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Are the Columbia River Basalts, Columbia Plateau, Idaho, Oregon, and Washington, USA, a Viable Geothermal Target? A Preliminary Analysis

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ABSTRACT

The successful development of a geothermal electric power generation facility relies on (1) the identification of sufficiently high temperatures at an economically viable depth and (2) the existence of or potential to create and maintain a permeable zone (permeability $>10^{-14}$ m^2) of sufficient size to allow efficient long-term extraction of heat from the reservoir host rock. If both occur at depth under the Columbia Plateau, development of geothermal resources there has the potential to expand both the magnitude and spatial extent of geothermal energy production. However, a number of scientific and technical issues must be resolved in order to evaluate the likelihood that the Columbia River Basalts, or deeper geologic units under the Columbia Plateau, are viable geothermal targets.

Recent research has demonstrated that heat flow beneath the Columbia Plateau Regional Aquifer System may be higher than previously measured in relatively shallow (<600 m depth) wells, indicating that sufficient temperatures for electricity generation occur at depths < 5 km. The remaining consideration is evaluating the likelihood that naturally high permeability exists, or that it is possible to replicate the high average permeability (approximately 10^{-14} to 10^{-12} m^2) characteristic of natural hydrothermal reservoirs. From a hydraulic perspective, Columbia River Basalts are typically divided into dense, impermeable flow interiors and interflow zones comprising the top of one flow, the bottom of the overlying flow, and any sedimentary interbed. Interflow zones are highly variable in texture but, at depths <600 m, some of them form highly permeable regional aquifers with connectivity over many tens of kilometers. Below depths of ~600 m, permeability reduction occurs in many interflow zones, caused by the formation of low-temperature hydrothermal alteration minerals (corresponding to temperatures above ~35 ºC). However, some high permeability ($>10^{-14}$ m^2) interflows are documented at depths up to ~1,400 m. If the elevated permeability in these zones persists to greater depths, they may provide natural permeability of sufficient magnitude to allow their exploitation as conventional geothermal reservoirs. Alternatively, if the permeability in these interflow zones is less than 10^{-14} m^2 at depth, it may be possible to use hydraulic and thermal stimulation to enhance the permeability of both the interflow zones and the natural jointing within the low-permeability interior portions of individual basalt flows in order to develop Enhanced/Engineered Geothermal System (EGS) reservoirs. The key challenge for an improved Columbia Plateau geothermal assessment is acquiring and interpreting comprehensive field data that can provide quantitative constraints on the recovery of heat from the Columbia River Basalts at depths greater than those currently tested by deep boreholes.

1. INTRODUCTION

Conventional geothermal resources are formed due to hydrothermal fluid circulation that results from the convergence of high temperatures and high permeability, typically fracture permeability produced as a result of recent or active faulting. Enhanced/Engineered Geothermal Systems (EGS) are an experimental class of geothermal resources, currently restricted to pilot projects, that require some form of mechanical, thermal, and/or chemical stimulation to develop the permeability necessary for the circulation of hot water or steam and the recovery of heat for commercial applications (DOE, 2008).

Successful implementation of geothermal projects requires (1) identification and characterization of those parts of the upper crust with temperatures high enough for geothermal power production, (2) determination of the conditions under which natural permeability exists or EGS stimulation can replicate the permeability characteristic of natural geothermal reservoirs, and (3) evaluation of the potential for maintaining effective reservoir permeability over the planned lifetime of the reservoir.

Although there are gaps in the spatial coverage of heat flow measurements in much of the United States and uncertainty in the estimation of thermal properties at depth, analysis of the existing thermal data indicates that much of the western United States and large areas in the rest of the country will be suitable for geothermal energy development using conventional or EGS development techniques, provided the rocks at depth are viable for reservoir creation (Williams and DeAngelo, 2011). As discussed below, results of data analysis and coupled heat- and fluid-flow modeling presented by Burns et al. (2015) indicate that temperatures in the deeper portions of the Columbia River Basalts are high enough to be of interest for geothermal development. One remaining critical element, and the focus for this paper, is determining those conditions under which naturally-high permeability exists or where it is possible to develop the high average permeability characteristic of natural geothermal reservoirs. Our analysis of EGS for the Columbia Plateau is limited to the potential for creation of connected open fractures given the current state of the science of EGS and available knowledge of deep geology.

2. GEOLOGY OF THE COLUMBIA PLATEAU

The Columbia Plateau lies in a structural and topographic basin within the Columbia River drainage. It is bounded on the west by the Cascade Range, on the east by the Rocky Mountains, on the north by the Okanogan Highlands, and on the south by the Blue Mountains (Fig. 1). The Columbia Plateau is underlain by a thick sequence of Columbia River Basalt Group (CRBG) lava flows, a series of more than 300 flows and sedimentary interbeds that erupted 17 million to 6 million years ago. CRBG flows were emplaced primarily as sheet flows that were areally extensive, often covering tens-of-thousands of km^2. CRBG sheet flows often transition to mega-scale compound flow geometries near flow margins. Individual flows range in thickness from 3 to more than 100 m (Tolan et al., 1989, Drost et al., 1990). In the south-central portion of the Columbia Plateau, the total thickness of the CRBG is estimated to exceed 5 km (Reidel et al., 2002, Burns et al., 2011). Thick sedimentary deposits overlie the basalts in a number of hydraulically separated structural basins (Smith et al., 1989; Reidel and Tolan, 2013), but basalt units occur at or near land surface over most of the Columbia Plateau (Burns et al., 2011). CRBG units are variably folded and faulted. Generally, structural intensity is higher within the uplifted Blue Mountains and within the Yakima Fold Belt (i.e., the area to the north of the Horse Heaven Hills).

Stratigraphically, the CRBG has been divided into six geologic formations by Swanson and others (1979): Imnaha Basalt, Picture Gorge Basalt, Prineville Basalt, Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt. Beneath the Columbia Plateau, the thickest and most extensive of the CRBG formations are, in order of decreasing volume and extent, the Grande Ronde, the Wanapum, and the Saddle Mountains Basalts.

The pre-CRBG units (labelled “Older Bedrock” on Fig. 1) are composed of various rock types (Campbell, 1989; Kahle and others, 2009). In Washington and Idaho, the outcrops of these rocks bordering the CRBG consist mostly of sedimentary and granitic rocks. In Oregon, the bordering older rocks are sedimentary, volcaniclastic, volcanic, plutonic, and metamorphic (Drost and others, 1990). Beneath the CRBG, the older rocks are poorly defined in both composition and extent, so our discussion of permeability under the Columbia Plateau is restricted to the CRBG.

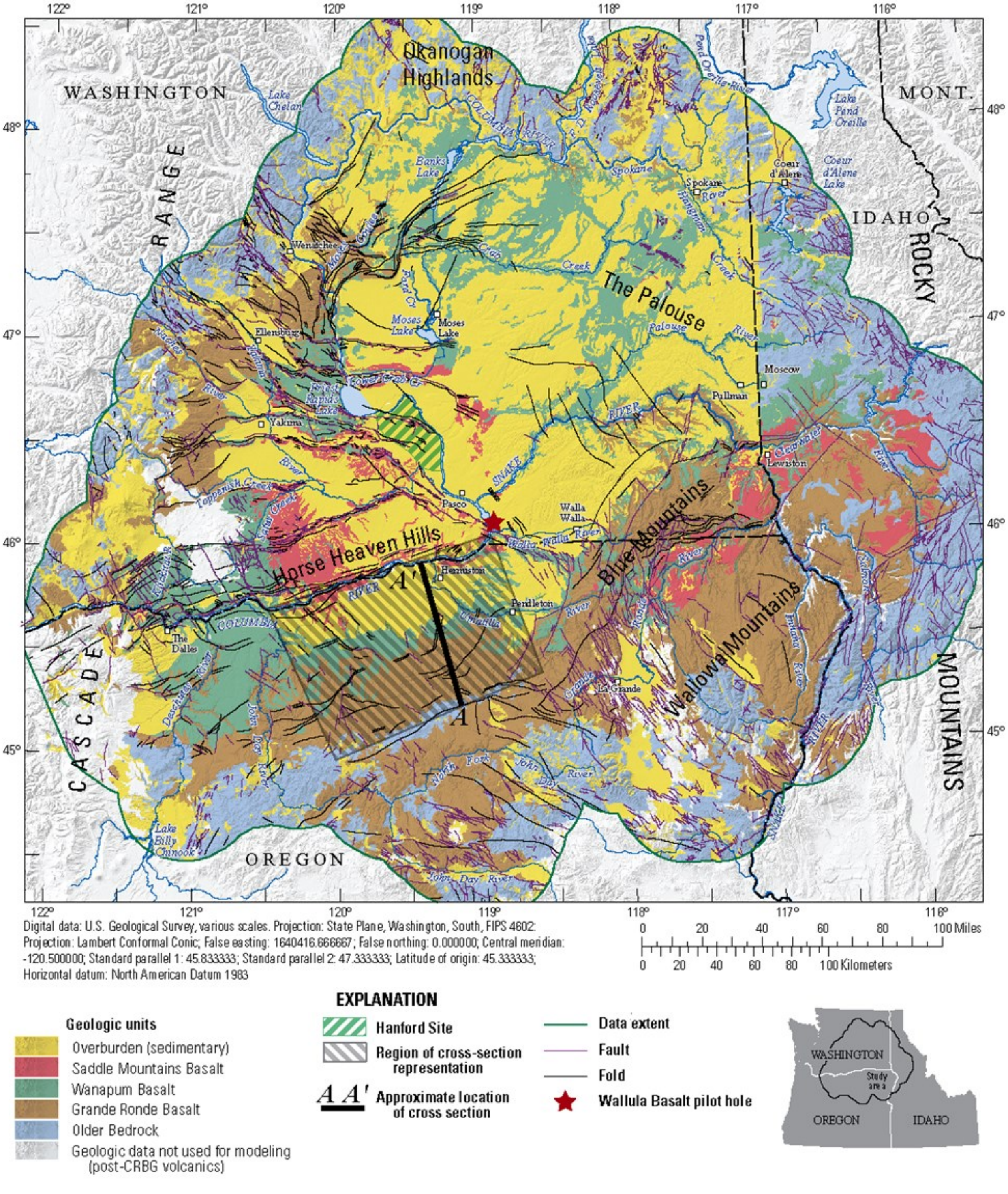
More detailed descriptions of the geology are provided by Kahle et al. (2009) and Tolan et al. (2009), who discuss the general geology, structural geology, and hydrogeologic framework of the CRBG units in the vicinity of the Columbia Plateau; Burns et al. (2011), who describe the three-dimensional characteristics of the geology of the Columbia Plateau Regional Aquifer System (CPRAS); and GSA Special Paper compilations on the Columbia River Flood Basalt Province (Reidel and Hooper, 1989; Reidel et al., 2013).

3. HEAT FLOW BENEATH THE COLUMBIA PLATEAU

Coupled heat- and groundwater-flow simulations demonstrate that average heat flow at depth under the CPRAS is likely closer to the value of ~70-80 mW/m^2 expected for Tertiary tectonic provinces (Pollack et al., 1993) than previous mapping exercises (Williams et al., 2008a,b, Williams and DeAngelo, 2011) had indicated (Burns et al., 2015). Most existing heat-flow measurements within the CRBG are from depth shallower than 600 m [the estimated thickness of the highly permeable part of the CPRAS (Burns et al., 2015)] or near regional groundwater discharge zones, so that conductive heat-flow maps generated using these data are likely influenced by groundwater flow. Simulations and sparse field data demonstrated that conductive heat flow dominates at greater depths, providing sufficient thermal gradients such that temperatures exceeding 150 ºC occur at depths < 5 km (Fig. 2).

4. PERMEABILITY IN THE COLUMBIA RIVER BASALTS: CONCEPTUAL MODELS AND OBSERVATIONS

In the following sections, the terms permeability, hydraulic conductivity, and transmissivity are used to describe the ease of fluid flow, generally corresponding to the usage in the cited source. The three terms are correlated but not synonymous, and understanding the definition of each allows us to compare the work summarized by different authors. Hydraulic conductivity (K; units: L/T) is the coefficient that converts a gradient in hydraulic head to the Darcy flux. Transmissivity is equal to the hydraulic conductivity times the thickness of the corresponding geologic unit (units: L^2/T), and this term is frequently used when it is not possible to make a reliable estimate of saturated thickness (e.g., during an aquifer test where unit thickness is sampled only at the borehole). Hydraulic conductivity depends on both the properties of the porous media (its permeability, also called intrinsic permeability; units: L^2) and the properties of the fluid (its density and viscosity). When considering liquid water systems, and for measurements of hydraulic conductivity that vary over orders of magnitude, most of the variation is due to changes in permeability, because variations in viscosity and density are relatively small under typical environmental conditions. The term bulk permeability is used to describe the average permeability of geologic material, integrating the influence of discrete high-permeability units and surrounding lower permeability units.



Digital data: U.S. Geological Survey, various scales. Projection: State Plane, Washington, South, FIPS 4602: Projection: Lambert Conformal Conic; False easting: 1640416.666667; False northing: 0.000000; Central meridian: -120.500000; Standard parallel 1: 45.833333; Standard parallel 2: 47.333333; Latitude of origin: 45.333333; Horizontal datum: North American Datum 1983

Figure 1: Study area and geologic map data used to construct the geologic model of the Columbia Plateau regional aquifer system, Idaho, Oregon, and Washington (Burns et al., 2011). The Columbia Plateau proper is the structural lowland between the Blue Mountains and the Cascade Range. The Saddle Mountains, Wanapum, and Grande Ronde Basalts comprise the Columbia River Basalt Group in the vicinity of the Columbia Plateau. The cross-section is the approximate location of 2-D heat flow modeling shown in Fig. 2, and the shaded area shows the region of the domain that the model represents.

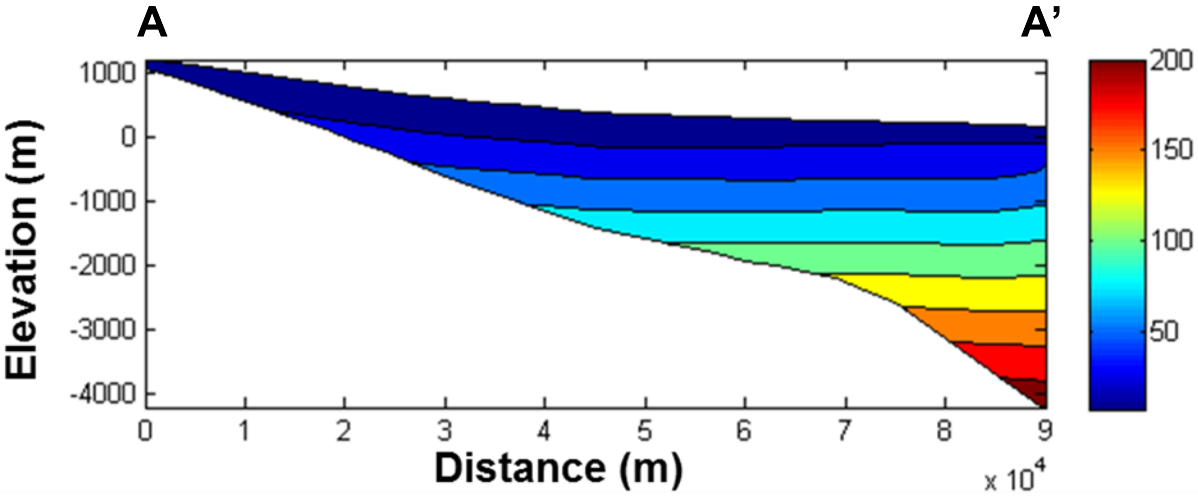


Figure 2: Simulated temperatures (contour interval 25 °C, starting at zero) from a representative cross-section from the Blue Mountains to the Columbia River (Fig. 1) through the Columbia River Basalts (from Burns et al., 2015). Heat conduction is assumed to dominate in the older rock beneath the CRBG. Assuming a basal heat flow of 80 mW/m^2, temperatures are estimated to exceed 150 ºC at depths >3 km. The thickest parts of the CRBG (estimated to be ~5 km) are to the northeast of this cross-section. Elevation is measured relative to mean sea level.

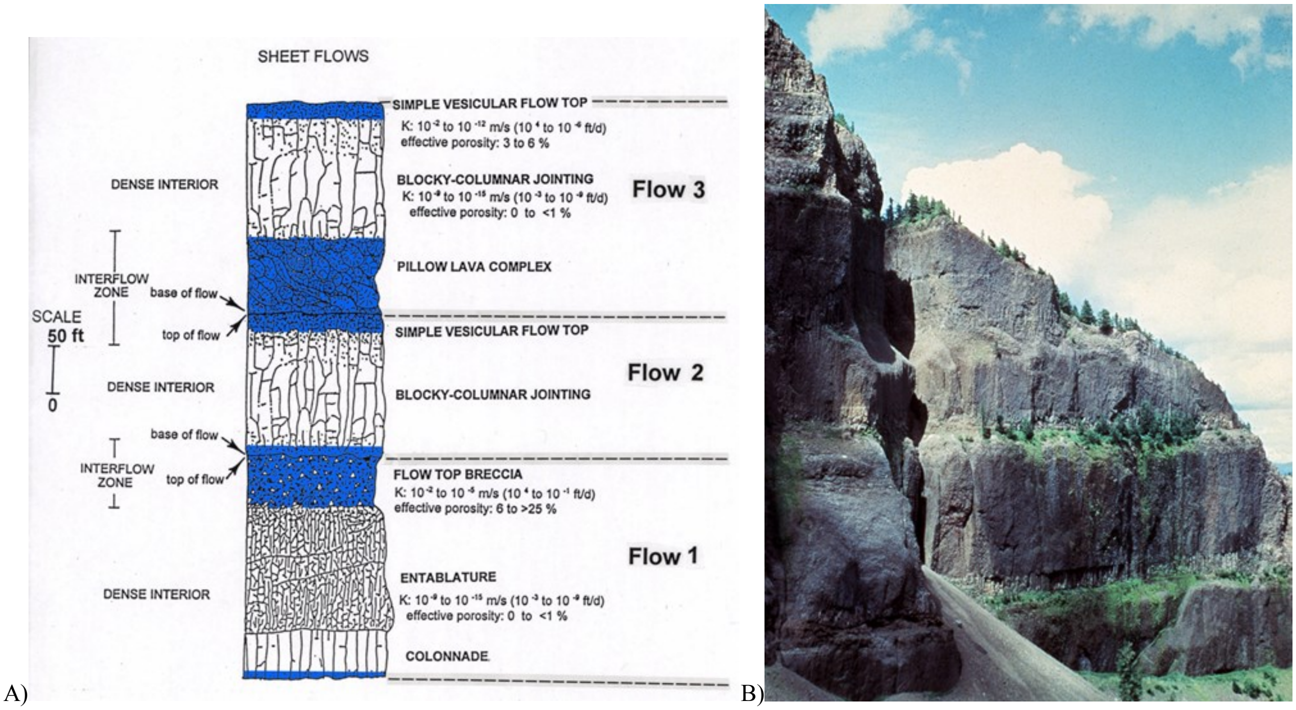


Figure 3: A) Typical internal features of Columbia River Basalt Group (CRBG) flows. Permeable interflow zones (blue) are separated by dense, relatively impermeable flow interiors. At depth, permeability of interflow zones tends to be reduced by hydrothermal alteration at temperatures greater than ~35 ºC. Sedimentary interbeds (not shown) are variable in texture and may form confining units between permeable flow bottoms and the overlying flow tops, store water for release into aquifers, or may be aquifers themselves. B) Photograph of a series of five CRBG flows that display entablature and colonnade jointing. Despite the joints, spring flow originates from interflow zones, not the dense lava flow interiors.

4.1 Permeability of the Columbia Plateau Regional Aquifer System

Groundwater moves through the CRBG through preferential pathways developed mainly during lava emplacement. Most CRBG lava flows consists of a dense flow interior and flow tops and flow bottoms with a variety of textures (Swanson et al., 1979; Reidel et al., 2002, Fig. 3). Although flow interiors have joints and fractures, they typically do not transmit water easily. Flow tops and bottoms are commonly vesicular or brecciated, and may or may not be permeable. Local permeability of flow tops and bottoms can be highly variable over short distances as a result of paleo-environmental conditions and emplacement processes (Beeson et al., 1989; Tolan et al., 2009), but high-permeability zones tend to be connected, resulting in highly transmissive aquifers at the regional scale. The CRBG thus comprises a stack of laterally extensive sheet flows, with relatively thin permeable zones hosted by flow tops and flow bottoms separated by relatively thick dense flow interiors of low permeability. Thin permeable aquifers are estimated, on a regional scale, to typically occupy about 10 percent of the total thickness. Flow interiors have both low permeability and low storage characteristics, so that they form effective confining units. As a result, the aquifer system is highly anisotropic, with the effective horizontal hydraulic conductivity (K_h) controlled by the fraction of the thickness occupied by thin aquifers, and the effective vertical hydraulic conductivity controlled by the dense flow interiors. Effective bulk horizontal permeability is frequently more than 10^4 times greater than bulk vertical permeability (summary Tables 2-4 of Kahle et al., 2011). Flow interiors also commonly have negligible porosity, compared to an approximate value of 0.25 for thin interflow zone aquifers (Reidel et al., 2002).

Although available data suggest that horizontal hydraulic conductivity may decrease with increasing depth, earlier modeling studies were unable to confirm substantial depth-dependence (Burns et al., 2015). Hansen et al. (1994) simulated groundwater flow through the entire thickness of the CPRAS, but during calibration they found indications that horizontal hydraulic conductivity values might decrease with increasing depth. They invoked the equations of Weiss (1982), assuming that K_h decreases as a function of overburden pressure only, resulting in a typical reduction in permeability by a factor of less than two over the entire thickness. More recent simulations of the CPRAS (Ely et al., 2014) tested the hypothesis that horizontal permeability decreases with increasing depth using robust parameter estimation techniques, but found that the calibration data were insufficient to support or refute a persistent vertical trend in permeability. Hansen et al. (1994) estimated that CRBG bulk K_h ranges from $3.0\text{x}10^{-7}$ to $3.0\text{x}10^{-5}$ m/s, and Ely et al. (2014) estimated that CRBG bulk K_h ranges from $3.5\text{x}10^{-6}$ to $9.9\text{x}10^{-5}$ m/s. Both studies found that K_h varies laterally, with lower K_h occurring in areas with more intense geologic structure (more folds and faults) and higher K_h in relatively undeformed areas.

A compilation of published K_h values from hydraulic tests of CRBG units yielded values ranging from 10^{-15} to 0.21 m/s, over 14 orders of magnitude (Kahle et al., 2011). These tests include both lava interflows (aquifers) and flow interiors (confining units). The K_h estimates from aquifer pump tests documented a narrower range for CRBG aquifers, $2.8\text{x}10^{-7}$ to 0.21 m/s. Near the center of the CPRAS, Spane (1982) found that hydraulic conductivity in the deeper Grande Ronde Basalts tends to be 2-3 orders of magnitude lower than that in the overlying Saddle Mountains and Wanapum Basalts (Fig. 4). However, the Grande Ronde Basalts do not have uniformly lower K_h values throughout the CPRAS (plate 6 of Hansen et al., 1994, and Ely et al., 2014), indicating that the reduction in permeability observed by Spane (1982) may be related to confining depth, temperature, proximity to structurally complex areas, and the degree of hydrothermal alteration.

To allow comparison of all hydraulic conductivity data and to develop estimated relations for simulations, Burns et al. (2015) converted all estimates of permeability, hydraulic conductivity, and transmissivity to effective bulk permeability (Fig. 4). Permeability of the basalt interflow zones can be estimated by multiplying bulk permeability values by 10. Because the permeability measurements exhibit considerable variability, a running average value (black line on Figure 4) was computed using a 200 m moving depth interval. Based on the limited amount of deep aquifer-test data, permeability apparently decreases with depth, with a substantial decline in permeability apparently starting at a depth of about 600 m and slowing below 900 m. This rapid reduction in permeability is attributed to hydrothermal alteration that becomes effective in the temperature range 35-45 ºC. While deep data are sparse, pore-filling alteration minerals (dominated by Fe-rich smectite clays, celadonite, zeolites, and silica) are commonly observed in flow tops and filling the joints and fractures of flow interiors (Reidel 1983; Horton 1991; Reidel et al. 2002; Zakharova et al. 2012). Below the temperature threshold (~600 m), conduction is the dominant mechanism of heat flow (Burns et al., 2015).

Intraflow structures, folds, and faults also affect flow paths through the CPRAS by forming flow barriers or preferential pathways for groundwater flow (Newcomb 1959, Wozniak, 1995, Tolan et al., 2009, Porcello et al., 2009, Snyder and Haynes 2010, Kahle et al., 2011, Burns et al., 2012a,b). Faults can create horizontal flow barriers by juxtaposing thin aquifers with flow interiors, and the barrier effect can be enhanced by alteration of the fault gouge and shatter breccia to low-permeability clay-rich minerals. At the regional scale, geologic structure apparently has the net effect of reducing effective horizontal hydraulic conductivity (Ely et al., 2014). As a result, regional modeling efforts tend to predict lower horizontal hydraulic conductivity than those reported from aquifer tests (for example, Hansen et al., 1994, Kahle et al., 2011). Similarly, modeling efforts result in higher predicted vertical hydraulic conductivity (for example, Hansen et al., 1994) than the values suggested by aquifer tests on basalt flow interiors (for example, Long et al., 1982), because vertical connectivity at the regional scale is affected by the emplacement geometry of individual lava flows, so that water can flow through the vertical stack of lavas via preferred pathways (Burns et al., 2015). From a regional perspective, most faults do not act as pathways for significant vertical fluid flow (Ely et al., 2014). However, recently active faults can transmit water vertically, cross-connecting permeable zones, until alteration of the freshly-exposed fault breccia plugs vertically connected flow paths. Most deep wells analyzed by Spane (2013) are located near the Wallula Fault Zone or within the Yakima Fold Belt, where hydrothermal alteration may have been enhanced. Interflow zones at similar depths in low-deformation areas (e.g., the Palouse to the east, Fig. 1) may have higher permeability.

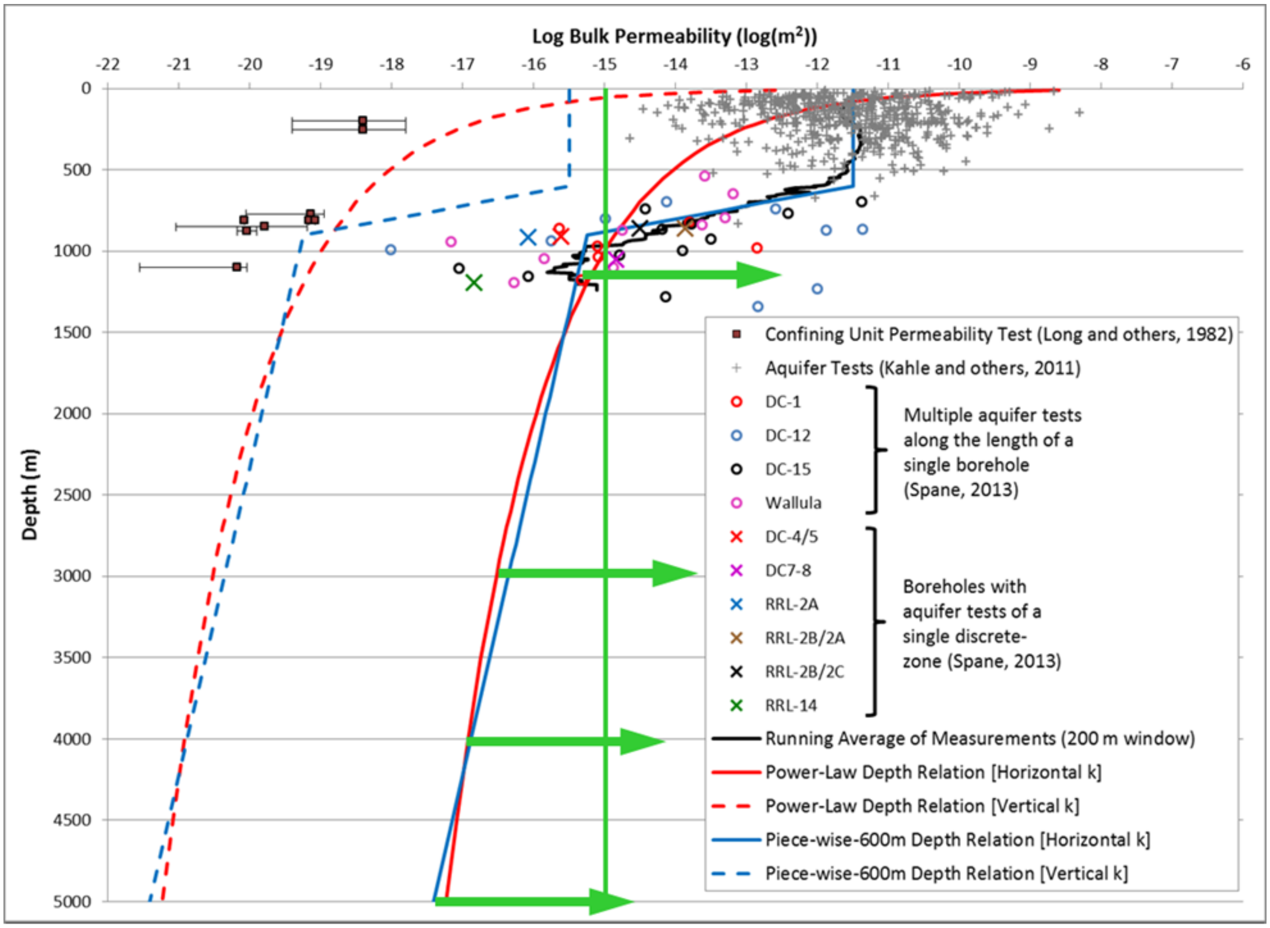


Figure 4: Bulk permeability measurement compilation and depth relations estimating average bulk permeability with depth for the CRBG (after Burns et al., 2015). The vertical green line represents a bulk permeability of 10^{-15} m^2, which corresponds to interflow zone permeability of ~10^{-14} m^2, sufficient permeability for geothermal resource development (Bjornsson and Bodvarsson, 1990). At all sampled depths (i.e., <1.5 km) there is significant variability in permeability of individual interflow zones, including at depths such that hydrothermal alteration is predicted to have occurred (> 600 m). The trend of high permeability zones at each depth is shown with constant-length green arrows (assuming constant variability with depth), indicating that sufficient natural permeability may exist at all depths within the CRBG.

Less commonly, dikes act as barriers to horizontal groundwater flow. CRBG dikes can be vertically and horizontally extensive, cross-cutting many aquifers. Following dike emplacement, residual heat may have driven local hydrothermal circulation that resulted in the formation of pore-plugging alteration minerals near the dike, restricting vertical flow.

Groundwater flows through thin aquifers from the uplands towards large regional rivers (Fig. 5), entering aquifers preferentially in the uplands, where precipitation is higher and lava flow margins are exposed, and exiting at the lowest elevations, where lava flows are connected to streams and canyons. The older Grande Ronde Basalt and Wanapum Basalt flows tend to be more voluminous and more areally extensive and have also undergone more deformation, forming structural and erosional troughs into which younger, less-voluminous Saddle Mountains Basalt flows were emplaced. Some deeper CRBG aquifers may be completely covered by younger CRBG units, restricting recharge.

Groundwater exits CRBG aquifers into rivers and streams and by pumping of wells. The strongest control on hydraulic head in any CRBG aquifer is often the lowest elevation at which the aquifer intersects the land surface (Burns et al., 2012a). Where an aquifer intersects a large regional river, hydraulic head in that aquifer may be similar to hydraulic head in that river. If there is a flow barrier between an aquifer and the large regional river, that aquifer may discharge at higher elevations where upland streams intersect the aquifer (Fig. 5). Groundwater downgradient of the stream-aquifer intersection may be very old (because it is on a long slow flowpath), while water that seasonally fills the upper portions of the aquifer may be much younger. This conceptual model explains why deep aquifers near the center of the Columbia Plateau are more geochemically evolved (Kahle et al., 2011), and why there is significant groundwater contribution year-round to springs and streams near the crest of the Blue Mountains (the anticlinal ridge covered by CRBG flows near the southeastern boundary of the study area).

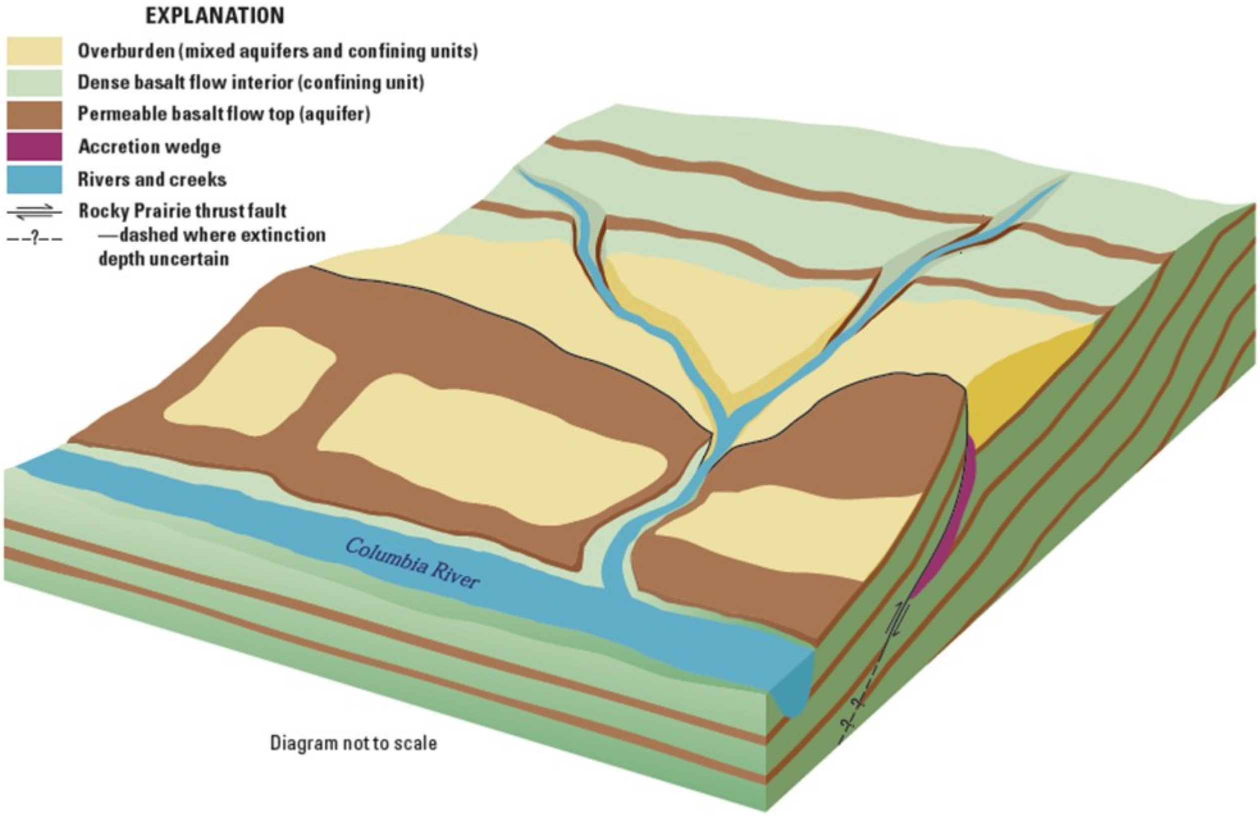


Figure 5: Conceptual model of common features of CRBG aquifer system geometry (from Burns et al., 2012a). Upland recharge enters thin aquifers at flow margins, then flows towards rivers and streams. Geologic structures can act as flow barriers that may or may not cross-cut all aquifers. Deep permeable zones are commonly unconnected with the region of vigorous groundwater flow, so that these slow moving, possibly stagnant, waters do not significantly perturb the deep conductive thermal regime.

4.2 Natural Permeability Beneath the Regional Aquifer System

The thickness of vigorous groundwater flow in the CRBG upper permeable zone is controlled by two factors: (1) the presence of permeable CRBG interflow zones that are connected over great lateral distances, and (2) connection of the permeable CRBG interflow zones to recharge areas and discharge areas. Even if there was no permeability reduction with depth (Fig. 4), groundwater flow might be negligible in deep permeable CRBG interflow zones, because these permeable zones are disconnected from land surface.

Despite the fact that average permeability of CRBG interflow zones apparently decreases to less than 10^{-14} m^2 [the minimum value commonly interpreted as sufficient for geothermal development (Bjornsson and Bodvarsson, 1990)] at depths below ~1 km (Fig. 4), there exists considerable variability in permeability of individual interflows at any sampled depth (Burns et al., 2014). The permeability of individual interflow zones may be greater than 3 orders of magnitude larger than the mean (Fig. 4). If this pattern persists with depth, and Manning and Ingebritsen (1999) and Saar and Manga (2004) models of permeability with depth are correct (red and blue lines on Fig. 4, respectively), then CRBG interflow zones with sufficient natural permeability for conventional geothermal development may exist near the center of the Columbia Plateau, where the CRBG sequence is 3-5 km-thick.

The existence of permeable CRBG zones at >600 m depth was capitalized upon for the Wallula Basalt Pilot Hole for carbon sequestration testing (Spane et al.., 2012, Zhakarova et al., 2012). A target zone at a depth of 850 m was identified, and an extended 20-day aquifer test was performed. Test results indicated a reduction in transmissivity at a hydraulic radius of ~ 50 m, resulting in inner higher-transmissivity and outer lower-transmissivity zones. Assuming a typical interflow thickness of ~3 m, the inner higher-transmissivity zone was estimated to have a permeability of $\sim 10^{-12.35}$ m^2, and the outer zone (radius of investigation estimated to be > 300 m) to have a permeability of $10^{-13.45}$ to $10^{-13.34}$ m^2, the combined regions having sufficient permeability and hydraulic radius for a conventional geothermal project.

Whereas regional groundwater flow can rely on complex horizontal connectivity to transmit water from recharge to discharge areas, a geothermal project needs to engineer recharge and discharge within a single permeable and connected zone. Drilling with a particular CRBG aquifer as the target can be challenging. Over distances of a few tens of meters, the natural variability of the CRBG interflow zone can result in a permeable region in one well, but insufficient permeability in the other well. The variability in interflow zones is the result of paleo-environmental conditions and emplacement processes (Beeson et al., 1989, Tolan et al., 2009, Lite, 2013). While permeable CRBG interflow zones are commonly well-connected over significant distances, the connection could be conceptualized as a trellis, with enhanced connections correlated to paleo-topographic conditions.

4.3 The Potential for Engineered Permeability

Williams and DeAngelo (2015) postulated a procedure to identify viable EGS targets: (1) estimate temperatures in the crust to constrain the thermal resource base, (2) determine the orientation and magnitudes of the principal stresses at depths such that temperatures are of interest for geothermal power production, (3) develop three-dimensional geologic models to describe lithologic variations at those depths, (4) apply calibrated models for permeability creation using available information on stress and lithologic properties at depth, and (5) determine recoverable heat and power from those potential reservoir volumes that possess sufficient permeability creation potential. The changes in permeability predicted by sensitivity to effective normal stress and fracture compliance need to be quantified in absolute terms before they can be incorporated into predictive models for EGS potential.

The highly structured, statistically repeating nature of individual CRBG flows (Fig. 3) could provide a predictable structural framework in which EGS reservoirs can be developed. Structural settings, principal stress orientations, and the anisotropy of the stress tensor vary across the Columbia Plateau. In general, the Columbia Plateau is characterized by a predominantly compressive stress regime favoring reverse faulting or a mixture of reverse and strike-slip faulting (Heidbach et al., 2008). At the Hanford site, borehole breakouts indicate that the regional stress is oriented roughly north-south (Paillet and Kim, 1987), but evidence from the Wallula Basalt pilot hole and vicinity is consistent with horizontal compressive stresses oriented northwest to southeast (Zakharova et al., 2012). These varying stress conditions, along with pervasive primary cooling joints and secondary fractures within CRBG flows, suggest a variety of failure envelopes that may be suitable for permeability enhancement of the pre-existing fractures.

Two zones of weakness within the CRBG that might create long continuous fractures are readily apparent: (1) interflow zones, and (2) columnar or blocky joints that form orthogonally to the basalt interflows (Fig. 3). Basalt interflow zones have higher porosity and may contain sedimentary interbeds and alteration clays that can act as a lubricant for thrust faulting (e.g., Burns et al., 2012a). However, it is unclear under what conditions an interflow zone might create open fractures rather than crushing existing pores or plastically deforming clays. If sufficient permeability can be engineered within deep interflow zones, deviated holes could be drilled into these subhorizontal zones. Stimulation could target an interflow zone to create a tabular heat exchanger bounded by the flow interiors above and below. Further studies will need to account for the potential accommodation of stress by interflow materials.

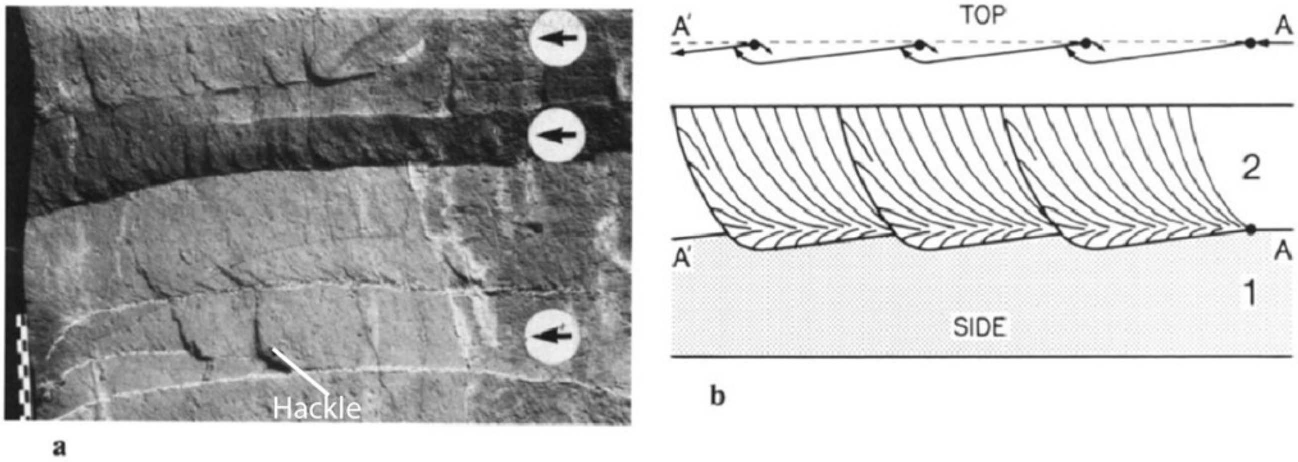


Figure 6: a) Columnar joint surface showing plumose structure, hackles and individual joint surfaces. Arrows indicate joint propagation direction. Curved large breaks have greater relief at the lower edges of cracks, where they begin; b) Idealized formation of three secondary crack surfaces by interrupted propagation of the main crack. Figure adapted from DeGraff and Aydin (1987).

At depth, columnar or blocky joints tend to be closed by overburden pressure. They commonly do not transmit water, as evidenced by high vertical head gradients (Burns et al., 2012b) and the infrequent occurrence of hydrothermal alteration minerals. However, cooling joints exhibit significant surface morphology owing to progressive failure during the fracture growth process. Surface morphology is composed of plumose structures, individual joint surfaces, and hackles. Hackles are linear breaks in crack surface topography that are radial in nature and concentric with respect to the cooling fracture initiation point. Joint propagation leaves a plumose structure on the joint surface, which provides significant topographic relief on cooling joint surfaces at many scales (DeGraff and Aydin, 1987). Shear stimulation experiments on faults and fractures with similar surface morphology at the Desert Peak geothermal reservoir have shown that permeability in otherwise low-permeability rocks can be increased by an order of magnitude (Dempsey et al., 2015) by self-propping of existing fractures. Thus, the abundance of existing fractures, the fracture surface morphology, and anisotropic and heterogeneous state of stress suggest that similar shear stimulation experiments may hold promise in the CRBG. High-pressure stimulation of individual CRBG flows, particularly along directionally drilled wellbores, could reduce normal tractions acting on columnar and secondary joint sets sufficiently to induce shear propping. The high spatial density of joints could provide ample heat exchange area to turn the generally low-permeability CRBG flows into viable geothermal resources.

5. RESEARCH NEEDS

The previous discussions highlight the evidence for sufficient temperatures at an economically viable depth and the possibility of natural or engineered permeability with the CRBG under the Columbia Plateau, acknowledging inherent uncertainties. In the absence of knowledge about specific areas of higher heat flow, or higher temperatures at shallower depths, the primary consideration is whether or not sufficient permeability might be encountered or created. Current evidence suggests that sufficiently deep CRBG units in areas with less geologic structure are more likely to have geologic strata that are contiguous for distances sufficiently long to engineer a productive heat exchanger.

In the search for an elusive geologic target to serve as a heat exchanger of sufficient length (e.g., columnar jointing or open connected interflow zone), it would be useful to develop statistical relations for occurrence of geologic targets conditioned upon nearby geology, which at depth, consists of geologic strata encountered in the current and adjacent boreholes. For example, transition probability statistics might be employed to identify the probability of drilling into a permeable interflow zone within the next 100 m conditioned upon geology encountered in the borehole thus far, other nearby borehole data, and available geophysical data. These transition probability statistics can be compiled from existing boreholes and geologic outcrops, provided that near surface CRBG features are representative of features encountered at greater depths. Even when a geologic target is not encountered in an exploration borehole, 3D geostatistical modeling might be used to identify when the dips of certain strata (measured using borehole geophysical methods) encountered in a borehole might be used to identify proximal targets, giving estimates of distance and direction. This can reduce the uncertainty in where to drill to create a heat exchanger in the subsurface.

A three-dimensional heat and fluid flow model of the CPRAS [based on the groundwater flow simulation model of Ely et al. (2014)] could be calibrated using existing thermal gradient data to estimate depth to viable reservoir temperatures and to explore spatial variability in deep geothermal heat flux. While the cross-sectional modeling of Burns et al. (2015) illustrates that the general heat flow pattern is explained by advective transport of heat, representation of 3D complexity of this system will allow a more complete analysis of available heat flow data, and may identify regions where heat flow patterns cannot be explained solely by advective transport, indicating variations in the underlying geothermal heat flow pattern.

Regional stress-strain modeling of the Columbia Plateau could be used to identify regions where fracture permeability (engineered and natural) is most likely to facilitate creation of a geothermal heat exchanger. Overlaying favorable stress-strain regions with higher simulated temperatures at shallower depths (from combined heat and groundwater flow modeling) and favorable geologic structure could identify areas for focused geothermal exploration.

On the Columbia Plateau, there are few deep wells, and none that target the areas that appear to be of most interest for geothermal development. A targeted drilling program would eventually be required to show efficacy of the proposed models, which are based on knowledge of the shallow CRBG system.

6. CONCLUSIONS

Recent research has demonstrated that heat flow beneath the CPRAS may be higher than that measured in relatively shallow (<600 m depth) wells, indicating that sufficient temperatures for electricity generation occur at depths < 5 km. An analysis of existing CRBG data, compiled mostly from <1 km, indicates that sufficiently high natural permeability may exist at depths of up to 5 km, and that it may be possible to find or replicate the high average permeability (approximately 10^{-14} to 10^{-12} m^2) characteristic of natural hydrothermal reservoirs. The key challenge for an improved Columbia Plateau geothermal assessment, and identification of specific favorable zones for geothermal development, is acquiring and interpreting comprehensive field data in order to locate geologic strata that can serve as viable geothermal heat exchangers at depths greater than those currently sampled by deep boreholes.

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