THE GEOLOGICAL SOCIETY
OF AMERICA®

Permeability correlation structure of the Columbia River Plateau and implications for fluid system architecture in continental large igneous provinces

Richard S. Jayne and Ryan M. Pollyea
Department of Geosciences, Virginia Polytechnic Institute and State University, 926 W Campus Drive, Blacksburg, Virginia 24061, USA

ABSTRACT

The well-known observation that permeability tends to decrease with depth has been invoked to explain and/or model the effects of fluid and heat flow within numerous societally relevant geological processes. However, this study finds that continental large igneous provinces may deviate from the classical permeability decay trend. We compile a new permeability database for the Columbia River Basalt Group (CRBG), United States, and show that average CRBG permeability (1) exhibits little depth dependence between 0 and 500 m; (2) systematically decays between ~500 and 950 m depth; and (3) increases by 1.5 orders of magnitude between 950 and 1450 m depth. Further analysis indicates that CRBG permeability is spatially correlated with a 5:1 horizontal anisotropy ratio, and the direction of maximum horizontal spatial correlation is parallel to the longitudinal axis of the bedrock depression underlying the CRBG. To explain these observations, we hypothesize that rapid CRBG emplacement and subsequent lithospheric subsidence induces bending moment stresses within the CRBG that result in spatially correlated permeability at regional scales and increasing permeability at depth. Because continental large igneous provinces (LIPs) are characterized by rapid emplacement and subsequent subsidence, this study implies that that bending moment stresses may be a characteristic feature affecting the permeability structure of continental LIPs.

INTRODUCTION

Permeability within Earth's brittle crust governs heat and mass transport from microscopic to continental scales. At the macro scale, crustal permeability is known to regulate Earth's natural CO_2 emissions, thermal output, and pore-fluid pressure within the lithosphere (Ingebritsen and Manning, 1999). Consequently, permeability plays a fundamental role in earthquake occurrence and crustal strength (Townend and Zoback, 2000), metamorphic CO_2 degassing (Kerrick and Caldeira, 1998), global geothermal resource distributions (Saar, 2011), and ore deposits (Weis, 2015). While the importance of crustal permeability is well known, mapping the spatial variability of permeability remains a fundamental challenge in the geosciences, particularly at depths greater than several hundred meters (Gleeson et al., 2011). To overcome this barrier, the geoscience community has a rich history developing permeability scaling relationships. In one classic example, Neuman (1990) found that while hydraulic conductivity (a proxy for permeability) is scale-dependent, the superposition of homogeneous hydraulic conductivity fields into successively larger scales exhibits self-similar scaling dynamics that can be adequately characterized by a random fractal model. Perhaps the most well-known and widely implemented permeability scaling law is the permeability-depth (*k-z*,) relation discovered by Manning and Ingebritsen (1999), which shows that crustal-scale permeability in metamorphic terrain decreases with depth as a power law, $k \approx 10^{-14}$ m^2 × $(z/1000\text{ m})^{-3.2}$, where k is permeability (m^2) and z is depth (m).

The Manning and Ingebritsen (1999) *k-z* scaling relation has been invoked to explain numerous geologic phenomena. For example, Townend and Zoback (2000) invoked *k-z* scaling to support the observations that permeability is ~10^{-17} to 10^{-16} m^2 at 1–10 km depth, which permits hydraulic communication between the atmosphere and seismogenic zone, and prevents long-term overpressure on critically stressed faults. To extend this *k-z* model to shallow depths, Saar and Manga (2004) combined heat flow and hydroseismicity observations from the Oregon Cascades (northwest United States) with numerical modeling to propose a piecewise *k-z* scaling relation in which vertical permeability undergoes exponential decay until ~800 m depth, beyond which the power law *k-z* relation holds. The combined *k-z* relation is often implemented in numerical modeling studies of deep geological processes where permeability data are either sparse or not available. The *k-z* scaling relation has been used to refine our understanding of classical basin-scale fluid flow (Jiang et al., 2009), and to constrain numerical modeling studies of ore formation (Weis, 2015), hydrothermal fluid circulation within mid-ocean ridges (Barreyre et al., 2018), heat flow estimates within continental large igneous provinces (LIPs) (Burns et al., 2015), meteoric water infiltration within orogenic belts (Pollyea et al., 2015), and permeability on Mars (Clifford and Parker, 2001).

Our study considers the applicability of *k-z* scaling in LIPs by developing a new permeability database (874 records) for the Columbia River Basalt Group (CRBG), western United States (Fig. 1), and calculating the permeability-depth profile. Our analysis indicates that bulk permeability within the CRBG does not follow the expected depth-dependent trend between 950 and 1450 m, and we hypothesize that this deviation from classical *k-z* scaling laws results from rapid emplacement, subsequent lithospheric subsidence, and the development of bending moment stresses.

METHODS

A database of spatially referenced permeability values was compiled from previously published aquifer test data within the CRBG. This database shows that CRBG permeability spans 13 orders of magnitude (10^{-21} m^2 to 10^{-8} m^2). After filtering the data to exclude measurements from the low-permeability flow interiors, the resulting database used for analysis comprises 800 bulk permeability measurements from 577 wells. The complete description of database sources, quality control measures, and verification of internal consistency is described in the GSA Data Repository[1].

We calculated the *k-z* profile on the basis of a 200 m moving average using the methods proposed by Burns et al. (2015), and 1σ dispersion about the mean was calculated to quantify uncertainty in the *k-z* profile (Fig. 2).

The spatial correlation of CRBG bulk permeability was quantified by first applying a $\log_{10}$ transform to the data and then calculating the experimental semivariogram as:

---

[1] GSA Data Repository item 2018259, the Columbia River Basalt Group permeability database compiled for this study, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

GEOLOGY, August 2018; v. 46; no. 8; p. 715–718 | GSA Data Repository item 2018259 | https://doi.org/10.1130/G45001.1 | Published online 12 July 2018

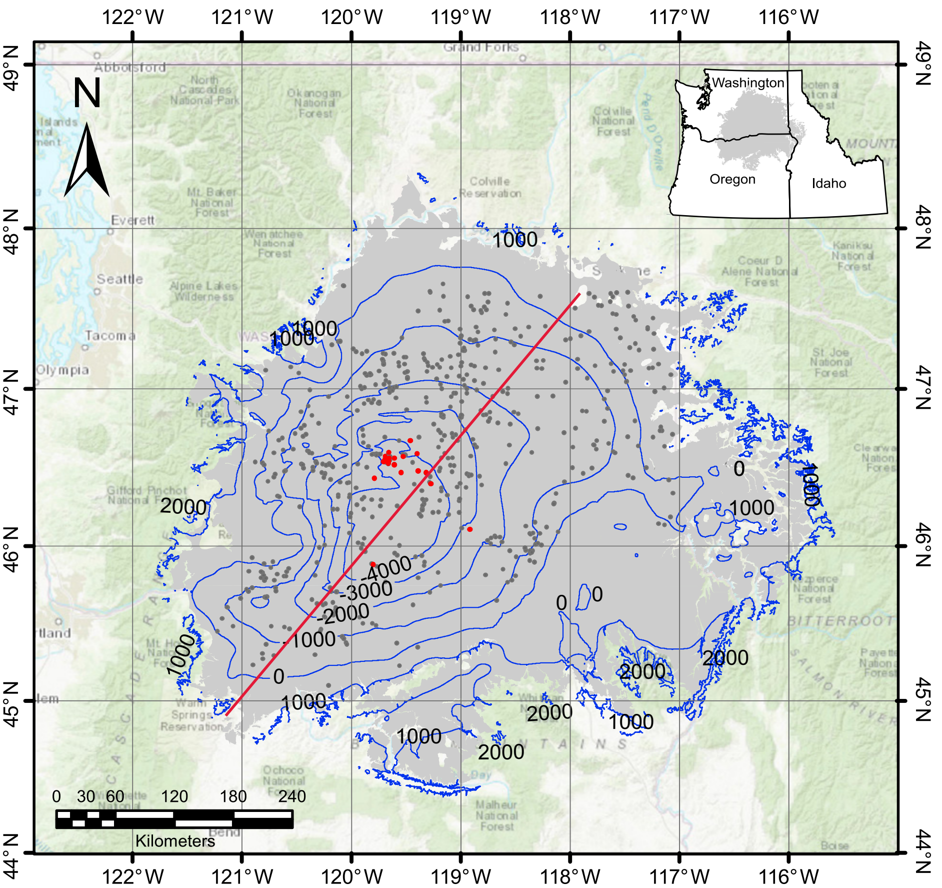

Figure 1. Study area map of the Columbia River Plateau, USA, with Columbia River Basalt Group (CRBG) shown in gray shading. Dark gray circles denote well locations with hydrologic data used in this study, and red circles denote wells greater than 950 m depth (Table DR1 [see footnote 1]). Blue contour lines show the bedrock elevation in meters above mean sea level (m amsl) (Burns et al., 2011). Thick red line is N40°E, and direction of maximum horizontal spatial correlation for CRBG permeability. Base map from Esri (https://www.esri.com).

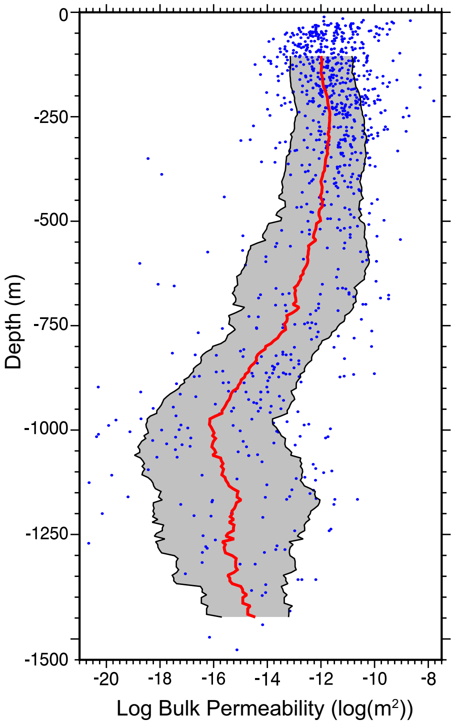

Figure 2. Permeability-depth profile calculated as a 200 m running average (red line) with 1σ dispersion (gray shading) and individual permeability values (blue dots).

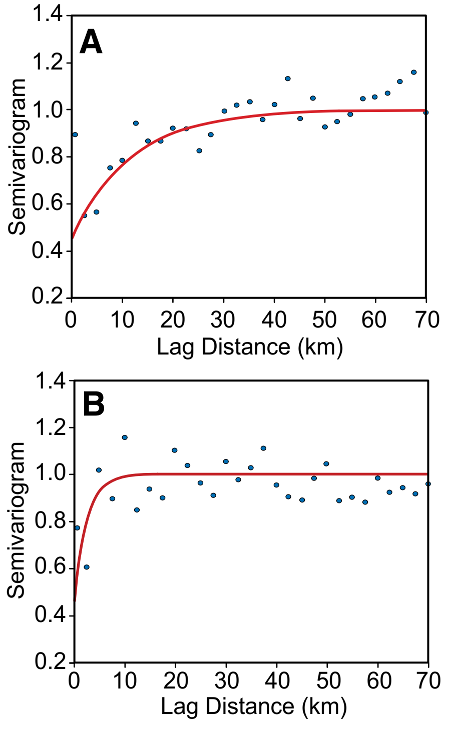

Figure 3. Spatial correlation model for Columbia River Basalt Group (CRBG, western USA) permeability, with horizontal experimental semivariograms for maximum (N40°E) (A) and minimum (N130°E) (B) spatial correlation directions. Each semivariogram is normalized over the variance. Circles denote experimental semivariogram (text Equation 1), and red line denotes model semivariogram with parameters shown in Table 1.

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left(z_i - z_{i+h}\right)^2, \qquad (1)$$

where, $N(h)$ is the total number of data pairs separated by a spatial lag distance (h), and z_i and z_{i+h} are the head and tail values of each data pair, respectively (Deutsch and Journel, 1998). The two-dimensional (2-D) semivariogram map reveals the presence of spatial anisotropy oriented N40°E and N130°W (Fig. DR1 in the Data Repository), and directional experimental semivariograms were modeled to quantify correlation range in the direction of maximum (N40°E) and minimum (N130°W) spatial continuity (Fig. 3).

RESULTS

Our k-z calculations (Fig. 2) show that average bulk CRBG permeability (1) exhibits no apparent depth dependence between 0 and 500 m; (2) systematically decays by four orders of magnitude between ~500 and 950 m depth; and (3) increases by 1.5 orders of magnitude between 950 and 1450 m depth. The k-z results between 0 and 950 m are generally consistent with those of Burns et al. (2015), which also suggests that rapid permeability decay with depth is likely in continental flood basalt provinces (Burns et al., 2015). In contrast, our results indicate that permeability increases by 1.5 orders of magnitude between 950 and 1450 m depth. To support the results presented in Figure 2, we observed that 1σ dispersion about the moving average systematically decreases with increasing depth beyond 950 m despite fewer data within the 950–1450 m depth interval. Moreover, there are 21 permeability data above the 1σ threshold, while only 9 data points are below. The increasing k-z trend beyond 950 m is further supported by a single CRBG permeability measurement of 5.7×10^{-15} m^2 at 1828 m depth, which is not included in the moving average calculations because the depth is more than 200 m beyond the deepest datum shown in Figure 2. These results suggest that the trend of increasing permeability within the 950–1450 m depth interval may be robust on the basis of currently available data.

Semivariogram analysis reveals that (1) CRBG permeability is spatially correlated with a 5:1 anisotropy ratio in the horizontal direction (Table 1); (2) the directions of maximum and

TABLE 1. MODEL SEMIVARIOGRAM PARAMETERS

Model Type	Nugget	Sill	Range (km)
Horizontal Semivariogram			
Exponential*	0.45	0.55	35
Exponential†	0.45	0.55	7.5
Vertical Semivariogram			
Model Type	**Nugget**	**Slope**	**ω§**
Power	0.4	1.55	0.35

*N40°E: Direction of maximum spatial correlation
†N130°E: Direction of minimum spatial correlation
§Exponent for power law semivariogram

minimum spatial correlation are oriented N40°E and N130°E, respectively; and (3) the vertical semivariogram is characterized by a power law model comprising a sill of 0.55 and exponent (ω) of 0.35 (Fig. 3). In comparing the direction of maximum horizontal spatial correlation with the depth to bedrock below the CRBG (Burns et. al., 2011), we find that the direction of maximum horizontal spatial correlation (N40°E) for CRBG permeability aligns remarkably well with the longitudinal axis of the bedrock underlying the Columbia River Plateau, which is oriented ~N42°E (Fig. 1).

DISCUSSION

Our results indicate that CRBG bulk permeability exhibits an unexpected increasing trend within the 950–1450 m depth interval (Fig. 2), and that the direction of maximum spatial correlation aligns with the longitudinal axis of the underlying bedrock depression (Fig. 1). We interpret these results in the context of CRBG emplacement. The CRBG comprises a layered assemblage of ~300 Miocene-age flood basalts with an areal extent of 200,000 km^2, aggregate thickness of 1–5 km, and total estimated volume of 224,000 km^3 (Reidel et al., 2002). Long and Wood (1986) showed that during emplacement, CRBG flows initially followed an east-to-west paleoslope, and then ponded within a north-south–trending paleobasin that subsequently experienced local clockwise rotation (Hooper and Conrey, 1989). This is evident in bedrock contours underlying the CRBG, which show that (1) the CRBG occupies a bedrock depression trending ~N42°E (Fig. 1), and (2) the thickness of individual CRBG members generally increase near the center of the bedrock depression (Burns et al., 2011).

At the time of initial CRBG eruptions (ca. 17 Ma), the Columbia River Plateau was undergoing uplift, and the Grande Ronde and Imnaha eruptions (17–15.5 Ma) produced ~94% of the total CRBG volume over a period of 1.5 m.y. (Reidel et al., 1989). This volume and emplacement rate rapidly loaded the underlying crust as high-density mafic rocks accumulated over comparatively lower-density felsic rocks, which caused a down warp in the continental crust underlying the Columbia River Plateau (Hales et al., 2005). Since that time, the Columbia River Plateau has been undergoing subsidence at a decreasing rate from 0.7–1.0 cm yr^{-1} (15.6 Ma) to the current rate of ~0.003 cm yr^{-1} (Reidel et al., 1989).

The lithospheric response to loading is well documented in the case of continental ice-sheet advance/retreat (e.g., Walcott, 1970a) and volcanism (Jackson and Wright, 1970; Moore, 1970; Clague and Dalrymple, 1987). In the context of glacial advance and volcano construction, rapid lithostatic loading in both oceanic and continental crust induces rapid evolution in the principal stresses (e.g., Hieronymus and Bercovici, 1999; Walcott, 1970a; Bianco et al., 2005). During continental glaciation, the lithostatic response to rapid loading has been linked to bending moment stresses at the base of an ice sheet that induce tensile fractures and increase the permeability of basal ice (Boulton and Caban, 1995). Although there are fewer studies of the lithostatic response to continental LIPs, Walcott (1970b) showed that flexural rigidity of continental lithosphere decreases by two orders of magnitude for long-term loading conditions (>~10^4 yr), and that this flexural response is controlled by both elastic and viscous processes. Johnston et al. (1998) suggested that, in the presence of loading-induced subsidence, a bending moment will increase lateral compressive stresses at shallow depths, while decreasing compressive stresses at greater depths.

Reidel et al. (1989) indicated that the Columbia River Plateau has been undergoing subsidence at a decreasing rate (0.1–0.003 cm yr^{-1}) since the Grande Ronde eruptions. The occurrence of regional subsidence after CRBG emplacement suggests that the entire CRBG assemblage has been undergoing flexure, which would result in a bending moment about the longitudinal axis of the underlying bedrock depression (~N42°E). The presence of a bending moment about this longitudinal axis is similar to the tangential longitudinal strain model of Ramsay (1967). Within the CRBG, bending moment stresses acting orthogonal to the longitudinal axis of the underlying bedrock depression would preferentially dilate fracture apertures oriented parallel to longitudinal axis of the underlying depression, thus increasing permeability (Fig. 4). In the context of the CRBG *k-z* profile, most permeability data are from portions of the CRBG with thicknesses ranging from ~1000 to 4000 m, which suggests that the neutral surface for the complete CRBG assemblage occurs between 500 and 2000 m depth. Although variable CRBG thickness and neutral surface depth will dilute the signal of reversal in the *k-z* trend, the distinct permeability decay between 500 and 950 m, combined with the modestly increasing permeability beyond 950 m depth, suggests that the bending moment stress model reasonably explains the observed *k-z* trend even when taking into account the variable thickness of the CRBG.

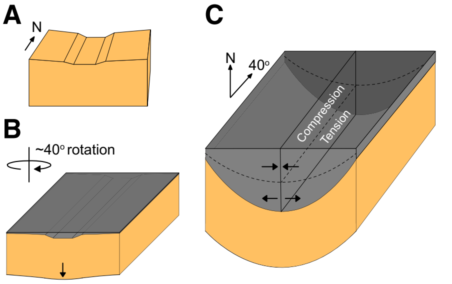

Figure 4. Schematic illustrating the effects of a bending moment on Columbia River Basalt Group (CRBG, western USA) permeability. A: Prior to Imnaha eruptions (17–15.5 Ma), the paleobasin was oriented north (Long and Wood, 1986). B: Columbia River Plateau experienced 40°E rotation contemporaneously with initial CRBG emplacement at ca. 17 Ma. C: ~94% of total CRBG volume was emplaced between 17 and 15.5 Ma, which resulted in rapid loading and post-emplacement subsidence, and induced a bending moment about the longitudinal axis of the basin oriented N40°E. Arrows denote compression and tension above and below the neutral axis (dashed line), respectively, and orthogonal to the longitudinal axis.

Coffin and Eldholm (1994) compiled and analyzed all *in situ* LIPs younger than 250 Ma and showed that LIP emplacement is generally characterized by lithospheric uplift, rapid emplacement, and post-emplacement subsidence, which implies that bending moment stresses may be characteristic features of continental LIPs. Based on our analysis of CRBG permeability architecture, the broader implication is that the *k-z* characteristics of continental LIPs may not follow classical decay trends. Because fracture permeability governs the rate of mass and heat flow through the mafic rocks (e.g., Garven, 1995), the bending moment hypothesis for the permeability architecture of continental LIPs may have important implications for groundwater resource management, geothermal heat flow, and the development of geo-engineered reservoirs. For example, Saar (2011) suggested that minimum permeability for thermal advection is 5×10^{-17} to 5×10^{-15} m^2, and, as a result, the thermal signature of continental LIPs may exhibit unusual characteristics, alternating between advection and conduction at depths below the neutral surface of the bending moment. Moreover, continental LIPs continue to be considered for a wide range of geological engineering applications, including long-term nuclear waste storage, natural gas storage, and geologic CO_2 sequestration, the feasibility of which depend, to a large extent, on the hydraulic architecture of the host reservoir.

CONCLUSIONS

Permeability-depth scaling is frequently invoked to explain and/or model the effects of fluid and heat flow on numerous societally relevant geological processes. In this study, we find that continental LIPs may deviate from the classical permeability decay trend. Our results show that CRBG permeability (1) exhibits little depth dependence between 0 and 500 m; (2) systematically decays between ~500 and 950 m depth; and (3) increases by 1.5 orders of magnitude between 950 and 1450 m depth. Further analysis indicates that CRBG permeability is spatially correlated with a 5:1 horizontal anisotropy ratio, and the direction of maximum horizontal spatial correlation is parallel to the longitudinal axis of the bedrock depression underlying the CRBG. To explain these observations, we hypothesize that rapid CRBG emplacement and subsequent lithospheric subsidence has induced bending moment stresses within the CRBG that affect the depth-dependence and spatial correlation of fracture-controlled permeability. Because uplift, rapid loading, and post-emplacement subsidence generally characterize continental LIP emplacement, we infer that the effects of bending moment stresses may be a characteristic feature of the LIP permeability structure.

ACKNOWLEDGMENTS

We thank Jerry P. Fairley for insightful discussions about Columbia River Basalt Group permeability, as well as Richard D. Law, Steven E. Ingebritsen, and Richard J. Walker for their thoughtful reviews of an early draft of this manuscript. We also thank editor Quigley for his careful stewardship of our manuscript. This study received financial support from the U.S. Department of Energy National Energy Technology Laboratory through cooperative agreement DE-FE0023381 (PI Pollyea).

REFERENCES CITED

Barreyre, T., Olive, J.A., Crone, T.J., and Sohn, R.A., 2018, Depth-dependent permeability and heat output at basalt-hosted hydrothermal systems across mid-ocean ridge spreading rates: Geochemistry Geophysics Geosystems, v. 19, p. 1259–1281, https://doi.org/10.1002/2017GC007152.

Bianco, T.A., Ita, G., Becker, J.M., and Garcia, M.O., 2005, Secondary Hawaiian volcanism formed by flexural arch decompression: Geochemistry Geophysics Geosystems, v. 6, Q08009, https://doi.org/10.1029/2005GC000945.

Boulton, G.S., and Caban, P., 1995, Groundwater flow beneath ice sheets: Part II—Its impact on glacier tectonic structures and moraine formation: Quaternary Science Reviews, v. 14, p. 563–587, https://doi.org/10.1016/0277-3791(95)00058-W.

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

Burns, E.R., Williams, C.F., Ingebritsen, S.E., Voss, C.I., Spane, F.A., and DeAngelo, J., 2015, Understanding heat and groundwater flow through continental flood basalt provinces: Insights gained from alternative models of permeability/depth relationships for the Columbia Plateau, USA: Geofluids, v. 15, p. 120–138, https://doi.org/10.1111/gfl.12095.

Clague, D.A., and Dalrymple, G.B., 1987, The Hawaiian-Emperor Volcanic Chain, Part 1: Geologic evolution, *in* Decker, R.W., et al., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper, v. 1350, p. 5–54.

Clifford, S.M., and Parker, T.J., 2001, The evolution of the Martian hydrosphere: Implications for the fate of a primordial ocean and the current state of the northern plains: Icarus, v. 154, p. 40–79, https://doi.org/10.1006/icar.2001.6671.

Coffin, C.F., and Eldholm, O., 1994, Large igneous provinces: crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1–36, https://doi.org/10.1029/93RG02508.

Deutsch, C.V., and Journel, A.G., 1998, GSLIB: Geostatistical Software Library and User's Guide: New York, Oxford University Press, p. 369.

Garven, G., 1995, Continental-scale groundwater flow and geologic processes: Annual Review of Earth and Planetary Sciences, v. 23, p. 89–117, https://doi.org/10.1146/annurev.ea.23.050195.000513.

Gleeson, T., Smith, L., Moosdorf, N., Hartmann, J., Dürr, H.H., Manning, A.H., van Beek, L.P., and Jellinek, A.M., 2011, Mapping permeability over the surface of the Earth: Geophysical Research Letters, v. 38, L02401, https://doi.org/10.1029/2010GL045565.

Hales, T.C., Abt, D.L., Humphreys, E., and Roering, J.J., 2005, A lithospheric instability origin for Columbia River flood basalts and Wallowa Mountains uplift in northeast Oregon: Nature, v. 438, p. 842, https://doi.org/10.1038/nature04313.

Hieronymus, C.F., and Bercovici, D., 1999, Discrete alternating hotspot islands formed by interaction of magma transport and lithospheric flexure: Nature, v. 397, p. 604–607, https://doi.org/10.1038/17584.

Hooper, P.R., and Conrey, R., 1989, A model for the tectonic setting of the Columbia River basalt eruptions, *in* Reidel, S.P., and Hooper, P.R., eds, Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Papers, v. 239, p. 293–306, https://doi.org/10.1130/SPE239-p293.

Ingebritsen, S.E., and Manning, C.E., 1999, Geological implications of a permeability-depth curve for the continental crust: Geology, v. 27, p. 1107–1110, https://doi.org/10.1130/0091-7613(1999)027<1107:GIOAPD>2.3.CO;2.

Jackson, E.D., and Wright, T.L., 1970, Xenoliths in the Honolulu Volcanic Series: Journal of Petrology, v. 11, p. 405–433, https://doi.org/10.1093/petrology/11.2.405.

Jiang, X.W., Wan, L., Wang, X.S., Ge, S., and Liu, J., 2009, Effect of exponential decay in hydraulic conductivity with depth on regional groundwater flow: Geophysical Research Letters, v. 36, L24402, https://doi.org/10.1029/2009GL041251.

Johnston, P., Wu, P., and Lambeck, K., 1998, Dependence of horizontal stress magnitude on load dimension in glacial rebound models: Geophysical Journal International, v. 132, p. 41–60, https://doi.org/10.1046/j.1365-246x.1998.00387.x.

Kerrick, D.M., and Caldeira, K., 1998, Metamorphic CO_2 degassing from orogenic belts: Chemical Geology, v. 145, p. 213–232, https://doi.org/10.1016/S0009-2541(97)00144-7.

Long, P.E., and Wood, B.J., 1986, Structures, textures, and cooling histories of Columbia River basalt flows: Geological Society of America Bulletin, v. 97, p. 1144–1155, https://doi.org/10.1130/0016-7606(1986)97<1144:STACHO>2.0.CO;2.

Manning, C., and Ingebritsen, S., 1999, Permeability of the continental crust: Implications of geothermal data and metamorphic systems: Reviews of Geophysics, v. 37, p. 127–150, https://doi.org/10.1029/1998RG900002.

Moore, J.G., 1970, Relationship between subsidence and volcanic load, Hawaii: Bulletin of Volcanology, v. 24, p. 563–576.

Neuman, S.P., 1990, Universal scaling of hydraulic conductivities and dispersivities in geologic media: Water Resources Research, v. 26, p. 1749–1758, https://doi.org/10.1029/WR026i008p01749.

Pollyea, R.M., Van Dusen, E.W., and Fischer, M.P., 2015, Topographically driven fluid flow within orogenic wedges: Effects of taper angle and depth-dependent permeability: Geosphere, v. 11, p. 1427–1437, https://doi.org/10.1130/GES01120.1.

Ramsay, J.G., 1967, Folding and Fracturing of Rocks: New York, McGraw-Hill, 568 p.

Reidel, S.P., Fecht, K.R., Hagood, M.C., and Tolan, T.L., 1989, The geologic evolution of the central Columbia Plateau. *in* Reidel, S.P., and Hooper, P.R., eds, Volcanism and Tectonism in the Columbia River Flood -Basalt Province: Geological Society of America Special Papers, v. 239, p. 247–264, https://doi.org/10.1130/SPE239-p247.

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

Saar, M., and Manga, M., 2004, Depth dependence of permeability in the Oregon Cascades inferred from hydrogeologic, thermal, seismic, and magmatic modeling constraints: Journal of Geophysical Research: Solid Earth, v. 109, B04204, https://doi.org/10.1029/2003JB002855.

Saar, M.O., 2011, Geothermal heat as a tracer of large-scale groundwater flow and as a means to determine permeability fields: Hydrogeology Journal, v. 19, p. 31–52, https://doi.org/10.1007/s10040-010-0657-2.

Townend, J., and Zoback, M.D., 2000, How faulting keeps the crust strong: Geology, v. 28, p. 399–402, https://doi.org/10.1130/0091-7613(2000)28<399:HFKTCS>2.0.CO;2.

Walcott, R., 1970a, Isostatic response to loading of the crust in Canada: Canadian Journal of Earth Sciences, v. 7, p. 716–727, https://doi.org/10.1139/e70-070.

Walcott, R., 1970b, Flexural rigidity, thickness, and viscosity of the lithosphere: Journal of Geophysical Research, v. 75, p. 3941–3954, https://doi.org/10.1029/JB075i020p03941.

Weis, P., 2015, The dynamic interplay between saline fluid flow and rock permeability in magmatic-hydrothermal systems: Geofluids, v. 15, p. 350–371, https://doi.org/10.1111/gfl.12100.

Manuscript received 4 April 2018
Revised manuscript received 22 June 2018
Manuscript accepted 30 June 2018

Printed in USA