hydraulic properties of the various CRBG aquifers – including hydraulic conductivity, porosity, and storativity – are wide-ranging and indicate that a large variability in local flow characteristics is expected. Few CRBG wells are completed in the Study Area and hydraulic characteristics of the CRBG aquifers are sparse. Hydraulic properties for the CRBG aquifers based on both regional and available local information are presented below.

Hydraulic Conductivity

A range of hydraulic conductivity values are reported for CRBG aquifers in USDOE (1988), Whiteman et al. (1994), and Sabol and Downey (1997) and are summarized in **Table 2-1**. The values of hydraulic conductivity reported in Whiteman et al. (1994) rely heavily on data reported on driller's well reports from many wells that are open to multiple CRBG aquifers. These lateral conductivities integrate values over the entire depth of penetrated CRBG, and therefore reflect the contribution from inter-layer vertical movement of groundwater past CRBG flow pinch-outs, faulting, and other discontinuities in individual CRBG flow layers. Consequently, the hydraulic conductivities of an individual interflow zone within the tested intervals may be higher (or lower) than the reported value.

Table 2-1. Reported Hydraulic Conductivity Ranges for CRBG Aquifers

		Hydraulic Conductivity Ranges			
Feature		**feet/day**	**m/day**	**References**	**Comments**
Flow tops	Kh	1x10^{-6} to 1,000	3x10^{-7} to 3x10^{-2}	USDOE, 1988	Mean = 0.1 feet/day
	Kv	3x10^{-9} to 3x10^{-3}	9x10^{-10} to 9x10^{-4}	USDOE, 1988	--
		1x10^{-5} to 1x10^{-1}	3x10^{-6} to 3x10^{-2}	Sabol and Downey, 1997	Measured near Lind, WA
Flow interiors	Kh	1x10^{-9} to 1x10^{-3}	3x10^{-10} to 3x10^{-4}	USDOE, 1988	Approx. 5 orders of magnitude < flow tops
	Kv	3x10^{-9} to 3x10^{-3}	9x10^{-10} to 9x10^{-4}	USDOE, 1988	--
		1x10^{-5} to 1x10^{-1}	3x10^{-6} to 3x10^{-2}	Sabol and Downey, 1997	Measured near Lind, WA
Flow tops	Kh	7x10^{-3} to 1,892	2x10^{-3} to 6x10^{2}	Whiteman et al., 1994	Vertically averaged for Saddle Mountains Basalt
	Kh	7x10^{-3} to 5,244	2x10^{-3} to 6x10^{3}		Vertically averaged for Wanapum Basalt
	Kh	5x10^{-3} to 2,522	5x10^{-3} to 6x10^{2}		Vertically averaged for Grande Ronde Basalt
Ellensburg Formation interbeds	Kh	1x10^{-6} to 1	3x10^{-7} to 3x10^{-1}	USDOE, 1988	Mean for various interbeds = 0.01 to 0.1 feet/day
	Kh	1x10^{-6} to 100	3x10^{-7} to 3x10^{-1}	Sabol and Downey, 1997	Measured for interbeds in the Pasco Basin

Reproduced from Tolan et al. (2009)

Notes: Kh is horizontal hydraulic conductivity; Kv is vertical hydraulic conductivity; CRBG is Columbia River Basalt Group; USDOE is U.S. Department of Energy

Storativity

Values of storativity in the CRBG are commonly between 10^{-4} and 10^{-5} reflecting the high degree of confinement of the interflow zones and incompressible aquifer matrix. Higher values of storativity calculated from some aquifer tests may indicate less confinement in some parts of the CRBG system. Some may represent tests in the uppermost basalt interval that are hydraulically connected through surface fractures to the overlying suprabasalt sediments or land surface.

Effective Porosity

Total porosities measured from cores of Grande Ronde Basalt interflow zones range from 0.07 to 0.30 (USDOE, 1988), although it has been suggested that these values overstate bulk effective porosity on a large scale relevant for ASR. Effective porosity typically is less than total porosity because not all pore spaces are interconnected. The median effective porosity value for basalt interflows reported by LaSala and Doty (1971) is 0.15.

2.3.3 Recharge and Discharge

The suprabasalt aquifer, and the uppermost part of the CRBG aquifer sequence to some extent, is recharged naturally from precipitation and snowmelt runoff and artificially by irrigation from wells and water from the Columbia Basin Project (Brown, 1979). Most of the groundwater recharge to the suprabasalt sediments in the Pasco area is from the Smith Canyon and Esquatzel Coulees. Irrigation-related recharge is predominately from canal/wasteway leakage and infiltration of irrigation return flow. Canal lining and improvements in irrigation practices are suspected to have decreased the recharge from these potential sources in recent years. Where pumping of the shallow water table aquifer has generated water-table depressions and induced gradients towards wells, the suprabasalt sediments receive recharge directly from the Columbia River.

Recharge to the deeper CRBG aquifer can be also from natural and artificial sources. Potential recharge pathways include deep erosional windows (e.g., coulee incision), structural features (e.g., folds/faults/dikes), and shallow subsurface outcrop areas.

The Columbia and Snake Rivers are at base-level elevations and groundwater flowing through the suprabasalt sediments in the Study Area ultimately discharge to these rivers. Unconfined groundwater in the Study Area discharges directly to the Columbia River, either naturally from the unconfined aquifer system's hydraulic connection with the river, or artificially via a network of agricultural drains or collection ditches and pumping stations. Natural groundwater discharge from the CRBG aquifer system is primarily to the Columbia River where confining units are absent, and/or from incised surficial drainages where the units crop out at the surface at downgradient locations from the Study Area.

Incision into the CRBG intraflow zones, and consequent formation of erosional windows into deeper CRBG aquifers, can create recharge/discharge areas into and out of CRBG aquifers. Throughout the Columbia Plateau, erosional windows potentially connecting CRBG aquifers are known to occur in the Channeled Scablands region of the Columbia Plateau and can be inferred from geologic mapping. Such erosional windows into the upper portion of the Saddle Mountains Basalt section do exist along the eastern boundary of the Pasco Basin (Tolan et al., 2009) and likely serve as local recharge points for the upper-most portion for the Saddle Mountains Basalt aquifer system.

2.3.4 Groundwater Movement

Groundwater generally moves from areas of higher to lower elevations in unconfined aquifer systems and from locations of higher to lower pressure in confined systems. This section discusses the general groundwater movement in the unconfined suprabasalt and confined CRBG aquifer systems.

2.3.4.1 Suprabasalt Sediments

Results from groundwater investigations in the south Pasco Basin show lateral water-level gradients to be similar to structural gradients, with groundwater moving southward toward the Pasco syncline, a structural low now followed by the Columbia River along the southern margin of the Study Area. Extensive irrigation over the years has led to rising water levels, drainage problems, and dewatering needs in some parts of the Pasco Greenbelt and Study Area. The United States Army Corps of Engineers (USACE) installed above- and below-ground levees in places along the Columbia River to protect low-lying areas from Lake Wallula as part of the McNary Dam project (Brown, 1979). Groundwater draining to the river from the unconfined suprabasalt aquifer system in these areas is collected by ditches constructed behind the levees and pumped into the Columbia River to manage shallow groundwater levels and ponding in those areas. Consequently, the downgradient movement of groundwater towards the Columbia River in some portions of the suprabasalt sediment aquifer system is affected and redirected by a network of agricultural drains, mostly located north of the Study Area (Heywood et al., 2016), and by levees, collection ditches and pump stations in low-lying areas along the Columbia River.

Because of the drainage and dewatering needs and unconfined aquifer conditions, the suprabasalt aquifer system is expected to have a very limited storage capacity. Recharge to the suprabasalt aquifer could contribute to ponding in low-lying areas and impact active management of shallow groundwater levels. The aquifer's direct hydraulic connection with the river also could contribute to losses of stored water to the river and significantly limit the volume of ASR supply water available for recovery. Expectedly low storage capacity and recovery volume, drainage concerns, and dewatering needs preclude the suprabasalt aquifer as a potential ASR storage zone.

2.3.4.2 CRBG Aquifers

As noted in Section 2.2.2.2, groundwater within the CRBG generally occurs as a series of confined aquifers hosted within CRBG interflow zones and associated Ellensburg Formation sedimentary interbeds. In their original undisturbed state, individual interflow zones are as laterally extensive as the sheet flows that define them.

Where not fractured by faults and folding, the basalts typically exhibit high horizontal and vertical hydraulic conductivities in the vesicular/brecciated and weathered zones associated with the permeable interflow zones, and low horizontal and vertical hydraulic conductivities in the dense flow interiors. Lateral groundwater movement is primarily within the interflow zones. Where flows are laterally extensive (and not crossed by permeable faults or open boreholes), there is little vertical hydraulic connectivity between flows.

CRBG beneath the Study Area generally dips at a low angle toward the structural low of the Pasco syncline. Groundwater in the deeper CRBG aquifer system is stored and transmitted primarily in interflows, or several combined interflows, and likely moves southward along structural gradients like groundwater in the overlying suprabasalt sediments.

2.3.5 Wells and Groundwater Levels

Available water well data were obtained from Ecology‘s Environmental Information Management System (EIM) and Washington State Well Report databases. A total of 840 water well logs were identified within the

Study Area. The wells identified are shown on **Figures 1** through **7** in **Attachment B**, and summarized in **Tables 1** and **2** of **Attachment B**.

Of the 840 water wells identified, 781 (93 percent) were classified as suprabasalt wells and 48 (6 percent) as basalt wells based on stratigraphic depths from the isopach maps (Tolan et al., 2007). The remaining 11 wells (1 percent) could not be categorized because no well depths were reported. A subset of the 840 available well logs were reviewed to estimate a range of groundwater levels and seasonal groundwater level fluctuations in the suprabasalt and CRBG aquifer units, production rates, and type of use.

Depth to water reported on the well logs range between approximately 25 and 175 feet in wells completed in the suprabasalt aquifer and between 0 and 250 feet in wells completed in basalt. Groundwater levels are generally deeper to the northern portion of the Study Area and shallower to the south. The groundwater level for one 400-foot deep basalt well (Well Log ID: 438115, drilled in 1989) located in the south-central portion of the Study Area near the Columbia River is reported as artesian. This well appears completed in the Ice Harbor and Elephant Mountain Members of the upper Saddle Mountains Basalt. In the northern portion of the Study Area, groundwater levels are reported to range between 85 and 170 feet in the suprabasalt aquifer and between approximately 130 and 185 feet in the CRBG aquifer.

Reported static water levels were compared between seasonal well pairs based on location. Seasonal (spring-Autumn) groundwater level fluctuations ranged between 2 and 25 feet in the suprabasalt sediments and between 0 and 20 feet in the CRBG aquifer.

Basalt wells in the Study Area are reported to produce between 10 and 650 gpm. Many of these are domestic wells. Suprabasalt wells are reported to produce between 15 and 3,000 gpm (MSA, 2013; Brown, 1979). Many of the high-producing suprabasalt wells are for irrigation purposes.

2.3.6 Current Groundwater Uses in the Pasco Area

Specification of the type of use was limited to information obtained from the EIM database search; the type of use is not reported in search results from the State Well Report database. Of the 34 wells identified in the Study Area from the EIM database search, 24 (70 percent) are reported to be domestic supply wells and 10 (30 percent) are irrigation wells.

While suprabasalt wells do not cluster in any particular area, basalt wells are more common in Sections 4, 6, 21, and 27 of T09N, R29E (**Figures 2** through **6** in **Attachment B**). In general, most wells are located near the Columbia River, either south of Argent Road or in the northwest area of the City. All basalt wells appear completed in the upper portion of the Saddle Mountains Basalt (i.e., Ice Harbor, Elephant Mountain, or Pomona Members). None appear completed below the Pomona Member.

Two deep basalt wells were drilled for the U.S. Government Naval Air Station circa 1943. The wells are approximately 1,050-feet deep and are located near the Tri-Cities Airport (see **Appendix A** of **Attachment A**). Based on their completed depths, the wells may be completed in the upper portion of the Wanapum Basalt. No construction diagrams were discovered for these wells and their current status is unknown.

2.4 Groundwater and Surface Water Interactions

The suprabasalt aquifer system is generally understood to be in direct hydraulic connection with surface water bodies in the Pasco Basin (Brown, 1979). Though groundwater in the suprabasalt sediments ultimately discharge to the Columbia River in the Study Area, the river can also recharge the suprabasalt sediments when river (i.e., Lake Wallula) stage is higher than water table elevations in the vicinity of the river. Rise in the groundwater base level of the suprabasalt aquifer at the southern end of the Study Area was observed after completion of the McNary Dam in 1954 (Brown, 1979). Stage elevations in Lake Wallula under normal operations currently range between 335 and 340 feet (USACE, 2020). During changing river elevations, the interaction between surface water and groundwater takes place as bank storage. During periods of elevated river stage, the suprabasalt sediment water table level is temporarily raised near the river channel by recharge from the river. River recharge volumes entering as bank storage will then discharge back to the river some time later when river stage levels decrease. The extent of the bank storage zone exchange and the time lag for river stage changes to affect suprabasalt aquifer levels will depend on the degree of hydraulic connectedness between the two systems, magnitude of changes in hydraulic gradient between the two systems resulting from changing river stages, and hydraulic characteristics of the aquifer system.

CRBG aquifers in the Study Area do not appear to be in direct hydraulic connection with the Columbia River (**Figures 2-4** and **2-5**). Natural groundwater discharge to and potential exchange with the river would likely take place where confining units are absent, and/or in areas where surficial drainages have incised into basalt interflow zones. Low-permeability CRBG interbeds and dense flow interiors are widespread throughout the area and act to confine water groundwater in interflow zones. CRBG outcrops are present near Ice Harbor Dam on the Snake River, though the outcrop is in the same place as the Ice Harbor Dike system, which likely functions as a flow-limiting or no-flow boundary condition.

2.5 Groundwater Quality

Understanding water quality dynamics is essential to evaluating the technical feasibility of an ASR program. This section presents a summary of the general groundwater quality characteristics for the Saddle Mountain and Wanapum basalts based on review of the regional and local groundwater quality data and data from ASR feasibility studies for the Willowbrook and Kennewick ASR wells (Golder 2001 and 2012b). The Willowbrook ASR feasibility study includes water quality data for eight private domestic wells completed in the upper Saddle Mountain (seven wells) and Wanapum (one well) basalts. Additional details are provided in a technical memorandum prepared by Golder Associates, Inc. (see **Attachment C**).

2.5.1 Saddle Mountain Basalt Aquifers

Groundwater in the Saddle Mountain Basalt is most commonly classified as calcium-magnesium bicarbonate type, followed by sodium-bicarbonate type. Groundwater of the sodium-bicarbonate type is generally found downgradient in the Columbia Plateau close to the Columbia River and in deeper wells (>400 feet bgs), while groundwater of the calcium-magnesium-bicarbonate type is found in upgradient areas and relatively shallow wells (< 400 feet bgs). Calcium-magnesium-sulfate-chloride type water is also found in the Saddle Mountain Basalts, though typically in areas with thin overburden coverage and in relatively shallow wells, and is interpreted to be indicative of recently recharged water (Steinkampf, 1989).

Water quality data from Steinkampf (1989) for the Saddle Mountain Basalt aquifer units are provided in **Table 1** of **Attachment C** and are briefly summarized below:

- pH values ranged from circum-neutral to alkaline (7.0 to 8.7 standard units; s.u.)
- Specific conductance values demonstrated a large range from 175 to almost 1,500 microSiemens per centimeter (µS/cm)
- The average nitrate (+nitrite) concentration in wells was approximately 5 milligrams per liter as nitrogen (mg/L-N).

Groundwater nitrate concentrations above 2 mg/L-N are indicative of anthropogenic influence (Steinkampf, 1989). Elevated nitrate generally occurs in shallow Saddle Mountain Basalt wells and is likely attributed to impacts from agriculture.

Groundwater quality samples collected from seven private domestic wells completed in the Saddle Mountain Basalt as part of the Willowbrook ASR feasibility study (Golder, 2001) are provided in **Table 2** of **Attachment C**, and are briefly summarized below:

- Circum-neutral pH values
- Alkalinity concentrations of approximately 120 to 180 mg/L (as $CaCO_3$)
- Dissolved oxygen concentrations ranging from approximately 1.0 to 10 mg/L
- Nitrate was detected in all but one well at concentrations up to 10 mg/L-N
- The presence of dissolved oxygen and nitrate is indicative of oxidized groundwater conditions
- Low levels of iron (up to 0.3 mg/L), manganese (up to 0.09 mg/L) and selenium (up to 0.007 mg/L) were detected in some wells
- Iron and manganese concentrations each exceeded secondary drinking water standards (SMCLs) in one well

The pH, alkalinity, dissolved oxygen and nitrate values, as well as major ion concentrations, from samples collected from the private domestic wells were all within the ranges for Saddle Mountain Basalt reported by (Steinkampf, 1989; **Table 1** in **Attachment C**). Groundwater quality at all wells met the primary drinking water standards for all monitored constituents per Chapter 246-290-310 WAC.

2.5.2 Wanapum Basalt Aquifers

Similar to the Saddle Mountain Basalts, Wanapum Basalt groundwater is most often classified as calcium-magnesium bicarbonate, followed by sodium-bicarbonate. Groundwater of the sodium-bicarbonate type is the dominant water type in downgradient and deeper wells (> 800 feet bgs) (Steinkampf, 1989). Total dissolved solids (TDS) concentrations range from approximately 70 to 1,100 mg/L, with a mean of 270 mg/L. Areas with higher Wanapum Basalt TDS concentrations correlate with areas where there is an upward hydraulic gradient from the lower Grande Ronde Basalt aquifer system, particularly in the vicinity of the Pasco Basin (Steinkampf, 1989). Water quality data for the Wanapum Basalt aquifer units are summarized in **Table 1** of **Attachment C**. The mean reported concentrations for measured constituents were generally similar between the Saddle Mountain and Wanapum Basalt wells. Wanapum Basalt wells report a larger range in pH values (6 to 9 s.u.).

A groundwater quality sample was collected from one private domestic well (BMID#2) completed in the Wanapum Basalt as part of the Willowbrook ASR feasibility study (Golder, 2001) (see **Table 2** in **Attachment C**). Reported concentrations were within the ranges reported by Steinkampf (1989). Dissolved iron and manganese were both detected in this well, with manganese exceeding the SMCL of 0.05 mg/L. Dissolved oxygen was low (0.2 mg/L). The presence of iron and manganese, and a low concentration of dissolved oxygen, is likely indicative of reducing conditions.

Groundwater quality data from nearby ASR feasibility studies, as well as the operational Kennewick ASR system, are likely indicative of Wanapum groundwater quality in the Pasco Basin. **Tables 3** and **4** in **Attachment C** summarize the native background water quality for two deep basalt wells drilled and tested as part of the Kennewick ASR study (ASR-1 and ASR-MW-1) and the Willowbrook well. **Table 3** in **Attachment C** also summarizes the range in water recovered from storage during ASR pilot testing (GSI, 2020).

The background groundwater from the two Kennewick basalt wells pre-ASR, which are completed in the Priest Rapids and Frenchman Springs Members of the Wanapum Basalt, is categorized as a sodium-bicarbonate water type. Groundwater from the Willowbrook and BMID#2 wells, which are completed in the Priest Rapids Member, was observed to be a bicarbonate-type with more of a calcium-sodium type cation ratio (Golder 2001). The groundwater quality data from the wells are summarized below:

- Groundwater quality meets all the primary and secondary drinking water standards (per Chapter 246-290-310 WAC) in the wells
- Low levels of manganese (0.079 mg/L) have been detected above the SMCL (0.05 mg/L) in the BMID#2 well
- Sodium has been detected above the advisory limit of 20 mg/L, with an overall range of about 22 to 93 mg/L
- Groundwater pH is circum-neutral with a range of 7.3 to 8.0 s.u.
- Groundwater temperatures were elevated, with a range of 24 to 28 °C (75 to 82 °F)
- Redox conditions are anoxic, as indicated by low dissolved oxygen, measurable iron, manganese, and sulfide, low concentrations of nitrate and sulfate, and the presence of methane
- Background native groundwater is low to moderately alkaline, with a range in alkalinity as calcium carbonate ($CaCO_3$) of about 70 to 200 mg/L

Dissolved concentrations of methane were postulated by Johnson et al. (1993) as related to thermogenic sources, likely generated from biogenic interbeds and/or sedimentary rocks buried deep beneath the CRBG, and migrating upward into the CRBG aquifers along faults associated with the Yakima Fold Belt.

2.5.3 Summary

ASR pilot testing through six cycles at the Kennewick ASR-1 well have shown no adverse impacts of mixing of Columbia River source water with native CRBG groundwater. Given the relatively close proximity of Pasco to Kennewick, we anticipate the groundwater characteristics of the Saddle Mountain and Wanapum Basalt aquifers in the Pasco Basin will be similar to the native groundwater conditions observed in Kennewick ASR-1, ASR-MW-1, and the Willowbrook Wells (located approximately 7 to 8 miles from Pasco).

SECTION 3: **Source Water Availability**

The City water utility includes both a potable water system that delivers treated surface water to its customers and a separate non-potable irrigation system that primarily uses groundwater supplemented with a surface water river intake system. The City currently holds water rights for its potable and irrigation water systems, and water rights for stand-alone systems such as individual park irrigation and supplemental irrigation water for disposal of effluent at the Pasco Process Water Reuse Facility. The focus for this study is source water availability from the City's potable and irrigation systems.

3.1 Potable System

The supply source for the City's potable system is treated surface water from the Columbia River. The layout of the water system and surface water diversions for the potable system are shown on **Figure 3-1**. Water rights for and the capacity of the potable system are summarized in the following subsections.

Preferred ASR development locations to meet growing demands for the potable system are shown on **Figure 3-1** as Recharge/Recovery Areas A-D.

3.1.1 Water Rights

The City currently holds 10 water rights for its existing potable system (RH2, in preparation). These water rights total 32,223 gpm (46.4 mgd) of instantaneous withdrawal (*Qi*) and 19,655.75 acre-feet per year (afy) (6.4 billion gallons; BG) of annual withdrawal (*Qa*) from the McNary Pool of the Columbia River for the Butterfield and West Pasco WTPs (**Table 3-1**). Excluded from these *Qi* and *Qa* totals are 2,244 gpm (3.23 mgd) and 3,613.5 afy (1.18 BG) of water rights identified as being used under the Quad Cities water right (QCWR) permit through agreement with the other cities, and the City's share of the remainder of the QCWR.

Table 3-1. City of Pasco Potable System Water Rights

			Instantaneous Rate, *Qi* (gpm)		
Water Right No.	**Water Right Stage**	**Point of Diversion**	**Additive**	**Non-Additive**	**Annual Volume, *Qa* (afy)**
G3-*10704C(A)	Superseding Certificate	West Pasco and Butterfield	375	0	76.2
G3-*10704(B)	Permit	Butterfield	0	375	132.8
G3-25177C(A)	Superseding Certificate	West Pasco and Butterfield	300	0	0
G3-25177C(B)	Superseding Certificate	West Pasco and Butterfield	0	300	158.7
G3-26081C(A)	Superseding Certificate	West Pasco and Butterfield	400	0	291.3
G3-26081C(B)	Superseding Certificate	West Pasco and Butterfield	0	400	190
S3-*17908C	Superseding Certificate	West Pasco and Butterfield	15,709	0	7,000
S4-30976	Permit	West Pasco and Butterfield	1,122	0	1,806.75
S4-33044(A)	Permit	West Pasco and Butterfield	3,097	0	5,000
S3-30852	ROE	West Pasco and Butterfield	11,220	0	5,000
	TOTALS		**32,223**	**-**	**19,655.75**

Adapted from RH2 (in preparation); ROE is Record of Examination

3.1.1.1 Quad Cities Interruptible Water Rights

The City is one-quarter owner of the undeveloped portion of the QCWR (S4-30976)[3]. The undeveloped portion of this water right totals 168 cubic feet per second (cfs) and 89,392 afy, of which 42 cfs (18,850 gpm; 27.1 mgd) and 22,348 afy (7,300 MG) is the City's portion. If unmitigated, this water right is subject to minimum instream flow limitations (interruptible) as specified in the permit provisions (summarized in **Figure 3-2**).

The approved points of diversion under this water right for the City are the West Pasco and Butterfield Intake locations (**Figure 3-1**).

Based on the BiOp Compliance Plan contained within the January 2016 Regional Water Forecast and Conservation Plan (RH2, 2016), the probability of water being available (uninterrupted) each month based on a 15-year period of record between water years 2005 through 2019 ranges between 9 and 64 percent during the late spring and summer months (June through August), and between 88 and 91 percent during the winter months (January through March). The period of highest availability is from December through March, which has a probability of between 85 and 91 percent (**Table 3-2**).

Table 3-2. Quad Cities Interruptible Water Right Water Availability

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
% Water Available	83	58	85	91	88	88	62	73	64	38	9	76
Days Water Available	25/31	17/30	26/31	28/31	24/28	27/31	18/30	22/31	19/30	11/31	2/31	22/30

Adapted from RH2 (in preparation). The shaded area represents a period that historically has had the highest water availability

3.1.2 Physical Capacity

The potable water system is capable of providing off-season supply from both the WPWTP and the Butterfield WTP. Off-season (November through March) firm capacity exceeds off-season demand by an estimated 21,586 gpm (31.1 mgd) (RH2, in preparation). The Butterfield WTP however, is distant from the City's irrigation system and from most future growth and demand in the water system, and was not considered as a recharge supply source.

The WPWTP future firm capacity is assumed to be 15 mgd (with one 3 mgd membrane skid out of service), and the demand served by the WPWTP is currently approximately 25 percent of the City's winter demand (1.8 mgd). Adding a conservative estimate of all future growth related demand (4.8 mgd) results in a year 2036 demand of approximately 6.6 mgd (RH2, in preparation). The remaining WPWTP firm capacity could provide up to an estimated 8.4 mgd as source water for aquifer recharge during the months of November through March, which would equate to an estimated 1,270 MG.

3.1.3 Water Availability

Water demand served from the City's uninterruptible potable system water rights is currently approximately equal to the water right limit for both the instantaneous rate and annual volume. When comparing existing,

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[3] The Quad Cities water right (QCWR) permit identifies a total allocation of 178 cubic feet per second (cfs) (79,892 gpm) and 96,619 acre-feet, to be distributed amongst the Quad Cities (Pasco, Kennewick, Richland, and West Richland) in phases.

uninterruptible water rights to 2036 demand projections, the potable system is estimated to have a *Qi* surplus of approximately 2,962 gpm and a *Qa* deficit of approximately 884 afy (RH2, in preparation). As a result, no annual volume is available under the existing uninterruptible potable water rights portfolio for aquifer recharge during the off-season. There is however, a maximum of 18,850 gpm (27.1 mgd) and 22,348 afy (7,300 MG) of water available for use under the City's interruptible portion of the Quad Cities water right, which can be diverted from the West Pasco or Butterfield Intakes when flow provisions are met. Based on the maximum 27.1 mgd capacity and number of days that water is historically available (uninterrupted) for use (**Table 3-3**), an estimated total of 3,306 MG would be available for aquifer recharge during the November through March off-season.

Table 3-3. Off-Season ASR Supply Water Availability

Offseason Recharge Month	(1) **% Water Historically Available for Recharge**	**Days Water Historically Available for Recharge**	(2) **Estimated Total ASR Supply Water from QCWR** (MG)	(3) **Estimated Total ASR Supply Water from WPWTP** (MG)	***Estimated Total ASR Supply Water Remaining from QCWR*** *(MG)*
NOV	58	17	461	143	*318*
DEC	85	26	705	218	*486*
JAN	91	28	759	235	*524*
FEB	88	24	650	202	*449*
MAR	88	27	732	227	*505*
TOTAL AVAILABLE FOR RECHARGE (MG)			**3,306**	**1,025**	***2,281***

Notes: (1) From **Table 3-2**; (2) City's interruptible *Qi* share of the Quad Cities water right = 27.1 mgd; (3) off-season WPWTP firm capacity estimate = 8.4 mgd.

The 8.4 mgd firm capacity of the WPWTP during the off-season is the factor limiting source water availability for aquifer recharge. Based on the number of days that water is historically available (uninterrupted) for use (**Table 3-3**), an estimated total of 1,025 MG (of the total 1,270 MG available) would be available for aquifer recharge during the November through March off-season. An estimated 2,281 MG remains available as ASR supply water from the City's portion of the QCWR for use during the off-season.

No water quality limitations are anticipated to reduce the estimated 8.4 mgd off-season firm capacity estimate from the WPWTP. Several municipalities throughout the Pacific Northwest use treated drinking water as source water for ASR in basalt-hosted aquifer systems, including the cities of Kennewick, Walla Walla, and Pendleton. These cities report no adverse geochemical interactions between the recharge source water and the background groundwater or changes in water quality attributable to geochemical reactions during the ASR pilot test or ongoing ASR operations.

3.2 Irrigation System

The supply source for the irrigation system is surface water from the Columbia River and groundwater from a series of wells completed in the suprabasalt sediment aquifer. Source water for the irrigation system is untreated. The layout of the water system and wells for the irrigation system are shown on **Figure 3-1**.

Preferred ASR development locations to meet growing demands for the irrigation system are shown on **Figure 3-1** as Recharge/Recovery Areas A-D.

3.2.1 Water Rights

The City currently holds 24 water rights for its existing irrigation system (RH2, in preparation). These water rights total a *Qi* of 17,608 gpm (25.4 mgd) and *Qa* of 7,217 afy (2,350 MG). The irrigation system water rights authorize pumping from 11 wells[4] and use from two surface water diversions (Columbia River Intake and the Butterfield Intake).

The period of use of the irrigation system water rights are variable. The period of use for approximately half of the rights are specified as February through October, while several others are unspecified or general in nature (i.e., “seasonal”). Year-round usage is allowed for four groundwater rights associated with the First Place, Desert Estates, Linda Loviisa, and I-182 wells.

3.2.1.1 Interruptible Irrigation Water Rights

Surface water rights for diversion from its Columbia River Intake, totaling 2,998 gpm (4.32 mgd) and 1,276 afy (420 MG), are interruptible based on the Instream Resources Protection Program for the Main Stem Columbia River in Washington State (Chapter 173-563 of the Washington Administrative Code; WAC). The water rights are interruptible if the March 1 forecast for the April-September runoff at The Dalles, Oregon[5] is 60 million acre-feet (maf) or less. Over a 60-year period of record from 1961 through 2020, the March 1 forecast has only been 60 maf or less on two occasions (1977 and 2001).

3.2.1.2 508-14 Irrigation Water Rights

The 508-14 Area is an administrative boundary established by Ecology under Chapter 508-14 WAC. Water rights issued by Ecology within this area must remain in permit stage indefinitely until it can be determined if the water tapped is public water (in which case a certificate could issue), or if it is artificially stored groundwater of the Columbia Basin Project. The City currently holds nine 508-14 provisioned water rights as part of its irrigation system, totaling 5,965.5 gpm (8.59 mgd) and 2,263 afy (740 MG).

3.2.1.3 Family Farm Act Irrigation Water Rights

The Family Farm Water Act (FFWA), codified in Chapter 90.66 Revised Code of Washington (RCW), was passed as an initiative on November 8, 1977 and has been amended in 1979 and 2001. This statute set limits on the number of agricultural acres that can be irrigated by one person or entity with water rights obtained after passage of the law. There are many different types of Family Farm Water Rights as defined in RCW 90.66.050 and each type has specific conditions for its use. The City currently holds seven FFWA provisioned water rights within its irrigation system portfolio, totaling 3,848 gpm (5.54 mgd) and 1,610 afy (520 MG).

3.2.1.4 Pending Change Applications

The City currently has 43 pending water right change applications before the Franklin County Water Conservancy Board (FCWCB). The water right total for all of the water rights proposed to be changed is 39,142 gpm (564 mgd) and 16,368.6 afy (5,330 MG). This includes all of the irrigation system water rights plus 21,534 gpm (31 mgd) and 9,152 afy (2,980 MG) from other water rights. Several of the change applications are requesting to (1) consolidate all existing points of withdrawal and points of diversion to all water rights, (2) make the period of use year round, (3) make the purpose of use municipal, and (4) make the place of use the area served by the City.

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[4] First Place, Desert Sunset, Island Estates, Sirocco, Road 52, Village at Pasco Heights, Northwest Commons, Desert Estates, Linda Loviisa, I-182, and Powerline Road (MSA, 2013).

[5] As published by the National Weather Service in Water Supply Outlook for the Western United States.

3.2.1.5 Self-Assessment

Current pump capacities fall below authorized maximum instantaneous yield (*Qi*) at several of the City's irrigation wells. At others, the observed operational rate exceeds the allowed *Qi*. In total, the system capacity nearly matches the sum of the individual water rights capacities, though the water rights structure to allow for redistributing rate and volume amongst the various locations does not currently exist. The currently authorized annual volume (*Qa*) is not being used in total (a sum of individual rights). **Table 3-4** compares the current irrigation system water rights to the actual pumping rate of the irrigation sources and volume pumped during the 2015 irrigation season, which was reportedly the highest demand season.

Table 3-4. Irrigation System Comparison of Water Rights with Water Use

Qi (gpm)	2015 Water Use (gpm)	Difference (gpm)	*Qa* (afy)	2015 Water Use (afy)	Difference (afy)
17,608	17,750	-142	7,217	6,660	557
17,958	17,750	208	7,537	6,660	877

Note: The shaded area represents the City's authorized *Qi* and *Qa* pending approval of the proposed change/transfer of G3-26578C

Adapted from RH2 (in preparation)

3.2.2 Physical Capacity

The irrigation system has an approximate total supply capacity of 17,750 gpm (25.5 mgd). Of this total, the Columbia River Intake accounts for 3,000 gpm (4.3 mgd) while the remaining capacity is provided by the 11 City irrigation wells. For the purposes of off-season (November through March) aquifer recharge via the irrigation system's Columbia River Intake, capacity is limited by the capacity of the USBR/Harris Road booster pump station. The booster station has a capacity of approximately 1,950 gpm (2.8 mgd). The City's Road 108 booster station pumps to an easterly portion of the system in a separate transmission and distribution system than the USBR/Harris Road booster station, and is not likely to contribute to off-season recharge capabilities.

Source improvements could increase the system's total and firm capacity by 6,000 gpm (8.6 mgd). Converting two Columbia River Intake pumps that have been historically utilized for the potable water system to irrigation system use would result in a capacity increase of approximately 5,400 gpm (7.8 mgd). Improving the performance by replacing or reconditioning the irrigation wells and consolidating their groundwater rights could improve the irrigation system capacity by another 600 gpm (0.9 mgd).

The City is coordinating with the South Columbia Irrigation District (SCBID) and U.S. Bureau of Reclamation (USBR) to determine the feasibility of accessing and utilizing municipal and industrial (M&I) water to meet future source capacity shortfalls (maximum of 20 cfs, or 9,000 gpm, and 2,500 afy). The City's initial request for 1,000 afy has been submitted to USBR and is currently under review. For the purposes of this investigation, no M&I water was included in the source capacity estimates.

With the added improvements and because there is no irrigation demand during the off-season, the irrigation system could provide up to an estimated 23,750 gpm (34.2 mgd) as source water for aquifer recharge during the months of November through March.

3.2.3 Water Availability

Current water rights constraints limit the irrigation system from being a potential source for ASR. Current use of water from the irrigation system nearly matches the sum of the individual water rights capacities. Though there currently appears to be an approximate *Qa* surplus of 557 afy (**Table 3-4~~3~~**), the period of use authorized under the various irrigation system water rights limits when those rights can be used during the off-season for ASR. In addition, projections of irrigation system demand by year 2036 show that irrigation demand will exceed the irrigation system's current water rights by approximately 3,000 afy (RH2, in preparation). The rate and volume of water available for off-season aquifer recharge from the irrigation system sources however, could increase if the pending water right change applications are approved as requested.

Despite potential increases in water right availability from the pending change applications, the untreated nature of the irrigation system supply sources likely prevent them from being suitable sources for aquifer recharge, without treatment. Groundwater produced by the irrigation wells is high in nitrate (20-30 mg/L-N; MSA, 2013) and the surface water source is not filtered and susceptible to elevated turbidity levels and microbial contamination. None of the irrigation system supply sources are disinfected. Untreated and unfiltered source water from the irrigation system could cause ASR well performance issues during recharge (i.e., bioslime or sediment clogging of the wellbore) and antidegradation concerns in target aquifer storage zones.

3.3 Conclusions

The projected future demands on the potable water system (Murraysmith, 2019) suggest that the City does not have enough uninterruptible water right annual volume to meet future potable demands or that could be used for aquifer recharge during the off-season. The irrigation system has a small amount of annual volume that is not currently being used, but the period of use limits the ability to utilize that water as source water for aquifer recharge during the off-season. In addition, future irrigation system demands are expected to exceed the existing irrigation system water rights, leaving no excess water that could be used as source water for ASR. Unsuitable water quality and lack of treatment also prevents the irrigation system supply sources from being potential sources for ASR.

The City's potable water system does have access to the interruptible portion of the Quad Cities water right via their West Pasco and Butterfield Intakes when instream flow provisions on the Columbia River are met. The 8.4 mgd firm capacity of the WPWTP during the off-season compared against the number of days that water is historically available (uninterrupted) for use under the QCWR, results in an average of between 4.8 mgd (November) and 7.6 mgd (January) of source water available for recharge, totaling an estimated 1,025 MG of water available for storage during the November through March off-season. The potable supply sources are filtered and treated, and no water quality limitations are anticipated to reduce the off-season firm capacity estimate from the WPWTP for ASR.

Some loss of source water stored in the target aquifer storage zone(s) is likely and will limit full recovery of the volume of water recharged by an estimated 10 percent. This means that of the 1,025 MG estimated to be available as source water for ASR recharge from the potable system, only an estimated 922 MG will be available for recovery and beneficial use.

The estimated 922 MG of stored water available for recovery and beneficial use is enough to cover the entire projected shortfall for the potable system, but only a portion (432 MG, or 23 percent) of the projected shortfall for the irrigation system. The potable system reportedly has some firm capacity volume surplus during the shoulder months of October and April, which could expand the off-season recharge period and storage volume. The surplus volume however, was assumed not to be available to the system in the future (RH2, in preparation). As a result, additional sources of water would be needed to meet the peak-season shortfall remaining for the irrigation system, either as additional recharge source water from the Butterfield WTP or in combination with M&I water from SCBID/USBR to offset the projected irrigation demands.

SECTION 4: **Conceptual ASR Storage Model**

This section presents a conceptual ASR storage model based on the hydrogeologic framework and hydraulic characteristics of the CRBG aquifer units present beneath the Study Area. The conceptual model was used to estimate aquifer storage capacity and reservoir storage radius based on source water availability, storage volume requirements, and conceptualized ASR wells. The conceptual model also was used to estimate the region potentially affected by anticipated ASR operations and to inform preferred hydrogeologic settings for ASR within Pasco that appear suitable for further development consideration. Conceptual designs for two prototype ASR wells are presented in Section 4.7. This conceptual model, including the ASR well concepts and designs and candidate storage areas, will need to be refined and updated as further data are gathered during subsequent work activities.

4.1 Storage Requirements

Peak-season (May through September) demand shortfalls of 3.2 mgd (490 MG) and 12.3 mgd (1,880 MG) are respectively predicted for the potable and irrigation systems by year 2036 (**Tables 1-1** and **1-2**; RH2, in preparation), which equates to a total shortfall of 15.5 mgd (2,370 MG). Of the 1,025 MG of total volume available for off-season recharge identified (RH2, in preparation), 922 MG is estimated to be available for recovery and beneficial use during the peak-season assuming a 10 percent loss factor during aquifer storage (**Table 4-1**). The estimated 922 MG storage volume is enough to meet the 2036 projected shortfall for the potable system, leaving 432 MG of storage volume available to help meet the projected shortfall for the irrigation system. An additional 13.2 mgd (1,610 MG) of off-season capacity would be needed to make up the remaining storage volume needed to achieve the total 2036 demand shortfall for both systems.

Table 4-1. Source Water Availability and Storage Volume Requirements

Offseason Recharge Month	[1] **% Water Historically Available for Recharge**	**Days Water Historically Available for Recharge**	[2] **Total Water Available for Recharge from WPWTP** (MG)	[3] **Additional Source Water Needed for Recharge** (MG)	***Total Source Water Needed for Recharge to Achieve 2036 Demand Shortfalls*** *(MG)*
NOV	58	17	143	224	*367*
DEC	85	26	218	343	*562*
JAN	91	28	235	370	*605*
FEB	88	24	202	317	*518*
MAR	88	27	227	356	*583*
TOTAL AVAILABLE FOR RECHARGE (MG)			**1,025**	**1,610**	**2,635**
[4] **TOTAL AVAILABLE FOR RECOVERY** (MG)			**922**	**1,449**	**2,372**

Notes: (1) From **Table 3-2**; (2) Off-season firm capacity estimate of 8.4 mgd; (3) 13.2 mgd of additional off-season firm capacity needed; and (4) assumes 10 percent loss factor during aquifer storage, leaving only 90 percent of the volume of water recharged during the off-season available for recovery and beneficial use during the peak season.

The City's remaining portion from the QCWR is enough to cover the additional source water needed to meet the remaining 13.2 mgd (1,610 MG) shortfall for the irrigation system. Though source water available for recharge under the QCWR is interruptible, off-season source capacity from the WPWTP is the primary factor limiting the volume of water available for recharge and storage. Either additional off-season source capacity (e.g., Butterfield WTP or an alternative source option) is needed to achieve the 1,610 MG storage volume shortfall, or additional peak-season irrigation source water (e.g., SCBID/USBR) is needed to reduce the projected 2036 irrigation deficit, or possibly some combination thereof.

The Butterfield WTP was not considered as a source water option for off-season recharge because it is distant from the irrigation system and distant from most future growth and demand in the water system. Further attention however, can be given to this potential source water option as part of the Task 3 – Source Option Analysis work given the identified storage requirement shortfall. Until additional off-season source capacity is identified and/or projected irrigation demands can be offset by alternative irrigation supply sources, the ASR supply for this phase of the feasibility study is assumed to originate from the WPWTP.

4.2 Aquifer Storage Capacity

A basic estimation of the available aquifer storage capacity (acre-feet) can be calculated as follows:

$$Volume = SAh$$

where, S is the storativity (dimensionless), A is the aquifer extent or area in acres, and h is the available buildup in feet. The total available buildup is estimated at 130 feet, assuming that water levels in the upper portion of the Saddle Mountains Basalt are similar to the water levels in the lower portion and in the Wanapum Basalt. The aquifer extent was estimated as the region bounded by several faults and folds (**Figure 1-2**). Bounding the Pasco Basin to the west is the Horn Rapids anticline and the May Junction fault, to the north is the Umtanum-Gable anticline, to the east is the Ice Harbor Dike system, and to the south is the Wallula Fault zone. Each of these geologic structures likely act as flow boundaries. The area encompassing this region is estimated at 256,000 acres (Reidel et al., 2020; and Reidel and Tolan, 2013) (**Figure 2-1**). Using storativity values typical of confined basalt aquifers (1×10^{-3} to 1×10^{-5}), the available aquifer storage capacity could range between approximately 110 and 10,800 MG (or between 333 and 33,280 acre-feet). Using a basalt storativity of 4×10^{-4} calculated from data collected during Kennewick ASR pilot testing (GSI, 2020), the available aquifer storage capacity is estimated at 13,312 acre-feet, or roughly 4,300 MG.

The storage capacity estimate assumes however, that the aquifer characteristics remain the same over both time and distance, and that no flow-limiting boundary conditions significantly affect the rate of buildup during recharge. The folds and faults mapped in the area may create barriers to groundwater flow, and the extent to which these potential boundary conditions affect piezometric pressure in the basalt aquifer system during recharge will need to be evaluated as part of future work activities.

4.3 Recharge/Recovery Well Concepts

A conceptual ASR wellfield design for this phase of the feasibility study was developed to accept a maximum recharge rate of 8.4 mgd, consistent with the off-season firm capacity rate available from the WPWTP. Should other potential source water options be identified in subsequent tasks of this study, the ASR wellfield design will need to be revised to meet storage volume requirements needed to achieve the 2036 projected demand shortfall for both systems.

The number of ASR wells required to achieve target recharge rate objectives will depend on actual hydraulic characteristics and aquifer conditions beneath the preferred recharge/recovery locations. Results from the Kennewick ASR program and findings discussed in Sections 2.0 and 4.2 suggest that the basalt aquifer system is potentially capable of storing the ASR supply from the WPWTP. One advantage that an ASR system in the Pasco area has over the location where the Kennewick ASR system is located, is the ability to stack ASR storage in more than one basalt zone. The groundwater level in the Kennewick ASR well after it was drilled and constructed measured 355 feet bgs, approximately 30 feet above the top of an 80-foot thick interflow zone within the Umatilla Member, the bottom-most member of the Saddle Mountains Basalt Formation. This interflow zone was not considered a target storage zone for the Kennewick ASR system because of the potential to dewater the interflow zone during ASR recovery pumping (i.e., the pumping water level would have likely been drawn down to below the top of the Umatilla interflow zone). Consequently, that zone was cased and sealed and not utilized for storage. Shallower basalt groundwater levels compared to the basalt stratigraphy in the Pasco area suggests the possibility of having at least two ASR storage zones: one in the Saddle Mountains Formation and one in the Wanapum Formation. The Wanapum Formation is considered confined and isolated from the overlying Saddle Mountain Formation by tuffaceous claystone, siltstone and sandstone of the Mabton interbed. The Mabton interbed is understood to be present throughout much of the region. Interflow zones within each formation are further confined by dense basalt flow interiors.

Stacking ASR storage zones is not only cost-effective, but also reduces the potential for ASR activities to impact existing groundwater users. Instead of distributing ASR wells over large areas to reduce interference affects from closely-spaced, mutually pumping (or recharging) wells completed in the same storage zone, the ASR wells can be stacked and completed in multiple zones at the same site, reducing pumping, piping, and property acquisition costs.

Because recharge water availability is interruptible during the off-season, the ASR wellfield must be designed and capable of recharging water at the maximum rate of 8.4 mgd (approximately 6,000 gpm) when it becomes available to meet storage volume requirements. This would require an estimated four ASR wells designed to recharge at 1,500 gpm each. Two ASR well pairs could be located at one site and two at another. Each pair would consist of one ASR well completed in the Umatilla Member of the Saddle Mountains Basalt and one in the Roza or Frenchman Springs Members of the Wanapum Basalt. The final number and configuration of wells required to achieve these injection rates will depend on site-specific aquifer characteristics determined as part of a subsurface “proof-of-concept” exploration program should the City decide to pursue an ASR program.

Recovery pumping rates are recommended to be greater than recharge rates to help maintain optimal well performance. Assuming a 10 percent loss factor during aquifer storage, 922 MG is estimated to be available for recovery and beneficial use during the 153-day peak-demand season. This equates to an average recovery rate of 6 mgd (4,200 gpm) and individual pumping rates of up to 2,100 gpm for two recovery wells operating simultaneously. Carousel pumping (i.e., rotating production between wells) amongst the four wells would be recommended to reduce idle times that the wells are not in operation.

4.4 Recharge Reservoir Radius

The radius of the recharge reservoir (distance from an ASR well that source water will displace native groundwater, sometimes referred to as the “bubble” radius) depends on the total recharge volume and the hydraulic characteristics of the aquifer, and can be estimated as:

$$Recharge\ Reservoir\ Radius = \sqrt{\frac{V}{7.48 * \pi * b * \mathrm{n_e}}}$$

where, V is the volume of water recharged (gallons), π is 3.14159, b is the cumulative thickness of the interflow zones (feet), and n_e is the effective porosity (dimensionless). The recharge reservoir radius is inversely proportional to b and n_e, so the greater b and n_e, the smaller the radial distance source water will displace native groundwater away from the well during recharge. The storage radius assumes plug flow with no mixing (advection/dispersion) between recharge source water and native groundwater.

The recharge reservoir radius was developed for two scenarios to estimate the extent of the ASR storage zone by recharging two ASR concept wells. The first scenario assumes that all four wells are located in close proximity to each other, and are all completed across the same 150 feet of interflows within one basalt unit (estimated based on interflow thicknesses of the Frenchman Springs Members of the Wanapum Basalt). The storage radius for this scenario is estimated to be 1,400 feet, using an assumed effective porosity of 0.15 (LaSala and Doty, 1971). This indicates that even given a relatively large storage volume, the basalt aquifer will store most of the recharge water within a short distance of a proposed ASR wellfield.

The second scenario assumes that two well pairs will be stacked at two different locations, with one well at each location completed in the Umatilla Member of the Saddle Mountains Basalt, and the other completed in the Roza or Frenchman Springs Members of the Wanapum Basalt. The estimated storage radius for each Umatilla ASR well is approximately 1,200 feet (based on an assumed interflow thickness of 50 feet). The estimated storage radius for each Wanapum Basalt well is 1,600 feet if completed in the Roza Member (based on 30 feet of interflows) and 700 feet if completed in the Frenchman Springs Member.

4.5 Region Potentially Affected by ASR Operations

The distance the source water will move away from an ASR well during recharge or towards the well during pumping is much smaller (closer to the well) than the extent of changes in groundwater level due to ASR operations. This is because changes in groundwater level involve pressure response rather than the actual movement of water molecules. The amount and areal extent of water level buildup or drawdown depends on the physical characteristics of the aquifer, such as transmissivity and storativity, as well as the actual recharge and recovery rates and durations. In aquifers with high transmissivity and low storativity, groundwater level changes in response to pumping or recharge spread rapidly over large areas. The Saddle Mountains and Wanapum Basalts are laterally extensive except where faults and folds may have compartmentalized the basalt aquifer, and even if compartmentalized, the aquifer may be able to transmit a significant amount of water.

Because the aquifer's hydraulic response to recharge or recovery pumping will propagate further than the actual movement of source water during recharge, the region potentially affected by ASR operations was estimated by predicting changes in groundwater level (s, in feet) at a distance from the ASR well (or wellfield) (*r*, in feet) using the modified non-equilibrium equation for confined aquifers (Cooper and Jacob, 1946) and aquifer parameters estimated from available literature:

$$s = \frac{264Q}{T} \log \frac{0.3Tt}{r^2S}$$

where, *Q* is the pumping rate in gpm, *T* is aquifer transmissivity in gpd/foot, *t* is pumping time in days, and *S* is storativity (dimensionless). For this analysis, both the anticipated rate and duration for ASR recharge[6] and recovery pumping[7] were estimated to evaluate the aquifer's hydraulic response to anticipated ASR activities, for both a 4-well wellfield and for two sets of stacked ASR well pairs (2x2 wellfield). A range in transmissivity of 50,000 to 500,000 gpd/foot was used to account for the variability in published values for the Wanapum Basalt in the vicinity of the Study Area[8]. A transmissivity values of 27,800 gpd was assigned to the Saddle Mountains Basalt, based on the Welch's log located in Kennewick to the south of the Study Area (see **Figure A-6A** of **Attachment A**).

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[6] Average of 4,800 gpm recharge for 151 days to meet the 1,025 MG storage volume requirement

[7] Pumping rate of 4,200 gpm for 153 days split between two wells to recover 90 percent of the volume of water recharged. Recovery pumping rates are recommended to be greater than recharge rates to maintain optimal well performance.

[8] Transmissivity values are based on existing wells within the Pasco Basin, including the Kennewick ASR well, Kennewick's Willowbrook well, and packer tests completed at the Hanford Site (GSI, 2020, Golder, 2001, Tolan, 2009, Guzowski et. al., 1984, and Strait and Mercer, 1987.

The anticipated influence due to both recharge and pumping activities for the 4-well wellfield or 2x2-wellfield is summarized in **Table 4-2**. These estimates were calculated for both ASR well concepts to evaluate the ability to reduce the hydraulic pressure response within the aquifer(s) by stacking ASR wells. Due to the recovery rates necessary to provide water over the demand season, the first scenario assumes that only two wells will pump simultaneously (for a combined rate of approximately 4,200 gpm) from the Wanapum Basalt. The second scenario assumes that one of the stacked wells will pump from the Saddle Mountains Basalt and one well will pump out of the Wanapum Basalt.

Table 4-2. Summary of Hydraulic Influence from ASR Operations

Well Siting Options	ASR Operation	Distance from ASR wells (miles)	Estimated Influence (feet)
Scenario A: 4-Well ASR wellfield completed within one basalt aquifer; 4 wells operating during recharge and two during pumping	Recharge (WB)	1 to 2	7 to 58
	Recovery (WB)	1 to 2	6 to 51
Scenario B: 2x2 ASR wellfield, with stacked ASR well pairs completed at two locations; all wells operating during recharge and one pair during pumping	Recharge (SMB)	1 to 2	33 to 47
	Recovery (SMB)	1 to 2	29 to 41
	Recharge (WB)	1 to 2	3 to 29
	Recovery (WB)	1 to 2	3 to 26

Notes: “SMB” = Saddle Mountain Basalt; “”WB” = Wanapum Basalt

Influence calculated using assumed transmissivity values of 27,800 gpd/ft for the Saddle Mountains Basalt and a range of 50,000 to 500,000 gpd/ft for the Wanapum Basalt; storativity of 4.0 x 10-3; injection duration of 151 days; recovery duration of 153 days.

The predicted hydraulic response during anticipated ASR operations for a 4-well wellfield completed in the Wanapum Basalt (Scenario A in **Table 4-2**) is estimated at 51-58 feet at a radial distance of 1 mile from the wellfield and 6-7 feet at a distance of 2 miles. The predicted hydraulic response is reduced if the ASR storage zones are stacked. The predicted hydraulic response during anticipated ASR operations for two wells completed in the Saddle Mountains Basalt (Scenario B in **Table 4-2**) is estimated at 41-47 feet at a radial distance of 1 mile and 29-33 feet at a distance of 2 miles. The predicted response for two wells completed in the Wanapum Basalt (Scenario B in **Table 4-2**) is estimated at 26-27 feet at a radial distance of 1 mile and 3 feet at a distance of 2 miles.

Within the Pasco basin, the majority of the groundwater users appear to produce water from the suprabasalt aquifer. Few wells in the Study Area are completed in the CRBG aquifer and none appear completed below the Pomona Member. As a result, pumping-related influences on existing basalt groundwater users from ASR wells completed in the Umatilla Member or members of the underlying Wanapum Basalt are anticipated to be minimal to absent. Two deep (~1,050 feet) basalt wells drilled circa 1943 located near the Tri-Cities Airport (see **Appendix A** of **Attachment A**) may be completed in the upper portion of the Wanapum Basalt. No construction diagrams were discovered for these wells and their current status is unknown. As documented by the Kennewick ASR program (GSI, 2015; Golder, 2012a), the CRBG aquifers in the Study Area are confined and no hydraulic response to ASR operations were observed in CRBG aquifer units overlying the storage zone.

4.6 Candidate Recharge Areas

The primary objective of this evaluation is to recommend preferred hydrogeologic settings for ASR within Pasco, based on the potential for each candidate site to meet the anticipated storage requirements suitable for ASR. For the purposes of this report, preferred locations within the Study Area where ASR could help address future demand growth for the potable and irrigation systems (RH2, in preparation) have been identified as Recharge/Recovery Areas A through D (see **Figures 2-3, 2-4** and **3-1**).

Findings through this course of the study suggest that the hydrogeologic conditions beneath Areas A through C are favorable, with no apparent advantages or disadvantages across the three sites. Based on available information, the target ASR storage zones are relatively thick (**Figure 2-4**) and likely to be productive and capable of achieving target recharge injection and recovery pumping rates. Each of these sites are estimated to be potentially capable of storing the 1,025 MG storage volume requirement and no adverse groundwater quality conditions were identified based on available information. The Umatilla Member of the Saddle Mountains Formation thins eastward from Recharge/Recovery Areas A through C (**Figure 2-4**), which may limit recharge/recovery capacities or prevent stacking of ASR storage zones in that portion of the City. ASR development sites considered in the eastern portion of the City may be limited to storage zones within members of the Wanapum Basalt only.

The hydrogeologic conditions beneath Recharge/Recovery Area D are somewhat less favorable. Because basalt groundwater levels are generally deeper in the northern portion of the Study Area than the southern portion, potential ASR development sites located along the southern margin of Recharge/Recovery Area D may have less available water-level buildup capacities (and less storage potential without having to seal wellheads and recharge under pressure) than areas A through C. Potential ASR development sites within Recharge/Recovery Area D should target the northwest portion of this area (see **Figures 2-3** and **2-4**). This portion of the Study Area has the thickest ASR storage zones, particularly in the Umatilla Member.

As this feasibility study progresses, additional scoring categories and related criteria will be incorporated based on findings from subsequent tasks to refine rankings of preferred ASR development sites. Such factors are likely to include source water quality and availability, infrastructure needs/constraints, geochemical compatibility, potential water treatment needs, and planning-level cost estimates.

Another factor to consider in assessing preferred hydrogeologic settings for ASR in the Study Area is the availability of data used for this feasibility study. Though the amount and quality of the data available are important in that it defines the level of assessment that can be done, the absence or presence of available data should not govern the priority ranking of potential ASR development sites. Rather than a scored criterion, a sub-ranking will be incorporated to identify the data available for this study. The available data sub-ranking will then be included in the overall priority ranking without changing the overall rank. The value of this sub-ranking is that it assists in further scoping of future work considerations by identifying major and minor data gaps identified as part of this feasibility study.

4.7 ASR Well Prognosis

Conceptual well designs were developed for two prototype ASR wells: one targeting completion in the interflow production zones within the Saddle Mountains basalt and the other within the Wanapum basalt. The conceptual design for each well was developed based on an assumed pump size (capable of producing 2,000 gpm) and using the general hydrogeologic conditions identified during this desktop feasibility study in the area of potential ASR development sites. Both designs are for combination recharge and pumping wells, each used to recharge and store water during the off-season when surplus water is available and to pump and recover the stored water when needed. Both designs assume that each well will be advanced to the base of the target aquifer system. The resulting conceptual design for each basalt ASR well is shown on **Figure 4-1**, and includes the following key design features/assumptions summarized in **Table 4-3**.

Table 4-3. Conceptual Design Elements for Saddle Mountains and Wanapum Basalt ASR Wells

	Descriptions	
Conceptual Design Element	**Saddle Mountains Basalt**	**Wanapum Basalt**
Static water level (est.)	130 feet bgs	130 feet bgs
Well depth	1,000 feet bgs	1,750 feet bgs
Surface casing	20-inch nominal diameter, low-carbon steel casing with 0.375-inch wall thickness to 30 feet bgs	20-inch nominal diameter, low-carbon steel casing with 0.375-inch wall thickness to 30 feet bgs
Surface seal	2-inch annular surface cement grout seal consisting of type I, II or III Portland cement from 0 to 30 feet bgs	2-inch annular surface cement grout seal consisting of type I, II or III Portland cement from 0 to 30 feet bgs
Intermediate production casing	16-inch nominal diameter, low-carbon steel casing with 0.375-inch wall thickness, from surface to 700 feet bgs	16-inch nominal diameter, low-carbon steel casing with 0.375-inch wall thickness, from surface to 1,200 feet bgs
Intermediate seal	1½-inch annular intermediate cement grout seal consisting of type I, II or III Portland cement from 0 to 700 feet bgs	1½-inch annular intermediate cement grout seal consisting of type I, II or III Portland cement from 0 to 1,200 feet bgs
Open borehole	15-inch nominal diameter open borehole extending from base of intermediate casing/seal to total well depth	
Liner casing	12-inch nominal diameter, low-carbon steel casing with 0.3125-inch wall thickness	
Liner screen	12-inch pipe-size diameter, stainless steel, continuous wire-wrap screen with 0.100-inch slot size, strength-rated to depth of 2,000 feet	

SECTION 5: **Data Gaps and Future Work Considerations**

Data gaps may require additional research, further investigation, and/or monitoring to better address related uncertainties for future phases of the project. This section identifies data gaps and recommends future work needed to address the identified data gaps. The data gaps and proposed recommendations may be further refined or expanded once the Task 3 – Source Option Analysis work has been completed for this study (RH2, in preparation).

5.1.1 Data Gaps

Following are a summary of data gaps that have been identified by the consultant team as part of this Task 2 – Hydrogeologic Feasibility Study. The data gaps pertain to geologic and hydrogeologic data, groundwater quality and geochemical data, and water rights. The data gaps are identified and described below, and have been deemed as having significant effects on either the assessment to be conducted under subsequent project tasks or on work that might take place following completion of this ASR feasibility assessment.

5.1.1.1 Geologic and Hydrogeologic Information

The primary geologic and hydrogeologic data gaps consist of geologic characterization data, site-specific aquifer hydraulic characteristics, groundwater levels, and storage zone capacities. Limited data are available to characterize the depth, thickness, and characteristics of the basalt aquifer units in the Study Area and near potential ASR development sites. Less than 10 percent of the wells identified within the Study Area are basalt wells, most of which appear to penetrate only the upper portion of the basalt aquifer system. Consequently, the number, thickness, and hydraulic characteristics of the water-bearing interflow zones; presence and thickness of sedimentary interbed units; seasonal groundwater level fluctuations in the basalt aquifer units; and productivity of the interflow zones are not well known in the vicinity of potential ASR development sites.

5.1.1.2 Groundwater Quality and Geochemical Data

There are no site-specific native groundwater quality data available for the potential target storage zones in the Pasco area. Native groundwater quality in the Kennewick area can be variable with respect to water type and geochemical conditions, but is within the regional range reported by Steinkampf (1989). It is assumed that the native groundwater quality in the Saddle Mountain and Wanapum Basalt units in the Pasco area will be similar to the groundwater quality in the Kennewick area, but a site-specific ASR test well is recommended to determine the compatibility of the native receiving groundwater with the proposed source water as part of the feasibility for an ASR system in Pasco.

5.1.1.3 Water Rights

In addition to the water rights held by the City for their potable and irrigation water systems, the City has also water rights for stand-alone systems, such as individual park irrigation and supplemental irrigation water for disposal of effluent at the Pasco Process Water Reuse Facility. These rights could offset the peak-season shortfall remaining for the irrigation system and potentially reduce the need for additional source water for ASR from the Butterfield WTP, M&I water from SCBID/USBR, or potential new (alternative) source water options (e.g., collector or riverbank filtration wells).

5.1.2 Future Work Considerations

The following future work considerations are recommended to address the data gaps identified in the preceding section and to provide data that are needed for subsequent project tasks. The critical data gaps and the actions to fill them are outlined below.

5.1.2.1 Exploratory Drilling and Testing

Based on the available well records for the Pasco area, it appears there are very few water supply wells that have been drilled into the lower Saddle Mountains Basalt (*i.e.*, Umatilla Member) or the Wanapum Basalt aquifer units. Given the general lack of any specific data on potential CRBG storage zones in the Study Area, a drilling and testing program would be needed to further assess ASR feasibility at a potential candidate development site. The primary purpose of drilling and testing would be to fill site-specific data gaps regarding the geologic conditions, aquifer hydraulic characteristics, groundwater levels, groundwater quality, and geochemical characteristics of potential aquifer storage zones. A drilling and testing program is recommended to obtain this information through supplemental investigations, which is recommended to include:

- Drilling and testing an exploratory borehole or full-size ASR well. Drilling and testing of a full-size ASR test well is recommended over a smaller-diameter exploratory borehole because the latter is not capable of testing at high recharge or recovery flow rates or capable of adequately assessing geochemical reactions in the storage zone further away from the wellbore. ASR feasibility is best confirmed from a full-size ASR well designed for its purpose.
- Conducting step- and constant-rate pumping tests to determine well performance, aquifer productivity, and aquifer hydraulic characteristics in the vicinity of the ASR test well. Conducting a step-injection test is recommended also to characterize the water level response in the ASR test well under recharging conditions.
- Conducting interval step- and constant-rate tests in a single ASR test well to assess the hydraulic and groundwater quality characteristics of multiple potential storage zones within the Saddle Mountains and Wanapum aquifer units. This would provide information to assess the potential for stacking ASR storage zones. Stacking the storage zones at a single ASR development site can save site acquisition and facility costs and construction and operation costs for a larger piping network.
- Collecting and analyzing samples from water produced during the pumping tests to characterize baseline groundwater quality conditions of the target storage zone(s). Collecting and analyzing samples of the proposed source water option during the anticipated recharge period also is recommended to characterize source water quality conditions.
- Analyzing drill cuttings obtained from the test well to identify basalt stratigraphy, characterize geochemistry of the aquifer solids, and evaluate the potential for water-water and rock-water interactions. These data can then be used for predictive geochemical modeling (e.g., PHREEQC) to evaluate the potential for geochemical reactions in target storage zones during ASR operations and how they may affect groundwater quality or the quality of water recovered from storage.

5.1.2.2 Water Rights

Recommended next steps to refine future irrigation system demand needs include:

- Compiling and comparing the water right portfolios for the City’s stand-alone systems against actual use, to assess the possibility of using potential excess water from those water rights to meet future irrigation demands directly and to reduce the amount of water needed to be diverted for ASR during the off-season.

SECTION 6: **References**

Brown, R.E. 1979. A review of water well data from the unconfined aquifer in the eastern and southern parts of the Pasco Basin: RHO-BWI-C-56, Rockwell Hanford Operations, Richland, Washington. 57 pp, 19 plates.

Cooper, H.H., Jr. and C.E. Jacob. 1946. A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History: Transactions, American Geophysical Union v. 27, No. 4.

GSI Water Solutions, Inc. (GSI). 2015. City of Kennewick ASR Year 1 Pilot Testing Report. Prepared for the City of Kennewick. June 2015.

GSI. 2020. City of Kennewick ASR Year 6 Pilot Testing Summary Report, ASR Cycle 06 Testing – 2019 Operations. Prepared for the City of Kennewick. February 2020.

Golder Associates, Inc. (Golder). 2001. Hydrogeologic Feasibility for Aquifer Storage and Recovery at the Willowbrook Well. Prepared for City of Kennewick. Project no. 003-1146.004. November 19, 2001.

Golder. 2012a. City of Kennewick ASR Feasibility Study: Phase 2. Attachment No. 1: ASR-1 Test Well Drilling, Construction, and Testing. Prepared for City of Kennewick. June 2012.

Golder. 2012b. City of Kennewick ASR Feasibility Study: Phase 2 Technical Report prepared for City of Kennewick. Project no. 083-99742.003. September 21, 2012.

Heywood, C.E., S.C. Kahle, T.D. Olsen, J.D. Patterson, and E. Burns. 2016, Simulation of Groundwater Storage Changes in the Eastern Pasco Basin, Washington. United States Geological Survey, Scientific Investigations Report 2016-5026.

Johnson, V.G., Graham, D.L., and Reidel, S.P. 1993. Methane in Columbia River basalt aquifers—Isotopic and geohydrologic evidence for a deep coal-bed gas source in the Columbia Basin, Washington: American Association of Petroleum Geologists Bulletin, v. 77, no. 7, p. 1192–1207.

LaSala, A.M., Jr., and Doty, G.C., 1971. Preliminary Evaluation of Hydrologic Factors Related to Radioactive Waste Storage in Basaltic Rocks at the Hanford Reservation, Washington. U.S. Geological Survey Open-File Report.

Murraysmith, Inc. 2019. Comprehensive Water System Plan for City of Pasco, prepared by Murraysmith, Inc. June 2018, revised January 2019.

Murray, Smith & Associates (MSA). 2013. Irrigation System Master Plan for the City of Pasco, Washington. Prepared by Murray, Smith & Associates, Inc. in association with GSI Water Solutions, Inc. December 2013.

Reidel, S.P., and T.L. Tolan. 2013. The Grande Ronde Basalt, Columbia River Basalt Group, in, Reidel, S.P., V.E. Camp, M.E. Ross, J.A. Wolff, B.S. Martin, T.L. Tolan, and R.E. Wells, eds. The Columbia River Flood Basalt Province: Geological Society of America Special Paper 497. p. 117-153.

Reidel, S.P., K.R Fecht, I.L. Hutter, T.L. Tolan, and M.A Chamness. 2020. The Olympic-Wallowa lineament – a new look at an old controversy. Geological Society of America Bulletin. May 2020. 19 pp. doi.org/10.1130/B35454.1.

RH2 Engineering, Inc. (RH2). 2016. Regional Water Forecast and Conservation Plan, City of Kennewick, City of Pasco, City of Richland, City of West Richland. Prepared by RH2 Engineering, Inc. January 2016.

RH2. In Preparation. City of Pasco Aquifer Storage and Recovery Study, Task 3 – Source Option Analysis. Prepared for GSI Water Solutions, Inc.

Sabol, M.A., and S.E Downey. 1997. Support document for consideration of the eastern Columbia Plateau aquifer system as a sole-source aquifer: Seattle, Washington. U.S. Environmental Protection Agency. Document 910/R-97-002. 35 pp.

Steinkampf, W.C. 1989. Water-Quality Characteristics of the Columbia Plateau Regional Aquifer System in Parts of Washington, Oregon, and Idaho. United States Geological Survey. Water-Resources Investigations Report 87-4242.

Tolan, T.L. 2020. Preliminary Hydrogeologic Characterization of the Pasco, WA, Area. Prepared for GSI Water Solutions, Inc. December 2020.

Tolan, T.L., Lindsey, K.A., Nielson, M., and Loper, S., 2007. Geologic framework of selected sediment and Columbia River basalt units in the Columbia Basin Groundwater Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington (Ed. 2): Prepared for the Columbia Basin Ground Water Management Area, Othello, Washington, 423 p., 41 plates.

Tolan, T.L., B.S Martin, S.P. Reidel, J.L. Anderson, K.A. Lindsey, and W.C. Burt. 2009. An introduction to the stratigraphy, structural geology, and hydrogeology of the Columbia River flood-basalt province – a primer for the GSA Columbia River Basalt Group field trips, in, O'Connor, J.E., R.J. Dorsey, and I.P. Madin, eds. Volcanoes to Vineyards – geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Trip Guide. 15 pp. 599-643.

USACE. 2020. Walla Wall District Website, McNary Lock and Dam Project Pertinent Data, https://www.nww.usace.army.mil/Locations/District-Locks-and-Dams/McNary-Lock-and-Dam/, no posted document date, last accessed December, 2020.

USDOE. 1988. Site characterization plan reference repository location, Hanford Site, Washington. Washington D.C., U.S. Department of Energy. DOE/RW-0164, v. 1-2.

Whiteman, K.J., J.J. Vaccaro, J.B. Gonthier, and H.H. Bauer. 1994. Hydrological framework and geochemistry of the Columbia Plateau aquifer system in parts of Washington, Oregon, and Idaho. U.S. Geological Survey Professional Paper 1413-B. 73 pp.

Figures

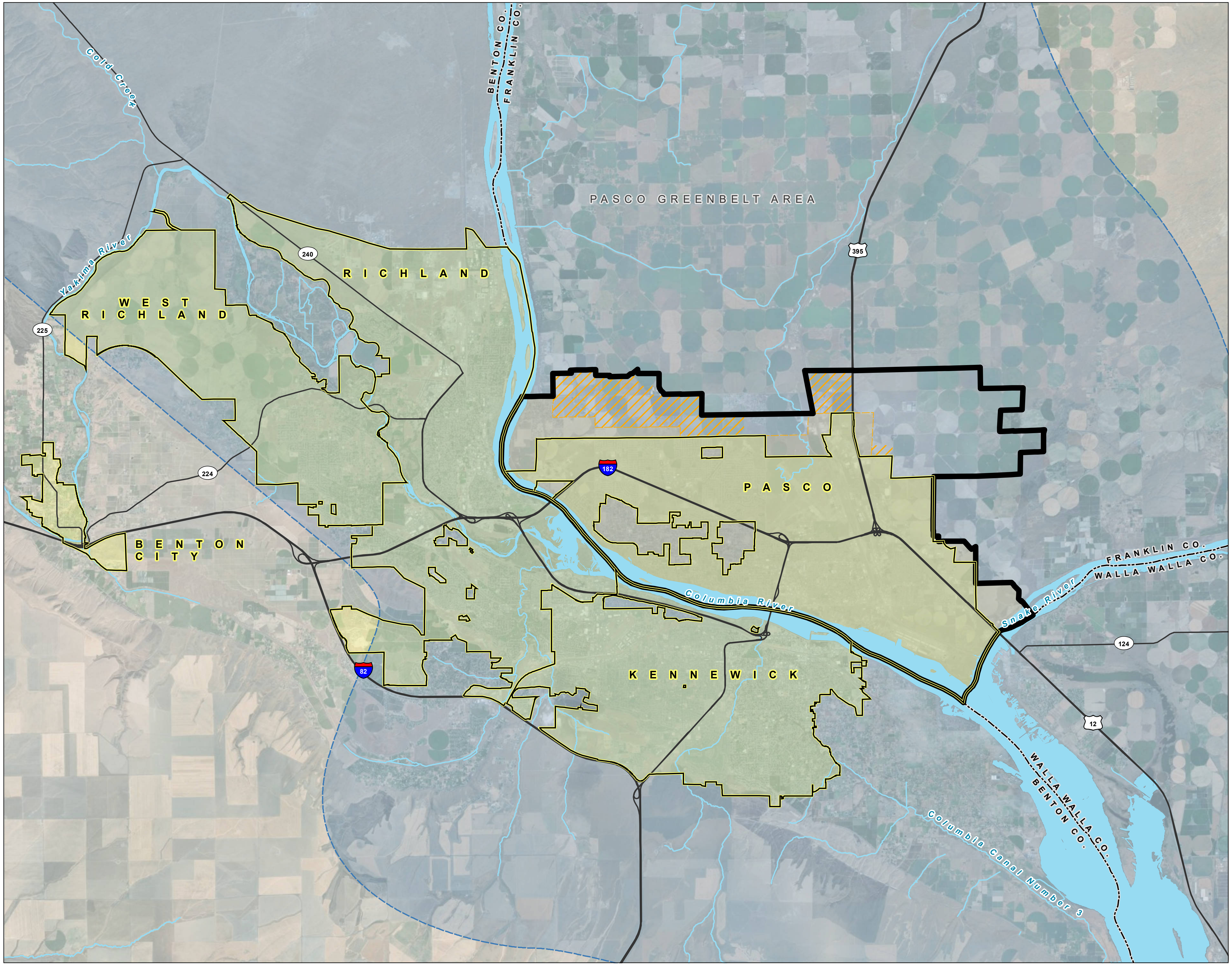


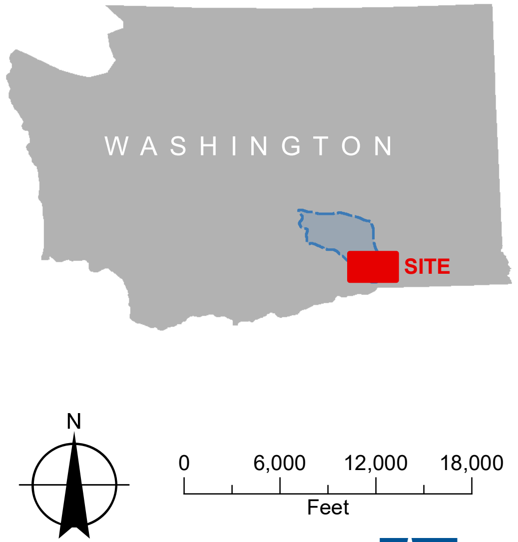
FIGURE 1-1

Overview Map

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington

LEGEND

Study Area
Pasco Basin
City Boundary
Urban Growth Boundary (UGB)
Expanded 20-Year UGB
Major Road
Watercourse
Waterbody



Date: December 14, 2020
Data Sources:

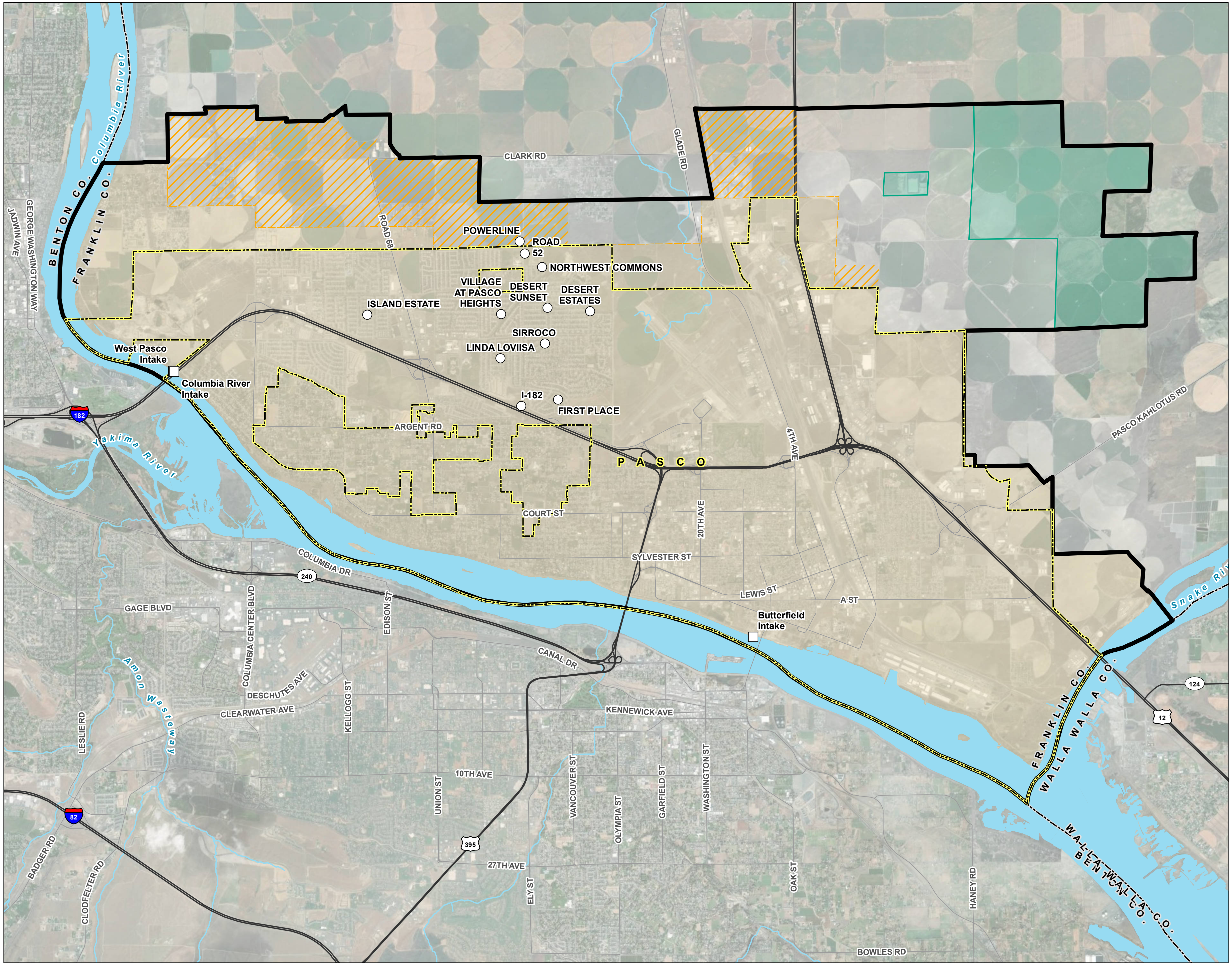
GSI Water Solutions, Inc.

Document Path: Y:\0880_City_of_Pasco\Source_Figures\Hydro_FA_ASR_FA\Figure1-1_Overview.mxd, npalmer

FIGURE 1-2

Study Area

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington



LEGEND

○ Pasco Irrigation Well
☐ Intake
▭ Study Area
▭ City of Pasco
▨ Urban Growth Boundary (UGB)
▨ Expanded 20-Year UGB
🟩 City Process Water Reuse Facility and Farm Circles
╱ Major Road
～ Watercourse
▨ Waterbody

N

0 3,000 6,000 9,000
Feet

Date: December 11, 2020
Data Sources:

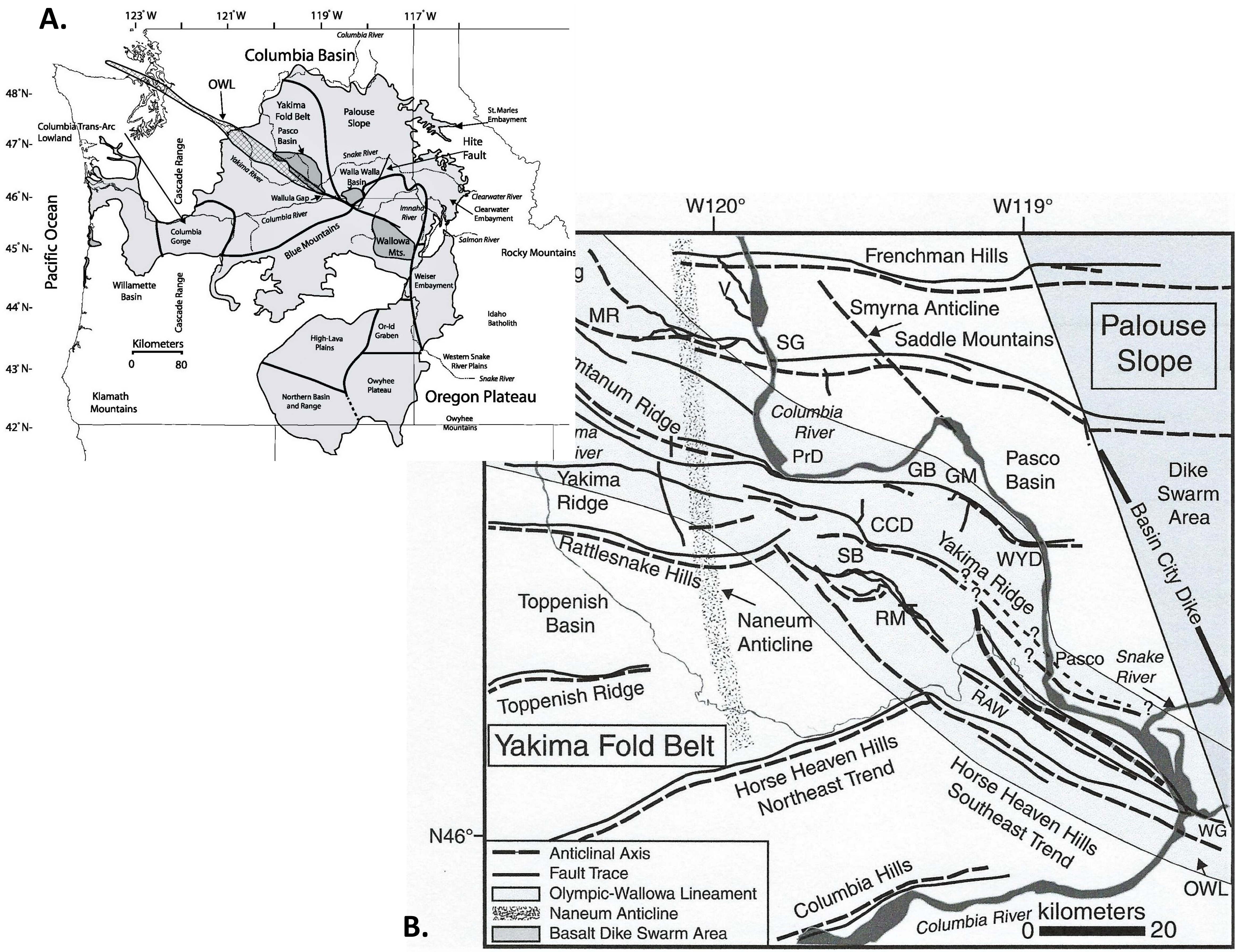
GSI Water Solutions, Inc.

Document Path: Y:\0880_City_of_Pasco\Source_Figures\Hydro_FA_ASR_FA\Figure1-2_StudyArea.mxd, npalmer

FIGURE 2-1

Geologic Setting

Hydrogeologic Feasibility
Assessment, Aquifer Storage and
Recovery Feasibility Study
City of Pasco, Washington



NOTES

A. Map showing the location of the Pasco Basin in relation to geologic structural sub-provinces and the extent of the Columbia River Flood Basalt Province. From Reidel et al. (2020, Figure 1).

B. Major geologic features of the Pasco Basin area and vicinity. V-Vantage; SG-Sentinel Gap; PrD-Priest Rapids Dam; OWL-Olympic Wallowa lineament; Cl Mt- Cleman Mt.; GM-Gable Mtn.; GB-Gable Butte; CCD-Cold Creek depression; WYD- Wye Barricade depression; RM-Rattlesnake Mtn.; RAW-Rattlesnake-Wallula alignment; WG-Wallula Gap. From Reidel et al. (2013, Figure 8).

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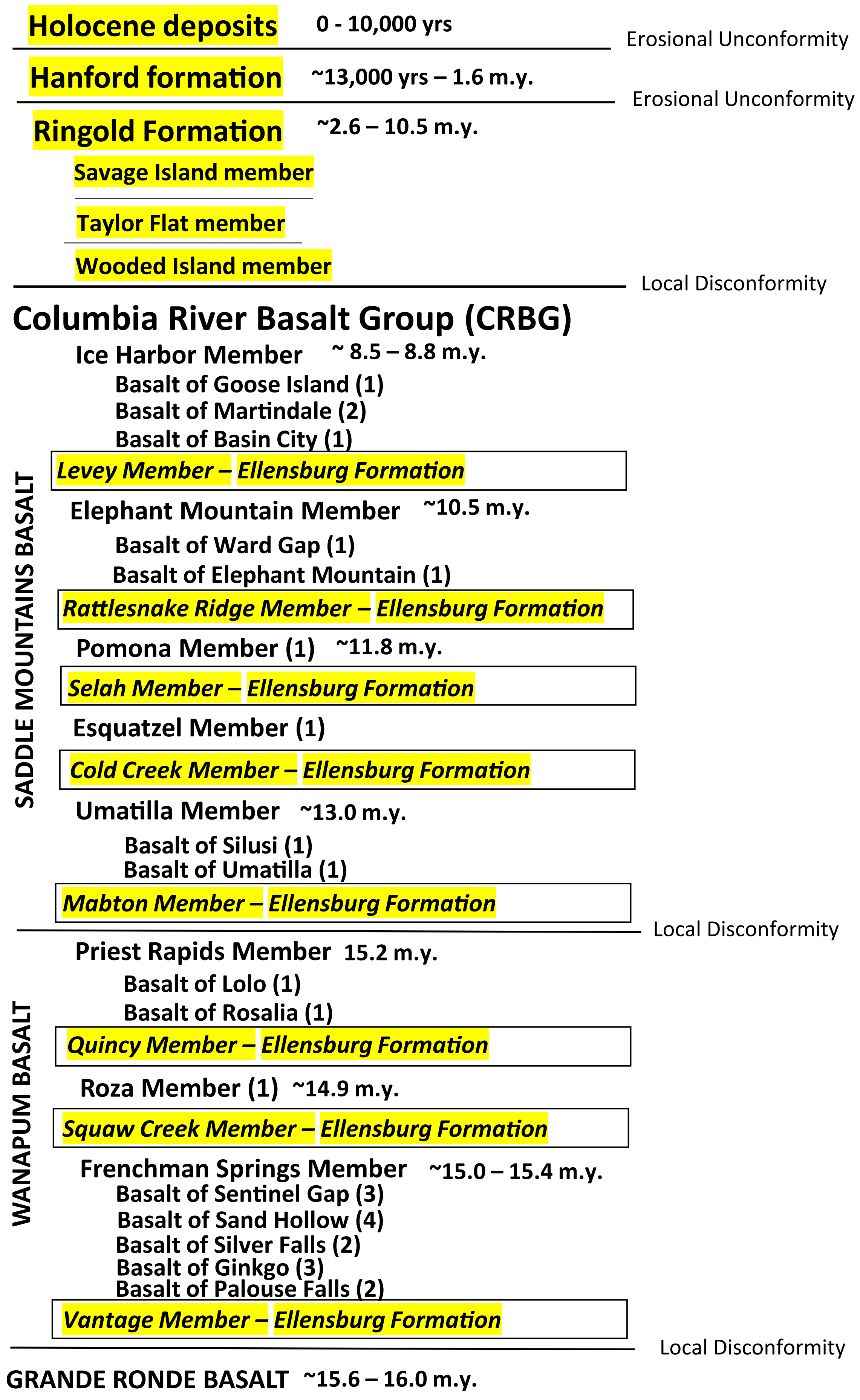
Water Solutions, Inc.

FIGURE 2-2

Stratigraphic Column, Major Units of the Pasco Area

Hydrogeologic Feasibility
Assessment, Aquifer Storage and
Recovery Feasibility Study
City of Pasco, Washington



Holocene deposits 0 - 10,000 yrs

Erosional Unconformity

Hanford formation ~13,000 yrs – 1.6 m.y.

Erosional Unconformity

Ringold Formation ~2.6 – 10.5 m.y.
Savage Island member
Taylor Flat member
Wooded Island member

Local Disconformity

Columbia River Basalt Group (CRBG)

SADDLE MOUNTAINS BASALT

Ice Harbor Member ~ 8.5 – 8.8 m.y.
Basalt of Goose Island (1)
Basalt of Martindale (2)
Basalt of Basin City (1)

Levey Member – Ellensburg Formation

Elephant Mountain Member ~10.5 m.y.
Basalt of Ward Gap (1)
Basalt of Elephant Mountain (1)

Rattlesnake Ridge Member – Ellensburg Formation

Pomona Member (1) ~11.8 m.y.

Selah Member – Ellensburg Formation

Esquatzel Member (1)

Cold Creek Member – Ellensburg Formation

Umatilla Member ~13.0 m.y.
Basalt of Silusi (1)
Basalt of Umatilla (1)

Mabton Member – Ellensburg Formation

Local Disconformity

WANAPUM BASALT

Priest Rapids Member 15.2 m.y.
Basalt of Lolo (1)
Basalt of Rosalia (1)

Quincy Member – Ellensburg Formation

Roza Member (1) ~14.9 m.y.

Squaw Creek Member – Ellensburg Formation

Frenchman Springs Member ~15.0 – 15.4 m.y.
Basalt of Sentinel Gap (3)
Basalt of Sand Hollow (4)
Basalt of Silver Falls (2)
Basalt of Ginkgo (3)
Basalt of Palouse Falls (2)

Vantage Member – Ellensburg Formation

Local Disconformity

GRANDE RONDE BASALT ~15.6 – 16.0 m.y.

NOTE

Chart showing the major stratigraphic units found in the greater Pasco, Washington, area. Yellow highlight denotes sedimentary unit. Number in parentheses to the right of CRBG unit names denotes the number individual basalt flows likely present beneath this area. Ages of units are approximate. “yrs. = years for present; “m.y.” = millions of years before present. Modified from Tolan et al. (2007) and Reidel et al. (2013).

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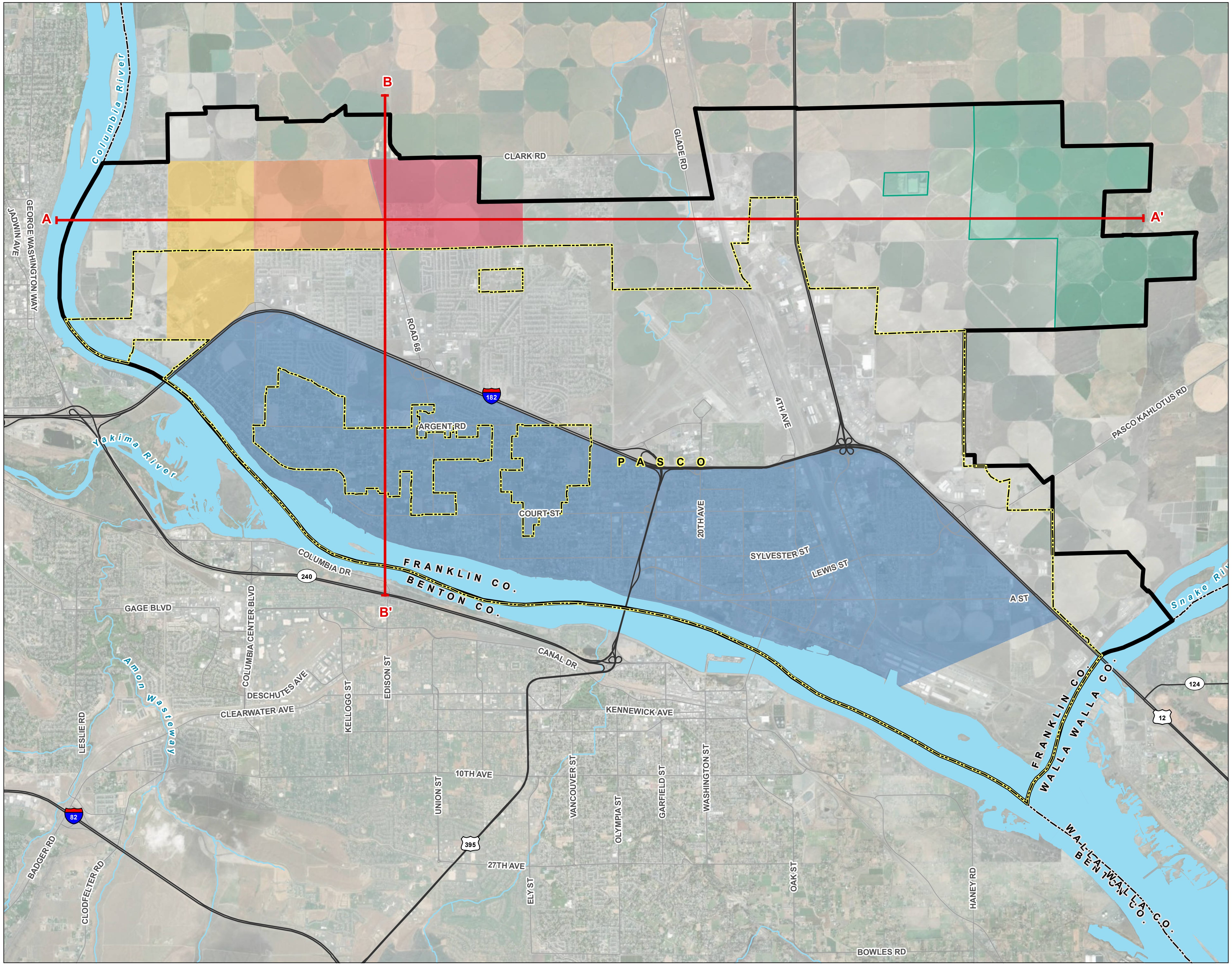


FIGURE 2-3

Cross Section Overview

Hydrogeologic Feasibility
Assessment, Aquifer Storage and
Recovery Feasibility Study
City of Pasco, Washington

LEGEND

🟥 Cross Section Line

Preferred Recharge/Recovery Areas

🟨	Area A
🟧	Area B
🟥	Area C
🟦	Area D

All Other Features

▭	Study Area
▭	City of Pasco
🟩	City Process Water Reuse Facility and Farm Circles
╱╲	Major Road
∼	Watercourse
●	Waterbody

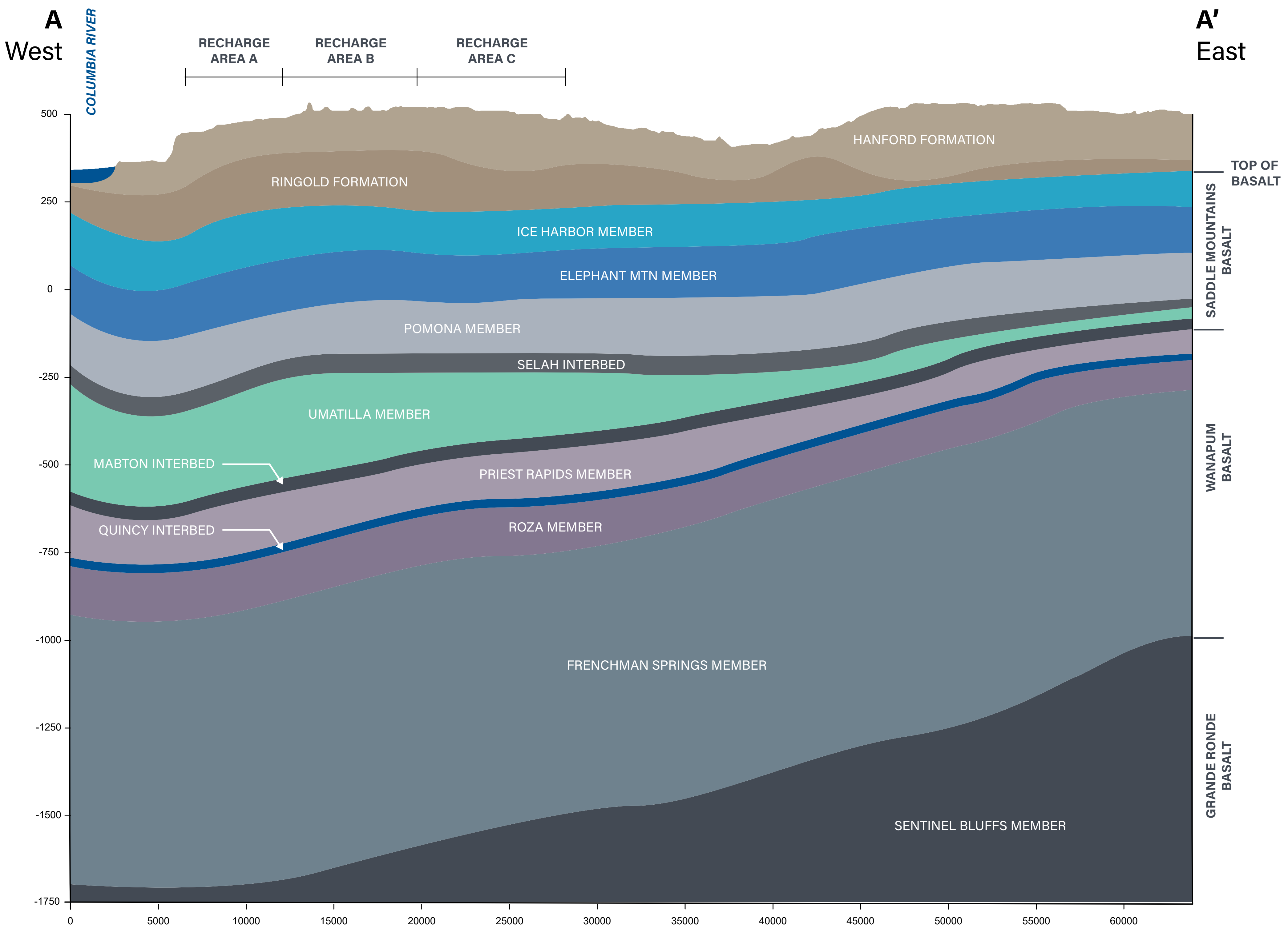
Date: December 21, 2020
Data Sources:

GSI Water Solutions, Inc.

FIGURE 2-4

Cross Section A

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington



LEGEND

- Hanford Formation
- Ringold Formation

Columbia River Basalt Group (CRBG)

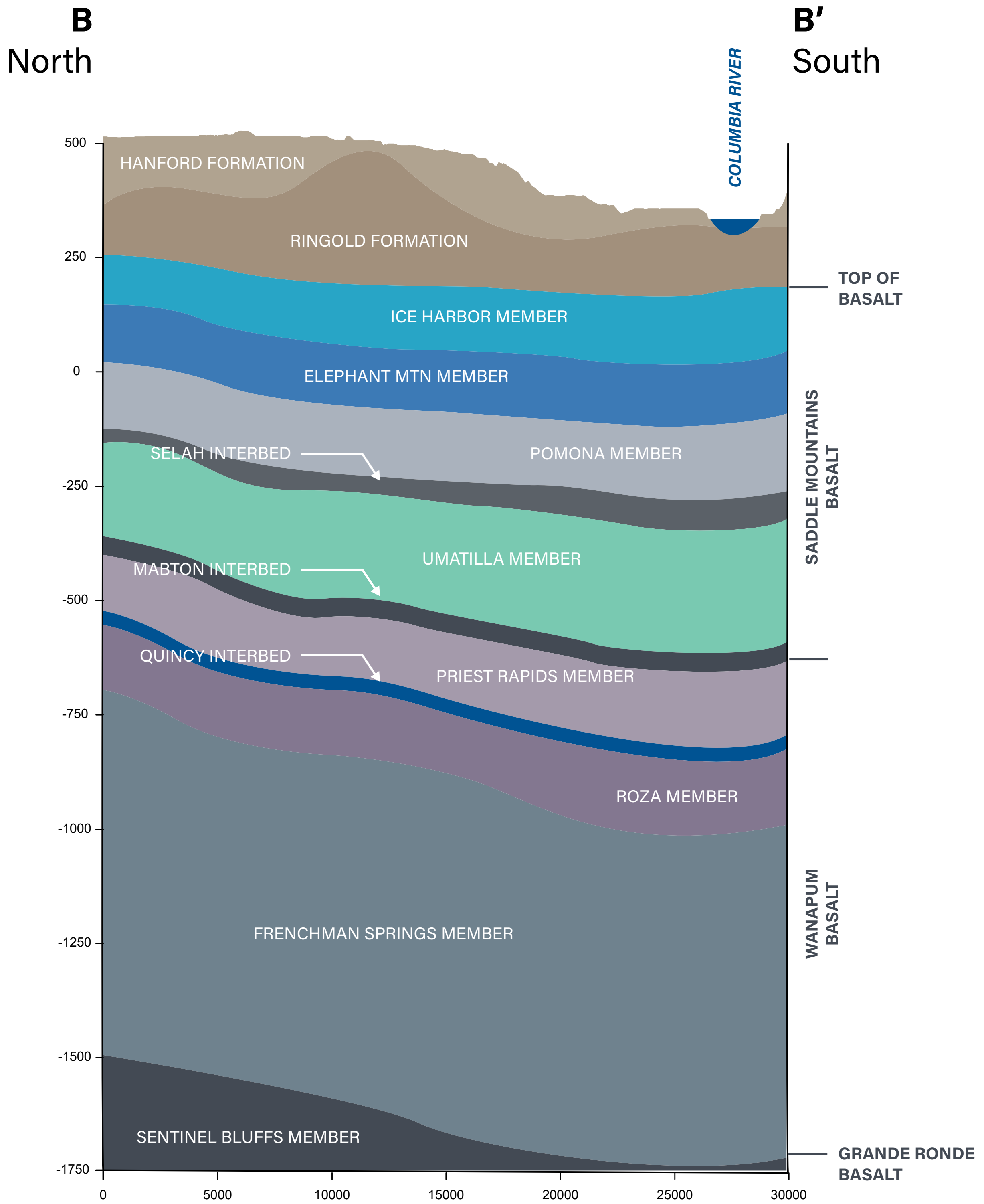
- Ice Harbor Member
- Elephant Mtn Member
- Pomona Member
- Selah Interbed
- Umatilla Member
- Mabton Interbed
- Priest Rapids Member
- Quincy interbed
- Roza Member
- Frenchman Springs Member
- Sentinel Bluffs Member

GSI Water Solutions, Inc.

FIGURE 2-5

Cross Section B

Hydrogeologic Feasibility
Assessment, Aquifer Storage and
Recovery Feasibility Study
City of Pasco, Washington



LEGEND

■ Hanford Formation

■ Ringold Formation

Columbia River Basalt Group (CRBG)

■ Ice Harbor Member

■ Elephant Mtn Member

■ Pomona Member

■ Selah Interbed

■ Umatilla Member

■ Mabton Interbed

■ Priest Rapids Member

■ Quincy interbed

■ Roza Member

■ Frenchman Springs Member

■ Sentinel Bluffs Member

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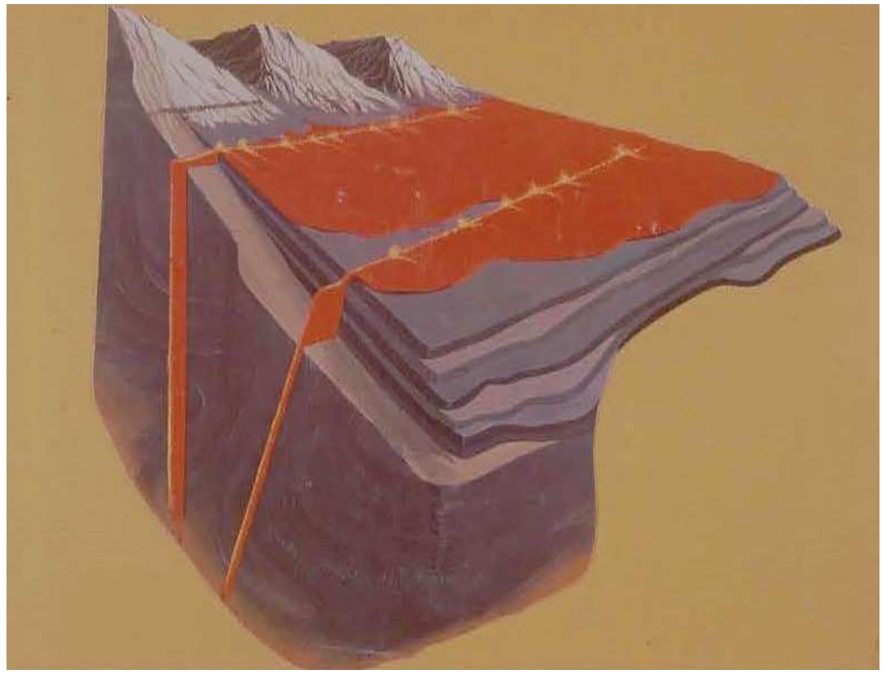
CRBG SHEET FLOW EMPLACEMENT



SHEET FLOWS

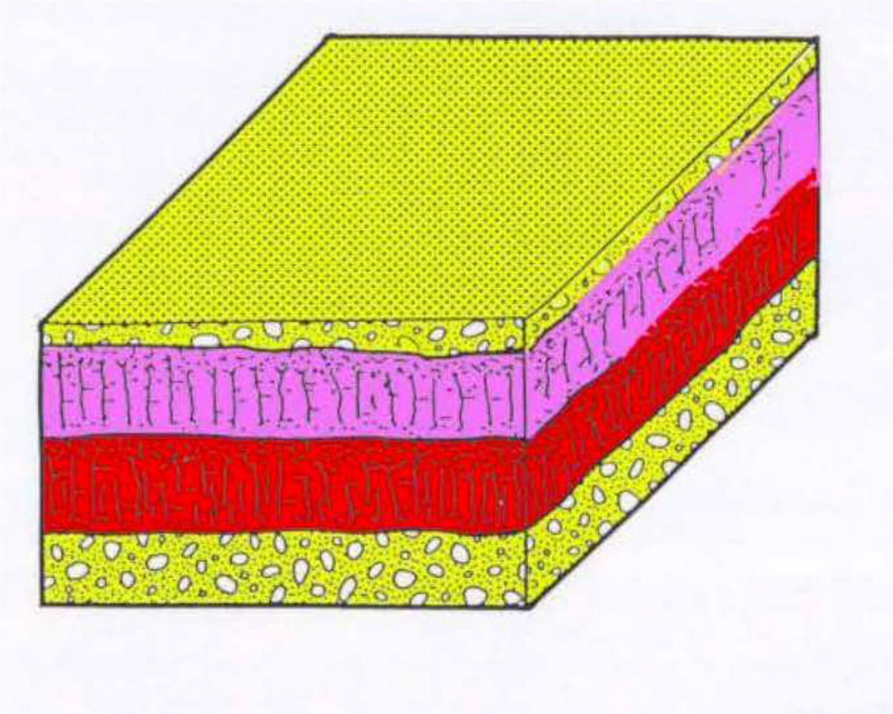


FIGURE 2-6

Sheet Flow Emplacement Model

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington

NOTE
A basaltic sheet flow results when lava is erupted at a high rate and advances away from the vent as a single, uniform, moving sheet of lava. This type of basalt flow consists of a relatively extensive, single layer or “sheet” of lava. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops and flow bottoms. FromTolanetal.(2009).

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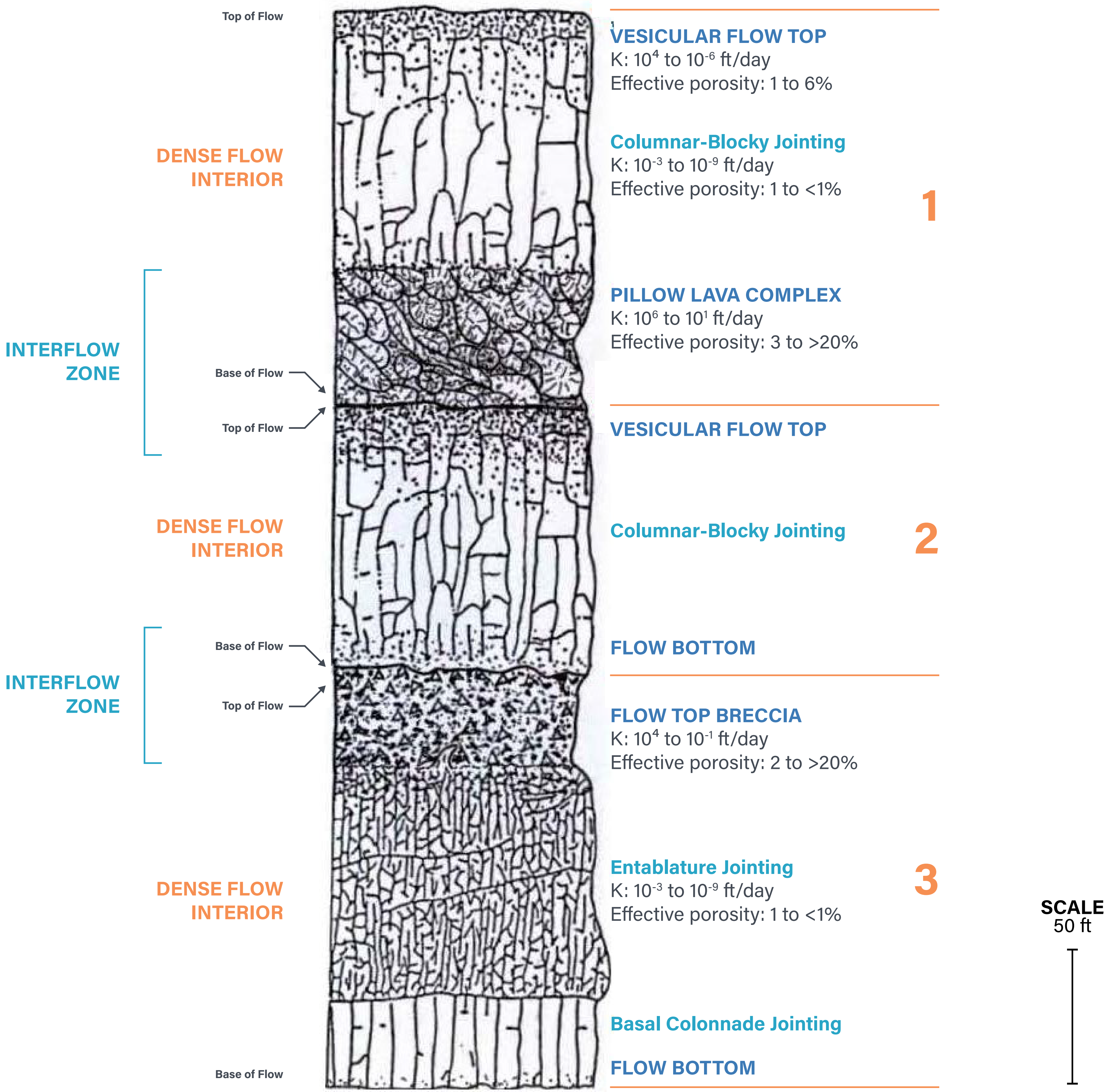

FIGURE 2-7

Basalt Intraflow Structures

Hydrogeologic Feasibility
Assessment, Aquifer Storage and
Recovery Feasibility Study
City of Pasco, Washington

NOTE

Example Illustrating the arrangement of internal structure (termed “intraflow structures”) and terminology within a sequence of 3 CRBG sheet flows and the terminology. Modified from Tolan et al. (2009).

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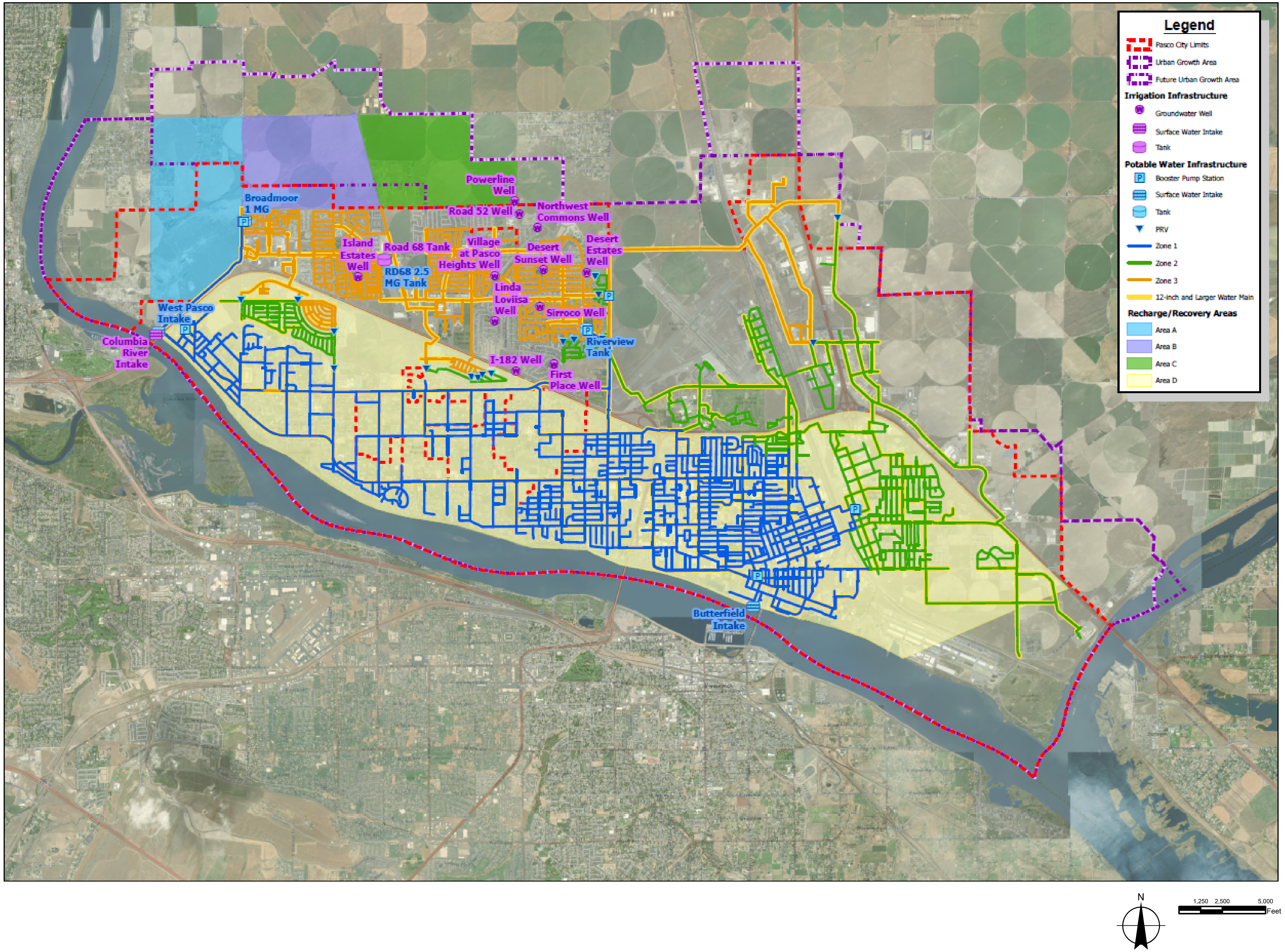

FIGURE 3-1

Existing Portable Water and Irrigation System Infrastructure

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington

LEGEND

🟥 Pasco City Limits
▨ Urban Growth Area
▨ Future Urban Growth Area

Irrigation Infrastructure

● Groundwater Well
▤ Surface Water Intake
● Tank

Potable Water Infrastructure

P Booster Pump Station
▤ Surface Water Intake
● Tank
▼ PRV
— Zone 1
— Zone 2
— Zone 3
— 12-inch and Larger Water Main

Recharge/Recovery Areas

🟦 Area A
🟪 Area B
🟩 Area C
🟨 Area D

NOTE

Developed by RH2

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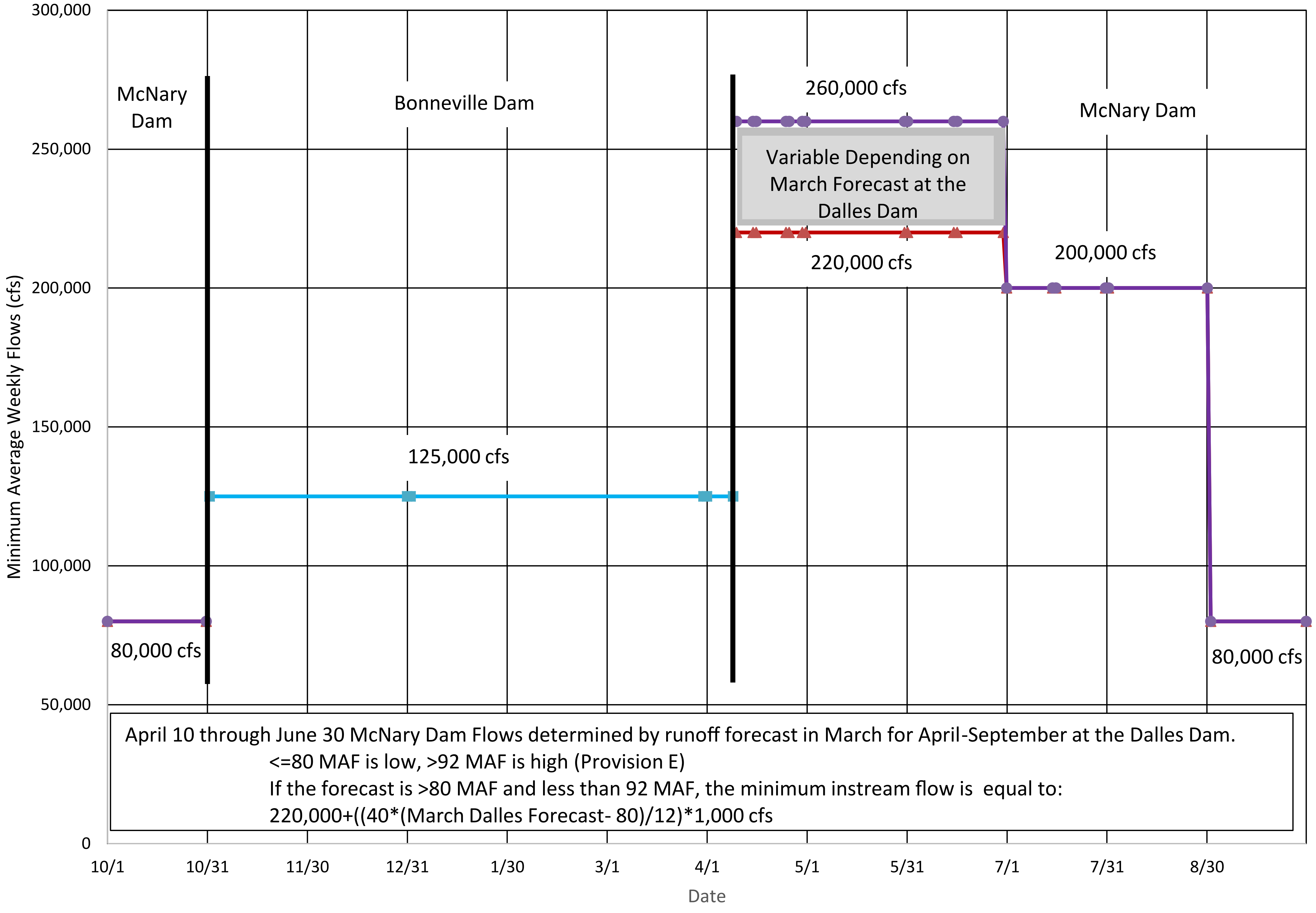


April 10 through June 30 McNary Dam Flows determined by runoff forecast in March for April-September at the Dalles Dam.
<=80 MAF is low, >92 MAF is high (Provision E)
If the forecast is >80 MAF and less than 92 MAF, the minimum instream flow is equal to:
220,000+((40*(March Dalles Forecast- 80)/12)*1,000 cfs

FIGURE 3-2

Columbia River Minimum Flows

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington

LEGEND

- Provision E McNary Low
- Provision E McNary High
- Provision E Bonneville Low

NOTE

Developed by RH2

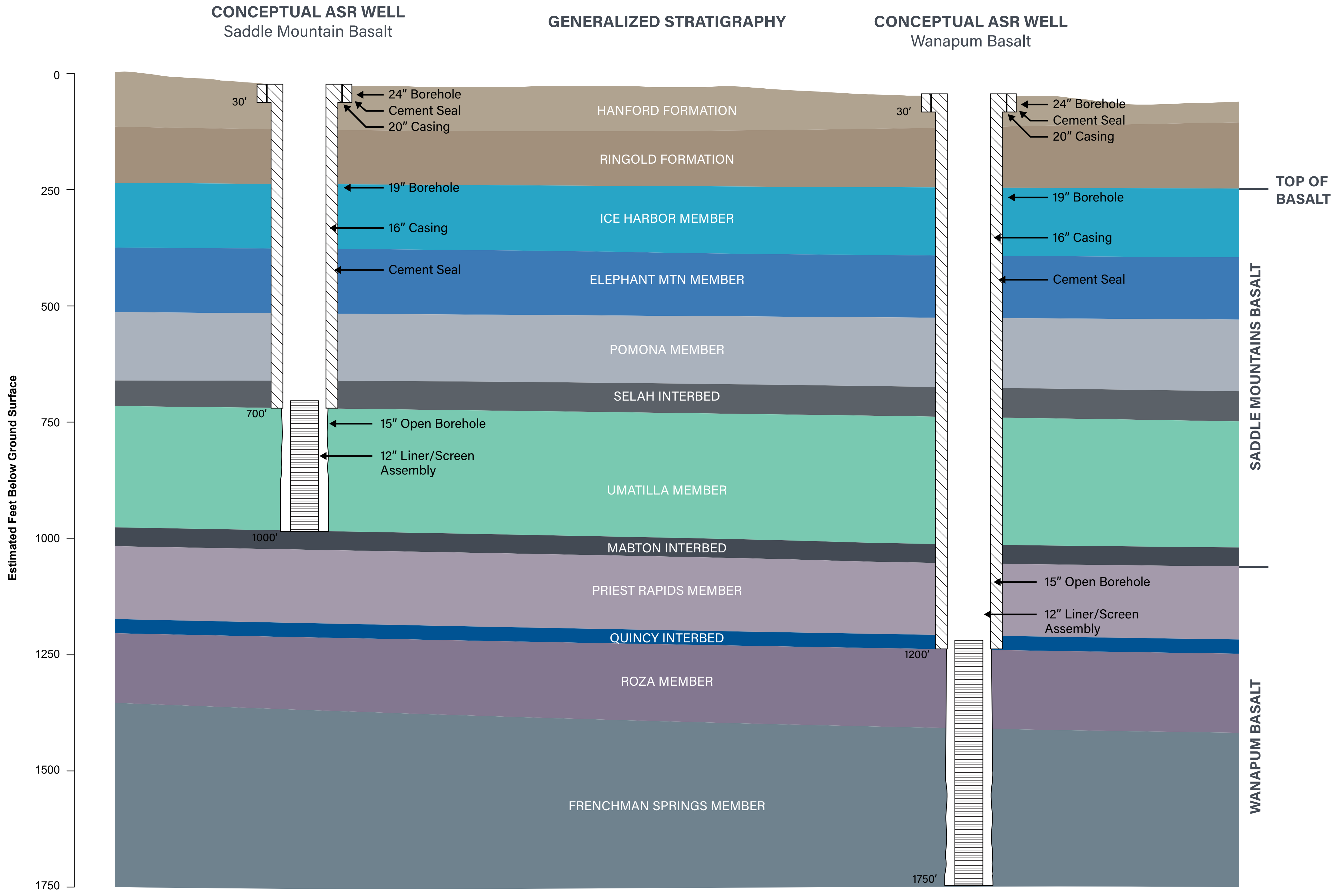


FIGURE 4-1

Conceptual Schematic Design ASR Wells

Hydrogeologic Feasibility Assessment, Aquifer Storage and Recovery Feasibility Study
City of Pasco, Washington

LEGEND

■ Hanford Formation

■ Ringold Formation

Columbia River Basalt Group (CRBG)

■ Ice Harbor Member

■ Elephant Mtn Member

■ Pomona Member

■ Selah Interbed

■ Umatilla Member

■ Mabton Interbed

■ Priest Rapids Member

■ Quincy interbed

■ Roza Member

■ Frenchman Springs Member

■ Sentinel Bluffs Member

NOTES

Final depths will be determined based on conditions encountered during drilling.

The Wanapum Basalt well will target completion in either the Roza or Frenchman Springs Member based on results obtained from a drilling and testing program.

GSI Water Solutions, Inc.

Attachment A

Preliminary Hydrogeologic Characterization of the Pasco, Washington Area. By T.L. Tolan

INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

PRELIMINARY HYDROGEOLOGIC CHARACTERIZATION OF THE PASCO, WASHINGTON, AREA

A Technical Memorandum Prepared for:

GSI Water Solutions, Inc.

December 2020

By:

Terry L. Tolan, LHG
INTERA, Inc.
3240 Richardson Road, Suite 2
Richland, Washington 99354

Hydrogeologist
210
Terry L. Tolan
Terry L. Tolan

Expires 08/31/2021

PURPOSE

The purpose of this memorandum is to present a preliminary characterization of the subsurface geology and hydrogeology of the greater Pasco, Washington, area in support of an aquifer storage and recover (ASR) feasibility study for the City of Pasco. This preliminary hydrogeologic characterization memorandum will provide an initial basis for identifying potential stratigraphic units beneath this area that may be hydrogeologically suitability to be utilized for an ASR program. The descriptions of the geology and hydrogeology presented in the following sections is based on available (published and unpublished) geologic mapping and subsurface data, hydrogeologic reports, and WADOE water supply well records. The basic area stratigraphy, structural geology, and hydrogeology presented in the following sections was compiled and synthesized for sources referenced.

INTRODUCTION

The Pasco Basin is located near the eastern edge of the Yakima Fold Belt structural sub-province within the Columbia River Flood Basalt Province (Figure 1A). The Pasco Basin is both a topographic and structural low and is geologically defined the following features:

- On the west by the northwest-trending anticlinal folds and faults that define the Rattlesnake-Wallula alignment (RAW), a portion the larger regional northwest-trending Olympic- Wallowa lineament (Figures 1A and 1B; Reidel et al., 1989, 2013, 2020).

- On the north by the east-west-trending portion of the Saddle Mountains which is a Yakima Fold Belt anticlinal ridge (Reidel, 1984).

- On the east by the combination of the westward-dipping Palouse Slope-Jackass anticline/monocline and the north-northwest-trending Columbia River Basalt Group (CRBG) dike swarm (Figure 1B) that consists of Saddle Mountains Basalt (Ice Harbor Member) and Wanapum Basalt (Frenchman Springs Member) feeder dikes (USDOE, 1988, p. 1.3-38; Swanson et al., 1975, 1980; Reidel et al., 1989, 2020).

The bedrock geology of the Pasco Basin (Figure 2) is dominated by the flood-basalt flows of the middle to late Miocene CRBG and the interbedded sediments of the Ellensburg Formation. The CRBG flows are overlain by late Miocene-Pliocene sediments of the Ringold Formation that were deposited by rivers and in lakes (Newcomb et al., 1972; USDOE, 1988; Lindsey, 1995, 1996; Reidel and Tolan, 2013b). The geologically youngest, wide-spread unit within the Pasco Basin is the Quaternary-age Hanford formation (Figure 2). These sediments typically consist of unconsolidated deposits of silt, sand, and gravel that were deposited by multiple cataclysmic floods ("Missoula Floods") from about 1.6 million years to 13,000 years ago (Waitt et al., 2009; Pluhar et al., 2006; Lindsey et al., 1994). All three of these major stratigraphic units (Figure 2) can host significant aquifers and do serve as important sources of groundwater throughout much of this region (Burns et al., 2011). Because of their important role as aquifers, each of these major stratigraphic units will be described in more detail in the following section.

PASCO BASIN STRATIGRAPHY

General

The purpose of this section is to present a general description of the geology of the stratigraphic units that are present beneath the City of Pasco area (Figure 2). The stratigraphic unit descriptions presented in the following sections are based upon surface and subsurface geologic mapping studies previously conducted by the U.S Geological Survey , Washington State Geological survey, Columbia Basin Ground Water Management Area ("GWMA") by Tolan et al. (2007) and Lindsey et al. (2007), a series of deep, continuous core, boreholes drilled in the southeastern portion of the Hanford site by the U.S. Department of Energy, City of Kennewick ASR project (e.g., Pitre and Gerst, 2014), and driller's logs from deep water supply wells drilled in, and around, the greater Pasco area. Collectively these data sources provide a general three-dimensional framework of the extent, thickness, and characteristics of the stratigraphic units, and the aquifers that they may host, beneath the greater Pasco area.

Suprabasalt Sediments

The term "suprabasalt sediments" is used to collectively identify the sediment deposits that overlie the CRBG to the ground surface. In the greater Pasco Basin area these sediments can be subdivided into Holocene (or "recent") deposits, Hanford formation, and Ringold Formation (Figure 2).

Holocene Deposits

In the greater Pasco area Holocene sediments (Figure 2) dominantly consist of relatively unconsolidated, wind-deposited silt (“loess”) and sand (active and stabilized sand dunes) that unconformably overlie the Hanford formation. In the Pasco Basin area these Holocene deposits can range from less than 2 feet- to greater than 15 feet-thick (DOE/RL-2002-39; Lindsey et al., 2007). In the Pasco area these sand and silt deposits typically comprise the uppermost portion of the unsaturated (vadose) zone and typically do not host groundwater except locally within coulees and along the Columbia River (Brown, R.E., 1979).

Hanford Formation

The informally named Hanford formation (Figure 2) consist of unconsolidated deposits of silt, sand, and gravel that were deposited in the Pasco Basin by a series of cataclysmic flood (“Missoula Floods”) events that originated due to the failures of large, glacial ice-dammed lakes from around 1.6 million years until about 13,000 years ago (Waitt et al., 2009; Pluhar et al., 2006; Lindsey et al., 1994). Each cataclysmic flood event is estimated to have occurred over a very brief period of less than 7 to 12 days in duration (O’Connor and Baker, 1992; Denlinger and O’Connell, 2010) and eroded and transported huge amounts of sediments. These turbid floodwaters entered the Pasco Basin via a number of different channels (Figure 3), but could only exit the basin via Wallula Gap. This narrow constriction resulted in the hydraulic damming of the advancing floodwaters which caused the repeated formation of a very short-lived lake (Lake Lewis) that was up to 900 feet-deep (Benito and O’Connor, 2003; Denlinger and O’Connell, 2010).

The Pasco area lies within several of the main channel floodwater pathways (Figure 3). As a result of this, the Hanford formation sediments that were deposited throughout this area are predominately unconsolidated, massive to bedded, open framework, coarse gravel and sand, with only very minor amounts of silt present (Figure 4). Both water well logs and sand/gravel mining operations (e.g., Figures 5 and 6) in this area have confirmed this. Subsurface mapping of the thickness of the Hanford formation in the greater Pasco area (Figure 7; Lindsey et al., 2007) indicate that these deposits can collectively range from 40 feet-thick to more than 300 feet-thick.

Given the sedimentological characteristics of the Hanford formation gravel and sand deposits associated with cataclysmic flood pathways, it is not surprising that they are considered as the most permeable suprabasalt sediments within the Pasco Basin (Newcomb et al., 1972; Brown, R.E., 1979; Kahle et al., 2011). The Hanford formation deposits within the Pasco area often comprise a large portion of the vadose zone (unsaturated interval between the ground surface and water table), but proximal to the Columbia and Snake Rivers and within cataclysmic flood channels, can host a significant portion of the unconfined (“water table”) aquifer (Newcomb et al., 1972; Brown, R.E., 1979; Lindsey et al., 2007).

Water wells within the greater Pasco Basin area that completed in the unconfine Hanford formation aquifer (coarse gravel and sand deposits) are reported to have yields between 1,000 to greater than 3,000 gallons per minute (gpm) (Brown, R.E., 1979, p. 23; Lindsey et al., 2007). The areal extent, thickness, and general hydraulic properties of the Hanford formation deposits within the Pasco area would indicate that they might qualify as a suitable ASR hydrogeologic candidate (Gibson and Campana, 2014; Gibson, 2018; Gibson et al., 2019). However, additional investigation would be needed to determine if the Hanford formation deposits within the Pasco area would be able to retain potentially stored water for the required period(s) of time required for this ASR project and also determine if the stored water might cause an unacceptable rise in the local water table (unconfined aquifer) causing local flooding.

Ringold Formation

In the greater Pasco Basin area, the Ringold Formation (Figures 2 and 8) consists of interbedded, unconsolidated to cemented, clay, silt, sand, and gravel deposited by rivers, and within lakes, associated with the ancestral Columbia River system from about 10.5 to 2.6 m.y. (Newcomb, 1958; Newcomb et al., 1972; Grolier and Bingham, 1978; Tallman et al., 1979, 1981; Fecht et al., 1987; Smith et al., 1989; Lindsey et al., 1994; Lindsey 1996; Reidel and Tolan, 2013b). Originally the Ringold Formation sediments thinned from the structural lows within the subsiding Pasco Basin onto the upland areas that define the margins this basin. The Ringold Formation is estimated to have once achieved a maximum total thickness of 1,200 feet within the greater Pasco Basin area (Tallman et al., 1979; Lindsey, 1996). Deposition of Ringold sediments ended about 2.6 m.y. ago when broad regional uplift began in Washington and Oregon and the ancestral Columbia River (and tributaries) began to re-incise. The original extent and thickness of Ringold Formation sediments within the Pasco Basin have been significantly modified due to erosion by the cataclysmic floods. As a result of the cataclysmic flood erosion, the preserved thickness of the Ringold Formation is highly variable within the Pasco Basin, ranging from being totally absent to greater than 400 feet-thick (Newcomb et al., 1972; Grolier and Bingham, 1978; Tallman et al., 1979, 1981; Lindsey et al., 1994; Lindsey 1996; Lindsey et al., 2007).

Within the greater Pasco Basin area Lindsey (1996) subdivided the Ringold Formation into three informal members (Figure 2), from oldest to youngest:

- Wooded Island member – consists dominantly of poorly consolidated to well cemented river (fluvial) gravel deposits with interbedded sand and overbank (silt and clay) deposits (Figure 9).
- Taylor Flat member – consists dominantly of poorly consolidated to moderately cemented fluvial sand and overbank deposits with minor fluvial gravel deposits (Figure 10).
- Savage Island member – consists dominantly of poorly consolidated to moderately cemented clay, silt, and diatomite lacustrine deposits and paleosols (Figure 11).

In the Pasco area, both the Taylor Flat and Savage Island members have been removed by cataclysmic flood erosion and only deposits belonging to the Wooded Island member are inferred to be present based on interpretation and analysis of water well logs (Lindsey et al., 2007). Due largely to cataclysmic flood erosion, the thickness of the Wooded Island member deposits beneath the Pasco study area is highly variable, ranging from absent to greater than 200 feet-thick (Figure 12).

Along with the Hanford formation, the Wooded Island member in much of the Pasco area also plays host to the unconfined aquifer (Newcomb et al., 1972; Brown, R.E., 1979; Lindsey et al., 2007; Kahle et al., 2011). However, given the physical characteristics of the Wooded Island member (i.e., presence of variable cementation within the conglomerate and the presence of interbedded overbank (silt/clay) deposits) it commonly is significantly less permeable than the Hanford formation sediments. In the Pasco area this often results in much lower yields from water supply wells completed in the saturated portion of the Wooded Island member than in a comparable, saturated portion of the Hanford formation. As Brown (R.E., 1979, p. 23) stated:

"In materials such as the Ringold Formation conglomerate, yields of wells are much lower, normally a few hundreds of gallons per minute. If a thick enough section of conglomerate were saturated and penetrated by a well, yields could approach possibly 1,000 gallons per minute or even more. In most instances, however, the conglomerates are terminated at shallow depths by the silts and clays and basalt, thus precluding high yields."

It should be noted the overbank (silt/clay) deposits that are interbedded within the Wooded Island conglomerate can be locally extensive and thick enough to form a confining layer resulting in the creation of a local "confined aquifer" beneath these silt/clay deposits. Hydrogeologic studies of the Wooded Island member conducted on the Hanford Site (e.g., Williams et al., 2000, 2002; Last et al, 2009; DOE/RL-2019-66 (Rev. 0), 2020) have clearly documented this fact.

Although the permeabilities and resultant yields of the Wooded Island member generally are significantly lower than the Hanford formation, the areal extent and thickness of the member within the Pasco area would indicate that the unit might qualify as a suitable ASR hydrogeologic candidate, depending on project requirements (Gibson and Campana, 2014; Gibson, 2018; Gibson et al., 2019). Also like the Hanford formation, additional investigation would be needed to determine if the Wooded Island member deposits within the Pasco area have characteristics necessary to accept and yield water at suitable rates, and retain and store enough water for the required period(s) of time required for this ASR project. It would also be necessary determine if the stored water might cause an unacceptable rise in the local water table (unconfined aquifer) causing local flooding.

CRBG and Ellensburg Formation Interbeds

Introduction

As noted at the beginning of this Technical Memorandum, the CRBG, and associated sediment interbeds of the Ellensburg Formation, do host confined aquifers that could be potentially utilized for the Pasco ASR project. However, nearly all past, and on-going, ASR projects in eastern Washington and Oregon have targeted and developed confined aquifers hosted by the CRBG (Gibson and Campana, 2014; Gibson, 2018; Gibson et al., 2018, 2019). Give the general success of these CRBG ASR projects elsewhere, the primary focus of the following sections will be on the upper portion of CRBG, specifically the Saddle Mountains and Wanapum Basalts (Figures 2 and 8) since they contain the shallowest potential CRBG ASR candidate aquifers beneath the Pasco area. Given the commonality of the internal physical characteristics of individual CRBG flows, and their importance in controlling the hydrogeologic behavior of groundwater within the CRBG (potential ASR candidate zones), a description of these common internal flow physical features will be presented first and followed by a discussion of the individual CRBG and Ellensburg Formation units likely present beneath the Pasco area.

CRBG Basics

The CRBG consists of more than 350 continental tholeiitic flood basalt sheet flows that cover a 77,220 square miles portion of Washington, Oregon, and western Idaho (Figure 1A) and have an estimated total volume of 53,740 cubic miles (Reidel et al., 2013b). The maximum thickness of the CRBG is inferred to occur beneath Pasco Basin area where it is estimated to be greater than 10,000 feet-thick (Reidel et al., others, 1989a,b, 2013a). These flood-basalt flows that were erupted over an 11-million-year period from about 16.8 to 5.5 Ma (Swanson et al., 1979a; Tolan et al., 1989; Barry et al., 2013) from a series of north-northwest-trending linear fissure systems located in eastern Washington, eastern Oregon, and western Idaho (Swanson et al., 1979b; Tolan et al., 1989; Reidel et al., 2013b). Although CRBG eruptive activity spanned a period of 11.3 million years, nearly all (99 volume %) of the CRBG flows (Figure 13) were emplaced over a 1.6 million-year period from 16.8 to 15.2 Ma (Reidel et al., 2013b; Barry et al., 2013).

During the peak period of CRBG eruptive activity (Figure 13), many of the flows erupted were of extraordinary size, ranging from 240 cubic miles to greater than 1,200 cubic miles in volume. The molten lava that formed theses huge flows often spread for hundreds of miles away from their source vents and eventually inundated areas encompassing many thousands of square miles (Tolan et al., 1989, 2009; Reidel et al., 2013b). Data from studies of CRBG flows and dikes (Tolan et al., 1989, 2009; Reidel et al., 1994, 2013b, 2018; Reidel and Tolan, 2013b) suggest that the emplacement rates for these gigantic basalt flows ranged from less than one months to a maximum period of several years. The volume and extent of these vast CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history and represent the largest individual lava flows know on the earth (Tolan et al., 1989).

Detailed study and mapping of the Columbia River flood-basalts throughout their extent found that it is possible to define stratigraphic units that can be reliably identified and correlated on a regional basis (e.g., see Swanson et al., 1979a,b; Beeson et al., 1985; Reidel et al., 1989b, 2013b; Wells et al., 1989; Reidel and Tolan, 2013a; Martin et al., 2013). CRBG units are identified using a combination of lithology, paleomagnetic properties, and geochemical composition with regards to superposition. Figure 2 presents the basic CRBG stratigraphy for the CRBG beneath the Pasco study area. Note that the sedimentary interbeds between CRBG units are not considered part of the CRBG, but are instead designated as units belonging to the Ellensburg Formation Figures 2 and 8).

The vast regional extent and physical size of most CRBG flows is also an extremely important factor in developing an understanding of how confined aquifers hosted by this thick sequence of basalt flows behave. Foremost is the recognition of the fact that the CRBG consists of a regionally extensive series of thick sheet flows and not a series of small compound flows or “Hawaiian basalt flow model” (Figure 14). Realization of this fact has forced a major revisions and reevaluations of the conceptual models, both regional- and local-scales, of CRBG hydrogeology and aquifer systems (Tolan et al., 2009; Vaccaro et al., 2009; Kahl et al., 2011; Burns et al., 2011, 2012, 2016). The following sections provide a brief, general overview of the nature and physical characteristics CRBG and its importance in understanding CRBG hydrogeology and aquifer systems.

Physical Features of CRBG Flows

Individual CRBG flows typically display characteristics consistent with sheet flows (Swanson et al., 1979a,b; Beeson et al., 1985, 1989; Tolan et al., 1989, 2009; Reidel et al., 1989b, 1994, 2013b, 2018; Beeson and Tolan, 1990, 1996; Reidel and Tolan, 1992, 2013a; Reidel, 1998, 2005). CRBG flows only exhibit the complex features, like those associated with compound flows, at their flow margins or distal ends (Beeson et al., 1989a; Reidel and Tolan, 1992; Reidel et al., 1994, 2013b; Beeson and Tolan, 1996; Reidel, 1998; Tolan et al., 2009). The Saddle Mountains and Wanapum Basalts flows present beneath the Pasco area (Figure 2) were emplaced as sheet flows and display a distinct three-part internal structure consisting of a flow top, a dense interior, and a flow bottom (Figure 15). All three of these types of intraflow structures play important roles in defining CRBG aquifers and aquitards (confining layers) within the CRBG aquifer system (Tolan et al., 2009). The physical and hydraulic properties of the flow top, in combination with the overlying flow bottom (and any Ellensburg Formation sediment that might be present) is termed the "interflow zone" (Figure 15) and typically hosts for water-bearing (aquifer) zones while the dense flow interiors act as aquitards within the CRBG aquifer systems. Due to the overall importance of these intrinsic CRBG flow features to our understanding of the CRBG aquifer system they will be discussed in more detail in the following sections.

Flow Tops. The flow top is the chilled, glassy upper crust of the flow. It may consist of vesicular to scoriaceous basalt, displaying pahoehoe- or a'a-like (rubbly to brecciated) textures (Diery, 1967; Swanson and Wright, 1981; USDOE, 1988; Tolan et al., 2009; Reidel et al., 2013b). Typically, a CRBG flow top occupies approximately 10 to 20% of the thickness of a flow, but in extreme case it can range from < 1% to >90% of the entire flow thickness. The physical character of flow tops falls between two basic end-members, a simple *vesicular flow top* and a *flow top breccia* (Figure 15). A ***<u>vesicular flow top</u>*** (tops of flow 1 and 2, Figure 15) commonly consists of glassy to fine-grained basalt that displays a rapid increase in the density of vesicles ("frozen gas bubbles") as you near the top of the flow (USDOE, 1988; McMillan et al., 1989). Vesicles may be isolated or interconnected (USDOE, 1988). CRBG simple vesicular flows commonly display features and textures indicative of pahoehoe flows (i.e., has a glassy, smooth, and billowy or undulating surface). A ***<u>flow top breccia</u>*** consists of angular, scoriaceous to vesicular fragments of basaltic rubble that lies above a zone of non-fragmented, vesicular to vuggy basalt (top of flow 3, Figure 15). Flow top breccias can be very thick (over half the flow thickness - more than 100 feet-thick) and laterally extensive (USDOE, 1988; Tolan et al, 2009). There are two models for the origin of CRBG flow top breccias, (1) the scoria (breccia) was originally produced along the linear fissure system and subsequently rafted away on top of the flowing lava and (2) an autobrecciation process like that which creates a'a flows in Hawaii. In either case, laterally extensive flow top breccias are relatively common flow top feature within the CRBG.

Dense Flow Interior. CRBG dense flow interiors typically consist of massive basalt that is characterized by typically non-vesicular, glassy to crystalline basalt that contains numerous contraction joints (termed "cooling joints"). These cooling joints formed in response to tensional stress created by the contraction of solidified portions of a basalt flow as it cooled below the solidus (Spry, 1962). CRBG cooling joints most often form regular patterns or styles, with the two most common being columnar-blocky jointing and entablature-colonnade (Figure 15). ***<u>Columnar-blocky jointing</u>*** typically consists of mostly vertically oriented, poorly to well-formed, polygonal columns that can range from 1 foot to greater than 10 feet in diameter (flows 1 and 2, Figure 15). The vertical columns are often cut by horizontal to subhorizontal cooling joints. ***Entablature-colonnade jointing*** (flow 3, Figure 15) displays a more complex pattern that forms within a single flow. The entablature portion displays patterns varying from numerous, irregular jointed small columns to randomly oriented cooling joints that abruptly overlie a thinner zone displaying well-developed columnar jointing. The transition zone between the entablature and the basal colonnade may be very narrow, generally less than an inch in width. Typically, the entablature is thicker than the basal colonnade, often comprising at least two-thirds of the total flow thickness. Another characteristic of entablatures is that the basalt comprising it contains a very high percentage of glass (50 to 95%) in contrast to the colonnade (Long and Wood, 1986; USDOE, 1988). While entablature-colonnade jointing style is commonly observed in CRBG flows, it is a very uncommon jointing pattern for lava flows elsewhere in the world. The origin of entablature-colonnade jointing has been the subject of much speculation and conjecture (e.g., Long and Wood, 1986; Reidel et al., 1994), but has not been resolved.

Frequency and spacing of cooling joints measured in outcrops indicate that their frequencies typically range from 1 to 37 joints per meter (3.28 feet) with entablatures showing a greater number of joints per meter than colonnades. While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be typically 77% to >99% filled with secondary minerals (clay, silica, zeolite) and void spaces that do occur are typically not interconnected (USDOE, 1988; Lindberg, 1989). The presence of pervasive secondary minerals filling the cooling joints accounts for the very low hydraulic conductivity values ("K" on Figure 15) measured within CRBG flow dense interiors and explains why the interiors of CRBG flows act as aquitards within CRBG aquifer systems (Tolan et al., 2009).

Cooling joints are distinct from secondary tectonic fractures (i.e., faults, shear zones, and joint sets) that can transect CRBG flows. These secondary tectonic fractures are distinguishable by their appearance and occurrence. Tectonic fractures typically occur in sets of parallel to subparallel, closely spaced fractures. The presence of associated shatter breccias and gouge (often altered to clay) distinguishes them from cooling joints. See the section on *Secondary Controls of CRBG Hydraulic Characteristics* for a more detailed discussion of these features and their impact on CRBG aquifers.

Flow Bottoms. The physical characteristics of CRBG flow bottoms (Figure 15) are largely dependent on the environmental conditions the molten basalt lava encountered as it was emplaced (Mackin, 1961; Swanson and Wright, 1978, 1981; USDOE, 1988; Beeson et al., 1989; Reidel et al., 1994; Beeson and Tolan, 1996; Tolan et al., 2009). If the advancing CRBG lava encountered relatively dry ground, a simple ***flow bottom*** (flows 2 and 3, Figure 15) results that commonly consists of a narrow, <2-foot-thick zone of sparsely vesicular, glassy to very fine-grained basalt (base of flows 2 and 3, Figure 15). Simple flow bottoms are very common within the CRBG.

If advancing CRBG lava encountered water (e.g., lakes, rivers, and/or areas of water-saturated, unconsolidated sediments), far more complex flow bottom structures formed (Mackin, 1961; Grolier and Bingham, 1978; Beeson et al., 1979, 1989; Swanson et al., 1979b; Tolan and Beeson, 1984; Ross, 1989; Reidel et al., 1994; Beeson and Tolan, 1996; Tolan et al., 2009; Wells et al., 2009). Where advancing lava encountered a lake, a ***pillow lava complex*** (base of flow 1, Figure 15) would be created as the molten lava flowed into the lake. A pillow complex consists of elongate to spherical lobes of basalt (pillows) set in a matrix of glassy basalt fragments. The pillows represent subaqueous pahoehoe flow lobes that advanced down the front of the pillow lava delta. Studies of the active formation of basaltic pillow lavas in Hawaii (e.g., Moore et al., 1973; Moore, 1975; Tribble, 1991) indicate that molten lava can smoothly flow into the ocean without thermal disruption (phreatic brecciation) if a thin film of highly insulating steam protects the lava from contact with the seawater. This process allows for the formation of subaqueous lava tubes (pahoehoe flow lobes that advance and grow in a manner like observed on land (Swanson, 1973; Moore, 1975; Hon et al., 1994). Disruption of this insulating steam barrier (e.g., wave action, currents, and gas explosions within the lava lobe) allows water to come into direct contact with molten lava resulting in the production of glassy debris (hyaloclastite) by phreatic brecciation. CRBG pillow lava complexes and hyaloclastites are not an uncommon feature, but their occurrence and distribution are a direct reflection of the paleodrainage patterns that existed at the time of their emplacement (Tolan and Beeson, 1984; Fecht et al., 1987; Beeson et al., 1989a; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel and Tolan, 2013).

Lateral Intraflow Structures Variation. Intraflow structures within individual CRBG flows (i.e., flow tops, dense interiors, and flow bottoms) in their originally, undisturbed state are continuously present throughout the extent of each CRBG flow. However, the appearance and thickness of intraflow structures within a flow often vary laterally throughout the flow's extent. These lateral variations often occur gradually, but in some cases can occur very abruptly. The primary factors that control changes within intraflow structures is the paleoenvironment conditions at the time the intraflow structure formed (USDOE, 1988; Beeson et al., 1989; Reidel et al., 1994; Tolan et al., 2009). Studies in the central Columbia Basin (USDOE, 1988) showed that lateral intraflow structures (i.e., flow top breccias, dense interior jointing patterns, and pillow lava complexes) in Saddle Mountains, Wanapum, and Grande Ronde Basalts can dramatically change over very relatively short distances.

Saddle Mountains and Wanapum Basalts and Ellensburg Formation – Pasco Area

In the Pasco area, the flows of the Saddle Mountains and Wanapum Basalts, along with interbedded Ellensburg Formation sediments, are considered potential targets for the Pasco ASR project since they host the uppermost portion of the CRBG confined aquifer system beneath this area. Plates 1 and 2 present two geologic cross-sections through the Pasco area that depict the inferred subsurface CRBG geology based on the best available geologic and hydrogeologic information gathered from the following sources:

- Geologic interpretation of water well driller's logs in the Pasco area conducted by the Columbia Basin GWMA (Tolan et al., 2007).
- Geologic logs from deep cored wells (Appendix A) in the southeastern portion of the U.S. Department of Energy Hanford Site (Myer and Price, 1981; USDOE, 1988).
- Geologic logs from the City of Kennewick CRBG ASR well project (Cunnane, 2011; Pitre and Gerst, 2014) and the geologically logged Welch's water supply well in Kennewick (NW1/4 NW1/4 section 6, T8N, R30E) (Appendix A).
- Surface geologic mapping of the greater Pasco area (Grolier and Bingham, 1971, 1978; Swanson and Helz, 1979; Swanson et al., 1980; Myers and Price, 1981; Hagood, 1986; Reidel and Fecht, 1994a,b; Reidel et al., 2020).

The following sections provide a brief description of the CRBG and Ellensburg Formation units, from youngest to oldest, depicted in the geologic cross-sections (Plates 1 and 2).

Ice Harbor Member, Saddle Mountains Basalt. The 8.5 Ma Ice Harbor Member (Figures 2 and 16) represents the youngest CRBG unit in the area and may consist of up to 3 units and may consist of a total of two to four sheet flows. Often the uppermost (youngest) Ice Harbor flow present has either an eroded flow top (where Ringold Formation overlies it) or a deeply weathered vesicular flow top. In the Hanford Site core-hole DC-15 (Appendix A) they encountered two Ice Harbor flows, with the lower flow having a 20 foot-thick flow top breccia. The Ice Harbor flows commonly have blocky to columnar jointing and normal flow bottom. The thickness of the Ice Harbor Member in the Pasco area is estimated to range from 100 to >150 feet thick (Plates 1 and 2).

Where more than one Ice Harbor Member flow is present, water supply wells that penetrate these interflow zones within the Ice Harbor Member indicate that they do produce groundwater. However, groundwater yields from the Ice Harbor Member interflow zones (aquifers) are commonly low, ranging from 20 to 50 gpm. The low groundwater yields from the Ice Harbor Member interflow (aquifer) zones suggests that this unit is not a viable candidate for this ASR project.

Levey Member, Ellensburg Formation. The Levey Member of the Ellensburg Formation (or “Levey interbed”) is defined as sediments found between the 8.5 Ma Ice Harbor Member and 10.5 Ma Elephant Mountain Member of the CRBG (Figure 2). In the Pasco area the Levey sediments were likely deposited by the ancestral Salmon-Clearwater River (forerunner of the Snake River; Figure 16) and in this area consists of semi-indurated silt, clay, and fine sand. Thickness of the Levey interbed in the Pasco area is estimated to range from 10 feet- to 20 feet-thick (Plates 1 and 2).

Elephant Mountain Member, Saddle Mountains Basalt. The 10.5 Ma Elephant Mountain Member typically consists of two unit each represented by a single flow in the Pasco area (Figures 2 and 16). The younger Ward Gap flow often has a simple vesicular flow top, a well-developed entablature-colonnade dense interior, and a simple vesicular flow bottom. The older Elephant Mountain flow often has a flow top breccia (10 to 40 feet-thick) and a well-developed entablature-colonnade dense interior. The flow bottom of the Elephant Mountain flow can range from a thin (< 2 feet-thick) simple vesicular flow bottom to a basal pillow complex (ranging from 2 to 10 foot-thick) in some areas. The total thickness of the Elephant Mountain Member is variable within the Pasco area due to thickening and thinning of these flows during the emplacement process (pre-existing topography). The total thickness of the Elephant Mountain Member in the Pasco area is estimated to range from 90 feet- to 140 feet-thick (Plates 1 and 2).

Groundwater yields from Elephant Mountain Member interflow zones (aquifers) are highly dependent on the type of flow top/flow bottom intraflow structures that are present at the well location. In the Pasco Basin where Elephant Mountain Member interflow zones consist of simple vesicular flow tops/flow bottoms, the groundwater yield from these zones are often lower than 50 gpm. However, where either a flow top breccia and/or basal pillow complex is present, groundwater yields from Elephant Mountain Member interflow zones (aquifers) can be much higher, ranging from 100 to greater than 300 gpm (USDOE, 1988). If the right combination of Elephant Mountain flow top breccia/flow bottom (pillow complex) were present, it is possible that the Elephant Mountain Member might potentially be a viable ASR target. However, there is no data on the nature of the Elephant Mountain Member interflow zones beneath the Pasco area currently available.

Rattlesnake Ridge Member, Ellensburg Formation. The Rattlesnake Ridge Member of the Ellensburg Formation (or "Rattlesnake Ridge interbed") is defined as sediments found between the 10.5 Ma Elephant Mountain Member and 11.8 Ma Pomona Member of the CRBG (Figure 2; Swanson et al., 1979b). In the Pasco area, the Rattlesnake Ridge interbed is inferred to consist of semi-indurated silt, clay, and possibly fine-sand which represent overbank deposits of the ancestral Salmon-Clearwater River (Figure 16). The Rattlesnake Ridge interbed is believed to be a very thin deposit in the Pasco area, likely ranging from 1 foot- to 5 feet-thick (Plates 1 and 2).

Pomona Member, Saddle Mountains Basalt. The 11.8 Ma Pomona Member (Figure 2-2) typically consists of a single flow within the Pasco Basin, but can locally consist of two "flow-lobes" that together collectively define a single sheet flow (USDOE, 1988; Reidel and Fecht. 1994a,b). The Pomona flow (and flow lobes) commonly have a 5 foot- to 15 foot-thick simple vesicular flow top, entablature jointing with a thin basal colonnade dense interior, and thin, vesicular flow bottom. Less commonly the Pomona flow may locally have a 10 foot- to 20 foot-thick flow top breccia and a thin (less than 5 foot-thick) basal pillow lava complex. The thickness of the Pomona Member in the Pasco Basin is variable due to thickening and thinning of this lava flow during the emplacement process (pre-existing topography). Based on limited well data in, and adjacent to, the Pasco area, the estimated thickness of the Pomona Member ranges from 120 feet- to 150 feet-thick (Plates 1and 2).

Like the Elephant Mountain Member, groundwater yields from Pomona Member interflow zones are highly dependent on the type of flow top/flow bottom intraflow structures that are present at the well location. In the Pasco Basin where Pomona Member interflow zones consist of simple versicular flow tops/flow bottoms, the groundwater yield from these zones are often less than 30 gpm. However, where a flow top breccia and/or basal pillow complex is present, groundwater yields from the Pomona Member interflow zones can be greater than 100 gpm (USDOE, 1988). Like the Elephant Mountain Member, there is no currently available data on the nature and groundwater yields from the Pomona Member interflow zones beneath the Pasco area. However, the generally low groundwater yields from the Pomona Member interflow (aquifer) zones elsewhere in the Pasco Basin suggests that this unit is not a likely candidate for this ASR project.

Selah Member, Ellensburg Formation. The Selah Member of the Ellensburg Formation (or "Selah interbed") is defined in the Pasco area the sediments found between the 11.8 Ma Pomona Member and older Esquatzel Member of the CRBG (Figure 2; Swanson and others, 1979b). If the Esquatzel Member happens not to present in the Pasco study area, then the Selah Member would encompass all sediments from the base of the Pomona Member to the top of the Umatilla Member (Figure 17). In the Pasco area, the Selah interbed likely consists of semi-indurated silt/clay and sand may be capped (directly overlain by the Pomona flow) by a volcanic ash (tuff). This tuff is often fused to a perlitic vitric tuff due to heat from the cooling Pomona lava. The Selah Member sediments are believed to represent overbank deposits of the ancestral Salmon-Clearwater River (Figure 2-16). Thickness of the Selah interbed in Pasco area likely ranges from 30 feet- to 60 feet-thick (Plates 1 and 2).

Esquatzel Member, Saddle Mountains Basalt. The Esquatzel Member (Figures 2 and 16) typically consists of a single sheet flow in the Pasco Basin (Reidel, unpublished data). The Esquatzel flow commonly has a flow top breccia (comprising 20 to 30% of the total flow thickness), a well-developed entablature-colonnade jointed dense interior, and a thin vesicular flow bottom. The Esquatzel Member is mainly confined to the northern and western portions of the Pasco Basin (Figure 16). Thickness of the Esquatzel Member is variable within Pasco Basin due to thickening and thinning due to pre-existing topography. The Pasco area may staddle the southern flow margin (Figure 16) of the Esquatzel flow producing a highly variable, north to south thickness that ranges from zero (south) to greater than 50 feet- to over 100 feet-thick in the north (Plates 1 and 2). The approximate location of the southern margin of this flow is based on the geologic log for the Welch's well (Appendix A).

There is no specific information available on potential groundwater yields from the Esquatzel Member in the Pasco Basin area.

Cold Creek Member, Ellensburg Formation. The Cold Creek Member of the Ellensburg Formation (or "Cold Creek interbed") is defined in the Pasco Basin as sediments found between the Esquatzel Member and the 13.0 Ma Umatilla Member of the CRBG (Figures 2 and 17). Where the Esquatzel Member (or Asotin Member is absent; Figure 17), the sediments between the Pomona and Umatilla Members are defined as the Selah Member of the Ellensburg Formation. In the Pasco Basin the Cold Creek interbed typically consists of semi-indurated silt/clay which are interpreted to represent overbank deposits of the ancestral Salmon-Clearwater River (Figure 16). Thickness of the Cold Creek interbed in the Pasco area ranges from absent to >70 feet-thick (Plates 1 and 2; USDOE, 1988).

Umatilla Member, Saddle Mountains Basalt. The 13.0 Ma Umatilla Member in the Pasco Basin typically consists of two units (Figure 2) that are each represented by a single sheet flow. Based on the geologic log for the Welch's well (Appendix A), both Umatilla units are likely present beneath the Pasco area. Each Umatilla flow can have either a simple vesicular flow top or a flow top breccia, both commonly display well-developed entablature-colonnade jointed dense interiors and thin vesicular flow bottoms or less commonly a "flow bottom breccia" as appears to be present at the bottom of the Sillusi flow in the Welch's well (Appendix A). Total thickness of the Umatilla Member is variable, ranging from 180 feet- to more than 270 feet-thick within the Pasco Basin (USDOE, 1988; Tolan et al., 2009) due to thickening and thinning of these lava flows during the emplacement process (pre-existing topography). The thickness of the Umatilla Member beneath the Pasco area is inferred to be approximately 180 feet- to 200 feet-thick (Plates 1 and 2).

As noted above for the other Saddle Mountains Basalt members, groundwater yields from Umatilla Member interflow zones are highly dependent on the type of flow top/flow bottom intraflow structures that are present at the well location. In the Pasco Basin where Umatilla Member interflow zones consist of simple versicular flow tops/flow bottoms, the groundwater yield from these zones are often less than 50 gpm. However, where a flow top, or flow bottom, breccia zones are present groundwater yields from these interflow zones can be many times greater (USDOE, 1988). The ability of flow breccia zones to produce high groundwater yields is clearly documented demonstrated in the Welch's well which was drilled in 1981 (Appendix A). Based on the geologist and driller's logs (Appendix A), the Welch's well penetrated an interflow zone (base of the Sillusi flow/top of the Umatilla flow) within the Umatilla Member that consisted of a flow bottom breccia/flow top breccia that was approximately 50 feet-thick and capable of very high groundwater yields (pump-tested at 1,390 gpm with 100 feet of drawdown; Welch's well log, Appendix A). The driller reported that this water-bearing zone had artesian pressure - flowing well at ground surface. The high groundwater yield from this Umatilla Member interflow (aquifer) zone in the Welch's well indicates that it could serve as a viable ASR candidate zone – if present beneath the Pasco area.

Mabton Member, Ellensburg Formation. The Mabton Member of the Ellensburg Formation (or "Mabton interbed") is defined as sediments found between the Umatilla Member and the top of the Wanapum Basalt (Figures 2 and 17). Few wells in the Pasco Basin outside of the Hanford Site have been drilled deep enough to penetrate the Mabton interbed (see Appendix A). Based on the limited data from this area, the Mabton interbed appears to consist of semi-indurated silt, sand, and tuffs representing overbank deposits of the ancestral Salmon-Clearwater River. Thickness of the Mabton interbed the Pasco area is inferred to range from 30 feet- to 50 feet-thick (Plates 1 and 2).

Priest Rapids Member, Wanapum Basalt. The 15.2 Ma Priest Rapids Member (Figures 2) consists of two units, each represented by a single sheet flow, in the southern and southeastern portion of the Pasco Basin (Myers and Price, 1981; USDOE, 1988, Tolan et al., 2007). There is no direct subsurface information on the Priest Rapids Member beneath the Pasco area. The only information on the Priest Rapids Member comes from geologically logged deep wells to the west (City of Kennewick ASR wells; Appendix A) and northwest (Hanford Site well DDH-3, DC-15, DB-1, and DB-2; Appendix A). The geologic logs from these deep wells suggest that only the younger Lolo flow is likely present beneath the Pasco area. The Lolo flow may have either a thin (less than 10 feet-thick) flow top breccia (DDH-3 geologist log, ARH-ST-137 (1976, p. C-30); Appendix A) to a thin simple vesicular flow top, a well-developed columnar-blocky jointed dense interior, and a thin vesicular flow bottom. Thickness of the Lolo flow varies within Pasco Basin to thickening and thinning due to pre-existing topography. Beneath the Pasco area, the thickness of the Lolo flow is estimated to range from 130 feet- to 170 feet-thick (Plates 1 and 2).

There is no specific information available on potential groundwater yields from the Priest Rapids Member in the Pasco area. Based on the inferred characteristics of the Lolo flow's intraflow structures and interflow zones likely present, it is estimated that this flow would have low to intermediate range (20 to 200 gpm) groundwater yields. Since there is no available data on the nature and groundwater yields from the Priest Rapids Member beneath the Pasco area it cannot be ruled out as a candidate for this ASR project.

Quincy Member, Ellensburg Formation. The Mabton Member of the Ellensburg Formation (or "Quincy interbed") is defined as sediments found between the bottom of the Priest Rapids Member and the top of the Roza Member (Figures 2 and 17). Few wells in, and adjacent to, the Pasco area have been drilled deep enough to penetrate the Quincy interbed (see Appendix A). Based on the limited data from this area, the Quincy interbed appears to consist of semi-indurated silt, clay, and diatomite, with minor beds of fine sand, which represent a lacustrine (lake) depositional environment (Fecht et al, 1987; Reidel and Tolan, 2013b). Thickness of the Quincy interbed in the Pasco area could be highly variable, potentially ranging from less than 5 feet- to more than 20 feet-thick (Plates 1 and 2).

Roza Member, Wanapum Basalt. In the greater Pasco Basin area, the 14.9 Ma Roza Member (Figures 2) can consist of up to three sheet flows (Myers and Price, 1981; USDOE, 1988, Martin, 1989; Tolan et al., 2007). The southern margin of the Roza Member is inferred to lie south of the Pasco area and follows roughly along the track of the modern-day Snake River (USDOE, 1988; Martin, 1989). However as noted above for Priest Rapids Member, there is no direct subsurface information on the Roza Member beneath the Pasco area. The only information on the Roza Member comes from geologically logged deep wells to the northwest (Hanford Site well DDH-3, DC-15, and DB-2; Appendix A). The geologic logs from these deep wells suggest that at least one Roza flow is likely present beneath the Pasco area. This Roza flow may have either a thin (less than 10 feet-thick) simple vesicular flow top or possibly a 30 foot- to 50 foot-thick flow top breccia (DDH-3 geologist log, ARH-ST-137 (1976, p. C-32); Appendix A), a well-developed columnar-blocky jointed dense interior, and a thin vesicular flow bottom. Thickness of the Roza flow varies within Pasco Basin due to thickening and thinning due to pre-existing topography. Beneath the Pasco area the thickness of the Roza flow is estimated to range from 140 feet- to 170 feet-thick (Plates 1 and 2).

There is no specific information available on potential groundwater yields from the Roza Member in the Pasco Basin. However, if the Roza flow beneath the Pasco area does possess a 30 foot- to 50 foot-thick flow top breccia, this interflow zone might be capable of moderate to high (greater than 500 gpm) groundwater yields and might be a good potential candidate for this ASR project.

Squaw Creek Member, Ellensburg Formation. The Squaw Creek Member of the Ellensburg Formation (or “Squaw Creek interbed”) is defined as sediments found between the bottom of the Roza Member and the top of the Frenchman Springs Member (Figures 2 and 17). Few wells in, and adjacent to, the Pasco area have been drilled deep enough to penetrate the Squaw Creek interbed (see Appendix A). Based on the limited data from this area, the Squaw Creek interbed appears to consist of semi-indurated silt, clay, and diatomite which represent a lacustrine (lake) depositional environment (Fecht et al, 1987; Reidel and Tolan, 2013b). Thickness of the Squaw Creek interbed the Pasco area is likely very thin, ranging from 0 feet- to less than 2 feet-thick (Plates 1 and 2).

Frenchman Springs Member, Wanapum Basalt. In the Pasco Basin area, the 15.0 to 15.4 Ma Frenchman Springs Member (Figures 2) consists of between 9 to 14 sheet flows that has been subdivided into five separate units (USDOE, 1988, Tolan et al., 1989, 2007; Martin et al., 2013). All five of the Frenchman Springs Member subunits (Figure 2) are inferred to be present beneath the Pasco area (Tolan et al., 1989; Martin et al., 2013). However as noted for the other Wanapum Basalt members, there is no direct subsurface information on the Frenchman Springs Member beneath the Pasco area. The only information on the complete Frenchman Springs Member section comes from geologically logged deep wells to the northwest (Hanford Site well DDH-3 and DC-15; Appendix A), west (Kennewick ASR wells. Appendix A), and south (Wallula Gap surface geologic section, ARH-ST-137 (1976, p. B.22-B.26). The geologic logs from these deep wells and measured Frenchman Springs Member surface section at Wallula Gap show that at more than half of the flows present at these locations have flow top breccias that comprise from 10% to more than 40% of the individual flow thickness, well-developed columnar-blocky jointed dense interiors, and typically a thin vesicular flow bottom. Beneath the Pasco area, the total thickness of the Frenchman Springs Member is estimated to be from 700 feet- to 800 feet-thick (Plates 1 and 2).

There is no specific information available on potential groundwater yields from the Frenchman Springs Member in the Pasco Basin. However, the possible presence of apparently areally extensive, multiple, flow top breccias within the Frenchman Springs Member section throughout this area would indicate that these flow top breccias are also present beneath Pasco area. There is a high likelihood that one, or more, of these Frenchman Springs Member interflow zones are capable of moderate to very high (greater than 1,000 gpm) groundwater yields would make them good potential candidates for this ASR project.

Vantage Member, Ellensburg Formation. The Vantage Member of the Ellensburg Formation (or "Vantage interbed") is defined as sediments found between the bottom of the Wanapum Basalt (Frenchman Springs Member) and the top of the Grande Ronde Basalt (Figures 2 and 16). Few wells near the Pasco area have been drilled deep enough to penetrate the Vantage interbed (see Hanford Site wells DDH-3 and DC-15, Appendix A). Based on the limited data from this area, the Vantage interbed appears to consist of semi-indurated clay and paleosol (deeply weathered basaltic "soil") developed on top of the uppermost Grande Ronde Basalt flow (Fecht et al, 1987; Reidel and Tolan, 2013b). Thickness of the Vantage interbed the Pasco area is likely very thin, ranging from 0 feet- to less than 2 feet-thick (Plates 1 and 2).

Hydrogeology of the CRBG

Introduction

In the above sections, the physical characteristic of CRBG sheet flow intraflow structures have been defined and described. These basic CRBG internal flow structures (e.g., Figure 5) play a major role in governing the hydraulic properties and behavior groundwater within CRBG aquifers. The following sections ill proved a more detailed description of our current understanding of how all of these features and various other geologic factors, both internal and external, combine to create and control the CRBG aquifer system in general and beneath the Pasco area.

Background

Before the late 1990's to early 2000's, numerous groundwater investigations had been previously conducted in the Columbia Plateau region to better understand the hydraulic properties and characteristics of CRBG aquifers and to develop a model of how various factors (e.g., CRBG flow physical characteristic/properties, tectonic features/properties, erosional features, climate, etc.) interact to create and govern this "semi-confined to locally confined" groundwater system (e.g., Newcomb, 1961, 1969; Hogenson, 1964; Luzier et al., 1968; Luzier and Skrivan, 1975; Brown, J.C., 1978, 1979; Gephart et al., 1979; Oberlander and Miller, 1981; Vaccaro, 1986; Drost and Whiteman, 1986; Livesay, 1986; Strait and Mercer, 1987; Davies-Smith et al., 1988; Lite and Grondin, 1988; USDOE, 1988; Burt, 1989; Lum et al., 1990; Hansen et al., 1994; Spane and Webber, 1995; Steinkampf and Hearn, 1996; Packard et al., 1996; Sabol and Downey, 1997). Unfortunately for these hydrogeologists, the prevailing Columbia River basalt conceptual model during this time envisioned the basaltic lava flows that underlie the Columbia Plateau were erupted and emplaced in a manner very similar to basalt flows produced by active Hawaiian basaltic volcanism ("Hawaiian model"). As discussed above, we now know that Hawaiian basaltic volcanism model is not a correct analog model for CRBG volcanism. Using the Hawaiian model as an analog for the CRBG resulted in several flawed assumptions being incorporated into the CRBG hydrogeologic model included:

1) CRBG collectively consist of many thousands, to potentially hundreds of thousands of individual "shoestring" lava flows that were erupted from numerous, coalescing shield volcanoes across the entire extent of the CRBG.
2) That individual CRBG flows would have restricted areal extents and likely not travel more than 5 to 10 miles from there source vent (i.e., localized compound flow geometries; Figure 14).
3) Typical emplacement geometries of shoestring basalt flows (Figure 18) result in a generally unconfined to semi-confined aquifer system where groundwater can typically move both horizontally and vertically through and around individual flows as well as through flow interiors via cooling joints, except where local confining layers (clay/silt sediment interbeds) would occasionally give rise to localized confined aquifer conditions.
4) The CRBG groundwater flow system would generally behave as an unconfined aquifer system at broader regional scales and would allow for both widespread vertical and horizontal movement (including recharge and discharge) of groundwater within the CRBG (Figure 19).

By the late 1980's and early 1990's CRBG researchers had realized that the Hawaiian model was not an analog for the CRBG flood basalt province or the emplacement of individual CRBG flows (USDOE, 1988; Reidel and Hooper, 1989). However, many of the hydrogeologists working on the CRBG aquifer system were slow to realize that the "Hawaiian model" had been invalidated and replaced by a totally new model that recognized the vast extent thickness of individual CRBG flows and that the internal physical characteristics of these flood-basalt flows do not resemble either Hawaiian a'a or pahoehoe flows (Figure 18). Some hydrogeologist researchers (e.g., Newcomb, 1961, 1969; USDOE, 1988; Johnson et al., 1993; Wozniak, 1995; Tolan et al., 2000) recognized that the data collected from the CRBG aquifer system did not fit the Hawaiian model and had suggested alternative models for the CRBG aquifer system. This resulted in substantial disagreement regarding the hydraulic characteristics and hydrologic behavior of CRBG aquifer systems on both the local and regional scale. Much of this confusion and disagreement is in large part due to the continuing unfamiliarity with above mentioned revisions to CRBG physical geology and under-estimating its importance and the role of other geologic features on controlling CRBG aquifer systems.

By the late 2000's, the fundamental importance of the revisions to CRBG physical geology on the understanding and modeling of the CRBG aquifer systems has become widely accepted (e.g., Tolan et al., 2009; Burt et al., 2009; Vaccaro et al., 2009, Eaton et al., 2009; Burns et al., 2016). The general similarity of the hydrogeologic characteristics, properties, and behavior of the CRBG aquifers across this flood-basalt province is one of the most significant findings to emerge from these studies. Therefore, much of the general knowledge of the characteristics and behavior CRBG aquifers in one area can be generally applied to CRBG aquifers in other areas. The purpose of the following sections is to briefly summarize the basic hydrogeologic characteristics of CRBG aquifer system and what we can infer about the Saddle Mountains and Wanapum Basalts aquifers beneath the Pasco area.

Hydraulic Characteristics of CRBG Intraflow Structures

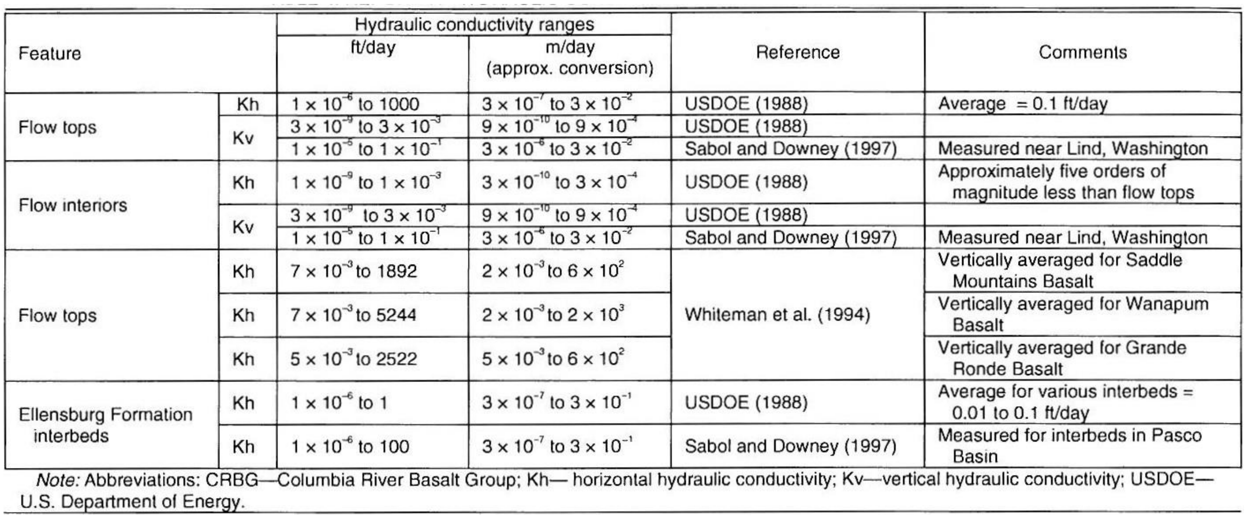
Groundwater within the CRBG section generally occurs as a series of confined aquifers hosted within interflow zones and associated Ellensburg Formation sedimentary interbeds. The physical characteristics and properties of individual CRBG flows affect their intrinsic hydraulic properties and influence the potential distribution of groundwater within the CRBG sheet flows (Figures 14 and 15). As discussed earlier, CRBG sheet flows exhibit a basic three-part internal arrangement of internal intraflow structures (Figure 15) that originate during the emplacement and cooling of the lava flows. The combination of a flow top of one flow and the flow bottom of the overlying flow is commonly referred to as the "interflow zone." It is widely agreed that groundwater in most CRBG aquifers primarily resides within the interflow zones (Newcomb, 1969; Oberlander and Miller, 1981; Lite and Grondin, 1988; Davies-Smith et al., 1988; USDOE, 1988; Wozniak, 1995; Tolan et al., 2000; Reidel et al., 2002; Tolan and Lite, 2008; Eaton et al., 2009; Burt et al., 2009; Vaccaro et al., 2009; Tolan et al., 2009; Burns et al., 2016) and these interflow zones, in comparison to the flow's dense interior, serve as the predominant water-transmitting zones (aquifers) within the CRBG (USDOE, 1988). In their original undisturbed state, individual interflow zones are as laterally extensive as the sheet flows that define them. Given the extent and thickness (geometry) of individual interflow zones, this creates a series of relatively tabular, stratiform layers that potentially host aquifers within the CRBG (Figure 15).

The presence of interbedded sediments can either enhance (e.g., sandstone and conglomerate) or inhibit (e.g., mudstone and paleosols) groundwater storage and movement within CRBG interflow zones. Another critical aspect with respect to interflow zones, that is not commonly recognized, is their potential lateral variability. As previously discussed, thick flow top breccias are known to abruptly end with a much thinner normal flow top taking its place (e.g., Figure 20a). The same is true for flow bottom features (e.g., pillow complexes) that can abruptly end or transition to a simpler flow bottom. These intraflow structure "facies changes" can result in radical changes of the hydraulic properties and behavior of individual CRBG aquifers being pumped by wells (Figure 20b).

The physical properties of CRBG flow dense interiors result in this portion of the flow being essentially impermeable for all practical purposes (Newcomb, 1969; Oberlander and Miller, 1981; Davies-Smith et al., 1988; Lite and Grondin, 1988; USDOE, 1988; Lindberg, 1989; Wozniak, 1995; Tolan et al., 2009; Burt et al., 2009; Eaton et al., 2009). While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be largely filled with secondary minerals (clay, silica, zeolite) and void spaces that do occur are typically not interconnected (USDOE, 1988; Lindberg, 1989). The fact that CRBG dense flow interiors typically act as aquitards accounts for the confined behavior exhibited by CRBG aquifers. Artesian (flowing) conditions have been encountered within many areas around the Columbia Plateau (e.g., Welch's well in Kennewick (Appendix A).

A range of hydraulic conductivity values are reported for CRBG aquifers in USDOE (1988), Whiteman et al. (1994), and Sabol and Downey (1997) and are summarized in Table 1. The values of hydraulic conductivity reported in Whiteman et al. (1994) rely heavily on data reported on driller's well reports from many wells that are open to multiple CRBG aquifers. These lateral conductivities integrate values over the entire depth of penetrated CRBG and therefore, reflect the contribution from inter-layer vertical movement of groundwater past CRBG flow pinch-outs, faulting, and other discontinuities in individual CRBG flow layers. The hydraulic conductivities of an individual interflow zone within the tested intervals may be substantially higher (or lower) than the reported value.

Table 1. Reported Hydraulic Conductivity Ranges for CRBG aquifers. Reproduced from Tolan et al. (2009).



Feature		Hydraulic conductivity ranges		Reference	Comments
		ft/day	m/day (approx. conversion)		
Flow tops	Kh	1×10^{-6} to 1000	3×10^{-7} to 3×10^{-2}	USDOE (1988)	Average = 0.1 ft/day
	Kv	3×10^{-9} to 3×10^{-3}	9×10^{-10} to 9×10^{-4}	USDOE (1988)	
		1×10^{-5} to 1×10^{-1}	3×10^{-6} to 3×10^{-2}	Sabol and Downey (1997)	Measured near Lind, Washington
Flow interiors	Kh	1×10^{-9} to 1×10^{-3}	3×10^{-10} to 3×10^{-4}	USDOE (1988)	Approximately five orders of magnitude less than flow tops
	Kv	3×10^{-9} to 3×10^{-3}	9×10^{-10} to 9×10^{-4}	USDOE (1988)	
		1×10^{-5} to 1×10^{-1}	3×10^{-6} to 3×10^{-2}	Sabol and Downey (1997)	Measured near Lind, Washington
Flow tops	Kh	7×10^{-3} to 1892	2×10^{-3} to 6×10^{2}	Whiteman et al. (1994)	Vertically averaged for Saddle Mountains Basalt
	Kh	7×10^{-3} to 5244	2×10^{-3} to 2×10^{3}		Vertically averaged for Wanapum Basalt
	Kh	5×10^{-3} to 2522	5×10^{-3} to 6×10^{2}		Vertically averaged for Grande Ronde Basalt
Ellensburg Formation interbeds	Kh	1×10^{-6} to 1	3×10^{-7} to 3×10^{-1}	USDOE (1988)	Average for various interbeds = 0.01 to 0.1 ft/day
	Kh	1×10^{-6} to 100	3×10^{-7} to 3×10^{-1}	Sabol and Downey (1997)	Measured for interbeds in Pasco Basin

Note: Abbreviations: CRBG—Columbia River Basalt Group; Kh— horizontal hydraulic conductivity; Kv—vertical hydraulic conductivity; USDOE—U.S. Department of Energy.

Values of storativity in the CRBG are commonly between 10^{-4} and 10^{-5} reflecting the high degree of confinement of the interflow zones and incompressible aquifer matrix (Conlon and others, 2005, McFarland and Morgan, 1998). Higher values of storativity calculated from some aquifer tests may indicate less confinement in some parts of the shallow CRBG aquifer system. Some may represent tests in the uppermost basalt interval that are hydraulically connected through surface fractures to the overlying suprabasalt sediments or land surface. Lateral facies changes in the interflow zones (e.g., Figure 20), wells open to multiple interflow zones, and the presence of structural boundaries complicate estimation of aquifer parameters based on Theisien analysis of pumping test data and may result in misleading parameter values.

The available data on hydraulic properties of the various CRBG aquifers, including permeability, porosity, and storativity, indicate that a large variability in local flow characteristics is expected. However, hydraulic data is generally sparse and cannot be extrapolated easily to other locations within the area. Finally, pumping and recharge can locally alter hydraulic gradients and flow directions during the year, especially near aquifer boundaries.

Secondary Controls on CRBG Hydraulic Characteristics

There are several processes that can modify the specific, and overall, hydraulic characteristics and behavior of CRBG aquifers and aquitards. These include tectonic fracturing forming faults/tectonic joints, folding, presence of CRBG feeder dikes, and secondary mineralization/alteration. The potential effect and impact of these various processes on CRBG groundwater systems can range from benign to profound. Understanding their impact on CRBG aquifers is critically important to accurately interpreting the behavior of CRBG aquifer systems in any specific locality.

Faults and Tectonic Joints. The presence of faults that cut through the CRBG have long been recognized as important features that can impact both lateral and vertical groundwater movement within the CRBG aquifers (e.g., Newcomb 1959, 1961, 1969; Lite and Grondin, 1988; USDOE, 1988; Johnson et al., 1993; Tolan et al., 2000, 2009; Reidel et al., 2002; Burt et al., 2009). Faulting in the CRBG tends to produce a roughly planar zone composed of coarsely shattered basalt that grades into very fine rock flour. Figure 21 presents a diagrammatic sketch of the typical physical features and terminology for a fault zone cutting CRBG flows. The width of the fault zone (shatter breccia and gouge) can be highly variable (< 1 foot- to >300 feet-thick) and its thickness typically depends on:

1) Magnitude of fault displacement.

2) Type of fault (low-angle fault vs. high-angle fault).

3) Type(s) of CRBG intraflow structures cut by the fault (Price, 1982; Reidel, 1984; Hagood, 1986; Anderson, 1987; USDOE, 1988).

The dense interior portions of CRBG flows have a greater mechanical strength than either the flow top or flow bottom (interflow zone). This greater susceptibility is typically manifested by the widening of the fault zone, and associated effects, as it passes through these mechanically weaker portions of the flow (Price, 1982; USDOE, 1988). It has also been suggested that the presence of water within intraflow structures may decrease the relative strength of the rock and may be another factor contributing to deformational behavior in flow tops and flow bottoms (USDOE, 1988).

Fault zone shatter breccias (Figure 22) often display significant degrees of alteration (clays) and/or secondary mineralization (silica, zeolite, calcite, and pyrite). These materials can cement shatter breccias and create a rock that is so massive and tough that CRBG fault breccias are commonly more resistant to erosion than unbrecciated CRBG (Myers and Price, 1981; Price, 1982; Anderson, 1987). The types of secondary minerals present within CRBG fault zones appears to be dependent both environmental conditions (oxidizing vs. reducing) and in situ conditions (e.g., water chemistry, thermal regime, hydrologic regime; Myers and Price, 1981; Price, 1982; USDOE, 1988).

Faults have been found to impact the CRBG groundwater system in several ways. They can:

1) Form barriers to the lateral movement of groundwater and a series of faults can create hydrologically isolated areas “compartments”.

2) Faults and tectonic joints can provide a potential vertical pathway (of varying length) for vertical groundwater movement allowing otherwise confined CRBG aquifers to be in direct hydraulic communication.

3) They can expose interflow zones creating local opportunities for CRBG aquifer recharge and/or discharge.

The most relevant and important of these fault-induced impacts with regards to the Pasco area is the presence of major faults associated with the RAW and Umtanum Ridge extension/Saddle Mountains form the western and northern hydrogeologic boundaries, respectively, of the Pasco Basin (Figure 1). The southeastern extension of the Yakima Ridge anticline and inferred fault(s) (part of the RAW; Figure 1) lies along the western boundary of the Pasco area. The Yakima Ridge fault, along with other parallel faults associated with the RAW (Reidel et al., 2020), likely form a hydrogeologic barrier that inhibits groundwater within CRBG aquifers from moving from the Pasco area to the west and southwest. Majors faults associated with the Saddle Mountains, and possibly associated with the eastward extension of Umtanum Ridge (Figure 1), create barriers to horizontal groundwater movement within the CRBG aquifer system (USDOE, 1988).

The ability of faults that cut the CRBG aquifer systems to provide a vertical groundwater pathway (either up or down) is highly dependent on both the both lateral and vertical heterogeneities within the fault zone's hydraulic properties. For example, the degree of secondary alteration and mineralization of the shatter breccia along a fault zone often varies. Where shatter breccias are highly altered and/or mineralized, this "cementation process" drastically reduces, or destroys, the permeability of these zones. Variations in the completeness of this process would produce hydrologic heterogeneities along the trace of the fault. Even if a fault zone is completely healed by secondary alteration and mineralization, renewed movement (seismic activity) on the fault could produce new permeability within the cemented fault shatter breccia (e.g., USDOE, 1988; Johnson et al., 1993).

Folding. Several groundwater investigations in the Columbia Plateau area have noted that folds (primarily anticlinal and monoclinal folds) affect the occurrence and movement of groundwater through CRBG aquifers (e.g., Newcomb 1961, 1969; Gephart et al., 1979; Oberlander and Miller, 1981; Lite and Grondin, 1988; USDOE, 1988; Burt, 1989; Packard et al., 1996). In many cases, folds have been identified as groundwater barriers or impediments that either block or restrict lateral groundwater movement through the CRBG aquifer system (e.g., Newcomb, 1969; Oberlander and Miller, 1981; USDOE, 1988). Because most of the folds in this region have genetically related faults, one would initially suspect that the observed impacts of folds on the CRBG aquifer system are caused by related faults. However, the process of folding the CRBG can affect the hydraulic characteristics of interflow zones.

During the process of folding, slippage parallel to the layers (CRBG flows) will occur, in part, to accommodate structural shortening. An analogy for this process is seen when a deck of playing cards is flexed and the individual cards slip past one another to accommodate the flexure. The tighter the flexure of the cards, the greater the "intercard" slippage. In folds, this type of flexural slip typically occurs within CRBG interflow zones (Newcomb, 1969; Price, 1982; Anderson, 1987) which are the mechanically weakest layers in the CRBG. The effects of this flexural slip on CRBG interflow zone range from minor shearing to nearly complete destruction (production of fault shatter breccia/gouge material) and are directly related to the intensity and magnitude of deformation (Price, 1982; Anderson, 1987). This process also impacts the original hydraulic characteristics of interflow zones, reducing or even destroying the permeability of these features (Newcomb, 1969).

With regards to the Pasco area, this process may play a minor role along the eastern boundary of the Pasco Basin/Palouse Slope (Figure 1) which was originally defined by the southwest-dipping, north-northwest-trending monoclinal fold (Jackass monocline/anticlinal; Newcomb et al., 1972; Myers and Price, 1981; Caggiano and Duncan, 1983). However, the presence of Ice Harbor Member (Saddle

Mountains Basalt) and Frenchman Springs Member (Wanapum Basalt) feeder dikes, discussed in the next section, probably have a far greater hydrogeologic impact on potential lateral movement (from the east to the west) of groundwater within the CRBG aquifer system.

CRBG Feeder Dikes. As indicated on Figure 1, the eastern boundary of the Pasco Basin is in part defined by the presence of multiple north-northwest-trending CRBG dikes and associated vents (Swanson and Helz, 1979; Swanson et al., 1980; Martin et al., 2013; Reidel et al., 2020). These dikes once served as long, linear, vertical conduits that supplied the magma to the land surface that produced individual basalt flows belonging to both the older Frenchman Springs Member of the Wanapum Basalt and the younger Ice Harbor Member of the Saddle Mountains Basalt (Figure 2). As illustrated in Figure 2-23, CRBG feeder dikes are essentially vertical “walls” of dense, non-vesicular basalt (from 3 feet- to more than 20 feet-wide) than extend from the base of the basalt flow it fed (paleo-land surface) to the magma chamber (more than 30 miles below the ground surface). Individual dikes have a linear surface length that extended for many tens of miles (Swanson and Helz, 1979; Swanson et al., 1975). Surface geologic mapping of the eastern boundary area (Swanson and Helz, 1979; Swanson et al., 1980; Reidel and Fecht, 1994a,b) and aeromagnetic survey mapping of the area produced by Flinn et al. (1998) clearly shows the extent of these north-northwest-trending CRBG feeder dikes along the eastern side of the Pasco area (Figure 24).

These north-northwest-trending CRBG feeder dikes that define the eastern boundary of the Pasco Basin also define the eastern “hydrogeologic boundary” of the Pasco Basin. In the case of the Ice Harbor Member dikes, these dikes represent vertical, subsurface “sheet walls” composed of dense basalt that transect all CRBG flows present beneath the base of the Ice Harbor Member. As Figure 23 illustrates, these dikes are vertical barriers which largely blocks horizontal groundwater movement through the interflow zones (aquifers) that they cut. It is also possible that the extreme heat from the molten magma in these dikes may have temporarily created local hydrothermal conditions (proximal to the dike) that resulted in the alteration of, or precipitation of secondary minerals within, adjacent interflow zones (aquifers) also reducing their original permeability.

Secondary Mineralization and Alteration. Secondary processes can change the physical characteristics of CRBG interflow zones and consequently, affect the hydraulic properties of these features. The common aspect to all these secondary processes is that they fundamentally change the original physical (and hydraulic) characteristics of CRBG flow tops and flow bottoms. The two most important of these processes are:

- Paleosol Development and Laterization - If a sufficiently long hiatus occurred between emplacement of CRBG flows, weathering and chemical breakdown of the glassy vesicular flow top/flow top breccia will occur and lead to soil (clay) formation. This process would typically alter and destroy the original physical texture of a portion of the flow top as well as most of its original permeability. The extent of the flow top involved, and degree to which these paleosols are developed varies tremendously. Factors controlling their development are thought to be duration of interval before the flow top is covered by the next CRBG flow, absence of sediment cover, and environmental conditions (e.g., climate, vegetation, paleogeography, etc.).

- Precipitation of secondary minerals - After the emplacement and burial of the CRBG flows, secondary minerals (e.g., silica, cryptocrystalline quartz, calcite, zeolite, pyrite, clay minerals, etc.) can partially to completely fill existing voids within interflow zones. Processes by which precipitation of these minerals occurs can be very complex and is dependent on a host of variables including groundwater chemistry, groundwater mobility/mixing rates, groundwater residence time, and local geothermal regime (USDOE, 1988). The net effect of secondary mineralization on CRBG interflow zones is a reduction, ranging from slight to total, in the permeability of these zones. This process also is important in sealing cooling fractures in dense flow interiors.

Stratigraphic Controls on Groundwater Flow in CRBG Aquifers

Groundwater flow direction and rates within CRBG aquifers depend on the presence and extent of both intrinsic and external factors and features associated with the CRBG flows. As described above, groundwater within CRBG aquifers is separated from one another by very low permeability dense flow interiors. Some groundwater flow may occur locally around the flow margins (pinch-outs), through vertically oriented tectonic fractures and/or faults, and uncased wells that connect multiple CRBG aquifers. However, overall vertical groundwater flow rate through the basalt dense flow interiors between interflow zones is expected to be many orders of magnitude lower than the horizontal flow through the interflow zones because of the very low permeability of dense flow interiors (Figure 15).

From a hydrogeologic standpoint, understanding the distribution and stratigraphy of both interbedded and suprabasalt sediments is important since they can either enhance CRBG aquifers by increasing groundwater storage or conversely act as additional confining layers (aquitards). In addition, the termination of CRBG flows may allow Ellensburg units to be in local hydrologic communication with each other, and in some case post-CRBG (suprabasalt) sediments, which may occur beneath the Pasco area. Incision into, and through, CRBG intraflow zones can create “erosional windows” into deeper CRBG aquifers and allow CRBG aquifers to either discharge to, or receive recharge from surface water or the unconfine aquifer hosted by suprabasalt sediments (e.g., Lindsey et al., 2007; Tolan et al., 2007) as discussed in the following section.

Potential CRBG Aquifer Recharge and Discharge

The unique nature of the CRBG aquifers provides very limited opportunities for significant direct recharge (Newcomb, 1959, 1969; USDOE, 1988; Hansen et al., 1994; Tolan et al., 2007), especially within the Pasco Basin. Recharge may slowly occur by diffuse percolation through the CRBG flow interiors over large areas. The very low vertical permeability of undisturbed CRBG dense flow interiors limits the rate of recharge by this process, but the large areal extent of the CRBG could potentially result in significant recharge on geologic time scales. Only CRBG interflow zones that are directly exposed to suprabasalt sediment aquifers or exposed at the surface can receive direct recharge (Figure 25). However, the development of secondary mineralization along vertical fractures (USDOE, 1988; Lindberg, 1989) greatly reduces, or eliminates, vertical permeability and thus severely limits the potential for recharge via this pathway over time (Figure 25B).

Infiltration vertically downward along faults, past the ends of CRBG flow pinchouts, where CRBG flows are breached by erosional windows, and on highlands within, and bordering, the flood-basalt province are potential mechanisms for recharge of CRBG interflow zones. However, the predominant mechanism for enhanced recharge, particularly at rates and on time scale relevant to stresses imposed by withdrawals in most areas (i.e., water supply wells), is direct infiltration to CRBG interflow zones (e.g., Figure 25) where they are present at, or near, the surface, and in direct hydrologic connection with surface water or exposed to percolating precipitation (Newcomb, 1959; USDOE, 1988; Vaccaro et al., 2009; Kahle et al., 2011; Burns et al., 2012). Interflow zones of a given CRBG unit typically crop out, or are in connection with overlying sediment, over a limited area and thus may only have limited recharge potential by this mechanism. Climatic and other hydrologic changes over time may reduce (or increase, e.g., irrigated farming) the water available for recharge at the locations where a given CRBG interflow zone is present to accept recharge, and thus the unit may receive significantly less (or more) recharge under present conditions than in the past.

On the Columbia Plateau, recharge of the deeper Wanapum and Grande Ronde aquifers is inferred to result from interbasin groundwater movement originating around the edge of the Columbia Plateau in areas where the Wanapum and Grande Ronde Basalts are exposed (Gephart et al., 1979; USDOE, 1988; Hansen et al., 1994; Kahle et al., 2011) and from downward through overlying CRBG flows (Hansen et al., 1994), although the hydraulic properties of CRBG flow dense interiors would extremely limit the effectiveness of this recharge mechanism. Geochemical tracers and age dating of groundwater within the CRBG aquifer system in the central Columbia Plateau region (Columbia Basin Groundwater Management Area) indicates that deeper CRBG units (Wanapum and Grande Ronde Basalts units) received the bulk of their recharge in the Pleistocene. Interflow zones of many of these deeper CRBG units are not in direct connection with existing surface water sources and precipitation amounts are very low relative to evapotranspiration. Also the presence of faults/folds and CRBG dikes can result in a series of vertical barriers to horizontal groundwater movement within the CRBG forming hydraulically isolated CRBG aquifer “compartments”. The overall result is the amount of recharge to the CRBG aquifer system is typically very small relative to of current groundwater withdrawals via water supply wells, rendering the CRBG aquifers vulnerable to overdraft (“groundwater mining”).

Potential discharge areas for the CRBG aquifers (i.e., Saddle Mountains, Wanapum and Grande Ronde aquifers) in the Columbia Plateau region are inferred where folding/faulting and uplift/deep erosion brings CRBG flows close to the surface. The CRBG regional aquifer discharge model of Hansen et al. (1994) (Figure 19B) has been shown not to be viable given the hydraulic/physical properties of CRBG basalt flows in this stratiform regional aquifer system. Throughout the Columbia Plateau, erosional windows potentially connecting surface water sources with CRBG aquifers are known to occur in the Channeled Scablands region of the Columbia Plateau (Figure 26) and can be inferred from geologic mapping (e.g., Stoffel et al., 1991; Reidel and Fecht 1994a,b; Schuster et al., 1997). Such erosional windows (cataclysmic flood channels) into the upper portion of the Saddle Mountains Basalt section, specifically the Ice Harbor Member-Levy interbed-Elephant Mountain Member-Rattlesnake Ridge interbed-top of the Pomona Member, are known to be present along the eastern boundary of the Pasco Basin (Tolan et al. 2007). It is inferred that these erosional windows into the CRBG aquifer system are providing some limited local recharge to the upper-most portion for the Saddle Mountains Basalt aquifer system. However, this recharge water is largely from Human-related activities which results in the recharge water having potential water quality issues which may impact the overall water quality within the receiving CRBG aquifer.

CRBG Groundwater Resource Limitations

For the reason discussed above, CRBG aquifers present challenges to sustainable groundwater development throughout their extent (e.g., Luzier et al., 1968; Luzier and Skrivan, 1975; Oberlander and Miller, 1981; Lite and Grondin, 1988; Conlon et al., 2005; Vaccaro et al., 2009; Kahle et al., 2011; Burns et al., 2012). The hydraulic properties inherent to CRBG aquifers have led to overdraft conditions in many areas (e.g., Odessa region, Quincy Basin). Low storativity values and relatively high horizontal conductivity of interflow zones combined with very low vertical conductivity of dense flow interiors result in productive confined aquifers. With time, pumping produces rapidly moving and coalescing cones of depression with low annual recharge rates. High horizontal conductivity in interflow zones allows high well yields, but low vertical permeability, potential for aquifer compartmentation, and limited recharge pathways result in low (to no) annual recharge rates. Combined with low storativity and low bulk porosity, these factors commonly lead to overdraft of CRBG aquifers. The presence of low permeability boundaries such as faults or interflow "facies changes" can exacerbation of seasonal drawdowns and limit (or eliminate) opportunity for annual recovery of the hydraulic head.

Another issue is with older CRBG water well construction. Prior to the 1970's, state regulatory agencies typically considered the entire CRBG to be a "single aquifer" (with a few exceptions) and it was the "accepted wisdom" by well drillers that the greater the well's open interval within the CRBG the greater your potential water production would be. This water well construction practice resulted in numerous wells (many thousands of wells) that were open to multiple CRBG interflow zones (aquifers). The consequences of this "open-hole" well construction resulted in depressurizing, and ultimately dewatering, of many CRBG aquifers. Rapid depressurizing of small, compartmentalized CRBG aquifers led to water-level declines, increased pumping costs, and when declines fall below pumps, results in "chasing water" (deepening) in wells. In some cases, this type of CRBG water well construction also enabled suprabasalt sediment aquifer groundwater (with poor water quality) to enter the well due to either no, or bad, well casing seal construction. Identifying which CRBG aquifers have been compromised by "open-hole" CRBG water supply wells is an important factor to consider with regards to a potential CRBG ASR project. Ideally, a new CRBG ASR well would be open to a single CRBG aquifer that few, if any, of the existing water supply wells in the immediately vicinity have penetrated.

Based on the available WADOE well record, the majority of the existing water wells in the Pasco area that are completed in the CRBG are tapping aquifers within the upper portion of Saddle Mountains Basalt (Ice Harbor Member/Levey interbed/Elephant Mountain Member/Rattlesnake Ridge interbed/ top of the Pomona Member), and very few water supply wells have apparently been drilled into the lower Saddle Mountains Basalt (i.e., Umatilla Member) or the Wanapum Basalt aquifers. The deeper Saddle Mountains and Wanapum Basalts (Umatilla, Priest Rapids, Roza and Frenchman Springs Members) appear have only been penetrated by two deep water supply wells according to Grolier and Bingham (1971):

- A well in T9S, R29E, section 21, which reached a total depth 1,043 ft below ground surface (Grolier and Bingham, 1971, Appendices II & III; see Appendix A).

- A well in T9S, R30E, section 18, which reached a total depth 1,030 ft below ground surface Grolier and Bingham, 1971, Appendices II & III).

Both deep wells were drilled in the early 1940's based on Grolier and Bingham (1971) report. Note that neither of these deep well logs are in the WADOE well database.

Summary

This memorandum was prepared to support an aquifer storage and recover (ASR) feasibility study for the City of Pasco and presents a preliminary description and assessment of the subsurface geology and hydrogeology of the greater Pasco, Washington, area. The descriptions of the geology and hydrogeology presented here are based on available (published and unpublished) geologic and hydrogeologic information and data sources cited within this memorandum.

The City of Pasco area ("Pasco area") is located within the southern portion of the Pasco Basin (Figure 1), a geologically structural basin. The boundaries of the Pasco Basin are geologically defined by (1) northwest-trending faulted, anticlinal ridges (RAW – Yakima Fold Belt) to the west, east-west-trending faulted, anticlinal ridges (Saddle Mountains and Umtanum Ridge - Yakima Fold Belt) to the north, and the on the east by the by the westward-dipping Palouse Slope (Jackass anticline/monocline) and the north-northwest-trending Columbia River Basalt Group (CRBG) dike swarm (Figure 1B). The major stratigraphic units that underlie this area (Figure 2) and host aquifers that might be potential ASR targets horizons, from youngest to oldest, are:

- Pleistocene-age cataclysmic flood (Hanford formation) sediments.
- Pliocene to Miocene Ringold Formation sediments.
- Middle Miocene Columbia River Basalt Group and associated Ellensburg Formation sediments.

The cataclysmic flood and Ringold Formation sediments that underlie the greater Pasco area are collectively called the "suprabasalt sediments". The suprabasalt sediments serve as the host for the upper-most, unconfined to semi-confined aquifer system beneath the Pasco area.

The Hanford formation sediments beneath the Pasco area consist of unconsolidated, bedded, sand and gravel deposits (Figures 5 and 6) which have excellent aquifer hydraulic properties (very high hydraulic conductivities and transmissivities). The Hanford formation sediments in the Pasco area often comprise a large portion of the vadose zone – the unsaturated interval between the ground surface and water table. In areas proximal to the Columbia and Snake Rivers and within cataclysmic flood channels/coulees, Hanford formation sediments can host the unconfined ("water table") aquifer. Water supply wells in the greater Pasco area that have been completed in the unconfine aquifer hosted by the Hanford formation (coarse gravel and sand deposits) can have maximum yields between 1,000 to greater than 3,000 gpm. The areal extent, thickness, general hydraulic properties, and relatively shallow depth of the Hanford formation in the Pasco area does make them a potentially viable ASR candidate. However, given the potential ease and rate that groundwater might move laterally through the Hanford formation aquifer, and potential to lose stored water to the Columbia River, additional site-specific analysis and investigations for a potential Pasco Hanford formation ASR site would be necessary to determine if the targeted Hanford formation aquifer would be able to retain (store) the needed volume(s) of ASR water for the required period(s) of time required for this ASR project. Also, this site-specific analysis would needed to determine if the storing ASR water in the unconfined Hanford aquifer might potentially cause an unacceptable rise in the local water table (unconfined aquifer) leading to possible local flooding issues.

Underlying the Hanford formation in the Pasco area (Figure 12) are the poorly consolidated to well cemented ancestral river gravel deposits (Figure 9), with interbedded sand and silt/clay beds, that belong to the Wooded Island member of the Ringold Formation (Figure 2). These Ringold Formation deposits serve as the host of much of the unconfined aquifer beneath the Pasco area. In contrast to the Hanford formation, physical and aquifer hydraulic properties of the Wooded Island member sediments (i.e., due to the presence of variable cementation within the conglomerate (e.g., Figure 9) and the presence of interbedded silt/clay deposits) are drastically different - very much lower hydraulic conductivities and transmissivities. Thus, the unconfined aquifer hosted by the Ringold sediments beneath the Pasco area typically has far lower groundwater yields from water supply wells completed in it in comparison to Hanford aquifer. The Ringold aquifer can also locally exhibit confined aquifer conditions created by locally extensive and thick silt/clay deposits which form a confining layer.

Although the Ringold aquifer hydraulic properties are not as good as those of the Hanford formation, their areal extent, thickness, and relatively shallow depth within the Pasco area does make them a potential ASR candidate to evaluate. Like the Hanford formation aquifer, additional site-specific analysis and investigation of a Ringold aquifer candidate location viability would be needed to address the same potential issues identified above for a Hanford aquifer ASR site.

Beneath the suprabasalt sediments are the flood-basalt flows of the CRBG and interbedded Ellensburg Formation sediments. Most past, and on-going, ASR projects in eastern Washington and Oregon have targeted and developed confined aquifers hosted by the CRBG (Gibson and Campana, 2014; Gibson, 2018; Gibson et al., 2018, 2019) to address declining water levels in those aquifers, and because the potential to lose water in CRBG aquifers is generally low. Give the general success of these CRBG ASR projects elsewhere, they were the primary focus of this memorandum, specifically the Saddle Mountains and Wanapum Basalts (Figures 2 and 8) since they contain the shallowest potential CRBG ASR candidate aquifers beneath the Pasco area.

Most CRBG flows were emplaced as vast sheet flows (Figure 14) and have the same general internal arrangement of intraflow structures (Figure 15). The laterally extensive flow tops and flow bottoms of the basalt flows, and Ellensburg Formation interbeds present between the flows, form an “interflow zone” (Figure 15) which can have both the physical and hydraulic properties to serve the host for groundwater (aquifer) and a potential ASR candidate target. While the interflow zones can host aquifers, the dense interior portion of the CRBG flow serves as an impermeable barrier to vertical groundwater movement between interflow zones (aquifers). In their original undisturbed state, individual interflow zones are as laterally extensive as the CRBG sheet flows that define them. Given the extent and thickness (geometry) of individual interflow zones, this creates a series of relatively tabular, stratiform layers that can host a series of confined aquifers within the CRBG (Figure 15).

Except for several very deep water supply wells that were drilled in the early 1940’s, no deep geologically logged wells that entirely penetrate the Saddle Mountains Basalt and Wanapum Basalt have been drilled in the Pasco area. This results in there being no site-specific geologic or hydrogeologic data on the CRBG, and the presence of potential CRBG ASR candidate targets, beneath the Pasco area. Given the regionally extensive nature and continuity of individual CRBG units within the Pasco Basin (Figure 2), it is possible to extrapolate both surface and subsurface geologic/hydrogeologic data from locations in the greater Pasco Basin into the Pasco area of interest.

The extrapolation of geologic/hydrogeologic data and information from the surrounding Pasco Basin suggests that a number of potential CRBG interflow zones are likely present beneath the Pasco area which might be potentially suitable CRBG ASR candidates. The following CRBG candidate interflow zones were identified as possible having the physical/hydrogeologic properties suitable for ASR. These candidate interflow zones are listed from shallowest to deepest:

- Elephant Mountain Member: Basalt of Ward Gap-Basalt of Elephant Mountain interflow zone (Figure 2). Potential as ASR candidate: low to moderate.
- Base of the Elephant Mountain Member – Rattlesnake Ridge interbed interflow zone (Figure 2). Potential as ASR candidate: low to moderate.
- Umatilla Member: Basalt of Sillusi-Basalt of Umatilla interflow zone (Figure 2). Potential as ASR candidate: moderate to excellent. This is the producing CRBG aquifer in the Welch's well (Appendix A).
- Base of Priest Rapids Member – Quincy interbed – flow top of Roza Member (Figure 2). Potential as ASR candidate: moderate to good.
- Frenchman Springs Member – multiple (+11) interflow zones (Figure 2). Potential as ASR candidate: moderate to excellent.

Given the general lack of any specific data on these above listed CRBG ASR candidate zones, an exploratory borehole would be needed to acquire additional data further access the potential viability and suitability of these CRBG candidate zones.

REFERENCES CITED

Anderson, J.L., 1987, Structural geology and ages of deformation of a portion of the southwest Columbia Plateau [Ph.D. thesis]: Los Angeles, University of Southern California, 283 p.

ARH-ST-137, 1976, Preliminary feasibility study on storage of radioactive wastes in Columbia River basalts: Richland, Washington, Atlantic Richfield Hanford Company, v. 1 & 2.

Barry, T.L., Kelley, S.P., Reidel, S.P., Camp, V.E., Self, S., Jarboe, N.A., Duncan, R.A., and Renne, P.R., 2013, Eruption chronology of the Columbia River Basalt Group, *in*, Reidel, S.P., V.E. Camp, M.E. Ross, J.A. Wolff, B.S. Martin, T.L. Tolan, and R.E. Wells, eds., The Columbia River Flood Basalt Province: Geological Society of America Special Paper 497, p. 45-66.

Beeson, M.H., and Tolan, T.L., 1990, The Columbia River Basalt Group in the Cascade Range-a middle Miocene reference datum for structural analysis: Journal of Geophysical Research, v. 95, p. 19,547-19,559.

Beeson, M.H., and Tolan, T.L., 1996, Field trip guide to Columbia River Basalt intracanyon flows in western Oregon and Washington-Ginkgo, Rosalia, and Pomona flows: Cordilleran Section meeting of the Geological Society of America, Portland, Oregon, 35 p.

Beeson, M.H., Perttu, R., and Perttu, J., 1979, The origin of the Miocene basalt of coastal Oregon and Washington: Oregon Geology, v. 41, p.159-166.

Beeson, M.H., Tolan, T.L., and Anderson, J.L., 1989, The Columbia River Basalt Group in western Oregon; Geologic structures and other factors that controlled flow emplacement patterns, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 223-246.

Beeson, M.H., Fecht, K.R., Reidel, S.P., and Tolan, T.L., 1985, Correlations within the Frenchman Springs Member of the Columbia River Basalt Group: New insights into the middle Miocene tectonics of northwest Oregon: Oregon Geology, v. 47, p. 87-96.

Bjornstad, B.N., Horner, J.A., Vermeul, V.R., Lanigan, D.C., and Thorne, P.D., 2009, Borehole completion and conceptual hydrogeologic model for the IFRC well field, 300 Area, Hanford Site: Richland, Washington, Pacific Northwest National Laboratory, PNNL-18340, 1003 p.

Benito, G., and O'Conner, J.E., 2003, Number and size of last-glacial Lake Missoula floods in the Columbia River valley between Pasco Basin and Portland, Oregon: Geological Society of America Bulletin, v. 115, p. 624-638.

Brown, J.C., 1978, Discussion of geology and ground-water hydrology of the Columbia Plateau with specific analysis of the Horse Heaven Hills, Sagebrush Flat, and Odessa-Lind areas, Washington: Washington State University, Pullman, Washington, College of Engineering Research Report 78/15-23, 51 p.

Brown, J.C., 1979, Investigation of stratigraphy and groundwater hydrology, Columbia River Basalt Group, Washington: Washington State University, College of Engineering Research Division Research Report 79/15-37, 60 p.

Brown, R.E., 1979, A review of water well data from the unconfined aquifer in the eastern and southern parts of the Pasco Basin: RHO-BWI-C-56, Rockwell Hanford Operations, Richland, Washington, 57 p., 19 plates.

Burns, E. R., Morgan, D. S., Lee, K.K., Haynes, J.V., and Colon, T.D., 2012, Evaluation of long-term water-level declines in basalt aquifers near Mosier, Oregon: US Geological Survey Groundwater Resources Program Scientific Investigations Report 2012-5002, 146 p.

Burns, E. R., Morgan, D. S., Peavler, Rachael S., and Kahle, Sue C., 2011, Three- dimensional model of the geologic framework for the Columbia Plateau Regional Aquifer System, Idaho, Oregon, and Washington: US Geological Survey Groundwater Resources Program Scientific Investigations Report 2010-5246, 44 p.

Burns, E.R., Williams, C.F., Tolan, T.L., and Ole Kaven, J., 2016, Are the Columbia River Basalts, Columbia Plateau, Idaho, Oregon, and Washington, USA, a viable geothermal target? A preliminary analysis: Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209, p. 1-11.

Burt, W.C., 1989, The hydrogeology of structurally complex basalts in Black Rock and Dry Creek Valleys, Washington: University of Idaho, Moscow, Idaho, M.S. thesis, 78 p.

Burt, W.C., Conlon, T., Tolan, T.L., Wells, R.E., and Melady, J., 2009, Hydrogeology of the Columbia River Basalt Group in the northern Willamette Valley, Oregon, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards – geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Trip Guide 15, p. 697-736.

Caggiano, J.A., and Duncan, D.W., eds. 1983, Preliminary interpretation of the tectonic stability of the Reference Repository Location, Cold Creek Syncline, Hanford Site: Richland, Washington, Rockwell Hanford Operations, RHO-BW-ST-19P, 189 p.

Conlon, T.D., Wozniak, K.C., Woodcock, D., Herrera, N.B., Fisher, B.J., Morgan, D.S., Lee, K.K., and Hinkle, S.R., 2005, Ground-water hydrology of the Willamette basin, Oregon: U.S. Geological Survey Scientific Investigations Report 2005-5168, 83 p

Davies-Smith, A., Bolke, E.L., and Collins, C.A., 1988, Geohydrology and digital simulation of the ground-water flow system in the Umatilla Plateau and Horse Heaven Hills area, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 87-4268, 72 p.

Denlinger, R.P. and O'Connell, D.R.H., 2010, Simulations of cataclysmic outburst floods from Pleistocene Glacial Lake Missoula: Geological Society of America Bulletin, v.122, no. 5/6, p. 678-689.

Diery, H. D., 1967, Stratigraphy and structure of the Yakima Canyon between Roza Gap and Kittitas Valley, Central Washington [Ph.D. thesis]: Seattle, University of Washington, 117 p.

DOE/RL-2002-39, 2002, "Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin," Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE/RL-2019-66 (Rev. 0), 2020, Hanford Site groundwater monitoring report for 2019: Richland, Washington, U.S. Department of Energy, Richland Operations, 696 p.

Drost, B.W. and Whitman, K.J., 1986, Surficial geology, structure, and thickness of selected geohydrologic units in the Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 84-4326.

Eaton, L., Melady, J., and Tolan, T., 2009, Successful implementation of ASR in basalt-hosted aquifers in the Pacific Northwest of the United States: Boletin Geologio y Minero, v. 120, no. 2, p. 131-156.

Fecht, K. R., Reidel, S.P., and Tallman, A.M., 1987, Paleodrainage of the Columbia River system on the Columbia Plateau of Washington State—A Summary, *in* Schuster, J.E., ed., Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p 219-248.

Flinn, C.A., Brenner, K.C., McCafferty, A.E., and Kucks, R.P., 1998, Washington aeromagnetic maps and data: U.S. Geological Survey Open-File Report 98-241.

Gephart, R.E., Arnett, R.C., Baca, R.G., Leonhart, L.S., Spane, F.A., Jr., 1979, Hydrologic studies within the Columbia Plateau, Washington - an integration of current knowledge: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-ST-5.

Gibson, M.T., 2018, Assessing managed aquifer recharge potential – from small to large scale evaluations: Oregon State University, Ph.D. dissertation, 199p.

Gibson, M.T., and Campana, M.E., 2014, A desktop suitability assessment of aquifer storage (ASR) and recovery in Washington State: Oregon State University report prepared for Washington Department of Ecology, 50 p.

Gibson, M.T., Campana, M.E., and Boylan, N., 2019, Hanford Site aquifer storage and recovery evaluation: Oregon State University report prepared for Washington Department of Ecology, 87 p.

Gibson, M.T., Campana, M.E., and Nazy, D., 2018, Estimating aquifer storage and recovery (ASR) regional and local suitability – a case study in Washington State, USA: Hydrology, v. 5, 19 p.

Grolier, M.J., and Bingham, J.W., 1971, Geologic map and sections of parts of Grant, Adams, and Franklin Counties, Washington: U.S. Geological Survey Miscellaneous Geologic Investigations Series Map I-589, scale 1:62 500, 6 sheets.

Grolier, M.J., and Bingham, J.W., 1978, Geology of parts of Grant, Adams, and Franklin Counties, east-central Washington: Washington Division of Geology and Earth Resources Bulletin 71, 91 p.

Hagood, M.C., 1986, Structure and evolution of the Horse Heaven Hills in south-central Washington: Richland, Washington, Rockwell Hanford Operations, RHO-BW-SA-344 P, 1 plate, 190 p.

Hansen, A.J., Jr., Vaccaro, J.J., and Bauer, H.H., 1994, Ground-water flow simulation of the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey, Water-Resources Investigations Report 91-4187, 81 p.

Hogenson, G., 1964, Geology and ground water of the Umatilla River basin, Oregon: U.S. Geological Survey Water-Supply Paper 1620, 162 p.

Hon, K., Kauahikaua, J., Denlinger, R., and MacKay, K., 1994, Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 106, p. 351-370.

Johnson, V.G., Graham, D.L., and Reidel, S.P., 1993, Methane in Columbia River basalt aquifers - isotopic and geohydrologic evidence for a deep coal-bed gas source in the Columbia Basin, Washington: The American Association of Petroleum Geologists Bulletin, v. 77, p. 1192-1207.

Kahle, S.C., Morgan, D.S.., Welch, W.B., Ely, D.M., Hinkle, S.R., Vaccaro, J.J., and Orzol, L.L., 2011, Hydrogeologic framework and hydrologic budget components of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho: US Geological Survey Groundwater Resources Program Scientific Investigations Report 2011-5124, 66 p.

Last, G.V., Thorne, P.D., Horner, J.A., Parker, K.R., et al., 2009, Hydrogeology of the Hanford Site Central Plateau – a status report for the 200 West Area: Pacific Northwest National Laboratory, Richland, WA, PNNL-17913, Rev. 1, 155 p.

Lindberg, J.W., 1989, A numerical study of cooling joint width and secondary mineral infilling in four Grande Ronde Basalt flows of the central Columbia Plateau, Washington, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 169-185.

Lindsey, K.A., 1995, Miocene- to Pliocene-aged suprabasalt sediments of the Hanford Site, south-central Washington: Bechtel Hanford, Inc., Richland, Washington, BHI-00184, Rev. 0, 150 p., 6 plates.

Lindsey, K.A., 1996, The Miocene to Pliocene Ringold Formation and associated deposits of the ancestral Columbia River system, south-central Washington and north-central Oregon: Washington Department of Natural Resources, Division of Geology and Earth Resources Open-File Report 96-8, 178 p.

Lindsey, K.A., Reidel, S.P., Fecht, K.R., Slate, J.L., Law, A.G., and Tallman, A.M., 1994, Geohydrologic setting of the Hanford Site, south-central Washington, *in,* Swanson, D.A.,and Haugerud, R.A., eds., Geologic field trips in the Pacific Northwest: Geological Society of America Annual Meeting, Seattle, Washington, v.1, p. 1C.1-1C.

Lindsey, K.A., Tolan, T.L., Nielson, M., and Loper, S., 2007, Geologic framework of the suprabasalt Sediments aquifer system, Columbia Basin Ground Water Management Area, Washington State: Othello, Washington, Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, 52 p., 28 plates.

Livesay, D.M., 1986, The hydrogeology of the upper Wanapum Basalt, upper Cold Creek Valley, Washington [M.S. thesis]: Pullman, Washington State University, 159 p.

Lite, K.E., Jr., and Grondin, G.H., 1988, Hydrogeology of the basalt aquifers near Mosier, Oregon - a ground water resources assessment: Oregon Department of Water Resources Ground Water Report, no. 33, 119 p.

Long, P.E., and Wood, B.J., 1986, Structures, textures, and cooling histories of Columbia River basalt flows: Geological Society of America Bulletin, v. 97, p. 1144-1155.

Lum, W.E., Smoot, J.L., and Ralston, D.R., 1990, Geohydrology and numerical analysis of ground-water flow in the Pullman-Moscow area, Washington and Idaho: U.S. Geological Survey Water-Resources Investigations Report 89-4103, 73 p.

Luzier, J.E., and Skrivan, J.A., 1975, Digital-simulation and projection of water-level declines in basalt aquifers of the Odessa-Lind area, east-central Washington: U.S. Geological Survey Water-Supply Paper 2036, 56 p.

Luzier, J.E., Bingham, J.W., Burt, R.J., and Barker, R.A., 1968, Ground-water survey, Odessa-Lind area, Washington: Washington Division of Water Resources Water-Supply Bulletin 36, 31 p.

Mackin, J.H., 1961, A stratigraphic section in the Yakima Basalt and Ellensburg Formation in south-central Washington: Washington Division of Mines and Geology Reports of Investigations 19, 45 p.

Martin, B.S., 1989, The Roza Member, chemical stratigraphy and flow distribution, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Paper 239, p. 85–111.

Martin, B.S., Tolan, T.L., and Reidel, S.P., 2013, Revisions to the stratigraphy and distribution of the Frenchman Springs Member, Wanapum Basalt, *in*, Reidel, S.P., V.E. Camp, M.E. Ross, J.A. Wolff, B.S.

Martin, T.L. Tolan, and R.E. Wells, eds., The Columbia River Flood Basalt Province: Geological Society of America Special Paper 497, p. 155-179.

McFarland, W.D., and Morgan, D.S., 1996, Description of the ground-water flow system in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Supply Paper 2470-A, 58 p.

McMillan, K.C., Long, P.E., and Cross, R.W., 1989, Vesiculation in Columbia River basalts, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 157-167.

Moore, J.G., 1975, Mechanism of formation of pillow lava: American Scientist, v. 63, p. 269-277.

Moore, J.G., Phillips, R.L., Grigg, R.W., Peterson, D.W., and Swanson, D.A., 1973, Flow of lava into the sea, 1969-1971, Kilauea volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 537-546.

Myers, C.W., and Price, S.M., eds., 1981, Subsurface geology of the Cold Creek syncline: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-ST-14.

Newcomb, R.C., 1958, Ringold Formation of Pleistocene age in type locality, The White Bluffs, Washington: American Journal of Science, v. 256, p. 328-340.

Newcomb, R.C., 1959, Some preliminary notes on ground water in the Columbia River basalt: Northwest Science, v. 33, no. 1, p. 1-18.

Newcomb, R.C., 1961, Storage of ground water behind subsurface dams in the Columbia River basalt, Washington, Oregon, and Idaho: U.S. Geological Survey Professional Paper 238A, 15 p.

Newcomb, R.C., 1969, Effect of tectonic structure on the occurrence of ground water in the basalt of the Columbia River Group of The Dalles area, Oregon and Washington: U.S. Geological Survey Professional Paper 383-C, 33 p.

Newcomb, R.C., Strand, J.R., and Frank, F.J., 1972, Geology and groundwater characteristics of the Hanford Reservation of the U.S. Atomic Energy Commission, Washington: U.S. Geological Professional Paper 717, 78 p.

O'Conner J.E., and Baker, V.R., 1992, Magnitudes and implications of peak discharges from glacial Lake Missoula: Geological Society of America Bulletin, v. 104, p. 267-279.

Oberlander, P.L., and Miller, D.W., 1981, Hydrologic studies in the Umatilla structural basin - an integration of current knowledge: Oregon Department of Water Resources, unpublished preliminary report, 41 p.

Packard, F.A., Hansen, A.J., Jr., and Bauer, H.H., 1996, Hydrogeology and simulation of flow and the effects of development alternatives on the basalt aquifers of the Horse Heaven Hills, south-central Washington: U.S. Geological Survey Water-Resources Investigations Report 94-4068, 92 p.

Pitre, C., and Gerst, J., 2014, Observation well ASR-ME-1 installation and testing, City of Kennewick ASR feasibility study, Phase 3 – ASR observation well: Golder Associates, Inc., consultant report to the City of Kennewick, Washington, 159 p.

Pluhar, C.J., Bjornstad, B.N., Reidel, S.P., Coe, R.S., and Nelson, P.B., 2006, Magnetostratigraphic evidence from the Cold Creek bar for onset of ice-age cataclysmic floods in eastern Washington during the early Pleistocene: Quaternary Research, v. 65, p. 123-135.

Price, E.H., 1982, Structural geology, strain distribution, and tectonic evolution of Umtanum Ridge at Priest Rapids Dam, and a comparison with other selected localities within the Yakima fold belt structures, south-central Washington: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-SA-138, 197 p.

Reidel, S.P., 1984, The Saddle Mountains: The evolution of an anticline in the Yakima fold belt: American Journal of Science, v. 284, p. 942-978.

Reidel, S.P., 1998, Emplacement of Columbia River flood basalt: Journal of Geophysical Research, v. 103, p. 27, 393-27,410.

Reidel, S.P., 2005, A lava flow without a source: The Cohasset Flow and its compositional components, Sentinel Bluffs Member, Columbia River Basalt Group: Journal of Geology, v. 113, p. 1-21.

Reidel, S.P., and Fecht, K.R., 1994a, Geologic Map of the Richland 1:100,000 Quadrangle, Washington:

Washington State Department of Natural Resources, Division of Geology and Earth Resources Open File Report 94-8, scale 1:100,000, 1 sheet, 21 p. text.

Reidel, S.P. and Fecht, K.R., 1994b, Geologic Map of the Priest Rapids 1:100,000 Quadrangle, Washington: Washington State Department of Natural Resources, Division of Geology and Earth Resources Open File Report 94-13, scale 1:100,000, 1 sheet, 22 p. text.

Reidel, S.P., and Tolan, T.L., 1992, Eruption and emplacement of flood basalt: An example from the large-volume Teepee Butte Member, Columbia River Basalt Group: Geological Society of America Bulletin, v. 104, p. 1650-1671.

Reidel, S.P., and Tolan, T.L., 2013a, The Grande Ronde Basalt, Columbia River Basalt Group, *in*, Reidel, S.P., V.E. Camp, M.E. Ross, J.A. Wolff, B.S. Martin, T.L. Tolan, and R.E. Wells, eds., The Columbia River Flood Basalt Province: Geological Society of America Special Paper 497, p. 117-153.

Reidel, S.P., Camp, V.E., Tolan, T.L., and Martin, B.S., 2013b. The Columbia River flood basalt province – stratigraphy, areal extent, volume, and physical volcanology, *in*, Reidel, S.P., V.E. Camp, M.E. Ross, J.A. Wolff, B.S. Martin, T.L. Tolan, and R.E. Wells, eds., The Columbia River Flood Basalt Province: Geological Society of America Special Paper 497, p. 1-43.

Reidel, S. P., Fecht, K.R., Hagood, M.C., and Tolan, T.L., 1989a, The geologic evolution of the Central Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 247-264.

Reidel, S.P., Johnson, V.G., and Spane, F.A., 2002, Natural gas storage in basalt aquifers of the Columbia Basin, Pacific Northwest USA – a guide to site characterization: Richland, Washington, Pacific Northwest National Laboratory, PNNL-13962, 277p.

Reidel, S.P., Tolan, T.L., Camp, V.E., 2018, Columbia River flood basalt flow emplacement rates – fast, slow, or variable: Geological Society of America Special Paper 538, p. 1-19.

Reidel, S.P., Tolan, T.L., Hooper, P.R., Beeson, M.H., Fecht, K.R., Bentley, R.D., and Anderson, J.L., 1989b, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 21-53.

Reidel, S.P., Fecht, K.R., Hutter, I.L., Tolan, T.L., and Chamness, M.A., 2020, The Olympic-Wallowa lineament – a new look at an old controversy: Geological Society of America Bulletin, May 2020, 19 p., doi.org/10.1130/B35454.1.

Reidel, S.P., Camp, V.E., Tolan, T.L., Kaufmann, J., and Garwood, D., 2013, The tectonic development of the Columbia River flood basalt province, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., eds., The Columbia River Flood Basalt Province: Geological Society of America Special Paper 497, p. 293-324.

Reidel, S.P., Tolan, T.L., and Beeson, M.H., 1994, Factors that influenced the eruptive and emplacement histories of flood basalt flows: A field guide to selected vents and flows of the Columbia River Basalt Group, in Swanson, D.A., and Haugerud, R.A., eds., Geologic field trips in the Pacific Northwest: Geological Society of America Annual Meeting Field Guide, p. 1B-1-18.

Schuster, J.E., Gulick, C.W., Reidel, S.P., Fecht, K.R., and Zurenko, S., 1997, Geologic map of Washington-Southeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-45, scale 1:250 000, 2 sheets, 20 p. text.

Spane, F.A. and Webber, W.D., 1995, Hydrochemistry and hydrogeologic conditions within the Hanford Site upper basalt confined aquifer system: Battelle Pacific Northwest Laboratory, Richland, Washington, Report PNL-10817, 40 p.

Sabol, M.A., and Downey, S.E., 1997, Support document for consideration of the eastern Columbia Plateau aquifer system as a sole-source aquifer: Seattle, Washington, U.S. Environmental Protection Agency, Document 910/R-97-002, 35 p.

Spry, A., 1962, The origin of columnar jointing particularly in basalt flows: Geological Society of Australia Journal, v. 8, p. 191-216.

Smith, G.A., Bjornstad, B.N., and Fecht, K.R., 1989, Neogene terrestrial sedimentation on and adjacent to the Columbia Plateau, Washington, Oregon, and Idaho, *in*, Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 187-198.

Steinkampf, W.C., and Hearn, P.P., Jr., 1996, Ground-water geochemistry of the Columbia Plateau aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey Open-File Report 95-467, 67 p.

Stoffel, K. L, Joseph, N.L., Waggoner, S.Z., Gulick, C.W., Korosec, M.A., and Bunning, B.B., 1991, Geologic Map of Washington-Northeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-39.

Strait, S.R. and Mercer, R.B., 1987, Hydraulic property data from selected test zones on the Hanford Site: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-DP-051, Rev. 2, 31p.

Swanson, D.A., 1973, Pahoehoe flows from the 1969-1971 Mauna Ulu eruption, Kilauea volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 615-626.

Swanson, D.A., and Helz, R.T., 1979, Bedrock geologic map of the vent system for the Ice Harbor Member of the Saddle Mountains Basalt, Ice Harbor Dam – Basin City area, southeast Washington: U.S. Geological Survey Open-File Report 79-292, 8 sheets.

Swanson, D.A., and Wright, T.L., 1978, Bedrock geology of the northern Columbia Plateau and adjacent areas, *in* Baker, V.R., and Nummedal, D., eds., The Channeled Scabland: A guide to the geomorphology of the Columbia Basin, Washington: Washington D.C., Planetary Geology Program, Office of Space Science, National Aeronutics and Space Administration, p. 37-57.

Swanson, D. A., and Wright, T.L., 1981, Guide to geologic field trip between Lewiston, Idaho and Kimberly, Oregon, emphasizing the Columbia River Basalt Group, *in* Johnston D.A., and Donnelly-Nolan, J., eds., Guides to some volcanic terranes in Washington, Idaho, Oregon, and northern California: U.S. Geological Survey Circular 838, p. 1-28.

Swanson, D.A., Anderson, J.L., Bentley, R.D., Camp, V.E., Gardner, J.N., and Wright, T.L., 1979a, Reconnaissance geologic map of the Columbia River Basalt Group in Washington and adjacent Idaho: U.S. Geological Survey Open-File Report 79-1363, scale 1:250,000.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979b, Revision in the stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p.

Swanson, D.A., Wright, T.L., and Helz, R.T., 1975, Linear vent systems and estimated rates of magma production and eruption of the Yakima Basalt on the Columbia Plateau: American Journal of Science, v. 275, p. 877-905.

Swanson, D.A., Wright, T.L., Camp, V.E., Gardner, J.N., Helz, R.T., Price, S.M., Reidel, S.P., and Ross, M.E., 1980, Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla Walla Quadrangles, southeast Washington and adjacent Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-1139, scale 1:250 000, 2 sheets.

Tallman, A.M., Fecht, K.R., Marratt, M.C., and Last, G.V., 1979, Geology of the Separation Areas, Hanford Site, south-central Washington: Richland, Washington, Rockwell Hanford Operations, RHO-ST-23, 158 p., 12 plates.

Tallman, A.M., Fecht, K.R., Marratt, M.C., and Last, G.V., 1981, Suprabasalt sediment of the Cold Creek Syncline area, *in*, Myers, C.W., and Price, S.M., eds., Subsurface geology of the Cold Creek syncline: Richland, Washington, Rockwell Hanford Operations, RHO-BWI-ST-14.

Tolan, T.L., and Beeson, M.H., 1984, Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorge and their relationship to the Troutdale Formation: Geological Society of America Bulletin, v. 95, p. 463-477.

Tolan, T.L. and Lite, K., 2008, Geology and hydrogeology of the Columbia River Basalt Group -a field trip guide to selected localities in the Columbia River Gorge, Oregon: Prepared for the NGWA International Conference on Nonrenewable Ground Water Resources Field Trip, October 15, 2008.

Tolan, T.L., Campbell, N.P., and Lindsey, K.A., 2000, Exploring the hydrogeology of the Columbia River Basalt Group - a field guide to selected localities in the Columbia Plateau, Washington: Third Washington State Hydrogeology Symposium, October 14-15, 2000, Tacoma, Washington, 66 p.

Tolan, T.L., Lindsey, K.A., Nielson, M., and Loper, S., 2007. Geologic framework of selected sediment and Columbia River basalt units in the Columbia Basin Groundwater Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington (Ed. 2): Prepared for the Columbia Basin Ground Water Management Area, Othello, Washington, 423 p., 41 plates.

Tolan, T.L., Martin, B.S., Reidel, S.P., Anderson, J.L., Lindsey, K.A., and Burt, W., 2009. An introduction to the stratigraphy, structural geology, and hydrogeology of the Columbia River flood-basalt province – a primer for the GSA Columbia River Basalt Group field trips, *in*, O'Connor, J.E., R.J. Dorsey, and I.P. Madin, eds., Volcanoes to Vineyards – geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Trip Guide 15, p. 599-643.

Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 1-20.

Tribble, G.W., 1991, Underwater observations of active lava flows from Kilauea volcano, Hawaii: Geology, v. 19, p. 633-636.

USDOE , 1988, Site characterization plan reference repository location, Hanford Site, Washington: Washington D.C., U.S. Department of Energy, DOE/RW-0164, v. 1-2.

Vaccaro, J.J., 1986, Columbia Plateau regional aquifer-system study, *in*, Sun, R.J., ed., Regional aquifer-system analysis program of the U.S. Geological Survey summary of projects, 1978-1984, p. 141-145.

Vaccaro, J.J., Jones, M.A., Ely, D.M., Keys, M.E., Olsen, T.D., Welch, W.B., and Cox, S.E., 2009, Hydrogeologic framework of the Yakima River basin aquifer system, Washington: U.S. Geological Survey Scientific Investigations Report 2009–5152, 106 p.

Waitt, R.B., Denlinger, R.P., and O'Connor, J.E., 2009, Many monstrous Missoula floods down Channeled Scabland and Columbia Valley *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards – geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Trip Guide 15, p. 775-844.

Wells, R.E., Niem, A.R., Evarts, R.C., and Hagstrum, J.T., 2009, The Columbia River Basalt Group—From the gorge to the sea, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards—Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Trip Guide 15, p. 737–774, doi:10.1130/2009.fld015(32).

Wells, R.E., Simpson, R.W., Bentley, R.D., Beeson, M.H., Mangan, M.T., and Wright, T.L., 1989, Correlation of Miocene flows of the Columbia River Basalt Group from the central Columbia River Plateau to the coast of Oregon and Washington, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 113-130.

Whiteman, K.J., Vaccaro, J.J., Gonthier, J.B., and Bauer, H.H., 1994, Hydrological framework and geochemistry of the Columbia Plateau aquifer system in parts of Washington, Oregon, and Idaho: U.S. Geological Survey Professional Paper 1413-B, 73 p.

Williams B.A., Bjornstad, B.N., Schalla, R., and Webber, W.D., 2000, Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington: Pacific Northwest National Laboratory, Richland, WA, PNNL-12261.

Williams B.A., Bjornstad, B.N., Schalla, R., and Webber, W.D., 2002, Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington: Pacific Northwest National Laboratory, Richland, WA, PNNL-13858.

Wozniak, K.C., 1995, Chapter 2 - Hydrogeology, *in* Hydrogeology, groundwater chemistry, and land uses in the lower Umatilla Basin Groundwater Management Area, northern Morrow and Umatilla Counties, Oregon - Final Review Draft: Salem, Oregon, Oregon Department of Environmental Quality Report, p. 2.1-2.80.

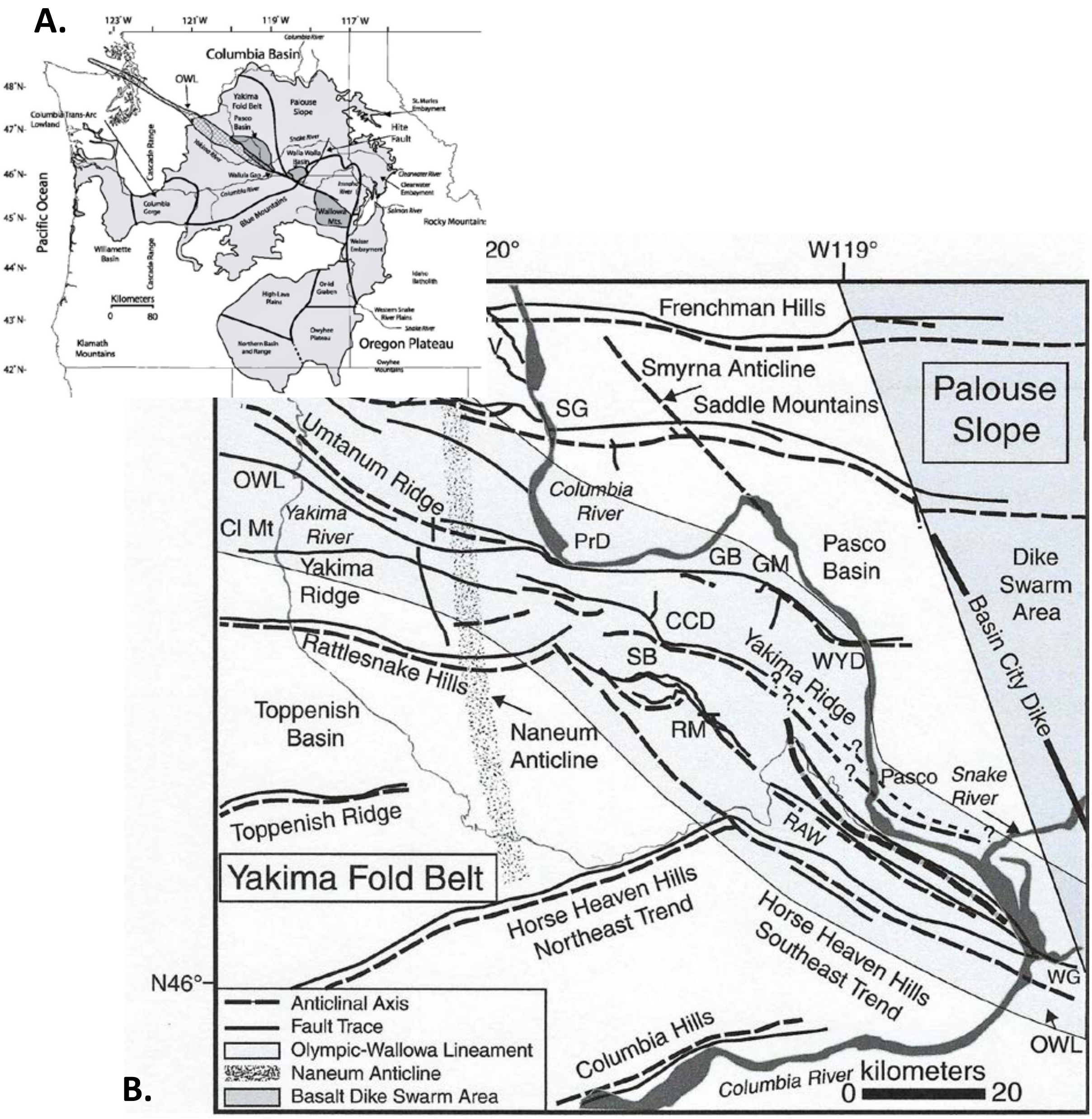


Figure 1. A. Map showing the location of the Pasco Basin in relation to geologic structural sub-provinces and the extent of the Columbia River Flood Basalt Province. From Reidel et al. (2020, Figure 1). B. Major geologic features of the Pasco Basin area and vicinity. V-Vantage; SG-Sentinel Gap; PrD-Priest Rapids Dam; OWL-Olympic Wallowa lineament; Cl Mt- Cleman Mt.; GM-Gable Mtn.; GB-Gable Butte; CCD-Cold Creek depression; WYD- Wye Barricade depression; RM-Rattlesnake Mtn.; RAW-Rattlesnake-Wallula alignment; WG- Wallula Gap. From Reidel et al. (2013, Figure 8).

Holocene deposits **0 - 10,000 yrs**

Erosional Unconformity

Hanford formation **~13,000 yrs – 1.6 m.y.**

Erosional Unconformity

Ringold Formation **~2.6 – 10.5 m.y.**

Savage Island member

Taylor Flat member

Wooded Island member

Local Disconformity

Columbia River Basalt Group (CRBG)

SADDLE MOUNTAINS BASALT

Ice Harbor Member **~ 8.5 – 8.8 m.y.**
Basalt of Goose Island (1)
Basalt of Martindale (2)
Basalt of Basin City (1)

Levey Member – Ellensburg Formation

Elephant Mountain Member **~10.5 m.y.**
Basalt of Ward Gap (1)
Basalt of Elephant Mountain (1)

Rattlesnake Ridge Member – Ellensburg Formation

[illegible] Member (1) **~11.8 m.y.**

Selah Member – Ellensburg Formation

Esquatzel Member (1)

Cold Creek Member – Ellensburg Formation

Umatilla Member **~13.0 m.y.**
Basalt of Silusi (1)
Basalt of Umatilla (1)

Mabton Member – Ellensburg Formation

Local Disconformity

WANAPUM BASALT

Priest Rapids Member **15.2 m.y.**
Basalt of Lolo (1)
Basalt of Rosalia (1)

Quincy Member – Ellensburg Formation

Roza Member **~14.9 m.y.**

Squaw Creek Member – Ellensburg Formation

Frenchman Springs Member **~15.0 – 15.4 m.y.**
Basalt of Sentinel Gap (3)
Basalt of Sand Hollow (4)
Basalt of Silver Falls (2)
Basalt of Ginkgo (3)
Basalt of Palouse Falls (2)

Vantage Member – Ellensburg Formation

Local Disconformity

GRANDE RONDE BASALT **~15.6 – 16.0 m.y.**

Figure 2. Chart showing the major stratigraphic units found in the greater Pasco, Washington, area. Yellow highlight denotes sedimentary unit. Number in parentheses to the right of CRBG unit names denotes the number individual basalt flows likely present beneath this area. Ages of units are approximate. “yrs. = years for present; “m.y.” = millions of years before present. Modified from Tolan et al. (2007) and Reidel et al. (2013).

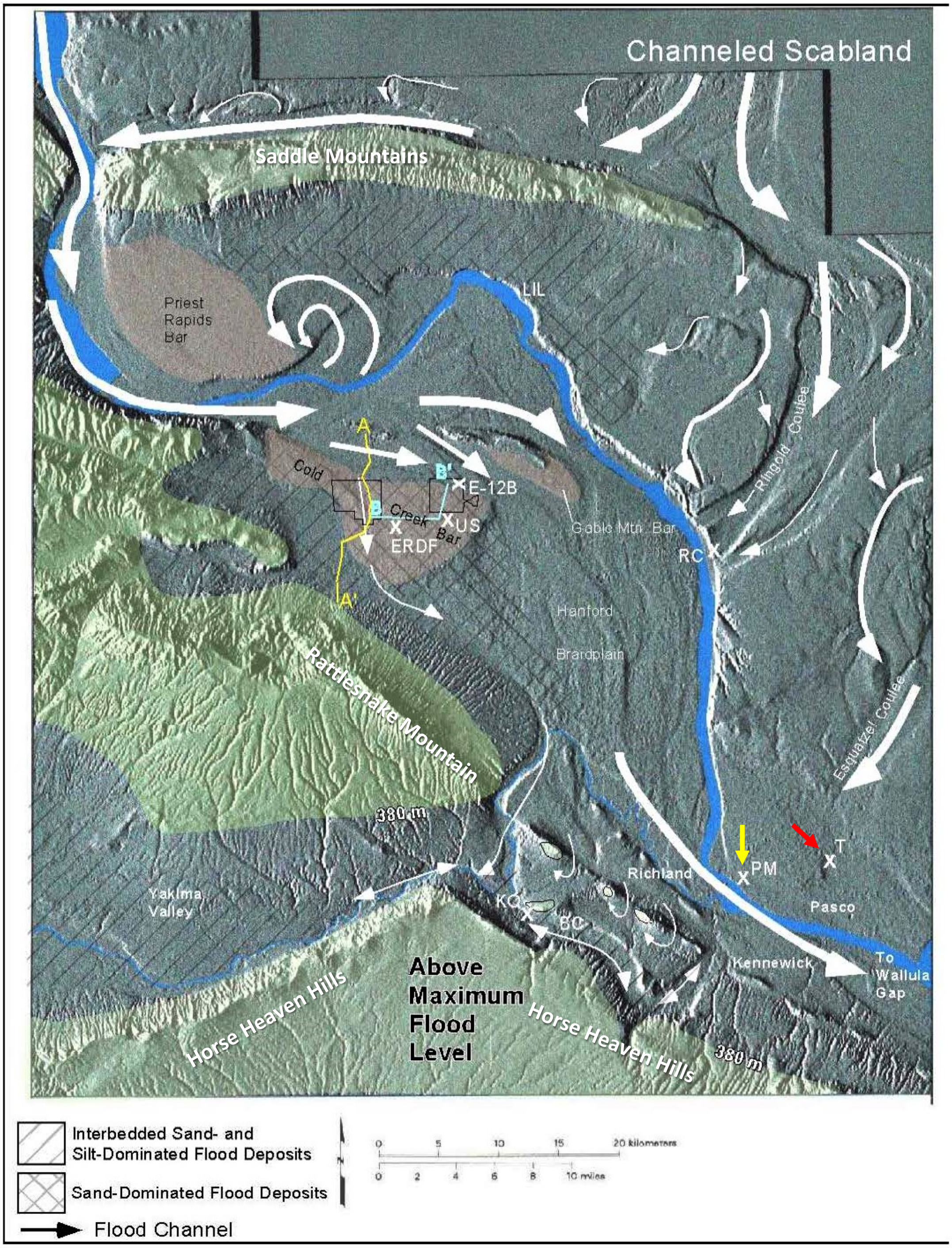


Figure 3. Map showing the routes of the last large-scale cataclysmic flood ("Missoula Flood") flow pathways (white arrows) in the greater Pasco Basin area. Pale-green shade denote areas above the maximum cataclysmic flood level. Red arrow denotes location of the Transtate Borrow Pit exposure shown in Figure 5 and yellow arrow denotes location of the Pre-Mix Borrow Pit exposure shown in Figure 6. Modified from DOE/RL-2002-39 (rev. 0, Figure A-20).

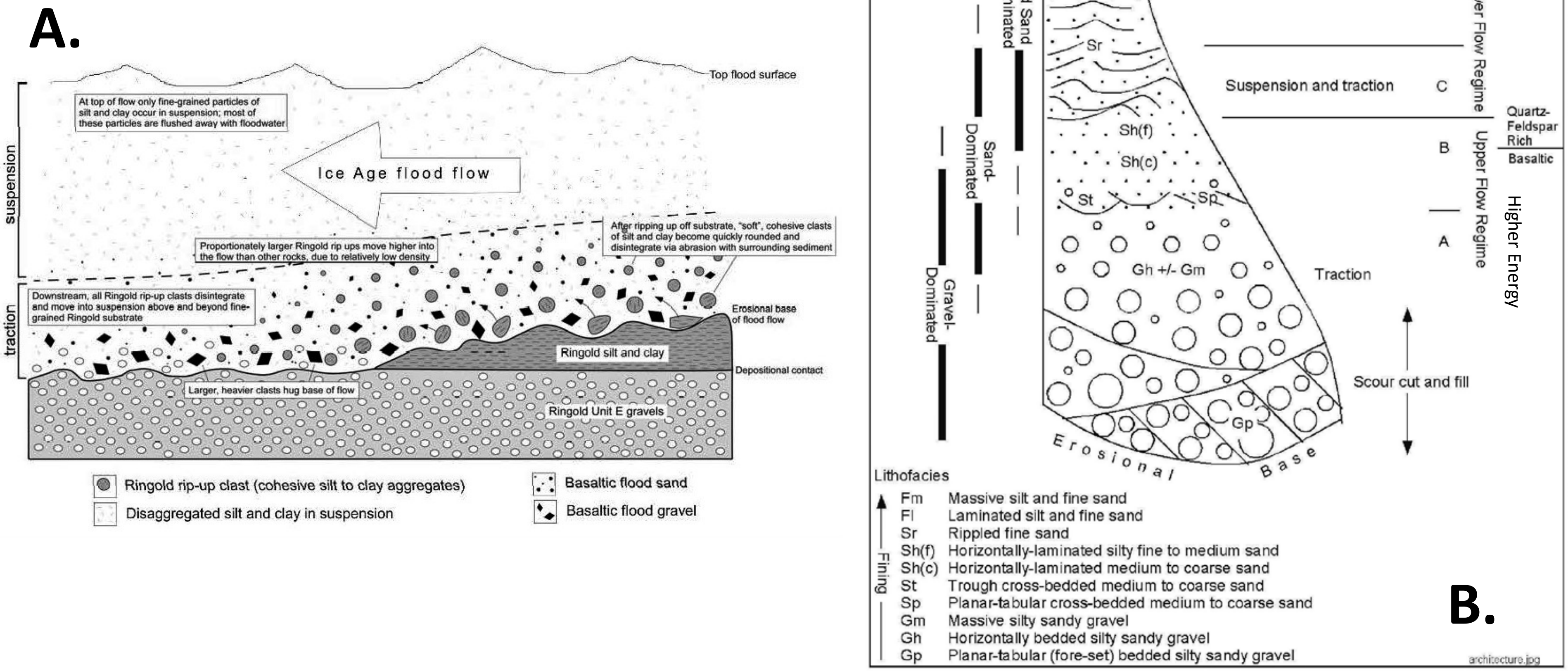
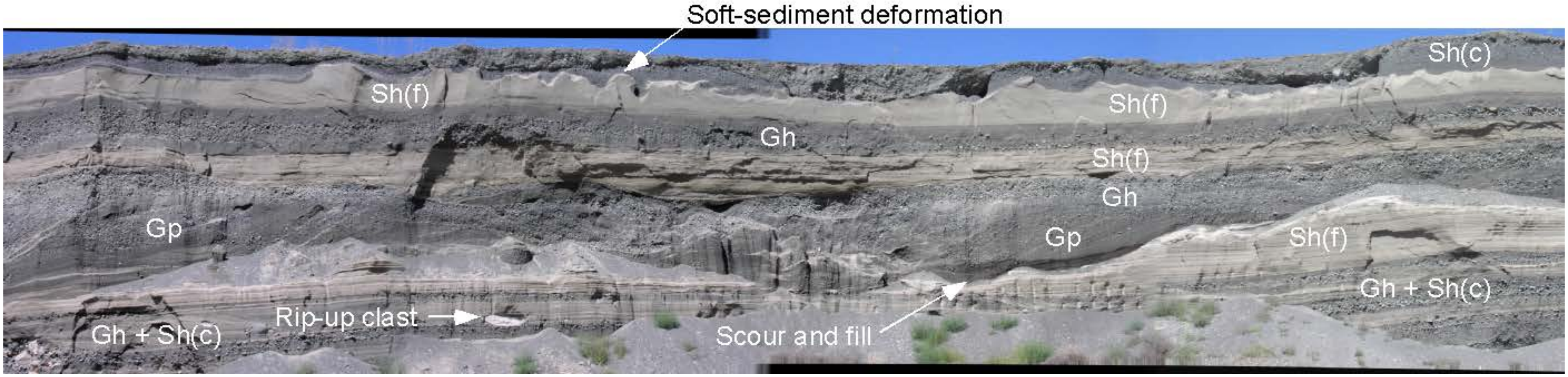


Figure 4. A. Diagrammatic model for sediment transport and stratification during a cataclysmic flood event. Coarser sediment (boulders, gravel, and very coarse sand) were moved as tractive bedload, while progressively above the zone of traction finer sediment (sand, silt and clay) were entrained within the turbulent floodwaters. Such erosion and transport occurred with each cataclysmic flood event. From Bjornstad et al. (2009, Figure 4.16). B. Hanford formation sedimentary deposits (facies) architecture. The presence of absence of specific types of deposits (facies) is initially a function of the relative energy level associated each cataclysmic flood event at that geographic location and its preservation potential during subsequent cataclysmic flood events. Modified from DOE/RL-2002-39 (Rev. 0, Figure A-25).



Key - Lithofacies Labels

Fining

Fm	Massive silt and fine sand
Fl	Laminated silt and fine sand
Sr	Rippled fine sand
Sh(f)	Horizontally-laminated silty fine to medium sand
Sh(c)	Horizontally-laminated medium to coarse sand
St	Trough cross-bedded medium to coarse sand
Sp	Planar-tabular cross-bedded medium to coarse sand
Gm	Massive silty sandy gravel
Gh	Horizontally bedded silty sandy gravel
Gp	Planar-tabular (fore-set) bedded silty sandy gravel

Figure 5. Example of high-energy cataclysmic flood deposits of the Hanford formation deposits in the Pasco area as exposed in the Transtate Borrow Pit in July 2001 (location "T" on Figure 3). See Figure 4 for explanation of lithofacies labels. Modified from DOE/RL-2002-39 (rev. 0), Figure B-2.

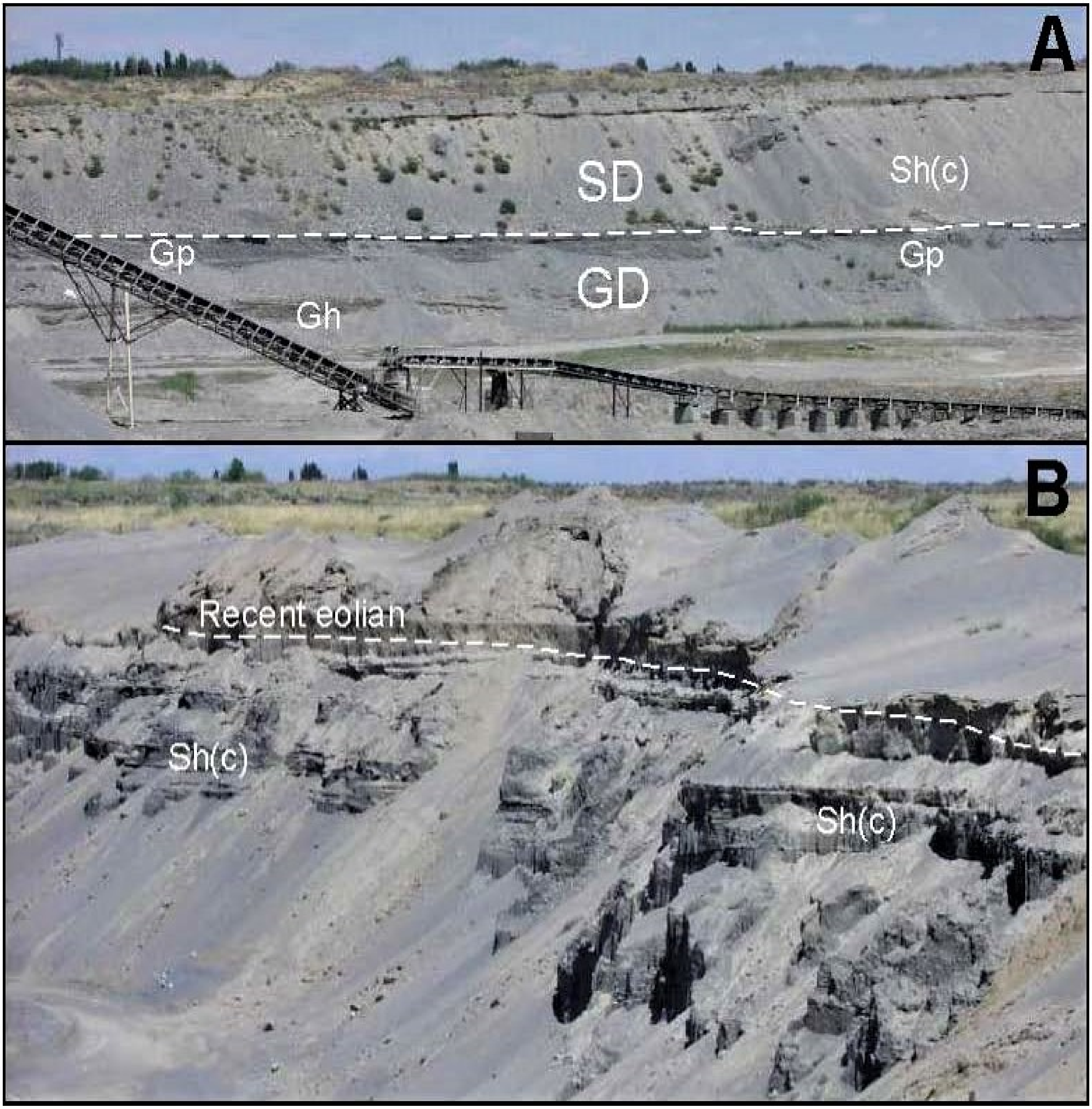


Figure 6. Cataclysmic flood deposits exposed in the Pre-Mix Borrow Pit, Pasco, Washington (location “PM” on Figure 3). A. More than 33 feet of sand-dominated deposits (SD) overlying gravel-dominated deposits (GD).
B. Close-up of the sand-dominated deposits that consist mainly of horizontally laminated, basaltic (“salt and pepper sands”), medium- to coarse-grained sand. See Figure 4 for explanation of lithofacies labels. From DOE/RL-2002-39 (rev. 0), Figure B-6.

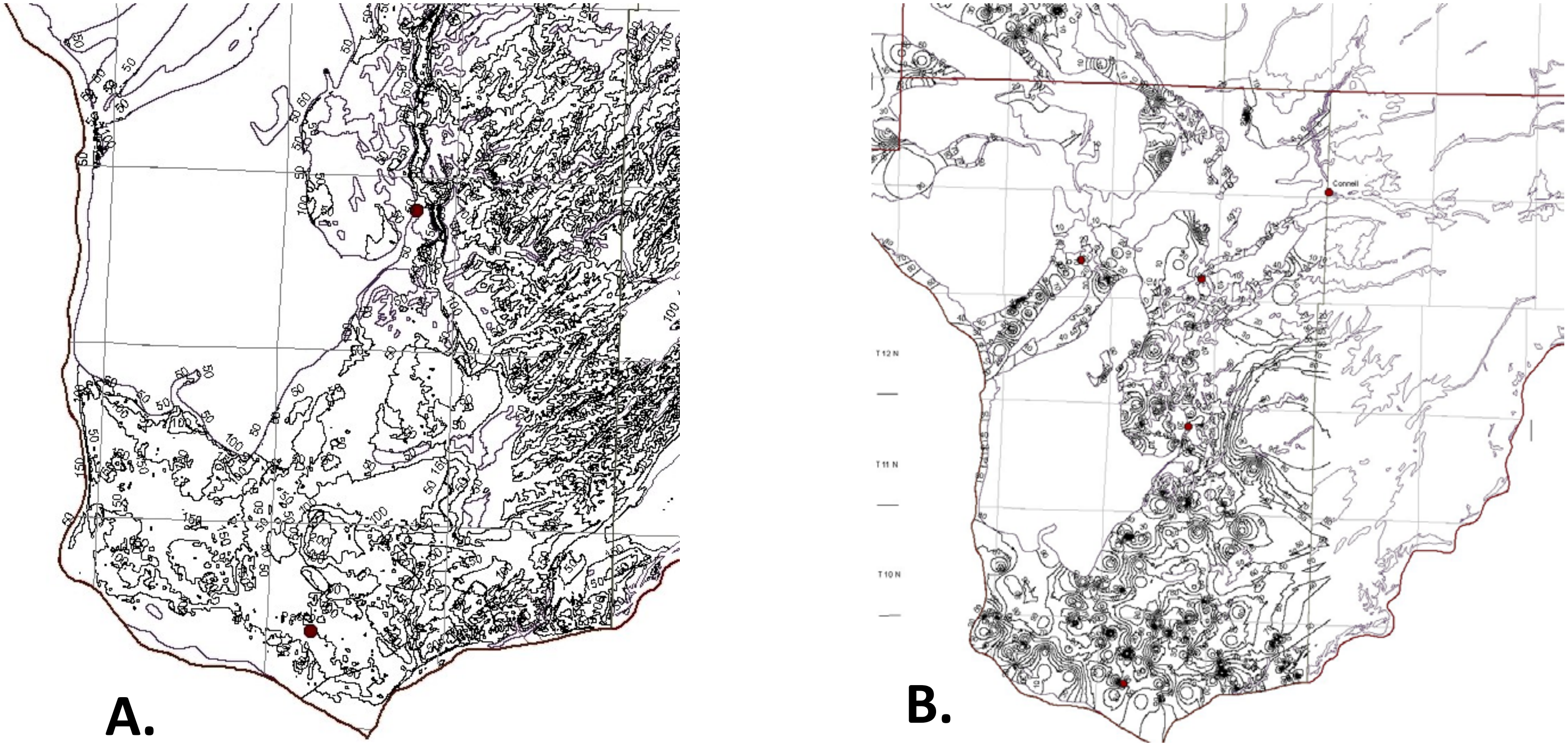


Figure 7. A. Thickness (isopach) map of the Hanford formation gravel in the greater Pasco area. B. Thickness (isopach) map of the Hanford formation sand in the greater Pasco area. From Lindsey et al. (2007).

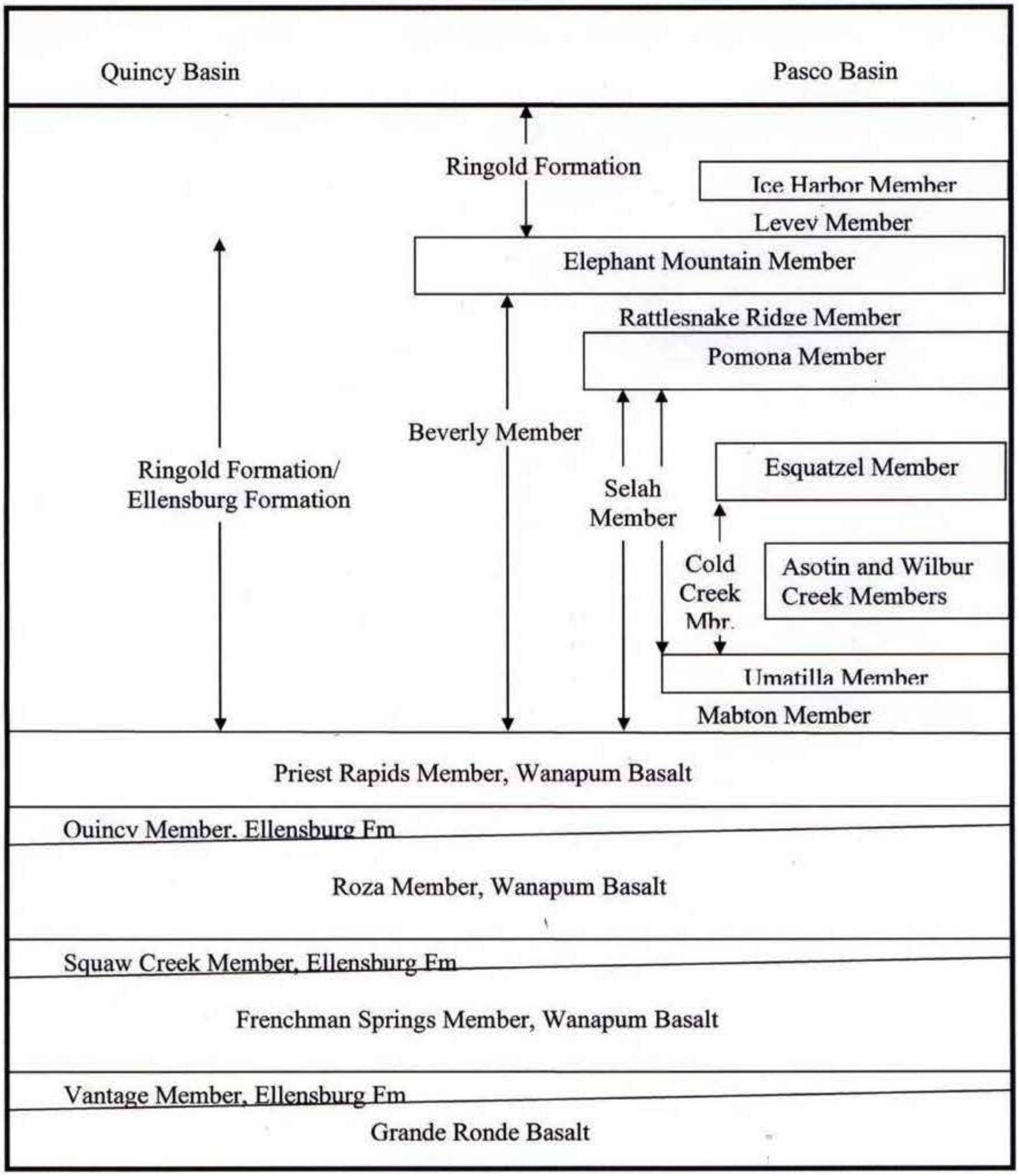


Figure 8. Diagram illustrating stratigraphic relations between the CRBG, Ellensburg Formation interbeds, and Ringold Formation in the greater Pasco Basin – Quincy Basin region. From Tolan et al. (2009, p. 621).

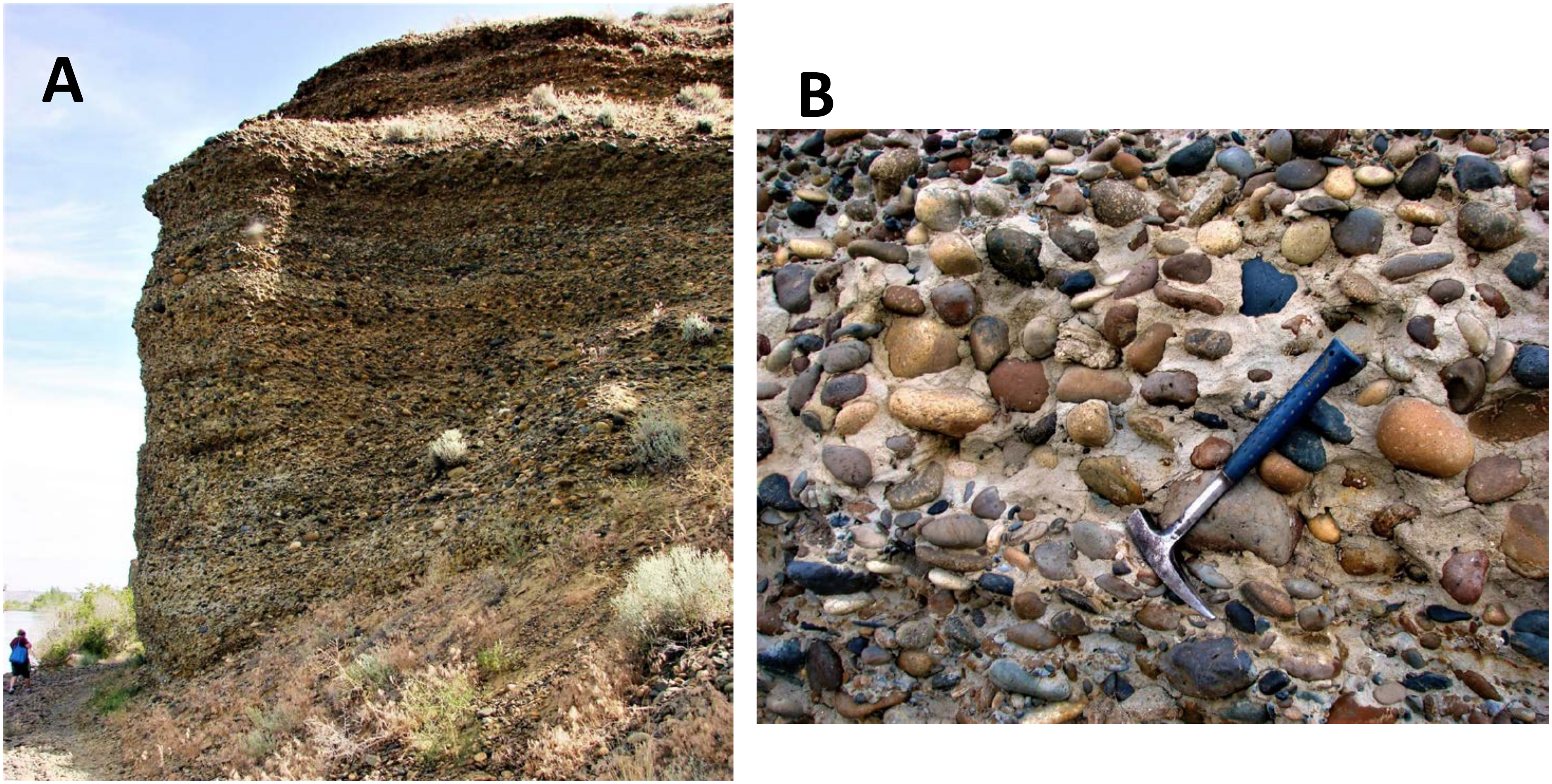


Figure 9. Photograph of exposures of the Wooded Island member of the Ringold Formation at its type-location along the east bank of the Columbia River north of the Pasco area. A. Outcrop of variable indurated (cemented) Wooded Island conglomerate (pebble- to cobble-size gravel). B. Close-up view of the Wooded Island conglomerate.

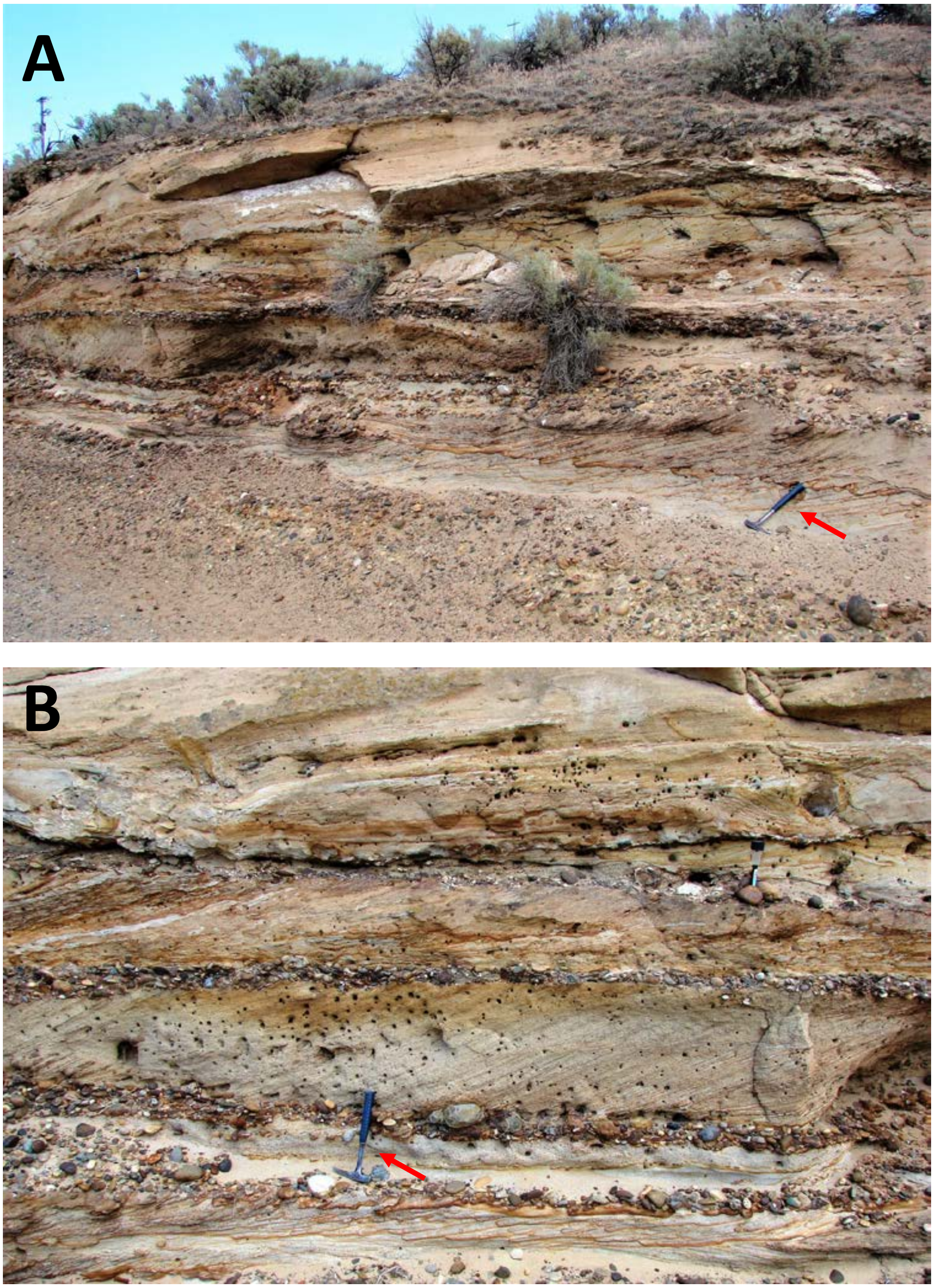
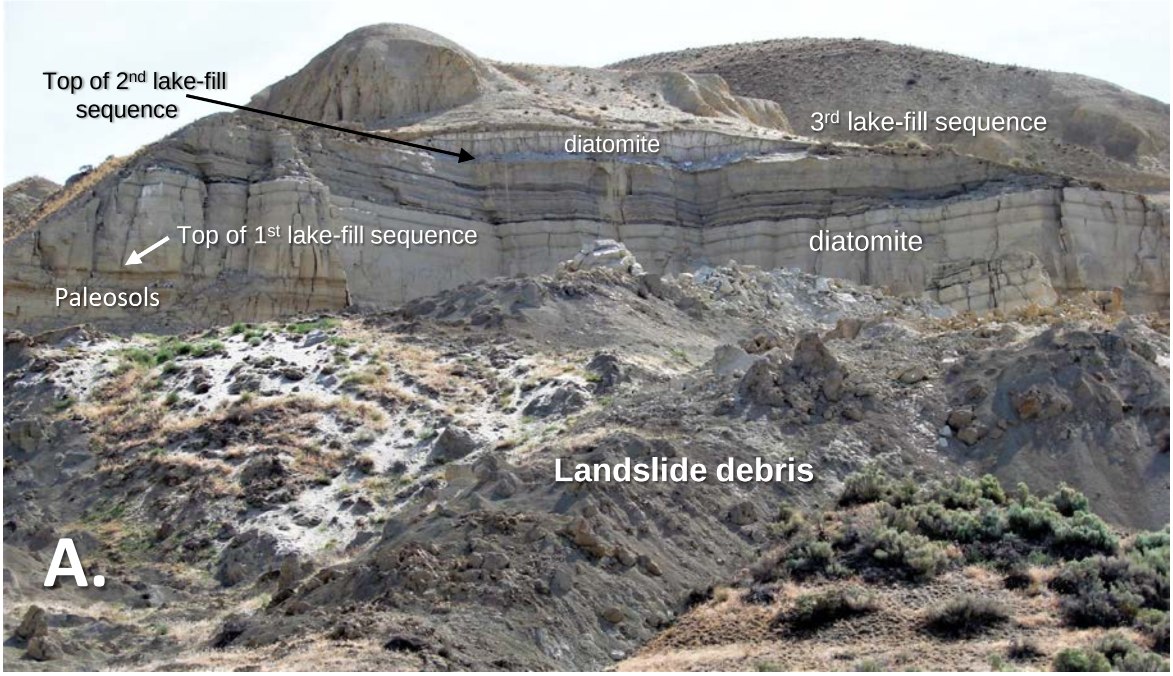


Figure 10. A. Photographs of an outcrop of the Taylor Flat member (note hammer for scale) that overlies the Wooded Island member outcrop seen in Figure 9. B. Close-up view of the Taylor Flat member sandstone with thin beds of small pebble- to small cobble-size gravel.



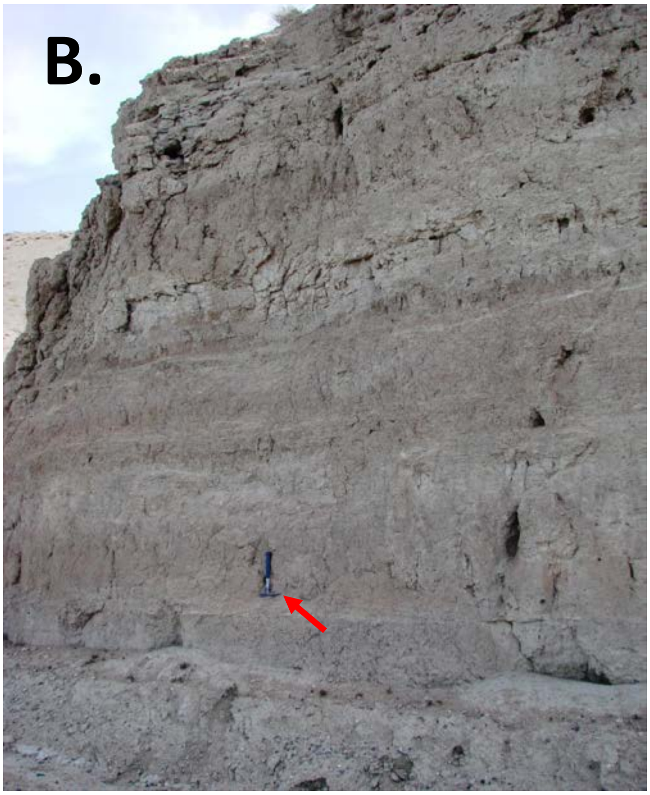


Figure 11. A. Exposures of Savage Island member lacustrine/paleosol sediments in the White Bluffs, east of Ringold Coulee. B. Silt/clay beds of the Savage Island member . The darker bands represent paleosol development on these beds. Note hammer for scale.

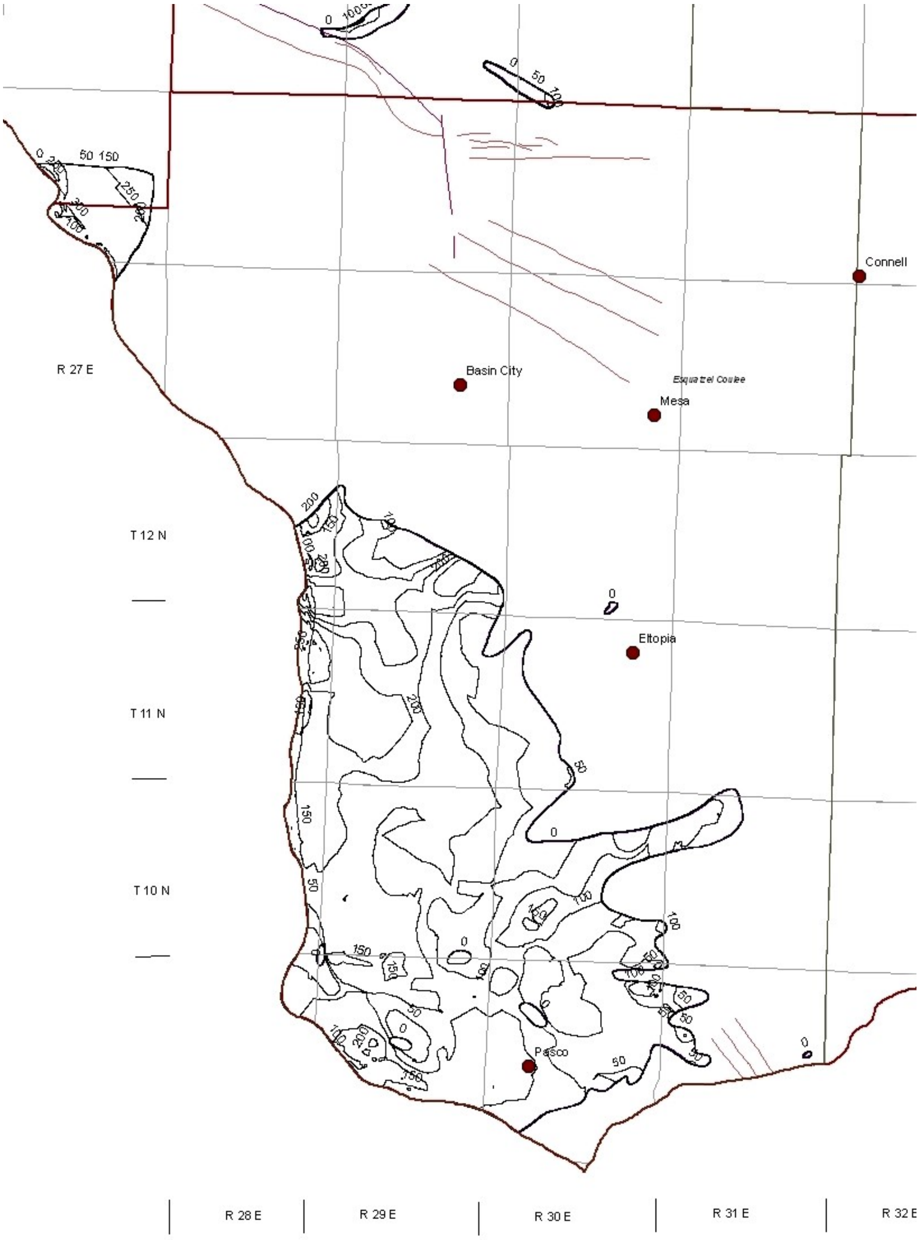


Figure 12. Map showing the thickness of the Wooded Island member of the Ringold Formation beneath the Pasco study area. From Lindsey and Tolan (2007).

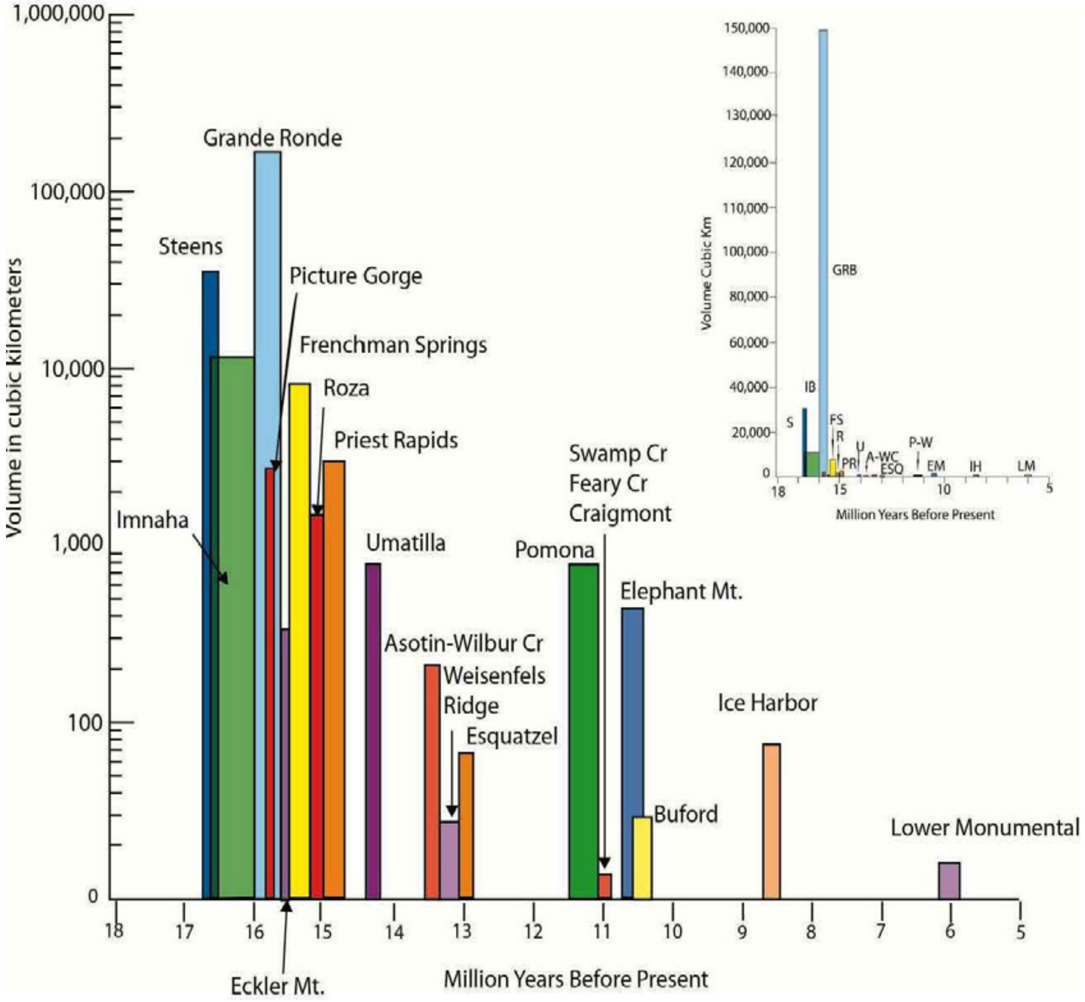


Figure 13. Erupted CRBG volume verses time. Note that on the above diagram the volume axis has a logarithmic scale in comparison to the smaller inset diagram (linear scale). From Barry et al. (2013).

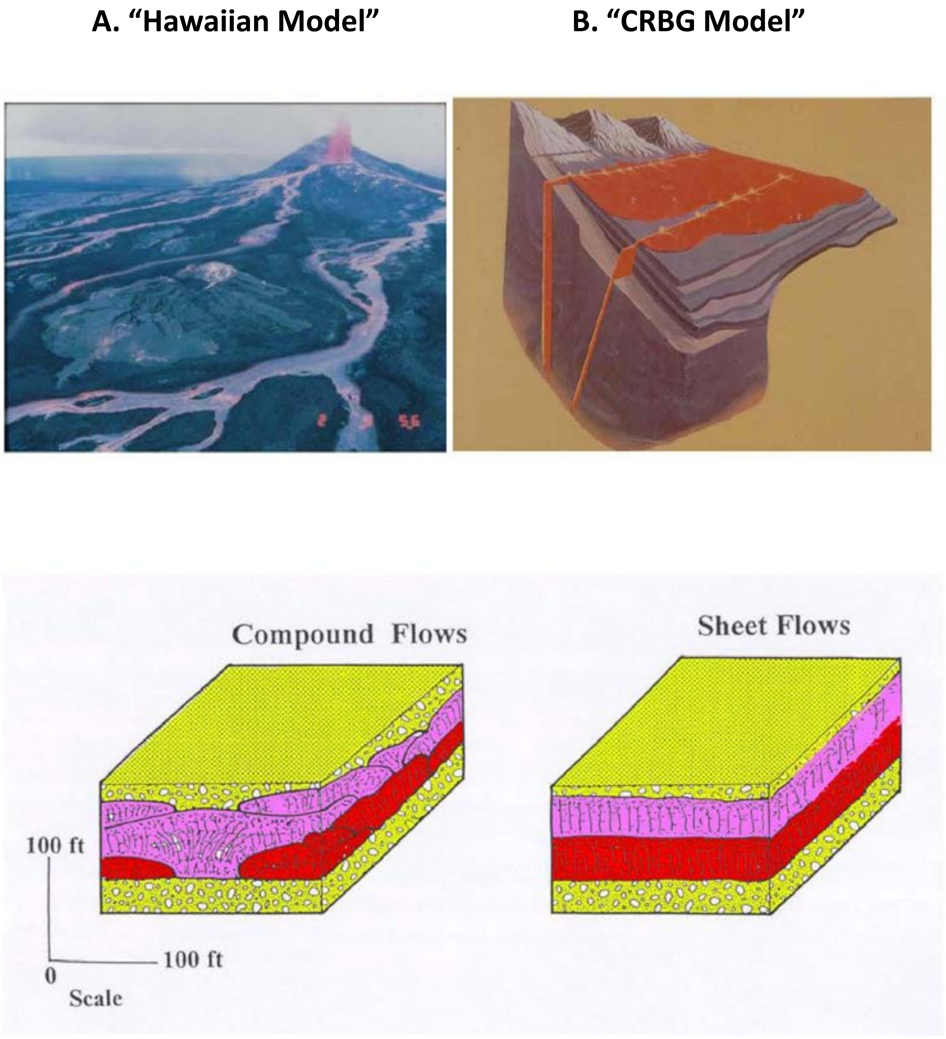


Figure 14. Comparison of basaltic compound and sheet flows. A. a basaltic compound flow develops when the lava advances away from its vent in a series of distinct and separate lobes (flows) of flowing lava. Each lobe is subsequently covered by later lava lobes as the emplacement of lava continues. This results in the accumulation of elongated basalt flows with numerous, local, discontinuous, and relatively thin layers of basalt lava. B. A basaltic sheet flow results when lava is erupted at a high rate and advances away from the vent as a single, uniform, moving sheet of lava. This type of basalt flow consists of a relatively extensive, single layer or “sheet” of lava. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops and flow bottoms. From Tolan et al. (2009).

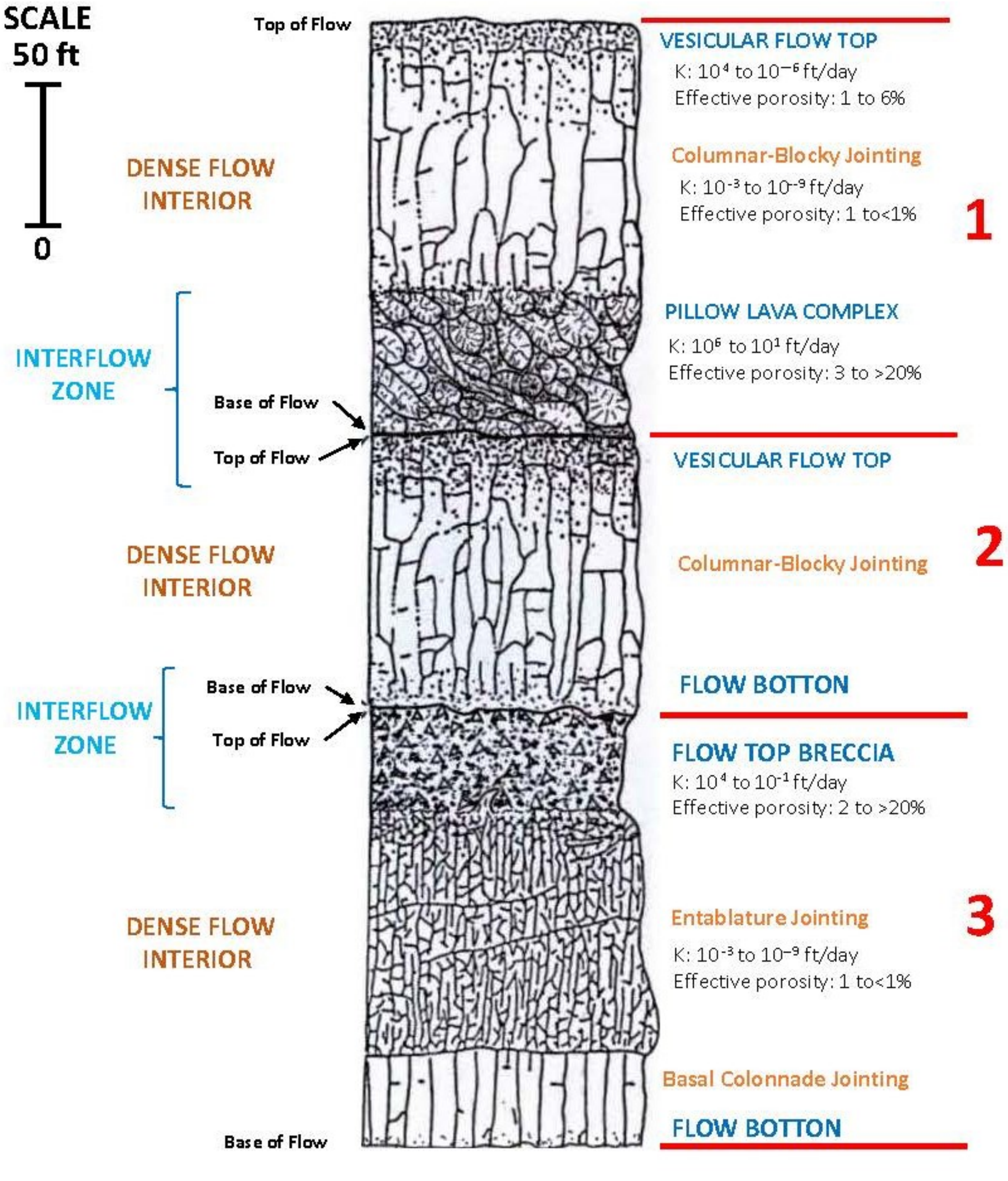


Figure 15. Example Illustrating the arrangement of internal structure (termed “intraflow structures”) and terminology within a sequence of 3 CRBG sheet flows and the terminology. Modified from Tolan et al. (2009).

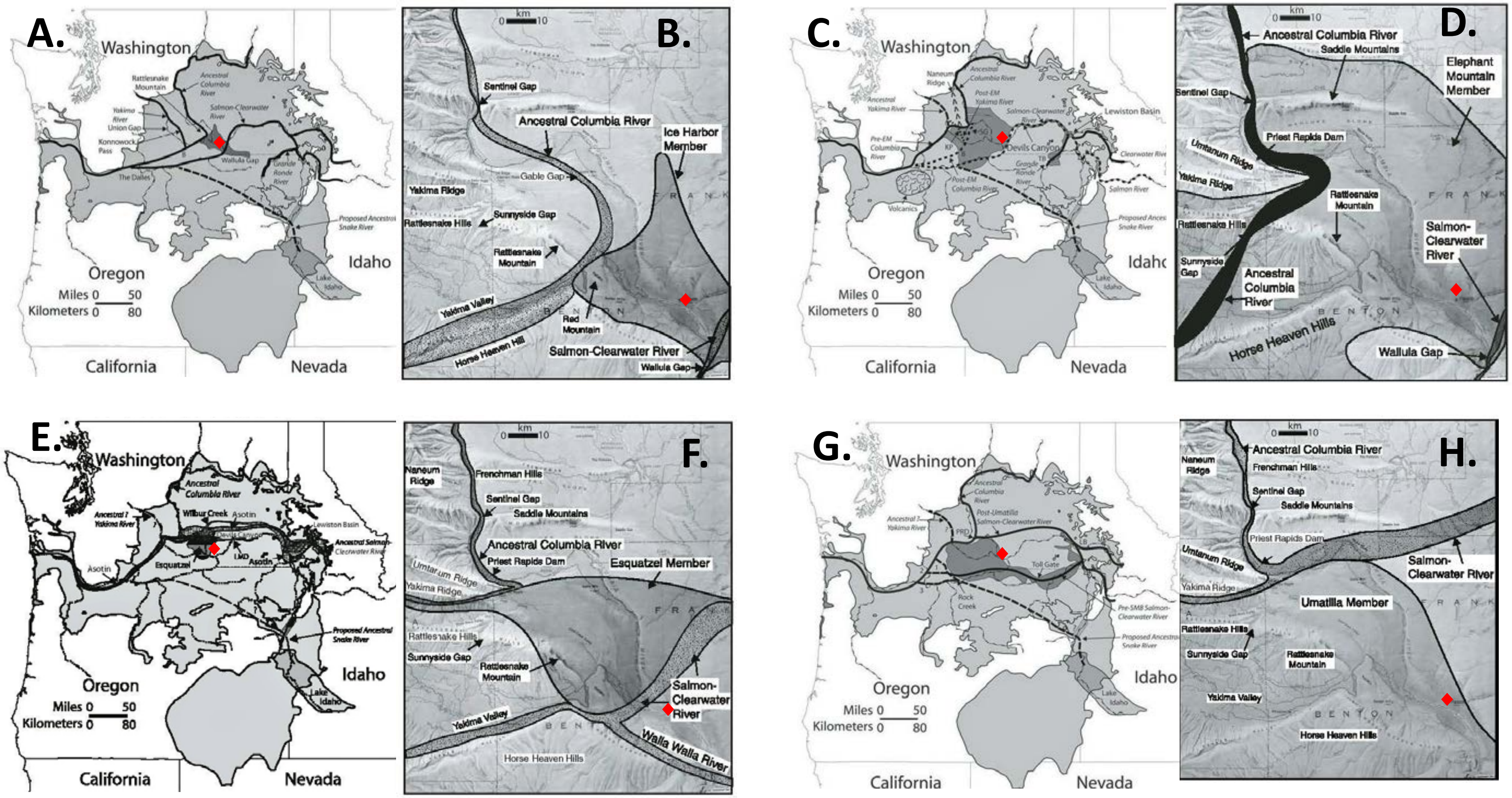


Figure 16. Maps showing the original regional and Pasco area extents of selected Saddle Mountains Basalt members that are inferred to be present beneath the Pasco area (red diamond) in relation to the ancestral Columbia River system. A. Regional extent of the Ice Harbor Member. B. Ice Harbor Member extent in the Pasco area. C. Regional extent of the Elephant Mountain Member. D. Elephant Mountain Member extent in the Pasco area. (Note - the Pomona Member is present and its originally extent would have entirely covered the Pasco area map and is omitted for this reason) E. Regional extent of the Esquatzel Member. F. Esquatzel Member extent in the Pasco area. G. Regional extent of the Umatilla Member. D. Umatilla Member extent in the Pasco area. Reproduced from Reidel and Tolan (2013).

Figure 17. Diagram illustrating stratigraphic nomenclature and relationships between the CRBG, Ellensburg Formation, and suprabasalt sediments in the Pasco study area. SMB = Saddle Mountains Basalt. Modified from Tolan et al. (2009).

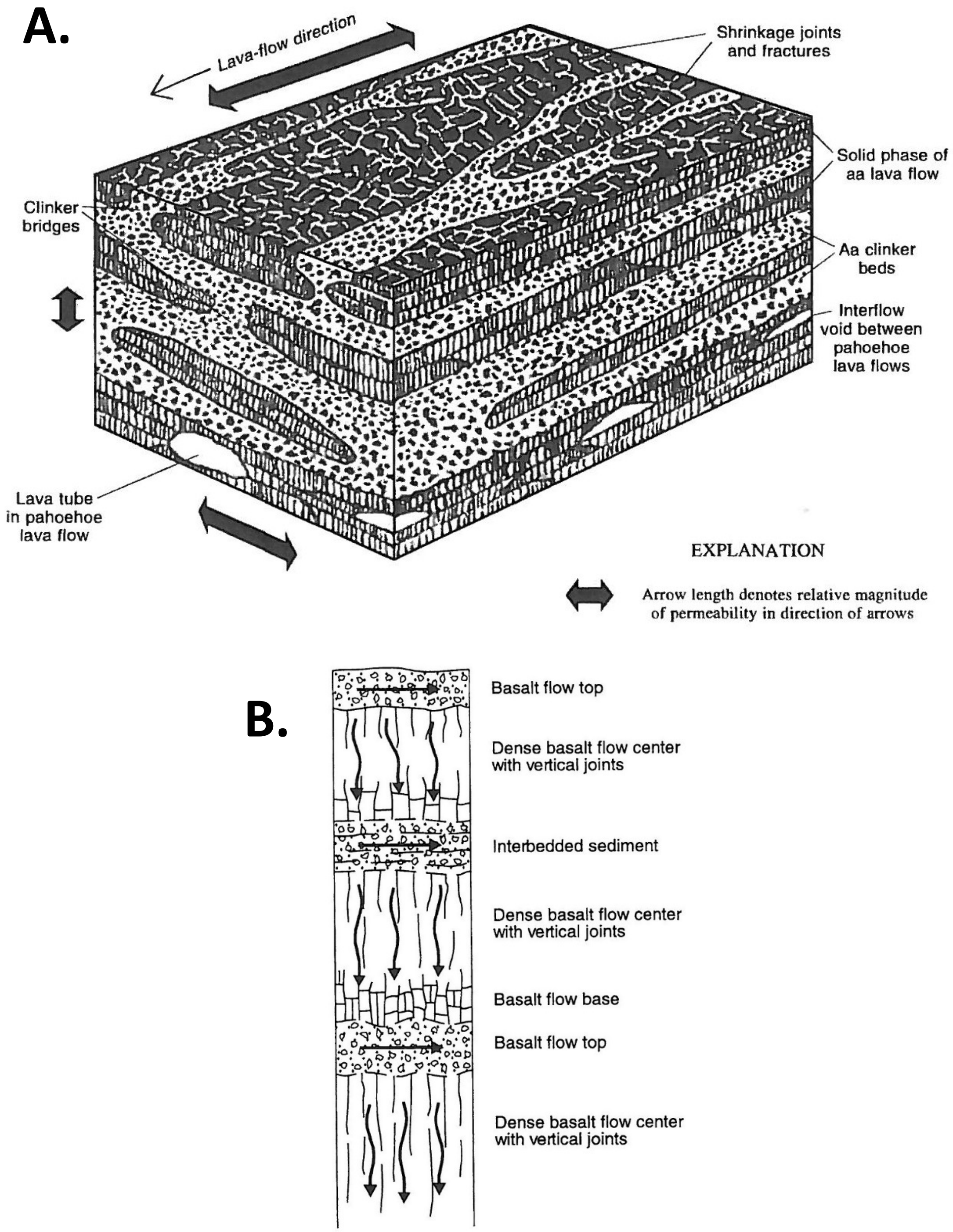


Figure 18. A. Diagram depicting common Intraflow structures and their arrangement in Hawaiian a'a and pahoehoe flow sequences and the relative ability for groundwater movement through these features. Reproduced from Hunt (1996, Figure 7, p. B13). B. Diagram depicting inferred lateral and vertical groundwater pathways within CRBG flows based on the Hawaiian model. Reproduced from Drost et al. (1997).

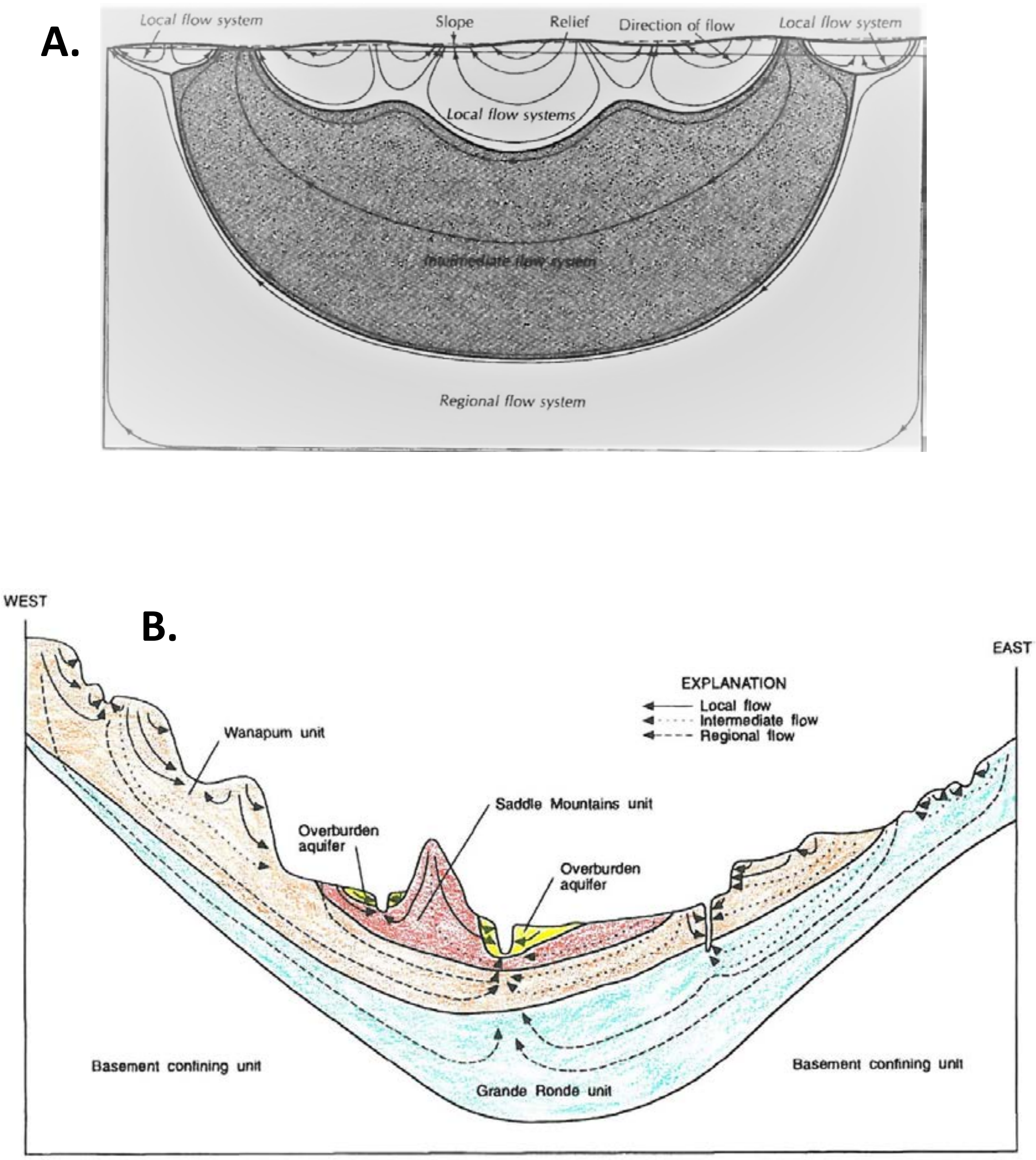


Figure 19. A. Theoretical development of local, intermediate, and regional groundwater flow systems within a deep basin aquifer system. The stippled area represents the intermediate flow system. From Toth (1963). B. Conceptual model of the regional, intermediate, and local CRBG aquifer system based on the Hawaiian basalt flow model. Note the similarity to Toth's (1963) deep basin aquifer system model. In this conceptual model it is assumed that the regional and intermediate aquifers (i.e., Grande Ronde and Wanapum Basalts aquifers) discharge to the major rivers (e.g., Columbia, Snake, Yakima, Deschutes, John Day, Walla Walla Rivers). Discharge from the CRBG aquifers to the major rivers is assumed to be possible because of the assumption that groundwater can move vertically along cooling joints in the dense interiors of CRBG flow (see Figure 2-18B). From Hansen et al. (1994, Figure 7, p. 54).

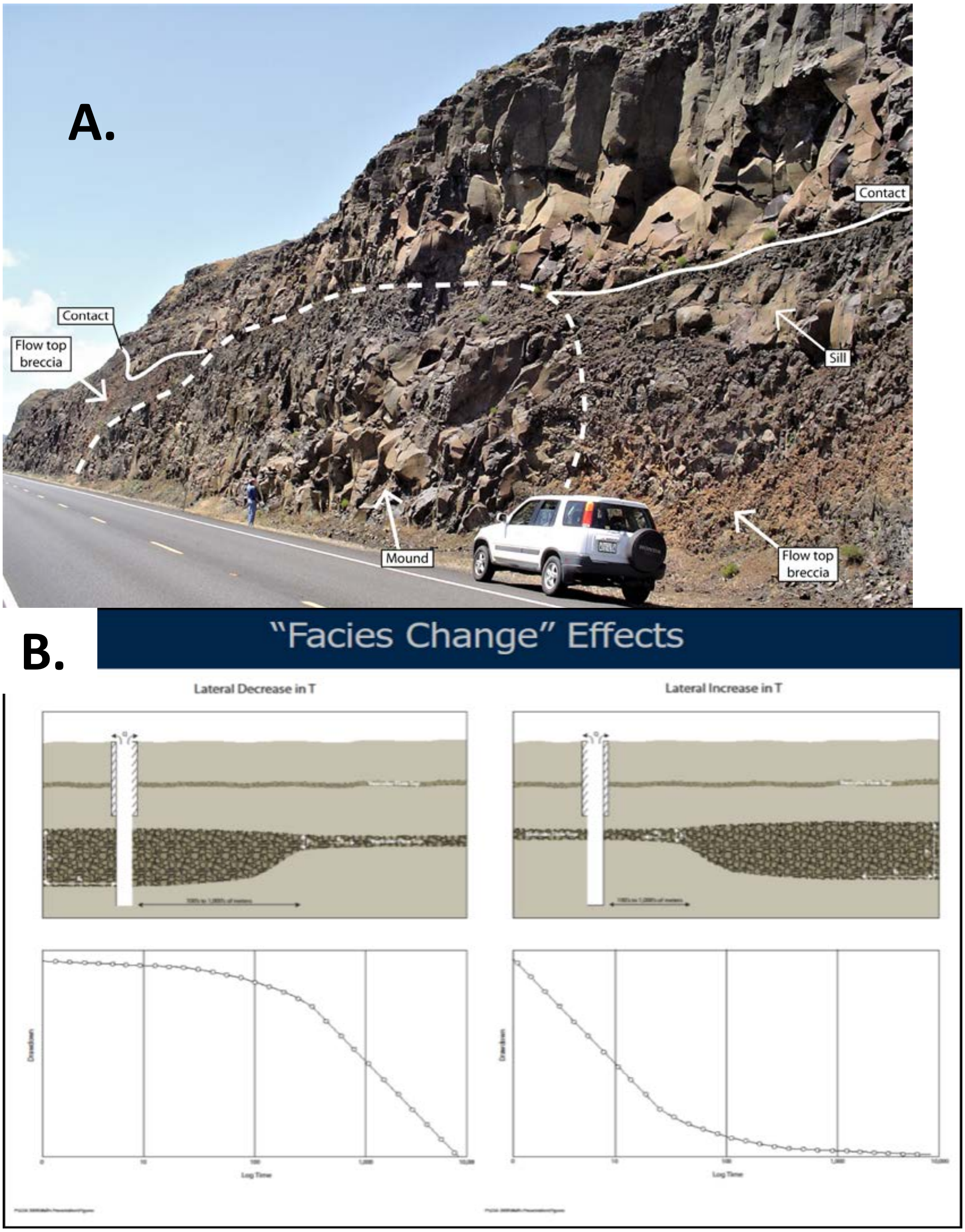


Figure 20. Roadcut exposing the lateral transition from a flow top breccia to a simple vesicular top In a Frenchman Springs Member flow. B. Pair of schematics illustrating a simplified response to pumping a single CRBG interflow zone which transitions lateral from a simple vesicular flow top to a flow top breccia (“facies change”) that have differing hydraulic characteristics. The diagrams on the left illustrates the water level response (negative boundary) within the pumping well that penetrates a flow top breccia that laterally transitions to a lower transmissivity simple flow top. The illustration on the right side depicts the possible response of a well completed within the simple vesicular flow top (lower transmissive portion of the interflow zone) that “sees” the higher transmissivity portion of the interflow zone (flow top breccia) in the late time water level data.

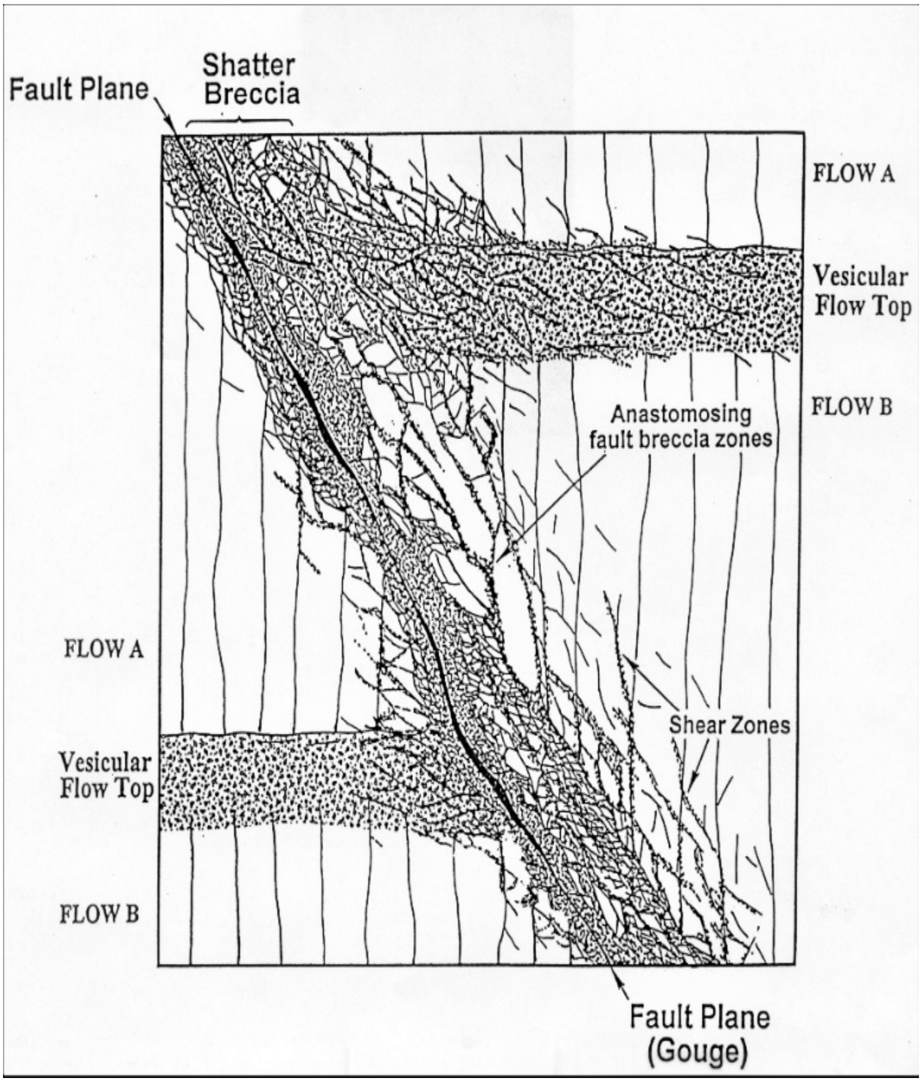


Figure 21. Diagram depicting common features found within fault zones that transect CRBG flows. Reproduced from Tolan et al. (2009).

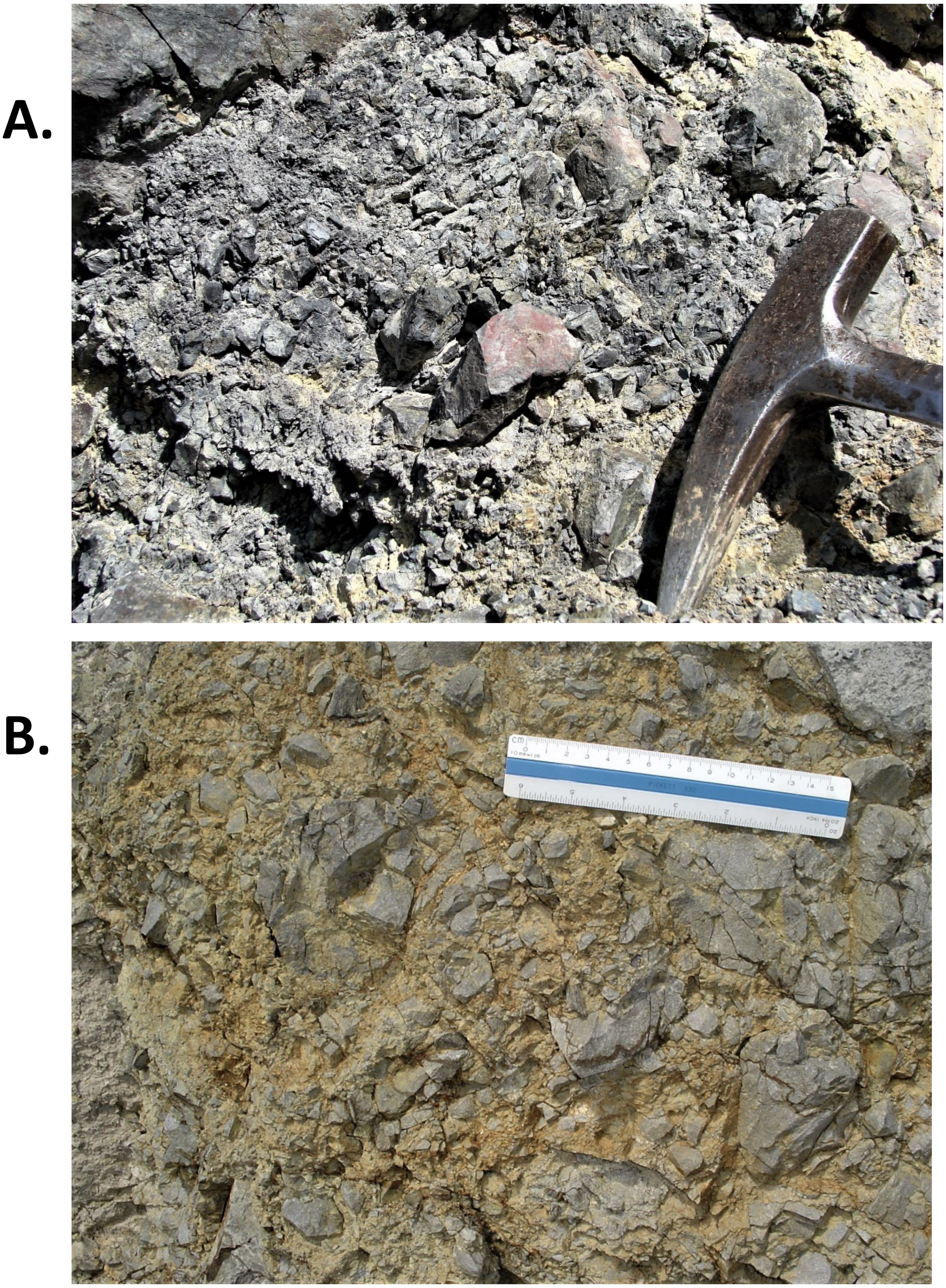


Figure 22. A. Relatively unaltered/weathered fault shatter breccia in a CRBG flow dense interior.
B. Altered/weathered fault shatter breccia in a CRBG flow dense interior. Note that the smaller basalt fragments have completely altered to clay.

CRBG Dike

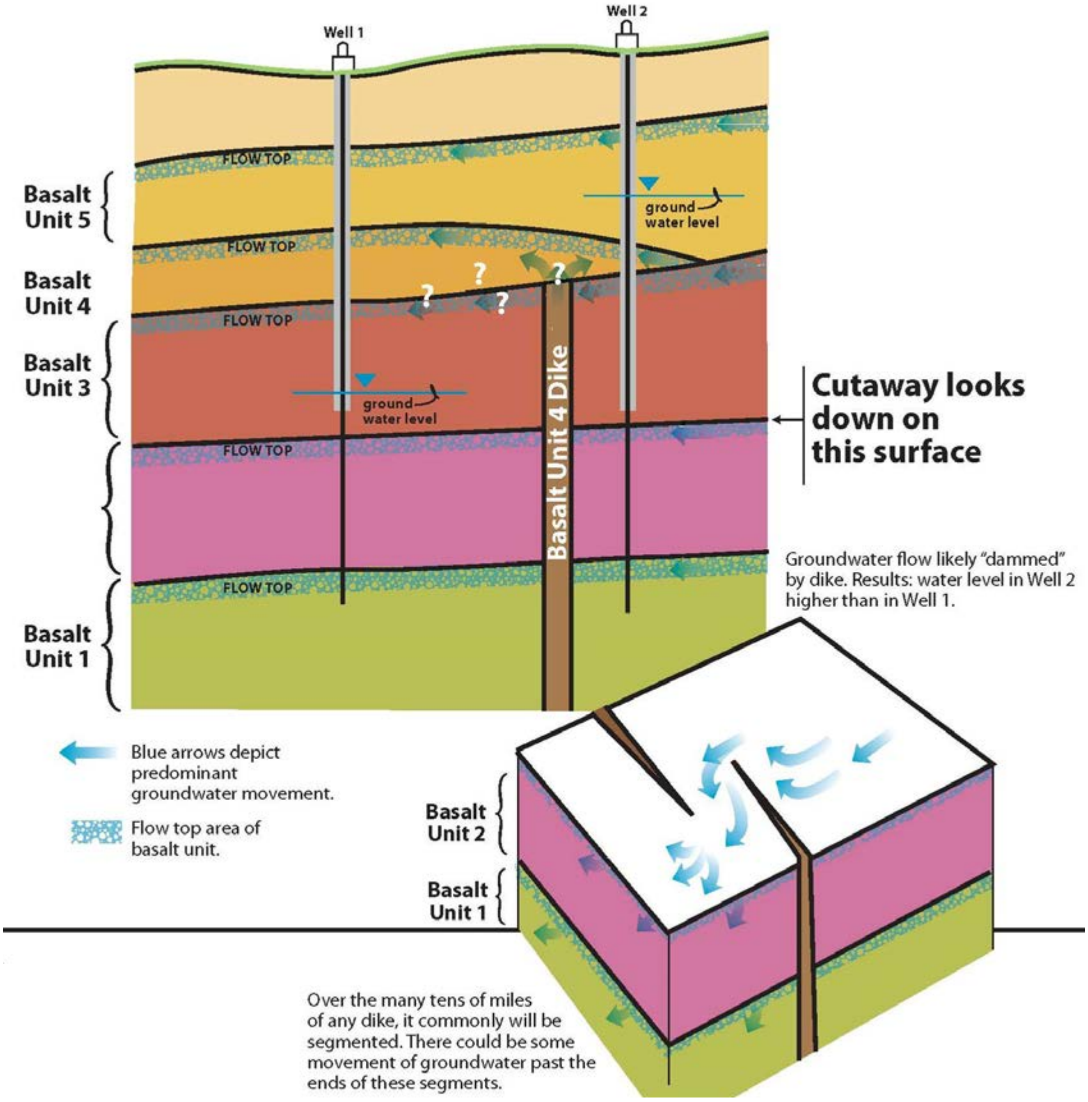


Figure 23. Diagrams illustrating the potential impact of CRBG feeder dikes on the CRBG aquifer system. CRBG linear feeder dikes represent the vertical conduit that enabled CRBG magma to reach the surface and "erupt" the molten lava that formed an individual CRBG flow. In this diagram the dike was the source for the lava that formed Basalt Unit #4. The Basalt Unit #4 dike would have extended vertically from the magma chamber to the paleo-ground surface (more than 30 miles) and could have had a total linear surface length of more than 50 miles. As the diagram shows, CRBG dikes can have significantly impact a CRBG aquifer system where present as in the case of the eastern boundary of the Pasco Basin. From Columbia Basin GWMA (2010).

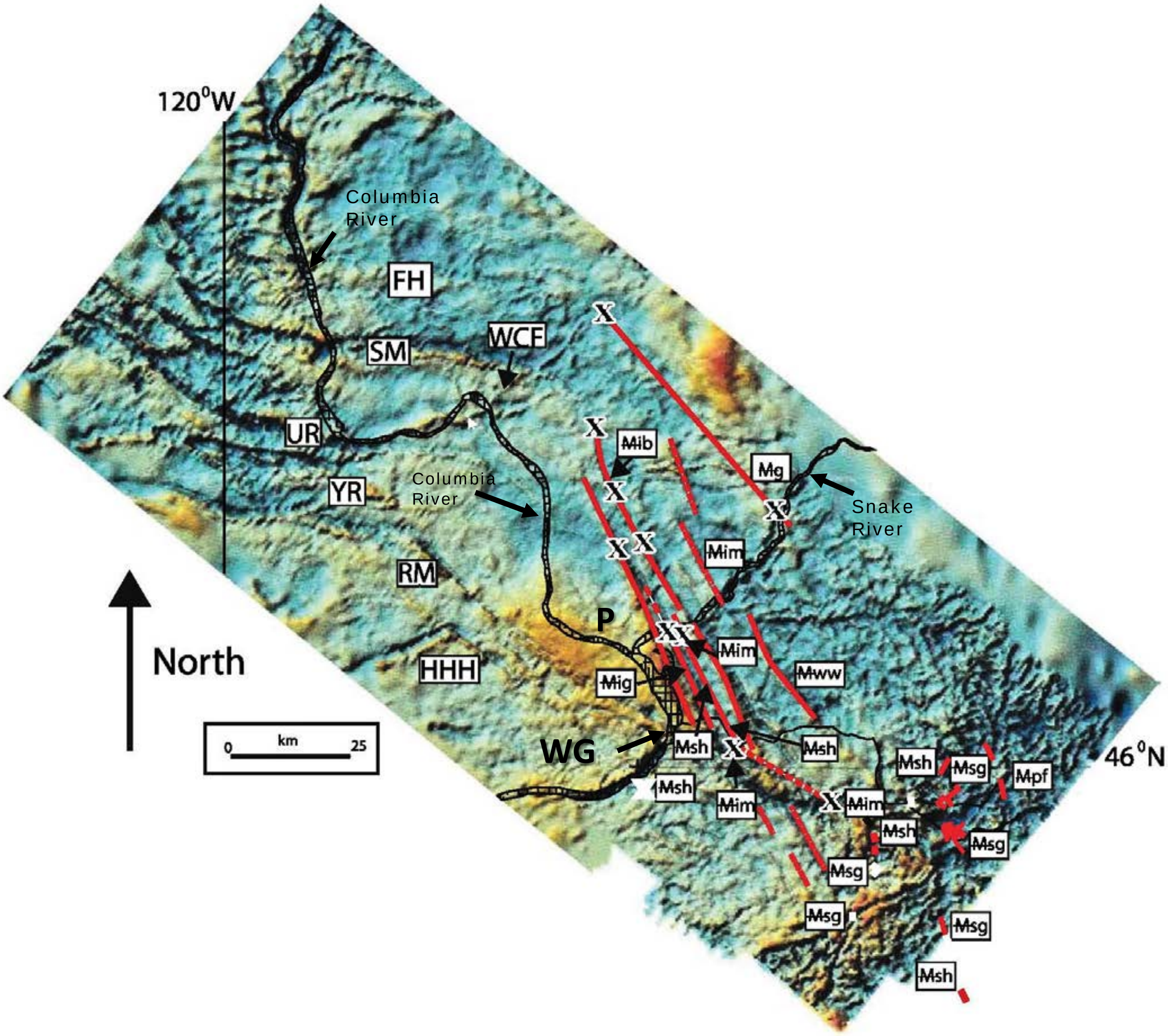


Figure 24. Portion of Flinn et al. (1997) aeromagnetic map of the greater Pasco Basin area as annotated by Reidel et al. (2020) to show locations of mapped CRBG vents and dikes. **X** indicates CRBG vents and the red lines are traces of CRBG dikes. Geographic features: P – Pasco; WG – Wallula Gap; HHH – Horse Heaven Hills; RM – Rattlesnake Mountain; YR – Yakima Ridge; UR – Umtanum Ridge; SM – Saddle Mountains; FH – Frenchman Hills. CRBG units: ~~M~~ig – Goose Island, Ice Harbor Member; ~~M~~im – Martindale, Ice Harbor Member; ~~M~~ib – Basin City, Ice Harbor Member; ~~M~~sg – Sentinel Gap, Frenchman Springs Member; ; ~~M~~sh – Sand Hollow, Frenchman Springs Member; ; ~~M~~g – Ginkgo, Frenchman Springs Member; ; ~~M~~pf – Palouse Falls, Frenchman Springs Member; ; ~~M~~ww – Walla Walla Member (Saddle Mtns. Basalt – overlies Ice Harbor Member in the Walla Walla Basin).

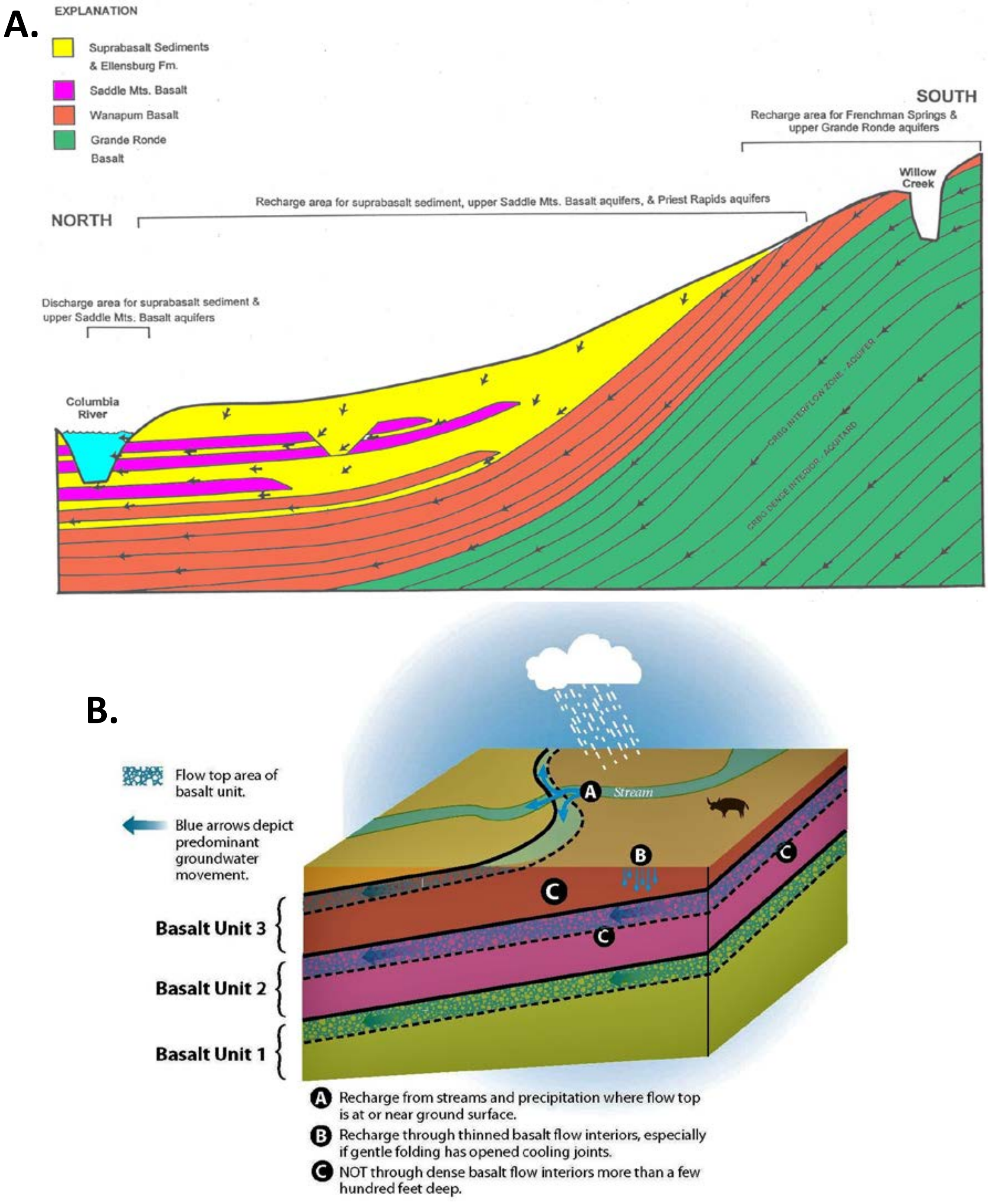
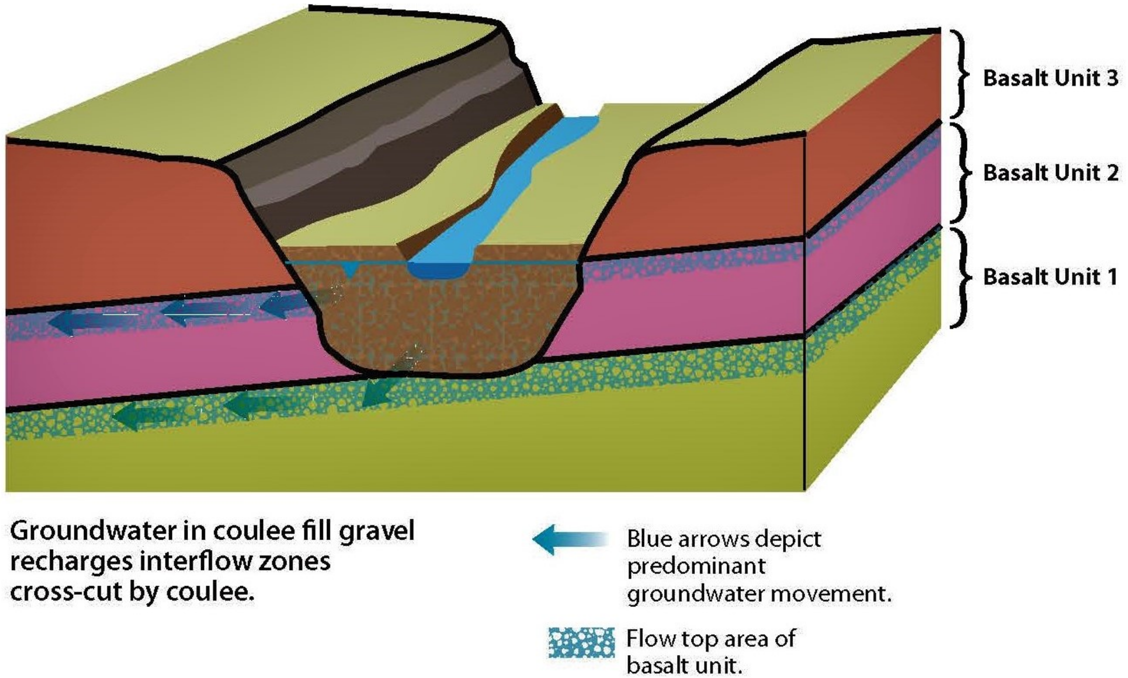
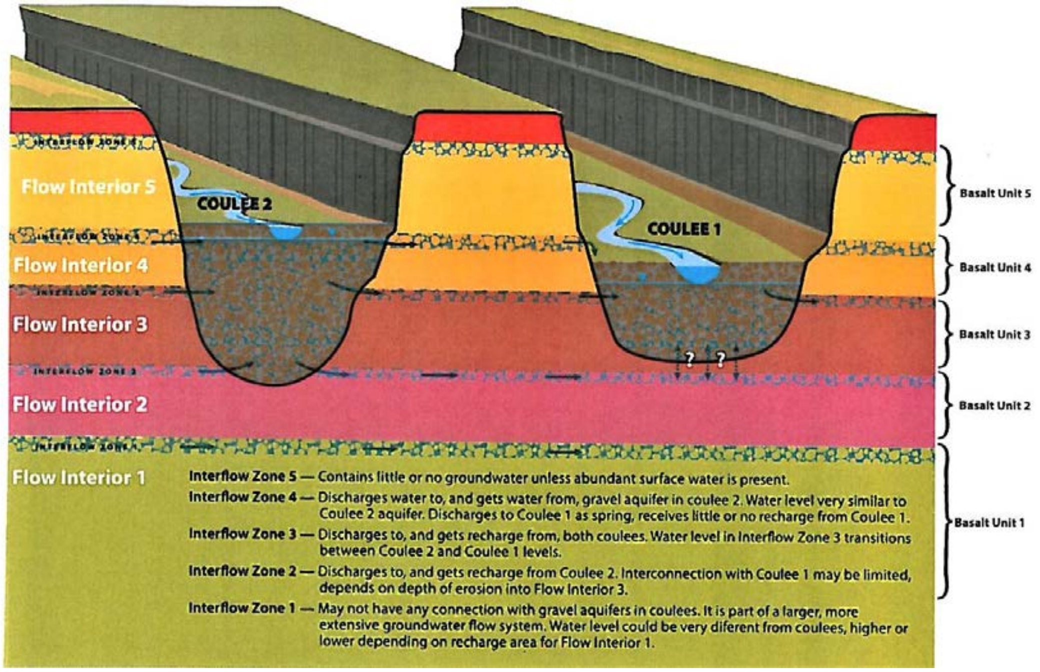


Figure 25. A. Diagrammatic sketch showing the potential recharge and discharge pathways for the suprabasalt sediment and CRBG aquifers systems in the Umatilla Basin, Oregon. After Tolan et al., 2009, Figure 21). B. Diagram depicting potential recharge pathways for CRBG interflow zone exposed at the surface. From Columbia Basin GWMA (2010) .



Groundwater in coulee fill gravel recharges interflow zones cross-cut by coulee.



Interflow Zone 5 — Contains little or no groundwater unless abundant surface water is present.

Interflow Zone 4 — Discharges water to, and gets water from, gravel aquifer in coulee 2. Water level very similar to Coulee 2 aquifer. Discharges to Coulee 1 as spring, receives little or no recharge from Coulee 1.

Interflow Zone 3 — Discharges to, and gets recharge from, both coulees. Water level in Interflow Zone 3 transitions between Coulee 2 and Coulee 1 levels.

Interflow Zone 2 — Discharges to, and gets recharge from Coulee 2. Interconnection with Coulee 1 may be limited, depends on depth of erosion into Flow Interior 3.

Interflow Zone 1 — May not have any connection with gravel aquifers in coulees. It is part of a larger, more extensive groundwater flow system. Water level could be very diferent from coulees, higher or lower depending on recharge area for Flow Interior 1.

Figure 26. Block diagrams showing two CRBG confined aquifer(s) discharge/recharge scenarios associated with unconfined aquifer host by suprabasalt sediments within cataclysmic flood erosional channels (coulees). From Columbia Basin GWMA (2010).

APPENDIX A

GEOLOGIC WELL LOGS AND MEASURED SURFACE GEOLOGIC SECTIONS FROM THE GREATER PASCO BASIN

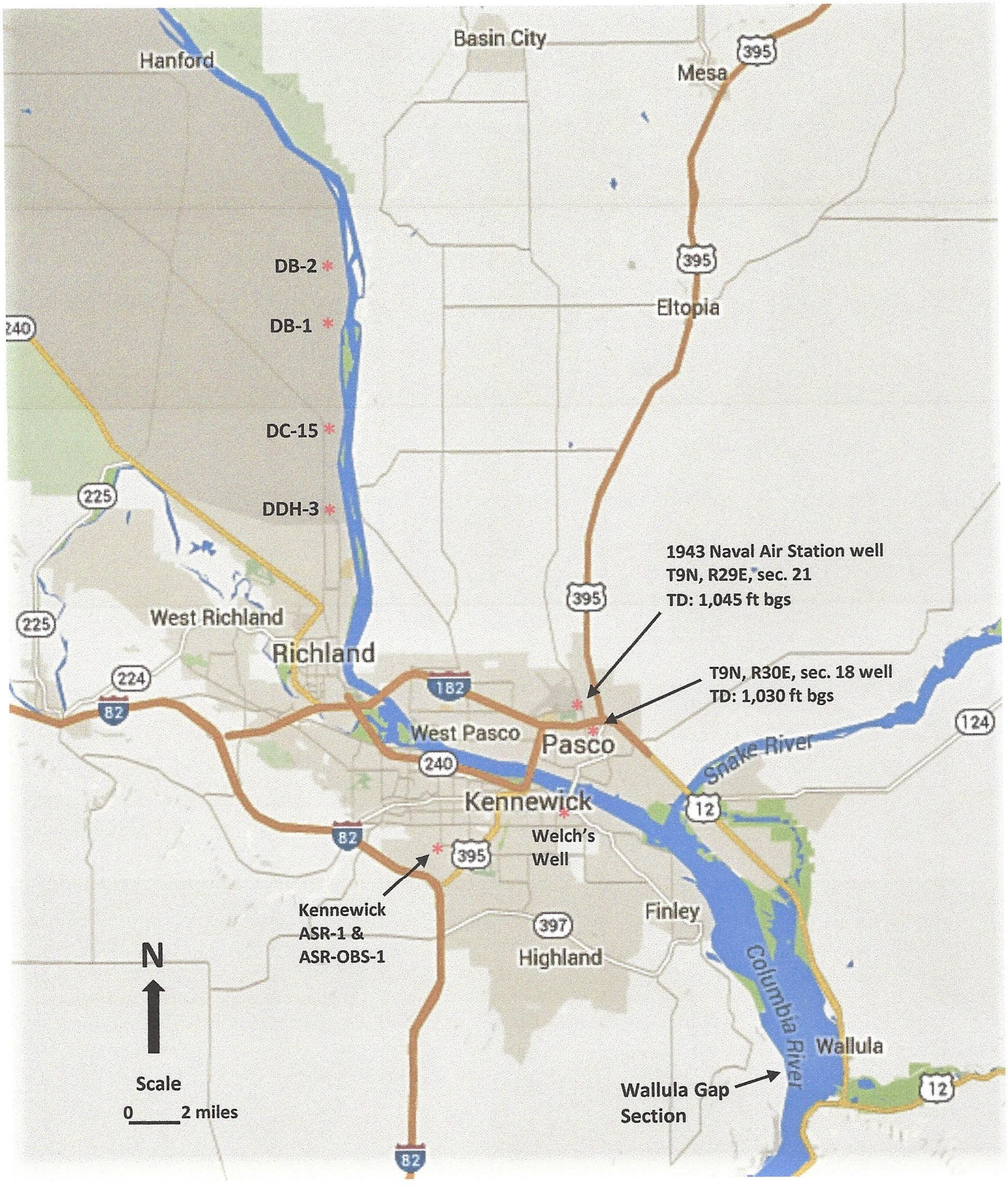


Figure A-1. Map showing the approximate location of selected deep boreholes, wells, and measured geologic sections discussed in this memorandum.

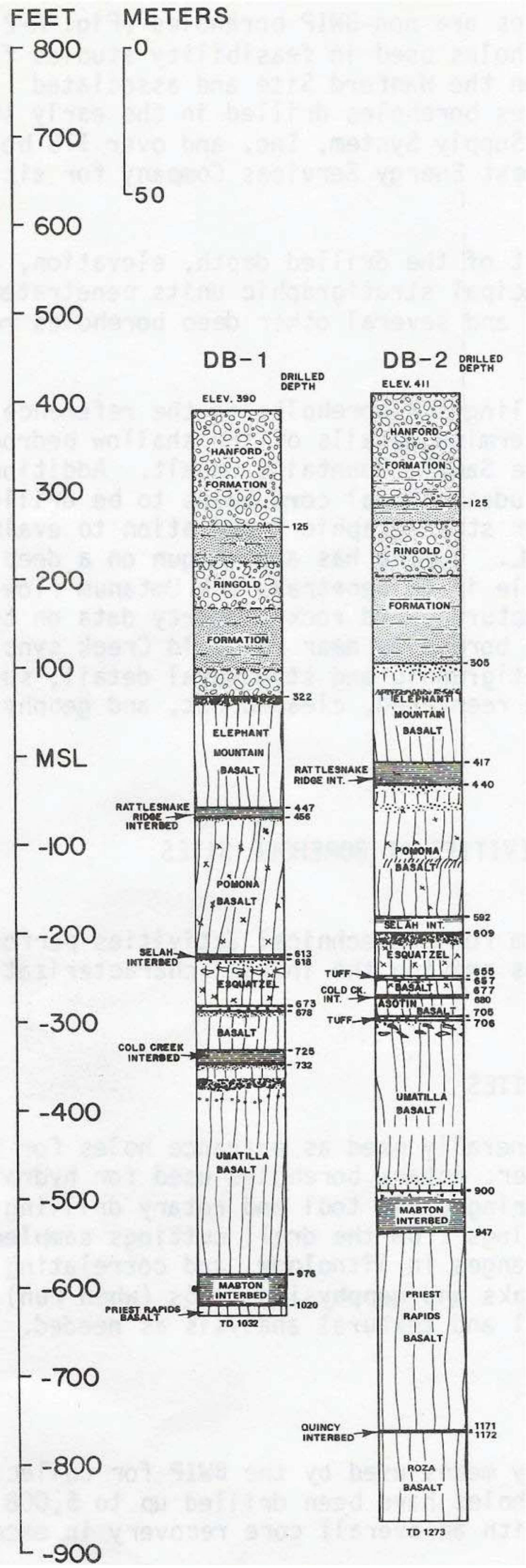


Figure A-2. Geologic borehole logs for Hanford Site boreholes DB-1 and DB-2. See Figure A-1 for Approximate well locations. Reproduced from Myers and Price (1981).

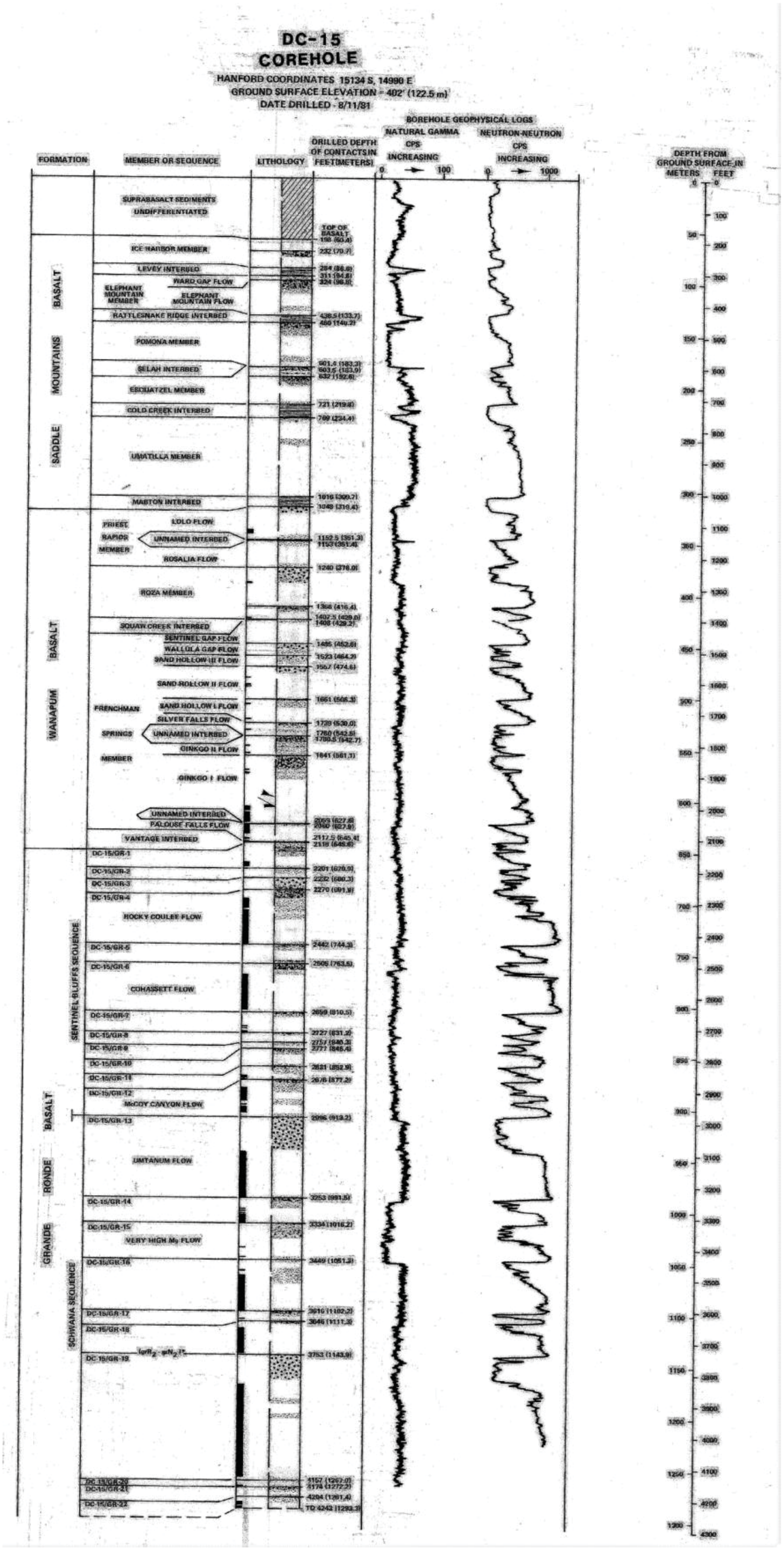


Figure A-3A. Geologic log for Hanford Site borehole DC-15. See Figure A-3B for explanation of symbols used on this log.

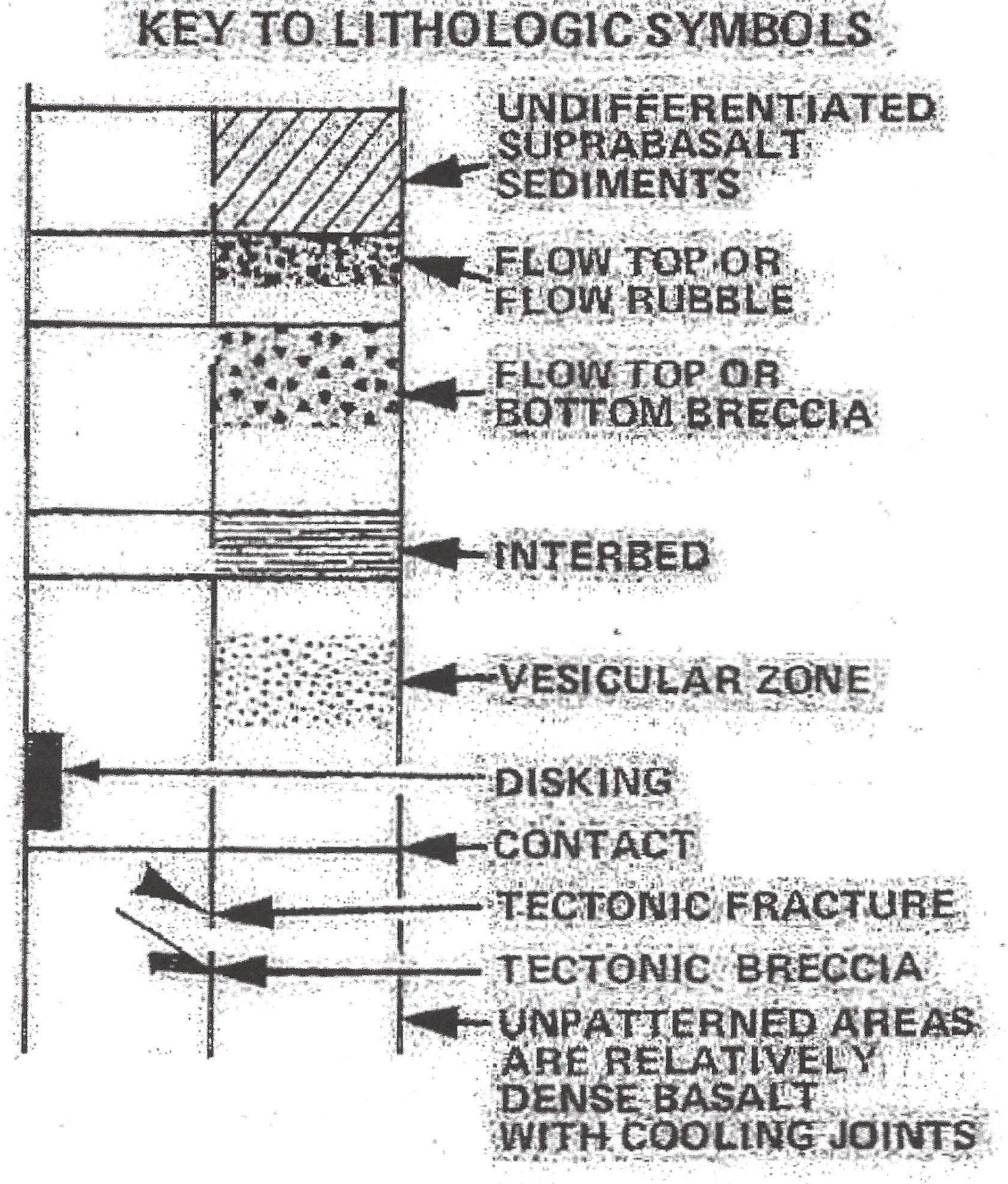


Figure A-3B. Explanation of symbols used on the geologic log in Figure A-3A.

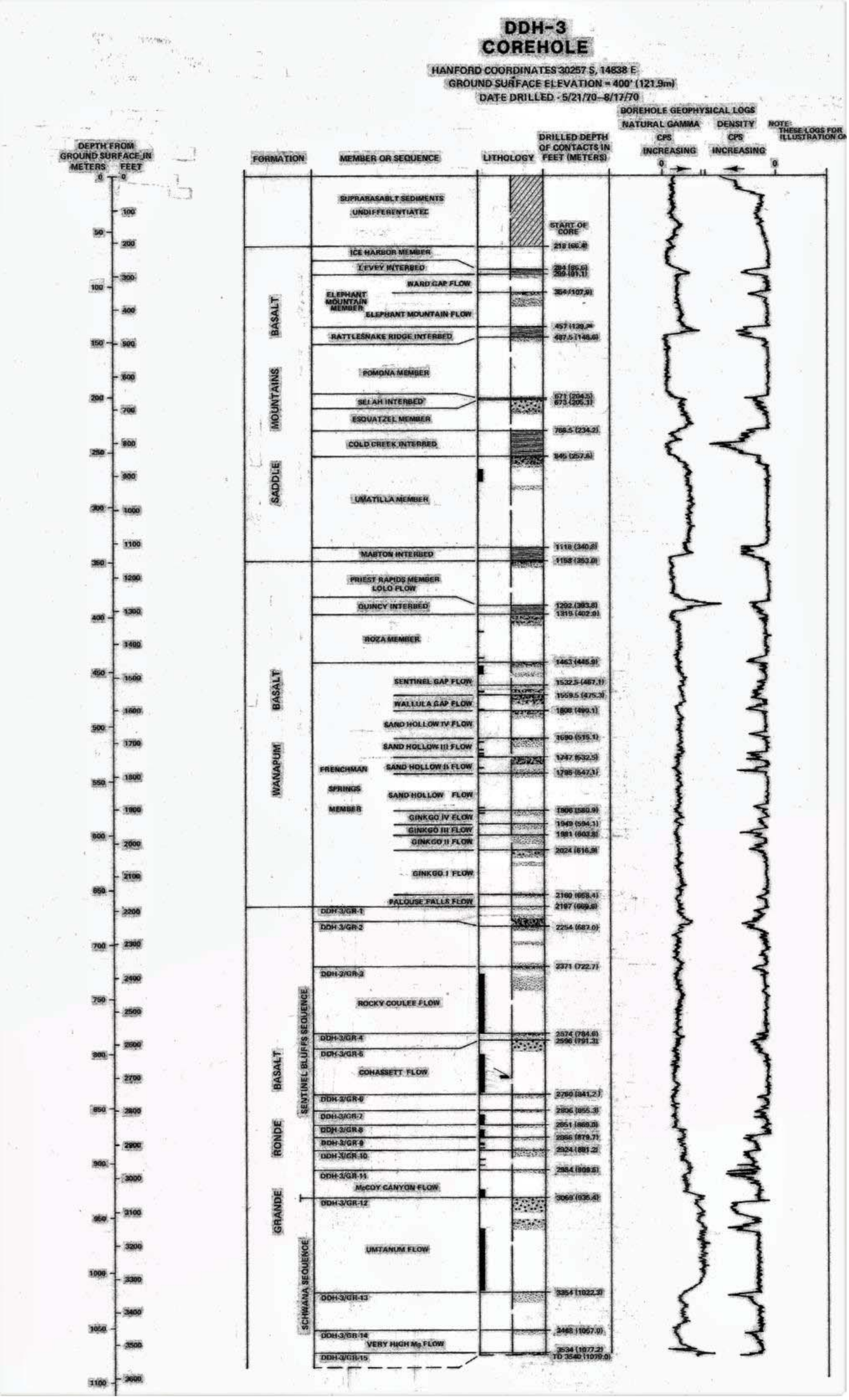


Figure A-4A. Geologic log for Hanford Site borehole DDH-3. See Figure A-4B for explanation of symbols used on this log.

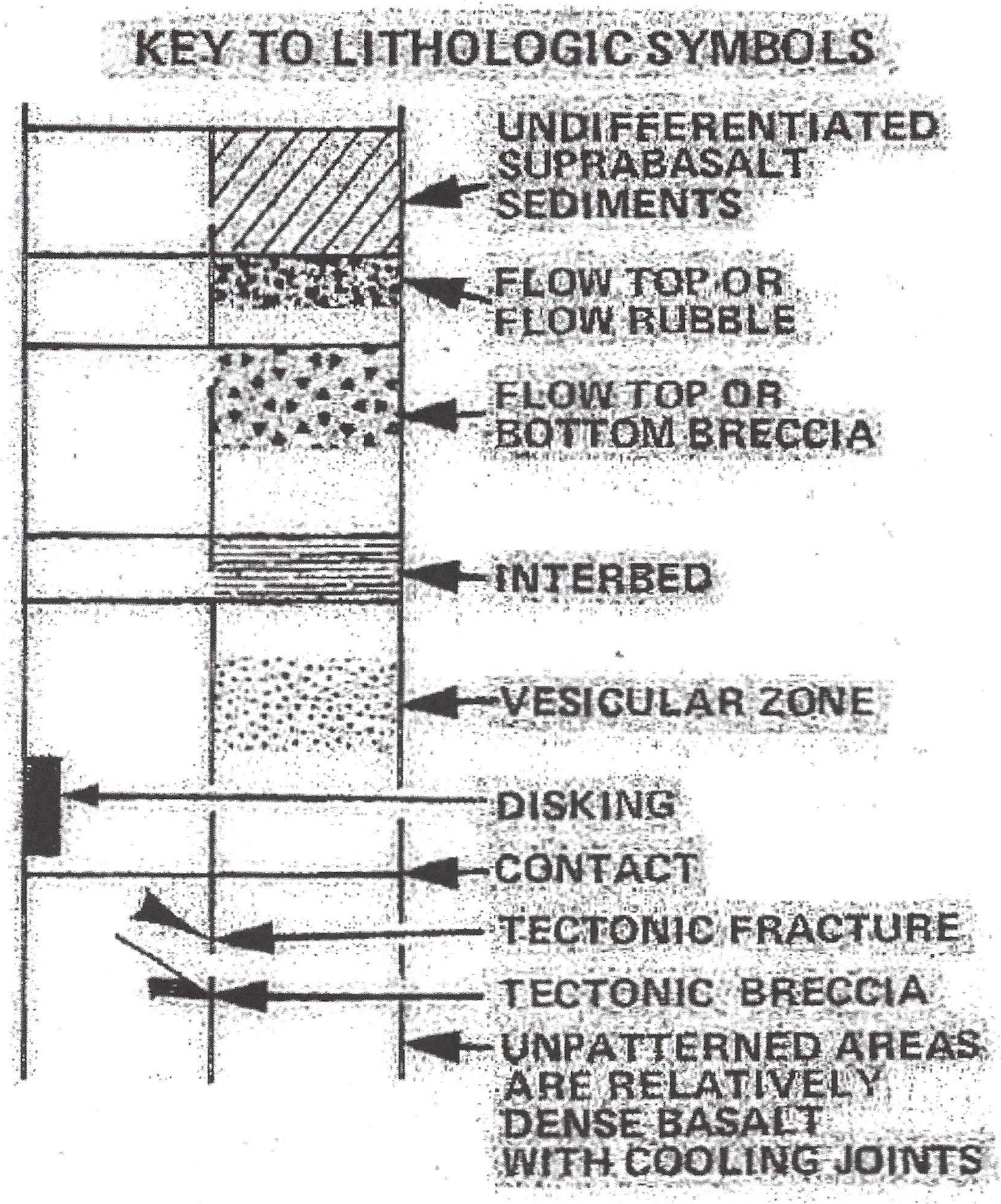
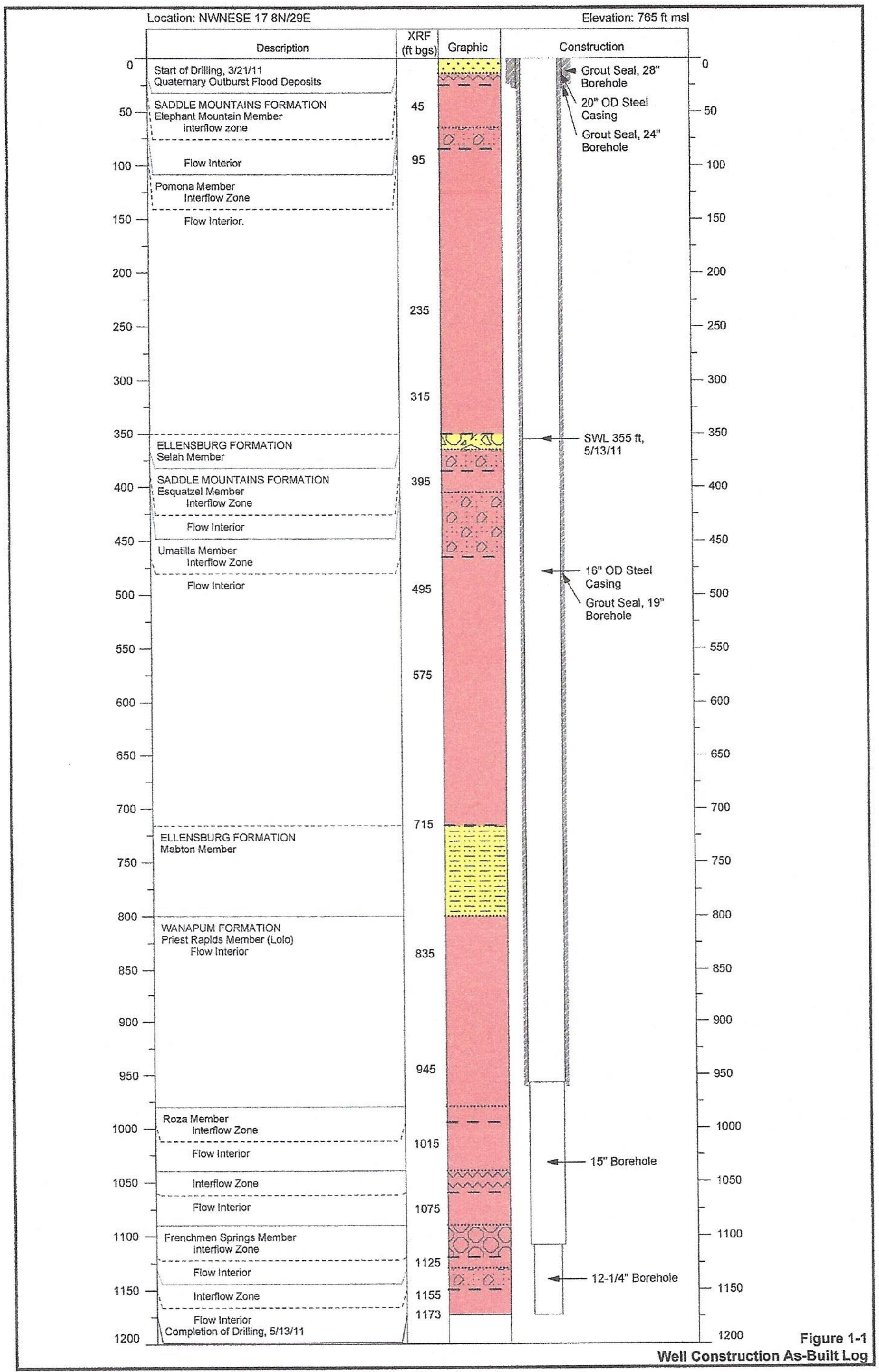
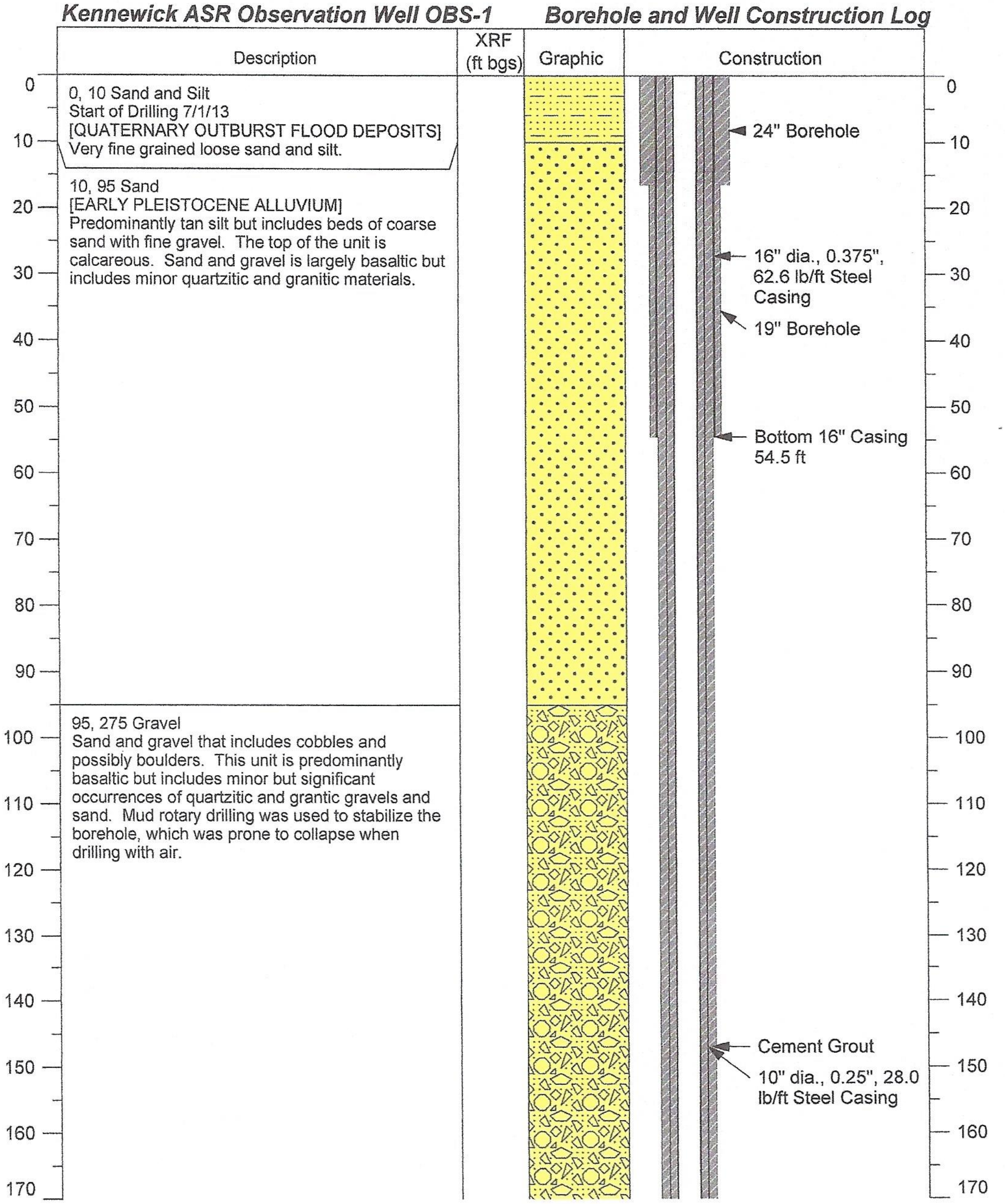


Figure A-4B. Explanation of symbols used on the geologic log in Figure A-4A.



Western Groundwater Services

Figure A-5A. Geologic log for the City of Kennewick ASR well 1.



Kennewick ASR Observation Well OBS-1 ***Borehole and Well Construction Log***

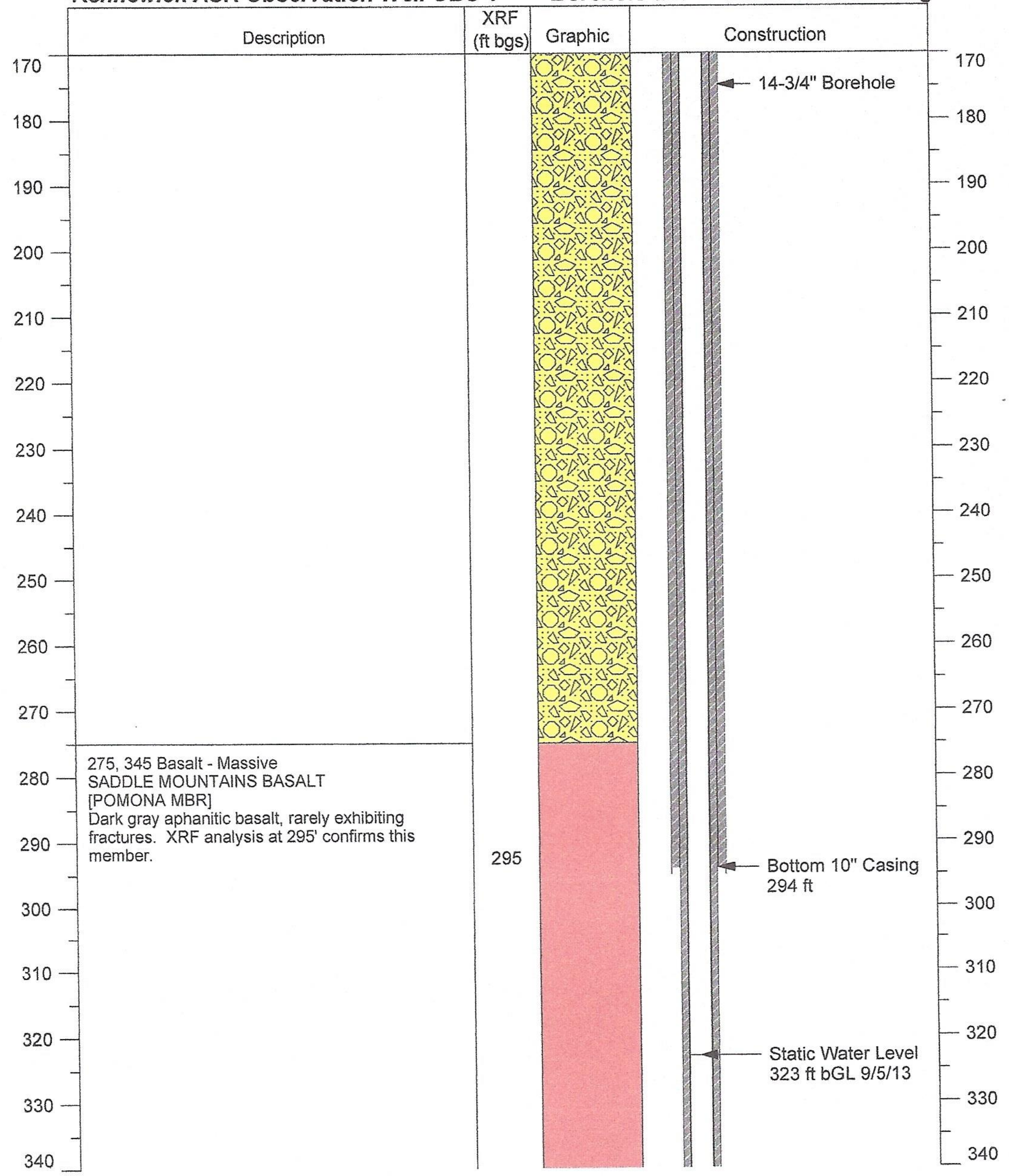
0, 10 Sand and Silt
Start of Drilling 7/1/13
[QUATERNARY OUTBURST FLOOD DEPOSITS]
Very fine grained loose sand and silt.

10, 95 Sand
[EARLY PLEISTOCENE ALLUVIUM]
Predominantly tan silt but includes beds of coarse sand with fine gravel. The top of the unit is calcareous. Sand and gravel is largely basaltic but includes minor quartzitic and granitic materials.

95, 275 Gravel
Sand and gravel that includes cobbles and possibly boulders. This unit is predominantly basaltic but includes minor but significant occurrences of quartzitic and grantic gravels and sand. Mud rotary drilling was used to stabilize the borehole, which was prone to collapse when drilling with air.

Figure A-5B. Geologic log for the City of Kennewick ASR observation well 1.

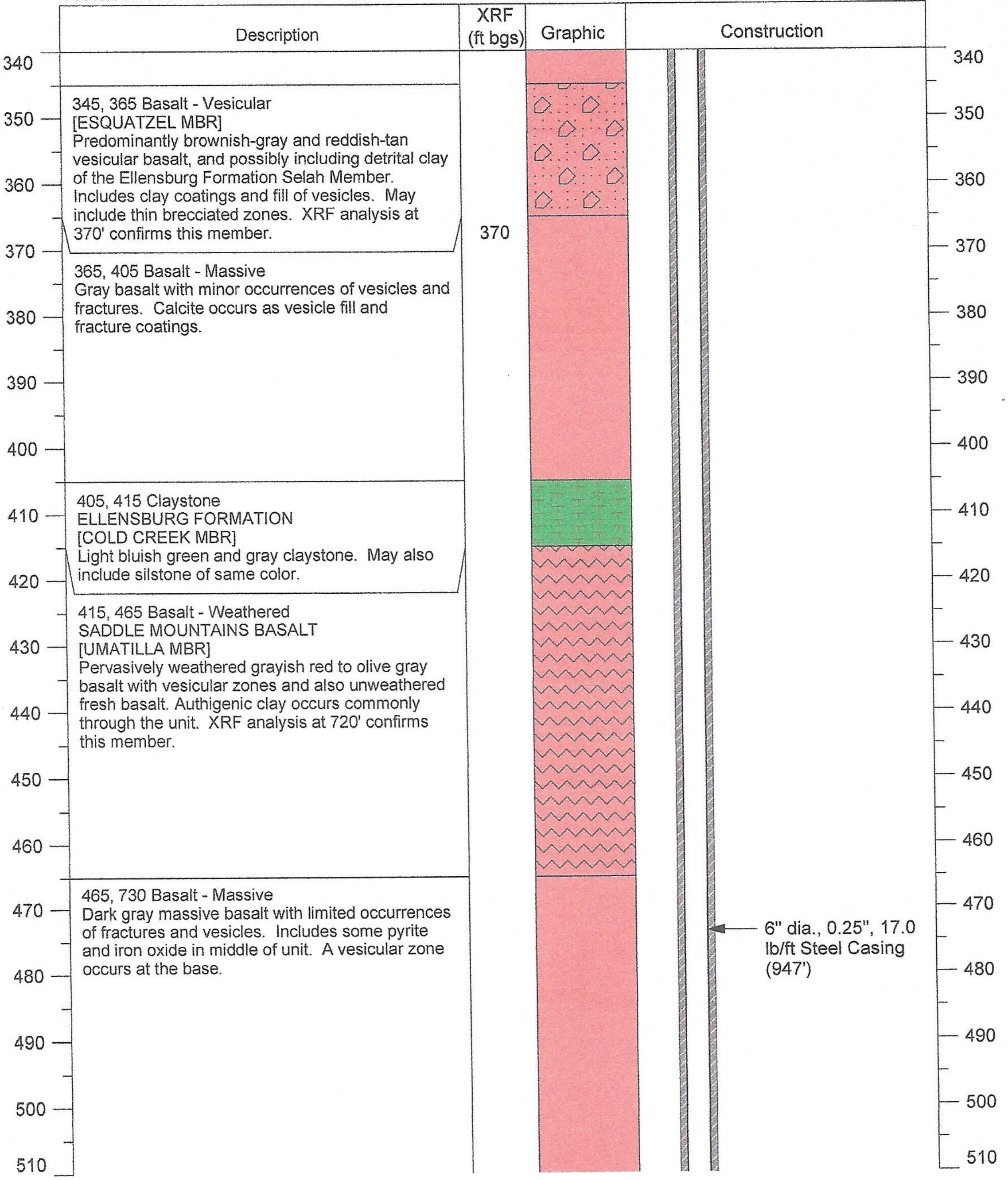
Kennewick ASR Observation Well OBS-1 *Borehole and Well Construction Log*



275, 345 Basalt - Massive
SADDLE MOUNTAINS BASALT
[POMONA MBR]
Dark gray aphanitic basalt, rarely exhibiting fractures. XRF analysis at 295' confirms this member.

Figure A-5B (Continued). Geologic log for the City of Kennewick ASR observation well 1.

Kennewick ASR Observation Well OBS-1 ***Borehole and Well Construction Log***



345, 365 Basalt - Vesicular
[ESQUATZEL MBR]
Predominantly brownish-gray and reddish-tan vesicular basalt, and possibly including detrital clay of the Ellensburg Formation Selah Member. Includes clay coatings and fill of vesicles. May include thin brecciated zones. XRF analysis at 370' confirms this member.

365, 405 Basalt - Massive
Gray basalt with minor occurrences of vesicles and fractures. Calcite occurs as vesicle fill and fracture coatings.

405, 415 Claystone
ELLENSBURG FORMATION
[COLD CREEK MBR]
Light bluish green and gray claystone. May also include silstone of same color.

415, 465 Basalt - Weathered
SADDLE MOUNTAINS BASALT
[UMATILLA MBR]
Pervasively weathered grayish red to olive gray basalt with vesicular zones and also unweathered fresh basalt. Authigenic clay occurs commonly through the unit. XRF analysis at 720' confirms this member.

465, 730 Basalt - Massive
Dark gray massive basalt with limited occurrences of fractures and vesicles. Includes some pyrite and iron oxide in middle of unit. A vesicular zone occurs at the base.

Figure A-5B (Continued). Geologic log for the City of Kennewick ASR observation well 1.

Kennewick ASR Observation Well OBS-1 **Borehole and Well Construction Log**

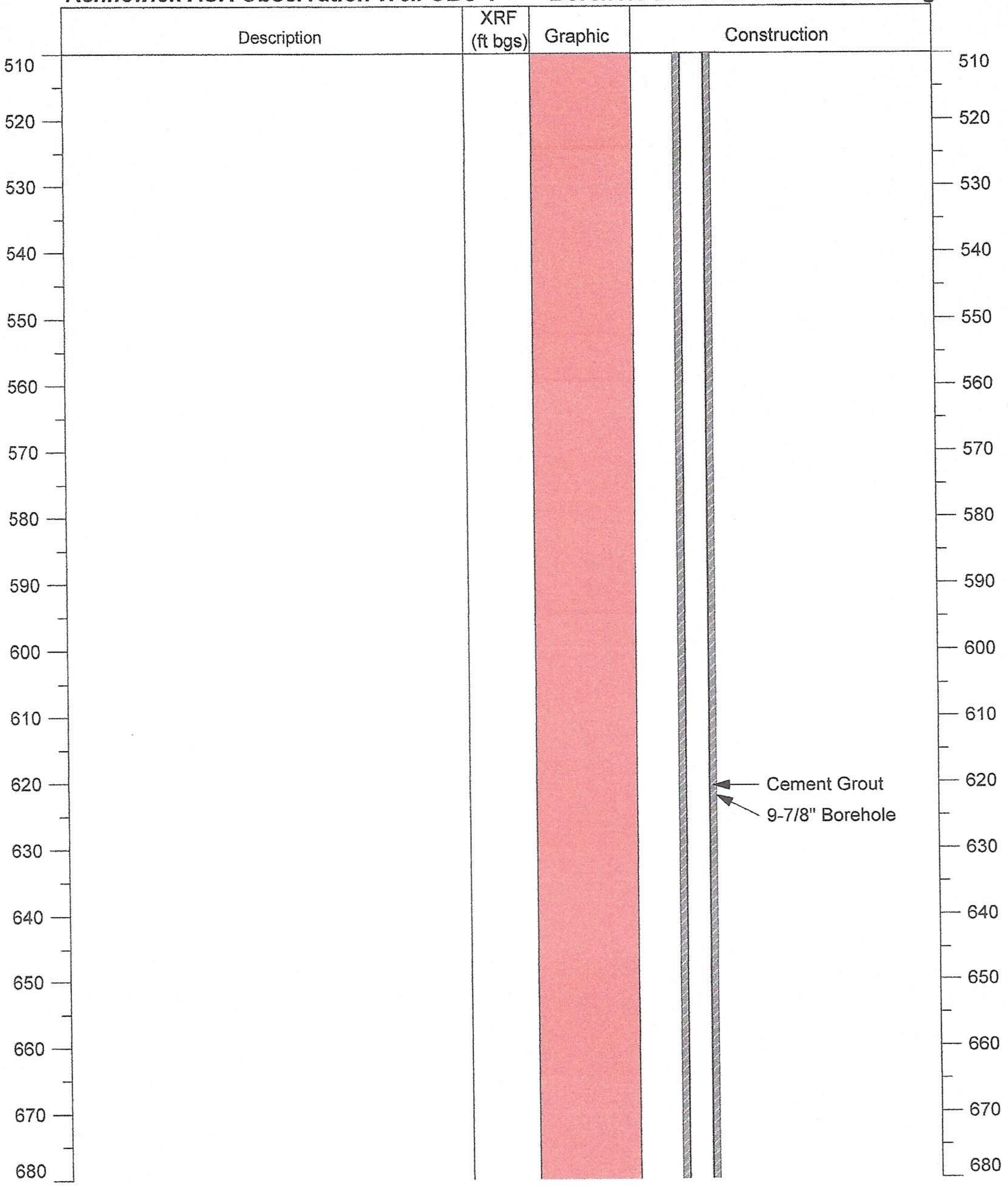
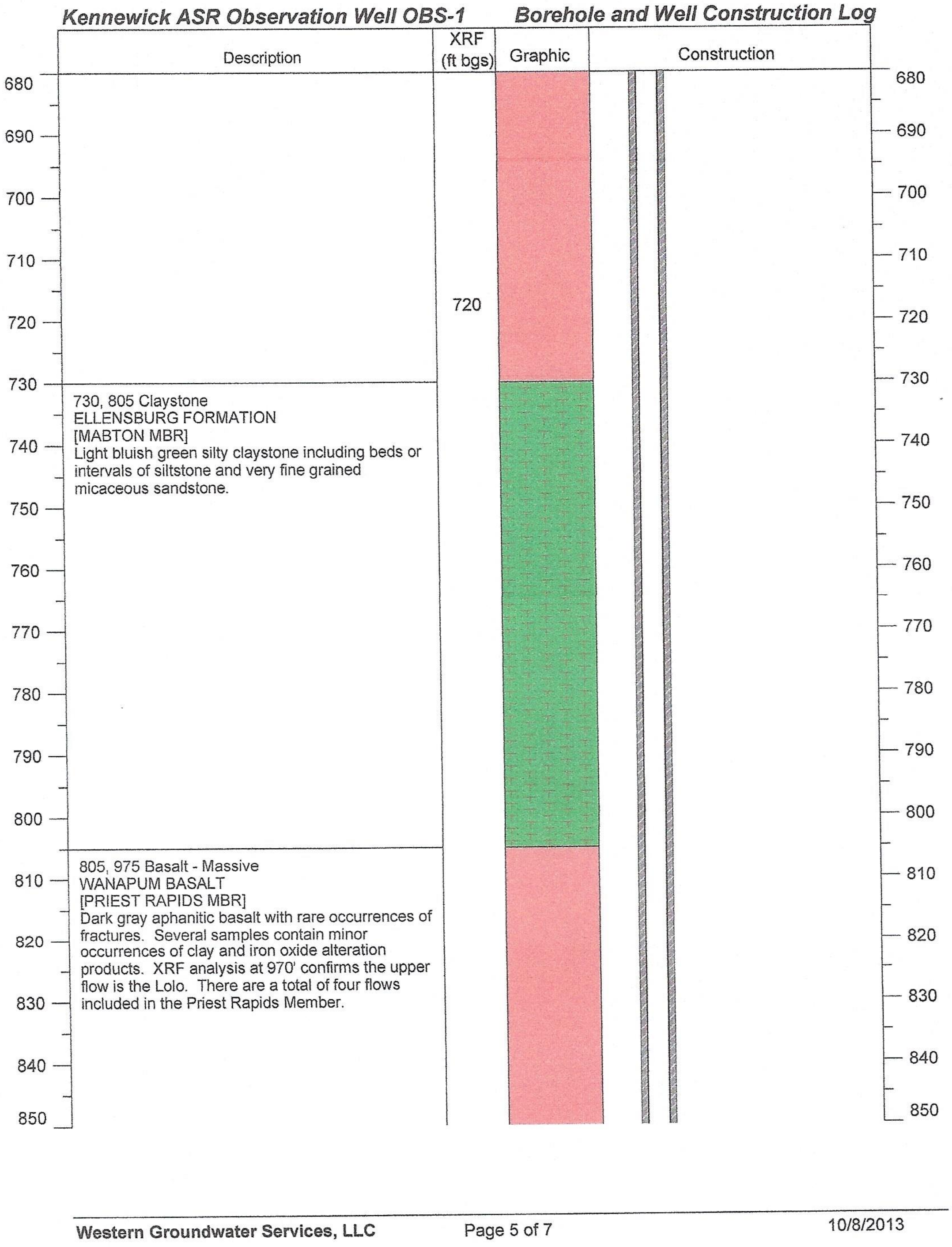


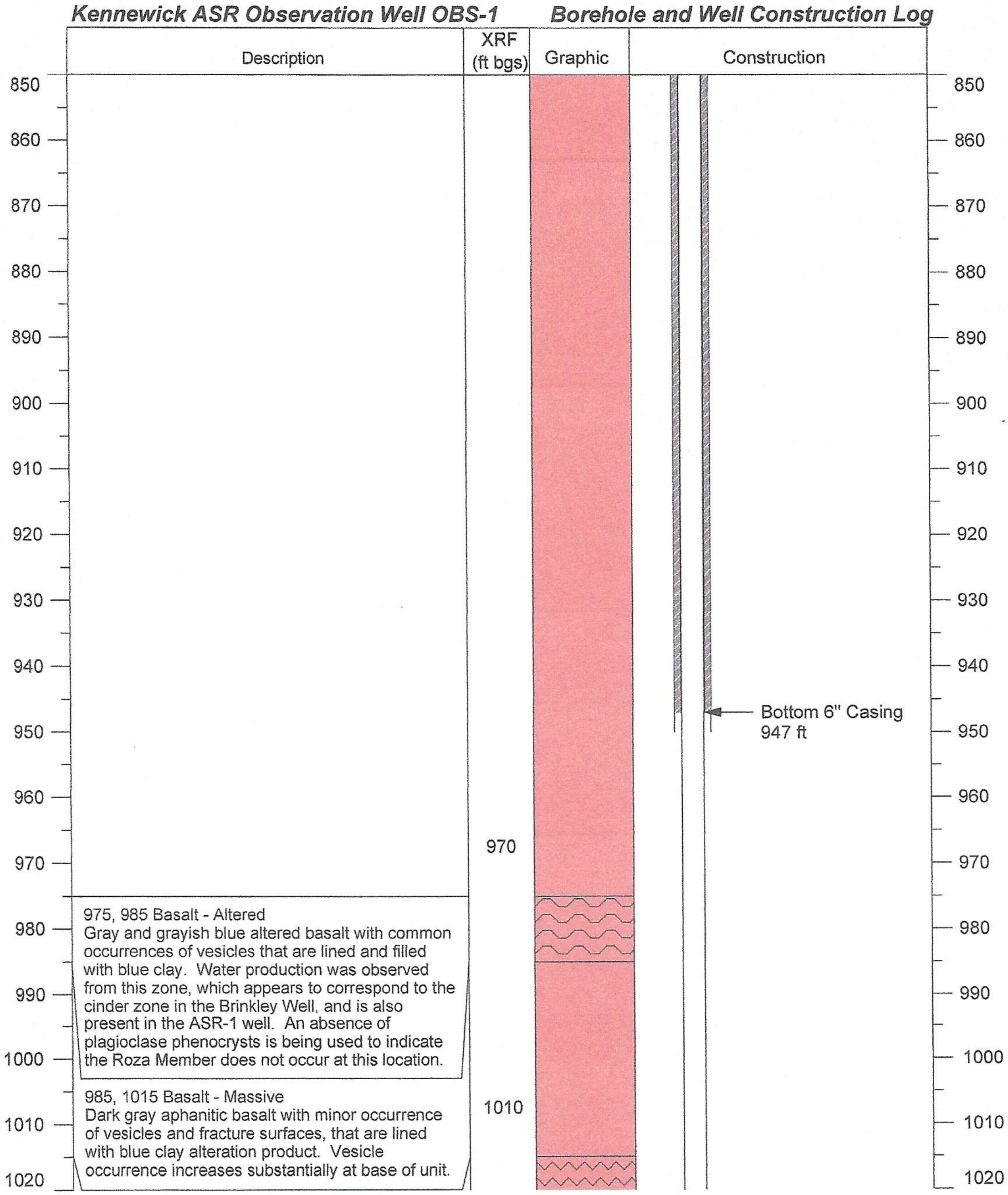
Figure A-5B (Continued). Geologic log for the City of Kennewick ASR observation well 1.



730, 805 Claystone
ELLENSBURG FORMATION
[MABTON MBR]
Light bluish green silty claystone including beds or intervals of siltstone and very fine grained micaceous sandstone.

805, 975 Basalt - Massive
WANAPUM BASALT
[PRIEST RAPIDS MBR]
Dark gray aphanitic basalt with rare occurrences of fractures. Several samples contain minor occurrences of clay and iron oxide alteration products. XRF analysis at 970' confirms the upper flow is the Lolo. There are a total of four flows included in the Priest Rapids Member.

Figure A-5B (Continued). Geologic log for the City of Kennewick ASR observation well 1.



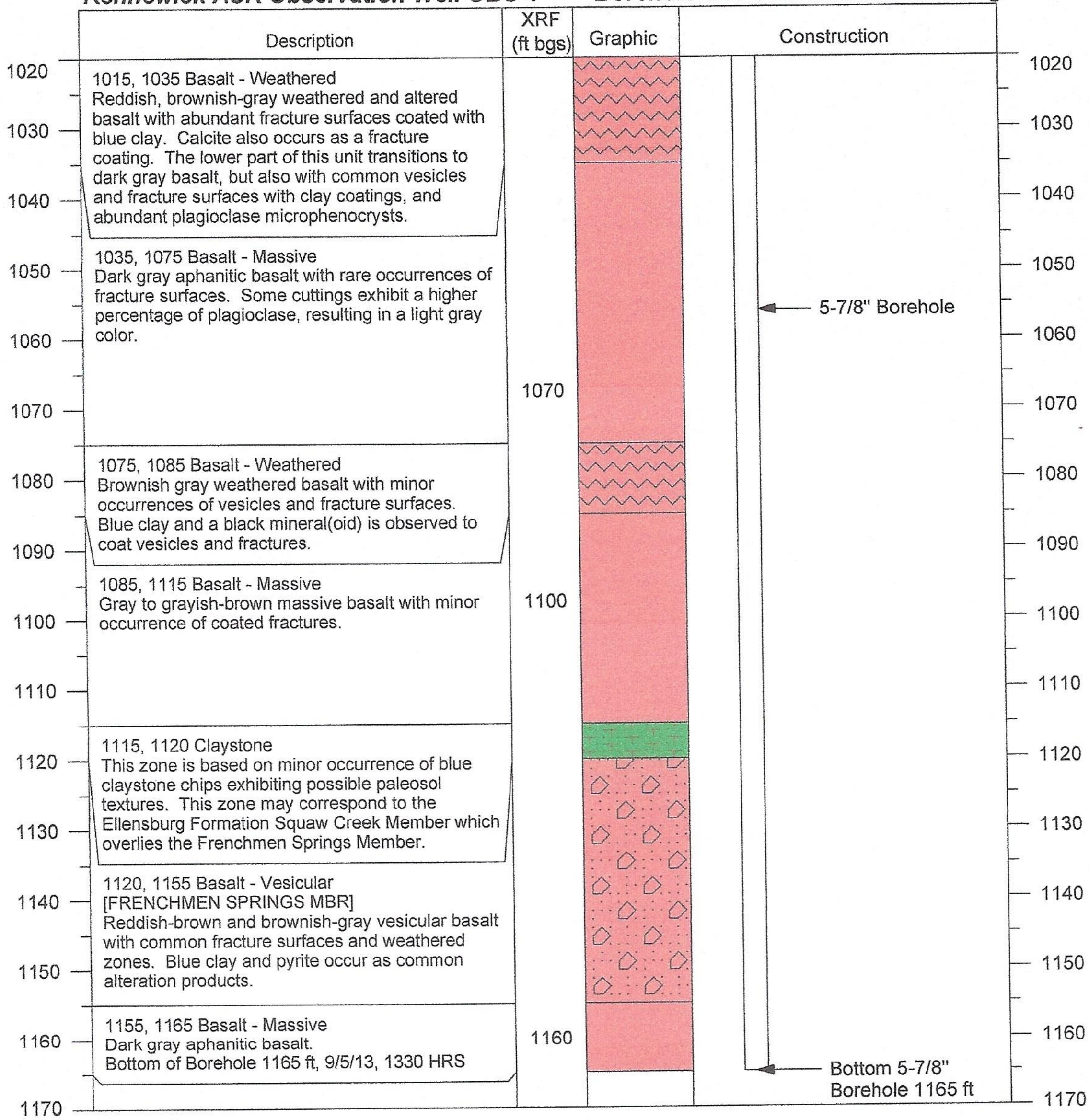
Kennewick ASR Observation Well OBS-1 Borehole and Well Construction Log

975, 985 Basalt - Altered
Gray and grayish blue altered basalt with common occurrences of vesicles that are lined and filled with blue clay. Water production was observed from this zone, which appears to correspond to the cinder zone in the Brinkley Well, and is also present in the ASR-1 well. An absence of plagioclase phenocrysts is being used to indicate the Roza Member does not occur at this location.

985, 1015 Basalt - Massive
Dark gray aphanitic basalt with minor occurrence of vesicles and fracture surfaces, that are lined with blue clay alteration product. Vesicle occurrence increases substantially at base of unit.

Figure A-5B (Continued). Geologic log for the City of Kennewick ASR observation well 1.

Kennewick ASR Observation Well OBS-1 **Borehole and Well Construction Log**



1015, 1035 Basalt - Weathered
Reddish, brownish-gray weathered and altered basalt with abundant fracture surfaces coated with blue clay. Calcite also occurs as a fracture coating. The lower part of this unit transitions to dark gray basalt, but also with common vesicles and fracture surfaces with clay coatings, and abundant plagioclase microphenocrysts.

1035, 1075 Basalt - Massive
Dark gray aphanitic basalt with rare occurrences of fracture surfaces. Some cuttings exhibit a higher percentage of plagioclase, resulting in a light gray color.

1075, 1085 Basalt - Weathered
Brownish gray weathered basalt with minor occurrences of vesicles and fracture surfaces. Blue clay and a black mineral(oid) is observed to coat vesicles and fractures.

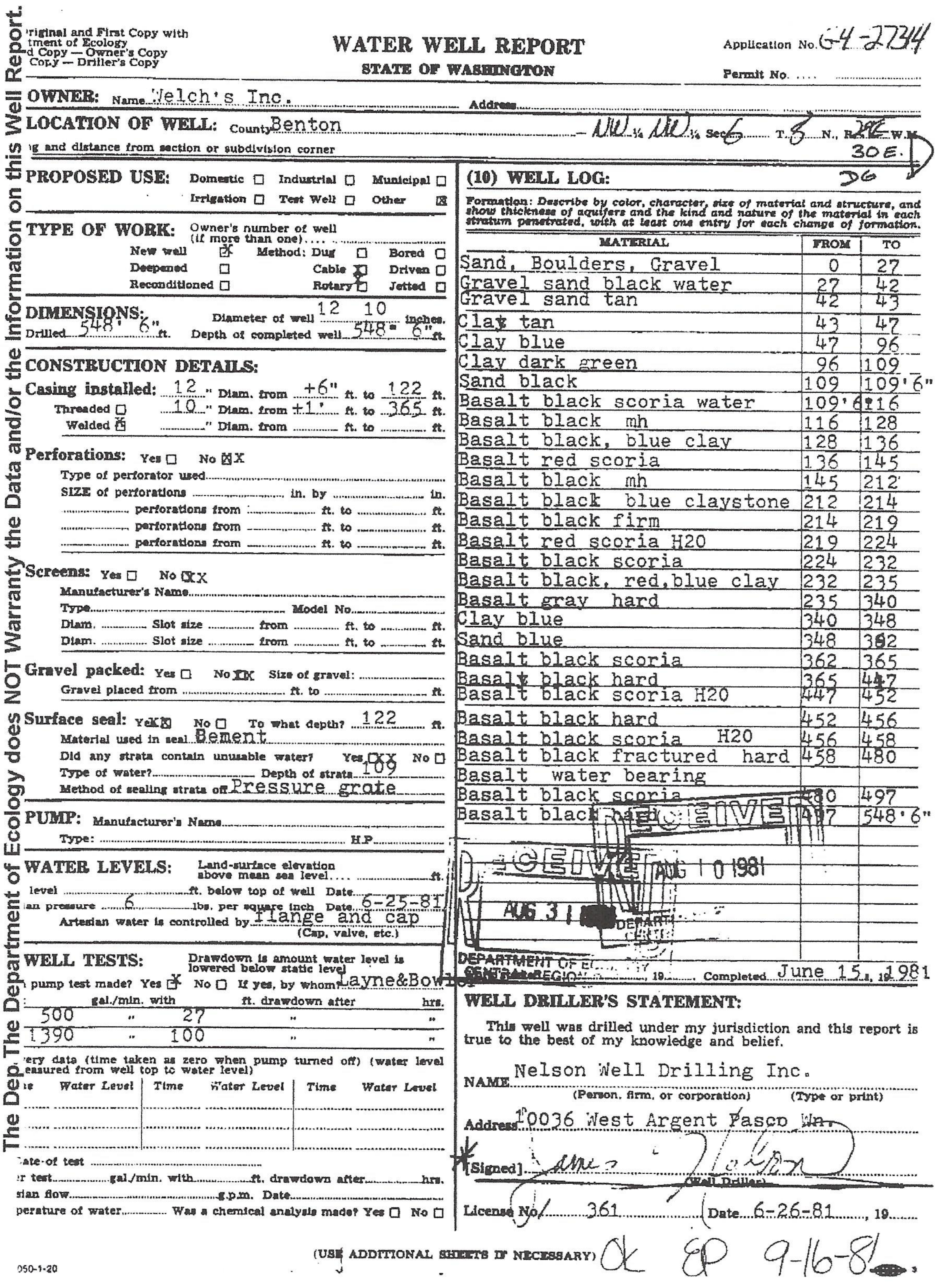
1085, 1115 Basalt - Massive
Gray to grayish-brown massive basalt with minor occurrence of coated fractures.

1115, 1120 Claystone
This zone is based on minor occurrence of blue claystone chips exhibiting possible paleosol textures. This zone may correspond to the Ellensburg Formation Squaw Creek Member which overlies the Frenchmen Springs Member.

1120, 1155 Basalt - Vesicular
[FRENCHMEN SPRINGS MBR]
Reddish-brown and brownish-gray vesicular basalt with common fracture surfaces and weathered zones. Blue clay and pyrite occur as common alteration products.

1155, 1165 Basalt - Massive
Dark gray aphanitic basalt.
Bottom of Borehole 1165 ft, 9/5/13, 1330 HRS

Figure A-5B (Continued). Geologic log for the City of Kennewick ASR observation well 1.



'riginal and First Copy with
tment of Ecology
d Copy — Owner's Copy
Copy — Driller's Copy

WATER WELL REPORT

STATE OF WASHINGTON

Application No. G4-2734

Permit No. ....

OWNER: Name Welch's Inc. Address

LOCATION OF WELL: County Benton — NW ¼ NW ¼ Sec 6 T. 8 N., R. ~~29E~~ 30E. W.M.

ɪg and distance from section or subdivision corner

PROPOSED USE: Domestic ☐ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☒

TYPE OF WORK: Owner's number of well (if more than one)....

New well ☒ Method: Dug ☐ Bored ☐
Deepened ☐ Cable ☒ Driven ☐
Reconditioned ☐ Rotary ☐ Jetted ☐

DIMENSIONS: Diameter of well 12 10 inches.
Drilled 548' 6" ft. Depth of completed well 548' 6" ft.

CONSTRUCTION DETAILS:

Casing installed: 12 " Diam. from +6" ft. to 122 ft.
Threaded ☐ 10 " Diam. from +1' ft. to 365 ft.
Welded ☒ " Diam. from ft. to ft.

Perforations: Yes ☐ No ☒X
Type of perforator used
SIZE of perforations in. by in.
perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.

Screens: Yes ☐ No ☒X
Manufacturer's Name
Type Model No.
Diam. Slot size from ft. to ft.
Diam. Slot size from ft. to ft.

Gravel packed: Yes ☐ No ☒X Size of gravel:
Gravel placed from ft. to ft.

Surface seal: YeX☒ No ☐ To what depth? 122 ft.
Material used in seal Bement
Did any strata contain unusable water? Yes ☒X No ☐
Type of water? Depth of strata 109
Method of sealing strata off Pressure grote

PUMP: Manufacturer's Name
Type: H.P.

WATER LEVELS: Land-surface elevation above mean sea level.... ft.
level ft. below top of well Date
ian pressure 6 lbs. per square inch Date 6-25-81
Artesian water is controlled by flange and cap (Cap, valve, etc.)

WELL TESTS: Drawdown is amount water level is lowered below static level
ı pump test made? Yes ☒ No ☐ If yes, by whom? Layne&Bowler

: gal./min. with	ft. drawdown after	hrs.
500 "	27 "	"
1390 "	100 "	"

ʼery data (time taken as zero when pump turned off) (water level ɛasured from well top to water level)

ɪe	Water Level	Time	Water Level	Time	Water Level

ɔate of test
ɪr test gal./min. with ft. drawdown after hrs.
sian flow g.p.m. Date
perature of water Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG: DG

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
Sand, Boulders, Gravel	0	27
Gravel sand black water	27	42
Gravel sand tan	42	43
Clay tan	43	47
Clay blue	47	96
Clay dark green	96	109
Sand black	109	109'6"
Basalt black scoria water	109'6	116
Basalt black mh	116	128
Basalt black, blue clay	128	136
Basalt red scoria	136	145
Basalt black mh	145	212
Basalt black blue claystone	212	214
Basalt black firm	214	219
Basalt red scoria H20	219	224
Basalt black scoria	224	232
Basalt black, red,blue clay	232	235
Basalt gray hard	235	340
Clay blue	340	348
Sand blue	348	362
Basalt black scoria	362	365
Basalt black hard	365	447
Basalt black scoria H20	447	452
Basalt black hard	452	456
Basalt black scoria H20	456	458
Basalt black fractured hard	458	480
Basalt water bearing		
Basalt black scoria	480	497
Basalt black hard	497	548'6"

RECEIVED
CEIVED AUG 10 1981
AUG 31 [illegible] DEPART
DEPARTMENT OF ECOLOGY
CENTRAL REGION

, 19...... Completed June 15, 1981

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME Nelson Well Drilling Inc.
(Person, firm, or corporation) (Type or print)

Address 10036 West Argent Pasco Wn.

[Signed] James Nelson
(Well Driller)

License No. 361 Date 6-26-81, 19

(USE ADDITIONAL SHEETS IF NECESSARY) Ok EP 9-16-81

050-1-20

Figure A-6A. Washington water well report for the Welch's well. See Figure A-1 for its location in relation to the Pasco area.

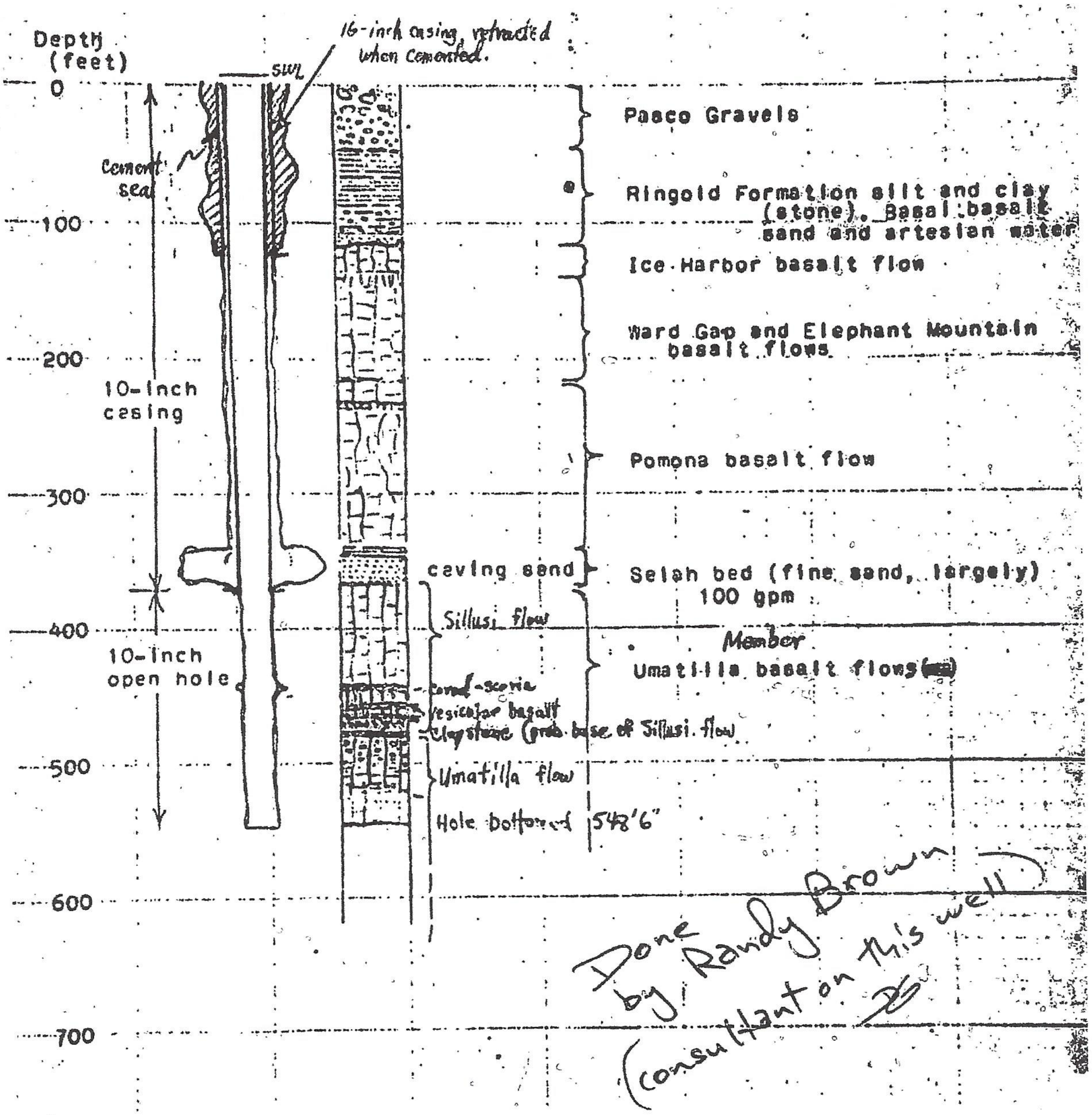
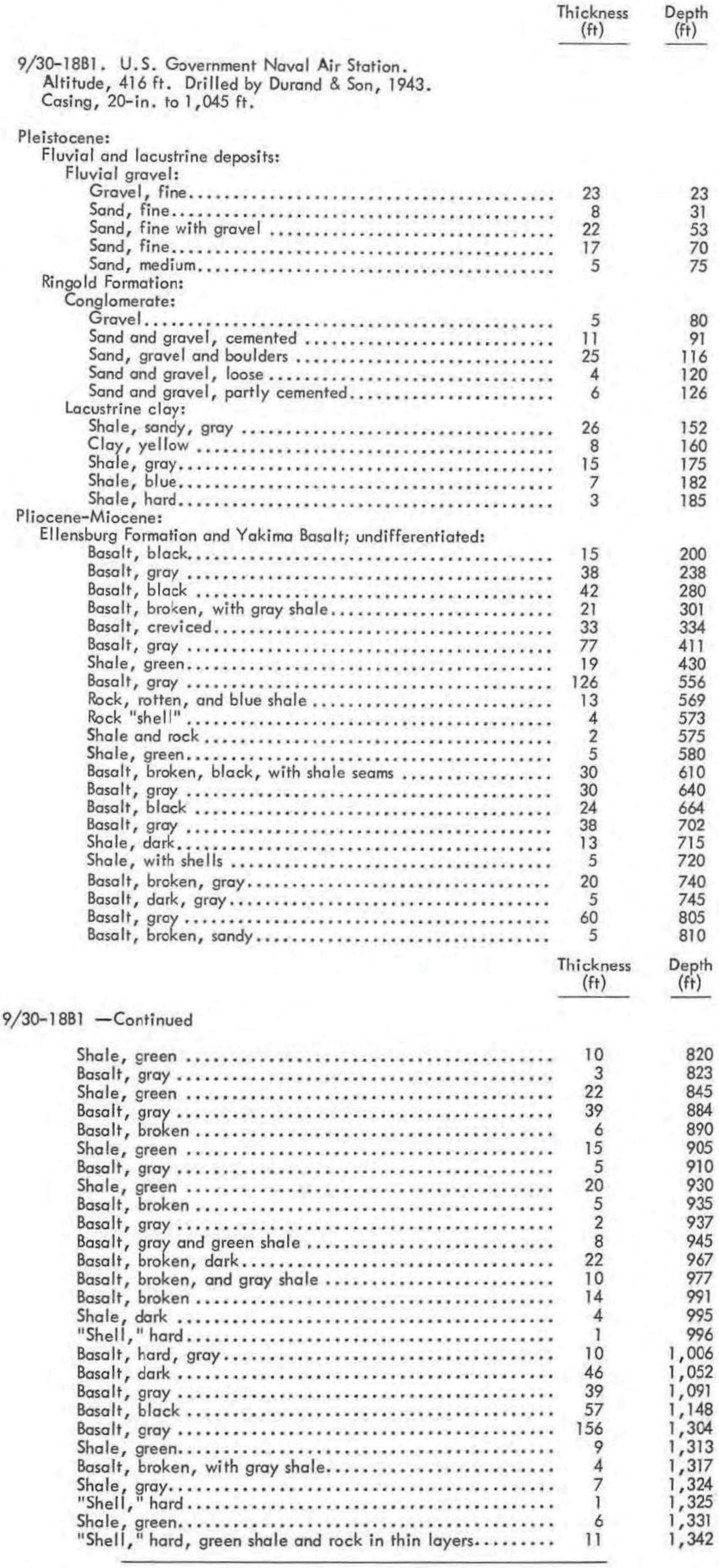


Figure A-6B. Geologic well log for the Welch's well based on the examination and geologic logging of drill-cuttings.



	Thickness (ft)	Depth (ft)
9/30-18B1. U.S. Government Naval Air Station. Altitude, 416 ft. Drilled by Durand & Son, 1943. Casing, 20-in. to 1,045 ft.		
Pleistocene:		
Fluvial and lacustrine deposits:		
Fluvial gravel:		
Gravel, fine	23	23
Sand, fine	8	31
Sand, fine with gravel	22	53
Sand, fine	17	70
Sand, medium	5	75
Ringold Formation:		
Conglomerate:		
Gravel	5	80
Sand and gravel, cemented	11	91
Sand, gravel and boulders	25	116
Sand and gravel, loose	4	120
Sand and gravel, partly cemented	6	126
Lacustrine clay:		
Shale, sandy, gray	26	152
Clay, yellow	8	160
Shale, gray	15	175
Shale, blue	7	182
Shale, hard	3	185
Pliocene-Miocene:		
Ellensburg Formation and Yakima Basalt; undifferentiated:		
Basalt, black	15	200
Basalt, gray	38	238
Basalt, black	42	280
Basalt, broken, with gray shale	21	301
Basalt, creviced	33	334
Basalt, gray	77	411
Shale, green	19	430
Basalt, gray	126	556
Rock, rotten, and blue shale	13	569
Rock "shell"	4	573
Shale and rock	2	575
Shale, green	5	580
Basalt, broken, black, with shale seams	30	610
Basalt, gray	30	640
Basalt, black	24	664
Basalt, gray	38	702
Shale, dark	13	715
Shale, with shells	5	720
Basalt, broken, gray	20	740
Basalt, dark, gray	5	745
Basalt, gray	60	805
Basalt, broken, sandy	5	810
9/30-18B1 —Continued		
Shale, green	10	820
Basalt, gray	3	823
Shale, green	22	845
Basalt, gray	39	884
Basalt, broken	6	890
Shale, green	15	905
Basalt, gray	5	910
Shale, green	20	930
Basalt, broken	5	935
Basalt, gray	2	937
Basalt, gray and green shale	8	945
Basalt, broken, dark	22	967
Basalt, broken, and gray shale	10	977
Basalt, broken	14	991
Shale, dark	4	995
"Shell," hard	1	996
Basalt, hard, gray	10	1,006
Basalt, dark	46	1,052
Basalt, gray	39	1,091
Basalt, black	57	1,148
Basalt, gray	156	1,304
Shale, green	9	1,313
Basalt, broken, with gray shale	4	1,317
Shale, gray	7	1,324
"Shell," hard	1	1,325
Shale, green	6	1,331
"Shell," hard, green shale and rock in thin layers	11	1,342

Figure A-7. Driller's log for the 1943 U.S. Government Naval Air Station well located in section 18, Township 9 North, Range 30 East than was drilled to a reported total depth (TD) of .1,045 feet below ground surface (ft bgs). See Figure A-1 for approximate location this well. Log reproduced from Grolier and Bingham (1971, p. 77-78). Grolier and Bingham (1971, p. 87) reported another nearby deep well (TD: 1,030 ft bgs) located in section 20, Township 9 North, Range 30 East (see Figure A-1 for location).

Measured Surface Geologic Sections in Wallula Gap Area

Reproduced From ARH-ST-137 (1976, v. 2)

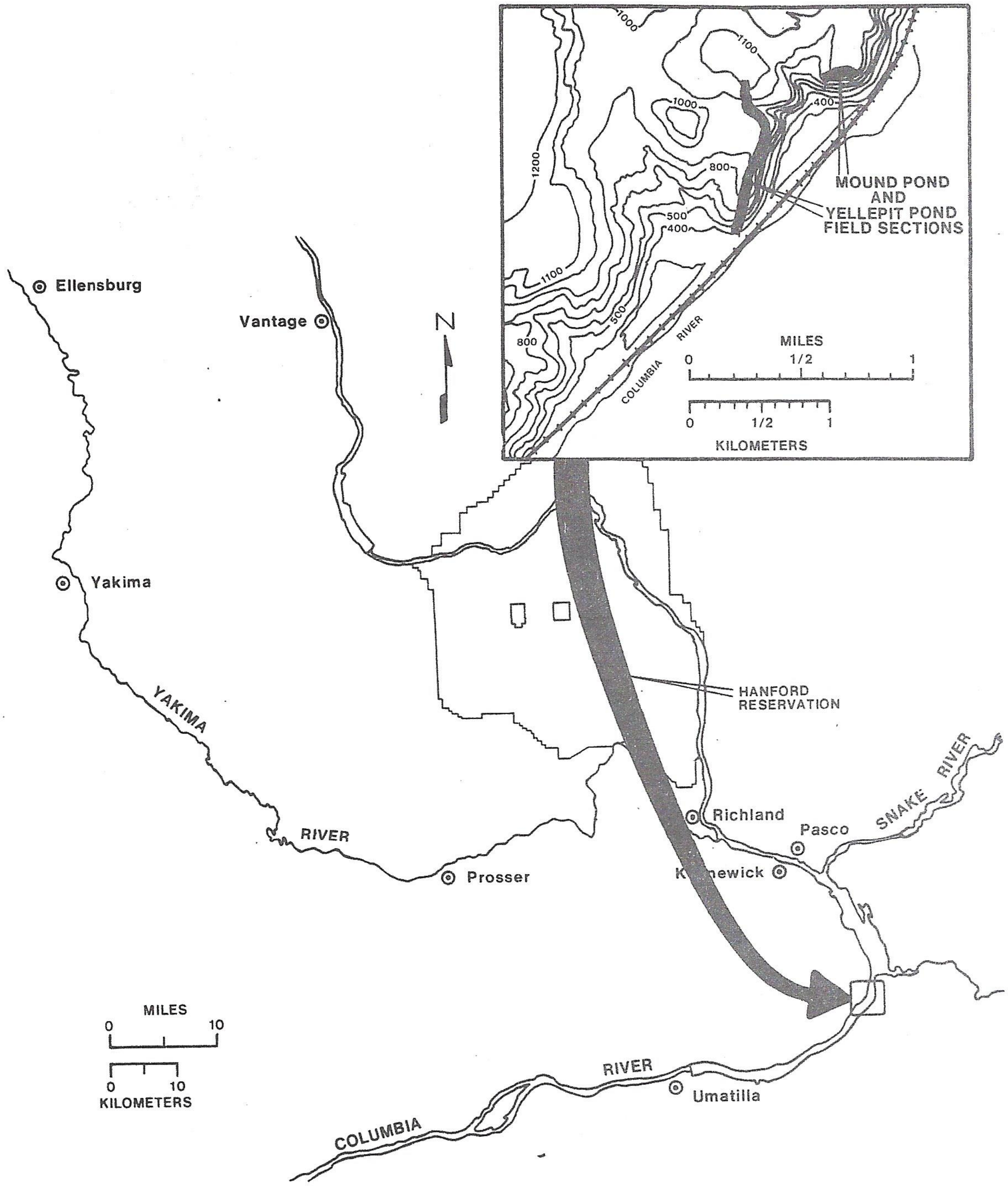


FIGURE B-13

LOCATION MAP FOR THE YELLEPIT-MOUND POND FIELD SECTIONS

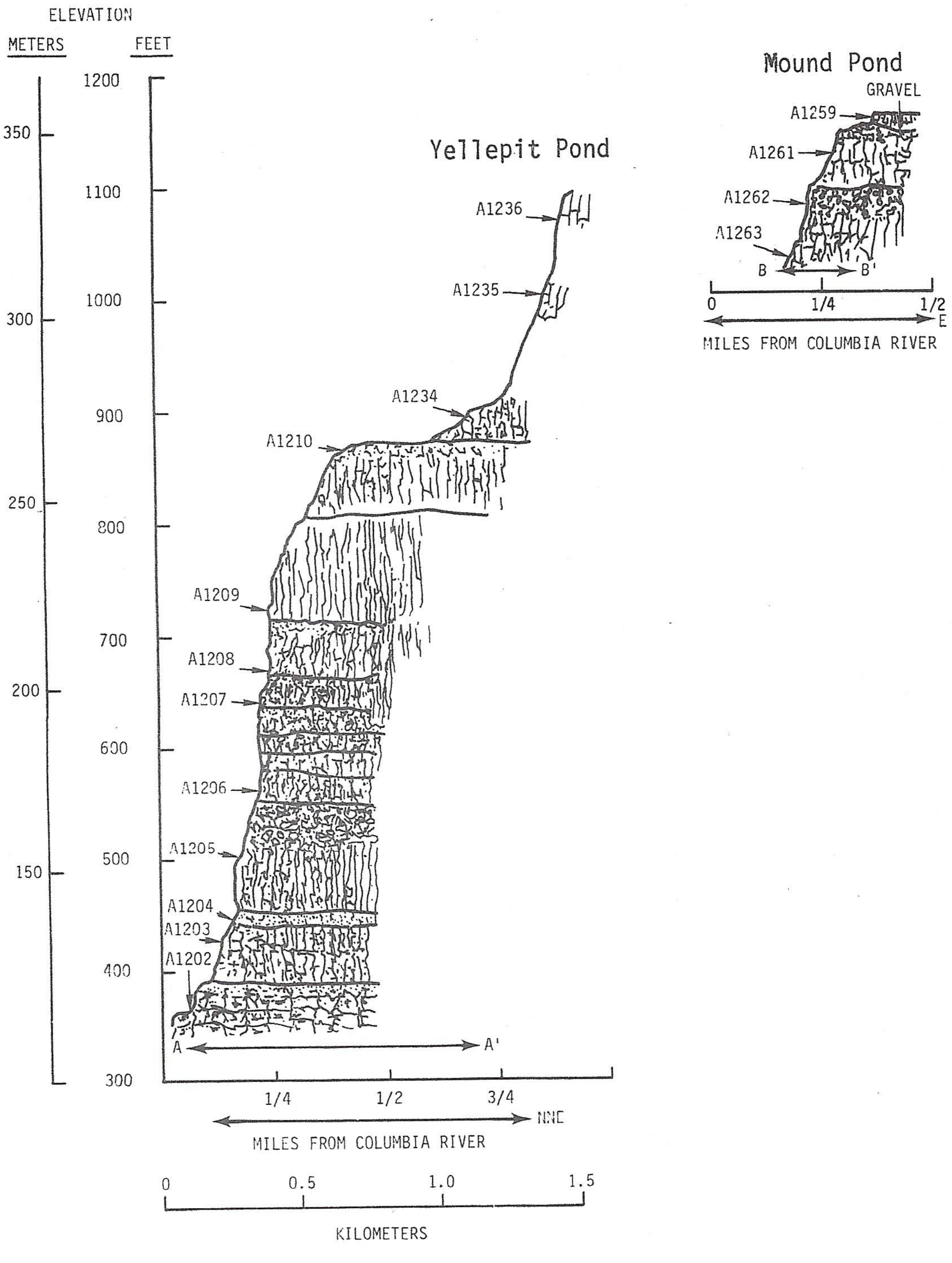
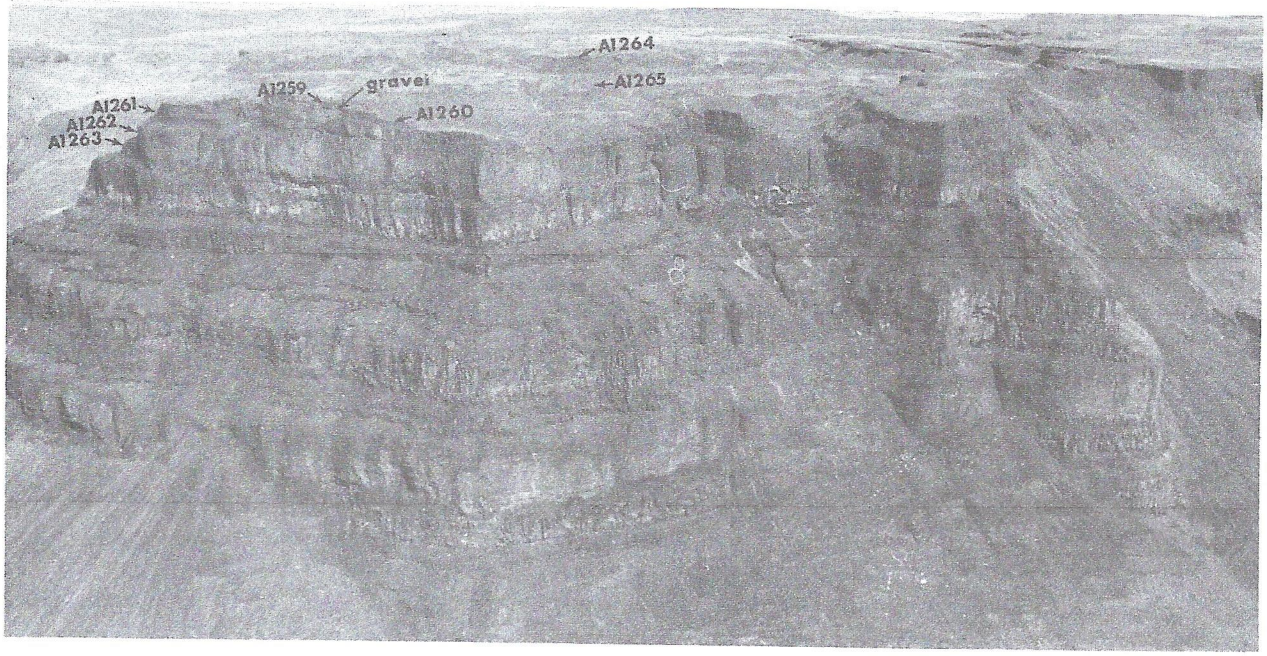
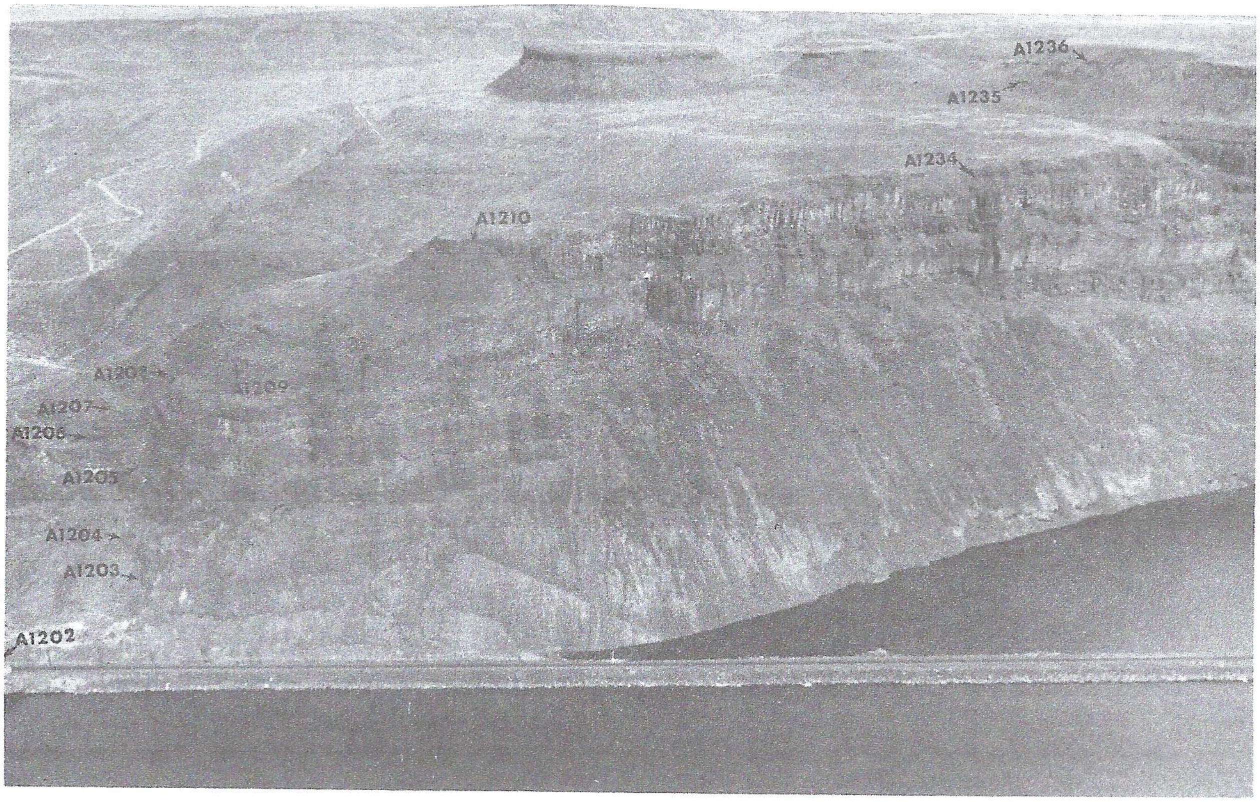


FIGURE B-14

YELLEPIT-MOUND POND CROSS-SECTIONS SHOWING SAMPLE LOCATIONS



Mound Pond Section



Yellepit Pond Section

FIGURE B-15

AERIAL PHOTOGRAPHS OF THE YELLEPIT-MOUND PONDS FIELD SECTION AREA SHOWING SAMPLE LOCATIONS

MAJOR OXIDE CONTENT, by Atomic Absorption Spectrometer

Sample Serial Number	SiO_2 %	Al_2O_3 %	FeO %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	Ba ppm	Vlty %	Mtl Bal %
A1236	56	13.5	12.8	3.1	5.7	3.5	2.7	2.4	3409	1.5	101.2
A1235	56	13.1	12.6	2.8	5.6	3.4	2.7	2.3	3974	1.5	100.0
A1234	53	12.7	14.7	4.5	7.6	2.6	1.3	2.5	583	2.9	101.8
A1210	54	12.8	13.9	4.1	7.6	2.7	1.6	2.6	689	1.6	100.9
A1209	54	13.4	14.3	4.8	8.0	2.8	1.3	2.6	656	1.4	102.6
A1208	53	13.2	14.3	4.9	8.1	2.8	1.4	2.7	689	1.5	101.9
A1207	53	13.0	14.1	4.8	7.8	2.6	1.3	2.6	735	2.1	101.3
A1206	53	13.0	14.0	4.5	7.6	2.7	1.5	2.8	683	1.1	100.2
A1205	51	13.6	13.8	4.8	8.2	2.7	1.3	2.6	795	2.0	100.0
A1204	51	13.6	14.4	4.4	7.6	2.7	1.4	2.6	722	2.1	99.8
A1203	52	13.0	14.3	4.7	7.8	3.0	1.4	2.6	646	2.0	100.8
A1202	52	12.6	14.0	4.4	7.7	2.9	1.4	2.8	698	1.8	99.6
A1259	49	13.4	14.6	6.7	10.2	2.4	0.8	2.7	620	1.2	101.0
A1260	53	13.1	12.9	3.1	6.2	3.0	2.5	2.5	3130	1.3	97.6
A1261	53	13.2	12.6	2.8	5.9	3.1	2.6	2.3	3560	1.4	96.9
A1262	54	12.4	12.0	2.7	5.5	3.0	2.8	2.2	3099	2.0	96.6
A1263	53	13.2	12.7	2.9	5.6	3.5	2.5	2.3	3239	1.1	96.8
A1264	53	13.3	12.4	2.8	5.7	3.1	2.6	2.2	3349	1.8	96.9
A1265	53	13.1	12.7	2.9	5.6	3.5	2.5	2.2	3545	1.4	96.9

NATURALLY OCCURRING RADIOACTIVE ISOTOPES, by Gamma Energy Analysis

Sample Serial Number	^{40}K µCi/kg x 10^{-3}	^{226}Ra + daughters µCi/kg x 10^{-3}	^{228}Th + daughters µCi/kg x 10^{-3}
A1236	21.5 ± 12%	0.58 ± 17%	0.86 ± 6.6%
A1235	18.0 ± 12	0.58 ± 18	0.95 ± 6.6
A1234	9.5 ± 15	0.50 ± 19	0.58 ± 7.0
A1210	12.3 ± 14	0.49 ± 19	0.73 ± 6.7
A1209	10.0 ± 14	0.42 ± 19	0.55 ± 6.9
A1208	9.4 ± 15	0.49 ± 19	0.42 ± 7.2
A1207	8.6 ± 16	0.48 ± 17	0.69 ± 6.8
A1206	9.5 ± 16	0.38 ± 22	0.53 ± 7.2
A1205	9.5 ± 15	0.32 ± 23	0.50 ± 7.8
A1204	9.3 ± 15	0.58 ± 16	0.51 ± 7.8
A1203	9.6 ± 15	0.35 ± 20	0.44 ± 7.3
A1202	10.6 ± 15	0.40 ± 21	0.59 ± 7.0

TRACE ELEMENTS, by Neutron Activation Analysis

Sample Serial Number	Na %	La ppm	Sm ppm	Fe %	Co ppm	Sc ppm	Cr ppm	Eu ppm	Th ppm	Tb ppm	Hf ppm	Ta ppm
A1235	2.01	46	9.7	7.7	24	23	6	4.6	5.6	1.5	9.7	2.6
A1234	1.95	23	7.5	11.2	39	33	20	2.0	1.9	1.8	5.8	1.8
A1204	1.97	26	7.4	10.9	37	34	23	2.2	2.3	1.4	4.5	1.7
A1203	2.05	23	7.4	11.4	42	35	23	2.0	2.3	1.6	5.8	1.8
A1202	2.03	28	8.0	11.1	36	35	16	2.3	2.2	1.4	4.9	2.1
A1259	1.97	42	11.0	12.8	50	45	225	3.4	0.9	1.5	11.1	4.3
A1260	2.20	42	9.9	9.4	27	26	7	3.5	5.0	-	11.7	-
A1261	2.30	49	10.3	9.3	24	23	7	4.3	5.6	1.1	11.9	3.0
A1262	2.35	44	10.5	10.0	27	26	11	4.7	6.6	1.6	13.0	3.5
A1263	2.40	45	10.3	10.0	26	24	10	4.4	6.0	1.2	12.1	3.0
A1264	2.25	49	10.5	9.1	26	24	9	4.1	7.4	1.3	9.2	2.8
A1265	2.30	49	10.6	9.9	24	25	12	4.3	6.0	1.8	12.0	2.9

TABLE B-V

TABULATION OF ANALYTICAL DATA FOR THE YELLEPIT-MOUND PONDS FIELD SECTIONS

Attachment B

Well Log Inventory
(Figures and Tables)

Attachment B

Tables 1 – 2

Table 1 - General Well Construction Information (Ecology)

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
1	164893	CURT & EDIT BENNINGHOVEN	8N30E	3	SENW	28	0	<Null>	W	Suprabasalt
2	164892	CURT & EDIT BENNINGHOVEN	8N30E	3	SWNE	35	0	<Null>	W	Suprabasalt
3	173072	STATE PARKS & RECREATION	8N30E	3	SWSE	45	8	<Null>	W	Suprabasalt
4	141728	JOHN CLARK	8N30E	3	SWSW	115	8	5/10/1993	W	Suprabasalt
5	296284	DENZELL	8N30E	4	NENE	37	6	3/20/1991	W	Suprabasalt
6	296285	DENZELL	8N30E	4	NENE	37	6	3/20/1991	W	Suprabasalt
7	296286	DENZELL	8N30E	4	NENE	37	6	3/20/1991	W	Suprabasalt
8	141936	JOHN SMITH	8N30E	4		42	6	10/5/1991	W	Suprabasalt
9	142959	Marion Hostetler	8N30E	4	NWNW	80	6	12/6/1995	W	Suprabasalt
10	1875512	Richard Giles	8N30E	4	SENE	160	6	8/23/2018	W	Suprabasalt
11	360510	CARTER WINKS	8N30E	5	NENE	50	6	4/24/2003	W	Suprabasalt
12	303059	SHANE KANYID	8N30E	5	NENE	120	6	11/30/2000	W	Suprabasalt
13	303055	SHANE KANYID	8N30E	5	NENE	120	6	11/30/2000	W	Suprabasalt
14	303056	SHANE KANYID	8N30E	5	NENE	135	6	11/30/2000	W	Suprabasalt
15	296606	MICHAEL CLAFTON BLDG	8N30E	10	NENW	59	6	2/1/1978	W	Suprabasalt
16	738129	MICHAEL CLAFTON BLDG	8N30E	10	NENW	59	6	1/1/1978	W	Suprabasalt
17	302833	LYNN KOHLER	8N30E	10	NWNE	60	6	5/3/1997	W	Suprabasalt
18	143257	MICHAEL CLAFTON BUILDERS	8N30E	10	NENW	67	6	6/15/1978	W	Suprabasalt
19	687713	AMY CHRISTENSEN	9N28E	1	NENE	--	--	9/30/2010	W	--
20	164137	CAMILLE KEYES	9N28E	1	NENW	34	6	4/23/1998	W	Suprabasalt
21	253943	MARK + AUDREE HOPKINS	9N28E	1	SENW	39	6	7/8/1999	W	Suprabasalt
22	172237	ROBERT BURNS	9N28E	1	SESE	40	18	4/29/1980	W	Suprabasalt
23	408195	JOHN AND HEATHER DOUGLAS	9N28E	1	NWNE	50	6	11/24/2004	W	Suprabasalt
24	412987	BUENA VISTA CUSTOM HOMES	9N28E	1	SWNE	73	6	7/20/2005	W	Suprabasalt
25	446128	LEGEND BUILDERS	9N28E	1	SWNE	75	6	7/18/2006	W	Suprabasalt
26	412985	BUENA VISTA CUSTOM HOMES	9N28E	1	SWNE	78	6	7/19/2005	W	Suprabasalt
27	314405	MITCH TAYLOR	9N28E	1	SWNE	80	6	1/16/2001	W	Suprabasalt
28	412147	BUENA VISTA CUSTOM HOMES	9N28E	1	SWNE	80	6	7/12/2005	W	Suprabasalt
29	412983	BUENA VISTA CUSTOM HOMES	9N28E	1	SWNE	80	6	7/18/2005	W	Suprabasalt
30	432694	LEGEND BUILDERS LLC	9N28E	1	SWNE	97	6	3/6/2006	W	Suprabasalt
31	435785	SCOTT CRAWFORD	9N28E	1	NWSE	100	6	1/12/2006	W	Suprabasalt
32	335915	JOHN AND DONNA STEWART	9N28E	1		112	6	4/3/2002	W	Suprabasalt
33	349429	PHILLIP WARREN	9N28E	1	SWNE	114	6	12/11/2002	W	Suprabasalt
34	432631	GEORGE SANDERSON	9N28E	1	NWNE	115	8	6/15/1992	W	Suprabasalt
35	172399	ROBERT/DEENECE STALLINGS	9N28E	1	SWSE	115	6	1/22/1994	W	Suprabasalt
36	316466	JEFF RENZ	9N28E	1	SWNE	115	6	12/4/2001	W	Suprabasalt
37	432628	SCOTT CRAWFORD	9N28E	1	SWSW	116	6	4/3/2001	W	Suprabasalt
38	446129	LEGEND BUILDERS	9N28E	1	SWNE	116	6	7/13/2006	W	Suprabasalt
39	349425	JAMES LAKE	9N28E	1	NW	118	6	12/3/2002	W	Suprabasalt
40	349426	ANTHONY SIMPSON/VIRGINIA BELKEY	9N28E	1	SWNE	118	6	12/5/2002	W	Suprabasalt
41	482055	BRUCE FLIPPO	9N28E	1	NE	118	6	5/25/2007	W	Suprabasalt
42	475318	SETH MCGARY	9N28E	1		118	6	3/1/2007	W	Suprabasalt
43	709362	AMY & ANTHONY CHRISTENSEN	9N28E	1	SWNE	118	6	3/2/2011	W	Suprabasalt
44	616618	BARRY OLSON	9N28E	1	SWNE	118	6	7/10/2009	W	Suprabasalt
45	1102608	John Douglas	9N28E	1	NENW	118	6	9/23/2015	W	Suprabasalt
46	314409	EILEEN & PHILIP PEISTRAP	9N28E	1	NENE	119	6	9/7/2001	W	Suprabasalt
47	349427	WILILAM PENNELL	9N28E	1	NW	119	6	12/9/2002	W	Suprabasalt
48	293724	GEORGE SANDERSON	9N28E	1	NWNE	120	8	11/19/1990	W	Suprabasalt
49	432629	GEORGE SANDERSON	9N28E	1	NWNE	120	8	11/17/1992	W	Suprabasalt
50	432630	GEORGE SANDERSON	9N28E	1	SWNE	120	8	6/17/1992	W	Suprabasalt
51	349428	MICHAEL AND CARRIE BREIER	9N28E	1	NW	120	6	12/10/2002	W	Suprabasalt
52	432627	RILEY CRISSNE	9N28E	1	NESW	120	6	7/10/2003	W	Suprabasalt
53	364067	DUCONE SMITH	9N28E	1	NENE	120	6	6/25/2003	W	Suprabasalt
54	380686	STEVE PORIE	9N28E	1	NWNE	120	6	5/18/2004	W	Suprabasalt
55	412143	BUENA VISTA CUMSTOM HOMES	9N28E	1	SWNE	120	6	6/29/2005	W	Suprabasalt
56	432696	LEGEND BUILDERS	9N28E	1	SWNE	120	6	3/8/2006	W	Suprabasalt
57	446131	LODGESTONE HOMES LLC	9N28E	1	NESW	120	6	7/7/2006	W	Suprabasalt
58	453202	LEGEND BUILDERS	9N28E	1	SWNE	120	6	8/4/2006	W	Suprabasalt
59	456234	LODGESTONE HOMES	9N28E	1	SESW	120	6	10/23/2006	W	Suprabasalt
60	544286	Duane Flippo	9N28E	1	SWNE	120	6	6/23/2008	W	Suprabasalt
61	616610	CLINT YOUNG	9N28E	1	SWNE	120	6	7/8/2009	W	Suprabasalt
62	1307526	Dave and Gaylene Pheysey	9N28E	1	NE	120	6	12/9/2015	W	Suprabasalt
63	1062762	Ben Andros	9N28E	1	NENW	120	6	9/1/2015	W	Suprabasalt
64	1624875	Michael Henry	9N28E	1	SWNE	120	6	2/20/2017	W	Suprabasalt
65	616620	JEFF RENZ	9N28E	1	SWNE	121	6	7/8/2009	W	Suprabasalt
66	679639	SID AND MARY BAUMAN	9N28E	1	SENW	122	6	12/9/2006	W	Suprabasalt
67	658246	Peter Strizhak	9N28E	1	SWNE	125	6	12/29/2009	W	Suprabasalt
68	432693	BUEAN VISTA CUSTOM HOMES	9N28E	1	SWNE	130	6	3/3/2006	W	Suprabasalt
69	594200	DAVE WHITE	9N28E	1	NWSW	130	6	5/12/2009	W	Suprabasalt
70	616608	Amy Phillips	9N28E	1	SWNE	130	6	10/15/2009	W	Suprabasalt
71	522524	ANDY MIX	9N28E	1	SWNE	135	6	4/2/2008	W	Suprabasalt
72	522541	ANDY MIX	9N28E	1	SWNE	135	6	4/2/2008	W	Suprabasalt
73	174937	SUNDEREN ESTATES	9N28E	1	NWNE	140	8	9/2/1998	W	Suprabasalt
74	372296	DONALD SWEEPE	9N28E	1	SENW	140	6	9/24/2003	W	Suprabasalt
75	470298	LEGEND BUILDERS	9N28E	1	SWNE	141	6	2/27/2007	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
76	412982	BUENA VISTA CUSTOM HOMES	9N28E	1	SWNE	141	6	7/14/2005	W	Suprabasalt
77	900411	Kristin Kunkel	9N28E	1	NWNE	143	6	11/8/2013	W	Suprabasalt
78	522550	IGNASIO OSORIO	9N28E	1	NESE	160	6	8/23/2007	W	Suprabasalt
79	924459	Jr and Teresa Trautvetter	9N28E	1	NENE	180	6	8/8/2014	W	Suprabasalt
80	1918206	John Douglas - Williams	9N28E	1	NESW	180	6	8/20/2019	W	Suprabasalt
81	407900	RONALD AND LYNN KELLY	9N28E	1	NWNE	181	6	4/25/2005	W	Suprabasalt
82	900403	Robin & Heather Maples	9N28E	1	NENE	184	6	11/26/2013	W	Suprabasalt
83	1891241	Walter Barraza	9N28E	1	NENE	185	6	5/16/2014	W	Suprabasalt
84	894441	Stephen and Susan Leavans	9N28E	1	NENE	190	6	7/12/2014	W	Suprabasalt
85	432632	DAVE KOHLER	9N28E	1	NWNE	191	10	2/10/1992	W	Suprabasalt
86	894761	Mike Costanzo	9N28E	1	NENE	195	6	9/4/2013	W	Suprabasalt
87	910197	AJ Wade	9N28E	1	NENE	196	6	4/9/2014	W	Suprabasalt
88	900367	Kim Michalson - Kim Michalson	9N28E	1	NENE	197	6	12/11/2013	W	Suprabasalt
89	900417	Todd Schadler	9N28E	1	NENE	197	6	2/7/2014	W	Suprabasalt
90	900365	Zach Underhill	9N28E	1	NENE	198	6	3/5/2014	W	Suprabasalt
91	930958	AJ Wade	9N28E	1	NENE	198	6	10/22/2014	W	Suprabasalt
92	1062763	Karl Schull	9N28E	1	NENE	198	6	6/4/2015	W	Suprabasalt
93	721665	Harry March	9N28E	1	SWNE	200	6	2/11/2011	W	Suprabasalt
94	894417	Brian Hill	9N28E	1	NENE	200	6	8/24/2012	W	Suprabasalt
95	1880508	Bob Johnson	9N28E	1	SENE	200	8	6/5/2018	W	Suprabasalt
96	894433	Gabriel Suarez	9N28E	1	NENE	200	6	8/30/2013	W	Suprabasalt
97	916999	INSPIRATION BUILDERS	9N28E	1	NENE	200	6	4/12/2014	W	Suprabasalt
98	948762	Robert Gomez	9N28E	1	SWNE	200	6	10/15/2014	W	Suprabasalt
99	1021475	Jeremy Gray	9N28E	1	SENE	200	6	2/17/2015	W	Suprabasalt
100	1784469	Victor and Veronica Silva	9N28E	1	NENE	200	6	6/1/2018	W	Suprabasalt
101	638721	CHAD LANGFORD	9N28E	1	NWNE	210	6	9/26/2008	W	Suprabasalt
102	1062765	Derek Anderson -	9N28E	1	NENE	210	6	5/29/2015	W	Suprabasalt
103	1062788	Derek Anderson -	9N28E	1	NENE	210	6	5/29/2015	W	Suprabasalt
104	658248	Bradley Mason	9N28E	1	SENE	212	6	1/28/2010	W	Suprabasalt
105	1571461	Tony and Amy Christensen	9N28E	1	NENE	212	6	7/8/2016	W	Suprabasalt
106	721667	DAVID AND JENNIFER DORSETT	9N28E	1	NENE	215	6	1/25/2011	W	Suprabasalt
107	967835	Viktor Denisyuk	9N28E	1	NENE	216	6	2/3/2015	W	Suprabasalt
108	894415	Robert Andelin	9N28E	1	NENE	217	6	9/12/2012	W	Suprabasalt
109	522547	ROBERT GOMEZ	9N28E	1	SENE	218	6	10/18/2007	W	Suprabasalt
110	1624862	AJ Wade	9N28E	1	SENE	218	6	2/28/2017	W	Suprabasalt
111	638725	CHAD HEARTLING	9N28E	1		220	6	3/6/2008	W	Suprabasalt
112	638723	SCOTT HAWS	9N28E	1	NW	220	6	10/10/2008	W	Suprabasalt
113	894413	Trinity Homes~ Kyle Pfundheller	9N28E	1	NENE	220	6	7/27/2011	W	Suprabasalt
114	566542	JAIDUR AND DARCI JO	9N28E	1	SW	226	6	6/5/2008	W	Suprabasalt
115	594205	FARRAH TAYLOR	9N28E	1	SENE	230	6	10/19/2008	W	Suprabasalt
116	522549	BRENT STENSON	9N28E	1	NESE	230	6	9/21/2007	W	Suprabasalt
117	543529	PAUL PARDINI	9N28E	1	NE	236.5	6	4/8/2007	W	Suprabasalt
118	688596	Thomas Elizondo	9N28E	1	SWNE	260	6	10/15/2010	W	Suprabasalt
119	638719	Storybook Homes	9N28E	1	NWSE	280	6	9/17/2009	W	Suprabasalt
120	894408	Gorden Gerken	9N28E	1	SWNE	282	6	12/17/2010	W	Suprabasalt
121	141419	JEFF JOYCE LUNDEN	9N28E	2	SESE	205	6	5/24/1993	W	Suprabasalt
122	141697	JOHN BELL	9N28E	11	NENE	36	6	9/1/1980	W	Suprabasalt
123	372426	DEL RAY INC	9N28E	11	NENE	120	6	12/2/2003	W	Suprabasalt
124	164267	CENTREL PRE MIX	9N28E	12	NESE	--	6	2/12/1998	W	--
125	294374	WAYNE WILSON	9N28E	12	NENE	--	6	<Null>	W	--
126	294375	WAYNE WILSON	9N28E	12	NENE	--	6	<Null>	W	--
127	163398	BART GALLANT	9N28E	12	SWNW	38	6	5/11/1997	W	Suprabasalt
128	1645166	City Of Pasco	9N28E	12	SESW	75	8	6/14/2017	W	Suprabasalt
129	163399	BART GALLANT	9N28E	12	SWNW	78	8	5/13/1997	W	Suprabasalt
130	872729	Bart Gallant	9N28E	12	SWNW	80	6	8/5/2013	W	Suprabasalt
131	1646845	Horrigan Farms	9N28E	12	NWSW	96	6	11/10/2017	W	Suprabasalt
132	1746422	Brad Boler	9N28E	12	NESE	120	6	2/9/2018	W	Suprabasalt
133	169585	KEVIN THOMAS	9N28E	13	NENE	113	6	8/23/1996	W	Suprabasalt
134	173573	TOM SAVAGE	9N28E	13	NWNE	130	6	5/4/1995	W	Suprabasalt
135	164854	COUNTRY GARDENS, INC.	9N29E	1	SESE	84	12	4/27/1966	W	Suprabasalt
136	416741	UNIVERSAL FROZEN FOODS	9N29E	1	NWSE	98.6	16	7/15/1988	W	Suprabasalt
137	432640	UNIVERSAL FROZEN FOODS	9N29E	1	NESW	122	16	8/11/1990	W	Suprabasalt
138	167692	HARRY PERKINS	9N29E	2	NESE	119	6	9/1/1975	W	Suprabasalt
139	172683	ROY CLARK	9N29E	2	NESE	120	6	10/6/1977	W	Suprabasalt
140	170279	LYNN/MARSHA HALSEY	9N29E	2	SE	122	6	6/17/1980	W	Suprabasalt
141	170485	MARV CULVER	9N29E	2	NESE	128	6	8/24/1983	W	Suprabasalt
142	163666	BILL YOUNG	9N29E	2	SE	133	8	2/3/1981	W	Suprabasalt
143	166904	GARLAND RANSOM	9N29E	2	SWSE	133	6	8/5/1977	W	Suprabasalt
144	166903	GARLAND RANSOM	9N29E	2	NWSE	138	6	4/27/1995	W	Suprabasalt
145	165283	DAVID L. CARTER	9N29E	2	SE	140	6	5/1/1980	W	Suprabasalt
146	164277	CHARLES/LEOLA BAGLEY	9N29E	2	NWSE	144	8	10/17/1982	W	Suprabasalt
147	169174	JOHN PETTIGREW	9N29E	2	NESE	160	6	4/13/1987	W	Suprabasalt
148	176654	JOEL REHFELD	9N29E	2	SESE	160	6	9/18/1997	W	Suprabasalt
149	253742	MARO HARO	9N29E	2	NWSE	160	6	7/26/2000	W	Suprabasalt
150	369765	ISAAC HARO	9N29E	2	NWSE	160	6	9/22/2003	W	Suprabasalt
151	435787	GARY SALSBURY	9N29E	2	NESE	160	6	3/7/2006	W	Suprabasalt
152	418230	GUIERMO GUZMAN	9N29E	2	NESE	160	6	8/19/2005	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
153	372728	RUSS BROOKS	9N29E	2	SWSE	160	6	7/18/2003	W	Suprabasalt
154	459439	CLEMENTE COSTANEDA	9N29E	2	SWSW	160	6	7/31/2006	W	Suprabasalt
155	459438	ALL AMERICAN CONSTRUCTION	9N29E	2	NWSW	160	6	10/5/2006	W	Suprabasalt
156	376900	ELVIN TRUSLEY	9N29E	2	SWSE	173	6	3/22/2004	W	Suprabasalt
157	1062786	LC Farms	9N29E	3	NESW	437	16	6/11/2015	W	Basalt
158	164011	BURLINGTON NORTHERN	9N29E	3	SESE	171	16	12/17/1980	W	Suprabasalt
159	164030	BURLINGTON NORTHERN, INC.	9N29E	3	SE	175	16	7/25/1975	W	Suprabasalt
160	169657	L. C. FARMING/FRED OLBERDING	9N29E	3	SWSW	199	6	2/14/1996	W	Suprabasalt
161	437571	FREDERICK OLBERDING	9N29E	3		213	6	4/19/2006	W	Suprabasalt
162	252832	MARLENE HAWLEY	9N29E	4	NWNW	--	6	6/30/1994	W	--
163	169367	KAM LENG HOUNPKASENT	9N29E	4	NWNW	425	8	9/30/1990	W	Basalt
164	322732	LEROY DICKERSON	9N29E	4	NWNE	490	6	8/3/1997	W	Basalt
165	848089	BOB & MARGRET SHUTZ	9N29E	4	SWSE	500	6	7/2/2012	W	Basalt
166	848164	BOB & MARGRET SHUTZ	9N29E	4	SWSE	500	6	7/2/2012	W	Basalt
167	968347	Evelin Rakhmestryuk	9N29E	4	SENW	505	6	8/19/2013	W	Basalt
168	894435	Victor Melnick	9N29E	4	SENW	520	6	8/26/2013	W	Basalt
169	894439	Miles Creed	9N29E	4	SESE	550	6	7/8/2013	W	Basalt
170	376543	ARNOLD/CAROL UHLMAN	9N29E	4	SENW	559	6	10/23/2003	W	Basalt
171	762031	MEL CLARK	9N29E	4	NWSE	570	6	6/12/2003	W	Basalt
172	163664	BILL WILLIAMS	9N29E	4	NWNE	124	6	3/1/1979	W	Suprabasalt
173	375930	BOB SCHUTZ	9N29E	4	SWSW	180	8	5/16/2003	W	Suprabasalt
174	173683	TRUMAN DECKER	9N29E	4	NWSE	188	6	5/7/1975	W	Suprabasalt
175	165694	DON FLUCHARTY	9N29E	4	SESE	190	6	5/21/1977	W	Suprabasalt
176	254526	JESSE + SUSAN GOIN	9N29E	4	SESE	193	6	10/21/1999	W	Suprabasalt
177	439827	JESSE/SUSAN GOIN	9N29E	4	SESE	193	6	10/21/1999	W	Suprabasalt
178	169655	L. B HARVILLE	9N29E	4	NWSE	195	6	2/16/1973	W	Suprabasalt
179	175881	DON PASSAGE	9N29E	4	SESE	201	6	2/3/1996	W	Suprabasalt
180	172590	RON PASSAGE	9N29E	4	NWSE	202	6	7/2/1979	W	Suprabasalt
181	173476	TIM WHITE	9N29E	4	SWNW	202	6	6/11/1992	W	Suprabasalt
182	577166	MARLENE HAWLEY	9N29E	4	NWNW	202	6	6/1/2000	W	Suprabasalt
183	790489	TIM WHITE	9N29E	4	SWSW	204	6	12/20/1996	W	Suprabasalt
184	163231	ARNOLD UHLMAN	9N29E	4	NESE	205	8	11/14/1980	W	Suprabasalt
185	171734	R. & SHARON HOWARD	9N29E	4	NESW	206	6	11/1/1980	W	Suprabasalt
186	164935	D. BUTTERFIELD/DAWSON	9N29E	4	SE	212	8	4/20/1976	W	Suprabasalt
187	171513	PAUL/MARJORIE WORDEN	9N29E	4	NESE	212.9	8	8/19/1994	W	Suprabasalt
188	436919	STACY N./SHARON K. COLE	9N29E	4	NESE	215	0	12/15/1994	W	Suprabasalt
189	165940	DOVE ALFORD	9N29E	4	NESE	218	12	3/22/1973	W	Suprabasalt
190	799462	James and Terri Dickenson - Dickenson	9N29E	4	NESE	270	6	11/17/2011	W	Suprabasalt
191	176954	JOSE ELIZONDO	9N29E	4	SENE	287	6	12/24/1998	W	Suprabasalt
192	176869	SAM CABLE GONZALEZ	9N29E	4	SESW	300	6	3/27/1999	W	Suprabasalt
193	351627	WADE EHLERS	9N29E	4	NENW	300	6	5/13/2002	W	Suprabasalt
194	659628	Evelin Rakhmestryuk	9N29E	4	SENW	300	8	6/15/2010	W	Suprabasalt
195	894403	Kingsley Berg	9N29E	4	NWSE	300	6	8/9/2012	W	Suprabasalt
196	436972	JESUS GONZALES	9N29E	4	NWSE	302	6	8/20/1992	W	Suprabasalt
197	174938	RONALD/SANDI KIRKPATRICK	9N29E	5	NWNE	157.1	6	1/19/1994	W	Suprabasalt
198	164003	BURLINGTON NORTHERN	9N29E	5	SE	193	16	2/26/1976	W	Suprabasalt
199	436973	JEFF PITTMAN	9N29E	6	NENW	345	6	4/20/1992	W	Basalt
200	635782	Josh Kuhn	9N29E	6	NWNW	360	6	11/9/2009	W	Basalt
201	407904	JOE FLERCHINGER	9N29E	6	NE	388	6	3/17/2005	W	Basalt
202	436976	ETTA STONE	9N29E	6	SWSW	120	6	5/20/1988	W	Suprabasalt
203	170037	LEVIN ELLIOT	9N29E	6	NWNW	120	6	5/18/1992	W	Suprabasalt
204	172136	RICK ALDRICH	9N29E	6	SWNE	155	6	7/2/1979	W	Suprabasalt
205	163476	BERNARD SCHOUVILLER	9N29E	6	SENW	160	6	9/25/1984	W	Suprabasalt
206	173577	TOM SITTON	9N29E	6	SENW	160	6	10/3/1984	W	Suprabasalt
207	168073	J L SMITH	9N29E	6	NWNE	164	6	7/20/1977	W	Suprabasalt
208	436975	DAVID F. GIESLER	9N29E	6	NWNE	170	6	3/20/1991	W	Suprabasalt
209	165908	DOUG BURNS	9N29E	6	NWSE	170	6	8/22/1985	W	Suprabasalt
210	173122	STEVE DILLEY	9N29E	6	SWNE	181	6	9/2/1977	W	Suprabasalt
211	330480	BRADLEY/SANDRA SEGER	9N29E	6	NE	199	6	4/5/2002	W	Suprabasalt
212	173118	STEVE CUNADAY	9N29E	6	SWNE	230	6	5/4/1978	W	Suprabasalt
213	176813	SARJIO VALENCIA	9N29E	6	NENE	235	6	9/22/1998	W	Suprabasalt
214	543527	ANDREW RICE	9N29E	6	SENW	235	6	2/27/2008	W	Suprabasalt
215	436974	MARY CUNNINGHAM	9N29E	6	NENE	260	6	6/16/1992	W	Suprabasalt
216	256922	KEN BRADLEY	9N29E	6	NWNE	280	6	1/14/2000	W	Suprabasalt
217	423598	ROBERT STALLINGS III	9N29E	6	SWNE	295	6	11/21/2005	W	Suprabasalt
218	164266	CENTRAL PREMIX	9N29E	7	SE	46	6	3/24/1978	W	Suprabasalt
219	369537	JASON SITTON	9N29E	8	NWSE	325	8	1/9/2003	W	Basalt
220	460236	COLEMEN VET CLINIC	9N29E	8	NE	365	6	10/26/2006	W	Basalt
221	165113	DANIEL E. SILVA	9N29E	8	SESE	460	6	9/11/1993	W	Basalt
222	165569	DESERT HILLS, INC.	9N29E	8	SWSW	133	16	7/12/1976	W	Suprabasalt
223	436979	TOM COYLE	9N29E	9	NENE	45	6	11/16/1991	W	Suprabasalt
224	138703	Dean Cook	9N29E	9	NENE	80	6	8/11/1994	W	Suprabasalt
225	149108	Ida Keys	9N29E	9	NESE	181	6	2/14/1995	W	Suprabasalt
226	169041	JOHN GREEN	9N29E	9	NENE	227	6	11/1/1978	W	Suprabasalt
227	294388	WILBUR JOHNSON	9N29E	10	NENW	135	8	9/2/1975	W	Suprabasalt
228	436982	VICTOR LENTZ	9N29E	10	SENE	179.6	6	3/22/1990	W	Suprabasalt
229	163008	ALBERT OVERTON	9N29E	10	SWSE	185	8	9/15/1971	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
230	171855	RAY BURDEN	9N29E	10		185	16	5/2/1975	W	Suprabasalt
231	761509	Martin Salas	9N29E	10	SENE	185	6	12/4/2011	W	Suprabasalt
232	172642	RONALD PASSAGE	9N29E	10	SENE	186	10	6/27/1974	W	Suprabasalt
233	436981	BRYAN LONG	9N29E	10	SENE	190	6	8/28/1990	W	Suprabasalt
234	174848	VERNON/FRANCES AUGE	9N29E	10	SWNE	190	6	4/4/1995	W	Suprabasalt
235	380628	VINNIE RIZZO	9N29E	10	SENE	190	6	5/10/2004	W	Suprabasalt
236	376536	DENNIS AND BETTY DEVERE	9N29E	10	SENE	192	6	12/8/2003	W	Suprabasalt
237	163657	BILL WHITE	9N29E	10	NWSW	193	6	2/13/1979	W	Suprabasalt
238	173456	TIM CROWNER	9N29E	10	SENE	195	6	3/17/1995	W	Suprabasalt
239	174849	WILLIAM P. & RUBY KENDRICK	9N29E	10	SWNE	195	6	5/18/1995	W	Suprabasalt
240	171969	RAY M. BURDEN	9N29E	10	SE	200	16	4/4/1975	W	Suprabasalt
241	172510	ROGER NELSON	9N29E	10	NWNE	200	6	8/9/1979	W	Suprabasalt
242	253945	TIM CROWENER	9N29E	10	NENE	200	6	8/24/1999	W	Suprabasalt
243	1656405	City Of Pasco	9N29E	10	SESE	200	20	7/31/2017	W	Suprabasalt
244	353599	MIKE LUKURT	9N29E	10	SESE	201	6	10/1/1995	W	Suprabasalt
245	408191	ESHMEIL YNIGUEZ	9N29E	10	SWNE	202	6	11/20/2004	W	Suprabasalt
246	409713	LUPE AYALA	9N29E	10	SWNE	202	6	11/13/2004	W	Suprabasalt
247	165268	DAVID/KATHY MICHAEL	9N29E	10	SWNE	203	6	5/16/1996	W	Suprabasalt
248	165449	DENNIS BAUGH	9N29E	10		205	6	12/28/1978	W	Suprabasalt
249	448307	DAVID MONTELONGO	9N29E	10		205	6	8/7/2006	W	Suprabasalt
250	163009	ALBERT OVERTON	9N29E	10	SWSE	208	8	9/22/1974	W	Suprabasalt
251	169303	JOSEPH PIZZARELLA	9N29E	10	SWNE	212	8	6/3/1991	W	Suprabasalt
252	175624	DIANE RICHARDS	9N29E	10	NENE	212	6	2/14/1996	W	Suprabasalt
253	358474	RICK LONG	9N29E	10	SENE	215	6	4/25/2003	W	Suprabasalt
254	169038	JOHN GOOSTREY	9N29E	10	SENE	218	6	2/15/1984	W	Suprabasalt
255	175882	DR. O. SMITH	9N29E	10	SWNE	220	6	2/18/1996	W	Suprabasalt
256	316467	MR. PAINE	9N29E	10	NENE	220	6	1/24/2001	W	Suprabasalt
257	175897	PAUL SHERMAN	9N29E	10	SENE	222	6	5/8/1996	W	Suprabasalt
258	175899	DIANE WEAVER	9N29E	10	SENE	224	6	6/25/1996	W	Suprabasalt
259	436980	JIM DALTON	9N29E	10	NESE	224	6	10/26/1996	W	Suprabasalt
260	341415	EDWIN THIESEN	9N29E	10	SENE	225	6	6/25/1998	W	Suprabasalt
261	358475	SCOTT LONG	9N29E	10	SENE	229	6	4/21/2003	W	Suprabasalt
262	176658	RYAN SAVAGE	9N29E	10	NWNW	230	6	11/5/1997	W	Suprabasalt
263	171506	PAUL THOMSON	9N29E	10	SWNE	232.5	6	3/28/1996	W	Suprabasalt
264	175904	JEFF MEARS	9N29E	10	NENE	244	6	10/11/1996	W	Suprabasalt
265	172236	ROBERT BROWN	9N29E	11	SESE	152	10	2/10/1981	W	Suprabasalt
266	164018	BURLINGTON NORTHERN INC.	9N29E	11	NWNW	159	16	12/30/1980	W	Suprabasalt
267	164008	BURLINGTON NORTHERN	9N29E	11	NWNW	161	16	1/15/1986	W	Suprabasalt
268	468088	CITY OF PASCO	9N29E	11	NWNW	184	16	9/22/2006	W	Suprabasalt
269	164028	BURLINGTON NORTHERN, INC.	9N29E	11	SESW	245	16	3/26/1974	W	Suprabasalt
270	164029	BURLINGTON NORTHERN, INC.	9N29E	11	SESW	280	16	3/28/1974	W	Suprabasalt
271	171652	PORT OF PASCO	9N29E	12	SW	59	12	12/9/1974	W	Suprabasalt
272	171650	PORT OF PASCO	9N29E	12	SE	86	16	12/4/1974	W	Suprabasalt
273	171651	PORT OF PASCO	9N29E	12	NWSE	100	12	12/24/1985	W	Suprabasalt
274	171654	PORT OF PASCO	9N29E	13	SW	78	16	11/21/1974	W	Suprabasalt
275	171653	PORT OF PASCO	9N29E	13	NW	98	16	11/7/1974	W	Suprabasalt
276	165516	DEPT OF NATURAL RESOURCES	9N29E	14		110	16	10/9/1975	W	Suprabasalt
277	545221	THE ANGELO CO	9N29E	14	SW	122	16	10/12/2007	W	Suprabasalt
278	164183	CARL LA FON	9N29E	14		145	6	3/1/1975	W	Suprabasalt
279	170182	LOU ELLISON	9N29E	14	NWSE	160	6	6/20/1986	W	Suprabasalt
280	164534	CITY OF PASCO	9N29E	14	NE	177	10	11/25/1987	W	Suprabasalt
281	171856	RAY BURDEN	9N29E	14	NW	232	16	9/21/1976	W	Suprabasalt
282	164017	BURLINGTON NORTHERN INC.	9N29E	15	SENW	312	16	6/11/1974	W	Suprabasalt
283	164031	BURLINGTON NORTHERN, INC.	9N29E	15	SESE	135	16	4/4/1979	W	Suprabasalt
284	436983	DENNIS WISE	9N29E	15	SWSW	168	6	12/7/1992	W	Suprabasalt
285	339463	CITY OF PASCO	9N29E	15	NW	188	16	7/1/2002	W	Suprabasalt
286	164013	BURLINGTON NORTHERN	9N29E	15	SENE	202	16	<Null>	W	Suprabasalt
287	436984	GORDON BRO CELLARS	9N29E	15	SWNE	213	6	12/9/1996	W	Suprabasalt
288	436986	FRANKLIN COUNTY P.U.D.	9N29E	15	SESE	218	6	9/18/1992	W	Suprabasalt
289	164009	BURLINGTON NORTHERN	9N29E	15	NWSE	228	16	1/14/1977	W	Suprabasalt
290	765196	DAVID GRAESCH	9N29E	16	SESE	420	6	4/18/2011	W	Basalt
291	172724	RUBEN BUTLER	9N29E	16	NE	64	6	11/1/1976	W	Suprabasalt
292	166132	ED BRASS	9N29E	16	NWSW	95	6	1/15/1976	W	Suprabasalt
293	166235	EDWARD BRASS	9N29E	16	NWSW	100	6	1/1/1972	W	Suprabasalt
294	254150	ANDREW WEIS	9N29E	16	SE	106	6	3/24/2000	W	Suprabasalt
295	173293	TED CLUM	9N29E	16	SESE	116	6	1/10/1977	W	Suprabasalt
296	165936	DOUGLAS REDFIELD	9N29E	16	NWSE	133	6	5/13/1976	W	Suprabasalt
297	894437	Bernardino Conreras	9N29E	16	SESE	140	6	8/14/2013	W	Suprabasalt
298	1874602	Doug Redfield	9N29E	16	SESE	160	6	11/3/2018	W	Suprabasalt
299	165528	DEPT. OF NATURAL RESOURCE	9N29E	16	NENE	176	16	9/10/1979	W	Suprabasalt
300	165529	DEPT. OF NATURAL RESOURCE	9N29E	16	SENW	220	16	7/10/1975	W	Suprabasalt
301	169787	LARRY LENHART	9N29E	17	SESW	245	6	3/13/1997	W	Basalt
302	168310	JAMES DART	9N29E	17	NESW	260	6	7/18/1978	W	Basalt
303	436989	CRAIG/JIM TEVAY	9N29E	17	SWNE	58	6	6/2/1992	W	Suprabasalt
304	163968	BUD CARPENTER	9N29E	17	SESW	60	6	2/11/1980	W	Suprabasalt
305	171878	RAY MONTGOMERY	9N29E	17		64	6	6/11/1976	W	Suprabasalt
306	254216	LEON SAMPSEL	9N29E	17	NESE	78	6	4/28/1999	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
307	355913	ROBERT AND NANCY DOTY	9N29E	17		80	6	2/20/1997	W	Suprabasalt
308	308987	GENE BATTY	9N29E	17	NWNW	91	6	4/30/2001	W	Suprabasalt
309	174423	WILLIAM MABRY	9N29E	17	NWSE	92	6	6/1/1951	W	Suprabasalt
310	436990	CRAIG/LINDA SMOOT	9N29E	17	NESW	98	6	4/8/1992	W	Suprabasalt
311	165662	DON BUSHEY	9N29E	17	NWSE	100	6	9/20/1986	W	Suprabasalt
312	378550	RICHARD BOSCH	9N29E	17	SENW	100	6	5/8/2003	W	Suprabasalt
313	436987	MIKE COLBY	9N29E	17	SWSE	104.6	6	10/5/1993	W	Suprabasalt
314	436988	MARION HUGHES	9N29E	17	NESW	120.6	6	5/28/1993	W	Suprabasalt
315	164010	BURLINGTON NORTHERN	9N29E	17	NENE	134	16	2/13/1976	W	Suprabasalt
316	455812	LAWRENCE PITTMAN	9N29E	17	NESW	160	6	10/7/2002	W	Suprabasalt
317	423286	JEFFREY TUCKSEN	9N29E	17	NWSE	203	6	11/3/2005	W	Suprabasalt
318	167969	HUGH FULTON	9N29E	17	NESW	205	6	1/14/1983	W	Suprabasalt
319	350659	MANUEL ROSAS	9N29E	18	NWNW	255	6	5/8/2001	W	Basalt
320	314408	WALLACE HARRIS	9N29E	18	NWNW	420	6	10/22/2001	W	Basalt
321	173150	STEVEN MATTHEWS	9N29E	18	SWNE	65	6	1/4/1996	W	Suprabasalt
322	172246	ROBERT CROW	9N29E	18	NWSE	82	6	8/18/1978	W	Suprabasalt
323	165201	DAVE HARRIS	9N29E	18	NWNW	94	6	7/7/1976	W	Suprabasalt
324	688799	STEVE BORCHERS	9N29E	18		118	6	10/8/2010	W	Suprabasalt
325	171174	LARRY GOODWIN	9N29E	18	NWNW	174	6	12/19/1994	W	Suprabasalt
326	915740	Ted and Meri Tschieky	9N29E	18	NENE	200	6	6/13/2012	W	Suprabasalt
327	163290	ARTHUR THIEL	9N29E	19	NENE	87	8	10/26/1989	W	Suprabasalt
328	176958	BRETT GROGAN	9N29E	20	NENW	226	6	4/12/1999	W	Basalt
329	166961	GARY KUSTER	9N29E	20	NESE	29	6	2/19/1996	W	Suprabasalt
330	164071	C. ALFORD	9N29E	20		33	6	5/2/1978	W	Suprabasalt
331	169549	KENNETH REISINGER	9N29E	20	SWNW	35	8	3/15/1970	W	Suprabasalt
332	163960	BRYAN KILBURY	9N29E	20	SWNE	37	6	5/3/1974	W	Suprabasalt
333	174263	WEBSTER JACKSON	9N29E	20	NESW	39	6	6/20/1996	W	Suprabasalt
334	167322	GLENN CONGER	9N29E	20	SESE	40	6	6/1/1976	W	Suprabasalt
335	386298	GUY WELKER	9N29E	20	NE	45	6	9/1/2004	W	Suprabasalt
336	170302	M. J. & JENNIE HANSEN	9N29E	20		47	6	7/5/1974	W	Suprabasalt
337	170161	LORAN & MARYLYNN HEINEN	9N29E	20	SWNW	53.8	6	4/3/1998	W	Suprabasalt
338	437017	G HARRIS	9N29E	20	NENW	54	6	4/30/1996	W	Suprabasalt
339	166468	EUGENE KIRBY	9N29E	20	NW	55	42	7/19/1973	W	Suprabasalt
340	1403367	David Torres	9N29E	20	SWNE	57	6	8/8/2014	W	Suprabasalt
341	376541	JEFF SMITH	9N29E	20	NENW	57.9	6	1/3/2003	W	Suprabasalt
342	376544	JEFF SMITH	9N29E	20	NENW	59	6	1/2/2003	W	Suprabasalt
343	171607	PHIL TEBOY	9N29E	20	NENW	64	6	7/19/1994	W	Suprabasalt
344	166947	GARY EAKIN	9N29E	20	SWNE	65	6	4/15/1983	W	Suprabasalt
345	170775	MIKE DETLOFF	9N29E	20	NENW	65	6	4/8/1994	W	Suprabasalt
346	351639	ANNA SINYUK	9N29E	20	SWNE	65	6	12/26/2002	W	Suprabasalt
347	165690	DON ERICKSON	9N29E	20	NENW	67	6	8/4/1978	W	Suprabasalt
348	174939	LOYD SMITH	9N29E	20	NWNW	73	6	1/27/1995	W	Suprabasalt
349	376896	TEODORO TORRES	9N29E	20	NENE	80	6	3/11/2004	W	Suprabasalt
350	334780	SHAWN BENNION	9N29E	20	SENE	92	6	5/21/2002	W	Suprabasalt
351	336806	ROBERT GREEN	9N29E	20	NENE	96.6	6	5/14/2002	W	Suprabasalt
352	166746	FRANKLIN COUNTY	9N29E	20		100	8	1/1/1956	W	Suprabasalt
353	174950	DWAYNE WELCH	9N29E	20	NWSE	130	6	7/6/1994	W	Suprabasalt
354	293679	FRANCIS SMITH	9N29E	20	SENE	140	6	6/15/1958	W	Suprabasalt
355	171342	PASCO SCHOOL DIST. #1	9N29E	20	NENE	210	12	3/6/1985	W	Suprabasalt
356	455596	CURTIS ROY	9N29E	21	NESE	225	6	10/13/2006	W	Basalt
357	1408429	Jessica Gow-Lee	9N29E	21	NENW	225	6	11/4/2015	W	Basalt
358	254217	THEOPHITE/GYDRAN DOVAY	9N29E	21	SESW	226	6	6/19/1999	W	Basalt
359	437238	JOHN M. ROACH	9N29E	21	SWSW	250	6	3/17/1989	W	Suprabasalt
360	437232	STEVE CREE	9N29E	21	NWNW	255	6	6/12/1990	W	Basalt
361	445873	RON OLIN	9N29E	21	NWSW	320	6	5/11/2006	W	Basalt
362	1629234	Olin Dean	9N29E	21	NWSW	320	6	6/15/2017	W	Basalt
363	478228	MONOGRAM OF PASCO	9N29E	21	NENE	525	6	5/4/2007	W	Basalt
364	166924	GARY BOSCH	9N29E	21		23	6	6/30/1977	W	Suprabasalt
365	169397	RAY BARDEN	9N29E	21	NWSE	26.6	6	5/19/1994	W	Suprabasalt
366	163902	BRIAN/AUDREY BERE	9N29E	21	NESW	27.6	6	12/7/1994	W	Suprabasalt
367	166701	FRANK MOCAER	9N29E	21	NWSW	28	5	3/1/1922	W	Suprabasalt
368	437231	CARL WISE	9N29E	21	NWSE	32	6	1/16/1991	W	Suprabasalt
369	166906	GARTH DRIVER	9N29E	21		34	8	1/8/1968	W	Suprabasalt
370	437217	DORIAN/CHARLOTTE HEYENS	9N29E	21	NWSE	35.2	6	5/16/1994	W	Suprabasalt
371	900371	Dennis & Rachel Zeigler	9N29E	21	SESE	37	6	8/15/2012	W	Suprabasalt
372	437140	JAMES ZEUTENHORST	9N29E	21	SWSW	38	6	8/7/1997	W	Suprabasalt
373	437235	JIM EDWARDS	9N29E	21	SWNE	38	6	5/17/1990	W	Suprabasalt
374	168810	JIM ZEUTENHORST	9N29E	21	SWSW	38	6	<Null>	W	Suprabasalt
375	170513	MARY JO CONYER	9N29E	21	SWNE	39	6	10/1/1996	W	Suprabasalt
376	171998	RICHARD BURNETT	9N29E	21	NENW	39	6	6/23/1975	W	Suprabasalt
377	176911	HANSON CONSTRUCTION	9N29E	21	SENW	39	6	1/28/1999	W	Suprabasalt
378	191751	STEVE HANSON	9N29E	21	NE	39	6	9/22/1999	W	Suprabasalt
379	437225	FLOYD MAHAFLEY	9N29E	21	NESW	39.5	8	7/20/1994	W	Suprabasalt
380	148829	ED THISSEN	9N29E	21	NENE	40	6	2/11/1999	W	Suprabasalt
381	148830	ED THIESSEN	9N29E	21	NENE	40	6	2/11/1999	W	Suprabasalt
382	148831	ED THIESSEN	9N29E	21	NENE	40	6	2/12/1999	W	Suprabasalt
383	169045	JOHN HAGER	9N29E	21	NWSW	44	6	4/2/1974	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
384	308717	CRAIG NELSON	9N29E	21	NWSW	45	6	3/5/2001	W	Suprabasalt
385	376551	STEVE HANSON CONSTRUCTION	9N29E	21	SWNW	45	6	3/22/2004	W	Suprabasalt
386	437233	STEVE HANSON	9N29E	21	SWNW	46	6	5/17/1990	W	Suprabasalt
387	308988	STEVE HANSON	9N29E	21	SENW	46	6	5/11/2001	W	Suprabasalt
388	437226	ALBERT CASTILLO	9N29E	21	SENW	50	6	6/25/1992	W	Suprabasalt
389	164182	CARL KLUVER	9N29E	21	NESE	50	6	1/18/1975	W	Suprabasalt
390	165227	DAVID/LORI PETERSON	9N29E	21	SWNE	52	6	9/27/1994	W	Suprabasalt
391	169056	JOHN HAUGEN	9N29E	21	SENE	53	6	12/18/1995	W	Suprabasalt
392	308338	DAVE BLASDEL	9N29E	21	SENE	54	6	10/30/2000	W	Suprabasalt
393	437220	BILL/BARB DAVIS	9N29E	21	NESW	56	6	12/22/1992	W	Suprabasalt
394	437221	BERT KRUEGER	9N29E	21	SWNE	57.5	6	12/21/1992	W	Suprabasalt
395	165557	DERRALD ZACKER	9N29E	21	NE	58	6	10/18/1974	W	Suprabasalt
396	168950	JOHN & SHEILA WRIGHT	9N29E	21	SWNW	58	6	10/1/1979	W	Suprabasalt
397	166744	FRANKIE ERICKSON	9N29E	21	NESE	59	6	7/1/1980	W	Suprabasalt
398	163872	BOYD BOOTHE	9N29E	21	SWNW	60	6	8/26/1974	W	Suprabasalt
399	1624863	Alex Bedoya	9N29E	21	SWNE	60	6	5/24/2017	W	Suprabasalt
400	175623	SPENCER OSBORNE	9N29E	21	NWSE	62	6	<Null>	W	Suprabasalt
401	437147	SPENCER OSBORNE	9N29E	21	NWSE	62	6	9/18/1995	W	Suprabasalt
402	174448	WILLIAM PARKER	9N29E	21		66	6	9/1/1975	W	Suprabasalt
403	172219	ROBERT ANDELIN	9N29E	21	SWNW	67	6	3/31/1988	W	Suprabasalt
404	165097	DANIEL L. MICHAEL	9N29E	21	NWNW	69	6	1/20/1962	W	Suprabasalt
405	169395	KATHY SHEETS	9N29E	21	NENW	69	6	5/28/1998	W	Suprabasalt
406	437230	STEVE DROKE	9N29E	21	NENE	69	6	11/19/1991	W	Suprabasalt
407	171863	RAY DEBEREC	9N29E	21	NENW	70	6	3/10/1978	W	Suprabasalt
408	172725	RUBEN BUTLER	9N29E	21	NWNE	70	6	2/10/1982	W	Suprabasalt
409	191551	TODD SCHADLER	9N29E	21	SENE	70	10	9/22/1999	W	Suprabasalt
410	172045	RICHARD HARE	9N29E	21	NENW	72	6	10/24/1978	W	Suprabasalt
411	173212	STEVEN QUENTIN	9N29E	21	SENW	72	6	10/12/1977	W	Suprabasalt
412	437224	LARRY SCHOTZ	9N29E	21	SWNE	73	6	9/18/1992	W	Suprabasalt
413	455990	HOWARD H. YOUNG	9N29E	21	NENE	75	8	1/1/1955	W	Suprabasalt
414	171014	N. R. BALLOW	9N29E	21	NWNE	75	6	8/12/1978	W	Suprabasalt
415	162919	ADAM ZACHER	9N29E	21	NENW	77	6	10/23/1980	W	Suprabasalt
416	437229	ED/MICHELE LARRABEE	9N29E	21	NWNE	77	6	2/3/1992	W	Suprabasalt
417	168845	JOE DEAN	9N29E	21	NENW	77	6	10/17/1988	W	Suprabasalt
418	174275	WES STORDAHL	9N29E	21	NWNE	77.5	6	9/22/1995	W	Suprabasalt
419	437223	EARL OWEN	9N29E	21	NWNE	78	6	9/21/1992	W	Suprabasalt
420	172422	ROBERT VANCLEAVE	9N29E	21	NWNE	78	6	5/19/1994	W	Suprabasalt
421	172817	SAM HANSEN	9N29E	21	NWNW	78.5	6	6/3/1997	W	Suprabasalt
422	167243	GERALD GILES	9N29E	21	NWNW	79	6	10/10/1978	W	Suprabasalt
423	408275	RAY DELEVIC	9N29E	21	NWNE	79	6	2/18/2005	W	Suprabasalt
424	163920	BRUCE/LINDA CLATTERBUCK	9N29E	21	NWNE	80	6	3/3/1995	W	Suprabasalt
425	309089	LOREN MATHEWS	9N29E	21	SENW	80	6	5/23/2001	W	Suprabasalt
426	339494	MILTON/DORIS ROBBINS	9N29E	21	SENW	80	6	5/15/2002	W	Suprabasalt
427	334782	ED & JAN BARRON	9N29E	21	SENW	80	6	5/13/2002	W	Suprabasalt
428	334781	BRENT AND DEBORAH SPURGEON	9N29E	21	SENW	80	6	5/16/2002	W	Suprabasalt
429	685788	Stephen Shelestovskiy	9N29E	21	SWNE	80	6	12/7/2009	W	Suprabasalt
430	639085	VICTOR STUPAK	9N29E	21	SWNE	80	6	11/19/2008	W	Suprabasalt
431	163946	BRUCE MEYER	9N29E	21	NENE	83	6	7/1/1979	W	Suprabasalt
432	168998	JOHN A. CRAWFORD	9N29E	21	NENW	86	6	5/19/1978	W	Suprabasalt
433	437227	AL BRAVER	9N29E	21	NWNW	92	6	4/23/1992	W	Suprabasalt
434	173496	TODD PIERCE	9N29E	21	NWNW	93	6	5/9/1998	W	Suprabasalt
435	380655	ROBERT AND REBECCA TABER	9N29E	21	NENE	96	6	5/17/2004	W	Suprabasalt
436	437222	JAMES NELSON	9N29E	21	NWNW	98	8	12/3/1992	W	Suprabasalt
437	543531	SCOTT HOWELL	9N29E	21	NENE	98.3	6	2/28/2008	W	Suprabasalt
438	594207	LARRY SCHATZ	9N29E	21	NWNW	100	6	3/6/2008	W	Suprabasalt
439	437237	MIKE ROACH	9N29E	21	SWSW	156	6	4/4/1990	W	Suprabasalt
440	437219	NED/LINDA PASCO	9N29E	21	SESW	159	6	3/16/1993	W	Suprabasalt
441	423430	JIM ZEUTENHORST	9N29E	21	NWNW	201	6	8/12/1997	W	Suprabasalt
442	491681	PETER MAKER	9N29E	21	SESW	220	6	8/14/2007	W	Suprabasalt
443	170305	M. K & KELLY SCHWAIBACH	9N29E	22	NESW	--	6	2/24/1998	W	--
444	432749	MICHAEL WOODS	9N29E	22	SWSW	268	6	1/24/2006	W	Basalt
445	438106	TIM WIBERG	9N29E	22	SESE	33	6	5/6/1994	W	Suprabasalt
446	165642	DOMINGO GARCIA	9N29E	22	NESE	36	6	1/10/1995	W	Suprabasalt
447	173300	TED KRONER	9N29E	22	NWSE	36.6	6	10/19/1995	W	Suprabasalt
448	164960	DANIEL/JENE RIDGLEY	9N29E	22	NWSE	37	6	1/27/1995	W	Suprabasalt
449	171864	RAY DICKMAN	9N29E	22	NENW	37.6	6	1/27/1998	W	Suprabasalt
450	174103	WARD PAGE	9N29E	22	NWSE	37.6	6	8/15/1995	W	Suprabasalt
451	170922	MONTY WARD	9N29E	22	NWSE	38	6	11/4/1994	W	Suprabasalt
452	176659	JOEL PAGE	9N29E	22	NESW	38	6	7/16/1998	W	Suprabasalt
453	174855	MIKE/KELLY SCHWALBACH	9N29E	22	SESE	40	6	5/25/1994	W	Suprabasalt
454	176130	LINDA BATES	9N29E	22	NWSW	40	6	8/7/1996	W	Suprabasalt
455	378725	ED THIESEN	9N29E	22	SENE	40	6	3/31/2004	W	Suprabasalt
456	438105	JIM STONE	9N29E	22	NWSE	44	6	5/18/1994	W	Suprabasalt
457	254527	CHARLES REMBO	9N29E	22	SWNW	45	6	11/8/1999	W	Suprabasalt
458	438108	HARVEY UNDERWOOD	9N29E	22	SENW	53.6	6	7/29/1991	W	Suprabasalt
459	252833	CHUCK STELTENPOHL	9N29E	22	SWNE	54.2	6	4/4/2000	W	Suprabasalt
460	438107	LLOYD INGRAHAM	9N29E	22	SWNW	55	6	6/24/1993	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
461	171343	PASTOR DALLAS DOBSON	9N29E	22	NESE	56	6	6/23/1988	W	Suprabasalt
462	378569	ED THIESEN	9N29E	22	SENE	60	6	3/16/2004	W	Suprabasalt
463	376548	CONNER CONSTRUCTION	9N29E	22	NWNE	63.6	6	12/31/2002	W	Suprabasalt
464	588586	PERRY EARLY	9N29E	22	NWSW	65	6	6/10/2007	W	Suprabasalt
465	172757	RUSSEL RHOADS	9N29E	22	NWSW	69	6	8/21/1975	W	Suprabasalt
466	167825	HERBERT JOHNSON	9N29E	22	NENW	70	6	4/13/1994	W	Suprabasalt
467	174869	BRIAN WORDEN	9N29E	22	NWNW	70	6	4/27/1998	W	Suprabasalt
468	418019	STEVE TOMKINS	9N29E	22	SENW	70	6	9/16/2005	W	Suprabasalt
469	1924772	David Torres	9N29E	22	SWNE	72	6	9/14/2019	W	Suprabasalt
470	409000	GARY BOSCH	9N29E	22	NENE	73	6	2/22/2005	W	Suprabasalt
471	406967	JEFF HENDLER	9N29E	22	NENE	73.5	6	12/29/2004	W	Suprabasalt
472	438104	GARY BOSCH	9N29E	22	NENW	73.6	6	7/2/1996	W	Suprabasalt
473	376538	GARY BOSCH	9N29E	22	SWNE	73.6	6	11/19/2003	W	Suprabasalt
474	172080	RICHARD MOREHOUSE	9N29E	22	NENW	74	6	7/1/1996	W	Suprabasalt
475	408277	ANTHONY ST MARTIN	9N29E	22	NENE	74	6	2/22/2005	W	Suprabasalt
476	336550	CONNER CONSTRUCTION	9N29E	22	NE	75	6	7/30/2002	W	Suprabasalt
477	376539	GARY BOSCH	9N29E	22	SWNE	75	6	11/20/2003	W	Suprabasalt
478	1924771	David Torres	9N29E	22	SWNE	75	6	9/15/2019	W	Suprabasalt
479	1924760	David Torres	9N29E	22	SWNE	75	6	9/16/2019	W	Suprabasalt
480	437370	GARY BOSCH	9N29E	22	NWNW	79.6	6	3/10/2001	W	Suprabasalt
481	438103	JOHN PETTIGREW	9N29E	22	NENW	80	6	3/10/1999	W	Suprabasalt
482	164880	CRAIG W. SMOOT	9N29E	22	SESE	82	6	9/30/1987	W	Suprabasalt
483	343517	GATMAN	9N29E	22	NENW	83	6	7/31/2002	W	Suprabasalt
484	166925	GARY BOSCH	9N29E	22	NW	84	6	8/20/1978	W	Suprabasalt
485	376532	NEAL BARTLESON	9N29E	22	NWNE	85	6	2/10/2004	W	Suprabasalt
486	163082	ALLEN NORDBY	9N29E	22	NWNW	86	6	2/27/1978	W	Suprabasalt
487	378554	CASEY LINDSTROM	9N29E	22	NENE	86	6	3/20/2003	W	Suprabasalt
488	170394	MARK FAST	9N29E	22	NENW	93	6	7/2/1978	W	Suprabasalt
489	174327	WILBURN J. PARKS	9N29E	22	NENE	100	6	8/22/1977	W	Suprabasalt
490	375946	LEO FAUST	9N29E	22		100	6	10/3/2003	W	Suprabasalt
491	445875	SAM MARTINEZ	9N29E	22	SWNE	100	6	3/31/2006	W	Suprabasalt
492	375002	JAVIAR AND VERNA RUIZ	9N29E	22	NENE	107	6	1/28/2004	W	Suprabasalt
493	413224	DAN MARTINEZ	9N29E	22	SWNE	114	6	12/20/2004	W	Suprabasalt
494	174285	WEST PASCO WATER SYSTEM	9N29E	22	NENE	130	12	9/1/1980	W	Suprabasalt
495	174870	CAROL CHAVEZ	9N29E	22	NWNW	159	6	5/6/1998	W	Suprabasalt
496	165029	DALLAS DOBSON	9N29E	22	NESE	160	6	7/30/1975	W	Suprabasalt
497	445877	DEAN OLIN	9N29E	23	NWNW	252	6	5/17/2006	W	Suprabasalt
498	1629254	Taras Danylyuk	9N29E	23	SESW	315	6	6/27/2014	W	Basalt
499	171829	RANDY NESS	9N29E	23	SWNW	35	6	2/17/1996	W	Suprabasalt
500	900409	David Torres	9N29E	23	SWSE	48	6	10/15/2013	W	Suprabasalt
501	172202	ROBERT & GEORGIA HARRIS	9N29E	23	NESE	50	40	4/1/1947	W	Suprabasalt
502	174215	WAYNE BAKER	9N29E	23		52	6	11/1/1976	W	Suprabasalt
503	685884	VEN AND NATALIE RYANDINSKIY	9N29E	23	SWNE	55	6	5/15/2010	W	Suprabasalt
504	294174	ROBERT GOVE	9N29E	23	NESE	57	6	9/16/1957	W	Suprabasalt
505	436914	DON FIAT	9N29E	23	NESE	60	6	11/20/1992	W	Suprabasalt
506	169514	KENNETH DEPUE	9N29E	23	NWNW	60	6	2/24/1983	W	Suprabasalt
507	171858	RAY CARLISLE	9N29E	23	SENW	60	6	9/23/1993	W	Suprabasalt
508	176814	MILO SCHMITT	9N29E	23	NENE	60	6	10/6/1998	W	Suprabasalt
509	175903	JOSE ZEPEDA	9N29E	23	SWSE	64	6	10/1/1996	W	Suprabasalt
510	163000	ALBERT GRAY	9N29E	23	SENW	67	6	9/26/1994	W	Suprabasalt
511	165003	DALE MAXSON	9N29E	23	SENW	67	36	11/6/1948	W	Suprabasalt
512	438109	DALLAS DENNIS YOUNG	9N29E	23	NESW	69	6	3/6/1993	W	Suprabasalt
513	436915	MIKE URLACHER	9N29E	23	NENW	70	6	12/14/1991	W	Suprabasalt
514	174076	WALTER CRAYNE	9N29E	23		70	6	5/27/1976	W	Suprabasalt
515	168842	JOE COSTANZO	9N29E	23	NWNW	72	6	12/20/1994	W	Suprabasalt
516	406974	GARY BOSCH	9N29E	23	NWNW	72	6	12/30/2004	W	Suprabasalt
517	436918	MARK BRADFORD	9N29E	23	NENW	73	6	6/4/1990	W	Suprabasalt
518	170499	MARVIN SCHADLER	9N29E	23	NENE	73	6	7/27/1979	W	Suprabasalt
519	308409	DENNIS FORTUNE	9N29E	23	NWNE	73	6	10/24/2000	W	Suprabasalt
520	173200	STEVEN CREE	9N29E	23	SWNE	74	6	5/1/1978	W	Suprabasalt
521	436916	EARL BAKLEY	9N29E	23	SWNE	77	6	11/15/1991	W	Suprabasalt
522	167188	GEORGE SCHMULJOHN	9N29E	23	SWNE	77	0	6/23/1992	W	Suprabasalt
523	436879	JOHN ROSE	9N29E	23	NWNW	78	0	8/4/1997	W	Suprabasalt
524	252834	JORGE GARCIA	9N29E	23	NWNW	78	6	4/5/2000	W	Suprabasalt
525	639095	JASON KANE	9N29E	23	NWSE	78	6	8/29/2008	W	Suprabasalt
526	166247	EDWARD PONN	9N29E	23	NWNE	79	6	10/27/1975	W	Suprabasalt
527	165329	DAVID ODONNELL	9N29E	23	SWNW	80	6	5/25/1977	W	Suprabasalt
528	436917	JIM LAKE	9N29E	23	NENE	80	6	10/30/1991	W	Suprabasalt
529	315576	ROSALBA VALDEZ	9N29E	23	NWNW	80	6	6/27/2001	W	Suprabasalt
530	378579	DUANE WELCH	9N29E	23	NWSE	80	6	8/23/2002	W	Suprabasalt
531	455125	NOE/NORMA CASTILLO	9N29E	23	NENW	80	6	10/11/2002	W	Suprabasalt
532	455123	JORGE GARCIA	9N29E	23	NENW	80	6	10/18/2002	W	Suprabasalt
533	391869	HARVEY WILLIS	9N29E	23	SWNE	80	6	10/29/2004	W	Suprabasalt
534	685882	Wayne Kane	9N29E	23	SENE	80	6	5/17/2010	W	Suprabasalt
535	843547	Ramiro Ramos	9N29E	23	NENW	80	6	4/20/2011	W	Suprabasalt
536	386407	WARREN BOGART	9N29E	23	NWNW	81	6	3/2/2004	W	Suprabasalt
537	766419	Adrian Scott	9N29E	23	NESW	81	6	9/6/2011	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
538	594147	TRAVIS MATSON	9N29E	23	NWNE	90	6	6/15/2004	W	Suprabasalt
539	766397	MARGARITA CONTU	9N29E	23	SWSE	100	6	8/5/2010	W	Suprabasalt
540	173292	TED CLUM	9N29E	23	NENE	116	6	1/10/1977	W	Suprabasalt
541	165002	DALE MAXSON	9N29E	23	SENW	137	6	3/28/1978	W	Suprabasalt
542	375761	SANTIAGO ALENCASTER	9N29E	23	SENE	145	6	2/25/2004	W	Suprabasalt
543	438114	RICHARD COLLINGHAM	9N29E	24	NWNW	37.6	8	8/11/1992	W	Suprabasalt
544	165335	DAVID SCHULTZ	9N29E	24	NENE	44	6	4/6/1988	W	Suprabasalt
545	438110	PETER LEMIEUX	9N29E	24	SWSW	52.4	6	11/7/1996	W	Suprabasalt
546	178036	CBC	9N29E	24	SWNE	71	4	<Null>	W	Suprabasalt
547	178037	CBC	9N29E	24	SWNE	73	4	<Null>	W	Suprabasalt
548	172480	RODNEY CHERRY	9N29E	24	NESW	73	6	4/1/1978	W	Suprabasalt
549	178035	CBC	9N29E	24	NENE	93	4	<Null>	W	Suprabasalt
550	396623	JOHN AIRLOPI	9N29E	24	NENE	97	6	12/18/2004	W	Suprabasalt
551	171655	PORT OF PASCO (#5)	9N29E	24	NWSE	100	12	12/24/1985	W	Suprabasalt
552	293528	COLUMBIA BASIN COLLEGE	9N29E	24	SENE	111.4	12	8/11/1971	W	Suprabasalt
553	174499	WINDSOR PARK PROPERTIES 5	9N29E	25	SESW	--	12	<Null>	W	--
554	294406	WINDSOR PARK PROPERTIES 5	9N29E	25	SESW	--	12	3/17/1989	W	--
555	294407	WINDSOR PARK PROPERTIES 5	9N29E	25	SESW	--	12	3/14/1989	W	--
556	438115	FLAMINGO TRAILER VILLAGE	9N29E	25	SW	406	8	6/9/1989	W	Basalt
557	168022	IRA COLLINS	9N29E	25	NWSW	24	42	3/1/1947	W	Suprabasalt
558	163870	BOYD L. & NEOLA L. HOOPS	9N29E	25		27	8	12/5/1974	W	Suprabasalt
559	164661	CLARENCE WIRTH	9N29E	25	NESW	28	41	5/15/1947	W	Suprabasalt
560	167771	HENRY KAHLIN	9N29E	25	NESW	29	46	3/1/1933	W	Suprabasalt
561	170560	MAX ARMSTRONG	9N29E	25	SWNW	30	6	7/11/1986	W	Suprabasalt
562	173554	TOM KOWARCH	9N29E	25	SWNW	30	6	9/21/1985	W	Suprabasalt
563	170779	MIKE DURANT	9N29E	25	SWNW	32	6	9/30/1985	W	Suprabasalt
564	163611	BILL LEAHY	9N29E	25	SWNW	34	6	10/31/1978	W	Suprabasalt
565	168155	J. W. FANNING	9N29E	25		35	8	12/10/1974	W	Suprabasalt
566	166874	G. L. NESWICK	9N29E	25	SWSW	39	6	5/1/1981	W	Suprabasalt
567	166350	ELOF E. OLSON	9N29E	25	NWNW	42	5	1/1/1936	W	Suprabasalt
568	173059	STATE OF WASHINGTON	9N29E	25	SENW	49	8	5/13/1980	W	Suprabasalt
569	163675	BILLY KERSLAKE	9N29E	25	NENW	50	36	<Null>	W	Suprabasalt
570	167710	HARVEY HATCH	9N29E	25	SWSW	53	6	12/1/1979	W	Suprabasalt
571	170346	MARDEN KOHLER	9N29E	25		83	6	5/24/1974	W	Suprabasalt
572	437990	CITY OF PASCO, WASHINGTON (B-4)	9N29E	26	NWSW	14.6	2	4/2/1993	W	Suprabasalt
573	166823	FRED WARREN	9N29E	26	NWNE	27.3	6	4/8/1988	W	Suprabasalt
574	166002	DUANE RAUGUST	9N29E	26	NESE	28	6	8/9/1982	W	Suprabasalt
575	438116	TIM FIFE	9N29E	26	NESE	30	6	4/30/1993	W	Suprabasalt
576	438119	JOHN PATRICK	9N29E	26	SENE	31	6	4/20/1988	W	Suprabasalt
577	166030	DWIGHT DAVISON	9N29E	26	NESE	32	6	8/9/1982	W	Suprabasalt
578	166760	FRED BRISTOW	9N29E	26	SENE	32	42	3/1/1949	W	Suprabasalt
579	308408	ROBERT GRIMES	9N29E	26	SENE	33	6	10/31/2000	W	Suprabasalt
580	166001	DUANE RAUGUST	9N29E	26	SE	35	6	7/26/1984	W	Suprabasalt
581	171812	RANDALL BROWN	9N29E	26	NESW	35	6	9/1/1957	W	Suprabasalt
582	253890	FORREST STEWART	9N29E	26	NWNW	35	6	6/1/2000	W	Suprabasalt
583	438117	GARY DUKELOW	9N29E	26	NWSW	37	6	4/15/1993	W	Suprabasalt
584	293742	H. E. COPELAND	9N29E	26		38	40	3/1/1946	W	Suprabasalt
585	166831	FREDDIE WALTON	9N29E	26	NESE	39	6	8/22/1981	W	Suprabasalt
586	169167	JOHN OVERMAN	9N29E	26	NESW	40	6	5/3/1984	W	Suprabasalt
587	172420	ROBERT VAN LIEW	9N29E	26	SE	40	6	8/26/1981	W	Suprabasalt
588	167222	GEORGE YOSHINO	9N29E	26	SWSE	41	6	2/7/1984	W	Suprabasalt
589	166180	ED RAY	9N29E	26	NESE	42	6	11/12/1981	W	Suprabasalt
590	168102	J. DAVID CLANCY	9N29E	26		42	3	3/1/1946	W	Suprabasalt
591	168478	JAY J. MONTGEMERY	9N29E	26	SENE	42	8	4/1/1962	W	Suprabasalt
592	166790	FRED KLOPPENSTEIN	9N29E	26		50	36	4/11/1946	W	Suprabasalt
593	176152	ROMA TAYLOR	9N29E	26	SESE	52	6	4/30/1997	W	Suprabasalt
594	438118	BEVERLY MARTINOLICH	9N29E	26	NENW	53	6	2/25/1992	W	Suprabasalt
595	163934	BRUCE FLIPPO	9N29E	26	SESE	55	6	<Null>	W	Suprabasalt
596	167709	HARVEY HATCH	9N29E	26		56	8	1/1/1970	W	Suprabasalt
597	174386	WILLIAM FOLEY	9N29E	26		70	6	6/27/1969	W	Suprabasalt
598	1746429	Colt Nickels	9N29E	26	SENE	83	8	7/9/2018	W	Suprabasalt
599	170964	MR. & MRS. RANDY BLACK	9N29E	26	NESW	110	6	7/1/1977	W	Suprabasalt
600	303362	RALPH FRAZIER	9N29E	26	NWNW	210	6	1/18/2001	W	Suprabasalt
601	163262	ARTHUR & CHARLOTTE STROMME	9N29E	27		22	4	5/1/1951	W	Suprabasalt
602	171967	REX MCMULLIN	9N29E	27	NENE	27.4	6	3/24/1994	W	Suprabasalt
603	253396	SANTOS GALLEGOS	9N29E	27	SENW	38	6	4/28/1999	W	Suprabasalt
604	314417	ERIC OLSEN	9N29E	27	SENW	38	6	9/19/2001	W	Suprabasalt
605	163289	ARTHUR E. STROMME	9N29E	27		40	6	4/1/1948	W	Suprabasalt
606	176657	TOM BOSCH	9N29E	27	NENW	40	40	5/7/1998	W	Suprabasalt
607	176662	TIM/MALIN WHITE	9N29E	27	NENW	40	6	10/30/1998	W	Suprabasalt
608	378581	GREGG BOSCH	9N29E	27	NENE	40	6	11/8/2002	W	Suprabasalt
609	171745	R. LLOYD/BLANCHE JOHNSON	9N29E	27		42	24	3/1/1948	W	Suprabasalt
610	173548	TOM KAYE	9N29E	27	NENW	45	6	10/14/1995	W	Suprabasalt
611	173549	TOM KAYE	9N29E	27	NENE	50	6	10/13/1995	W	Suprabasalt
612	174054	WALT APLEY	9N29E	27	NWNW	51	6	12/4/1979	W	Suprabasalt
613	351626	JOHN AND MABELLE DAVIS	9N29E	27	SWNE	56	6	5/15/2002	W	Suprabasalt
614	351625	SAUL AND MARIE CAMPOS	9N29E	27	SENE	56	6	5/22/2002	W	Suprabasalt

Identification			Location			Well Construction					
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
615	438573	TIM WHITE	9N29E	27	NENE	60	6	2/4/2000	W	Suprabasalt
616	256924	TIM WHITE	9N29E	27	NENE	60	6	8/29/2000	W	Suprabasalt
617	322124	TIM WHITE	9N29E	27	NESE	60	6	6/15/2001	W	Suprabasalt
618	347057	BRUCE BENNETT	9N29E	27	NENE	60	6	9/3/2002	W	Suprabasalt
619	369766	GREGG BOSCH	9N29E	27	NE	60	6	9/25/2003	W	Suprabasalt
620	767217	RAEZ RODRIGUEZ	9N29E	27	NWNW	75	6	10/1/2003	W	Suprabasalt
621	174286	WEST PASCO WATER SYSTEM	9N29E	27	SWNE	175	12	2/1/1977	W	Suprabasalt
622	163631	BILL SMITH	9N29E	28	NENW	321	6	8/29/1996	W	Basalt
623	293537	CORNELIUS KUFFEL, M.D.	9N29E	28		21.5	8	5/25/1963	W	Suprabasalt
624	172362	ROBERT PHILIP	9N29E	28	NENW	29	8	3/29/1962	W	Suprabasalt
625	438897	AURORA 701/PETER JOBS	9N29E	28	NENE	31	3.5	3/19/1993	W	Suprabasalt
626	176976	ANNE ERICKSON	9N29E	28	NENE	32	6	3/9/1999	W	Suprabasalt
627	438894	GENE REEP	9N29E	28	NWNW	32.4	6	3/26/1993	W	Suprabasalt
628	163632	BILL SMITH	9N29E	28	NENW	33	6	5/15/1997	W	Suprabasalt
629	439132	ELAINE LEE	9N29E	28	NWNE	33	6	8/23/1990	W	Suprabasalt
630	172515	ROGER OLSON	9N29E	28		33	6	5/16/1967	W	Suprabasalt
631	438898	BILL LAMPSON	9N29E	28	NWNW	35.3	6	3/17/1993	W	Suprabasalt
632	176655	DAVI TATE	9N29E	28	NENE	38	6	9/29/1997	W	Suprabasalt
633	1584480	Nathan Jenkins	9N29E	28	NENW	220	6	8/24/2016	W	Suprabasalt
634	439133	KEN KUKLINSKI	9N29E	29	NENE	26.6	6	3/25/1993	W	Suprabasalt
635	375911	TODD PIESEN	9N29E	29	NENE	40	6	5/22/1992	W	Suprabasalt
636	172414	ROBERT TIPPETT	9N30E	2	SENE	127	16	7/3/1974	W	Suprabasalt
637	439149	TIPPET LAND AND MORTGAGE CO.	9N30E	2	SWNE	139.6	16	12/30/1988	W	Suprabasalt
638	172409	ROBERT TIPPET	9N30E	2	SENW	140	6	6/2/1975	W	Suprabasalt
639	167466	H & G SOD CO. INC.	9N30E	2	SESW	157	8	10/2/1991	W	Suprabasalt
640	439148	GREG HIGGS	9N30E	2	SWSW	157.6	8	10/2/1991	W	Suprabasalt
641	439147	BRUCE/LORI STIGGY	9N30E	2	SESW	158	6	6/4/1993	W	Suprabasalt
642	172412	ROBERT TIPPETT	9N30E	2		159	16	10/10/1974	W	Suprabasalt
643	172417	ROBERT TIPPITT	9N30E	2	SWNE	165	16	3/19/1976	W	Suprabasalt
644	164188	CARL MARCHBANKS	9N30E	2	SWSW	210	8	1/23/1962	W	Suprabasalt
645	168742	JIM MINNEHAN	9N30E	4	SESE	186	12	7/31/1974	W	Suprabasalt
646	166086	EARL BLASDEL	9N30E	4	NWSE	220	16	11/2/1993	W	Suprabasalt
647	168072	J. E. LENTZ	9N30E	4	SESE	242	16	1/10/1978	W	Suprabasalt
648	349423	EARL BLASDEL	9N30E	5	SWSE	203.5	8	10/29/2002	W	Suprabasalt
649	164020	BURLINGTON NORTHERN INC.	9N30E	5	SW	225	16	3/18/1974	W	Suprabasalt
650	162770		9N30E	5	NESE	230	16	3/20/1973	W	Suprabasalt
651	439154	HERB RODE	9N30E	5	SESE	240	6	10/31/1992	W	Suprabasalt
652	164021	BURLINGTON NORTHERN INC.	9N30E	5	SESW	242	16	3/27/1974	W	Suprabasalt
653	294195	ROGERS WALLA WALLA, INC.	9N30E	6	SWSW	82.5	8	4/5/1966	W	Suprabasalt
654	294194	ROGERS WALLA WALLA, INC.	9N30E	6		85	6	5/1/1965	W	Suprabasalt
655	293545	COUNTRY GARDENS, INC.	9N30E	6		88	12	3/1/1966	W	Suprabasalt
656	439186	RODGERS POTATO SERVICE	9N30E	6	SW	98	8	1/30/1991	W	Suprabasalt
657	172415	ROBERT TIPPETT	9N30E	6	SWSE	101	6	3/4/1977	W	Suprabasalt
658	168392	JAMES MINNEHUN	9N30E	6	SWNW	102	8	3/30/1976	W	Suprabasalt
659	163057	ALLAN ROGERS	9N30E	6	NESW	105	8	3/21/1986	W	Suprabasalt
660	175900	DAVE & MARY JO VOOGE	9N30E	6	NENE	124	6	8/20/1996	W	Suprabasalt
661	172410	ROBERT TIPPETT	9N30E	6	SESE	132	16	9/3/1973	W	Suprabasalt
662	175865	ALLAN ROGERS	9N30E	6	SWSW	140	6	5/23/1996	W	Suprabasalt
663	175866	OLYMPIC POTATO	9N30E	6	SWSW	140	8	5/29/1996	W	Suprabasalt
664	799476	Joel Rogers - Rogers Potato Service	9N30E	6	SESE	144	8	4/24/2012	W	Suprabasalt
666	163932	BRUCE FARMS INC.	9N30E	6	SESW	165	8	8/11/1976	W	Suprabasalt
667	1629238	Rogers Potatoe Service	9N30E	6	SESW	221	8	4/7/2016	W	Suprabasalt
668	148661	ROBERT & MICHEAL MCKEE	9N30E	6	SESE	225	6	7/2/1998	W	Suprabasalt
669	439185	GORDON BRADSHAW	9N30E	6	SESE	245	6	6/28/1993	W	Suprabasalt
670	164891	CURRIE SEED CO.	9N30E	7	NESW	90	6	10/1/1980	W	Suprabasalt
671	163136	AMERICAN CHEM. & FERT CO.	9N30E	7	SWNE	96	6	5/6/1976	W	Suprabasalt
672	164720	CLIFFORD JAMES	9N30E	8	NWNE	600	6	6/15/1979	W	Basalt
673	439365	HERB BARRUS	9N30E	8	SESE	34	6	5/5/1988	W	Suprabasalt
674	167581	HAROLD COX	9N30E	8	NENW	129	16	3/7/1988	W	Suprabasalt
675	167582	HAROLD COX	9N30E	8	SENW	129	16	2/18/1988	W	Suprabasalt
676	170806	MIKE KOONS	9N30E	8	NWNW	133.6	6	9/10/1996	W	Suprabasalt
677	172411	ROBERT A. TIPPETT	9N30E	8	SWSE	135	16	9/1/1973	W	Suprabasalt
678	167634	HAROLD THOMPSON	9N30E	8		140	16	3/20/1974	W	Suprabasalt
679	163036	ALFORD FARM	9N30E	8	NENE	150.6	6	5/22/1990	W	Suprabasalt
680	172133	WILLIAM RICHARDSON	9N30E	8	NWNE	158	8	9/28/1981	W	Suprabasalt
681	439364	EDWIN THIESSEN	9N30E	8	NWNW	178	6	5/23/1990	W	Suprabasalt
682	445878	TIM TIPPETT	9N30E	8	NENE	188	6	6/8/2006	W	Suprabasalt
683	1918188	Trevor Gamache	9N30E	9	NWNW	410	6	9/3/2019	W	Basalt
684	439782	GREG/JOANNE MONTGOMERY	9N30E	9	NWNW	34	6	8/20/1991	W	Suprabasalt
685	783233	Shawna Deaver	9N30E	9	SWNE	38	6	3/23/2012	W	Suprabasalt
686	783235	Chastity Phichith	9N30E	9	SWNE	43	6	3/18/2012	W	Suprabasalt
687	168726	JIM LENTZ	9N30E	9	SE	165	16	1/10/1977	W	Suprabasalt
688	167579	HAROLD COX	9N30E	9	NWNW	206	16	10/4/1977	W	Suprabasalt
689	168108	J. E. LENTZ	9N30E	10	NWSW	154	16	1/17/1975	W	Suprabasalt
690	168727	JIM LENTZ	9N30E	10	NWSE	170	16	3/25/1977	W	Suprabasalt
691	167580	HAROLD COX	9N30E	10	NWNE	182	6	10/7/1993	W	Suprabasalt
692	164535	CITY OF PASCO	9N30E	11	NENE	143	16	1/16/1997	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
693	171730	R. GUY SULLIVAN	9N30E	11	SWSE	146	12	<Null>	W	Suprabasalt
694	164035	BURLINGTON NORTHERN, INC.	9N30E	11	NENE	152	16	4/17/1975	W	Suprabasalt
695	164036	BURLINGTON NORTHERN, INC.	9N30E	11	NWNW	153	16	6/11/1975	W	Suprabasalt
696	1918209	City Of Pasco	9N30E	11	NWNW	170	16	8/16/2019	W	Suprabasalt
697	315879	ERNEST LEE	9N30E	11	NW	183.2	6	12/7/2001	W	Suprabasalt
698	163617	BILL MIDDELTON	9N30E	11	SWSW	185	8	6/18/1994	W	Suprabasalt
699	164025	BURLINGTON NORTHERN R. R.	9N30E	11	SW	205	16	3/8/1975	W	Suprabasalt
700	493552	ERNEST & BONNIE LEE	9N30E	11	NW	261	6	7/17/2007	W	Suprabasalt
701	168725	JIM LENTZ	9N30E	12	NWNW	97	16	12/16/1975	W	Suprabasalt
702	439787	GUY SULLIVAN	9N30E	12	NW	140	6	4/1/1971	W	Suprabasalt
703	165532	DEPT. OF NATURAL RESOURCES	9N30E	16	SE	101	16	1/23/1973	W	Suprabasalt
704	173551	TOM KIDWELL	9N30E	16	NWSW	107	6	3/20/1981	W	Suprabasalt
705	165530	DEPT. OF NATURAL RESOURCES	9N30E	16		122	16	2/25/1973	W	Suprabasalt
706	165533	DEPT. OF NATURAL RESOURCES	9N30E	16	SWNW	123	16	12/28/1972	W	Suprabasalt
707	165534	DEPT. OF NATURAL RESOURCES	9N30E	16	SESW	132	16	10/29/1972	W	Suprabasalt
708	165531	DEPT. OF NATURAL RESOURCES	9N30E	16	NE	145	16	2/12/1973	W	Suprabasalt
709	166954	GARY GRABER	9N30E	17	NENW	97	6	3/30/1976	W	Suprabasalt
710	439795	VAN WORMER	9N30E	17	NW	99.5	6	4/22/1975	W	Suprabasalt
711	173552	TOM KIDWELL	9N30E	17	SE	100	6	2/14/1976	W	Suprabasalt
712	362417	VALMONT NORTHWEST	9N30E	17	SENW	108	6	5/6/2003	W	Suprabasalt
713	168682	JIM DUGAS	9N30E	17	SWSE	109.5	8	7/28/1976	W	Suprabasalt
714	166604	FORD DEVELOPMENT	9N30E	17	SWNW	120	6	1/1/1970	W	Suprabasalt
715	164798	COLUMBIA EAST PART	9N30E	17	SESE	130	16	2/1/1971	W	Suprabasalt
716	166953	GARY GRABER	9N30E	17	NW	140	6	7/6/1976	W	Suprabasalt
717	294225	STATE OF WASH. DEPT. OF ECOLOGY	9N30E	18		--	0	<Null>	W	--
718	293493	CITY OF PASCO	9N30E	19		246	12	9/9/1958	W	Suprabasalt
719	152692	FRANK PONTAROLO	9N30E	19	SESW	54	6	9/23/1974	W	Suprabasalt
720	150673	CITY OF PASCO	9N30E	19	NWNW	104	16	5/22/1978	W	Suprabasalt
721	418021	FRANCISCO MENDOZA	9N30E	20	NWNE	600	6	9/2/2005	W	Basalt
722	252835	MATHESON PAINTING	9N30E	20	SE	78	0	5/2/2000	W	Suprabasalt
723	155863	LEE MUDD	9N30E	20		85	6	4/2/1959	W	Suprabasalt
724	156161	LYLE H. CLOSE	9N30E	20		86	6	9/1/1956	W	Suprabasalt
725	157128	NORTHERN PACIFIC RAILWAY CO.	9N30E	20	SWNW	88	6	1/1/1925	W	Suprabasalt
726	189308	SPOKANE DETROIT DIESEL	9N30E	20	SWNE	90	6	10/22/1997	W	Suprabasalt
727	189309	SPOKANE DETROIT DIESEL	9N30E	20	SWNE	90	6	10/23/1997	W	Suprabasalt
728	189310	SPOKANE DETROIT DIESEL	9N30E	20	SWNE	90	6	10/24/1997	W	Suprabasalt
729	152829	FRONTIER MACHINERY INC.	9N30E	20	SENE	92	8	10/6/1969	W	Suprabasalt
730	153970	J. W. FANNING	9N30E	20	NWNE	95	6	3/19/1970	W	Suprabasalt
731	150701	CITY PASCO, CITY VIEW CEMETERY	9N30E	20	NESW	105	10	4/17/1974	W	Suprabasalt
732	155550	KING CITY TRUCK STOP	9N30E	20	NENE	105	6	4/6/1978	W	Suprabasalt
733	149234	AGUA DRILLING	9N30E	20	NENE	110		12/6/1977	W	Suprabasalt
734	158875	SEATTLE HARDWARE CO.	9N30E	20	NWSW	118	6	4/19/1948	W	Suprabasalt
735	183936	PASCO LANDFILL	9N30E	21		--	0	11/16/1990	W	--
736	137975	CITY OF KENNEWICK, WASH.	9N30E	21		46	0	<Null>	W	Suprabasalt
737	151639	DICK HOLMAN	9N30E	21	NENW	70	6	2/21/1977	W	Suprabasalt
738	157168	AGRI PACK INC.	9N30E	21	SESE	101.6	8	8/22/1995	W	Suprabasalt
739	253397	COLUMBIA BASIN L.L.C.	9N30E	21	SENE	111	8	5/12/1999	W	Suprabasalt
740	368601	PASCO SHOOL DIST	9N30E	21	NESW	118	6	6/3/2003	W	Suprabasalt
741	343522	PASCO SCHOOL DIST	9N30E	21	NWSE	119	8	8/16/2002	W	Suprabasalt
742	150824	COLUMBIA EAST PARTNERSHIP	9N30E	21	NENW	125	16	9/24/1970	W	Suprabasalt
743	161954	ANGELA/LARRY STERLING	9N30E	21	NENW	140	6	6/12/1996	W	Suprabasalt
744	183946	PASCO SANITARY LANDFILL	9N30E	22	NESW	91	2	4/8/1991	W	Suprabasalt
745	154789	JOE PALMAREZ	9N30E	22	NWSE	138.4	6	8/8/1979	W	Suprabasalt
746	153252	GILBERT MARQUEZ	9N30E	22	SESE	140	6	3/24/1983	W	Suprabasalt
747	864072	Middleton Six Sons Farms	9N30E	22	SESE	142	6	11/28/2012	W	Suprabasalt
748	439830	RICHARD AXELENDER	9N30E	22	SESE	145	6	9/6/1990	W	Suprabasalt
749	159673	TOMLINSON DAIRY FARMS, INC.	9N30E	22	NESW	145	16	7/1/1974	W	Suprabasalt
750	439833	MALON CUWGIL	9N30E	26	SESE	60	6	12/12/1992	W	Suprabasalt
751	159766	TRIPLE A FARMING CO.	9N30E	26	SESE	82.6	16	4/1/1994	W	Suprabasalt
752	150823	COLUMBIA EAST PARTNERSHIP	9N30E	26	NWSW	133	20	5/14/1970	W	Suprabasalt
753	158177	ROBERT ALDERSON	9N30E	26	SESW	137	8	7/18/1980	W	Suprabasalt
754	490698	RON JOHNSON	9N30E	27	NE	378	6	7/30/2007	W	Basalt
756	478229	FREEZE PACK INC	9N30E	27	SENE	401	6	4/30/2007	W	Basalt
757	498650	AGRI-PACK	9N30E	27	NE	420	8	10/22/2007	W	Basalt
758	149570	B P A FRANKLIN SUBSTATION PASCO	9N30E	27		650	12	12/29/1992	W	Basalt
759	292700	BPA FRANKLIN SUBSTATION	9N30E	27	SWNW	650	6	1/20/1993	W	Basalt
761	149319	ALDERSON	9N30E	27	NE	98	16	11/13/1975	W	Suprabasalt
762	439835	AL FOUNTAIN	9N30E	27	NENE	101	6	10/19/1990	W	Suprabasalt
763	173677	TRIPLE A FARMS INC	9N30E	27	SESE	106	16	10/31/1995	W	Suprabasalt
764	165571	DEVRIES DAIRY	9N30E	27	NW	111	16	4/19/1995	W	Suprabasalt
765	171495	PAUL SAVAGE	9N30E	27	SWNW	112	8	6/23/1978	W	Suprabasalt
766	543521	CARSON AG LLC	9N30E	27	SENE	113	12	4/29/2008	W	Suprabasalt
767	165523	DEPT. OF INTERIOR, BONNEVILLE	9N30E	27	NWSE	116	10	6/14/1951	W	Suprabasalt
768	163026	ALEXANDER BUXBAUM / RONALD	9N30E	27	SENE	120	8	1/8/1983	W	Suprabasalt
769	174293	WESTERN FARM SERVICE	9N30E	27	SENW	120	8	11/28/1982	W	Suprabasalt
770	166111	EARLE KAHL	9N30E	27	NWSW	121	6	7/1/1981	W	Suprabasalt
771	767247	CARRSON AG~ LLC	9N30E	27	SWNE	131	10	4/26/2011	W	Suprabasalt

Identification			Location			Well Construction				
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material
772	174158	WASHINGTON IDAHO LABORERS	9N30E	27	SESW	135	8	7/18/1980	W	Suprabasalt
773	368706	ED CAPERON	9N30E	27	SENW	140	6	2/21/2003	W	Suprabasalt
774	176663	SIMON LOPEZ	9N30E	27	NWSW	142	6	6/11/1998	W	Suprabasalt
775	164538	CITY OF PASCO	9N30E	28	NWSW	70	8	4/16/1985	W	Suprabasalt
776	173959	W. F MANN	9N30E	28	SWSE	78	8	6/24/1977	W	Suprabasalt
777	166840	FREEMAN JOHNSON	9N30E	28	SESE	81	8	7/1/1975	W	Suprabasalt
778	498719	HENRY/JULIET SPOONER	9N30E	28	NWNE	92	6	4/25/1972	W	Suprabasalt
779	409004	DON/BARBRA NORVELL	9N30E	28	NESE	93	6	4/17/2003	W	Suprabasalt
780	169586	KEYES & SCANLAN	9N30E	28	SENE	97	6	6/14/1980	W	Suprabasalt
781	164739	CLINT BUMGARNER - BONNIE BRAE	9N30E	28	NWSE	110	8	3/28/1960	W	Suprabasalt
782	164742	CLINTON BUMGARNER	9N30E	28	NWNW	110	8	9/18/1961	W	Suprabasalt
783	166344	ELMER RADA	9N30E	28	SWNE	110	8	6/14/1974	W	Suprabasalt
784	1644499	Joseph Rada	9N30E	28	SENE	115	8	10/9/2017	W	Suprabasalt
785	1746420	Doug Rada, Estate of	9N30E	28	SENE	117	6	3/27/2018	W	Suprabasalt
786	169550	KENNETH REISINGER	9N30E	28	SESE	119	8	7/15/1966	W	Suprabasalt
787	170018	LESLIE REISINGER	9N30E	28	SESE	119	8	12/15/1950	W	Suprabasalt
788	167847	HIDE AWAY MOTEL	9N30E	28	NWSE	125	6	6/24/1986	W	Suprabasalt
789	177875	BURLINGTON NORTHERN RAIL ROAD	9N30E	29	SWSE	20	2	5/9/1991	W	Suprabasalt
790	164539	CITY OF PASCO	9N30E	29	NENE	68	10	9/26/1995	W	Suprabasalt
791	439838	CITY OF PASCO	9N30E	29	NENE	86	8	8/12/1988	W	Suprabasalt
792	439837	PASCO SCHOOL DIST #1	9N30E	29	NENE	86.5	8	9/25/1997	W	Suprabasalt
793	294086	OUR LADY OF LOURDES HOSPITAL	9N30E	29	SWNW	168	8	1/1/1965	W	Suprabasalt
794	910369	Gooseridge Vinyards	9N30E	30	NENE	360	8	2/14/2014	W	Basalt
795	164541	CITY OF PASCO	9N30E	30	SW	64	8	12/11/1985	W	Suprabasalt
796	439841	SUN APT	9N30E	30	NENW	69	6	5/22/1986	W	Suprabasalt
797	434397	ROBERT HOUSER	9N30E	30		93	6	5/25/1990	W	Suprabasalt
798	171341	PASCO SCHOOL DIST. #1	9N30E	30	NESW	100	10	5/19/1978	W	Suprabasalt
799	315897	BOB PUTNAM	9N30E	30	NENE	107	6	10/24/2001	W	Suprabasalt
800	164283	CHARLES BAGLELY	9N30E	30	NWSE	140	6	12/1/1975	W	Suprabasalt
801	148432	BRAD WINDSOR	9N30E	31	NWNW	265	6	12/25/1996	W	Basalt
802	188980	CITY OF PASCO PUBLIC WORKS	9N30E	31	SWNE	17	6	11/12/1997	W	Suprabasalt
803	164542	CITY OF PASCO	9N30E	31	NENW	20	10	12/13/1974	W	Suprabasalt
804	188979	CITY OF PASCO PUBLIC WORKS	9N30E	31	SWNE	40	6	11/11/1997	W	Suprabasalt
805	176132	SHARON SYKES	9N30E	31	NWNW	90	6	8/15/1997	W	Suprabasalt
806	656360	MIKE WHITE	9N30E	31	NENW	92	6	8/7/2003	W	Suprabasalt
807	358826	MIKE WHITE	9N30E	31	NWNE	97	6	2/3/2003	W	Suprabasalt
808	358825	MIKE WHITE	9N30E	31	NENW	97	6	2/3/2003	W	Suprabasalt
809	171881	RAY PORTER	9N30E	31	SENE	110	6	8/25/1993	W	Suprabasalt
810	171667	PORT OF PASCO	9N30E	33	SWSE	26	20	3/8/1971	W	Suprabasalt
811	168930	JOEL G. STORY	9N30E	33	NENW	58	12	3/10/1975	W	Suprabasalt
813	173851	VERNON RICKORDS	9N30E	34	SWSE	89	10	3/1/1967	W	Suprabasalt
814	169706	LAKEVIEW MOBILE HOME PARK	9N30E	34	SWSE	96	12	7/10/1973	W	Suprabasalt
815	439842	GARY OSBORN	9N30E	34	NENW	97.4	6	11/19/1990	W	Suprabasalt
816	162900	AAA DAVING CO.	9N30E	34	NWNW	100	6	4/11/1978	W	Suprabasalt
817	173850	VERNON RICKORDS	9N30E	34	SWSE	100	10	3/1/1967	W	Suprabasalt
818	173239	SULLVAN & PEDERSON ENTERPRISES	9N30E	34	NENE	109	6	4/12/1978	W	Suprabasalt
819	164797	COLUMBIA EAST	9N30E	34	SWNE	115	16	1/24/1972	W	Suprabasalt
820	185672	TEXECO SNAKERIVER TERMINAL	9N30E	35	NENE	39	12	9/11/1992	W	Suprabasalt
821	173735	U. S. E. L. (HOOD PARK)	9N30E	35		56	12	8/4/1975	W	Suprabasalt
822	173449	TIDEWATAER SHAVER PARGE LINES	9N30E	35		115	10	12/19/1952	W	Suprabasalt
823	416259	DAVE ROMM	9N30E	36	NWNW	252	6	8/17/2005	W	Basalt
824	468090	ALAN ROMM	9N30E	36	NWNW	260	6	2/3/2007	W	Basalt
825	174371	WILLIAM BROWN	9N30E	36	SWNW	47	6	7/3/1962	W	Suprabasalt
826	171541	PERRY DRAKE	9N30E	36	NWNW	80	6	6/22/1976	W	Suprabasalt
827	164429	CHRIS AKERBLADE	9N30E	36	SWNW	83	6	7/8/1985	W	Suprabasalt
828	842531	Hugh McEachen II	9N30E	36	NWNW	92	2	3/9/2012	W	Suprabasalt
829	159827	U. S. BUREAU OF RECLAMATION	10N29E	31	SESE	313	8	1/21/1948	W	Basalt
830	254224	KURT BAIR	10N29E	31	SE	240	6	6/8/1999	W	Suprabasalt
831	156359	MARK SULLIVAN	10N29E	31	NESE	290	6	11/4/1997	W	Suprabasalt
832	154923	JOHN DOUGLAS	10N29E	33	SESW	325	12	2/10/1983	W	Basalt
833	768596	Balcom & Moe	10N30E	31	NESW	140	6	5/22/2011	W	Suprabasalt
834	339502	BURLINGTON NORTHERN	10N30E	31	SWSW	143.6	16	12/11/1981	W	Suprabasalt
835	339503	BURLINTON NORTHERN	10N30E	31	SWSE	170	16	1/4/1982	W	Suprabasalt
836	155892	LENTZ	10N30E	32	SESW	192	16	10/10/1975	W	Suprabasalt
837	155893	LENTZ FARMS	10N30E	32	NESW	222	6	3/11/1975	W	Suprabasalt
838	151707	DON BUES	10N30E	33	SWSW	221	16	3/11/1978	W	Suprabasalt
839	151708	DON BUES	10N30E	33	SWSW	223	16	7/13/1977	W	Suprabasalt
840	151709	DON BUES	10N30E	33	SWSW	229	8	6/22/1977	W	Suprabasalt
665/E24	172416	ROBERT TIPPETT	9N30E	6	SWSE	154	6	6/16/1977	W	Suprabasalt
755/E34	439836	BILL ROBINSON	9N30E	27	SW	384	6	3/26/1990	W	Basalt
760/E33	169445	KEN CREEK	9N30E	27	SENE	93	6	3/22/1977	W	Suprabasalt
812/E34	164799	COLUMBIA EAST PARTNERSHIP	9N30E	33	SENE	101	16	6/1/1973	W	Suprabasalt

Identification			Location			Well Construction					
Map ID	Well Log ID	Well Owner	Township Range	Section	Quarter-quarter Section	Total Depth (ft)	Well Diameter	Well Completion Date	Well Type	Aquifer Material

Notes:

Aquifer material determinded based on total depth and top of basalt isopach depths (Tolan et al., 2007).
"0" indicates no well depth no infer aquifer material
W = Water Well
-- = Not available

Table 2 - General Well Construction Information (EIM)

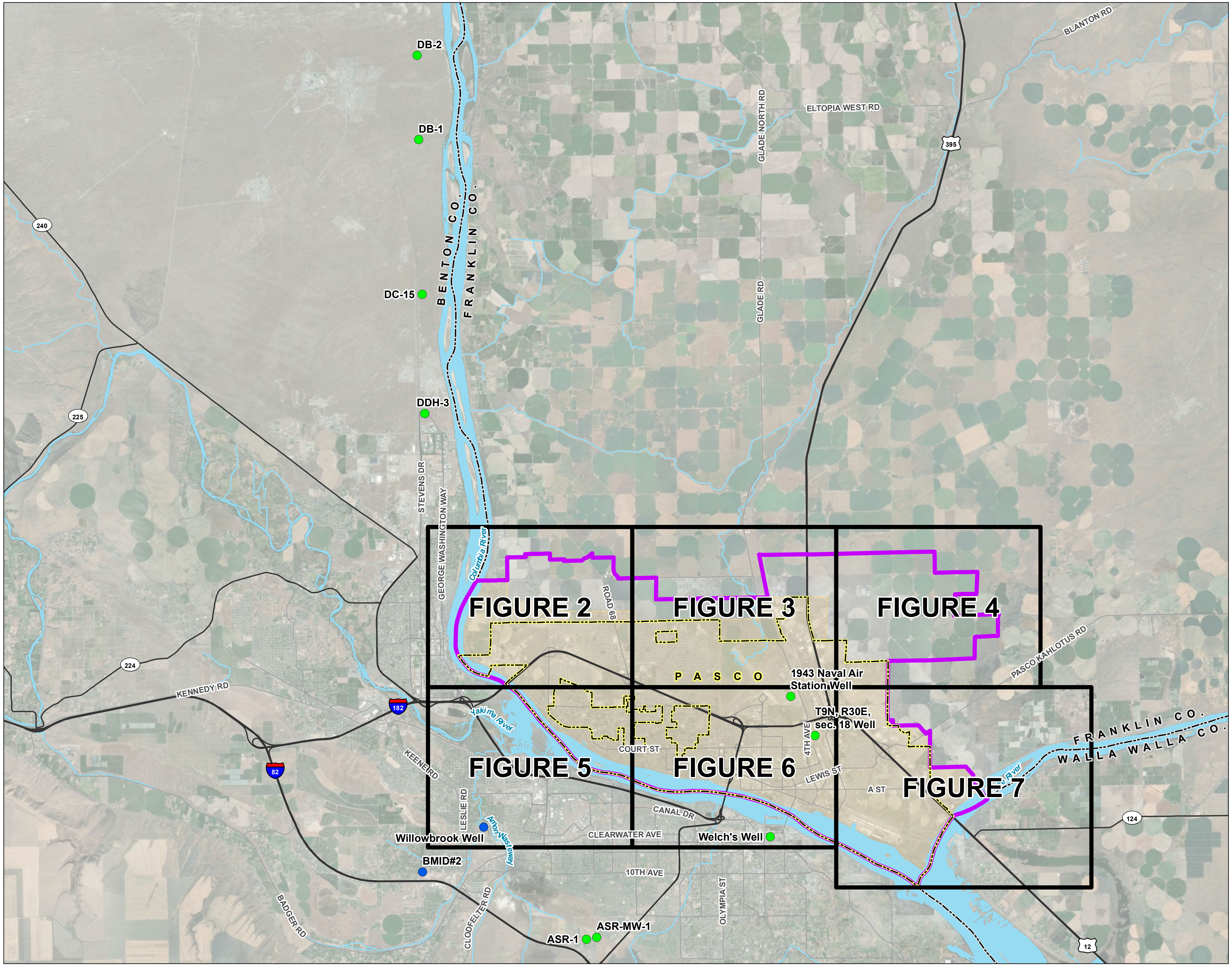
Identification		Well Construction and Use			
Map ID	Location ID	Total Depth (ft)	Aquifer Material	Well Use	Well Completion Date
E1	FCD202	0	--	Water Supply Well - Domestic	--
E2	FCD238	0	--	Water Supply Well - Domestic	--
E3	G1675	201	Suprabasalt	Irrigation Well	12/1/1975
E4	FCD204	0	--	Water Supply Well - Domestic	--
E5	FCD39	0	--	Irrigation Well	--
E6	FCD205	0	--	Water Supply Well - Domestic	--
E7	FCD60	0	--	Water Supply Well - Domestic	--
E8	FCD72	0	--	Water Supply Well - Domestic	--
E9	FCD103	0	--	Water Supply Well - Domestic	--
E10	FCD93	0	--	Water Supply Well - Domestic	--
E11	FCD91	0	--	Water Supply Well - Domestic	--
E12	FCD92	0	--	Water Supply Well - Domestic	--
E13	FCD 207	0	--	Water Supply Well - Domestic	--
E14	FCD206	0	--	Water Supply Well - Domestic	--
E15	FCD41	0	--	Water Supply Well - Domestic	--
E16	G0566	159	Suprabasalt	Irrigation Well	10/10/1974
E17	FCD55	0	--	Water Supply Well - Domestic	--
E18	FCD49	0	--	Water Supply Well - Domestic	--
E19	FCD54	0	--	Water Supply Well - Domestic	--
E20	G0637	228	Suprabasalt	Irrigation Well	5/9/1977
E21	G0629	242	Suprabasalt	Irrigation Well	11/18/1977
E22	G0591	230	Suprabasalt	Irrigation Well	12/20/1973
E23	FCD261	0	--	Water Supply Well - Domestic	--
665/E24	G2156	154	Suprabasalt	Water Supply Well - Domestic	6/6/1977
E25	FCD208	0	--	Water Supply Well - Domestic	--
E26	G0537	165	Suprabasalt	Irrigation Well	11/15/1976
E27	G0569	154	Suprabasalt	Irrigation Well	12/17/1975
E28	G0534	105	Suprabasalt	Irrigation Well	4/14/1974

Table 2 - General Well Construction Information (EIM)

Identification		Well Construction and Use			
Map ID	Location ID	Total Depth (ft)	Aquifer Material	Well Use	Well Completion Date
E29	FCD44	0	--	Water Supply Well - Domestic	--
E30	FCD223	0	--	Water Supply Well - Domestic	--
E31	FCD260	0	--	Water Supply Well - Domestic	--
755/E32	G0590	384	Basalt	Water Supply Well - Public	3/26/1990
760/E33	G0531	93	Suprabasalt	Water Supply Well - Domestic	3/17/1977
812/E34	G0578	101	Suprabasalt	Irrigation Well	5/1/1973

Attachment B

Figures 1 – 7



ATTACHMENT B
FIGURE 1
Well Log Inventory
Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND
- ● Additional Basalt Well
- ● Well From Tolan, 2020, Attachment A
- ☐ Figure Index
- ☐ Study Area
- ☐ City of Pasco
- ▨ Urban Growth Boundary
- Major Road
- Watercourse
- Waterbody

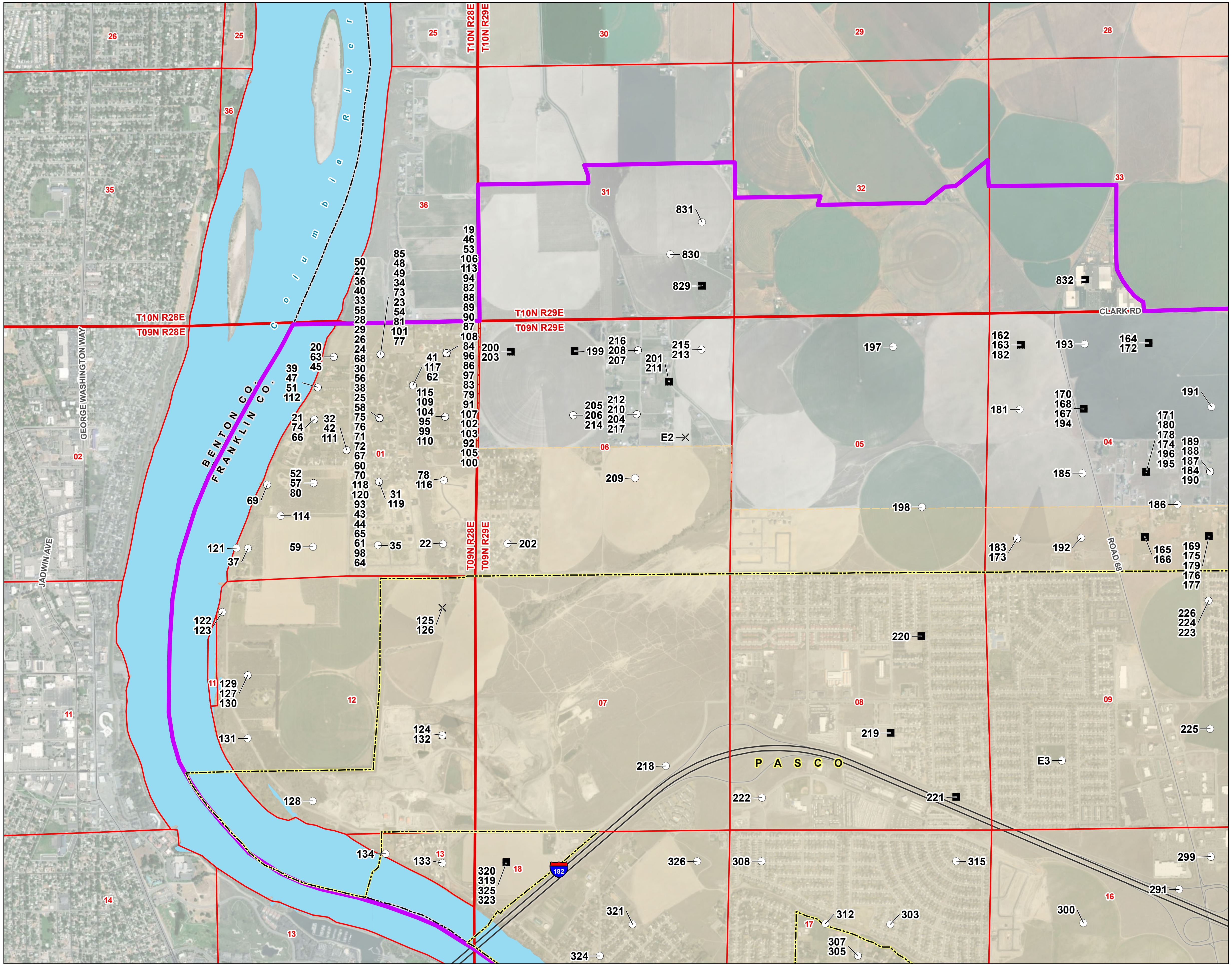
N

0 6,000 12,000
Feet

Date: December 10, 2020
Data Sources: City of Pasco

GSI Water Solutions, Inc.

Document Path: Y:\0880_City_of_Pasco\Source_Figures\FigureX_Well_Locations_DDP_Index.mxd, wkimmon



ATTACHMENT B
FIGURE 2
Well Log Inventory

Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND

- ▭ Study Area

Well

- ■ Basalt
- ○ Suprabasalt
- × Undetermined

All other Features

- ⬚ City of Pasco
- ▭ Urban Growth Boundary
- ╱╲ Major Road
- ～ Watercourse
- ▰ Waterbody

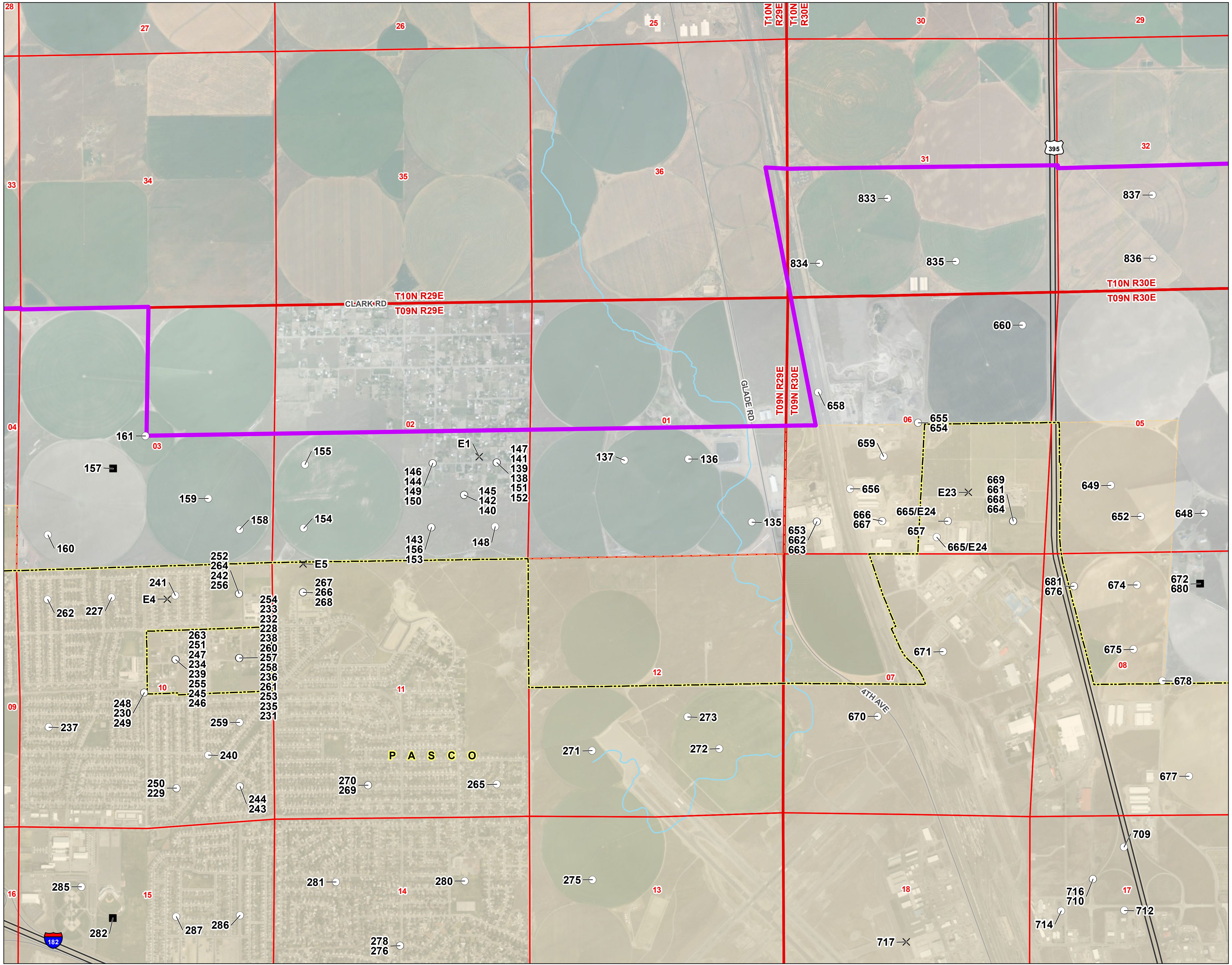
N

0 1,000 2,000 3,000
Feet

Date: December 10, 2020
Data Sources:

GSI Water Solutions, Inc.

Document Path: Y:\0880_City_of_Pasco\Source_Figures\FigureX_Well_Locations_DDP.mxd, wkimmon



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ATTACHMENT B
FIGURE 3
Well Log Inventory

Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND

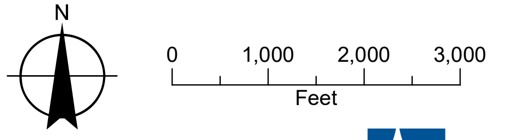
▭	Study Area

Well

■	Basalt
○	Suprabasalt
×	Undetermined

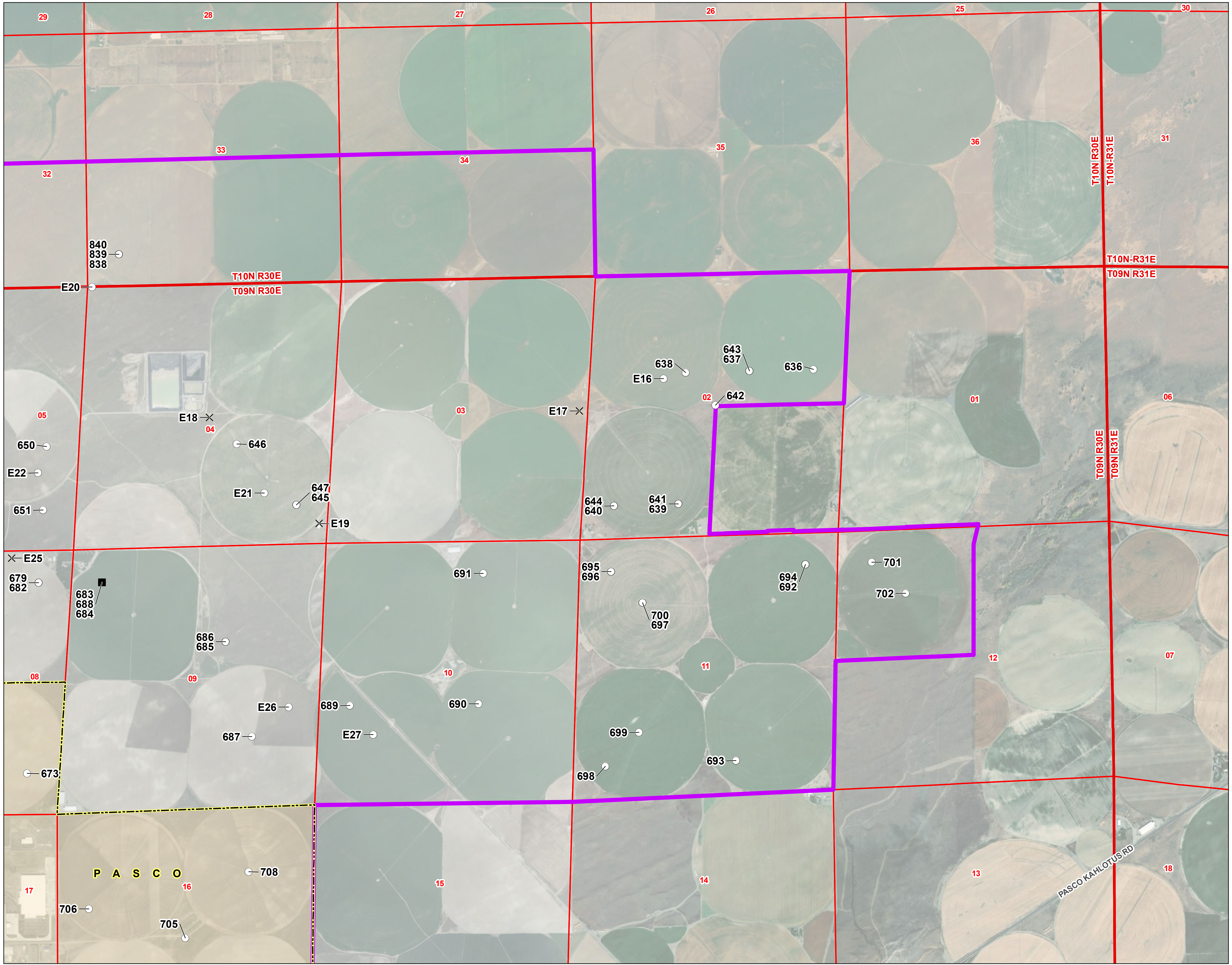
All other Features

⬚	City of Pasco
▭	Urban Growth Boundary
╱╲	Major Road
∼	Watercourse
▰	Waterbody



Date: December 10, 2020
Data Sources:

Water Solutions, Inc.



ATTACHMENT B
FIGURE 4
Well Log Inventory

Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND

Study Area

Well

- ■ Basalt
- ○ Suprabasalt
- × Undetermined

All other Features

- City of Pasco
- Urban Growth Boundary
- Major Road
- Watercourse
- Waterbody

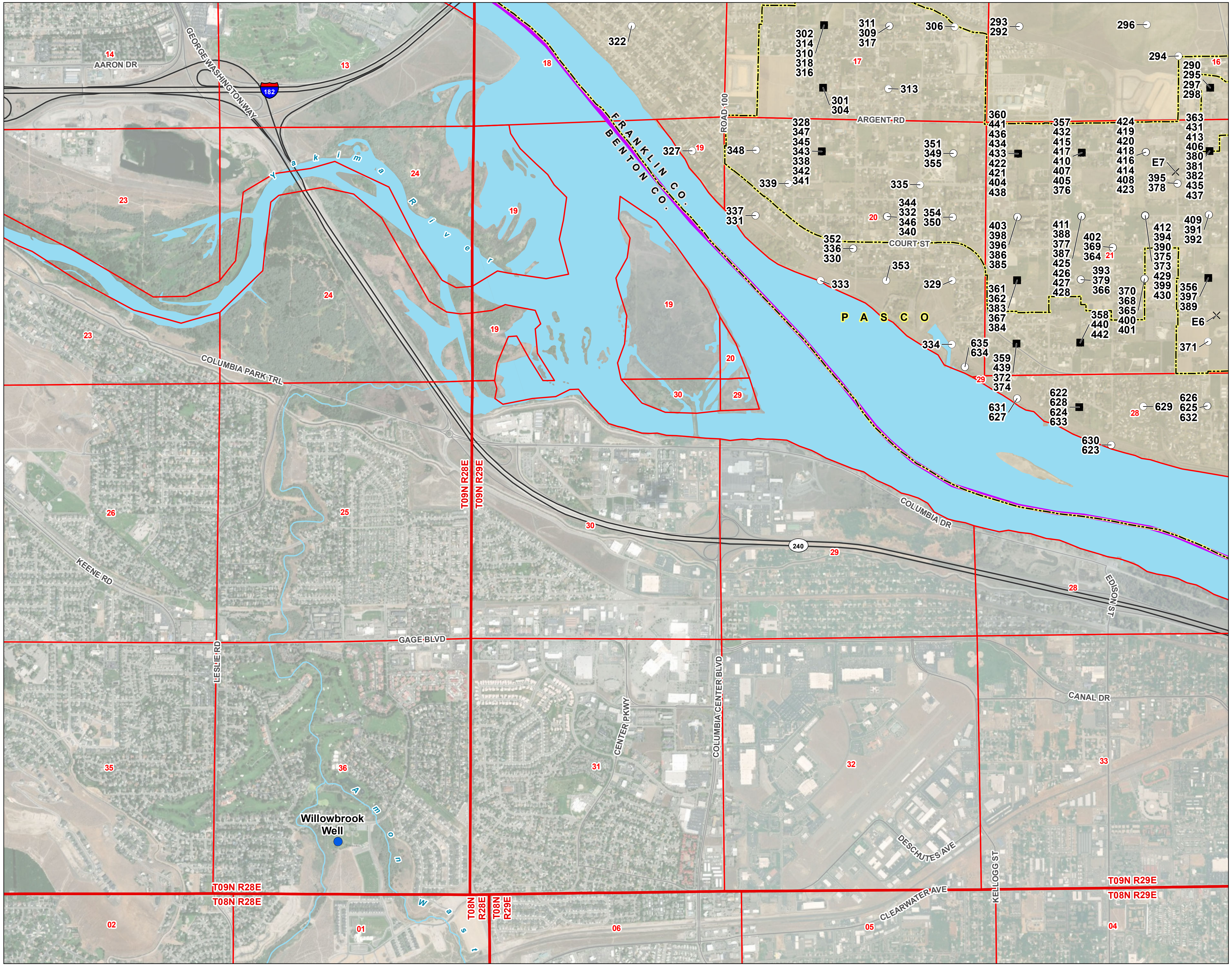
N

0 1,000 2,000 3,000
Feet

Date: December 10, 2020
Data Sources:

GSI Water Solutions, Inc.

Document Path: Y:\0880_City_of_Pasco\Source_Figures\FigureX_Well_Locations_DDP.mxd, wkimmon



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ATTACHMENT B
FIGURE 5

Well Log Inventory

Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND

- ▭ Study Area

Well

- ■ Basalt
- ○ Suprabasalt
- × Undetermined
- ● Additional Basalt Well

All other Features

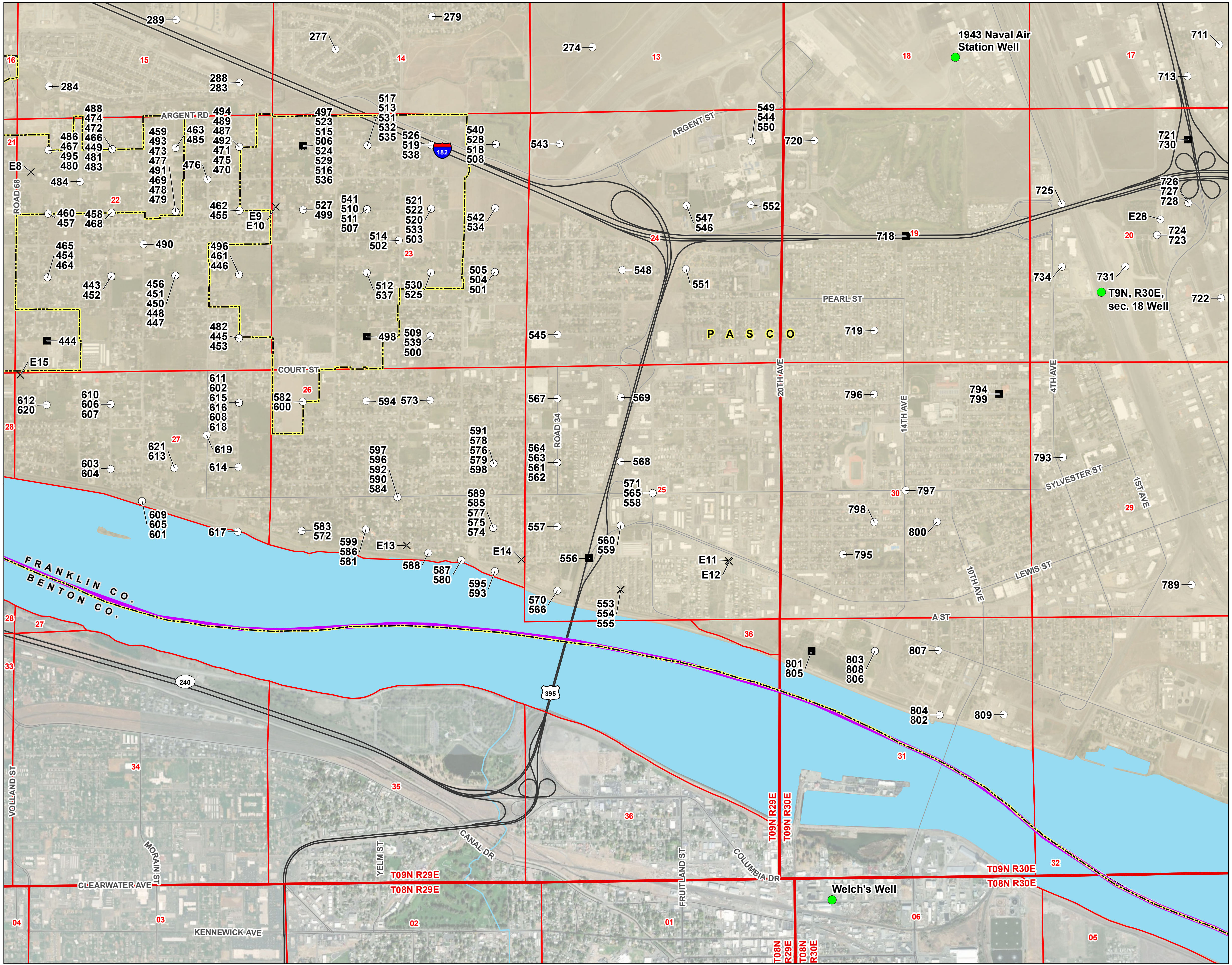
- ⬚ City of Pasco
- ▭ Urban Growth Boundary
- ╱╲ Major Road
- ∼ Watercourse
- ▨ Waterbody

N

0 1,000 2,000 3,000
Feet

Date: December 10, 2020
Data Sources:

GSI Water Solutions, Inc.



ATTACHMENT B
FIGURE 6
Well Log Inventory

Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND

- ▭ Study Area

Well

- ■ Basalt
- ○ Suprabasalt
- ✕ Undetermined
- ● Well From Tolan, 2020, Attachment A

All other Features

- ⬚ City of Pasco
- ▭ Urban Growth Boundary
- ╱╲ Major Road
- ∼ Watercourse
- ▨ Waterbody

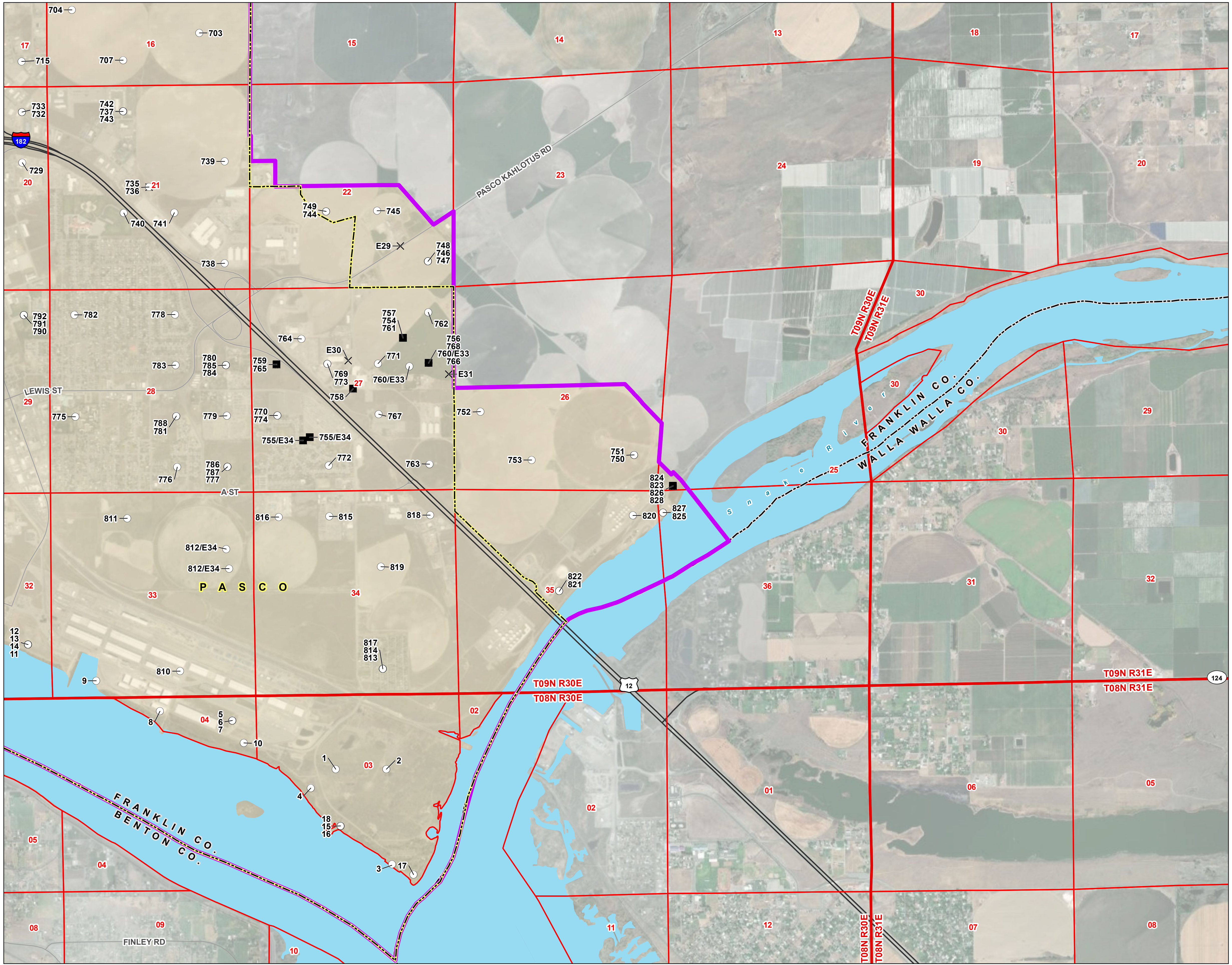
N

0 1,000 2,000 3,000
Feet

GSI Water Solutions, Inc.

Date: December 10, 2020
Data Sources:

Document Path: Y:\0880_City_of_Pasco\Source_Figures\FigureX_Well_Locations_DDP.mxd, wkimmon



ATTACHMENT B
FIGURE 7

Well Log Inventory

Hydrogeologic Feasibility Assessment,
Aquifer Storage and Recovery
Feasibility Study,
City of Pasco, Washington

LEGEND

▭ Study Area

Well

■ Basalt

○ Suprabasalt

× Undetermined

All other Features

⬚ City of Pasco

▭ Urban Growth Boundary

Major Road

Watercourse

Waterbody

N

0 1,000 2,000 3,000
Feet

GSI Water Solutions, Inc.

Date: December 10, 2020
Data Sources:

Document Path: Y:\0880_City_of_Pasco\Source_Figures\FigureX_Well_Locations_DDP.mxd, wkimmon

Attachment C

Pasco Aquifer Storage and Recovery Feasibility Assessment – Task 2 Groundwater Quality. By Golder Associates, Inc.

GOLDER

TECHNICAL MEMORANDUM

DATE December 11, 2020 **Project No.** 20147623

TO Kenny Janssen, RG
GSI Water Solutions, Inc.

CC

FROM Michael Klisch, Derek Holom, and Cheryl Ross **EMAIL dholom@golder.com**

PASCO AQUIFER STORAGE AND RECOVERY FEASIBILITY ASSESSMENT – TASK 2 GROUNDWATER QUALITY

This Technical Memorandum provides a summary of water quality characteristics, particularly redox and/or pH-sensitive parameters, of the Columbia River Basalt Group relevant to operation of an Aquifer Storage and Recovery (ASR) system. This Technical Memorandum is structured as a stand-alone document for inclusion in GSI Water Solutions Inc. (GSI) Pasco ASR Feasibility Study:

1.0 GROUNDWATER QUALITY

Understanding water quality dynamics is essential to evaluating the technical feasibility of an ASR program as well as showing compliance with regulatory requirements. A primary objective of the Pasco ASR feasibility study is to evaluate the potential for water quality changes to stored recharge water and/or native groundwater. This section presents groundwater quality characteristics for the Saddle Mountain and Wanapum basalts based on review of the regional and local water quality data and reports described below.

- Regional data obtained from published studies by Steinkampf of the United States Geological Survey (USGS) and others (Steinkampf 1989; GWMA 2009).
- Local data from ASR feasibility studies for the Willowbrook and Kennewick ASR-1 wells, which are both completed in the Wanapum basalt (Golder 2001 and 2012). Operational ASR data are also available for ASR-1 (GSI 2020). The Willowbrook ASR feasibility study includes water quality data for eight private domestic wells completed in the upper Saddle Mountain (seven wells) and Wanapum (one well) basalts.

1.1 Water Quality Characteristics of the Saddle Mountain Formation Aquifers

Groundwater quality can be classified based on its major ion composition. According to Steinkampf (1989), Saddle Mountain formation groundwater is most commonly classified as calcium-magnesium bicarbonate type, followed by sodium-bicarbonate type. Groundwater with sodium as its dominant cation generally occurs downgradient in the Columbia Plateau close to the Columbia River and in deeper wells (i.e. at depths greater than 400 feet below ground surface [bgs]). Calcium-magnesium-bicarbonate type water generally occurs in upgradient areas and relatively shallow wells (i.e. less than 400 feet bgs). Calcium-magnesium-sulfate-chloride type water also occurs in the Saddle Mountain basalts, typically in areas with thin overburden coverage and in relatively shallow wells (interpreted by Steinkampf (1989) to be indicative of recently recharged water). Water quality data for the Saddle Mountain basalt units from Steinkampf (1989) is summarized in Table 1. Reported groundwater pH values ranged from circum-neutral to alkaline (7.0 to 8.7). Specific conductance values demonstrated a large range from 175 to almost 1,500 microSiemens per centimeter (µS/cm). The average nitrate (+nitrite) concentration in wells was approximately 5 milligrams per liter as nitrogen (mg/L-N). Groundwater nitrate concentrations above 2 mg/L-N are indicative of anthropogenic influence (Steinkampf 1989). Elevated nitrate occurs in the shallow Saddle Mountain basalt wells and is likely attributed to impacts from agriculture.

Water quality samples were collected from seven private domestic wells completed in the Saddle Mountain Formation as part of the Willowbrook ASR feasibility study (Golder 2001). Groundwater quality data from these wells are summarized in Table 2. This data set provides groundwater concentrations for some metals which were not included in the USGS study (Steinkampf 1989). Groundwater samples reported circum-neutral pH values, alkalinity concentrations of approximately 120 to 180 mg/L (as $CaCO_3$) and dissolved oxygen concentrations ranging from approximately 1.0 to 10 mg/L. Nitrate was detected in all but one well at concentrations up to 10 mg/L-N. The presence of dissolved oxygen and nitrate is indicative of oxidized groundwater conditions. Reported pH, alkalinity, dissolved oxygen and nitrate values, as well as major ion concentrations, were all within the ranges for Saddle Mountain basalt reported by the USGS (Table 1). Low levels of iron (up to 0.3 mg/L), manganese (up to 0.09 mg/L) and selenium (up to 0.007 mg/L) were detected in some wells. Groundwater quality at all wells met the primary drinking water standards for all monitored constituents (i.e. all constituent concentrations were less than their respective maximum contaminant levels [MCLs] per Washington Administrative Code [WAC] 246-290-310). Iron and manganese concentrations each exceeded secondary drinking water standards (SMCLs) in one well.

1.2 Water Quality Characteristics of the Wanapum Formation

Water quality data for the Wanapum basalt units from Steinkampf (1989) is summarized in Table 1. Similar to the Saddle Mountain basalts, Wanapum basalt groundwater is most often classified as calcium-magnesium bicarbonate, followed by sodium-bicarbonate; where sodium-bicarbonate is the dominate water type in downgradient (i.e. further along a groundwater flow path) and deeper wells (i.e. deeper than 800 feet bgs) (Steinkampf 1989). Total dissolved solids (TDS) concentrations range from approximately 70 to 1,100 mg/L with a mean of 270 mg/L. Areas with higher TDS concentrations in the Wanapum basalts correlate with areas where there is an upward hydraulic gradient from the lower Grande Ronde aquifer system, particularly in the vicinity of the Pasco Basin (Steinkampf 1989). In comparison to the Saddle Mountain basalt wells, the Wanapum basalt wells report a larger range in pH values (i.e. from approximately 6 to 9 s.u.). Mean reported concentrations for measured constituents were generally similar between the Saddle Mountain and Wanapum basalt wells.

A water quality sample was collected from one private domestic well (BMID#2) completed in the Wanapum Formation as part of the Willowbrook ASR feasibility study (Golder 2001) (Table 2). Reported concentrations were within the ranges reported by the USGS (Table 1). Dissolved iron and manganese were both detected in this well and manganese exceeded the SMCL. The presence of iron and manganese, and a low concentration of dissolved oxygen, is likely indicative of reducing conditions.

Groundwater quality data from nearby ASR feasibility studies, as well as the operational Kennewick ASR system, are likely indicative of Wanapum Formation groundwater quality in the Pasco Basin. Data are available for the following wells:

- Kennewick ASR-1 and ASR-MW-1 (Golder 2012; GSI 2020) located approximately 7 miles to the south of Pasco. ASR-1 and ASR-MW-1 are completed in the Priest Rapids and Frenchman Springs Members of the Wanapum Formation at depths of 1,178 and 1,165 feet bgs, respectively. Well ASR-1 has been operational since July 2014 (start of ASR Cycle 01).
- The Willowbrook Well (Golder 2001) located in south Richland approximately 8 miles to the southwest of Pasco. The Willowbrook Well is completed to a depth of 1,208 feet bgs in the Priest Rapids Member of the Wanapum.

Table 3 is a summary of native background water quality for ASR-1 and ASR-MW-1, and a summary of the range in recovered water quality (i.e. maximum and minimum concentrations) of ASR cycles 01 through 06 (combined water quality from ASR-1 and ASR-MW-1) (GSI 2020). Water quality data for the Willowbrook Well are summarized in Table 4. Groundwater quality meets all the primary and secondary drinking water standards (per WAC 246-290-310) in the wells. Low levels of manganese (0.079 mg/L) have been detected above the SMCL (0.05 mg/L) in the BMID#2 well (Table 2) and sodium has been detected above the Washington state advisory limit of 20 mg/L in all of the Wanapum wells sampled during these ASR studies, with an overall range of about 22 to 93 mg/L (see Tables 2, 3, and 4).

The background groundwater based on data from ASR-1 and ASR-MW-1, which are completed in the Priest Rapids and Frenchman Springs members of the Wanapum aquifer, is categorized as a sodium-bicarbonate water type. The Willowbrook and BMID #2 wells, which are completed in the Priest Rapids member, was observed to be a bicarbonate-type water with more of calcium-sodium type cation ratio, based on data water quality data from the ASR feasibility study (Golder 2001).

Groundwater pH is circum-neutral with a range of 7.3 to 8.0 standard units (s.u.). Groundwater temperatures were elevated in Kennewick ASR-1,Willowbrook Well, and BMID#2 with a range of 24 to 28 °C (75.2 to 82.4 °F). Redox conditions are anoxic, as indicated by low dissolved oxygen, measurable iron, manganese, and sulfide, low concentrations of nitrate and sulfate, and the presence of methane. Background native groundwater is low to moderately alkaline, with a range in alkalinity as calcium carbonate ($CaCO_3$) of about 70 to 200 mg/L (Golder 2001; Golder 2012; GSI, 2020). Dissolved concentrations of methane were postulated by GWMA as related to thermogenic sources, likely generated from sedimentary rocks buried deep beneath the CRBGs and occurring along the trace of the Cold Creek Fault in the northwestern area of the Pasco Basin (GWMA 2009).

Aquifer solids from drill cuttings in the storage zones for ASR-1 were analyzed for geochemical composition as part of a source water compatibility study (Golder 2012). In ASR-1, the presence of pyrite (up to approximately 3 percent) was detected. Geochemical modeling predicted a change in the redox state of the groundwater from reducing to oxidizing, resulting in the oxidation of pyrite and precipitation of iron oxyhydroxide (ferrihydrite). Conservative mass balance calculations predicted the release of lead, molybdenum, and sulfur from the dissolution of pyrite and a minimal increase in arsenic (1 ug/L).

1.3 Data Gaps

There are no site-specific native groundwater quality data available for the proposed target storage zones in the Pasco area. Native groundwater quality in the Kennewick area can be variable with respect to water type and geochemical conditions but is within the regional range reported by Steinkampf (1989). We assume the native groundwater quality in the Saddle Mountain and Wanapum basalt units in the Pasco area will be similar to the groundwater quality in the Kennewick area, but a site-specific test well will be required to determine the compatibility of the native receiving groundwater with the proposed source water as part of the feasibility for an ASR system in Pasco.

1.4 Summary

Regional and local groundwater quality data available for review indicate groundwater characteristics of the Saddle Mountain and Wanapum aquifers are calcium-magnesium-bicarbonate to sodium-bicarbonate type waters, where the former is typically found in upgradient (in the Columbia Platuea), shallow wells and the latter is found in downgradient, deeper wells near the Columbia River. Groundwater quality is near-circum pH in the Wanapum and near-circum pH to alkaline in the Saddle Mountain formation. The Saddle Mountain wells generally have higher concentrations of dissolved oxygen and nitrates compared to the Wanapum wells, indicating oxidized groundwater conditions. In the Wanapum wells, the presence of iron, manganese, methane, and low levels of dissolved oxygen indicate reducing, anoxic groundwater conditions. Water temperatures are expected to be elevated in the Wanapum, based on previous observed ranges of 24 to 28 °C. Overall, drinking water quality standards are met for all primary and secondary constituents, with a few exceptions for iron and manganese that were detected slightly above their respective SMCLs. Sodium can also be expected above the state advisory level of 20 mg/L for both the Saddle Mountain and Wanapum basalts.

ASR pilot testing through six cycles in Kennewick ASR-1 have shown no adverse impacts of mixing of Columbia River source water with native basalt groundwater water. Given the relatively close proximity of Pasco to Kennewick, we anticipate the groundwater characteristics of the Saddle Mountain and Wanapum basalt aquifers in the Pasco Basin will be similar to the native groundwater conditions observed in Kennewick ASR-1, ASR-MW-1, and the Willowbrook Well (located approximately 7 to 8 miles from Pasco).

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Senior Project Hydrogeologist

C. Ross

Cheryl Ross, LHG (WA)
Principal Hydrogeochemist

DH/CR/

Distribution: GSI Water Solutions Inc.

https://golderassociates.sharepoint.com/sites/130627/project files/6 deliverables/task 2 - groundwater quality/final/20147623-tm-rev0-pasco asr task 2 gw quality.docx

LIST OF TABLES

REFERENCES

Columbia Basin Ground Water Management Area (GWMA). 2009. Groundwater Geochemistry of the Columbia River Basalt Group Aquifer System: Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties. June.

Golder Associates Inc. (Golder). 2001. Hydrogeologic Feasibility for Aquifer Storage and Recovery at the Willowbrook Well. Report prepared for City of Kennewick. Project no. 003-1146.004. November 19.

Golder. 2012. City of Kennewick ASR Feasibility Study: Phase 2 Technical Report prepared for City of Kennewick. Project no. 083-99742.003. September 21.

GSI Water Solutions Inc. (GSI). 2020. City of Kennewick ASR Year 6 Pilot Testing Summary Report, ASR Cycle O6 Testing – 2019 Operations. February 2020. Prepared by GSI Water Solutions, Inc.

Steinkampf, W.C. 1989. Water-Quality Characteristics of the Columbia Plateau Regional Aquifer System in Parts of Washington, Oregon, and Idaho. United States Geological Survey. Water-Resources Investigations Report 87-4242.

Tables

Table 1: Summary of USGS Regional Columbia River Basalt Groundwater Quality (Steinkampf 1989)

Analyte	Units	Drinking Water MCL/SMCL (WAC 246-290-310)	Saddle Mountain Basalt[1]			Wanapum Basalt[2]		
			Maximum	Minimum	Mean	Maximum	Minimum	Mean
pH	s.u.	6.5 to 8.5 (SMCL)	8.7	7.0	7.7	9.4	6.1	7.4
Specific Conductance	µS/cm	700 (SMCL)	1,460	175	498	1,970	102	403
Temperature	°C		26	8.6	18	43	6.2	16
Dissolved Oxygen	mg/L		10	0.1	4.5	11	0.1	5.2
Calculated Total Dissolved Solids	mg/L	500	890	140	340	1,100	69	270
Calcium	mg/L		98	1.9	38	180	0.8	33
Magnesium	mg/L		62	0.3	19	75	0.1	15
Sodium	mg/L	20 (advisory level)	100	7.3	35	130	2.4	28
Potassium	mg/L		13	1.5	6.9	22	0.9	4.9
Bicarbonate	mg/L		392	108	195	406	53	178
Sulfate	mg/L	250 (SMCL)	490	0.2	53	290	0.2	29
Chloride	mg/L	250	130	1.3	24	300	7	17
Fluoride	mg/L	2 (MCL) / 4 (SMCL)	2.9	0.2	0.6	3.4	0.1	0.5
Nitrate+Nitrite	mg/L as N	10 (nitrate) / 1 (nitrite)	54	0.1	4.8	35	0.1	3.7
Iron	mg/L	0.3 (SMCL)	0.8	0.003	0.03	1.1	0.003	0.03
Silica as SiO_2	mg/L		72	36	56	100	10	48

Notes:
Shaded cells identify exceedances of applicable MCL, SMCL, or advisory level (sodium)
1. Saddle Mountains Basalt - 131 samples
2. Wanapum Basalt - 410 samples
°C - degree Celcius
mg/L - milligrams per liter
µS/cm - microSiemens per centimeter
MCL - maximum contaminant level
N - nitrogen
s.u. - standard units of pH
SMCL - secondary maximum contaminant level
Source: Steinkampf (1989)

Table 2: Summary of Private Domestic Well Water Quality from Willowbrook ASR Study (Golder 2001)

Analyte	Units	PQL	Drinking Water MCL/SMCL WAC 246-290-310	SDLM		SDLM		SDLM		SDLM		SDLM		SDLM		SDLM		WPR	
				Pratt		Michel		Bettinghouse		Kid#3		Powers		Westcoast		Maxfield		BMID#2	
		(mg/L)		9/20/00	Q	9/20/00	Q	9/20/00	Q	9/20/00	Q	9/20/00	Q	9/19/00	Q	10/2/00	Q	9/18/00	Q
pH	s.u.	-	6.5 to 8.5 (SMCL)	7.62		7.27		7.47		7.66		7.66		7.55		7.33		7.65	
Eh	mV	-		393		359		360		349		350		411		367		319	
Conductivity	µS/cm	-	700 (SMCL)	172		196		492		469		304		294		430		214	
Temperature	^{o}C	-		13		17		16		17		18		21		17		24	
Dissolved Oxygen	mg/L	-		9.0		4.5		9.5	J	5.4		2.2		1.1		7.2		0.2	
Turbidity	NTU	-		0.1		0.2		0.3		0.2		2.4		3.6		0.3		0.3	
Calcium	mg/L	0.5		45		27		78		91		31		24		78		28	
Magnesium	mg/L	0.5		29		12		47		40		32		13		50		8.1	
Sodium	mg/L	2.5	20 (advisory level)	18		18		66		56		21		35		31		62	
Potassium	mg/L	5		ND		ND		9.3	J	6.9	J	7.6	J	10	J	9.1		16	
Alkalinity	mg/L as CaCO$_3$	-		159		116		172		164		142		181		183		166	
Sulfate	mg/L	0.3	250 (SMCL)	66	J	27	J	230	J	210	J	45	J	13		130		78	
Chloride	mg/L	0.3	250	22		10		68		68		9.7		12		71		7.6	
Fluoride	mg/L	0.06	2 (MCL) / 4 (SMCL)	0.29		0.32		0.44		0.34		0.56		0.32		0.43		0.51	
Ammonia	mg/L as N	0.04		ND		ND		ND		ND		ND		ND		ND		ND	
Nitrate	mg/L as N	0.03	10	3.5		1.1		6.8		9.8		2.1		ND		7.0		ND	
Boron	mg/L	0.5		ND		ND		ND		ND		ND		ND		ND		ND	
Bromide	mg/L	0.03		0.16		0.08		0.52		0.52		0.08		0.10		0.20		0.07	
Iron	mg/L	0.1	0.3 (SMCL)	ND		ND		ND		ND		0.33		ND		ND		0.18	
Manganese	mg/L	0.005	0.05 (SMCL)	ND		ND		ND		ND		0.014		0.091		ND		0.079	
Selenium	mg/L	0.003	0.05	ND		ND		0.007		0.004		ND		ND		ND		ND	

Notes:

Unit of well completion:

- SDLM - Saddle Mountains
- WPR - Wanapum Basalt, Priest Rapids Member

PQL - practical quantitation limit
ND - not detected
Q - laboratory qualifier
J - estimated value
Shaded cells identify exceedances of applicable MCL, SMCL, or advisory level (sodium)
°C - degree Celcius
CaCO$_3$ - calcium carbonate
mg/L - milligrams per liter
µg/L - micrograms per liter
µS/cm - microSiemens per centimeter
MCL - maximum contaminant level
mV - millivolts
N - nitrogen
ND - non detect
NTU - Nepthelometric turbidity units
SMCL - secondary maximum contaminant level
s.u. - standard units of pH
T.O.N. - threshold odor number
Source: Golder (2001)

Table 3: Summary of Kennewick ASR-1 and ASR-MW-1 Water Quality Data (GSI 2020)

Analyte Group / Analyte	Units	Groundwater (WAC 173-200-040)	Drinking Water MCL/SMCL (WAC 246-290-310)	RL	Native Groundwater			ASR Cycles 01 - 06 (ASR-1 and ASR-MW-1)	
					ASR-1 (Initial Testing)	ASR-1 (pre-ASR)	ASR-MW-1 (pre-ASR)		
					Result	Result	Result	Maximum	Minimum
FIELD PARAMETERS									
pH (field)	s.u.	6.5 to 8.5	6.5 to 8.5 (SMCL)	--	8.0	8.0	7.9	8.3	7.0
Specific Conductance	µS/cm		700 (SMCL)	--	424	376	421	468	291
Temperature	°C			--	27.2	27.3	11.1	24.0	14.8
Turbidity	NTU		1	--	ND	ND	--	0.6	0.1
Dissolved Oxygen	mg/L			--	0.32	0.17	3.7	0.9	0.01
Oxidation-Reduction Potential	mV			--	--	-37	--	-6.0	-66
INORGANICS									
Alkalinity	mg/L as $CaCO_3$			3	212	208	207	218	117
Ammonia-Nitrogen	mg/L as N			0.02	ND	0.08	0.06	0.34	0.03
Bicarbonate	mg/L as $CaCO_3$			3	210	208	207	218	117
Carbonate	mg/L as $CaCO_3$			3	ND	ND	ND	6	6
Chloride	mg/L	250	250	0.06	11.7	12.5	11.7	22.7	11.4
Cyanide	mg/L		0.2	0.003	ND	ND	--	ND	ND
Fluoride	mg/L	4	2 (MCL) / 4 (SMCL)	0.006	0.87	0.92	0.83	1.2	0.2
Hardness	mg/L as $CaCO_3$			0.4	70	64	--	176.0	19.0
Nitrate+Nitrite (total N)	mg/L as N		10 (nitrate) / 1 (nitrite)	0.008	ND	ND	ND	0.3	0.3
Nitrate-N	mg/L as N	10	10	0.008	ND	ND	ND	0.1	0.1
Nitrite-N	mg/L as N		1	0.004	ND	ND	ND	0.1	0.1
Orthophosphate as P	mg/L			0.004	0.018	ND	ND	2.1	0.2
Silica (as SiO_2)	mg/L			--	--	66.6	80.3	85.4	12.8
Sulfate	mg/L	250	250 (SMCL)	0.02	0.5	0.2	ND	34.5	0.2
Sulfide	mg/L			0.4	ND	ND	ND	ND	ND
TOTAL METALS / METALLOIDS									
Aluminum	mg/L		0.05 to 0.2 (SMCL)	0.03	ND	ND	ND	0.02	0.01
Antimony	mg/L		0.006	0.00002	0.00002	ND	ND	0.0013	0.0013
Arsenic	mg/L	0.00005	0.01	0.0001	0.0004	ND	ND	0.0033	0.0013
Barium	mg/L	1	2	0.00002	0.054	0.0514	0.0795	0.052	0.033
Beryllium	mg/L		0.004	0.000003	ND	ND	ND	ND	ND
Cadmium	mg/L	0.01	0.005	0.000003	0.000006	ND	ND	ND	ND
Calcium	mg/L			0.001	15	13.9	14	44.4	12.4
Chromium	mg/L	0.05	0.1	0.00004	0.0001	ND	ND	ND	ND
Cobalt	mg/L		--+	0.000003	0.000054	ND	ND	ND	ND
Copper	mg/L	1	1.3**	0.00002	0.00016	0.044	ND	0.085	0.001
Iron	mg/L	0.3	0.3 (SMCL)	0.002	0.044	0.018	0.030	0.260	0.010
Lead	mg/L	0.05	0.015**	0.000005	0.000084	ND	ND	ND	ND
Magnesium	mg/L			0.001	7.66	7.1	6.9	15.8	6.1
Manganese	mg/L	0.05	0.05 (SMCL)	0.00001	0.030	0.027	0.017	0.044	0.002
Mercury	mg/L	0.002	0.002	0.00002	--	--	--	ND	ND
Molybdenum	mg/L		--+	0.000008	0.011	0.002	--	2.1	0.005
Nickel	mg/L		0.1	0.00003	0.0005	ND	ND	0.008	0.001
Potassium	mg/L			0.03	12.9	11	13.9	14.2	3.3
Selenium	mg/L	0.01	0.05	0.0003	0.0006	ND	ND	ND	ND
Silver	mg/L	0.05	0.1 (SMCL)	0.000004	ND	ND	ND	ND	ND
Sodium	mg/L		20 (advisory level)**	0.02	62	55	70	71	19
Thallium	mg/L		0.002	0.000002	ND	ND	ND	ND	ND
Uranium	mg/L		0.03	0.000003	0.000007	ND	ND	0.0049	0.0012
Vanadium	mg/L		--+	0.00003	0.00039	ND	ND	0.0078	0.0025
Zinc	mg/L	5	5	0.0002	0.0005	0.0067	0.00624	0.0364	0.0010
DISINFECTION BY-PRODUCTS (DBPs) & RESIDUAL DISINFECTANTS									
Bromate	mg/L		0.01	0.0007	ND	ND	ND	ND	ND
Chlorite	mg/L		1	0.004	ND	ND	ND	ND	ND
Total Residual Chlorine	mg/L		4	0.009	ND	ND	--	0.17	0.06
Bromochloroacetic Acid	µg/L			--	--	ND	ND	ND	ND
Dibromoacetic Acid, DBAA	µg/L		See total HAA's	0.14	ND	ND	ND	ND	ND
Dichloroacetic Acid, DCAA	µg/L		See total HAA's	0.18	ND	ND	ND	ND	ND
Monobromoacetic Acid, MBAA	µg/L		See total HAA's	0.13	ND	ND	ND	ND	ND
Monochloroacetic Acid, MCAA	µg/L		70 (MCLG)	0.16	ND	ND	ND	ND	ND
Trichloroacetic Acid, TCAA	µg/L		20 (MCLG)	0.33	ND	ND	ND	1.29	1.29
Total Haloacetic Acids (Total HAA's)	µg/L		60	0.33	ND	ND	ND	1.29	1.29
Bromodichloromethane	µg/L	0.3	See TTHM	0.049	ND	ND	ND	1.58	1.58
Bromoform	µg/L	5	See TTHM	0.066	ND	ND	ND	ND	ND
Chloroform	µg/L	7	70 (MCLG)	0.032	ND	ND	ND	22.6	1.07
Dibromochloromethane	µg/L	0.5	60 (MCLG)	0.09	ND	ND	ND	0.85	0.85
Total Trihalomethane (TTHM)	µg/L		80	0.09					

Table 3: Summary of Kennewick ASR-1 and ASR-MW-1 Water Quality Data (GSI 2020)

Analyte Group / Analyte	Units	Groundwater (WAC 173-200-040)	Drinking Water MCL/SMCL (WAC 246-290-310)	RL	Native Groundwater			ASR Cycles 01 - 06 (ASR-1 and ASR-MW-1)	
					ASR-1 (Initial Testing)	ASR-1 (pre-ASR)	ASR-MW-1 (pre-ASR)		
					Result	Result	Result	Maximum	Minimum
MISCELLANEOUS									
Chemical Oxygen Demand	mg/L			3	ND	ND	ND	5.9	5.9
Color	Color units	15	15	5	ND	ND	--	5.0	5.0
Corrosivity†	Standard units	noncorrosive		--	--	-0.28	--	0.1	-0.7
Dissolved Organic Carbon	mg/L			0.07	0.83	0.70	0.52	2.1	0.2
MBAS (foaming agents)	mg/L	0.5	0.5 (SMCL)	0.05	ND	ND	--	ND	ND
Methane	mg/L			--	--	0.65	--	4.1	1.8
Odor	T.O.N	3 Threshold Nos.	3 Threshold Nos.	--	--	ND	--	ND	ND
Oxidation-Reduction Potential	mV			--	--	-37	--	-6.0	-65.7
pH (Laboratory)	s.u.	6.5 to 8.5	6.5 to 8.5 (SMCL)	--	8.02	7.81	--	8.23	7.17
Conductivity	µmhos/cm			--	--	492	445	498	322
Total Dissolved Solids	mg/L	500	500 (SMCL)	5	324	308	280	318	200
Total Organic Carbon	mg/L			0.07	0.42	0.72	0.67	1.81	0.71
Total Suspended Solids	mg/L			1	ND	ND	--	3.0	1.0
Turbidity	NTU		1	0.4	ND	ND	--	0.6	0.1
RADIOLOGICALS									
Gross Alpha	pCi/L	15	15	0.8	ND	<1 ± 0.853	<1 ± 0.834	ND	ND
Gross Beta	pCi/L	50	4 millirem/yr	1	8.3 ± 1.2	9.25 ± 0.831	6.77 ± 0.670	ND	ND
Radium 226	pCi/L	3	5 (as combined Radium)	0.2	0.50 ± 0.37	ND	0.12 ± 0.08	ND	ND
Radium 228	pCi/L	5 (as combined Radium)	5 (as combined Radium)	0.8	ND	1.16 ± 0.45	0.12 ± 0.45	ND	ND
Radon 222	pCi/L		300 or 4,000††	--	--	388 ± 4.3	70.29 ± 13.10	510.0	39.3
Strontium 90	pCi/L	8		--	ND	-1.06 ± 0.827	--	ND	ND
Uranium Activity	pCi/L			0.67	ND	ND	ND	3.3	0.8

Notes:

This table summarizes data presented in Table 3-2 in GSI (2020) - City of Kennewick ASR Year 6 Pilot Testing Summary Report

Volatile organic compounds (VOCs), synthetic organic compounds (SOCs), and herbicides / pesticides were non-detect and not shown in this summary table

--- indicates not analyzed, measured, or defined

Shaded cells identify exceedances of applicable MCL, SMCL, or advisory level (sodium)

** indicates analytes not regulated by the Washington State Board of Health, but acknowledged to have public health significance. Levels shown are "action levels" set by the EPA and referenced i

--+ indicates analyte is listed on the EPA Contaminant Candidate List (http://water.epa.gov/scitech/drinkingwater/dws/ccl/index.cfm)

°C - degree Celcius

$CaCO_3$ - calcium carbonate

mg/L - milligrams per liter

µg/L - micrograms per liter

µS/cm - microSiemens per centimeter

µmhos/cm - micromhos per centimeter

† - corrosivity analysis by Langelier Index

†† - proposed standard

MCL - maximum contaminant level

MCLG - maximum contaminant level goal

mV - millivolts

N - nitrogen

ND - non detect

NTU - Nepthelometric turbidity units

pCi/L - picocuries per liter

SMCL - secondary maximum contaminant level

s.u. - standard units of pH

T.O.N. - threshold odor number

Source: GSI (2020)

Table 4: Summary of Willowbrook Well Groundwater Quality

Analyte	Units	Drinking Water MCL/SMCL (WAC 246-290-310)	6/21/1991		4/11/1996		6/27/1996		9/25/2000	
			Result	Q	Result	Q	Result	Q	Result	Q
pH	s.u.	6.5 to 8.5 (SMCL)	---		7.82		---		7.51	
Eh	mV		---		55		---		355	
Conductivity	µS/cm	700 (SMCL)	350		---		410		167	
Temperature	°C		---		23.4		---		21.1	
Dissolved Oxygen	mg/L		---		---		---		0.36	
Turbidity (field)	NTU		---		---		---		---	
Turbidity (lab)	NTU		---		---		---		0.41	
Total Dissolved Solids	mg/L	500	---		---		330		130	
Total Suspended Solids	mg/L		---		---		---		2	
Calcium	mg/L		---		---		3.5		15	
Magnesium	mg/L		---		---		0.5		3.7	
Sodium	mg/L	20 (advisory level)**	65		---		93		22	
Potassium	mg/L		---		---		---		5	U
Alkalinity (Field)	mg/L as CaCO3		---		---		---		72	
Alkalinity (Lab)	mg/L as $CaCO_3$		---		---		---		74	
Sulfate	mg/L	250 (SMCL)	---		---		0.1	U	19	
Sulfide	mg/L		---		---		---		0.005	UJ
Chloride	mg/L	250	10		---		14		6	
Fluoride	mg/L	2 (MCL) / 4 (SMCL)	1.5		2		2.2		0.3	
Ammonia	mg/L as N		---		---		---		0.04	U
Nitrate	mg/L as N	10	0.2	U	0.2	U	0.01	U	0.031	
Nitrite	mg/L as N	1	---		---		0.05	U	0.03	U
Phosphate	mg/L		---		---		---		0.06	U
Aluminum	mg/L	0.05 to 0.2 (SMCL)	---		---		---		0.2	U
Antimony	mg/L	0.006	---		---		0.0005	U	0.003	U
Arsenic	mg/L	0.01	0.01	U	---		0.0005	U	0.003	U
Barium	mg/L	2	0.25	U	---		0.036		0.037	
Beryllium	mg/L	0.004	---		---		0.0005	U	ND	U
Boron	mg/L		---		---		---		0.5	U
Bromide	mg/L		---		---		---		0.03	U
Cadmium	mg/L	0.005	0.002	U	---		0.0005	U	0.0005	U
Chromium	mg/L	0.1	0.01	U	---		0.002		0.01	U
Copper	mg/L	1.3**	0.2	U	---		0.02	U	0.01	U
Cyanide	mg/L	0.2			---		0.005	U	0.01	UJ
Iron	mg/L	0.3 (SMCL)	0.1	U	---		0.05	U	0.1	U
Lead	mg/L	0.015**	0.002	U	---		0.0005	U	0.0005	U
Manganese	mg/L	0.05 (SMCL)	0.01	U	---		0.011		0.014	
Mercury	mg/L	0.002	0.0005				0.0005	U	---	
Methane	µg/L		---		---		---		2,000	
Nickel	mg/L	0.1	---		---		0.01	U	0.04	U
Selenium	mg/L	0.05	0.005	U	---		0.001	U	0.003	U
Silicon	mg/L		---		---		---		15	
Silver	mg/L	0.1 (SMCL)	0.01	U	---		0.01	U	0.01	U
Thallium	mg/L	0.002	---		---		0.0005	U	0.0005	U
Titanium	mg/L		---		---		---		0.0033	
Zinc	mg/L	5	0.2	U	---		0.02	U	0.01	
BOD (5-day)	mg/L		---		---		---		5	
COD	mg/L		---		---		---		5	U
TOC	mg/L		---		---		---		1.7	
Radon 222	pCi/L	300 or 4,000†			---		---		325+/-25	
Chloroform	µg/L	70 (MCLG)	---		---		---		5.1	
Bromodichloromethane	µg/L	See TTHM	---		---		---		0.59	
Dibromochloromethane	µg/L	60 (MCLG)	---		---		---		0.22	J
Bromoform	µg/L	See TTHM	---		---		---		0.4	U
TTHM (calculated)	µg/L	80	---		---		---		5.91	

Table 4: Summary of Willowbrook Well Groundwater Quality

Notes:

Shaded cells exceed MCL, SMCL, or advisory level

Action levels for copper, lead, and sodium

--- indicates not analyzed, measured, or defined

Well completed in Wanapum Basalt Priest Rapids Member

Q - laboratory qualifier
 J - estimated value
 U - not detected

** - indicates analytes not regulated by the Washington State Board of Health, but acknowledged to have public health significance. Levels shown are "action levels" set by the EPA and referenced in WAC 246-290-310

Source: Golder (2001)

°C - degree Celcius
$CaCO_3$ - calcium carbonate
mg/L - milligrams per liter
µg/L - micrograms per liter
µS/cm - microSiemens per centimeter
µmhos/cm - micromhos per centimeter
MCL - maximum contaminant level
MCLG - maximum contaminant level goal
mV - millivolts
N - nitrogen
ND - non detect
NTU - Nepthelometric turbidity units
pCi/L - picocuries per liter
SMCL - secondary maximum contaminant level
s.u. - standard units of pH
† - proposed standard