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Geohydrologic Factors and Current Concepts Relevant to Characterization of a Potential Nuclear Waste Repository Site in Columbia River Basalt, Hanford Site, Washington

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ABSTRACT

Geologic features are identified that may affect groundwater movement near a repository located in the Columbia River basalt beneath the Hanford Site, Washington State. These include pathways through flow interiors, flow contacts, and bedrock structural discontinuities. Four concepts are considered to describe groundwater movement in basalt. Differences between concepts principally focus on the degree of vertical leakage through basalt flow interiors. The existing geohydrologic data base is preliminary and is insufficient to conclusively support one groundwater-flow concept over another. However, it is proposed that available data tend to support the existence of distinct groundwater-flow systems having relatively low vertical leakage under low hydraulic-head gradients except where structural discontinuities are present. A number of geohydrologic characterization activities are under way to reduce the present uncertainty regarding potential groundwater pathways.

INTRODUCTION

The Basalt Waste Isolation Project (BWIP) is chartered to assess the possible use of Columbia River basalts beneath the Hanford Site as a geologic medium for disposal of nuclear waste in an underground repository (Fig. 1). The BWIP is administered by Rockwell Hanford Operations for the U.S. Department of Energy.

This paper provides an interpretive approach to identifying potential groundwater pathways in basalt beneath the Hanford Site. Emphasis is given to identifying stratigraphic and structurally controlled flow paths through which radionuclides might travel from a repository. Much of the data supporting statements found herein are contained in other reports [1-4] or are based on results of work underway by BWIP staff or subcontractor personnel.

A preferred repository location has been identified within the Hanford Site using a screening and ranking process [5-7]. The highest ranked site was designated the reference repository location (Fig. 1). A similar screening of individual basalt flows beneath the reference repository location has identified the Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum flows as candidate repository horizons (Fig. 2).

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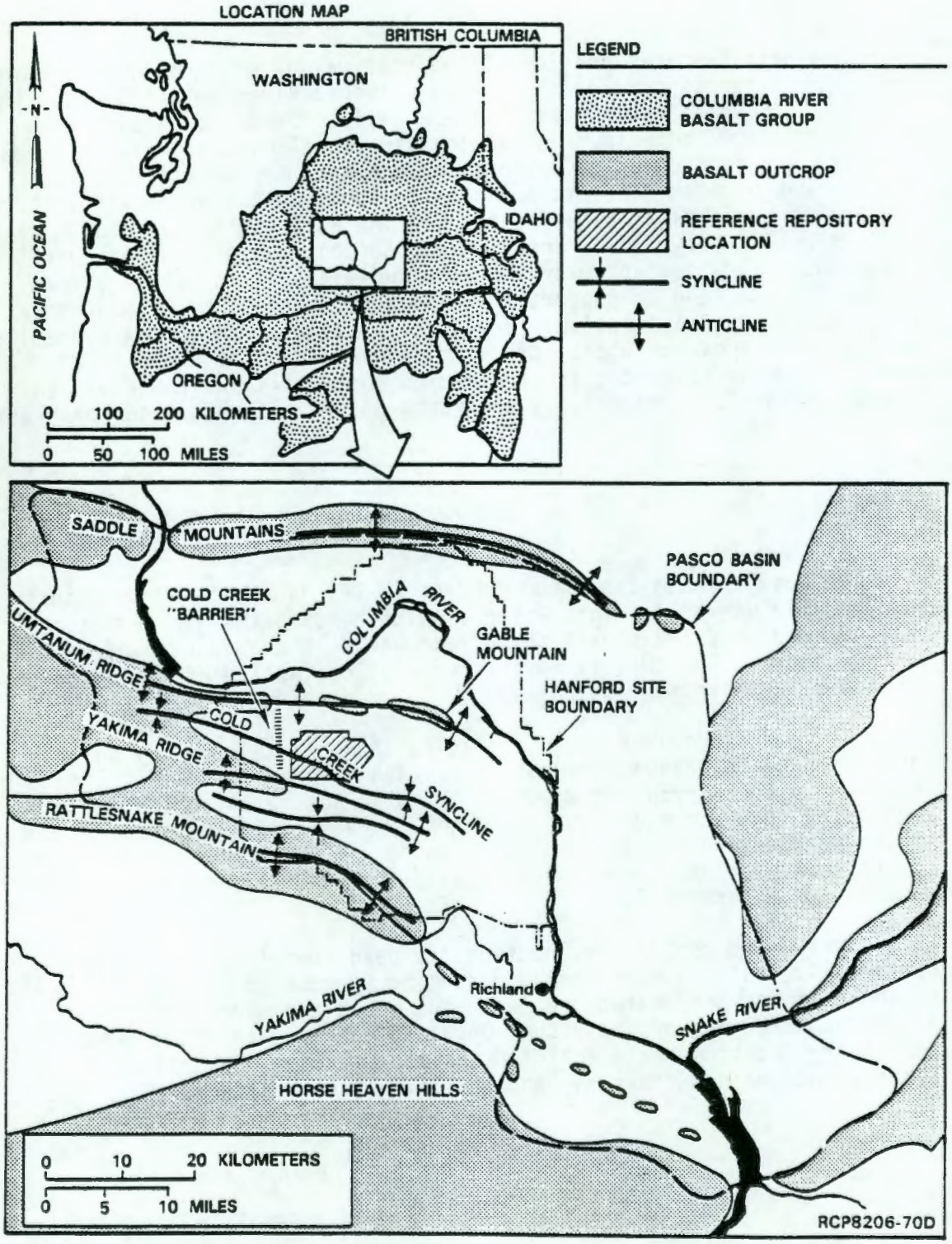
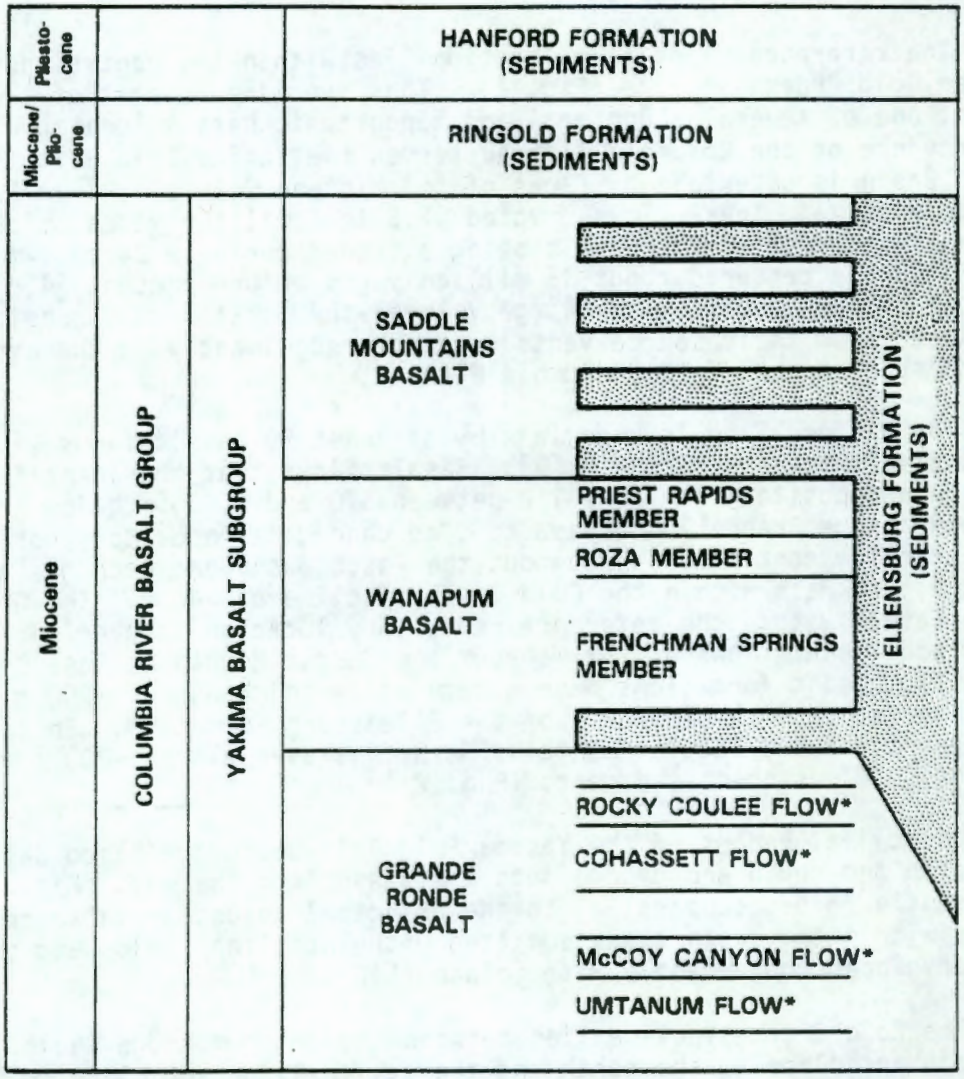


FIGURE 1. Extent of the Columbia River Basalt Group, Pasco Basin, and Reference Repository Location.



*BASALT FLOWS IDENTIFIED AS CANDIDATE REPOSITORY HORIZONS

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FIGURE 2. Generalized Stratigraphy of the Columbia River Basalt Group and Sediments Within the Pasco Basin.

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GEOLOGIC SETTING

The geologic setting of an area establishes the geometric framework for groundwater movement and, therefore, the pathways of radionuclides released from a repository.

The reference repository location lies within the central portion of the Cold Creek syncline (Fig. 1). This syncline is part of the Pasco Basin, one of several structural and topographic basins located within a subprovince of the Columbia Plateau termed the Yakima Fold Belt. The Pasco Basin is underlain by flows of the Miocene Columbia River Basalt Group (Fig. 2). These flows erupted 17.5 to 6 million years before present with ~99% of the basalt being extruded during a 2- to 3-million-year interval centered about 15 million years before present [4,8]. Because of low viscosity and large volume, the lavas spread considerable distances from their source vents located predominantly in the east and southeast portions of the Columbia Plateau.

The Hanford Site is underlain by at least 50 basalt flows with a cumulative thickness >3,000 m [9]. Basalt flows that are identified as candidate repository horizons lie between 870 and 1,100 m below ground surface in the Grande Ronde Basalt. The candidate repository horizons are laterally continuous throughout the Pasco Basin and each has an average thickness within the Cold Creek syncline of >40 m. The Grande Ronde Basalt within the reference repository location is overlain by up to 20 additional flows of the Wanapum and Saddle Mountains Basalts. These two basalt formations have a cumulative thickness of ~700 m and are interbedded with sediments of the Ellensburg Formation. In the Cold Creek syncline the Saddle Mountains Basalt is overlain by ~200 m of Miocene to Pleistocene sediments (Fig. 2).

Anticlinal ridges of the Yakima Fold Belt bound the Pasco Basin on the north and south and plunge into the basin from the west (Fig. 1). More subtle folds, subparallel to the principal folds, are also present. Faults within the basin are associated with anticlinal folds and probably developed concurrently with folding [10].

The Cold Creek syncline lies between the Umtanum Ridge-Gable Mountain anticline to the north and the Yakima Ridge anticline to the south. Beneath the reference repository location, the structure of the Saddle Mountains Basalt, as well as deeper basalt horizons, is interpreted as nearly flat lying (<5°). Geologic data suggest that the Pasco Basin was deforming at a low average rate of strain in the middle-to-late Miocene; geodetic data indicate that this rate has continued into the late Cenozoic [11-13].

Individual basalt flows range from a few meters to more than 100 m thick, averaging 30 to 40 m [14]. They generally consist of an upper vesicular and/or brecciated flow top overlying a more dense jointed

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interior. The flow top typically occupies ~15% of the total thickness of a flow, although vesicular and brecciated basalt can locally form up to ~50% of the total flow thickness [4].

The vast majority of fractures in flow interiors are joints created by thermal contraction during cooling of each flow. Lengths of individual fractures range from a few centimeters to several meters.

The flow interior consists of entablature and colonnade. The entablature is comprised of irregularly to regularly jointed rock with relatively small (~0.2 to 0.9 m diameter) columns. Column orientation is commonly subvertical but ranges from vertical to horizontal.

The colonnade consists of relatively well-formed columns (~0.5 to 2 m diameter) with fewer fractures than the entablature. Columns are normally upright but radiate locally and exhibit a variety of internal features. In some flows, the entablature overlies a single colonnade; in other flows, colonnade and entablature zones may be repeated in the flow interior [3].

The basal portion of a basalt flow is usually a thin (~0.5 m) zone of fractured, glassy basalt. Spiracles, zones of fissured glassy rock, may extend a few meters into the lower portion of a flow. Spiracles are thought to form when lava flowed over shallow bodies of water. If the lava flowed into deep water, a pillow zone may have developed at the base of a flow.

Fracture logging results indicate that typical fracture abundances in core samples range from 1 to 30 fractures/m. The majority of these fractures have narrow widths (<0.5 mm) that are now filled with multiple generations of secondary minerals [3]. The volume of unfilled fractures, particularly in the dense interior of Grande Ronde Basalt flows, is typically very small (<0.4 vol%).

POTENTIAL GROUNDWATER PATHWAYS

Groundwater movement in basalt most likely occurs along pathways found in three groups of features: (1) discontinuities within flow interiors, (2) flow contacts, and (3) bedrock structural discontinuities. These are illustrated in Figure 3, as is the proposed location of a repository within the dense central part of a flow interior.

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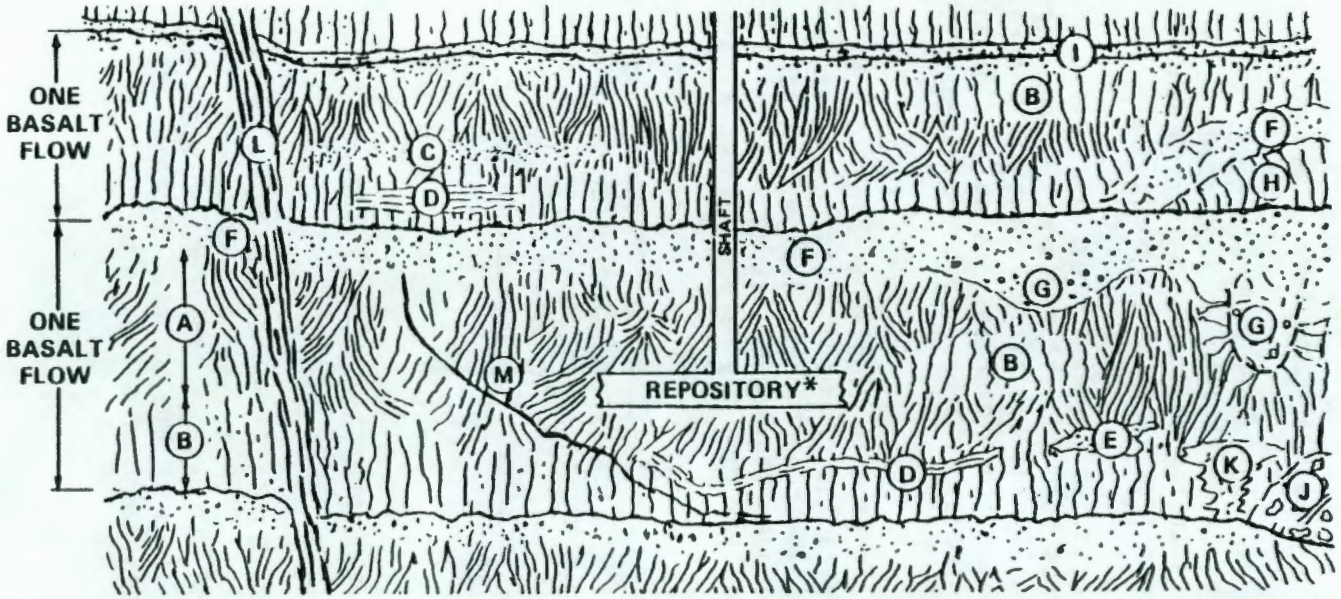

*HYPOTHETICAL LOCATION

NO HORIZONTAL OR VERTICAL SCALE INTENDED

FLOW INTERIOR DISCONTINUITIES

- A ENTABLATURE JOINTS
- B COLONNADE JOINTS
- C VESICULAR ZONE
- D PLATY ZONE
- E LOCAL FRACTURED ZONE

FLOW CONTACT

- F FLOW TOP
- G LOCAL THICKENING OF FLOW TOP BRECCIA
- H FLOW TERMINATION
- I SEDIMENTARY INTERBED
- J PILLOW BRECCIA
- K SPIRACLE OR SPIRACLE-LIKE FEATURE

BEDROCK STRUCTURAL DISCONTINUITIES

- L FAULT OR FRACTURE ZONE, HINGE OF FOLD, OR SHEAR ZONE
- M LOCALIZED TECTONIC FRACTURE

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FIGURE 3. Composite Cross Section of Possible Geologic Features in a Layered Basalt Sequence.

FLOW INTERIORS

Radionuclides released from a waste package normally travel through discontinuities in the flow interior before reaching flow contacts or bedrock structural discontinuities. The most ubiquitous discontinuities within the flow interior are cooling joints found in the entablature and colonnade portions of a flow (Fig. 3, features A and B).

Ten hydrologic tests (using pulse and constant-head injection test methods) have been conducted across the dense entablature and colonnade portions of individual flow interiors at depths from 350 to 1,200 m beneath the Hanford Site. Horizontal permeabilities* measured were $<10^{-11}$ m/s. Low permeabilities for flow interiors have also been reported by other investigators within the Hanford Site and Columbia Plateau [15,16]. Such low values in a fractured medium are attributed to a high degree of secondary mineral infilling, dead-end fracture space, and lithostatic loading. Field tests quantifying vertical permeabilities and evaluating test methodologies within flow interiors are in progress.

In lieu of direct measurements, a model-calculated estimate of the vertical-to-horizontal permeability anisotropic ratio within flow interiors has been derived by considering a hexagonal cooling-joint geometry and applying a flow balance. (This work was performed by D.T. Snow.) The ratio obtained was ~2:1. In addition, recent statistical modeling of fracture sets indicates a maximum anisotropic ratio of ~3.5:1 [17]. Thus, once field measurements become available, it is anticipated that vertical permeability values in structurally undeformed areas will not vary greatly from horizontal measurements now available.

Besides entablature and colonnade joints, other discontinuities potentially present within flow interiors include vesicular zones, platy zones, and zones of localized fracturing. These features are illustrated as features C, D, and E in Figure 3.

Within the Cold Creek syncline, a vesicular zone in the entablature of the Cohassett flow was hydrologically tested at three borehole sites. Permeability values range between 10^{-8} and 10^{-13} m/s. Whether or not low permeability is a typical characteristic of such vesicular zones is unknown.

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*In this report, the word permeability is used in place of hydraulic conductivity.

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A zone of ~1-m thickness was geophysically identified in the entablature near the base of the Umtanum flow in one borehole located in the reference repository location. A permeability of 10^{-4} m/s was calculated from pumping and slug tests. This is the highest permeability measured in a flow interior on the Hanford Site. Hydrologic tests across the Umtanum entablature/colonnade contact in other onsite boreholes indicate permeabilities of $\sim 10^{-13}$ m/s. Though the extent of this fracture zone is unknown, it is presently considered a localized feature, as symbolically shown in Figure 3 (feature E).

FLOW CONTACTS

After radionuclides travel through joints or other pathways within a basalt interior, they may enter a flow contact. Commonly, these contacts represent the nearest potential aquifers to a repository. Flow contacts may contain features F through K in Figure 3.

A flow top (Fig. 3, features F and G) forms a more or less continuous layer atop the flow interior. The flow top of an areally extensive basalt flow may cover several thousand square kilometers while its thickness, internal characteristics, and hydrologic properties spatially vary. Flow terminations (pinch outs), such as feature H in Figure 3, represent places where groundwater may move from one flow top to another without traversing a basalt interior.

Associated with some flow tops are sedimentary interbeds (Fig. 3, feature I) which also represent potential aquifers. Most interbeds are located in the Saddle Mountains Basalt, ~400 m above the shallowest basalt flow presently considered for repository construction.

To date, nearly 200 hydrologic tests have been conducted in flow tops and interbeds in some 35 separate boreholes across the Hanford Site. These data indicate that within both the Saddle Mountains and Wanapum Basalts, the permeabilities of most flow tops and interbeds range between 10^{-4} and 10^{-7} m/s with a geometric mean of $\sim 10^{-5}$ m/s. Most permeability values within Grande Ronde Basalt flow tops range between 10^{-5} and 10^{-9} m/s with a geometric mean of $\sim 10^{-7}$ m/s. In heterogeneous media, such as basalt, the use of geometric mean values is generally considered to provide the best integration of permeability over a large area [18,19] in computer simulations, while avoiding the complexity of local heterogeneities.

Existing hydrologic data, based on single-hole tests, suggest that flow top permeabilities are heterogeneous across the reference repository location. For example, the permeability of the Rocky Coulee flow top changes only slightly from 10^{-6} to 10^{-7} m/s while that of the Cohassett ranges between 10^{-6} and 10^{-11} m/s. Furthermore, geophysical log traces indicate that groundwater movement is sometimes channeled along narrow intervals ($\lesssim 1$ m) as opposed to being averaged across the

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entire effective thickness of the flow top. Such narrow intervals may have a higher local permeability than the "equivalent" permeability of the flow top's effective thickness. The number and in situ characteristics of these intervals can change over distances of a few kilometers.

Hydraulic heads measured across flow tops and interbeds both in piezometers and on a progressive drill and test basis suggest that the areal hydraulic gradient in the Cold Creek syncline is $\sim 10^{-4}$ m/m. Vertical head measurements across the deep basalts indicate either a slight upward gradient or essentially no gradient (i.e., vertical head profile). These preliminary data suggest that in nonstructurally deformed areas, groundwater movement appears to be predominantly lateral with the general flow direction semiconforming to the regional bedrock dip [16].

Pillow breccia zones (Fig. 3, feature J) have not been penetrated by boreholes in the Hanford Site and, thus, none have been hydrologically tested. However, their existence, as well as spiracles or spiracle-like features (Fig. 3, feature K), should be expected based on field observations in the Columbia Plateau. These features represent rock zones of possibly high permeability that may locally influence groundwater movement.

BEDROCK STRUCTURAL DISCONTINUITIES

Bedrock structural discontinuities represent zones of potentially significant fracture anisotropy (shown symbolically as features L and M, Fig. 3) that may hydraulically connect flow systems above and below a repository or they may represent low permeability barriers to groundwater movement. All bedrock in the western Pasco Basin is along some portion of a Yakima fold, either on a limb or in a hinge zone or trough. Steep limbs of tightly folded anticlines are usually reverse faulted and the hinge zones typically contain breccia, shears, and faults.

Synclinal troughs, where exposed in the Columbia Plateau outside of the Pasco Basin, appear to exhibit less strain than other portions of a Yakima fold structure [3]. However, the difficulty of directly extrapolating this regional characteristic to the Cold Creek syncline is that the latter is filled with sediment, precluding direct observation. However, because the trough of the Cold Creek syncline is a broad, open structure, it is interpreted to contain fewer bedrock structures relative to anticlinal areas. Nearly flat lying strata away from anticlinal hinge areas may be crossed by strike-slip faults. These faults, represented by feature L on Figure 3, may depict bedrock structural discontinuities having a linear extent of perhaps tens of kilometers. Inferred or known bedrock structures in the Cold Creek syncline have been reported [3] and are now under investigation.

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Observations of cliff exposures, man-made cuts, and tunnels through Columbia River basalt indicate that, even where flat-lying, the interiors of thick flows are locally crossed by subtle subhorizontal tectonic fractures that intersect cooling joints [4]. These fractures, shown symbolically as feature M on Figure 3, may be continuous on scales of tens to hundreds of meters. Many are thought to be of tectonic origin related to fold growth [20]; others are of uncertain origin and might be phenomena related to deposition or cooling of flows.

The gently dipping limbs of anticlines and synclines within the reference repository location contain small zones of tectonic breccia. These zones are typically <1-m thick in basalt core and are of unknown lateral extent [3]. A 5-m-thick tectonic breccia in the Frenchman Springs Member of the Wanapum Basalt in one borehole in the reference repository location was hydrologically tested using the pulse technique. A permeability of 10^{-11} m/s was measured [4]. It is unknown whether this low value is characteristic of other tectonic breccias.

The Cold Creek hydrologic "barrier" (Fig. 1) is an example of what is interpreted as a bedrock structural discontinuity that represents an impediment to lateral groundwater flow. From west to east across this feature, hydraulic heads abruptly drop as much as 150 m. In addition, hydrochemical data suggest that mineralized deep waters may be mixing vertically with more dilute, shallower groundwaters along or near this feature.

ALTERNATIVE GROUNDWATER FLOW CONCEPTS

When the existing geohydrologic data base is too preliminary to conclusively support a single groundwater-flow model, it is important to develop alternative working hypotheses. Such is the case in Figure 4 where four concepts are shown depicting groundwater movement in a layered basalt sequence such as beneath the reference repository location. In a broad sense, Figure 4 incorporates the range of concepts proposed to identify groundwater flow patterns. These concepts are listed below:

1. Concept A: This concept illustrates groundwater moving principally within heterogeneous, permeable flow tops separating flow interiors of relatively low vertical and horizontal permeability.

   Upward groundwater movement into shallower systems occurs as a result of (1) the positioning of flows where the front of one basalt flow of limited extent terminates atop a more continuous flow creating a direct conduit between two flow tops, or

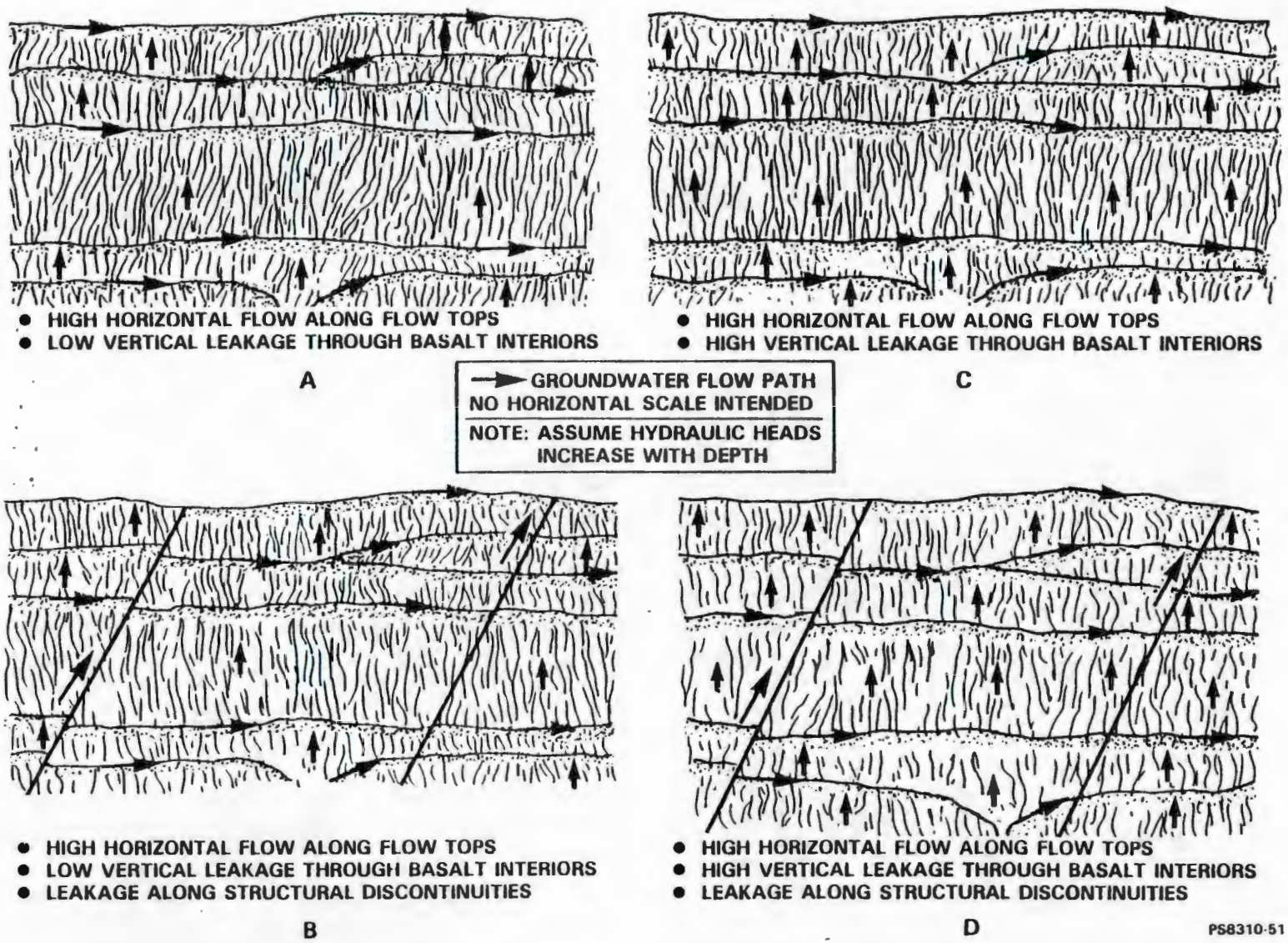

FIGURE 4. Alternative Concepts for Groundwater Movement Based on Anisotropy Contrasts and Hypothetical Structures.

(2) groundwater movement across low permeability flow interiors over large areas. In Concept A, local features of relatively high permeability (such as thickening of flow top breccia atop a spiracle) are not commonly juxtaposed. Basically, Concept A depicts an anisotropic, heterogeneous flow system undisturbed by major folds and faults.

2. Concept B: This concept is similar to Concept A except that basalt flows are crossed by bedrock structural discontinuities having potentially larger vertical permeabilities than the confining aquitards. On a local scale of several square kilometers, such discontinuities might represent individual tectonic fractures or shear zones. Regionally, these features could depict major fault zones. If rock movement has occurred, such structures could depict zones where the lateral continuity of flow contacts is disrupted causing a flow contact(s) to terminate against a flow interior(s) of lower permeability. In Concept B, structural discontinuities are heterogeneities having the potential for vertically connecting shallow and deep flow systems. Dependent upon the extent of fracture mineral infilling and/or fine gouge materials, these discontinuities could act as high permeability conduits or groundwater barriers. Overall, Concept B depicts rock volumes of relatively low vertical leakage bounded by structural discontinuities.

3. Concept C: This concept represents a flow system characterized by lateral groundwater movement in flow tops bounded by basalt interiors of relatively high leakage. The anisotropy of permeability between flow top and interior is considerably less than in Concept A. In Concept C, groundwater movement between deep and shallow systems occurs as a result of stratigraphic positioning/intersection of flow contacts and vertical leakage through unfilled or partially filled cooling fractures and other relatively high permeability primary features that are juxtaposed.

4. Concept D: This concept superimposes bedrock structural discontinuities on Concept C. As described under Concept B, such discontinuities might act as vertical conduits and/or low permeability barriers. Concept D depicts rock zones of relatively high vertical leakage bounded by structural discontinuities.

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CONCLUSIONS

Geologic features that we believe are potentially important in both local and regional groundwater movement are illustrated in Figure 3. The existing geohydrologic data base is too preliminary to conclusively support a single groundwater-flow concept. However, the overall concept that we currently interpret as most supported by available data for deep basalts is Concept B of Figure 4. Bedrock structural discontinuities in this concept are considered to be less frequent and more widely spaced in the gently dipping limbs of Yakima folds (e.g., within the reference repository location) than in the hinge areas and steeply dipping limbs of these folds.

A number of geohydrologic characterization activities are currently under way to reduce the present uncertainty regarding conceptual models and groundwater-flow paths. These include further analysis of the geologic features depicted in Figure 3 as well as large-scale, multi-well pump tests; vertical permeability measurements; installation of additional piezometers; and plans for an exploratory shaft involving breakout and testing within a candidate repository horizon. Studies are also underway of tectonic processes which may generate new groundwater-flow paths or alter the hydrologic properties of existing bedrock structures.

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