A Summary of Columbia River Basalt Group Physical Geology and its Influence on the Hydrogeology of the Columbia River Basalt Aquifer System: Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties

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EXECUTIVE SUMMARY

The Columbia River Basalt Group (CRBG) hosts a regional aquifer system in portions of Washington, Oregon, and Idaho which is the primary, and in many cases the only, water supply for numerous communities, small water systems, individual homes, industry, and agriculture. In much of the semi-arid Columbia Plateau, portions of the CRBG aquifer system have seen significant water level decline and do not appear to get significant, if any, natural recharge. The occurrence of ground water within the CRBG aquifer system is a significant concern to water resources managers in the region.

The CRBG consists of several hundred continental flood basalt flows. The CRBG extends from the Rocky Mountain foot hills in west central Idaho, through the Columbia Plateau of eastern and central Washington and north-central Oregon, to the Cascade Mountains and westward through the area of Portland, Oregon and across the Coast Ranges to the Pacific Ocean. In the central Columbia Plateau the CRBG can be thousands of feet thick. Individual Columbia River basalt flows typically are very widespread, cover many hundreds to several thousand square miles, and generally become thicker and more numerous in the central Columbia Plateau versus the edges. This, coupled with the physical geologic characteristics of CRBG flows indicates they formed as laterally extensive, uninterrupted sheets. This differs markedly from more typical compound basalt flows which display numerous, interfingering, discontinuous, lenticular layers. The net hydrologic result of this is that the aquifers within the sheet flows typical of the CRBG occur as a series of stratified (layered, or stratiform), planar-tabular, confined, water-bearing bodies.

Given the stratiform nature of the aquifer system within the CRBG, an understanding of basic physical geology is critical to understanding groundwater occurrence, recharge, discharge, and continuity and the resulting implications these have for long-term water resource planning and management. Aquifer horizons within the Columbia River basalt generally are associated with intraflow structures at the top (e.g., vesicular flow-top, flow-top breccias) and bottom (e.g., flow-foot breccias, pillow lava/hyaloclastite complexes) of sheet flows. The interiors of thick sheet flows (in their undisturbed state) have very limited to, at least locally, no permeability and act as aquitards, typically creating a series of “stacked” confined aquifers within the Columbia River basalt aquifer system.

The dominant groundwater flow pathway within this aquifer system is horizontal to subhorizontal along individual, laterally extensive, interflow zones. Given the physical properties of the Columbia River basalt, outcrop observations, and interpretations of well hydraulics vertical groundwater movement through undisturbed basalt flow interiors is greatly restricted. Vertical groundwater movement between layered CRBG aquifers is possible, but seems to occur predominantly under specific geologic and anthropogenic conditions where basalt flow interiors are disturbed (such as by folds or faults), truncated (such as by flow pinchouts, erosional windows), or where they are cross-connected by wells.
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INTRODUCTION

The Columbia River Basalt Group (CRBG) hosts a regional aquifer system covering more than 59,000 mi² in portions of Washington, Oregon, and Idaho. This system is the primary, and in many cases the only, water supply for numerous communities, small water systems, individual homes, industry, and several million acres of agriculture worth more than 5 billion dollars annually. In much of the semi-arid Columbia Plateau, apparent natural recharge is small, and portions of the CRBG aquifer system have seen hundreds of feet of water level decline. Some portions of this regional aquifer system also provide base flow to salmonid-bearing streams, including the Columbia and Snake Rivers. The occurrence of groundwater within the CRBG aquifer system clearly is a significant concern to water resources managers in the region.

The CRBG consists of several hundred Miocene age (between 6 and 17.5 Ma) continental flood basalt flows, each of which commonly covers thousands of square miles (Fig. 1). The CRBG extends from the Rocky Mountain foot hills in west-central Idaho, through the Columbia Plateau of eastern and central Washington and north-central Oregon, through the Cascade Mountains and westward across the northern Willamette Valley and across the Coast Range to the Pacific Ocean. The CRBG thickens towards the central Columbia Plateau, reaching its maximum thickness in eastern Washington and Oregon where it is over 10,000 feet thick. Geologic features in individual CRBG basalt flows associated with distance from volcanic source and volume of lava extruded; result in a highly ordered stratiform series of confined aquifer-aquiclude systems reflective of emplacement and subsequent deformation and erosion. Additionally, portions of the system exhibit significant geologic structural (e.g., folds and faults) overprinting.

Given the stratiform nature of the aquifer system within the CRBG, an understanding of the basic physical system is critical to understanding groundwater occurrence, recharge, discharge, and continuity and the resulting implications these have for long-term water resource planning and management. This report summarizes these basic geologic controls we interpret to be fundamental to controlling the occurrence and movement of groundwater in the CRBG aquifer system.

COLUMBIA RIVER BASALT GROUP (CRBG) GEOLOGY

Historical Perspective

The pioneering studies of Waters (1961), Mackin (1955, 1961), and Grolier and Bingham (1971, 1978) developed a basic Columbia River basalt stratigraphic framework that could be correlated and mapped over large geographic areas. Ensuing studies of the CRBG, employing traditional mapping methods coupled with geochemistry and paleomagnetic polarity tools, demonstrated that mappable units (Fig. 2) of regional extent (Fig. 3) could be uniquely defined (Swanson et al., 1979a, 1979b, 1980, 1981; Beeson and Moran, 1979). The impetus (and funding) for most CRBG research efforts from the late 1970's to 1988 was the U.S. Department of Energy’s (USDOE) Basalt Waste Isolation Project (BWIP). BWIP examined the suitability of constructing a deep, mined, repository for the
final disposal of high-level nuclear waste in the CRBG beneath the Hanford Site in south-central Washington State.

A tremendous amount of data and information was produced by BWIP and its cooperative research partners on a diverse range of CRBG geology and hydrogeology topics. Results from BWIP’s investigations are summarized in the first three volumes of BWIP’s Site Characterization Plan (USDOE, 1988). Geological Society of America Special Paper 239 (Reidel and Hooper, 1989) presents a comprehensive summary of results from this period of cooperative research into the regional stratigraphic framework and tectonics of the Columbia River flood basalt province. Several U.S Geological Survey (USGS) reports also explore the CRBG aquifer system (Drost and Whiteman, 1986; Steinkampf, 1989; Drost et al., 1990; Steinkampf and Hearn, 1996; Vaccaro, 1999). In the post-BWIP era, much of the effort in CRBG research has been directed into investigating emplacement processes and history (e.g., Reidel and Tolan, 1992; Reidel et al., 1994; Ho and Cashman, 1997; Self et al., 1996, 1997; Reidel, 1998), stratigraphy and hydrogeology (Lindsey and others, 1993; GWMA, 2007a, 2007b), and groundwater modeling (Drost et al., 1993; Packard et al., 1996; Bauer and Hansen, 2000). The following sections describe our current understanding of the physical characteristics of the CRBG.

**CRBG Basics**

Collectively the CRBG consists of a thick sequence of more than 300 continental tholeiitic flood basalt flows that cover an area of more than 59,000 mi² in Washington, Oregon, and western Idaho (Tolan et al., 1989) with a maximum thickness of over 10,000 feet occurring in the Pasco Basin area (Reidel et al., 1982, 1989a, 1989b). CRBG flows erupted during a period from about 17 to 6 Ma from long (6 to 30 mile) from north-northwest-trending linear fissure systems located in eastern Washington, northeastern Oregon, and western Idaho (Fig. 1). Although CRBG eruptive activity spanned an 11 million year period, most (>96 volume %) of the CRBG flows were emplaced over a 2.5 million year period from 17 to 14.5 Ma (Swanson et al., 1979a; Tolan et al., 1989) (Fig. 4).

During CRBG volcanism, most of the flows emplaced were of extraordinary size, commonly exceeding 215 to 340 mi³ in volume, traveled many hundreds of miles from their linear vent systems, and covered many thousands of square miles (Tolan et al., 1989; Reidel et al., 1989b). These enormous CRBG lava flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history. Figure 5 presents a same-scale comparison between a single, fairly typical CRBG flow, the Laki (Skaftar Fires) flow field which is in Iceland, the largest basalt eruption in recorded human history (Thordarson and Self, 1993), and the ongoing Pu’u O’eruption on the Island of Hawaii. CRBG flows represent the largest individual lava flows known on the earth (Tolan et al., 1989).

The flow of lava away from the vent systems was directed by major physiographic and tectonic features (i.e., Palouse Slope, Columbia Basin, and Columbia Trans-Arc Lowland) and continued regional subsidence (Reidel et al., 1994; Beeson et al., 1989; Reidel and Tolan, 1992) that combined to produce a regional, westward sloping pathway. Of these features, the Columbia Trans-Arc Lowland (Fig. 6) provided the voluminous CRBG flows with a lowland route across the Miocene Cascade Range in western Oregon.
and Washington (Beeson et al., 1989; Beeson and Tolan, 1990). As CRBG volcanism waned in the later Miocene (after 14.5 Ma), smaller volume, more infrequent CRBG lava flows continued to follow this paleoslope, but were more frequently confined to narrow river canyon(s) through the Cascade Range.

The CRBG has been divided into a host of regionally mappable units (Fig. 2). Unit definition is based on variations in physical, chemical, and paleomagnetic properties - in regard to stratigraphic position - that exist between flows and packets of flows (Swanson et al., 1979a; Beeson et al., 1985; Reidel et al., 1989b; Bailey, 1989). The CRBG underlying the Columbia Basin region is subdivided into four formations. These formations are, from youngest to oldest, the Saddle Mountains Basalt, Wanapum Basalt, Grande Ronde Basalt, and Imnaha Basalt (Swanson et al., 1979a, b). These formations have been 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 (e.g., Beeson et al., 1985).

The following sections summarize our current understanding of CRBG flow emplacement (both mode and rate), physical structures within CRBG flows, and sedimentary strata associated with the CRBG.

**Mode of Emplacement**

Rate and volume of lava erupted, lava composition and temperature (rheology), vent geometry, and topographic and environmental conditions all play significant roles in the eruption dynamics and overall geometry of individual basalt lava flows or flow fields (Shaw and Swanson, 1970; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson et al., 1989; Hon et al., 1994; Keszthelyi and Self, 1996; Self et al., 1996, 1997; Reidel, 1998). Lava flows exhibit two basic types of flow geometry: compound and sheet (Fig. 7).

A compound flow develops when lava advances away from its vent in a series of distinct and separate lobes (flows) of flowing lava. Each lobe is subsequently covered by later lava lobes as the emplacement of lava continues. This results in the accumulation of elongated bodies of basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava. In comparison, a sheet flow results when lava is erupted at a high rate and is able to advance away from the vent as a single, uniform, moving sheet of lava. This type of flow consists of a relatively extensive, single layer or sheet of lava. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops overlain by a variety of flow bottom features (Fig. 8).

Individual, large-volume CRBG flows (especially Grande Ronde and Wanapum Basalts) display characteristics consistent with sheet flows (Swanson et al., 1979a; Tolan et al., 1989; Reidel et al., 1989b, 1994; Reidel and Tolan, 1992; Beeson et al., 1985, 1989; Beeson and Tolan, 1990, 1996; Reidel, 1998). CRBG flows typically only exhibit the complex features associated with compound flows at their flow margins (Beeson et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998).

A much less common mode of emplacement for CRBG flows is as an intracanyon flow. In this case, an advancing CRBG sheet flow encounters a major river canyon which
serves to channel the lava into a pre-existing conduit. Such paleoriver canyons undoubtedly allowed some CRBG flows to travel significantly greater distances than they might have as sheet flows. Intracanyon flows are most extensive in the Saddle Mountains Basalt, but also occur along the edges of the Columbia Plateau in older CRBG units.

The development of major canyons within the ancestral Columbia River system during CRBG time was in large part governed by the length of time between large-volume CRBG flows. The emplacement of large-volume CRBG flows typically filled existing low-lying areas which also resulted in the obliteration of the medial to distal reaches of the ancestral Columbia River system. While this portion of the drainage system was essentially destroyed, the upper reaches outside the flood basalt province remained intact. This repeated disruption of the drainage system often resulted in the formation of lakes along the margin of the newly emplaced flows, but inevitably (months to centuries later) the streams and rivers established new courses proximal to the flow margins.

**Rate of Emplacement**

Two end-member models exist for the rate of emplacement of large-volume CRBG flows: rapid emplacement - on the order of weeks to months per flow (Shaw and Swanson, 1970; Swanson et al., 1975; Wright et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998) vs. slow emplacement - on the order of many years to centuries per flow (Self et al., 1991, 1993, 1996; Long et al., 1991; Finneamore et al., 1993; Murphy et al., 1997). Field and laboratory evidence collected to date (Swanson et al., 1975; Mangan et al., 1986; Wright et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Ho and Cashman, 1997; Reidel, 1998; Ho, 1999) appear to favor a mode of emplacement where rapid, laminar flow dominates. Evidence supporting the rapid emplacement model is discussed here.

The internal structure of CRBG flows (discussed in the next section) is relatively simple. The slow emplacement model requires slow lava discharge that would produce very distinctive flow features such as lava tubes and lava inflation structures that would result in relatively complex internal arrangement of flow structures (Chitwood, 1994; Hon et al., 1994; Self et al., 1996). Such complex flow features are rarely observed within CRBG flows except at their margins. The pervasive presence of simple internal flow structures in CRBG flows supports a rapid emplacement model (Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998).

Petrographic examination of quenched CRBG lavas (e.g., rinds from pillow lava) from medial to distal parts of the flow has shown that the crystallinity is no greater than that of the glassy selvage zone of the feeder dike. This indicates that little or no crystal nucleation and growth occurred from the time the lava was erupted to when it reached its most distal point – distances ranging from 120 to 300 mi (Shaw and Swanson, 1970; Swanson et al., 1975; Mangan et al., 1986; Wright et al., 1989; Ho and Cashman, 1997; Ho, 1999). These observations would not be consistent with long duration (slow) emplacement models.

A basalt glass composition-based geothermometry study has been conducted for the Ginkgo flow (Frenchman Springs Member, Wanapum Basalt) along its 300 mi (500-km) length to provide a quantitative estimate of heat loss (Ho and Cashman, 1997; Ho, 1999).
Results suggest cooling rates of 0.06 to 0.11°F/mi for the Ginkgo flow which are substantially lower than cooling rates observed in active and historic basalt flows (Ho and Cashman, 1997). This data favors a rapid emplacement model over a slow emplacement model that requires extreme thermal efficiencies to produce these cooling rates (Ho and Cashman, 1997, p. 405).

The lack of extensive pillow/hyaloclastite complexes along the length of CRBG intracanyon flows also favors a rapid emplacement model (Reidel et al., 1994; Beeson and Tolan, 1996). If CRBG intracanyon flows were emplaced over very long periods (years to centuries), dammed-off river(s) would have repeatedly overtopped the lava dam and reestablished their presence within their canyon(s) years before the flow reached its most distal point. This situation would result in the river encountering the advancing flow front and consequently the continuous creation of large quantities of hyaloclastic (glassy) debris and pillow lava. Features consistent with this aspect of a slow emplacement model are not found along the length of CRBG intracanyon flows.

**Intraflow Structures**

Vertical exposures through CRBG flows reveal that each basalt flow unit generally exhibits the same basic three-part internal arrangement of intraflow structures (Fig. 8). These features originated either during the emplacement of the flow, during the cooling and solidification of the lava after it ceased flowing, or following flow emplacement if/when sediment was deposited. CRBG intraflow structures are referred to as the flow top, flow interior, and flow bottom (Fig. 8). The combination of a flow top of one flow and the flow bottom of the overlying flow is commonly referred to as an *interflow zone* (Fig. 8). Where a sediment interbed is present between a flow top and an overlying flow bottom, the sediment would also be part of the interflow zone. The following paragraphs briefly summarize the physical nature of CRBG intraflow structures, exclusive of sediment interbeds. These are summarized later in a subsequent section.

The *flow top* is the crust that formed on the top of a molten lava flow. Flow tops commonly consist of glassy to very fine-grained basalt that is riddled with countless spherical and elongate vesicles. Vesicles represent gas bubbles that were trapped (frozen) as the flow solidified. These gasses were originally dissolved in the magma, but reduction in pressure as the magma reached the surface allowed these gasses to come out of solution. CRBG flow tops can display a wide range of variation in both their physical character and thickness (USDOE, 1988). The physical character of flow tops falls between two basic end-members, a simple vesicular flow top and a flow top breccia.

A simple *vesicular flow top* (Fig. 9) commonly consists of glassy to fine-grained basalt that displays a rapid increase in the density of vesicles as you near the top of the flow (USDOE, 1988; McMillian et al., 1989). Vesicles may be isolated or interconnected, resulting respectively in lower and higher permeability and effective porosity (USDOE, 1988). Contractional cooling joints, related to flow top formation/flow emplacement, can augment the overall permeability of this feature.

A *flow top breccia* (Fig. 10a) consists of angular, scoriaceous to vesicular fragments of basaltic rubble (Fig. 10b) that lies above a zone of non-fragmented, vesicular to vuggy basalt. Flow top breccias can be very thick, accounting for over half the flow thickness (>90 ft (30 m)) and laterally extensive (USDOE, 1988). There are two models for the
origin of CRBG flow top breccias, (1) the scoria (breccia) was originally produced along the linear fissure system and subsequently rafted away on top of the flowing lava and (2) an autobreccia process similar to that which creates flows in Hawaii. In either case, laterally extensive flow top breccias are relatively common features within the CRBG.

CRBG flow interiors typically consist of dense, non-vesicular, and glassy to crystalline basalt that contains numerous contraction joints (termed cooling joints) that formed when the lava solidified. CRBG cooling joints most often form regular patterns or styles, with the two most common being columnar-blocky and entablature-colonnade jointing. Columnar-blocky jointing typically consists of mostly vertical-oriented, poorly to well-formed, polygonal columns that can range from 2 feet to greater than 10 feet in diameter (Fig. 11). The vertical columns are often cut by horizontal to subhorizontal cooling joints. Entablature-colonnade jointing (Fig. 12) displays a more complex pattern that forms within a single flow. The entablature portion displays a pattern of numerous, irregular jointed small columns to randomly oriented cooling joints that abruptly overlie a thinner zone displaying well-developed columnar jointing. The transition zone between the entablature and the basal colonnade may be very narrow, generally less than 1 inch in width. Typically the entablature is thicker than the basal colonnade, often comprising at least two-thirds of the total flow thickness. Another characteristic of the entablature is that the basalt comprising it contains a very high percentage of glass (50 to 95%) in contrast to the colonnade (Long and Wood, 1986; USDOE, 1988). While entablature-colonnade jointing style is commonly observed in CRBG flows, it is actually a very uncommon jointing pattern for lava flows elsewhere in the world. The origin of entablature-colonnade jointing has been the subject of much speculation and conjecture (Long and Wood, 1986; Reidel et al., 1994), but has not been resolved.

The physical characteristics of CRBG flow bottoms largely are dependent on the environmental conditions the molten lava encountered as it was emplaced (Mackin, 1961; Swanson and Wright, 1978, 1981; USDOE, 1988; Beeson et al., 1989; Reidel et al., 1994; Beeson and Tolan, 1996). If the advancing CRBG lava encountered relatively dry ground conditions, the flow bottom that results typically consists of a narrow zone of sparsely vesicular, glassy to very fine-grained basalt (Fig. 13). This type of flow bottom structure is very common within the CRBG. However, where advancing lava encountered lakes, rivers, and/or areas of water-saturated, unconsolidated sediments, far more complex flow bottom structures formed (Mackin, 1961; Schmincke, 1967; Bentley, 1977; Grolier and Bingham, 1978; Byerly and Swanson, 1978; Swanson et al., 1979a; Swanson and Wright, 1978, 1981; Bentley et al., 1980; Camp, 1981; Beeson et al., 1979, 1989; Stoffel, 1984; Tolan and Beeson, 1984; Ross, 1989; Pfaff and Beeson, 1989; Reidel et al., 1994; Beeson and Tolan, 1996). Where advancing lava encountered a lake, a pillow lava complex (Fig. 14) would be created as the lava flowed into the lake. A pillow complex consists of elongate to spherical lobes of basalt (pillows) set in a matrix of glassy basalt fragments (hyaloclastite). The pillows represent subaqueous pahoehoe flow lobes that advanced down the front of the pillow lava delta.

Spiracles (Fig. 15) are much less common flow bottom features that are inferred to have been created when flowing lava rapidly crossed wet sediments and the trapped water within the sediments was superheated, explosively converting to steam. This localized phreatic explosion chills the overlying lava creating an irregular, cylindrical feature that
is partially filled with glassy, angular debris (hyaloclastite/breccia). **Spiracles** can range from 3 to more than 45 feet in diameter and can extend upward through CRBG flows for distances of more than 90 feet. Commonly **spiracles** terminate within the flow, but in rare cases they can pass entirely through the flow. In general, pillows form where there is a higher ratio of water to lava, and **spiracles** form where that ratio is much lower.

The last type of flow bottom structure involves lava/sediment interaction which created a wide range and scale of invasive features. Tongues and lobes of lava emanating from the base of advancing CRBG flows occasionally burrowed into poorly consolidated sediments due to inherent density differences. Where this invading lava encountered water-saturated sediments, phreatic brecciation sometimes occurred creating a basalt/sediment mixture called a peperite. CRBG flows are known to not only invade sediments, but were capable of lifting and rafting sediment blocks many miles (Byerly and Swanson, 1978; Swanson and Wright, 1978; Beeson et al., 1979, 1989; Stoffel, 1984; USDOE, 1988; Ross, 1989).

**MIOCENE-PLIOCENE (LATE NEOGENE) SEDIMENT GEOLOGY**

During the Neogene, subsidence within the Columbia Basin allowed for the accumulation of both CRBG flows and epiclastic/volcaniclastic sediments. Therefore, no discussion of CRBG geology and hydrogeology in the Columbia Basin is complete without at least an introduction to the late Neogene sedimentary units found overlying and interbedded within the lavas. While not the focus of this paper, a summary of these units is presented here.

Late Neogene sediments in the Columbia Plateau and surrounding region have been studied and mapped for almost a century (e.g., Bretz, 1917; Buwalda and Moore, 1927; Piper, 1932; Hodge, 1938, 1942; Warren, 1941; Lowry and Baldwin, 1952; Waters, 1955; Laval, 1956; Mackin, 1961; Trimble, 1963; Schmincke, 1964, 1967; Hodgenson, 1964; Newcomb, 1966; 1971; Bentley, 1977; Kent, 1978; Rigby et al., 1979; Swanson et al., 1979a, 1979b, 1981; Bentley et al., 1980; Farooqui et al., 1981a, 1981b; Tolan and Beeson, 1984; Dames and Moore, 1987; Hagood, 1986; Fecht et al., 1987; Smith, 1988; Smith et al., 1989; Lindsey, 1996). These studies have found that these sediments both interfinger with and overlie the CRBG. The stratigraphic relationships of these sediments with the CRBG provide a natural, mappable subdivision between; (1) those sediments intercalated with the CRBG (interbeds) and (2) those that overlie the CRBG (suprabasalt sediments).

The composition and mode of deposition of the Late Neogene sediments allow them to be further separated and locally differentiated (Buwalda and Moore, 1927; Piper, 1932; Waters, 1955; Hodge, 1938, 1942; Schmincke, 1964). The major late Neogene sedimentary units associated with the CRBG (Fig. 16) include:

1. **Ellensburg Formation** – interbedded with the CRBG throughout the region, and overlying it in the western Columbia Plateau in Washington;

2. **Latah Formation** – interbedded with, and locally overlying the CRBG in and along the eastern fringe of the Columbia Basin;
3. Ringold Formation and Snipes Mountain Conglomerate – overlying the CRBG in the Pasco Basin and lower Yakima Valley, respectively, of south-central Washington;

4. Dalles Formation, Chenowith Formation, McKay Creek Formation, and Alkali Canyon Formations – overlying the CRBG in the Umatilla-Dalles-Mosier basins of northern Oregon;

5. Troutdale Formation – overlying the CRBG in the western Columbia River Gorge, northern Willamette Valley, and southwestern Washington.

The following sections summarize the basic characteristics of these units.

Ellensburg Formation and Latah Formation - Sedimentary Interbeds in the CRBG

The nature and composition of sediments found interbedded with the CRBG vary greatly, ranging from epiclastic to volcaniclastic in origin. Sedimentary interbeds within the CRBG were deposited by ancient river (both channel and overbank deposits) and lake systems, and as air-fall tephra deposits and reworked tephras from Miocene volcanoes active in the Cascade Range and northern Basin and Range. Events controlling interbed deposition (Fecht et al., 1987; Smith, 1988; Smith et al., 1989) include: (1) emplacement of CRBG flows and their impact on paleodrainage systems, (2) synvolcanic sedimentation from Cascadian sources, and (3) local and regional tectonism (uplift/subsidence).

Individual interbeds range from less than 1 foot to over 100 feet (<1 to >30 m) thick and can be traced laterally over large areas (Mackin, 1961; Schmincke, 1964; Bentley, 1977; Grolier and Bingham, 1978; Swanson et al., 1979a; Fecht et al., 1987; Smith, 1988; DOE, 1988; Smith et al., 1989). Generally these are thickest around the edge of the Columbia Basin. In the central Columbia Basin, notably the central and eastern GWMA, sedimentary interbeds within the CRBG generally are very thin (<5 feet thick) to absent. Variability in interbed composition directly controls their impact on the hydraulic behavior of CRBG interflow zones (USDOE, 1988).

Sediment interbeds within the CRBG, referred generally as the Ellensburg Formation in Washington and Oregon and the Latah Formation in Idaho are subdivided into a number of formal and informal members as shown in Figures 2 and 16. These members (interbeds) are solely defined and recognized on the basis of which CRBG units lie above and below them (Laval, 1956; Mackin, 1961; Schmincke, 1964, 1967; Bentley, 1977; Grolier and Bingham, 1978; Swanson et al., 1979a; Fecht et al., 1987; Smith, 1988; DOE, 1988; Smith et al., 1989). A number of problems arise because stratigraphic definitions of these units are based solely on the identity of the confining CRBG units and not independent lithostratigraphic criteria. A fundamental problem with this scheme is that the defining CRBG units are not always present, and previously separate and named interbeds merge into one member or even become part of another formation. This situation can, and often does, create confusion when dealing with sedimentary interbed nomenclature.

Suprabasalt Sediment Stratigraphic Units

Those sedimentary strata overlying the CRBG and underlying Quaternary-age deposits are known by various names including the Ringold Formation, Alkali Canyon Formation, McKay Creek Formation, Chenowith Formation, Dalles Formation, and Snipes Mountain.
conglomerate. Like sediments interbedded within the CRBG, these late Miocene- to Pliocene-age suprabasalt sediments generally consist of two basic types:

- Epiclastic sediments derived from the CRBG or from a variety of pre-CRBG rocks. These epiclastic sediments were deposited in a variety of alluvial environments, including streams, floodplains, and lakes.
- Volcaniclastic (non-CRBG) sediments consisting mainly of tuffs derived from adjacent, active volcanic provinces (Cascade Range and northern Basin and Range).

Smith et al. (1989) provides a good comprehensive review of the suprabasalt sediments. Based on that report, and other regional studies, including Hodge (1938), Piper (1932), Farooqui et al. (1981a, 1981b), Fecht et al. (1987), Lindsey et al. (1993), Lindsey and Tolan (1996), and Lindsey (1996), the types of facies comprising the epiclastic sediments overlying the CRBG include:

- Mixed lithology conglomerate and felsic sand deposited within the ancestral Columbia River, Salmon-Clearwater River, and/or Snake River;
- Mixed lithology conglomerate with a basaltic sand matrix;
- Muddy, basaltic conglomerate;
- Weakly indurated, massively bedded, siltstone and claystone displaying characteristics indicative of paleosols; and
- Well stratified, weakly indurated, siltstone and diatomite deposited in lake environments.

The CRBG unit upon which these Miocene-Pliocene sediments were deposited varies from place to place across the region. Thus the age of the base of the suprabasalt sediments can vary from 6.5 Ma, where it overlies the youngest Saddle Mountain Basalt unit, to 15.3 Ma, where it overlies the Frenchman Springs Member of the Wanapum Basalt. These suprabasalt sediments commonly grade into Ellensburg and Latah Formation units where intervening CRBG units pinchout.

**GENERAL STRUCTURAL GEOLOGY OF THE REGION**

The Columbia Basin has experienced 4,500 to more than 10,000 feet of subsidence since the onset of CRBG volcanism approximately 17 million years ago (Myers and Price, 1979; Reidel et al., 1982, 1989b; USDOE, 1988; Watters, 1989). Although this region is commonly called the Columbia Plateau or Columbia Plain (Baker et al., 1987; USDOE, 1988), from a structural geology standpoint the region is more properly termed a basin due to its geometry controlled by the regional-scale subsidence experienced in the area (Campbell, 1989). In addition to subsidence, this region has been under a general north-south compression/east-west extension stress regime from at least the beginning of CRBG time (Davis, 1981; Myers and Price, 1979, 1981; Reidel et al., 1982, 1989a; USDOE, 1988; Watters, 1989) to the present-day (USDOE, 1988; Geomatrix, 1988, 1990). This stress regime has led to the formation of the folds and faults of the Yakima
Fold Belt and Columbia Trans-Arc Lowland. Deformation within the Cascade volcanic arc (e.g., intra-arc grabens) has overprinted these regional structures. Differences in the styles of folding and faulting permit designation of four distinct structural subprovinces: the Yakima Fold Belt, Blue Mountains, Palouse Slope, and Clearwater Embayment (Myers and Price, 1979; WPPSS, 1981; USDOE, 1988; Reidel et al., 1989a) (Fig. 17).

**Yakima Fold Structures**

The Yakima Fold Belt, which comprises approximately the western one-quarter of the GWMA, is characterized by a series of northeast-trending, continuous, 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 also commonly occur along the length of Yakima Folds (Swanson et al., 1979b, 1981; Bentley et al., 1980; Reidel, 1984; Anderson, 1987; Reidel et al., 1989a). These changes in fold geometry delineate ridge segments (Reidel, 1984; Anderson, 1987; USDOE, 1988; Reidel et al., 1989a). The length of individual ridge segments is quite variable, ranging from several kilometers to many tens of kilometers in length (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 cross-sectional geometry of anticlinal ridges within the Yakima Fold Belt 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 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). Other classes of faults, besides frontal faults and segment-defining cross-faults that are associated with Yakima fold structures include back thrust faults and out-of-syncline thrust faults (Anderson, 1987).

Faulting in the CRBG tends to produce a roughly planar zone composed of coarsely shattered basalt that grades into very fine rock flour. Figure 18 presents a diagrammatic sketch of the typical physical features and terminology for a fault zone cutting CRBG flows. The width of the fault zone (shatter breccia and gouge) can be highly variable (<1 foot to >400 feet thick) and its thickness typically 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 often display significant degrees of alteration (clays) and/or secondary mineralization (silica, zeolite, calcite, and pyrite). These materials can cement shatter breccias and create rocks that are highly resistant to erosion, even more so than unre brecciated 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 (e.g., water...
The dense interior portions of CRBG flows have a greater mechanical strength than either the flow top or flow bottom (interflow zone). This is largely due to the nature of these features. Dense flow interiors consist of a crystalline-glassy rock mass with cooling joints generally oriented perpendicular to layering. Conversely, interflow zones consist of a variety of vesicular, brecciated, and weak rock types, with or without intercalated sediment. Given these physical features, interflow zones are more susceptible to and affected by deformation because interlayer slippage is more likely to occur in the structurally weak interflow zone, than the structurally more competent glassy-crystalline flow interior during deformation. It has also been suggested that the presence of water within intraflow structure may decrease the relative strength of the rock and may be another factor that contributes to deformational behavior of flow tops and bottoms (USDOE, 1988). This greater susceptibility is typically manifested by the widening of the fault zone as it passes through mechanically weaker portions of the flow and the destruction of primary flow lithology, such as vesicles, in the axis of folds (Price, 1982; USDOE, 1988).

The development of the Yakima folds began during the time of the Grande Ronde Basalt emplacement (approximately 16 million years ago; Myers and Price, 1979, 1981; Bentley et al., 1980; WPPSS, 1981; Price, 1982; Reidel et al., 1982, 1989a, 1994; Reidel, 1984; Hagood, 1986; Anderson, 1987; USDOE, 1988) and have continued their growth through the present day. During CRBG time these developing folds were an important factor that influenced the location of paleodrainages of the ancestral Columbia River system (Fecht et al., 1987; Beeson et al., 1989; Beeson and Tolan, 1996).

**Palouse Slope and Blue Mountains**

The Palouse Slope and Blue Mountains are two structural provinces that comprise much of the eastern half of the Columbia Plateau (Fig. 17). Of these, the Palouse Slope is the dominant structural province in the central to eastern GWMA. The Palouse Slope is a regional dip slope (<1 to 2 degrees) extending from highs of 3,000 feet in westernmost Idaho and north-central Washington to lows 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, all units thicken, and new units are encountered as one encounters their up-dip edges.

Deformation on the Palouse Slope is primarily characterized by north to northwest trending and several 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).

The Blue Mountains, which lie south of the GWMA, is a broad uplift that is 20 to 40 mile wide and generally extends from northeast to southwest from the Lewiston, Idaho area into central Oregon. Much of the western edge of the Blue Mountains is delineated by a
major fault system, the Hite Fault (Tolan and Reidel, 1989). Numerous faults associated with the Hite Fault system, and transverse to it, are found in the Blue Mountains. Displacement on these faults, and other faults in this region, ranges from tens to hundreds of feet. The Hite Fault itself has over 1,000 feet of displacement. In Washington, the CRBG slopes generally to the northwest away from the Blue Mountains uplift, and the Hite Fault, at angles that commonly exceed 10 degrees.

Northwest-Trending Wrench Faults
Geologic mapping of 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, dextral (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 5 mi (8 to 80 km), and (5) seismicity with focal mechanism solutions indicating dextral strike-slip and/or oblique-slip movement.

Studies have found evidence that many of these northwest-trending faults developed contemporaneously with the Yakima folds and that deformation has apparently continued on at least some of these structures into the Holocene (Anderson and Tolan, 1986; Anderson, 1987; Dames and Moore, 1987). Recent minor earthquake activity (mainly small magnitude (< 3.0) events) is associated with several of the northwest-trending wrench faults in the western Columbia Plateau area (USDOE, 1988). Where northwest-trending faults intersect Yakima fold structures a variety of localized structures, ranging from small folds to a variety of faults, including grabens, commonly are found.

IMPLICATIONS FOR CRBG HYDROGEOLOGY
Introduction
Numerous studies of CRBG aquifers have been conducted within the Columbia Basin to better understand their hydraulic characteristics and to develop a model of how various factors (e.g., physical characteristics and properties of CRBG flows, tectonic features and properties, erosional features, climate, etc.) interact to create and govern the CRBG groundwater system (e.g., Hogenson, 1964; Newcomb, 1961, 1969; Brown, 1978, 1979; Gephart et al., 1979; Oberlander and Miller, 1981; Drost and Whiteman, 1986; Lite and Grondin, 1988; Davies-Smith et al., 1988; USDOE, 1988; Johnson et al., 1993; Hansen et al., 1994; Spane and Webber, 1995; Wozniak, 1995; Steinkampf and Hearn, 1996; Packard et al., 1996; Sabol and Downey, 1997; Bauer and Hansen, 2000). One of the most significant findings of these studies is the similarity of the hydrogeologic characteristics, properties, and behavior of the CRBG aquifers across the region. This similarity allows for the application of the knowledge of the general hydraulic characteristics and behavior of the CRBG aquifers to be applied to CRBG aquifers in other areas. This section presents a review of these general hydraulic characteristics.
Groundwater in the CRBG generally occurs in a series of aquifers hosted by the upper three CRBG formations (Grande Ronde, Wanapum, and Saddle Mountains) and the interstratified Ellensburg Formation. CRBG aquifers have been characterized as semi-confined to confined. The major water-bearing and transmitting zones (aquifers) within the CRBG are variously identified as occurring in sedimentary interbeds of the Ellensburg Formation, between adjacent basalt flows (in the interflow zones), and in basalt flow tops (Gephart et al., 1979; Hansen et al., 1994; Packard et al., 1996; Sabol and Downey, 1997; USDOE, 1988; Bauer and Hansen, 2000). Given the stratigraphic arrangement of these features (interbeds, interflow zones, and flow tops, etc.) it should be no surprise that lateral hydraulic gradients and groundwater flow directions in the CRBG aquifers are predominantly down structural dip.

The following sections summarize our assessment of the influence of CRBG intraflow structures on the hydrologic characteristics of the CRBG, larger scale stratigraphic controls on groundwater flow within the CRBG, and secondary (post-emplacement) controls on CRBG hydrology.

**Hydrologic Characteristics of CRBG Intraflow Structures**

The physical characteristics and properties of individual CRBG flows affect their intrinsic hydrologic properties and influence the occurrence of groundwater within the CRBG. Fundamental to this discussion is the mode of CRBG flow emplacement and types and extent of the intraflow structures associated with each flow. As reviewed earlier, there are three basic modes for lava flow-emplacement – compound flow, sheet flow, and intracanyon flow.

The internal arrangement of physical structures (intraflow structures) is far more irregular in compound flows than sheet flows. The presence of these structures in compound flows provides numerous potential pathways for groundwater movement through the flow because of the interconnection of individual flow tops and bottoms. However, based on surface and subsurface data and mapping, sheet flows are the most common type found in the CRBG (e.g., Beeson et al., 1985, 1989; Beeson and Tolan, 1990, 1996; Reidel and Tolan, 1992; Reidel et al., 1994; Reidel, 1998).

As described earlier, each CRBG sheet flow commonly exhibits a three-part internal arrangement of intraflow structures (the flow top, flow interior, and the flow bottom) (Fig. 8). Also, as described earlier, the combination of a flow top of one flow and the flow bottom of the overlying flow (with or without a sediment interbed) is referred to as the interflow zone. Individual interflow zones are as laterally extensive as the sheet flows between which they occur. In addition, they are separated by the glassy to crystalline mass of intervening dense flow interiors. Even though these dense interiors do contain cooling joints, most of these (>75%) are filled by secondary minerals, limiting the continuity of individual open joints (Lindberg, 1989). This, coupled with the planar-tabular distribution and thickness (geometry) of individual interflow zones and dense interiors results in a stratigraphic sequence of alternating relatively high permeability and relatively very low permeability (to impermeable) rocks.

It is widely agreed that within CRBG aquifers, given the typical distribution and physical characteristics of CRBG intraflow structures, groundwater primarily resides within the interflow zones (Newcomb, 1969; Oberlander and Miller, 1981; Lite and Grondin, 1988;
CRBG interflow zones are tabular, laterally extensive bodies which clearly have high permeability related to such physical features as flow top breccias and flow bottom pillow lavas. These physical properties are conducive to forming aquifers. The presence of interbedded sediments can either enhance (e.g., sandstone and conglomerate) or inhibit (e.g., mudstone and paleosols) groundwater storage and movement within this zone. Another critical aspect with regard to interflow zones that is not commonly recognized is their potential lateral variability. For example, thick flow top breccias and thin, normal flow tops are known to grade laterally into each other (Fig. 19). Similar transitions also are seen in flow bottoms. These intraflow structure (e.g., facies) changes can result in heterogeneity in hydraulic properties and behavior of individual CRBG interflow zones. The scale of these facies change heterogeneities is not well understood, but has important implications for predicting the response of CRBG aquifers to stress at local, and potentially, at larger scales.

The physical properties of undisturbed, laterally extensive, dense interiors of CRBG flows, e.g., a planar-tabular, glassy-crystalline body in which joints are 75% to 99% filled with secondary minerals, is strongly suggestive of dense flow interiors having little, to even locally no, effective porosity (Newcomb, 1969; Oberlander and Miller, 1981; Lite and Grondin, 1988; USDOE, 1988; Davies-Smith et al., 1988; Lindberg, 1989; Wozniak, 1995). While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be typically 77 to +99 percent filled with secondary minerals (clay, silica, and zeolite). Void spaces that do occur are typically not interconnected (USDOE, 1988; Lindberg, 1989).

Field data and inferences based on modeling studies suggest that the hydraulic properties of CRBG aquifers are laterally and vertically complex (e.g., Drost and Whiteman 1986; USDOE, 1988; Whiteman et al., 1994; Hansen et al., 1994). For example, vertical profiles of hydraulic head from Hanford site test wells indicate that there is the potential for upward movement of groundwater from Grande Ronde and Wanapum aquifers and downward movement of groundwater from the overlying Saddle Mountains aquifer (Johnson et al., 1993; USDOE, 1988). On the other hand, the regional water level contours for the Grande Ronde and Wanapum aquifers presented in Hansen et al. (1994) suggest that the direction of vertical flow between these two aquifers is variable over the region. However, the results of hydrologic tests in wells at the Hanford site show that lateral groundwater flow in the CRBG interflow zones appears to greatly exceed vertical movement through dense flow interiors (USDOE, 1988).

Hydraulic conductivity of CRBG flow tops reported in USDOE (1988) range from $1 \times 10^{-6}$ to 1,000 feet/day, and average 0.1 feet/day. This same report also indicates the hydraulic conductivity of dense, undisturbed flow interiors ranges from $1 \times 10^{-9}$ to $1 \times 10^{-3}$ feet/day, or at least 5 orders of magnitude less than flow tops. Vertically averaged lateral hydraulic conductivities were estimated in Whiteman et al. (1994) to range from $7 \times 10^{-3}$ to 1,892 feet/day for the Saddle Mountains, $7 \times 10^{-3}$ to 5,244 feet/day for the Wanapum, and $5 \times 10^{-3}$ to 2,522 feet/day for the Grande Ronde aquifers. The available data on hydraulic properties of the various CRBG aquifers, including permeability, porosity, and storativity, indicate that a large variability in local flow characteristics is expected.
Nevertheless, within the CRBG, groundwater is found predominantly within interflow zones that are separated by dense, very low permeability, flow interiors.

**Primary Stratigraphic Controls on Groundwater Flow in CRBG Aquifers**

The distribution, physical properties, and discontinuities found within the intraflow structures that comprise each CRBG flow unit (interflow zones and flow interiors) and formed at the time of flow emplacement form the primary stratigraphic control on groundwater occurrence within the CRBG aquifer system. Groundwater flow within an individual CRBG interflow zone (adjacent flow tops 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 typical 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 (Fig. 19).

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 (Fig. 20). Where pinchouts occur, the dense flow interior that typically separates successive interflow zones will be absent and these interflow zones will merge. Under such conditions, the groundwater seen in these zones should be expected to display a high degree of hydraulic continuity (Fig. 21). 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.

The 3rd Edition of GWMA’s subsurface geologic mapping report (GWMA, 2009) shows the geographic distribution of unit pinchouts for the majority of the primary water-bearing units found within the CRBG underlying the central Columbia Basin. These maps show that even within the most widespread units, those comprising the Wanapum Basalt and the Grande Ronde Basalt, unit pinchouts are more common around the edge of the basin than within the central portions of the basin. This has interesting implications for groundwater occurrence as the areas where unit pinchouts are more common also are up-gradient and generally experience higher precipitation. In addition, following this pinchout geometry from up-dip (up-gradient) to down-dip (down-gradient) areas, one should expect to see interflow zones bifurcate as new units are encountered as one moves from the fringe of the basin towards the depocenter of the basin. On a CRBG member and formational level Figure 22 illustrates an example of this basic geometry, which is seen not only in the Columbia Basin, but throughout the full extent of the Columbia River flood basalt province.

In addition to the basic distributional pinchouts summarized in the previous paragraph, many basalt flow pinchouts are found associated with major Yakima folds and the fringes of the Blue Mountains. Under such circumstances, the potential for hydraulic continuity will be greater than in those areas where flow units are laterally continuous.
From a hydrogeologic standpoint, understanding the distribution of CRBG units and interbedded Ellensburg sediments also is a very important aspect of any analysis or model of the CRBG aquifer system. First, where Ellensburg interbeds are composed of coarse-grained epiclastic sediments they can potentially host significant, usable quantities of groundwater. However, where an Ellensburg unit consists of fine-grained sediments, it may form an aquitard. Second CRBG flows do terminate and allow interbedded sediments units as well as post-CRBG (suprabasalt) sediments to be in local hydrologic communication with each other.

Secondary Controls on CRBG Hydraulic Characteristics
Natural processes and artificial features can modify the specific, and overall, hydraulic behavior of CRBG aquifers and aquitards. These include: (1) erosional windows, (2) tectonic fracturing forming faults/tectonic joints, (3) folding, (4) secondary mineralization, (5) feeder dikes and, (6) construction of uncased water wells through multiple CRBG aquifers. The potential effects on CRBG groundwater systems can range from benign to profound. Understanding these impacts is critically important to accurately interpreting the hydraulic of CRBG aquifer systems.

Erosional windows
Throughout the region there are numerous examples of erosion into, and through, multiple CRBG interflow zones in Channeled Scabland coulees and major river canyons (Fig. 23). The 3rd Edition of the GWMA subsurface geologic mapping report shows the effects of these erosional features on the lateral continuity of numerous CRBG units. Depending on the depth of incision through the CRBG, the presence of surface water and groundwater, and hydraulic gradient, these canyons can act as discharge areas for groundwater and/or recharge areas for groundwater. Figure 24 diagrammatically illustrates several of these possible relationships.

Faults and Tectonic Joints
The presence of faults that transect the CRBG can potentially impact groundwater movement (Newcomb 1959, 1961, 1969; Johnson et al., 1993) (Figs. 25 and 26). 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) supports interpretations regarding the potential for faults to act as barriers to groundwater flow. Johnson et al. (1993) interpreted the Cold Creek 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 basalt aquifers, thus producing a constriction in horizontal groundwater movement across the fault. Similar geologic settings are found along the Frenchman Hills and Saddle Mountains. The effect of faults on groundwater flow in these areas has not been investigated in detail, although we strongly suspect they act as major barriers within the groundwater system, effectively separating groundwater resources on either side of them.

Faults can form barriers to the lateral and vertical movement of groundwater; a series of faults can create hydrologically isolated areas. Faults and joints also can provide a vertical pathway (of varying length) for groundwater movement allowing otherwise confined CRBG aquifers to be in direct hydraulic communication. They can also provide
a direct connection between the surface and interflow zones creating local opportunities for aquifer recharge and/or discharge.

The ability of faults to affect CRBG groundwater 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 completeness of this process would produce hydrologic heterogeneities along the trace of the fault. Even if a fault zone is completely healed by secondary alteration and mineralization, renewed movement (displacement) on the fault could produce new permeable zones within the healed shatter breccia (e.g., USDOE, 1988; Johnson et al., 1993).

**Folding**

A number of groundwater investigations in the Columbia Plateau area have noted that folds (primarily anticlinal and monoclinal folds) affect the occurrence and movement of groundwater through CRBG aquifers (e.g., Newcomb 1961, 1969; Gephart et al., 1979; Oberlander and Miller, 1981; Lite and Grondin, 1988; USDOE, 1988; 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.

During the process of folding, slippage parallel to the layers (CRBG flows) will occur, in part, to accommodate structural shortening. An analogy for this process is seen when a deck of playing cards is flexed and the individual cards slip past one another to accommodate the flexure. The tighter the flexure of the cards is, the greater the interlayer slippage. In folds, this type of flexural slip typically occurs within CRBG interflow zones (Newcomb, 1969; Price, 1982; Anderson, 1987) which are the mechanically weakest layers in the Columbia River basalt (Fig. 27). The effects of this flexural slip on CRBG interflow zone range from minor shearing to nearly complete destruction (production of fault shatter breccia/gouge material) and are directly related to the intensity and magnitude of deformation (Price, 1982; Anderson, 1987). This process also impacts the original hydraulic characteristics of interflow zones, reducing or even destroying the permeability of these features (Newcomb, 1969; Yechiel et al., 2007).

**Secondary Alteration and Mineralization**

A number of different secondary processes can change the physical characteristics of CRBG interflow zones which, consequently, alter the hydraulic properties of these features. The common aspect to all of these secondary processes is that they fundamentally change the original physical (and hydraulic) characteristics of CRBG flow tops and flow bottoms. The two most important of these processes are briefly described in the following sections.
Paleosol Development: If a sufficiently long hiatus occurred between emplacement of successive CRBG flows, weathering and chemical breakdown of the glassy vesicular flow top would lead to soil formation. This process would typically alter and destroy the original physical texture of a portion of the flow top as well as most of its original permeability. The extent of the flow top involved, and degree to which these paleosols are developed varies widely. Factors controlling paleosol development are thought to include the length of time between emplacement of successive basalt flows, absence of sediment cover, and environmental conditions (e.g., climate, vegetation, paleogeography, etc.). It is interesting to note that deeply weathered flow top paleosols are not commonly observed in the subsurface within the CRBG in the Columbia Basin, suggesting relatively dry conditions may have persisted through much of CRBG time.

Precipitation of Secondary Minerals: After the emplacement and burial of the CRBG flows, low-temperature water-rock interactions resulted in formation of secondary minerals (e.g., silica, cryptocrystalline quartz, zeolites, clay minerals, calcite, pyrite, etc.) which partially to completely fill existing voids within interflow zones. Precipitation of secondary minerals depends on a number of variables including hydrochemistry, groundwater flow and mixing rates, residence times, and local geothermal regime (USDOE, 1988). The net effect of secondary mineralization on CRBG interflow zones is a reduction, ranging from slight to total, in the permeability of these zones. This process is also important in sealing cooling fractures within dense flow interiors.

Feeder Dikes
As noted earlier in this report, CRBG flows were emplaced by large volume volcanic eruptions. These eruptions generally occurred in elongated linear vent systems that potentially extended many miles across the landscape. The surficial and subsurface manifestation of these linear vent systems are feeder dikes (Fig. 28). Feeder dikes are the lava that solidified in the vent following flow unit emplacement.

The hydrologic influence of feeder dikes cross-cutting the CRBG aquifer system may be profound. Where these features are present they physically disrupt the lateral continuity of interflow zones they cross-cut. That being the case, it seems likely that CRBG feeder dikes have the potential to impede, if not block (at least locally), lateral groundwater movement through the planar-tabular interflow zones which dominates the CRBG groundwater system. Figure 29 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 Wells
Construction of water wells that are open to more than one CRBG interflow zone creates man-made, vertical pathways which allow groundwater to migrate between CRBG aquifers having different hydraulic heads (USDOE, 1988; Lite and Grondin, 1988; Wozniak, 1995). Historically, the construction of water wells open to multiple CRBG interflow zones (aquifers) has been the norm, rather than the exception. This is because the CRBG has generally been treated as a single aquifer, or a very small number of aquifers, instead of a multiple aquifer system. Therefore in regions where the CRBG groundwater is the primary source for domestic, agricultural, and/or industrial water use, locally significant vertical connectivity within the CRBG groundwater system can exist.
due to water wells open to different aquifers. This is even more important in areas where
the CRBG aquifers exhibit artesian conditions.

**Potential Recharge/Discharge – CRBG Aquifers**

Based on past studies direct recharge of shallower CRBG aquifers within the GWMA
region results from infiltration of precipitation, runoff, and irrigation water within, and
along the margins of, the Columbia Basin (Newcomb 1969; USDOE, 1988; Hansen et al.,
1994; Bauer and Hansen, 2000). Infiltration has been variously interpreted to be
vertically downward along faults, past the ends of flow pinchouts, where CRBG flows
are breached by erosional windows, on highlands within and bordering the Columbia
Basin, and through dense flow interiors. Recharge of the deeper Wanapum and Grande
Ronde aquifers is inferred to occur largely from interbasin groundwater movement
originating around the edge of the Columbia Basin in areas where limited exposures of
the Wanapum and Grande Ronde Basalts occur (Gephart et al., 1979; USDOE, 1988;
Hansen et al., 1994) and downward through overlying CRBG flows (Hansen et al., 1994;
Bauer and Hansen, 2000). However, based on the physical geology of the CRBG
summarized herein, it seems likely that vertical leakage through multiple, dense, CRBG
basalt flow interiors is greatly restricted and that the primary source of natural recharge
into the CRBG aquifer system is through erosionally thinned units, around erosional and
emplacement pinchouts, through open faults and tectonic fractures, and in up-dip areas
where units thin and pinchout and where successive interflow zones come into contact,
forming a direct hydraulic connection with each other.

Groundwater discharge from the shallow Saddle Mountains Basalt aquifer, where it
occurs, is inferred to be to surface water bodies (e.g., Columbia and Snake Rivers) or
suprabasalt sediment aquifers (Newcomb 1969; USDOE, 1988; Hansen et al., 1994).
Where the Wanapum Basalt aquifer is present at shallow depths, such as within Yakima
Fold anticlines, water gaps, and/or scabland coulees, it is also inferred to discharge to the
overlying suprabasalt sediment aquifer, surface waters (e.g., Crab Creek, Columbia, and
Snake Rivers), and the shallower Saddle Mountains Basalt aquifer, where present
(Hansen et al., 1994). Erosional windows through CRBG dense flow interiors at the top
of the CRBG aquifers also have been shown to allow direct interconnection between the
suprabasalt sediments and CRBG aquifers (Graham et al., 1984) and between CRBG
aquifers.

Potential discharge areas for the deeper aquifers (i.e., Wanapum and Grande Ronde
Aquifers) are uncertain, but groundwater flow is inferred to be generally southwestward
with discharge speculated to occur south of the Pasco Basin (USDOE, 1988) where folds
and faults bring Wanapum and Grande Ronde flows closer to the surface. Hansen et al.
(1994) and Bauer and Hansen (2000) have also speculated that discharge from deep
CRBG aquifers may be directly upward through multiple dense basalt flow interiors into
major rivers like the Columbia and Snake. However, it is difficult to envision this given
the physical properties of CRBG basalt flows in this stratiform aquifer system. If such
movement of groundwater through multiple, dense CRBG flow interiors is occurring, it
must be extremely slow, being measured in extremely long geologic terms, not human
terms.
The thick sequence of layered flood-basalt flows of the CRBG are prime sources of potable groundwater throughout their extent in Washington, Oregon, and Idaho. Having a realistic and accurate understanding of how ground water enters and moves through these flood-basalt flows is of fundamental importance to anyone working with CRBG aquifer systems (e.g. resource assessments, contaminant transport/fate, aquifer storage/recovery, regulatory assessment).

One of the most extraordinary features of the CRBG is the physical dimensions of individual layered basalt flows. A conceptual understanding of the nature of CRBG flows plays a critical role in accurately interpreting some of the unique hydrogeologic aspects of these basalt flows. During the peak period of CRBG eruptive activity (Grande Ronde and Wanapum Basalts) it was common for eruptions to rapidly (~2 to ~12 weeks) emplace individual flows having volumes of hundreds of cubic miles and for the lava to cover areas of several thousand square miles, creating the largest known lava flows on the Earth. This combination of huge volume and rapid emplacement typically produced simple sheet flows 30 to >300 feet thick. The great lateral extent of CRBG flows differs markedly from more typical compound basalt flows which display numerous, interfingering, discontinuous, lenticular layers.

Aquifer horizons within the CRBG generally are associated with intraflow structures at the top (e.g., vesicular flow-top, flow-top breccias) and bottom (e.g., flow-foot breccias, pillow lava/hyaloclastite complexes) of individual sheet flows. The interiors of thick sheet flows (in their undisturbed state) have, for all practical purposes, extremely limited permeability and may in effect be locally impermeable. As a consequence, they act as aquitards, typically separating groundwater in successive interflow zones. The net consequence of this is that groundwater within the CRBG occurs in a series of layered (stratiform), stacked confined aquifers.

The lateral continuity of these stratiform aquifers is controlled by the lateral continuity of the interflow zones (flow tops, flow bottoms, and sedimentary interbeds – if any) in which groundwater occurs and the lateral continuity of the dense flow interiors that separates these zones. Lateral continuity of CRBG interflow zones, and the groundwater within them, can be compromised by: (1) erosion into, or completely through, units, (2) the pinchout of dense flow interiors where flow units terminate and interflow zones merge, (3) structural features which have disrupted the stratigraphic sequence via folding and/or faulting, and (4) feeder dikes cross-cutting the stratigraphic sequence. Erosion and flow unit pinchouts generally promote hydrologic continuity between individual interflow zones. Conversely, feeder dikes and large folds likely form barriers or impediments to groundwater flow. Depending on the local characteristics of faults, they can act as either impediments or pathways for groundwater flow.

The dominant groundwater flow pathway within the CRBG aquifer system is horizontal to sub-horizontal and down-dip along individual, laterally extensive, interflow zones. Given the physical properties of the CRBG, outcrop observations, and interpretations of well hydraulics vertical groundwater movement through undisturbed basalt flow interiors is greatly restricted. However, vertical groundwater movement between layered CRBG
aquifers is possible, but only occurs under specific geologic and anthropogenic conditions where basalt flow interiors are disturbed (such as by folds or faults), truncated (such as by flow pinchouts, erosional windows), or where they are cross-connected by wells.

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of Natural Resources, Division of Geology and Earth Resources Geologic Map GM-39, 36 p., 3 plates.


Figure 1. Distribution map showing the redefined extent of the Columbia River Flood Basalt Province. MC = McDermitt caldera, OIG = Oregon-Idaho graben, WSRP = Western Snake River Plain. From Camp and Ross (2004).
Figure 2. Stratigraphic nomenclature of the CRBG. From Reidel et al. (1989b) and Tolan et al. (1989).
Figure 3. Maps showing the areal extent of selected CRBG formations exposed in the Columbia Plateau (from Reidel et al. (1989b) and Tolan et al. (1989)). These maps show the interpreted extent at the time of emplacement, not the current mapped extent. The boundary of the Columbia Basin Ground Water Management Area is shown in red.
Figure 4. Plot showing the emplacement history for the CRBG units based on volume estimates from Tolan et al. (1989). Note the change in scale for volume. Members consisting of a single flow (e.g., Pomona Member) are presented by a single line. Letters designate the following units: E = Eckler Mtn. Member; FS = Frenchman Springs Member; R = Roza Member; PR = Priest Rapids Member; U = Umatilla Member; W = Wilbur Creek Member; A = Asotin Member; WF = Weissenfels Ridge Member; EQ = Esquatzel Member; P = Pomona Member; EM = Elephant Mtn. Member; B = Buford Member; IH = Ice Harbor Member; L = Lower Monumental Member.
Although CRBG eruptive activity spanned an 11 million year period, most (>96 volume %) of the CRBG flows were emplaced over a 2.5 million year period from 17 to 14.5 million years ago.

Most CRBG flows were of extraordinary size, commonly exceeding 120 to 240 cubic miles in volume, traveled many hundreds of miles from their linear vent systems, and covered many thousands of square miles. These gigantic CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history, as a same-scale comparison between a CRBG flow, the Laki (Skalafell) flow field (largest basalt eruption in recorded human history), and the ongoing Pu'u O'o eruption on the Big Island of Hawaii shows. CRBG flows represent the largest individual lava flows known on the earth.

Field evidence also indicates that these gigantic CRBG flows were very rapidly emplaced – on the order of a few weeks to less than six months.

Figure 5. Same scale diagram comparing the extent of an average CRBG flow unit, Rosalia Flow, Priest Rapids Member, Wanapum Basalt to two modern basalt flow units.
Figure 6. Generalized sketch map showing the distribution of the Cascade Volcanic arc and the CRBG in relation to regional-scale tectonic features. The westward dipping Palouse Slope directed erupting CRBG lava towards the Pasco Basin and through the Cascade arc via the Columbia Trans-Arc Lowland. P = Portland, OR; D = The Dalles, OR; H = Mt. Hood; A = Mt. Adams, SH = Mt. St. Helens. Modified from Beeson and Tolan (1990).
**Sheet vs. Compound Flows.** Rate/volume of lava erupted, lava composition/temperature, vent geometry, topography, and environmental conditions all play significant roles in controlling the overall geometry of individual basalt lava flows or flow fields. There are two basic types of flow geometries – compound flows and sheet flows.

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

Individual, large volume CRBG flows (especially Grande Ronde and Wanapum Basalts) display characteristics consistent with sheet flows. CRBG flows typically only exhibit the complex features associated with compound flows at their flow margins.

![Figure 7](image.png)

Figure 7. Photographs and diagrams comparing the major features and flow unit geometry typical for compound flows and sheet flows.
Figure 8. Diagram showing the basic intraflow structures found in typical CRBG sheet flows.
Figure 9. Photograph of a relatively simple flow top. At the base of the outcrop the flow top is beginning to transition into the entablature/collonade jointing style of the dense flow interior. This outcrop is on Washington Highway 14 in Klickitat County.
Figure 10a. Outcrop of a relatively thick flow top breccia. Several flow lobes are visible in the flow top. Outcrop is located on Washington Highway 14 in Klickitat County.

Figure 10b. Close up photograph of the blocky textures typical of flow top breccias.
Figure 11. The classic columnar jointing seen in so many CRBG flow units. This outcrop is located on Oregon Highway 74 in Morrow County.
Figure 12. The entablature-collonade style of jointing also commonly seen in the CRBG. This outcrop is in Sentinel Gap, in Grant County on Washington Highway 243.
Figure 13. Normal CRBG flow contact. The flow contact is at the distinctive color change (gray-black above to red-brown below) where the geologist to the right is pointing with the hammer handle.
Figure 14. A classic pillow lava complex. This pillow lava complex, at the base of the Ginkgo flow, in the lower Frenchman Springs Member, is exposed on Washington Highway 24, in Grant County at the base of the Sand Hollow grade.
Figure 15. Two spiracles in the upper Frenchman Springs Member. Arrows point to the edges of the spiracles.
Figure 16. Diagram illustrating stratigraphic nomenclature and relationships between the CRBG and Ellensburg Formation interbeds, and suprabasalt sediments in the central and west-central portion of the Columbia Plateau, Washington. The pink highlight indicates CRBG units and the yellow highlight indicates Ellensburg sedimentary interbeds. From Smith et al. (1989).
Figure 17. Structural subprovinces in and around the Columbia Basin.
Figure 18. Diagram depicting common features found within fault zones that transect CRBG flows.
Figure 19. This outcrop shows the lateral variation possible in a flow top breccia. Hydrologically, such thickening and thinning of a flow top breccia could have profound impact on well pumping performance and boundary conditions inferred from pumping tests. This outcrop is located on Washington Highway 14 in Klickitat County.
Figure 20. Columbia River basalt flow layers are known to pinch out. These pinchouts essentially mark the lateral termination of individual basalt flow layers. Where layers pinchout, the impermeable flow interior is absent and potentially water-bearing flow tops and bottoms are in direct hydrologic connection. Flow margins create very limited (single flow) vertical connections. Outcrop is located on Washington Highway 28, west of Quincy in Grant County.
Figure 21. Diagram illustrating the probable hydrogeologic conditions likely occurring as CRBG units pinch out up-dip.
Figure 22. Diagrammatic illustration of the conceptual hydrogeologic model for the suprabasalt sediment and CRBG aquifer systems in the Umatilla Basin.
Figure 23. Wilson Creek coulee, in western Lincoln County, Washington. This coulee, like dozens in the region cross-cut multiple CRBG flow units, offering abundant opportunity to influence groundwater flow, recharge, and discharge.
Figure 24. Diagram illustrating the potential range of hydrogeologic conditions that might be seen in association with Cataclysmic Flood Channeled Scabland Coulees.
Faults, acting as groundwater dams offset permeable interflow zones, resulting in higher ground water levels on one side of the fault. Faults may also act as a conduit for vertical ground water flow, water moves up or down the fault zone depending on aquifer gradient.

Figure 25. This photograph shows basic geologic relationships in a fault zone. This outcrop is located on Washington Highway 14 in Klickitat County.
Figure 26. Diagram illustrating the probable impacts of faults on groundwater movement within the layered CRBG aquifer system.
Figure 27. Influence of folds on groundwater movement. In monoclones, during formation, the flexure zone, which is commonly associated with a reverse fault, experiences compressional forces that shear the layers, which reduces the porosity and permeability of the interflow zones. Groundwater elevations in a given interflow zone therefore are much higher upgradient of the flexure zone than downgradient of the flexure zone. This difference exists in part because of the elevation difference across the flexure zone, but also because the reduced permeability in the axis of the flexure zone causes the flexure zone to act as a partial, or nearly complete, hydraulic barrier to groundwater movement. In Yakima folds, folds can control the basalt aquifer system, usually forming barriers to ground water flow, and subdividing the aquifer system into ground water sub basins. Ground water systems on either side of these folds typically do not display significant hydrologic connection.
Figure 28. Feeder dikes, from which Columbia River basalt lave flows erupted millions of years ago, form long, nearly vertical subsurface features which probably form boundaries to groundwater flow. This outcrop is located in southern Franklin County several miles west (downstream) of Lower Monumental Dam.
Figure 29. Diagrammatic illustration of the probable impact of CRBG feeder dikes on CRBG hydrogeology within the strata they cross-cut.