Evidence for Hydrogeologic Compartmentalization in the Columbia River Basalt Aquifer System, Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington

Groundwater Flow Boundaries in GWMA

Legend

- High transmissivity
- Medium transmissivity
- Low transmissivity
- Faults
- Confined groundwater
- Unconfined groundwater
- High recharge
- Low recharge
- High chloride
- Low chloride
- High nitrate
- Low nitrate
- High sulfate
- Low sulfate
- High dissolved oxygen
- Low dissolved oxygen
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EXECUTIVE SUMMARY

Groundwater recharge, movement, and discharge in the Columbia River Basalt Group (CRBG) aquifer system has been characterized as: (1) strongly influenced by primary geologic framework controls (intraflow structure, stratigraphy, and structural geology) and strataform in nature resulting in discontinuities in the groundwater system to (2) weakly controlled by these features resulting in significant lateral and vertical hydrologic continuity. Ongoing hydrogeologic investigations in the CRBG underlying the Columbia Basin Ground Water Management Area (GWMA) reveal evidence for both regional and local compartmentalization in the aquifer system. This evidence includes water level data and groundwater geochemical data from several hundred wells. This water level and geochemical data (and interpretations) is being used to constrain and calibrate a GWMA-wide regional CRBG aquifer system groundwater flow model to be released in the spring of 2011. Several of the primary components of the model will be the importance of stratigraphic controls separating deeper and shallower portions of the aquifer system, the impact of folds and faults on portions of the aquifer system, and the apparent roles feeder dikes play in separating different flow regimes in the aquifer system.

Water level data for wells open to major CRBG units was evaluated using contour maps of the raw data and analyzed using statistical methods that evaluated the data against predicted groundwater pumping, ground surface and open interval elevation, and departures from regional water level trends. The results of these analyses are interpreted to indicate varying stratigraphic, feeder dike, and structural influences on the CRBG aquifer system across the GWMA. Historical water level data shows water levels in the shallower portions of the CRBG aquifer system are decoupled from those in the deeper aquifer system. Discontinuities in mapped water level data suggest stratigraphic controls on the CRBG aquifer system are present, forming significant hydrologic discontinuities separating shallower from deeper portions of the aquifer system, including those just within the Wanapum Basalt. The presence of lateral groundwater flow discontinuities, including major structures such as the Frenchman Hills and Saddle Mountains fault/ fold systems and portions of the Roza and Ginkgo feeder dike systems, also is suggested by analysis of the water level data. In each case multiple analyses show changes in water levels and groundwater decline rates that suggest these features separate CRBG groundwater flow regimes with varying degrees of hydrologic continuity.

GWMA has collected groundwater geochemical data from over 400 wells, primarily evaluating deeper, large production municipal and irrigation wells. These data are interpreted to indicate that wells open to the Grande Ronde Basalt predominantly are extracting water that is solely or largely late Pleistocene (12,000 to <50,000 years old) in age. Where evidence of the mixing of older groundwater and younger groundwater is found, large numbers of shallowly cased and sealed wells typically are present. Leakage through these wells likely is a primary driver for this groundwater mixing.

Based on the information compiled for this report several large-scale groundwater sub-systems are interpreted to occur in the GWMA. The boundaries between these sub-systems appear to
act to hinder, but not completely block, groundwater movement between each. In the northeastern GWMA a groundwater sub-system is interpreted to occur in that portion of Lincoln and Adams County lying east of the Roza feeder dike system. This groundwater sub-system is interpreted to extend eastwards from Adams County and southern Lincoln County into adjacent parts of southwestern Spokane County and western Whitman County. Groundwater flow within this sub-system generally is to the southwest and west. Surface drainages and lakes are still partially active. In Whitman County the impacts of the Palouse River (recharge or discharge or disconnected) are not known.

A central GWMA groundwater sub-system encompasses the area west of the Roza feeder dikes, essentially lying within the northern half of the Odessa Groundwater Management Subarea. Groundwater movement in this sub-system generally is two part. There is some groundwater flow from the east to the west, into the sub-system through the Roza feeder dike system. In addition, there appears to be groundwater movement from the northwest into this sub-system. In both of these cases this groundwater appears to be very old. Within this groundwater sub-system there is some evidence for local, relatively modern groundwater recharge along Crab Creek. However, the bulk of the groundwater pumped from the sub-system is fossil, being Pleistocene in age.

In the western GWMA another groundwater sub-system is centered on the Quincy Basin. The Quincy groundwater sub-system is bounded on the east by the inferred northern extension of the Ginkgo feeder dike system, north by the Beezley Hills, south by the Frenchman Hills anticline and fault system, and west by the dip slope of Hog Ranch anticline and the canyon of the Columbia River. CRBG groundwater flow in this sub-system, at least in the Wanapum Basalt, appears to be dominated by west to east movement off the Beezley Hills and the Hog Ranch anticline. This same trend may be present in the Grande Ronde Hills, although the available data is very limited. Groundwater in the southeast corner of this sub-system appears to be very old, >20,000 years. This suggests that groundwater influx from the east across the Ginkgo feeder dike system (which is up-gradient in the sense that water levels rise to the east) likely is limited and/or very slow. The extreme age of groundwater in the Wanapum and Grande Ronde Basalts in the southeast corner of the sub-system strongly suggests that Potholes reservoir is not a major source of recharge for anything but the shallowest part of this CRBG groundwater sub-system.

To the south of the Quincy groundwater sub-system, across the Frenchman Hills fold and fault system, lies the Royal-Othello groundwater sub-system. The Royal-Othello groundwater sub-system is bounded on the north, east, south, and west by the Frenchman Hills fold and fault system (anticline), Ginkgo feeder dike system, Saddle Mountains fold and fault system (anticline), and Columbia River, respectively. In addition, this sub-system appears to be further subdivided into an eastern and western portion, with this boundary delineated by a northwest-southeast oriented fault that completely crosses this groundwater sub-system. West of the cross-fault there is some evidence of relatively young recharge (and even modern water) from the Columbia River. Additional sources of relatively young groundwater recharge in this groundwater sub-system may occur along its southern margin, possibly tied to leakage.
associated with the Saddle Mountains fault system. Except for these recharge sources, groundwater throughout the majority of this groundwater sub-system is extremely old, with calculated C-14 ages being among the highest seen in the GWMA (>30,000 years).

A fifth CRBG groundwater sub-system lies east of the Ginkgo feeder dike system and south of the Frenchman Hills fold and fault system. One of the major features of this groundwater sub-system is deep coulee incision into the Wanapum Basalt, resulting in very limited lateral hydrologic continuity in these units above the top of the Grande Ronde Basalt. The portions of this groundwater sub-system that are truncated by these coulees typically contain relatively old groundwater except beneath the irrigated lands of the western part of the sub-system and possibly near the Palouse River on the east. The Grande Ronde Basalt may present a different picture though. The Grande Ronde Basalt is incised into, and dips westwards away from, the Snake River. Based on CRBG dips in this portion of this groundwater subsystem we infer that water from the Snake River might recharge the upper Grande Ronde Basalt and move down-dip to the west into the GWMA. However, there is a general lack of data for the Grande Ronde Basalt in this area, so this hypothesis remains untested.

The southernmost GWMA groundwater sub-system is found in the Pasco Basin, lying south of the Saddle Mountains fold and fault system and west of the Ginkgo dike system. To-date GWMA’s efforts in unraveling the CRBG groundwater flow system, especially in the Wanapum Basalt and Grande Ronde Basalt, have not been very intensive in this area. This is in large part because the bulk of irrigation water supplies are derived from surface canals, and as a consequence, few wells go in to the Wanapum Basalt, and even fewer into the Grande Ronde Basalt. Most irrigation wells in this groundwater sub-system only go into the Saddle Mountains Basalt which is thick and widespread in this sub-system while it is thin and/or absent in the other GWMA CRBG groundwater sub-systems delineated here. With that though, we feel confident that this sub-system is separated from the others because the features that define those sub-systems – folds, faults, and dikes – also bound the Pasco Basin sub-system.
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INTRODUCTION

Groundwater recharge, movement, and discharge in the Columbia River Basalt Group (CRBG) aquifer system has been characterized as: (1) strongly influenced by primary framework geologic controls (intraflow structure, stratigraphy, folds, faults, and feeder dikes) and strataform, or layered, in nature resulting in stratigraphic and cross-strata controls and discontinuities in the groundwater system to (2) weakly controlled by these features resulting in significant lateral and vertical hydrologic continuity. Ongoing hydrogeologic investigations in the CRBG underlying the Columbia Basin Ground Water Management Area of Adams, Grant, Franklin, and Lincoln Counties (GWMA) (Figure 1) reveal evidence for both regional and local discontinuities in this aquifer system that tend to compartmentalize it to varying degrees. This evidence includes: (a) water level data and water level decline data and (b) groundwater geochemical data.

In this report we summarize evidence for large-scale discontinuities in the CRBG groundwater flow system underlying the GWMA as suggested by water level and hydrochemical data. This report focuses on stratigraphy, folds, faults, and feeder dikes. We also examine, to a lesser extent, the importance of the modern coulee system in subdividing the CRBG aquifer system. The data, information, and interpretations described in this report were compiled as part of GWMA’s investigative efforts which have resulted in: (1) subsurface geologic maps (GWMA, 2009b, 2011c), (2) conceptual groundwater flow model development (GWMA, 2009a, 2009d; Tolan et al., 2009), (3) hydrochemical data collection (GWMA, 2009c, 2009e), and (4) reports to municipalities, stakeholders (GWMA, 2011a), and professional societies (Tolan et al., 2009).

Water level data summarized in this report from the shallower portions of the CRBG aquifer system are interpreted to show decoupling from those deeper in the system. Water level data also is interpreted to show changes across major linear features such as folds, faults, and dikes. This water level data also was evaluated and analyzed using statistical methods that evaluated the data against predicted groundwater pumping, ground surface and open interval elevation, and departures from regional static water level trends and water level decline trends. The results of these analyses are interpreted to reflect varying stratigraphic, feeder dike, and structural influences on CRBG groundwater systems across the GWMA. Hydrochemical data collected from over 400 wells (GWMA, 2009c, 2009e, 2011a) also is interpreted to show the influence of known and suspected geologic features that influence groundwater occurrence and recharge. These geologic features include stratigraphic controls that appear to inhibit vertical groundwater movement through undisturbed, laterally extensive units. Lateral groundwater flow discontinuities also are suggested by these data.

The results of this effort are being used to constrain and calibrate a regional CRBG aquifer system groundwater flow model for the GWMA (GWMA, 2011b). Based on the information and interpretations described herein, the GWMA groundwater flow model will simulate the influence of stratigraphic controls forming a layered aquifer system, the role of coulees (where present) in forming potential drains and recharge areas in portions of the CRBG aquifer system, the impact of folds and faults on contributing to lateral sub-divisions within the groundwater...
flow system, and the apparent roles CRBG feeder dikes play in separating different groundwater flow regimes, or aquifer sub-systems, in the GWMA. This work was funded by the Washington State Legislature through the Washington Department of Ecology (Ecology), and is one of several deliverables prepared by GWMA for that funding.

DATA

Comparing the CRBG stratigraphic framework, the known and inferred location of folds, faults, and dikes, and the distribution of coulees with water level and geochemical data reveals the possible influences of these features on the CRBG aquifer system beneath the GWMA. This section summarizes the physical nature of the geologic features that likely influence the CRBG aquifer system, and the water level data and hydrochemical data used to deduce the influences these features are interpreted to have on the CRBG aquifer system.

Geologic Features

GWMA lies within the Columbia River flood basalt province. The geologic features which are interpreted to have the most influence on the CRBG aquifer system in the GWMA are the coulees formed by the scouring of Pleistocene cataclysmic flood waters; folds and faults; CRBG feeder dikes; and stratigraphic layering.

Columbia River Basalt Group (CRBG) Stratigraphy

The CRBG is a thick sequence of more than 300 continental flood basalt flows that cover an area of more than 59,000 mi² in Washington, Oregon, and western Idaho (Tolan et al., 1989; Camp et al., 2003; Camp and Ross, 2004) with a maximum thickness of over 10,000 feet. Numerous reports have been written about a variety of CRBG topics, including petrology, stratigraphy, emplacement, tectonics, and hydrology. Several of the more recent compilations of CRBG geology and hydrogeology are found in USDOE (1988), Reidel et al. (2002), GWMA (2009a, 2009b, 2009d), Tolan et al. (2009), and Burns et al. (2011). The reader is referred to those reports, and the citations therein for more detailed discussions of CRBG geology and hydrogeology than are summarized herein.

The CRBG is divided into several regionally mappable units (Figure 2) based on variations in physical, chemical, paleomagnetic properties, and stratigraphic position between flows and packets of flows (Swanson et al., 1979a; Beeson et al., 1985; Reidel et al., 1989b; Bailey, 1989). The CRBG in the Columbia Basin region is subdivided into four formations, from youngest to oldest, the Saddle Mountains Basalt, Wanapum Basalt, Grande Ronde Basalt, and Imnaha Basalt (Swanson et al., 1979a, 1979b). These formations are further subdivided into members defined, as are the formations, on the basis of a combination of unique physical, geochemical, and paleomagnetic characteristics. These members can be, and often are, further subdivided into flow units consisting of one or more basalt flow (e.g., Beeson et al., 1985).

Vertical exposures through CRBG flows reveal that they generally exhibit the same basic three-part internal arrangement of intraflow structures. These features, which originated during the
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<tr>
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From Tolan and others (1989) and Riedel and others (1989 b)

Figure 2. Stratigraphic nomenclature for the Columbia River Basalt Group.
emplacement of the flow and subsequent cooling and solidification of the lava after it ceased flowing, are referred to as the flow top, flow interior, and flow bottom (Figure 3). The flow top is the crust that formed on the top of a molten lava flow. Flow tops range from simple, glassy to very fine-grained basalt that is riddled with countless spherical and elongate vesicles (Figure 4) to very brecciated or rubbly (Figure 5). Flow interiors are dense, non-vesicular, glassy to crystalline basalt that contain numerous contraction joints (termed cooling joints) that formed when the lava solidified. Joints are organized regularly and generally exhibit two main styles known as columnar and colonnade (Figure 6). With alteration, cooling joints become filled with precipitated minerals. The character of the flow bottom largely is dependent on the environmental conditions the molten lava encountered as it was emplaced. They can be thin, vesicular, and glassy if the flow encountered dry ground (Figure 4). Another primary type of flow bottom, pillow complexes (Figure 7), formed where the lava flowed into a body of water.

Interflow zones (Figure 3) are the intervals between successive lava flows that contain various combinations of flow top (from the underlying flow) and flow bottom (from the overlying flow) features. Interflow zones are hydrogeologically important because the strata comprising the interflow zone have porosity and permeability imparted by the vesicular and rubbly nature of flow tops and bottoms that is not seen in dense flow interiors. Where they outcrop, interflow zones can serve as basalt aquifer recharge and/or discharge sites. If a sediment interbed is present between the two flows, it would also be part of the interflow zone, contributing to interflow zone hydraulic properties based on the sediment interbed’s physical characteristics. CRBG flow interiors on the other hand, have very low to almost no inherent porosity and permeability because the cooling joints are largely filled with secondary minerals. Lindberg (1989) in one of the few comprehensive studies of cooling joint effective porosity found that 77 to >99 percent of all cooling joints studied are filled with secondary minerals and that the void spaces that do occur are not interconnected.

Distribution, physical properties, and discontinuities in the intraflow structures that comprise each CRBG flow unit (interflow zones and flow interiors) are one of the primary stratigraphic controls on groundwater occurrence within the CRBG aquifer system. Groundwater flow within an individual CRBG interflow zone (adjacent flow top and bottom, and, if present, a sediment interbed) is directly influenced by the intrinsic physical properties of that interflow zone and bounding basalt flow interiors. Such features as thick flow top breccias, sand and/or gravel interbeds, and/or pillow lava complexes will have higher permeability than simple vesicular flow tops, claystone interbeds, and/or simple flow bottoms. In addition, the lateral persistence of dominant lithologies, or facies, will impact the lateral hydrologic properties inherent to any interflow zone. Figure 8 provides one example of how variable some flow tops can be, with the one seen in the figure ranging from a thin, simple flow top to a thick flow top breccia in a very short distance.

The lateral distribution of dense flow interiors influences the degree of hydrologic connection between successive interflow zones. Although quite widespread, individual CRBG flows and their associated interflow structures do pinchout (Figure 9). Where pinchouts occur, the dense flow interior that typically separates successive interflow zones will be absent and the interflow
Figure 3. Diagram showing the basic intraflow structures found in typical CRBG sheet flows.
Figure 4. Photograph of a simple vesicular flow top. The flow top is found in the red colored band across the center of the photograph against which the sledge hammer is leaning.
Figure 5. Photograph of a typical flow top breccias. The blocky material against which the ruler (6-inches) is leaning constitutes the breccias blocks within this flow top.
Figure 6. Photograph of a typical dense flow interior. In the outcrop the upper portion of the flow constitutes the entablature, while the basal portion of the exposed dense flow interior is referred as collande.
Figure 7. Photograph of a pillow lava. The large sub-rounded blocks of dark rock are individual pillows encapsulated in a mass of glassy debris highlighted by the lighter colored surrounding material. In this outcrop the lighter colored material is palagonitic clay. In the subsurface this material commonly consists of disaggregated, glassy, sand-sized debris.
Figure 8. Photograph of facies variation in a flow top. In the photograph the flow top consists of breccias on either side of the mound but over the top of the mound the flow top is a simple vesicular one.
Area where groundwater from above and below the basalt layer to right could mix

Basalt flow layer pinchout where groundwater flow above and below the layer has the potential to merge

Figure 9. Photograph of a typical CRBG unit pinchout.
zones will merge. Under such conditions, the groundwater seen in these zones should be expected to display a high degree of hydraulic continuity (Figure 10). On a regional scale, such continuity could be important to understanding groundwater recharge and flow. In more laterally restricted CRBG units the potential for significant hydraulic continuity would be greater than in the more voluminous and widespread units. In addition, the geographic and structural distribution of pinchouts could influence groundwater conditions. From a hydrogeologic standpoint, understanding the distribution of CRBG units, pinchouts, lateral continuity, and interbedded Ellensburg sediments is a very important aspect of any analysis or model of the CRBG aquifer system.

**Coulees (Canyons)**

The lateral continuity of many CRBG units, including their interflow zones and dense flow interiors, are directly influenced by the locations and depths of coulees. Throughout the region there are numerous examples of erosion into, and through, multiple CRBG interflow zones in major river canyons (Figure 11) and the Channeled Scabland (Figure 12). The 3rd and 4th Editions of the GWMA subsurface geologic mapping report (GWMA, 2009a, 2011c) shows the effects of these erosional features on the lateral continuity of numerous CRBG units. The units having lateral continuity primarily influenced by coulee erosion in GWMA are those comprising the Saddle Mountains Basalt (primarily in the southern GWMA) and those comprising the Wanapum Basalt (primarily in the central and northern GWMA).

Coulees rarely incise deep enough to erode deeply into the top of the Grande Ronde Basalt, usually only scouring into the top of the uppermost unit, the Sentinel Bluffs Member (Figure 2). The only areas were erosion has had a significant influence on the Sentinel Bluffs Member, limiting its lateral continuity is on short reaches of the Snake River in eastern Franklin County, several reaches of the Columbia River in western Grant County, in the middle Crab Creek drainage in western Lincoln County and adjacent portions of northern Grant County, and around the northern fringe of the GWMA, adjacent to Lake Roosevelt. In the lower Wanapum Basalt, the lateral continuity of the various subunits of the Frenchman Springs Member are all influenced to a greater or lesser extent by major coulees across GWMA. Shallower Wanapum Basalt units, the Roza Member and Priest Rapids Member, and Saddle Mountains Basalt units all show the limiting influence of various coulees across their full extent.

Clearly, wherever a coulee fully cross-cuts a CRBG unit the lateral continuity of any groundwater moving down-dip in that unit will be effected (Figures 13 and 14). The shallower units will be broken up into a series of relatively small hydrologic systems that are completely bounded by the coulees that truncate them. Conversely, with increasing depth, units will be less impacted by coulee incision, and only influenced by those coulees deep enough to truncate the unit. In addition, depending on the depth of incision through the CRBG, the presence of surface water and groundwater, and hydraulic gradient, coulees can act as discharge areas (e.g., Figure 14) for groundwater and/or recharge areas for groundwater. Figure 13 diagrammatically illustrates several of these possible relationships.
Figure 10. Diagram illustrating probable hydrogeologic conditions occurring as groundwater moves down-dip and encounters flow pinchouts. Such conditions could explain how groundwater is able to move deep into the CRBG groundwater system without moving through dense basalt flow interiors.
Figure 11. Photograph showing the stacking of successive, planar-tabular CRBG units. The prominent terraces are flow unit contacts, essentially interflow zones, exposed in this canyon.
Figure 12. Photograph showing the stacking of successive, planar-tabular CRBG units exposed in a typical channeled scabland coulee. The prominent terraces are flow unit contacts, essentially interflow zones.
Figure 13. Diagram illustrating the potential range of hydrogeologic conditions that might be seen associated with Pleistocene Missoula flood scoured coulees.
Figure 14. Coulee cliff face exhibiting springlines that are emitting from planar-tabular flow tops in the CRBG.
Folds and Faults

Folds and faults within the GWMA occur in two main provences, the Yakima Fold Belt and the Palouse Slope (Figure 1). The Yakima Fold Belt, which comprises approximately the western one-third of the GWMA, is characterized by a series of roughly east-west trending, narrow (<1 mile to 3 miles wide), faulted anticlinal ridges that are separated by broad synclinal valleys 10 to 30 mile wide (Swanson et al., 1979b, 1981; Anderson, 1987; Watters, 1989; USDOE, 1988; Reidel et al., 1989a; Tolan and Reidel, 1989). Abrupt changes in fold geometry which delineate ridge segments occur along the length of Yakima Folds (Swanson et al., 1979b, 1981; Bentley et al., 1980; Reidel, 1984; Anderson, 1987; USDOE, 1988; Reidel et al., 1989a). The length of individual ridge segments is variable, ranging from several kilometers to many tens of kilometers long (Reidel, 1984; Anderson, 1987; USDOE, 1988; Reidel et al., 1989a, Tolan and Reidel, 1989). Ridge segment boundaries are commonly marked by cross-faults and folds (Reidel, 1984; Anderson, 1987; Reidel et al., 1989a). The three most prominent Yakima folds in the GWMA are the Saddle Mountains, Frenchman Hills, and Beezley Hills. In addition, the large anticline (hereafter referred to as the Heartline anticline) east of, and parallel to, Banks Lake also could be a Yakima fold belt structure.

The cross-sectional geometry of Yakima Fold Belt anticlines typically is asymmetric and varies along their length. The base of the anticline’s steeper limb is often bounded by an emergent fault termed a frontal fault (Anderson, 1987; Reidel et al., 1989a). Where erosion has exposed the core of these anticlines the emergent frontal fault commonly is observed to be a thrust fault (fault plane dipping 2° to 20°) that rapidly steepens and becomes a high-angle reverse fault (>80° dip) within the core of the fold (Anderson, 1987; USDOE, 1988; Reidel et al., 1989a). The amount of stratigraphic offset on these frontal fault zones varies from less than 150 feet to more than 2,400 feet (Reidel, 1984; Anderson, 1987; USDOE, 1988; Reidel et al., 1989a). Development of the Yakima folds began during Grande Ronde Basalt time (approximately 16 million years ago) and continues to the present day (Myers and Price, 1979, 1981; Bentley et al., 1980; Price, 1982; Reidel et al., 1989a, 1994; Reidel, 1984; Hagood, 1986; Anderson, 1987; USDOE, 1988).

Geologic mapping within the Yakima Fold Belt in the western and southern Columbia Plateau (Newcomb, 1969, 1970; Swanson et al., 1979b, 1981; Bentley et al., 1980; Anderson, 1987; Dames & Moore, 1987; Bentley, 1989) has found a number of northwest-trending, right-lateral strike-slip faults. These faults have been classified as wrench faults by most investigators (e.g., Bentley et al., 1980; Anderson and Tolan, 1986; Anderson, 1987; Dames and Moore, 1987; USDOE, 1988; Reidel et al., 1989a). This classification is based on their distinctive characteristics, including: (1) conjugate en echelon faults, (2) genetically related en echelon folds, (3) reversal of apparent dip-slip displacement along strike, (4) lengths of 5 to 50 miles (8 to 80 km), and (5) seismicity with focal mechanism solutions indicating dextral strike-slip and/or oblique-slip movement.

The Palouse Slope comprises much of the eastern two-thirds of the GWMA (Figure 1). The Palouse Slope is a regional dip slope generally of less than 1 to 2 degrees extending from high
of 3,000 feet above mean sea level (amsl) in western Idaho and north-central Washington to lows of approximately 350 feet amsl in south-central Washington (Myers and Price, 1979; USDOE, 1988). Across this structural province stratigraphic dip slightly exceeds the topographic slope. Consequently, as one goes down-slope (or down-dip) across the Palouse Slope (generally from the northeast to the southwest) the uppermost CRBG units generally get younger in age, units thicken, units are progressively deeper below the surface, and new units are found as one encounters their up-dip edges. Deformation on the Palouse Slope is primarily characterized by north to northwest trending and east-west trending folds with little or no apparent topographic expression (Swanson et al., 1980; Tolan and Reidel, 1989). Dips on these folds typically are less than 5 degrees. A few faults and shear zones, generally with the same orientation as the low amplitude folds noted above, have been mapped within this region (Tolan and Reidel, 1989).

Faulting in the CRBG (Figure 15) tends to produce a roughly planer zone composed of coarsely shattered basalt breccias to very fine rock flour, or gouge. The width of the fault zone (shatter breccia and gouge) can be highly variable (<1 foot to >400 feet thick) and its thickness depends on: 1) magnitude of fault displacement, 2) type of fault (low-angle fault vs. high-angle fault), and 3) type(s) of CRBG intraflow structures cut by the fault (Price, 1982; Reidel, 1984; Hagood, 1986; Anderson, 1987; USDOE, 1988). Fault zone shatter breccias and gouge often display significant degrees of alteration to clays and/or secondary mineralization by silica, zeolite, calcite, and pyrite. These materials can cement shatter breccias and create rocks that are highly resistant to erosion, even more so than unbrecciated CRBG (Myers and Price, 1981; Price, 1982; Anderson, 1987). The types of secondary minerals present within CRBG fault zones appear to be dependent on both environmental conditions (oxidizing vs. reducing) and on in situ conditions such as water chemistry, thermal regime, and hydrologic regime (Myers and Price, 1981; Price, 1982; USDOE, 1988).

Faults within the CRBG do impact groundwater movement, commonly impeding it (Newcomb 1959, 1961, 1969; Johnson et al., 1993) (Figure 16). An analysis conducted by Johnson et al. (1993) of hydrologic test data collected within the Saddle Mountains, Wanapum, and Grande Ronde Basalts across the Cold Creek fault (on the Hanford site) showed that fault to be a barrier to lateral groundwater movement along the axis of the Cold Creek syncline. They interpreted vertical permeability along the fault to be less than horizontal permeability in the upper CRBG aquifers, thus producing a constriction in horizontal groundwater movement across the fault. Similar geologic settings are found along the Frenchman Hills and Saddle Mountains. Faults can form barriers to the lateral and vertical movement of groundwater; a series of faults can create hydrologically isolated areas.

Conversely, faults also can provide a pathway (of varying length) for groundwater movement allowing otherwise separated portions of the CRBG aquifer system to have hydraulic continuity. On the Cold Creek fault Johnson et al. (1993) showed that in the deeper units cut by this fault a vertical groundwater flow pathway appears to be present, allowing upwards migration of methane from deeper to intermediate depth units. In a recent pumping test near Wallula Gap, just south of the southern end of the GWMA, warm water was found to enter an interflow zone during a 72-hour constant rate test (GSI, 2010). The proximity of the well to a major fault zones
Faults, acting as groundwater dams offset permiable interflow zones, resulting in higher groundwater levels on one side of the fault. Faults may also act as a conduit for vertical groundwater flow, water moves up or down in the fault zone depending on aquifer gradient.

Figure 15. This photograph shows the basic geologic relationships typically seen in fault zones cross-cutting the CRBG.
Figure 16. Diagram illustrating the basic hydrogeologic conditions potentially associated with faults in the CRBG. The diagram on the left shows potential conditions associated with a fault that acts as a barrier or impediment to groundwater flow. The diagram on the right shows potential conditions if the fault is a pathway to, or facilitates, groundwater movement in the CRBG.
(within 2 miles of the Horse Heaven Hills fault zones) and increased water temperature during the test suggests water was moving upwards (from deeper, warmer water systems) into the interflow zone that was pumped during the test. Faults, where they have not been sealed by post-movement mineralization and alteration, can provide a direct connection between the surface and interflow zones creating local opportunities for aquifer recharge and/or discharge (Reidel et al., 2002).

The ability of faults to affect CRBG groundwater flow systems in a variety of ways reflects the potential for both lateral and vertical heterogeneities in the physical characteristics of fault zones. For example, the degree of secondary alteration and mineralization along a fault zone may vary considerably. Complete alteration and/or mineralization of fault shatter breccias and gouge zones would “heal” these features and produce zones of very low permeability. Variations in the degree of alteration 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 (displacement) on the fault could produce new permeable zones within the healed shatter breccia (e.g., USDOE, 1988; Johnson et al., 1993).

A number of groundwater investigations in the Columbia Plateau area also have noted that folds (primarily anticlinal and monoclinal folds) can 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; 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 groundwater system are caused by related faults. However, the process of folding CRBG can affect the hydraulic characteristics of interflow zones by shearing the bedding plain and mechanically destroying interflow zone primary porosity (Newcomb, 1969; Yechiel et al., 2007).

**CRBG Feeder Dikes**

As noted earlier, CRBG flows were emplaced by large volume volcanic eruptions. These eruptions generally occurred from elongate linear vent systems that potentially extended many tens of miles across the landscape. The physical geologic manifestation of these linear vent systems are feeder dikes (Figure 17) and near vent facies basalts (Figure 18). Feeder dikes, some of which are preserved in outcrop (Figure 17), are the lava that solidified in the vent following the end of the eruptive episode.

Waters (1961) identified three dike swarms as feeders to the CRBG: the Monument, Grande Ronde, and Cornucopia. Additional mapping by Taubeneck (1970) found no gap between the northerly Grande Ronde and southerly Cornucopia swarms and merged them into a single giant swarm that he named the Chief Joseph (Figure 19). Beeson et al. (1985) and Reidel et al. (1989b) extended the Chief Joseph dike swarm to the north-central and northeastern margin of the CRBG. Chief Joseph dikes fed the main phase of CRBG volcanism that formed the rocks that
Figure 17. Photographs of a feeder dike cross-cutting CRBG layers. The photo on the left is as close up of the dike shown cross-cutting outcrops seen in the photo on the left.
Figure 18. Photograph of thinly layered Priest Rapids Member strata suggestive of emplacement near an eruptive vent. This outcrop is in northeastern Lincoln County.
Figure 19. Map showing the locations of known CRBG dikes and vents [Tolan et al., 2009].
dominate the CRBG, including the huge-volume flows of the Grande Ronde and Wanapum Basalts. Taubeneck (1970) estimates that at least 21,000 dikes occur in the Chief Joseph swarm at the level of the regional unconformity below the CRBG.

Taubeneck (1970) assumed that feeder dike numbers increased from north to south across the Chief Joseph dike swarm. However, the greatest number of basal flows and hence feeder dikes, occurs north of the Washington-Oregon border suggesting that more feeder dikes should occur in the northern part of the province, which would include the GWMA. Dikes are rarely isolated but instead occur in closely spaced clusters of 12 or more dikes per square mile; presumably, each cluster or sub-swarm represents an eruptive axis for CRBG volcanism (Taubeneck and Duncan, 1997).

The overall trend of the Chief Joseph swarm is N10°W ± 10°. The majority of feeder dikes dip within 30° of vertical, average 6 to 20 feet thick, are from a 1,000 feet to over 35 miles long, and often occur in en-echelon segments (Taubeneck, 1970). In general, Grande Ronde and Wanapum Basalt feeder dikes are located throughout the swarm and exposures of Wanapum feeder dikes and Grande Ronde Basalt flows indicate that feeder dikes extend to the northern border of the GWMA (Reidel et al, 1989b; Reidel, 2005). Saddle Mountains Basalt feeder dikes occur in the northern half of the Chief Joseph swarm and are localized near the center of the Columbia Plateau within and east of the GWMA (Figure 19). Within the northern half of the Chief Joseph swarm, the feeder dikes and vents for Frenchman Springs Member tend to be nearer to the center of the Columbia Plateau, including the central to eastern GWMA. Priest Rapids feeder dikes are nearer to the eastern margin of the Columbia Plateau along and east of the Washington-Idaho border; and the vents and feeder dikes for the Roza Member form an over 100 mile long system, which crosses the eastern GWMA, in between the Frenchman Springs and Priest Rapids feeder dike systems. Within GWMA the location and extent of specific Grande Ronde feeder dikes is unknown because of very limited exposures and the depth of the unit, commonly several hundred to over 1,000 feet below ground surface.

Where feeder dikes are present they physically disrupt the lateral continuity of the interflow zones they cross-cut. That being the case, it seems likely that CRBG feeder dikes have the potential to impede, and even block (at least locally), lateral groundwater movement through the planar-tabular interflow zones which dominates the CRBG groundwater system. Figure 20 offers a diagrammatic depiction of this potential relationship. Similar relationships have been observed in association with basalt feeder dikes on the island of Oahu in the Hawaiian Islands (J. Anderson, written comm., 2009).

Water Level Data

Figure 21 shows the locations of wells from which GWMA compiled water level data deemed to be useful in evaluating water level trends in individual wells and in specific areas. These data were obtained from Ecology, the U.S. Geological Survey (USGS), and individual well owners. The Ecology data consisted of three main types: (1) data from a small number of multi-level observation well clusters (piezometers) constructed during the 1970’s and early 1980’s, (2) data collected annually in the late winter and early spring from a variable number of wells each year,
Figure 20. Diagram illustrating the possible impact of CRBG feeder dikes on CRBG hydrogeology.
Figure 21. Map showing the distribution of wells in GWMA from which water level data was obtained.
and (3) water levels reported on well completion reports and collected at the time of well completion. The first two data sets were provided to GWMA by Ecology staff, and later was compiled from well records available on-line from Ecology. Water level data obtained from the USGS came from that agencies extensive data library compiled over the years for a variety of projects. Individual well owner data acquired by GWMA typically was from a small number of people and entities who keep records of their well(s) performance.

Although the smallest data set, the most informative water level data set used for the project was from the small number of piezometers located within the GWMA. Ecology has measured groundwater levels for as long as 40 years in several of these wells. In a vertically compartmentalized groundwater flow system nested wells (or piezometers) are a valuable tool for understanding differences in water level elevations and seasonal and longer-term water level trends exhibited by different water-bearing zones. These differences can be readily evaluated at a single cluster of nested wells (i.e., at one geographic location) because the water level measured in each individual well represents the water pressure in the interflow zone(s) open to that particular well.

Specifically, differences or similarities in groundwater elevation measurements collected in a given nested well can be used to interpret the degree of hydrologic continuity between different water bearing zones, both laterally and vertically. Regular measurements taken over a number of years provide a record of seasonal and long-term water level trends and, when compared with other nested well clusters, provide data that can be used to interpret the relative influences of regional-scale and sub-regional pumping and recharge on groundwater levels in the interflow zones monitored by the nested wells. Between the various wells in a nested well cluster, similarities or differences in water level elevation trends together are used to interpret the hydraulic relationship between interflow zones monitored by each well in the well cluster. If good vertical connection exists between interflow zones, the water levels in different interflow zones would be expected to be similar, and to react similarly over time. Conversely, differences in levels and/or trends can be interpreted to indicate hydrologic discontinuities between the monitored interflow zones.

In addition to evaluating the data associated with piezometers, the GWMA team also statistically analyzed the water level data. For the statistical analysis we used static water level data collected subsequent to 2003 from 338 wells with long-term water level records and 405 wells with short-term or single water level measurements to highlight local-scale (<10 mile) variability, and evaluate sub-regional hydrologic trends and discontinuities in relationship to major geologic structures. The long-term data record included the piezometer wells, annual data collected by Ecology for single wells, USGS data, and a small number of private and municipal wells.

Water level data was evaluated in several stages. The first stage of the process involved developing a predictive regional groundwater elevation trend regression model using geographically weighted regression (GWR) analysis, where the dependent variable static water level elevation, was predicted using groundwater pumping and other significant covariates.
The second stage consisted of variography using residuals from the GWR analysis and kriging ground water level elevation residuals across the region. The third stage involved transformation of interpolated residuals into continuous trends of 100 ft pixels as they deviated from mean residuals, and isolating patterns that are interpreted to exhibit meaningful spatial relationships. The resulting residual values, scaled by standard deviation from mean residual, were masked to the extent of the study area, and examined in relationship with observed prominent geologic features.

Using methods described by Yaneme (1967) the long-term data alone (n=338) provided an adequate sample size to draw inferences to the population of water wells within portions of the study area. However, analysis of these data alone revealed significant clustering (Moran’s I > 0.8) which may devalue statistic tests (Isaaks & Stravinsky 1989, Kovitz and Cristakos 2004). In addition, this data set, which is heavily center weighted did not adequately represent areas that are co-located with several prominent geological features. Preliminary evaluation of the interpolation using leave one out cross validation method suggested predictive modeled ground water data was inadequate based on regularized root mean square (RMS). Additionally, increasing level of error was observed, again, beyond the central region of the study area, in areas where long-term water level data was relatively sparse, which added difficulty into interpreting results that were spatially relevant to the geological features of interest.

For the aforementioned reasons, additional static water level data was taken from driller logs (n=405) (Figure 21). Static water level elevations from drillers logs were filtered for non-pumping months (November-March), consistent with the timing of long-term static water level measurements which were also taken in the non-pumping season. The inclusion of static water level data from drillers log vastly improved our ability to interpolate across the full extent of the GWMA, as well as improving clustering and predictive capabilities of raw static water level data.

In addition to examining static water level data directly, we developed an explanatory model to evaluate differences in static water level elevation leveraged by ground water pumping, as well as other potentially important covariates, including elevation of the top of major CRBG units (i.e. Saddle Mountains, Wanapum, and Grande Ronde) each well is open to. GWR builds a local regression equation for each feature in the dataset, and builds separate regression equations by incorporating the dependent and explanatory variables of features falling within the bandwidth of each target feature, depending on user input (bandwidth, kernel type, distance) (Fotheringham et al. 2002). Using a GWR model for explanatory data analysis is robust to data that exhibits spatial-autocorrelation and non-stationarity, which is often the case in spatially explicit data sets (Preston and Brakebill 1999). GWR permits parameter estimates to vary locally (Brudson et al. 2000, Fotheringham et al. 2000), whereas an ordinary regression model assumes that model structure remains constant through the study area.

Initially we used ordinary least squares to isolate the significant variables and develop the most parsimonious model for explaining the variation in static water levels. In addition to groundwater pumping, possible covariates included continuous variables (surface elevation, elevation at top of basalt, elevation at the bottom of seal, groundwater pumping, well depth)
and nominal variables (major open interval in the Grande Ronde, Wanapum, Saddle Mountains, and/or Sediment, or multiple). We evaluated the relationship between covariates and response variables for multicollinearity by examining a matrix plot for all variables. For our GWR model we used an adaptive kernel type, where the basis for the spatial context (the Guassian Kernel) is a function of a specified number of neighbors. Where the feature distribution is dense, the spatial context is smaller, where feature distribution is sparse, the spatial context is larger. We used Akaike Information Criterion to determine the extent of the Kernel. The map produced from this analysis of water level data is presented in Figure 22. Interpretations based on this map are discussed later in this report.

**Hydrochemical Data**

Earlier groundwater geochemical work by GWMA indicated that a large portion of the groundwater found within the CRBG aquifer system in the GWMA is Pleistocene in age, displaying calculated C-14 ages over 10,000 years (GWMA 2009c, 2009e). This suggested that modern recharge to much of the CRBG aquifer system within the GWMA is extremely limited or non-existent (GWMA 2009d). However, these same studies have also shown that suprabasalt sediment and CRBG aquifers in limited areas within the GWMA are recharged by modern surface water sources, but that in many areas this recharge is insufficient for providing sustainable yields at current pumping rates (GWMA 2009d).

This section summarizes the hydrochemical parameters used to evaluate differences in groundwater chemistry that could be due to compartmentalization resulting from stratigraphic (layered), dike, fold, and fault boundaries. For this evaluation, this report examines relative age parameters based on carbon-14, tritium, and chlorofluorocarbons (CFC’s). In addition, other hydrochemical parameters, including nitrate and cation ratio, is used to support the evaluation. A brief explanation of these parameters and their interpretation will allow the reader to gain a better understanding of the methodology used in this investigation. The following explanations of groundwater age, age tracers and analytical parameters are excerpted from GWMA (2009c, 2009e).

The age of groundwater can be defined by the amount of time a particular water molecule has spent below the ground surface. Groundwater age is thus an absolute value (e.g., 25 years or 1,500 ± 110 years for example). Groundwater age can also be discussed in terms of residence time, which refers to the amount of time it took for a water molecule to travel from its entry into the subsurface to its point of exit from the groundwater system, either through a well, spring, or other discharge to the surface. Groundwater age is numerically equivalent to groundwater residence time at the point of discharge (Kazemi et al., 2006).

Groundwater samples collected from pumping wells or springs often represent a composite mixture of water from different flow paths and therefore a mixture of water of different ages (Manning et al., 2005; Weissmann et al., 2002). The measurement and calculation of groundwater ages is further complicated by variable geologic and geochemical conditions relating to the recharge source, recharge rate, and groundwater flow paths and flow rates (the direction and spatial distribution of groundwater flow). In addition, and particularly for aquifer
Residual static water level deviation

Figure 22. Map showing calculated residual static water level elevation deviation from the observed water levels.
systems such as the CRBG where wells commonly are open to multiple water-bearing zones, groundwater samples collected from a well represent a flow-weighted composite of the water from the multiple water-bearing zones to which the well is open. Despite these potential complications in interpretation, groundwater ages have been widely measured, calculated, and applied in a variety of useful and critical areas of groundwater science (Kazemi et al., 2006). This is largely due to the increasing availability of a number of analytical methods, including tritium ($^3$H), tritium-helium ($^3$H/$^3$He), chlorofluorocarbons (CFCs), sulfur hexafluoride (SF$_6$), and carbon-14 ($^{14}$C, also referred to as radiocarbon).

Individual age-dating techniques are generally applicable to specific age ranges. However, because a groundwater system can have numerous recharge points, as well as temporally and spatially variable flow rates, water molecules in a water sample drawn from a well may have entered the system at different times and therefore are of different ages. In order to reduce the amount of uncertainty in groundwater age determinations, it is important to integrate results from more than one age-dating technique. In designing site-specific investigations, it is critical to select methods that are applicable for the expected span of groundwater ages (Figure 23). For example, if residence times in the part of the aquifer system being studied are certainly less than 60 years, a combination of age-dating techniques for dating young waters (e.g., tritium-helium and CFCs) may be sufficient. If the water sampled is likely to be a mixture of young and older groundwater (modern to thousands of years old), it is necessary to use at least one of the younger age-dating techniques in combination with at least one of the older age-dating techniques (e.g., CFCs and carbon-14). In general, employing multiple age tracers for a particular study provides for a more accurate characterization of groundwater age (e.g., Plummer et al., 2001).

**STRATIGRAPHIC INFLUENCES ON THE GROUNDWATER SYSTEM**

Evidence suggestive of stratigraphic controls on the CRBG groundwater system (e.g., springs and hydrographs) is common in the GWMA. In addition, groundwater geochemical data collected by the GWMA provides evidence that is interpreted to support this hypothesis. This section summarizes evidence of stratigraphic influences on the CRBG aquifer system.

**Springs**

Springs in the CRBG almost invariably are expressed as linear features, or springlines, that generally generally parallel the topographic contour of slopes and cliffs (Figure 14). In addition, when these springs are examined they almost always are associated with outcropping interflow zones (with and without interbedded sediment). In these outcrops evidence of groundwater discharge from vertical and sub-vertical cooling joints above and below the interflow zone is extremely rare. In the few places where water has been observed emitting from vertical joints, the joints are found immediately below a springline and they are open as a result of pressure release on the exposed rock surface. With that pressure release the joints expand (open) and some water may drain from the adjacent interflow zone into portions of the open joint(s).
The implication of such observations from a hydrologic perspective is obvious. Water is discharging from the interflow zone exposed in the slope forming the springline. In association with this, the underlying dense interior must have a low enough permeability to prevent water from draining from the bottom of the interflow zone and into and through the underlying dense interior.

**Well Hydrographs**

Well hydrographs offer a glimpse of hydrologic differences in the CRBG aquifer system that are easily explained when stratigraphic controls on groundwater occurrence are considered. The piezometer data described earlier offer a case in point.

One of these wells, Basalt Explorer, was reconfigured as a nested piezometer early in 1973. Prior to the rebuild a single composite water level was recorded in the well (Cline, 1984) (Figure 24a). When the well was rebuilt, the composite water level was replaced by three distinct water levels, one for each piezometer (Figure 24b). In addition, the deepest piezometer initially recorded the highest water level. In recent years the deep piezometer recorded groundwater level declines that displayed different trends than the other piezometers (Figure 24b).
Figure 24a. Water level fluctuations in the Basalt Explorer well before and after installation of piezometers, from Cline (1984).

Figure 24b. Water levels in Basalt Explorer piezometers following the installation of the piezometers.
Figure 25. Water levels in the AAE552 piezometer.
Figure 26. Water levels in the Davenport piezometer.
Figure 27. Water levels in the Almira piezometer.
Figure 28. Water levels in the Odessa piezometer.
Figure 29. Water levels in the Hanford piezometers, from DOW (1988).
nested piezometer wells in the GWMA include AAE552 in southern Adams County (Figure 25), and ones near Davenport (Figure 26), Almira (Figure 27), and Odessa (Figure 28).

Well AAE552, a five piezometer well in southern Adams County (AAE552) (Figure 25) suggests two groundwater systems in the Wanapum Basalt (upper and lower), and a deeper separate Grande Ronde Basalt hosted system. The piezometers near Davenport (Figure 26) display similar trends, generally rising and falling together. However, over 100 feet of water level separation between the monitored zones suggests a degree of hydrologic separation between the upper three piezometers and the lower piezometer. At Almira, Washington similar separation is seen between shallower and deeper groundwater systems (Figure 27). This is interpreted to show a Wanapum aquifer system separated from a shallow Grande Ronde aquifer system within the Sentinel Bluffs Member.

The Odessa piezometers (Figure 28) also show separation, with deeper and shallower water-bearing systems that display different long-term trends. Three groundwater systems are interpreted to be present, two in the Wanapum Basalt and one in the Sentinel Bluffs Member. Water level in the shallower of the two Wanapum piezometets is higher and displays a slight long-term rise which is not seen in the second, or deeper, Wanapum piezometer. These differing trends are interpreted to reflect a degree of hydrologic separation between a shallower Wanapum Aquifer system and a deeper Wanapum aquifer system in the Odessa area. The Sentinel Bluffs portion of the groundwater system displays a completely different trend, declining rather markedly throughout the period of the data record.

Observations at the Hanford Site (adjacent to the GWMA) during the 3-year period from 1984 through 1986 also show trends interpreted as evidence of stratigraphic compartmentalization of water-bearing zones in the CRBG. These data are seen in both differing time-trends and differing elevation of the piezometric surface (USDOE, 1988). Figure 29 shows the time trends in three separate boreholes containing six nested observation wells – three in Wanapum Basalt interflow zones (the Basalt of Rosalia, Priest Rapids Member; and the Basalt of Sentinel Gap and Basalt of Gingko, Frenchman Springs Member) and three in Grande Ronde Basalt interflow zones (the Basalt of Rocky Coulee and Basalt of Cohassett, Sentinel Bluffs Member; and Umtanum Member). These hydrographs display water levels that can be interpreted as evidence of an upward vertical hydraulic gradient through the entire section, as indicated by the progressive increase in groundwater elevations from the shallowest piezometer to successively deeper piezometers. Two of the three boreholes (DC-20C and DC-22C) show that this difference is slight between the three uppermost piezometers, but that this group of piezometers has notably lower groundwater elevations than those of the three deepest piezometers. Additionally, in all three boreholes (DC-19C, DC-20C, and DC-22C), during 1985 and 1986 the three shallowest piezometers in a given borehole show very different responses in timing to various anthropogenic events (drilling, pumping) and natural events (distant seismic events) than are observed in the three deepest piezometers. These two observations are interpreted to indicate that the CRBG interflow zones monitored by the three shallowest piezometers have limited hydraulic connection to the CRBG interflow zones monitored by the three deepest piezometers.
While these examples are few in number, they have the benefit of being relatively well controlled in that the data records are available and well construction is generally documented. In addition, when we consider such observations as up-hole and down-hole water flow recorded and seen on numerous well videos, cascading wells described by well owners, and thief zones these situations suggest the presence of vertical pressure differentials in the CRBG aquifer system. Such vertical pressure differentials would result from limited connectivity across layers, not widespread hydrologic continuity. These observations taken together are interpreted to indicate the limited potential for groundwater in the CRBG to move unhindered vertically through the a stratigraphic system consisting of multiple, undisturbed, dense flow interiors. That being the case, stratigraphic controls on the CRBG aquifer system must be considered. If these controls are indeed important, alternative explanations for apparent vertical hydraulic continuity must be evaluated. These could include flow unit thinning and pinchouts, open fault zones, and unsealed wells.

**Hydrochemical Distinctions near the East Low Canal**

GWMA sampled groundwater geochemistry from 18 large capacity irrigation wells located up to 4 miles from the East Low Canal to assess the potential for recharge to the CRBG aquifer system from irrigated agriculture operations (GWMA, 2011a). The potential for groundwater recharge from the East Low Canal, and adjacent irrigated land, was evaluated from wells located proximal (within ~1.8 miles) and distal (>1.8 to ~3.75 miles) to the canal at multiple locations in the northern GWMA. This was done using tritium, percent modern carbon, and hydrogen stable isotope data. Of these wells, all but 4 had shallow casing and seal depths (< 150 feet). For the remaining 3, well seals were less than 50 feet. Only one well in the sample set was deep sealed and cased, at 760 feet and 767 feet, respectively.

The groundwater geochemical data collected from these wells show differences between wells located proximal to, and distal from, the East Low Canal and adjacent irrigated lands (GWMA, 2011a). Distal wells have lower percent modern carbon (pmc) and tritium indicating a larger component of old basalt (or fossil) groundwater versus young water. In addition, distal wells also have δD values very close to that of fossil basalt groundwater (δD = −144.5‰) with one exception. This exception is a shallow cased well that is more susceptible to receiving modern recharge from the surface. Conversely, proximal wells, except for the deep cased and sealed well noted earlier, have higher pmc and tritium suggesting a large proportion of modern recharge and a smaller fossil groundwater component. Proximal wells, with one exception, also have δD values reminiscent of the East Low Canal (δD = −130.6‰). The exception is the deep cased well noted above, it has a δD value closer to fossil basalt groundwater. This is interpreted to be due to the deep casing and seal depth depth which prevents young water from moving down the well bore and entering the well.

The geochemical trends summarized in GWMA (2011a) for the area near the East Low Canal have an interesting corollary when compared to well drilling and deepening histories in the area. Anecdotal accounts indicate that most wells distal from the East Low Canal have been deepened due to falling static water levels. As these wells have been deepened they have
intersected and produced older, deeper water with less of a modern water signature. Conversely, wells more proximal to the canal generally have not been deepened. Anecdotal reports of well owners suggest that deepening of these wells has not been necessary because static water levels and pumping capacity in these wells recovers reliably during the non-pumping season. Given the shallow casing depths typical of these wells, <50 to <150 feet, borehole leakage of modern irrigation sourced shallow groundwater into the well likely is occurring, providing the recharge which maintains well performance.

**Geochemical Discontinuity Between the Alluvial Aquifer System and the CRBG Aquifer in the Quincy Basin**

In the Quincy Basin, both the unconfined alluvial (or suprabasalt sediment) and the confined CRBG aquifer systems were geochemically sampled in order to better understand the nature and extent of vertical connectivity between these water-bearing intervals and to assess possible recharge sources (GWMA, 2011a). This was done using pmc and tritium.

Across large portions of the GWMA, the regionally extensive CRBG aquifer system is overlain by sediments deposited by Pleistocene cataclysmic floods and older Mio-Pliocene alluvial (river) systems. In many portions of the western GWMA these sediments contain local groundwater systems and surface water is common. The area north of the Frenchman Hills, south of the Beezley Hills, and between Moses Lake and the Columbia River, referred to as the Black Sands, or Quincy Basin, is one of these areas. In the Quincy Basin the CRBG is overlain by up to as much as 200 feet of uncemented sandy to gravelly Pleistocene Missoula flood deposits, a laterally discontinuous sequence of older (Mio-Pliocene) sands and weakly cemented siltstone and claystone, and caliche which commonly separates these two sequences (GWMA, 2007, 2009b). The flood deposits, which range from a few feet thick to many tens of feet thick, often contain groundwater and can be quite productive, producing 100’s to over 1,000 gpm in some wells. The older strata, also known as the Ringold Formation, can be absent to as much as 100 feet thick (GWMA, 2007, 2009b). Although locally sandy intervals in it can produce significant water, generally this unit is a low volume water producer because it is dominated by siltstone and claystone lithologies.

Tritium and pmc data (Figures 30 and 31) analyzed from Quincy Basin alluvial aquifer system samples are elevated, and as a result they are interpreted to indicate that groundwater produced from sedimentary aquifer wells is predominantly modern (GWMA, 2011a). Conversely, tritium and pmc content are lower in CRBG wells, and interpreted to indicate that this groundwater is primarily fossil groundwater (GWMA, 2011a). The source of the modern water is interpreted to be largely from irrigation activity, and likely includes canal and wasteway leakage, infiltration from irrigated fields, and potentially some precipitation. With respect to the older CRBG groundwater, it is clear from the data collected to-date that a significant portion of the CRBG aquifer system underlying the Quincy Basin, especially the eastern half, contains groundwater that was recharged into the system over 10,000 years ago (GWMA, 2011a).
Figure 30. Percent modern carbon in Wanapum Basalt groundwater samples.
Figure 31. Tritium in Wanapum Basalt groundwater samples.
Figure 32. Percent modern carbon in Grande Ronde Basalt groundwater samples.
Examining the groundwater geochemical data collected to-date in the southeastern Quincy Basin, a discontinuity between relatively shallow CRBG groundwater systems in the Wanapum Basalt and surface water systems also is interpreted. Wanapum wells in this region are depleted in pmc (Figure 30) and tritium (Figure 31), even though surface water, including Potholes Reservoir, is widespread. This suggests surface water is not leaking or penetrating far into the underlying CRBG aquifer system. This is not unexpected given the largely undisturbed top of CRBG surface mapped earlier by GWMA in this area (GWMA, 2009a). To the west in the Quincy Basin pmc and tritium content in the Wanapum increases (Figures 30 and 31). In the western Quincy Basin, which is up dip of the eastern Quincy Basin, Wanapum Basalt units come to the ground surface and Wanapum interflow zones are in direct contact with surface waters. These include both canal and irrigation seepage waters. These physical conditions, coupled with groundwater geochemical data collected to-date, are interpreted to indicate the importance of up-dip recharge in areas where units thin and interflow zones are accessible to, and in contact with, surface waters.

COULEES AND THE GROUNDWATER FLOW SYSTEM

Figures 11, 12, 13, and 14 all illustrate the potential for coulee incision to influence the lateral continuity of CRBG interflow zones. In the three photographs there clearly is a physical disruption in the lateral continuity of the individual CRBG interflow zones. The discontinuity is manifest as springs, or discharge areas in the outcrops illustrated in Figure 14. Coulees containing water on the other hand may provide recharge areas for CRBG interflow zones in contact with the water, such as is diagrammatically illustrated in Figure 13. Elevated pmc in several Grande Ronde Basalt wells near Crab Creek west of Odessa and near Lind Coulee in the Warden area are interpreted to reflect this potential relationship (Figure 32). Conversely, if the up-dip area of a unit is found in a dry coulee one would surmise that little to no recharge is occurring.

Coulee incision resulting in compartmentalization generally is interpreted to only be a significant factor in the GWMA CRBG aquifer system to the depths of individual coulees and the CRBG stratigraphic unit(s) truncated by them. That being the case, one would expect the impacts of coulee incision to differ across the GWMA landscape, based on depth of incision into the CRBG and the CRBG units present. Across much of the GWMA the two most widespread shallow units are the Priest Rapids and Roza Members of the Wanapum Basalt. Looking at the distribution of the deeper of these two units, the Roza Member (Figure 33) it is readily apparent that it is broken up into a series of laterally restricted blocks, or terranses by a number of coulees. Roza groundwater in each of these blocks, if water were present, would discharge into coulees in down gradient areas. In areas where the Roza is deeper, such as in southern GWMA, coulee controlled compartmentalization would not occur. Deeper in the CRBG, units such as the Sentinel Bluffs Member, Grande Ronde Basalt (Figure 34) show less influence from coulee incision, and consequently less potential for coulee controlled compartmentalization. These maps though also point to another geometric relationship that is equally important to deeper CRBG unit hydrology, and that is the potential for direct recharge of deeper units in coulee
Figure 33. Extent and isopach map of the Roza Member Wanapum Basalt in the GWMA.
Figure 34. Structure contour map of the top of the Sentinel Bluffs Member, Garde Ronde Basalt
Figure 35. Major structural features in the GWMA.
tracts. The Sentinel Bluffs map (Figure 34) shows a number of areas where the unit is at, or very near, the bedrock bottom of several major coulees, including Crab Creek, Washtucna coulee, and significant reaches of both the Snake River and Columbia River canyons. In the presence of water, such a physical relationship argues for these deeper coulees and canyons being potential recharge areas for these deeper CRBG units that are otherwise rarely exposed in direct contact with surface water sources.

**INFLUENCE OF FOLDS AND FAULTS**

Many geologic structures (faults, folds and dikes) are present throughout the GWMA (Figure 35). This section summarizes evidence GWMA has collected to-date that suggests the basic influence of the larger fold and fault systems on the CRBG aquifer system in the GWMA.

**Frenchman Hills Fault and Fold System**

Using information taken from water well reports on both sides of the western half of the Frenchman Hills fold and fault system (west of Potholes Reservoir) GWMA compiled a history of well use, pumping, and water level that show a striking difference on either side of the structure. GWMA estimates that in the Quincy Basin, on the north side of the structure, groundwater pumping currently is approximately 124,800 acre feet per year (Figure 36). This is nearly 5 times the volume of groundwater pumping estimated on the south side of the structure in the Royal Basin where pumping is estimated to currently be approximately 21,900 acre feet per year (Figure 36). Coupled with this pumping, in the Quincy Basin the total depth of wells drilled each year has increased at approximately a rate of 2.9 feet/year while in the Royal Basin total well depths have increased each year at a rate of approximately 15.8 feet/year (Figure 37). Finally, static water level depths reported on either side of the structure are declining faster on the south side of the structure as compared to the north side (Figure 38). These trends are interpreted to indicate that hydrologic conditions on either side of the structure are significantly different with well deepening and water level declines occurring more quickly south of it, although groundwater use is 5 times greater on the north side of it.

For the eastern half of the Frenchman Hills fold and fault system, that portion east of Potholes Reservoir, the evidence for it acting as a significant boundary in the groundwater flow system is less well defined. Pmc (Figure 32), and tritium (Figure 39) in the Grande Ronde Basalt is generally similar and all indicate a high proportion of fossil groundwater. Water well records, unlike those reviewed for wells to the west, are much sparser and do not show the striking differences noted earlier. With that though, anecdotal comments GWMA staff have gotten from large well operators do suggest some sort of discontinuity along the trace of the fold and fault system. These well operators report differences in water levels, well deepening trends, water production, and water level declines on either side of the inferred position of the structure.
Figure 36. Groundwater pumping trends in the Quincy and Royal Basins
Figure 37. Reported maximum depth of wells in the Royal and Quincy Basins.
Figure 38. Average decline ratios in reported water levels in the Quincy and Royal Basins.
Figure 39. Tritium In Grande Ronde Basalt groundwater.
Saddle Mountains Fault and Fold System

The western half of the Saddle Mountains fold and fault system (Figure 35), defined as that portion of the structure west of Eagle Lakes and Scootenay Reservoir, is an obvious topographic and geologic feature (Reidel, 1984, 1988). In fact, it is a larger topographic feature, and the degree of structural deformation defined by fault offset and fold size is greater than seen in the Frenchman Hills. Unfortunately, direct evidence of hydrologic differences on either side of the Saddle Mountains structure is generally scarce because much of the south side of the structure is undeveloped from a groundwater pumping perspective. Nevertheless, given the physical conditions seen in the western Saddle Mountains fold and fault system we interpret that it has a significant boundary influence on the groundwater flow system, separating systems on either side.

With respect to the eastern half of the Saddle Mountains fold and fault system, that part lying east of Scootenay Reservoir, data described in GWMA (2011a) are interpreted to indicate it has an influence on the CRBG aquifer system. GWMA’s groundwater geochemical data show generally higher pmc (Figure 30) and tritium (Figure 31) in the Wanapum Basalt on the south side of the structure. Water level trends also suggests it acts as a potential barrier as water levels south of the structure are lower than those north of the structure (GWMA, 2011a). However, with this data, the structural offset on this portion of the structure is less than is seen to the west, and as a result its impact on the aquifer system likely is less than probably occurs to the west.

Northern Grant County and Western Lincoln County

In the northern GWMA major mapped structures consist predominantly of folds (Gulick, 1990; Gulick and Korosec, 1990; Waggoner, 1990). Faults do not seem to be common in this portion of GWMA, at least as portrayed on the available 1:100,000 geologic maps. The major mapped structure in the northern portion of the GWMA, the Heartline anticline, is a generally northeast-southwest oriented structure east of and paralleling Banks Lake (Figure 35). East and south of the Heartline anticline are a series of generally east-west, low amplitude anticlines and synclines (Waggoner, 1990). Most of these folds only extend eastwards a few miles into Lincoln County. A few of them extend further eastward into Lincoln County.

The northernmost of these structures extending a greater distance into Lincoln County is a syncline-anticline pair that extends eastwards from the county line almost to Wilbur. Artesian aquifer conditions have been reported by well owner/operators in and just south of Wilbur. This area of artesian groundwater generally lies north of, and up gradient/up-dip of the projected eastward extension of the folds noted above. Given this geometric relationship it is possible that this fold system acts as a down gradient groundwater flow boundary south of Wilbur, resulting in the artesian conditions suggested by local well operators.

Other evidence of structural influence on groundwater flow has been described in the upper Sinking creek area south and west of Wilbur. Work done in the upper Sinking Creek area suggests one, or more, east-west trending fault may be present (Wildrick, 1982). A structure
such as this could easily be associated with the mapped folds noted in the previous paragraph. The fault suspected to be present in the Sinking Creek area by Wildrick (1982) is inferred to hinder groundwater flow.

The southernmost of the eastward projecting folds is an anticline that becomes a south dipping monocline as it extends eastward across the middle reaches of Canniwi Creek and Marlin Hollow (north and west of Odessa). Reconnaissance done for this project and the Lincoln County passive rehydration project found a low amplitude anticline north of Odessa, Washington at Coffee Pot Lake (Figure 40). This anticline lies a few miles south of the monocline noted above. The area where the fold at Coffee Pot Lake is found also corresponds to an area where surface drainages become progressively more dewatered to the west, or downstream of the fold. East (upstream) of the fold streams generally flow most of the year and lakes are full, or nearly full, year round. West (downstream) of this fold streams experience more obvious flow diminishment and/or drying as do the lakes. Anecdotal comments by well owners suggest similar well conditions. This structure may form a part of the hydrologic boundary separating these apparently different hydrologic regimes.

**FEEDER DIKES AND POTENTIAL AQUIFER COMPARTMENTALIZATION**

Several CRBG feeder dike systems are known to occur within the GWMA. These known feeder dike systems are for the Ginkgo flow of the Frenchman Springs Member of the Wanapum Basalt, the Roza Member of the Wanapum Basalt, and the Ice Harbor Member of the Saddle Mountains Basalt (Figure 41) have been identified from surface geologic mapping, geochemical logging of drill cuttings from water wells, and aeromagnetic surveys. The water level data and groundwater geochemical data compiled and collected by GWMA are interpreted to suggest these features do have a role in sub-dividing the CRBG aquifer system within the GWMA.

**Basalt of Ginkgo, Frenchman Springs Member**

The Ginkgo feeder dike system within GWMA is interpreted to extend from the Snake River, near the southern end of GWMA, northwards into the west central GWMA (Figure 41). The northern end of this system likely occurs north of Moses Lake. This feeder dike system is observed in the Snake River canyon near Lower Monumental Dam (Figure 17), it has been identified in well cuttings and video logs in wells near Othello, and an apparent aeromagnetic anomaly follows a general line defined by these two points. The aeromagnetic anomaly is seen on a regional survey that shows a magnetic signature that stretches between these two locations, and extends further to the north (Figure 42).

Because the Ginkgo unit is generally buried deep below the ground surface (it is a unit deep in the Frenchman Springs Member of the Wanapum Basalt) it, and any dikes that feed its eruptions, is rarely exposed. Given its depth, the Ginkgo dike system would only have the potential to impact groundwater flow conditions deep in the Frenchman Springs Member and older Grande Ronde Basalt. This depth makes an evaluation of this dike’s effect on the groundwater system difficult as many wells with the potential to be influenced by it may also be open to water-bearing intervals above the Ginkgo flow and its dike system. As such, these
Figure 40. Photograph of the anticline seen at the narrows on Coffee Pot Lake.
Figure 41. Interpreted positions of major feeder dike segments in the GWMA.
Figure 42. Aeromagnetic map of the Columbia Basin GWMA. The linear trends in the southern GWMA are interpreted to reflect Ice Harbor and Ginkgo feeder dike trends.
wells would be influenced by the deeper groundwater system which might have potential feeder dike effects, and a shallower groundwater system above the Ginkgo which would not be influenced by the feeder dike system.

Water level decline data and geochemical data suggest there is some evidence for changes across the inferred position of the Ginkgo feeder dike. For example, tritium data in the Wanapum Basalt (Figure 31) suggest groundwater is older west of the inferred trace of the dike, than it is east of the dike. This could be interpreted to show the dike system forms a groundwater flow discontinuity that separates older water on the west (down gradient) from younger water on the east (up gradient) side of the dike. Water level data collected to-date is more ambiguous because most wells evaluated along the trace of the dike system are open to units above the Ginkgo, making an evaluation of the dikes influences on the deeper groundwater system difficult. However, the water level in Port of Othello #3, a Grande Ronde well, is significantly higher than any water levels seen just a few miles to the west in City of Othello wells. Such a trend, although not unequivocal proof of a groundwater flow boundary is consistent with a boundary down gradient of Port of Othello #3 such as is illustrated in Figure 20.

Roza Member, Wanapum Basalt

The Roza Member feeder dike system (Figure 41) also may influence the CRBG aquifer system. The Roza feeder dike system extends almost to the top of the CRBG across much of its extent, and as consequence, most CRBG wells on either side of it have the potential to be influenced by it regardless of their depth. Basic observations with respect to the Roza system are as follows.

Statistical analysis of water level data seems to suggest a fundamental change in physical conditions along the projected trend of the Roza feeder dike system. The analysis shows water levels in Wanapum Basalt and Grande Ronde Basalt wells on the west side of the projected trace of the feeder dike system are lower than projected regional conditions would suggest should be expected (Figure 22). Conversely, this same analysis shows that water levels in Wanapum Basalt and Grande Ronde Basalt wells east of the trend are higher than the predicted regional trends would suggest (Figure 22). Two hydrographs, one each for wells on either side of the feeder dike trend also suggests deeper water levels and more decline west of the projected trace of the feeder dike system, as compared to the east (Figure 43). The transition between areas of depressed water levels and areas of elevated water levels again seems to generally follow the predicted course of the dike system.

Another observation associated with the potential influence of the Roza feeder dike system on area hydrology, centers on the occurrence of surface water. Throughout much of its predicted extent in the GWMA and adjacent areas of eastern Washington, the Roza Member is exposed in coulee floors and other Pleistocene Missoula flood scoured valleys. Consequently, Roza feeder dikes will cross-cut every unit below the Roza Member, including those immediately underlying coulee bottoms. One such area where this occurs in GWMA is in Lake Creek near Odessa (Figure 44). Streams and lakes are generally more widespread and still active most of the year east (up gradient and upstream) of the predicted trace of the feeder dike system (Figure 35).
Figure 43. Water levels in 2 ERO wells on either side of the projected position of the Roza feeder dike system.
Figure 44. Roza feeder dikes at Taveres Lake.
Conversely, surface waters are much less extensive today than they were in the past on the west side (down gradient and downstream) of the predicted feeder dike system. Although this is not direct evidence of the influence of the Roza feeder dike system on surface hydrology, this physical relationship between projected dike trace and downstream dewatering of surface drainages as they flow across the trace of the feeder dike is interesting.

A final observation centers on the extent of aquifer system water level decline on the down gradient, or Odessa Groundwater Management Subarea (the Subarea) side, of the feeder dike system. The Odessa Groundwater Management Subarea is an area of extremely high historical pumping. A perennially stressed, and annually depleted surface water system, coupled with declining water levels in wells is found on the Subarea, or down gradient side of the projected trace of the Roza feeder dike system. Up gradient of this feeder dike system very different groundwater and surface water conditions are observed. We would hypothesize that the Roza feeder dike system is contributing to a groundwater flow discontinuity separating the Subarea from areas to the east.

**Other Dike Systems: Ice Harbor Member, Priest Rapids Member, and Grande Ronde Basalt Members**

Several other feeder dike systems are known, or suspected, to occur in the GWMA. Dikes for the Ice Harbor Member of the Saddle Mountains Basalt are known to occur in southern and central Franklin County (Swanson et al., 1975). The Priest Rapids dike system is projected to extend northwards into eastern Lincoln County (Reidel et al., 1989b; Reidel, 2005) where near vent facies rocks crop out north of Odessa (Figure 18). Grande Ronde Basalt unit dikes also probably underlie the GWMA. Earlier GWMA subsurface mapping (GWMA, 2009b) suggested a dike was present for the Ortley Member, deep in the Grande Ronde Basalt underlying central and northern Adams County, near and north of Lind, Washington.

In the cases of the Ice Harbor and Priest Rapids feeder dike systems there is some groundwater geochemical data and water level data that suggests a discontinuity might be associated with each system, separating somewhat different bodies of water on either side of the predicted feature. However, this interpretation should be considered preliminary at this time. With respect to the deeper Ortley Member feeder dike system, because so few wells go deep enough to allow us to begin to characterize aquifer conditions deep into the Grande Ronde, its influence, if any, on the groundwater system is currently unknown.

**CONCLUSIONS**

The CRBG aquifer system underlying the Columbia Basin GWMA is interpreted to be subdivided, or compartmentalized, at a fairly large scale. The geologic features forming these subdivisions, or compartments, include stratigraphic layering and folds, faults, and CRBG feeder dikes.
Layered Compartments

Based on the data and information currently available, large-scale compartmentalization related to stratigraphy appears to be associated with groups of units. On a local scale we do not commonly see evidence for hydrologic continuity between single, or small groups of, water-bearing interflow zones in many wells in a short time frame. Evidence for this includes well videos where up-hole and down-hole movement in the boring is observed, and pumping tests where observation wells in units other than the pumped unit do not respond. However, the groundwater geochemical data collected to-date, and long-term water level data currently available do suggest that at larger scales and time frames groups of water-bearing interflow zones do display some degree of hydrologic connection. These connections are interpreted to be mostly related to pinchouts, structures, and erosional features allowing a degree of interflow zone continuity, and not to widespread leakage through dense, undisturbed flow interiors.

Based on the data collected within GWMA to-date, the primary stratigraphic (or layered) compartments identified within the CRBG aquifer system generally are as described below. With this though, one should anticipate that collection of additional information these proposed layered sub-division may be modified. Some units may be combined, while others may be further sub-divided.

1. The Saddle Mountains Basalt: At this time we conclude that all Saddle Mountains Basalt units be grouped together GWMA-wide to form a single layered compartment because of similar, but commonly limited, distribution. Saddle Mountains units are limited to the southern GWMA (essentially south of the Frenchman Hills) and commonly display lateral truncations do to post-emplacement erosion. However, several Saddle Mountains units, most notably the Elephant Mountain Member and the Pomona Member (including interbedded sediments) have greater lateral continuity beneath the southern GWMA than other Saddle Mountains units. This might warrant eventually designating them as a separate layered unit(s), at least in the southern GWMA. However, the currently available data does not provide enough justification at this time to support such a sub-division.

2. Upper Wanapum Basalt, the Priest Rapids Member and Roza Member: The Priest Rapids Member and the Roza Member (including associated sediment interbeds) should be grouped together to form the next layered compartment. This grouping is related to the two units generally having a similar lateral distribution across most of the GWMA. In the southern GWMA, especially in the Pasco Basin, these two units are the shallowest widespread CRBG units below the much more limited distribution Saddle Mountains units. Conversely, with the exception of a portion of the central GWMA where the Priest Rapids Member is absent both units are generally incised through by Pleistocene Missoula flood coulees, similarly limiting their basic lateral distribution. Given the wide distribution of these units, we would anticipate that future data collection may lead to their separation into two units, or layers, beneath at least some portions of the GWMA.
3. The Frenchman Springs Member of the Wanapum Basalt: The Frenchman Springs Member present beneath most of GWMA, and in many areas either functioned as, or continues to function as, an important and productive groundwater development target. At this time we conclude that it should be treated as a single layered compartment because of the regional extent of the unit, but also because of the different pinchout positions of its component sub-units. Frenchman Springs sub-units overlap, with some of them having a wide lateral extent while others have far less lateral extent. We infer that these pinchouts will impart a degree of hydrologic continuity to the unit across the GWMA, although these connection may be tortuous and locally absent. As with the other Wanapum units, we would anticipate that if more data is collected in the future, that it might be possible that the Frenchman Springs Member could be separated into several layers beneath at least some portions of the GWMA.

4. Sentinel Bluffs Member, Grande Ronde Basalt: The Sentinel Bluffs Member is the uppermost Grande Ronde Unit beneath GWMA, and it is very widespread. It is only exposed in the deepest canyons and coulees, and as such, has much wider lateral distribution than overlying units that are incised into by surface drainages. Conversely, although widespread it is truncated or disturbed by all major structures and all post-Grande Ronde feeder dikes that cross-cut the GWMA. Finally, throughout its extent in GWMA where it is intersected by wells Sentinel Bluffs Member interflow zones are, or have been, major producers of groundwater. Given this combination of factors the Sentinel Bluffs Member is interpreted to be the next major major straiigraphic layered compartment within the GWMA. There are multiple water-bearing interflow zones within the Sentinel Bluffs member which may form important subdivisions within it. However, we cannot further sub-divide the Sentinel Bluffs Member at this time because of a paucity of hydrologic data.

5. The remainder of the Grande Ronde Basalt is treated as a single layered compartment at this time, largely because of very similar distribution patterns, but also because of a lack of data and information. As with the other widespread units, we would anticipate that if more data becomes available in the future that it might be possible to further sub-divide these deeper Grande Ronde units beneath at least some portions of the GWMA.

6. Within the GWMA we only subdivide the Grande Ronde Basalt down to the Wapshilla Ridge Member (GWMA, 2011c). Below this member two basic units are combined into a single basal hydrologic compartment for the purposes of this effort. The two units combined into this basal layer are pre-basalt crystalline metamorphic basement (beneath northern and central Lincoln County) and pre-Wapshilla Ridge undifferentiated Grande Ronde Basalt (beneath the balance of the GWMA).

We conclude that sediment interbeds are not appropriate criteria for subdividing the CRBG aquifer system beneath the GWMA. This conclusion is tied to two basic observations. One is that sediment interbeds where present beneath the GWMA commonly contain sand and gravel facies which will tend to allow the movement of groundwater, not block it. The other is that sediment interbeds beneath GWMA are laterally discontinuous, and as a result may only influence groundwater conditions on a local scale, where they are even present.
Figure 45. Major groundwater sub-systems in the Grande Ronde Basalt in GWMA.
Lateral Compartmentalization in the Deeper Groundwater System

Based on the stratigraphic layering, as summarized above, coupled with the known extent of folds, faults, and CRBG feeder dikes we have identified six major groundwater sub-systems within the Grande Ronde Basalt and lower Wanapum Basalt in the GWMA (Figure 45). These sub-systems are summarized below.

Northeastern GWMA

A northeastern GWMA groundwater sub-system interpreted to be found in that portion of Lincoln and Adams County lying east of the Roza feeder dike system, which forms is western boundary. The eastern boundary of this sub-system probably is the line of steptoes at and south of Reardan. Between these two boundaries the sub-system probably extends southwards into adjacent parts of southwestern Spokane County and western Whitman County. The northern boundary is the highlands above Lake Roosevelt. Within this sub-system groundwater movement is generally down-dip to the southwest and west. At this time reports of significant groundwater declines are not widespread, although it is fair to state that this region is not subject to the same pumping demands as are seen in other portions of the GWMA.

Modern recharge, if present, likely is restricted to deep coulees when water is present, up-dip areas on the CRBG above Lake Roosevelt, and possibly the flanks of steptoes where surface materials are conducive to relatively unhindered deep infiltration. Ancient recharge would have most likely occurred along the edge of CRBG where glacial lake Columbia once stood, in coulees where water spilled out of that lake, and possibly the flanks of steptoes where surface materials are conducive to relatively unhindered deep infiltration. Surface drainages and lakes are still an active component of the hydrology of this sub-system. In eastern Lincoln County upper the upper Crab Creek watershed experiences perennial stream flows. In nearby eastern Adams County the upper Cow Creek and Sprague Lake system is still active. East of the GWMA, in western Spokane County and western Whitman County lakes and streams appear to be perennially active.

The northeastern GWMA sub-system may be further dividable into two additional sub-systems. One would be defined by the Priest Rapids dike system which we interpret to be present in the northeastern part of Lincoln County, and would separate this area from the large sub-system to the southwest. The second sub-system may lie in the Wilbur area where a number of artesian wells are found. The sub-system defined by the Priest Rapids dike system would lie to the east of a band of near vent materials in the Priest Rapids Member being found in outcrops across the eastern Lincoln County. Unfortunately, the water level and groundwater geochemical data collected to-date for this area is even sparser that that collected elsewhere. For this reason we cannot go further in delineating the effects of this dike system. If it proves to be present, it likely would separate groundwater systems in northeastern most Lincoln County form those to the south and southwest. The Wilbur sub-system lies on the southern flank of the southwest-northeast oriented anticline that cuts across the northern end of Grant County and the northwestern corner of Lincoln County. This anticline forms the northern and western
boundary of the possible sub-system. The southern boundary lies somewhere south of the City of Wilbur. It may coincide with an east-west oriented anticline lying approximately halfway between Odessa, Washington and Wilbur. In both cases we have not yet collected enough data to confirm the presence or absence of these features, supporting the anecdotal information that suggests sub-system boundaries may be present. If data is collected that indicates the presence of these boundaries, than the northeastern aquifer sub-system would be subdivided into two sub-systems.

Central GWMA

A central GWMA groundwater sub-system encompasses the area west of the Roza feeder dike system, east of the Ginkgo feeder dike system, north of the Frenchman Hills fold and fault system, and south of the Heartline anticline. Groundwater movement in this subsystem generally is two part. There is some flow through the Roza dike system which likely moves southwest. In addition, there appears to be groundwater movement from the northwest off the Heartline anticline and into the sub-system. Within the sub-system groundwater movement overall appears to be to west and southwest. This area essentially encompasses the northern half of the Odessa Groundwater Management subarea and it experiences very high irrigation water pumping demands.

Modern groundwater recharge does appear to be present in the northwest and near Crab Creek. In these areas groundwater geochemistry suggests the presence of relatively young water in at least a portion of the groundwater sub-system. Other than this water though, analysis of the bulk of the groundwater samples collected by GWMA to-date suggests the vast majority of the water pumped from this groundwater sub-system is ancient, having been introduced in to the sub-system during the Pleistocene. Ancient recharge would have most likely occurred along the edge of CRBG where glacial Lake Columbia once stood, in coulees where water spilled out of that lake. Surface drainages and lakes are not perennially active in much of this sub-system, with the exception of the westernmost portion of it.

At this time further sub-division of this central GWMA subsystem is suspected, but not warranted on the basis of data we have collected. The suspicion of possible additional sub-system boundaries is based on anecdotal information we have collected from area well owners and operators. This anecdotal information suggests that there are clusters of wells that have performance that differs from others. One of these areas lies sub-parallel to the Lincoln County – Grant County line. The anecdotal information indicates wells west of this line generally perform better, and recover faster, than wells east of the line. Other anecdotal information suggests that a low production zone in the Grande Ronde Basalt lies south and parallel to Crab Creek west of Odessa. Wells in this trend are reported to be poor producers of water. Conversely, anecdotal evidence provided by well operators near Coulee City suggests good pumping conditions, and long-term trends that are not indicative of extensive water level and production declines. Future data collection may allow these sub-divisions to be better defined, but until such data is collected, we have not delineated further the sub-divisions within this sub-system, and these potential boundaries are not recognized in this report.
Quincy Basin

There appears to be a groundwater sub-system in the Quincy Basin that generally corresponds to the topographic expression of that Basin. This sub-system is bounded on the east by the inferred northern extension of the Ginkgo feeder dike, north by the Beezley Hills, south by the Frenchman Hills fold and fault system, and west by the dip slope of Hog Ranch anticline and the canyon of the Columbia River. Groundwater flow in this sub-system, at least in the Wanapum Basalt, appears to be dominated by west to east movement off the Beezley Hills and the Hog Ranch anticline. This same trend may be present in the Grande Ronde Basalt, although the available data is very limited.

Water in the southeast corner of the sub-system appears to be very old, >20,000 years. This suggests that groundwater influx from the east across the Ginkgo Dike System (which is up-gradient in the sense that water levels rise to the east) likely is limited and/or very slow. The extreme age of water in the Wanapum and Grande Ronde Basalts in the southeast corner of the sub-system strongly suggests that Potholes reservoir is not a major source of recharge for anything but the shallowest part of the sub-system.

Royal Basin

This sub-system is bounded on the north, east, south, and west by the Frenchman Hills fold and fault system (anticline), Ginkgo feeder dike system, Saddle Mountains fold and fault system (anticline), and Columbia River, respectively. In addition, this sub-system appears to be further subdivided into an eastern and western portion by a northwest-southeast oriented fault that completely crosses the sub-system. This cross-fault is located several miles west of the City of Royal City.

Groundwater geochemical data from the Wanapum Basalt is interpreted to indicate that water in much of this system is old (>20,000 years) and appears to have limited to no hydrologic connection to sub-systems to the north, east, and south of the sub-system boundaries. However, west of the cross-fault there is some evidence of inflow of relatively young and even modern water from the west. The source of this water is inferred to be the Columbia River, and recharged groundwater is interpreted to be moving to the east and away from the River. Additional sources of groundwater may be occurring along the southern margin of the sub-system and possibly tied to leakage associated with the Saddle Mountains fault system.

Southeast GWMA

Water level and groundwater geochemical data collected to-date suggests that the part of GWMA south of the Frenchman Hills fold and fault system and east of the Ginkgo feeder dike system forms a unique sub-system where much of the pumped groundwater is old. This seems to be especially true in the Wanapum Basalt. Groundwater in the Grande Ronde Basalt may present a different picture though. The Grande Ronde Basalt is incised into in places along the Snake River. To the west, the Grande Ronde Basalt dips down to the west, away from the River. Based on this geometry we would expect any recharge water from the Snake River to move...
west and southwest, down-dip into the Grande Ronde Basalt. However, there is a general lack of data in this area, so this hypothesis remains untested.

The northern boundary of this sub-system, the Frenchman Hills fold and fault system, may be broken up into a series of smaller features that generate a very complex boundary east of Warden. Anecdotal information from local well owners and operators suggests that the area just to the north of the main fault and fold is broken up into smaller sub-divisions. The available geologic mapping suggests this fold and fault system has several branches and forms a relatively complex pattern. This map pattern, when compared to the anecdotal stories from well owners which suggest very large differences in wells completed at similar depths over short distances, suggests these structural features maybe generating smaller scale hydrologic subdivision along the major regional boundary.

**Pasco Basin**

For the purpose of this discussion, the Pasco Basin groundwater sub-system is defined as the southern part of GWMA south of the Saddle Mountains fold and fault system and west of the Ginkgo feeder dike system. To-date GWMA’s efforts in unraveling the CRBG groundwater flow system, which have focused on the Wanapum Basalt and Grande Ronde Basalt, have not been very intensive in this area. This is in large part because the bulk of irrigation water supplies in the Pasco Basin are derived from surface canals, and very few wells penetrate completely through the Wanapum Basalt and into the Grande Ronde Basalt. With that thought we feel confident that this sub-system is separated from the others because the features that define those sub-systems – folds, faults, and dikes – also bound the Pasco Basin sub-system.

**Coulees and the Shallower CRBG System**

In the shallower Wanapum Basalt, essentially within the upper half of the Frenchman Springs Member, the Roza Member, and Priest Rapids Member, and the overlying Saddle Mountains Basalt the Ginkgo feeder dike system does not act as a sub-system boundary whereas the locations and depths of coulees become more important. These coulees will limit the lateral continuity of any CRBG unit they truncate, thus limiting the potential for groundwater within the shallower portion of the CRBG aquifer system to move laterally. In addition, coulees will form discharge points in down dip/down gradient areas and potential recharge areas in up dip/up gradient areas where surface water is present. The presence of coulees cross-cutting the shallower CRBG system will increase the number of groundwater sub-systems in these shallower CRBG units, relative to the deeper lower Wanapum and Grande Ronde aquifer systems.
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