NATURAL RESOURCES

GEOTHERMAL FAVORABILITY MODEL OF WASHINGTON STATE

by Darrick E. Boschmann,
Jessica L. Czajkowski, and
Jeffrey D. Bowman

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Open File Report 2014-02
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INTRODUCTION

In the early phases of geothermal exploration, many important geological details are unknown. A regional exploration model based on available data and exploratory principles can identify areas where it would be most profitable to obtain more detailed data. This study provides a new geothermal favorability model to serve as a regional guide for exploration and development of moderate- to high-temperature geothermal resources in Washington State that could be used for the generation of electricity. This does not preclude the development of low-temperature sources for direct-use applications, such as ground-source heat pumps. Model outputs are intended to supersede the geothermal resource map of Washington State (Korosec and others, 1981).

In 2011, the U.S. Department of Energy funded a three-year effort by state geological surveys to compile and collect all types of geothermal-related data for inclusion in the National Geothermal Data System (NGDS; http://geothermaldata.org/). In support of this effort, the Washington State Department of Natural Resources (WADNR), Division of Geology and Earth Resources (DGER), developed and (or) revised numerous datasets of existing geothermal and geologic data in Washington State. DGER was also funded to collect new geothermal-related data, including drilling four new temperature-gradient holes, sampling of 93 thermal and mineral springs for chemistry and isotope analysis, and logging temperature gradients in 47 existing wells.

We imported the newly compiled and collected data into a Geographic Information System (GIS). To gain a broad understanding of geothermal resource potential and favorability for development in Washington State, we ran a multi-criteria analysis of relevant spatial datasets to determine the spatial associations among various geologic and thermal features, infrastructure, and land-use. This GIS-based approach draws from and builds upon methods from previous GIS-based models of geothermal favorability applied to regional studies in Japan (Noorollahi and others, 2007), Iran (Noorollahi and others, 2008), Oregon (Poux and Suemnicht, 2012), and elsewhere. A western United States model from the U.S. Geological Survey (USGS)(Williams and DeAngelo, 2008; Williams and others, 2008a) includes Washington State (Fig. 1); however, the relevant data at the time of the modeling predated the data gathered during the NGDS effort. We used the existing data as well as the newly gathered NGDS data to create a Washington State–specific geothermal favorability model.

The model results are an assessment of geothermal resource potential and favorability on a regional basis and are not intended for site-specific evaluation of geothermal development potential. The modeling incorporates the most complete and accurate data compilations to date, but is nevertheless limited by the quantity, quality, and distribution of available data.

OVERVIEW OF MODEL STRUCTURE AND PROCESSING

The geothermal favorability model of Washington State can serve as a regional guide for identification of areas that merit a detailed geothermal resource investigation. The production of this model required the integration of derivative spatial data, including heat, permeability, elevation, proximity to electric transmission lines, and land-use. A weighted evaluation method, the analytic hierarchy process (AHP), was used to integrate the spatial data for modeling. The AHP assigns relative weights to input data by pair-wise comparison based on the assignment of perceived importance to each data type by multiple experts in a particular field of study (Saaty, 2008; Goepel, 2012).

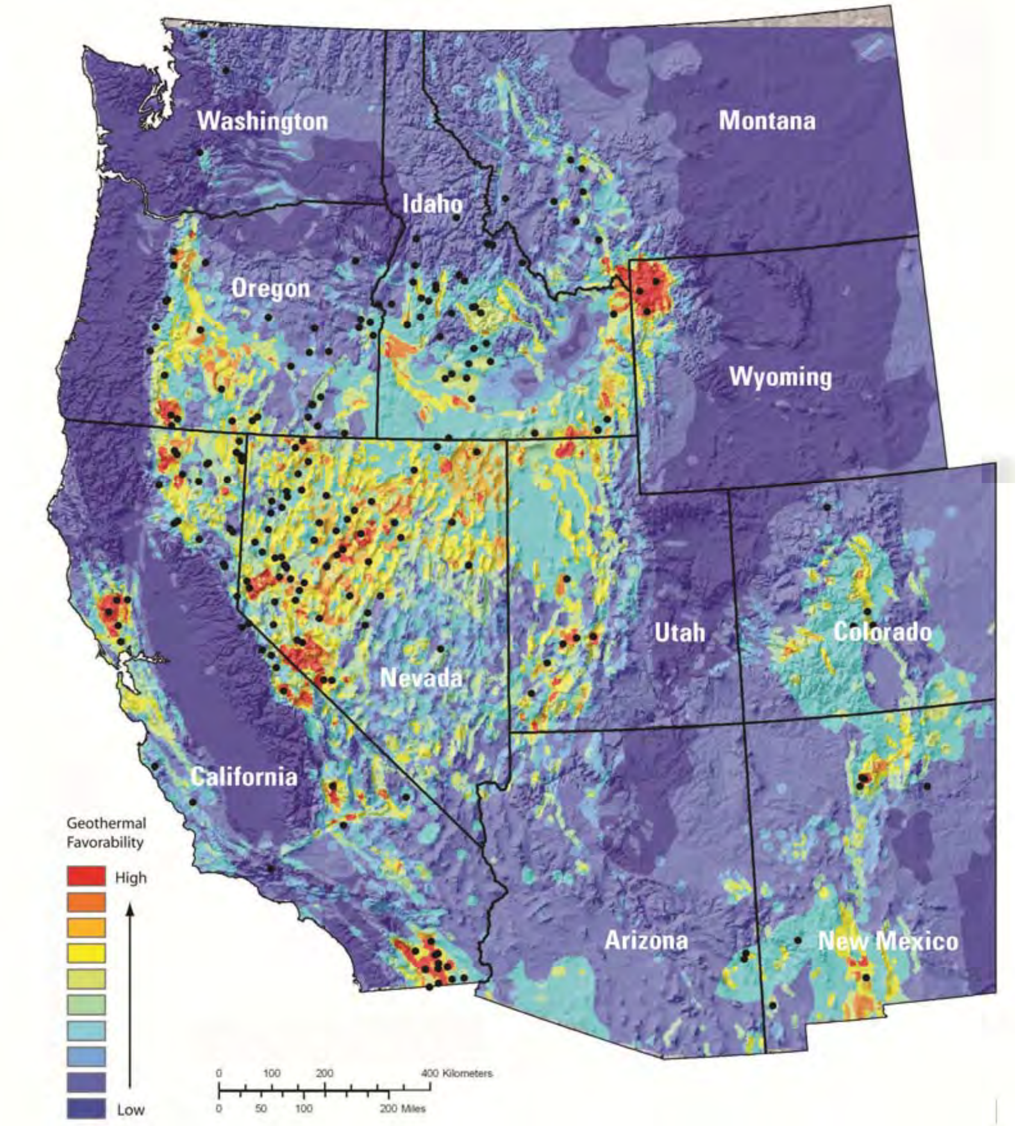


Figure 1. U.S. Geological Survey relative favorability model of occurrence for geothermal resources in the western contiguous United States. Identified geothermal systems are represented by black dots. Reprinted from Williams and others, 2008a.

Fuzzy linear transformation functions were used to model a linear spatial relationship between favorability and selected features, such that favorability increases linearly on a scale of 0 to 1 with increasing proximity. The maximum distance over which this linear relationship applies is user-determined and is herein referred to as the radius of influence (ROI). ROI was assigned to represent a conservative estimate of the spatial influence of features of interest; however, due to the regional nature of the model and numerous unknown local variables, ROI is undoubtedly overestimated at some locations and underestimated at others.

The geothermal favorability model of Washington State was constructed by first performing multiple iterative ArcGIS processes on vector data obtained from the NGDS data-gathering process. Data included volcanic vents, young silicic intrusive rock bodies, thermal/mineral springs, temperature gradients in wells, faults, earthquakes, electric transmission lines, and elevation. A combination of spatial buffering, Euclidean distance analysis, kernel density analysis, fuzzy linear transformations, kriging interpolations, and raster algebra techniques were applied to input datasets.

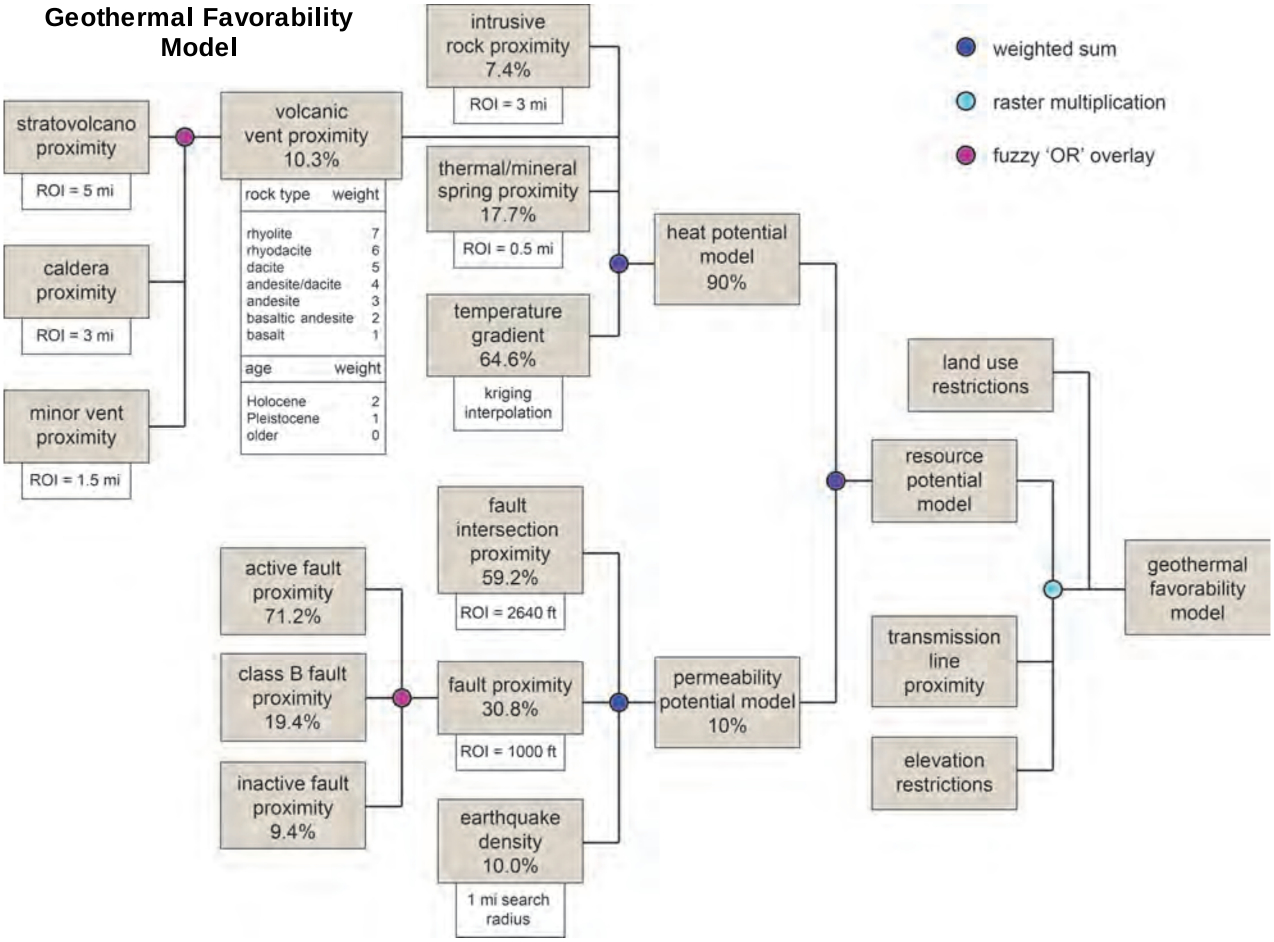


Figure 2. General structure of the geothermal favorability model of Washington State, including intermediate raster data, thematic models, and favorability input models, model processes (purple, cyan, and magenta circles), classification schemes, radius of influence (ROI), and analytic hierarchy process (AHP) weights (percent). Vector input data not shown.

These processes generated a series of intermediate datasets, including intrusive rock proximity, multiple volcanic-vent proximity, thermal/mineral spring proximity, temperature-gradient interpolation, multiple fault proximity, fault intersection proximity, and earthquake density rasters (Fig. 2). Several of the intermediate raster datasets involved a combination of AHP weight assignment with a fuzzy 'OR' raster overlay, a method that returns the maximum value of the overlain rasters at the cell location (see *Glossary of Terms*).

Using weighted sum geoprocessing, the intermediate rasters were further combined to create two separate thematic models—heat potential and permeability potential. The subsequent weighted sum of these two models produced the resource potential model. Raster multiplication of the resource potential model, transmission-line proximity raster, and elevation restrictions raster produced the geothermal favorability model. All rasters were processed and overlain at a 500-foot by 500-foot grid resolution.

HEAT POTENTIAL MODEL

Crustal heat at depths accessible by modern drilling technologies is a basic requirement for development of geothermal resources. The geothermal heat potential model (Plate, Fig. C) represents the shallow crustal heat potential in Washington State based on the spatial distribution of measured temperature gradients and multiple geologic features commonly associated with shallow geothermal systems.

The highest modeled heat potential is in the southern Cascade Range. There are also isolated areas of elevated heat potential in the North Cascades and a broad region of scattered moderate potential across much of the Columbia Basin. Areas west of the Cascade Range, including the Puget Lowland and Olympic Mountains, generally have the lowest modeled heat potential.

Data Inputs and Model Assumptions

The multi-criteria heat potential model is composed of the weighted sum of four intermediate rasters (Fig. 3): temperature gradient, thermal/mineral spring proximity, volcanic vent proximity, and intrusive rock proximity. Temperature gradient measurements from 791 wells in Washington and parts of Oregon, Idaho, and British Columbia (Plate, Fig. C) were compiled from the DGER geothermal well database (Czajkowski, 2014c), published data (Huang and Pollack, 1998; Fairbank and Faulkner, 1992; Jessop and others, 2005), and Southern Methodist University's Western Geothermal Areas Database (Blackwell, 2010). In large areas where no temperature gradients have been measured, a DGER database of bottomhole temperature data from water wells (Czajkowski, 2014c) was combined with average surface temperature (Gass, 1982) to calculate synthetic temperature gradients. The areal extents of young silicic intrusive rock bodies (Plate, Fig. C) were obtained from DGER 1:100,000-scale digital geologic map data (WADGER, 2010a) and geologic mapping by Hildreth and others (2003). Spatial and attribute data for volcanic vents and thermal/mineral springs (Plate, Fig. C) were obtained from recent compilations from DGER (Czajkowski and others, 2014b; Czajkowski and Bowman, 2014). Caldera margins for Kulshan and Davis Peak calderas were obtained from Hildreth and others (2003) and Evarts (2004)(Plate, Fig. C).

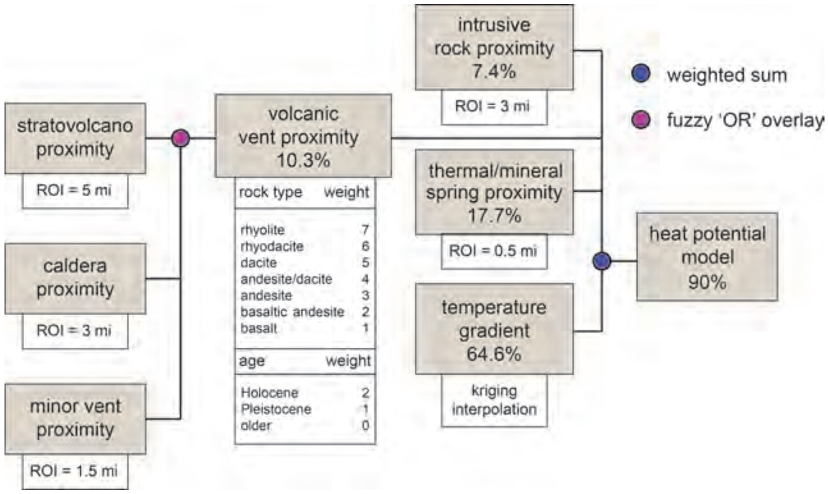


Figure 3. Classification scheme, analytic hierarchy process (AHP) weights (percent), and model parameters (purple and magenta circles) for the thematic heat potential model.

Temperature Gradient

A fundamental tool in the early stages of geothermal resource exploration is the down-hole measurement of temperature gradient—the rate of temperature increase with depth, typically expressed in degrees Celsius per kilometer (°C/km). Inevitably, the quantity and distribution of measurements is not sufficient to characterize the temperature gradient at all locations, so spatial interpolations are used to predict variations in temperature gradient across the state. Interpolation of this data does not consider lateral and vertical subsurface heterogeneities that may influence temperature gradient distribution.

Heat flow values are often used in such interpolations because heat flow incorporates variations in the thermal conductivity of subsurface rock and the effects of these variations on temperature gradient. However, the scarcity of available heat flow and thermal conductivity data for Washington State would result in inaccuracies in heat flow modeling, due to interpolation across the large distances between data points. Therefore, we opted to use the much more densely distributed temperature gradient data for the heat potential model.

Intrusive Rock Proximity

Young intrusive rocks are commonly associated with the presence of active geothermal systems. Due to their propensity to stall in the shallow crust, silicic intrusive rocks in particular are associated with geothermal resources (Smith and Shaw, 1973). In Washington State, the few Quaternary silicic intrusions are generally associated with igneous activity in the Cascade volcanic arc. The duration and surficial horizontal distance over which an intrusive body influences thermal conditions in the shallow crust varies depending on factors such as intrusion age, size, depth, and whether the cooling body loses heat by conduction alone or by convection of geothermal fluids within a permeable host rock (Muffler, 1993). At the regional scale of the model, these variables are not considered and, instead, the model uses a uniform 3-mile ROI from the margin of mapped silicic intrusive bodies (Fig. 3). The model does not include young silicic intrusions not exposed and mapped at the surface.

Volcanic Vent Proximity

The presence of volcanic vents is clear evidence of a history of elevated heat in the subsurface. Volcanic vents with a higher SiO_2 content have a higher magma viscosity and are therefore more likely to generate large shallow intrusive bodies that can provide heat to a geothermal system. In addition to magma composition, the duration and surficial horizontal distance over which an eruptive center will influence thermal conditions in the shallow crust varies depending on factors such as age, volcano type (cinder cone, stratovolcano, caldera, etc.), and the presence or absence of plutonic bodies. This model attempts to address these factors by weighting each vent by age and lithology, and by varying ROI according to volcano type (Fig. 3).

Thermal/Mineral Spring Proximity

Thermal springs are direct surface expressions of the presence of a geothermal system. Direct measurement of a thermal spring's surface temperature and chemical geothermometry of both thermal and cold mineral springs can provide information on the geothermal reservoir. The Na-K-Ca cation geothermometer calculation was used to estimate reservoir equilibrium temperatures for springs. Applicable analyses were performed using the Powell and Cumming (2012) spreadsheets for geothermal water geochemistry.

The spatial relation between spring location at the surface and the underlying geothermal reservoir is controlled by subsurface hydrogeological and structural conditions that vary greatly from location to location. In our model, site-specific hydrogeology is not considered; rather, the model weights each spring by its surface temperature and Na-K-Ca geothermometry, where available, and implements a 0.5-mile ROI from the location of the mapped thermal/mineral spring (Fig. 3).

Data Processing

The following paragraphs provide a general description of the data processing methods used to obtain the weighted rasters used in the heat potential and other models.

Temperature Gradient Raster

Kriging interpolation was used to predict continuous temperature gradient values across the state (*see* Table A1, for detailed interpolation parameters). Interpolation was performed at a 20,000-foot grid resolution and the resulting raster converted to a 500-foot grid resolution, using the bilinear resampling method, for inclusion in the heat potential model. The resulting temperature raster was normalized to a 0 to 1 scale using the raster calculator.

Intrusive Rock Proximity Raster

The intrusive rock proximity raster used late Pliocene to Holocene intrusive rhyodacitic to andesitic polygons from the source data. Euclidean distance analysis was performed on these polygons, and the resultant proximity raster was normalized to a 0 to 1 scale using a fuzzy linear transformation function with an ROI of 3 miles.

Volcanic Vent Proximity Raster

We set the buffering for volcanic vents by vent type as follows: stratovolcanoes = 5 miles, calderas = 3 miles, and minor vents = 1.5 miles. Individual buffer polygons for stratovolcanoes, calderas, and minor vents were separately converted to weighted rasters with the raster value equal to the product of age weight and rock type weight (Fig. 3). Separately, Euclidean distance analyses were performed on individual minor vents, stratovolcanoes, and calderas, and the resultant distance rasters were reclassified using fuzzy linear transformations with ROIs equal to the respective buffer distances. The minor vents, stratovolcano and caldera weighted rasters were multiplied by their respective reclassified distance rasters. Finally, the caldera, stratovolcano, and minor vent group rasters were combined using the fuzzy 'OR' overlay tool.

Thermal/Mineral Spring Proximity Raster

Thermal/mineral springs were first buffered to a distance of 0.5 miles. Non-overlapping groups of buffered polygons were then individually converted to weighted rasters with the raster value equal to the spring temperature. Separately, Euclidean distance analyses were performed on non-overlapping spring groups, and the resultant distance rasters were reclassified using fuzzy linear transformations with an ROI of 0.5 miles. The weighted rasters were then multiplied by the reclassified distance rasters for each non-overlapping group. Each group was combined using fuzzy ‘OR’ overlay. The same process was then performed for Na-K-Ca geothermometry temperatures, and the two resultant fuzzy ‘OR’ rasters (temperature and geothermometer) were summed and then normalized.

The four intermediate rasters for the multi-criteria heat potential model (temperature-gradient and intrusive rock, volcanic vent, and thermal/mineral spring proximity) were then combined using the weighted sum tool, based on the results of the AHP (Fig. 3). Observation-based data received higher weight in this process than theoretical, and intrusive rocks received little overall weight, due to their limited population and volume: intrusive rock proximity = 7.4%, volcanic vent proximity = 10.3%, thermal/mineral spring proximity = 17.7% and temperature gradient = 64.6%. The output raster was then normalized to a 0 to 1 scale.

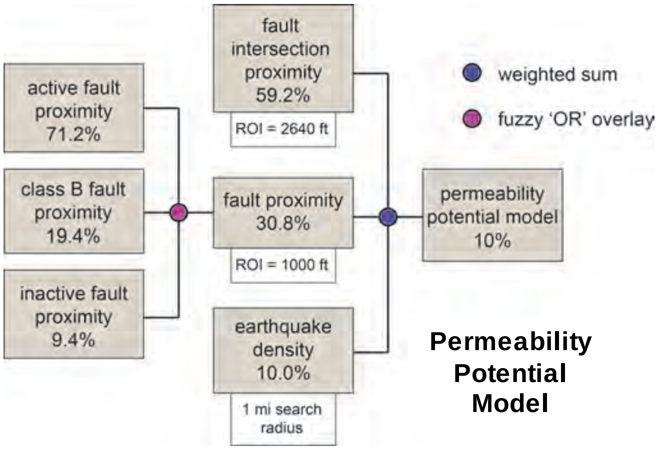


Figure 4. Classification scheme, analytic hierarchy process (AHP) weights (percent), and modeling processes (purple and magenta circles) for the thematic permeability potential model.

PERMEABILITY POTENTIAL MODEL

Conventional geothermal resource production requires significant reservoir permeability to enable thermal fluids to migrate freely through a reservoir and into the wellbore. The permeability potential model is based on the presence of known faults or recorded seismic activity (secondary permeability)(Fig. 4). We did not consider primary permeability (permeability of the rock mass prior to faulting) due to the number of assumptions necessary for this type of model.

The correlation between elevated strain rate and geothermal activity has been demonstrated by several authors (for example, Faulds and others, 2012); however, a scarcity of available strain-rate data and the complexity of strain variation across the state prohibit inclusion of strain-rate variations. Future work would benefit from an accurate model of regional strain to further refine the geothermal permeability potential model.

The highest modeled permeability potential is located in areas of dense fault intersection, such as the northernmost Olympic Peninsula and the southern Willapa Hills (Plate, Fig. E). Broad regions with recorded seismic activity are distributed widely along the western front of the Cascade Range, with isolated high-density regions located across much of the state.

Data Inputs and Model Assumptions

The multi-criteria permeability potential model is composed of the weighted sum of three intermediate rasters: fault proximity, fault intersection proximity, and earthquake hypocenter density (Fig. 4). For both the fault proximity and fault intersection proximity models, fault data were compiled from the DGER 1:100,000-scale digital surface geology, 1:500,000-scale digital surface geology, and active faults data within the digital seismogenic features database (WADGER, 2010a,b; Bowman and Czajkowski, 2014). Compilation of the faults from the three datasets included removing duplicates and ensuring active fault status was retained, when applicable. A total of 6,027 mapped faults and 5,795 fault intersections were included in the model (Plate, Fig. D). Earthquake hypocenter locations with a magnitude greater than 1.0 and a depth of less than 30 kilometers were taken from the DGER seismogenic features database (Bowman and Czajkowski, 2014) and include 14,166 earthquakes recorded from 1970 to 2011.

Fault Proximity

Faults are typically composed of a high-strain zone containing cataclasite and (or) fault gouge surrounded by a damage zone, a volume of fractured rock on either side of the fault plane. The damage zone can provide enhanced secondary permeability for the flow of fluids in the crust and is therefore a common drilling target for geothermal production wells in order to intersect zones of geothermal fluid upflow. The spatial extent of the damage zone for an individual fault is dependent on factors such as fault length, fault displacement, fault geometry, rock type, depth of faulting, tectonic environment, and fluid flow; thus, fault damage-zone thickness can vary by several orders of magnitude (Faulkner and others, 2011). Due to the regional scale of the model and its intended use, the effects of these particular variables on individual faults could not be considered; rather, the model assumes a 1,000-foot damage zone (ROI) from the surface trace of mapped faults.

It is well known that some faults or fault segments may *reduce* permeability via the presence of mineral precipitation or low-permeability, clay-rich fault gouge. The permeability potential model attempts to address the issue of mineral self-sealing by placing more importance on mapped faults with evidence of Quaternary slip; however, the regional scale of the model precludes consideration of hydraulic properties for individual faults or fault segments.

Fault Intersection Proximity

As noted above, secondary permeability resulting from crustal faulting can provide conduits for geothermal fluid circulation. Permeability is particularly enhanced along fault traces or in areas where multiple faults intersect or interact (Curewitz and Karson, 1997). The model considers the locations of fault intersections as relatively favorable for the presence of enhanced secondary crustal permeability. Due to the regional scale of the model, variables affecting the width of the damage zone at fault intersections are not considered individually; rather, the model assumes a 0.5-mile ROI from the intersection of mapped faults.

Earthquake Hypocenter Density

It is assumed here that measureable seismic signals represent the presence of crustal faults at depth. It is further assumed that locations with a higher density of earthquake activity have a higher likelihood of enhanced permeability. Due to the complexity of data processing, we did not attempt to account for depth or magnitude when calculating earthquake density.

Data Processing

Faults were classified as active, inactive, or class B (insufficient data to determine age), based on the designated geologic-age description from their respective source databases. A fault classification of ‘active’ assumes fault rupture within the Quaternary. Each reclassified raster was weighted based on the results of the AHP (active faults = 71.2%, class B faults = 19.4%, inactive faults = 9.4%). Separately, Euclidean distance analysis was performed on each of the three fault classes. The resultant distance rasters were normalized to a 0 to 1 scale using a fuzzy linear transformation function with ROI = 1,000 feet. The three reclassified and their respective weighted proximity rasters were combined using the fuzzy ‘OR’ overlay tool. Finally, the fault proximity raster was normalized to a 0 to 1 scale using the raster calculator.

To generate the fault intersection proximity raster, intersect analysis was performed on the compiled fault feature class, resulting in an output feature class with a point at each fault intersection location. Euclidean distance analysis was then performed on the fault intersection feature class, and the resultant distance raster was normalized to a 0 to 1 scale using a fuzzy linear transformation function with ROI set to 0.5 miles.

Kernel density analysis was performed on earthquake hypocenter data, implementing a search radius of 1 mile. The resulting kernel density raster was then normalized to a 0 to 1 scale.

The three normalized intermediate raster data layers for the multi-criteria permeability potential model were combined using the weighted sum tool, based on the results of the AHP (fault proximity = 30.8%, fault intersection proximity = 59.2%, earthquake density = 10.0%), and the output raster was normalized to a 0 to 1 scale. Higher weights were assigned to fault proximity and fault intersection proximity than to earthquake density because of the known association of enhanced permeability with mapped faults.

RESOURCE POTENTIAL MODEL

The geothermal resource potential model represents the relative geothermal potential in Washington State based on the preceding permeability and heat potential thematic models. The model is intended to highlight areas of elevated potential for the presence of moderate- to high-temperature geothermal resources; it is not intended to locate exact sites for geothermal exploration. This model represents geothermal resource potential without consideration of regulatory restrictions, land-management restrictions, or economic viability.

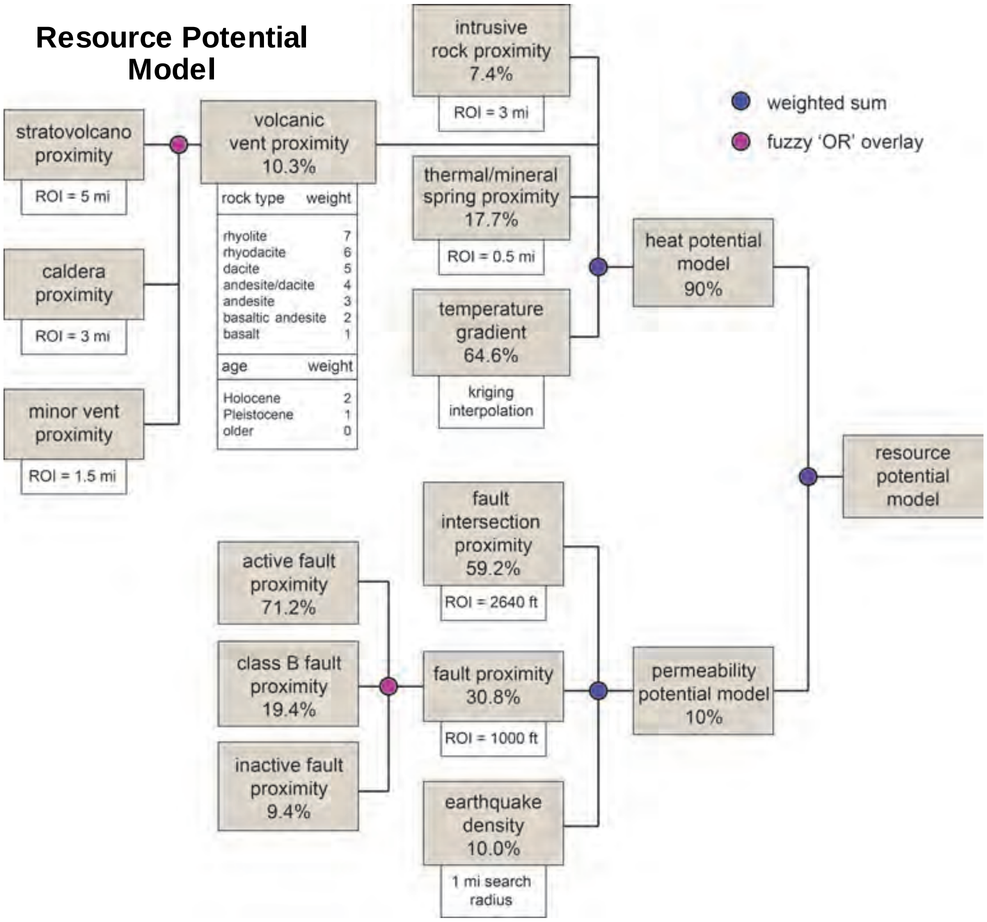


Figure 5. Classification scheme, analytic hierarchy process (AHP) weights (percent), and model parameters (purple and magenta circles) for the resource potential model.

The general trend of the resource potential model (Plate, Fig. F) is similar to that of the input heat potential model, owing to the high weight attributed to that model in the weighted sum. Locally, areas with elevated modeled permeability potential moderately increase the relative resource potential. The results are discussed in more detail below.

Data Inputs and Model Assumptions

The geothermal resource potential model is composed of the weighted sum of the preceding permeability potential and heat potential models (Fig. 5). In addition to the assumptions inherent in the permeability potential and heat potential models, the resource potential model assumes that areas with coincident elevated permeability and heat will have relatively higher favorability for the presence of moderate- to high-temperature geothermal resources.

Data Processing

The permeability and heat potential thematic models were combined using the weighted sum tool and weights suggested by multiple expert opinions (permeability potential model = 10%; heat potential model = 90%). Multiple iterations of this process were performed with differing weighted proportions of these two thematic models; the final ratio was chosen so as not to overemphasize areas with dense networks of faults but no suggested coincident heat potential. The output raster was normalized to a 0 to 1 scale.

TRANSMISSION LINE PROXIMITY

The transmission-line proximity component of the geothermal favorability model is intended to incorporate infrastructure constraints on development of moderate- to high-temperature geothermal resources. Although resource potential may be high in a given area, logistical issues and high costs related to connecting to the regional power-distribution grid may impede development.

Depending on line voltage, the cost of construction of new transmission lines for grid connectivity varies from $0.9 to $1.4 million dollars per mile, and a new 100-mile installation, including substations, can cost up to $0.43 million dollars per MW capacity (Hurlbut, 2012). Geothermal resources are commonly located in remote areas where the economics of interconnection with the regional power grid can make development of even the most favorable geothermal sites impractical. However, remote locations with high geothermal potential, while not feasible for development and interconnection with the regional power grid may still be successfully developed for local power production.

Data Inputs and Assumptions

The model assumes that favorability decreases linearly with distance from transmission lines with greater than 230 kV line voltage. Lines with voltages less than 230 kV were not considered to be market significant and are not included in the model. Transmission-line data was acquired from the National Geospatial Intelligence Agency (NGA) Homeland Security Infrastructure Program (HSIP)(2005) and cannot be displayed to the public for national security reasons.

Data Processing

Euclidean distance analysis was performed statewide on transmission lines greater than 230 kV line voltage, which were extracted from the source dataset, and the resultant distance raster was normalized to a 0 to 1 scale using the fuzzy linear transformation.

ELEVATION RESTRICTIONS

High elevations can be restrictive to development because of logistic and climatic conditions, especially in the Cascade Range, where annual snowfall can exceed 80 feet at elevations as low as 4,200 feet (Leffler and others, 2001). Most high-elevation areas are also remote, have little existing infrastructure, and may be inaccessible during several months of the year. Many areas thought to have high heat flow, such as Mount St. Helens volcano, a “Known Geothermal Resource Area” (KGRA)(Burkhardt and others, 1980), are at high elevation, making these areas challenging for geothermal-resource development.

In Washington, elevation restrictions are located predominantly in the Cascade Range, where maximum restriction is limited to major stratovolcanoes and scattered highlands in the North Cascades (Plate, Fig. G). There are also regions of elevation restriction in the Olympic Mountains, Blue Mountains, and Okanogan Highlands, and additional isolated areas of restrictive elevation along the western margin of the Columbia Basin.

Data Inputs and Model Assumptions

Elevation data was derived from USGS 10-meter digital elevation models (DEMs). While extreme elevation and climate do not necessarily preclude development of geothermal resources, the model assumes that favorability will decline linearly with increasing elevation above 5,000 feet, and elevations above 8,000 feet will prohibit any development activity.

Data Processing

Elevation data was resampled to a 500-foot grid resolution and normalized to a 0 to 1 scale using the fuzzy linear transformation as follows: maximum of 5,000 feet, minimum of 8,000 feet, such that elevations below 5,000 feet have a value of 1, elevations above 8,000 feet have a value of 0, and values decrease linearly from 1 to 0 between 5,000 and 8,000 feet.

LAND-USE RESTRICTIONS

Land-use restrictions have been placed on both public and private lands in Washington State that are managed for conservation of biological diversity or natural, recreational, or cultural uses. These restrictions may be legal or other effective means that prohibit the exploration and development of geothermal resources. Restricted lands include national parks, national wilderness areas, wildlife refuges, private conservations lands, and areas of critical environmental concern.

Land-use restricted areas are widespread in the Cascade Range, especially in the North Cascades where most of the uplands are designated federal wilderness areas (Plate, Fig. H). The South Cascades and Olympic Mountains also have significant land-use restrictions, and there are widely distributed restricted parcels throughout the rest of the state. In total, just over 10,000 square miles (~14%) of land in Washington State is designated as restricted for the purposes of this report. Much of this land has elevated geothermal resource potential, and the restrictions are a major obstacle for exploration and development.

Land-use data were collected from three sources: (1) the USGS Protected Areas Database of the United States (PAD-US; Gap Status Codes 1 and 2)(USGS, 2011), (2) the U.S. Bureau of Land Management (USBLM) Geothermal Resources Leasing Programmatic Environmental Impact Statement (USBLM and USFS, 2008), and (3) DGER corporate data (WADNR, 2007). These selected parcels are not necessarily precluded from the development of geothermal resources. Rather, they are areas where geothermal development is inhibited by specific types of land-management practices at the time of this report.

GEOTHERMAL FAVORABILITY MODEL

The geothermal favorability model (Fig. 2) is the final combination of the resource potential raster, transmission-line proximity raster, and elevation restrictions raster, and represents modeled favorability for development of geothermal resources in Washington State without consideration of land-use restrictions. Used in combination with land-use restrictions data (USBLM and USFS, 2008; USGS, 2011), this model can serve as a guide for selection of locations that may merit detailed geothermal resource exploration.

Data Processing

The geothermal favorability model is the result of raster multiplication of the resource potential model, transmission-line proximity raster, and elevation restrictions raster (Plate, Fig. A; Fig. 6B). Both elevation restriction and transmission-line proximity values reduce the resource potential when multiplied, except at locations where either transmission line proximity is at its highest or where no elevation restriction exists. The results of the favorability model are shown in the Plate (Fig. A) and Figure 6B; details of the results are discussed below.

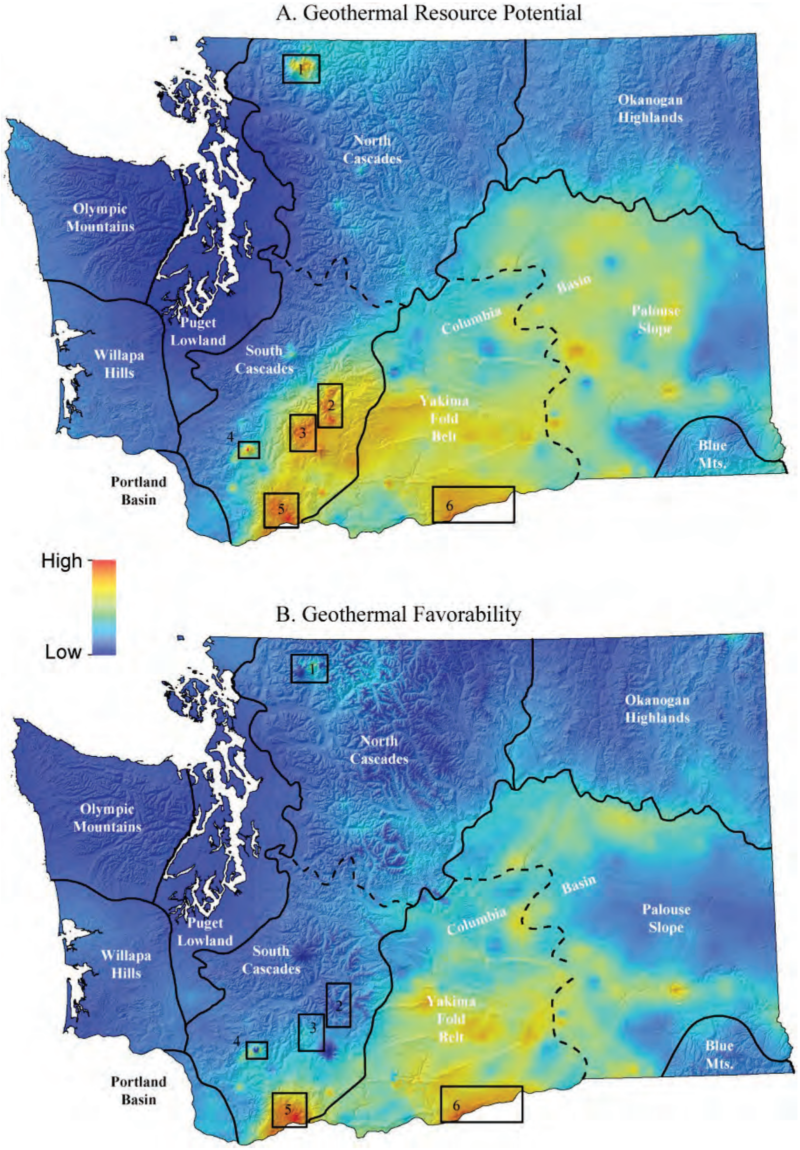
DISCUSSION

The geothermal favorability model shows relatively high favorability in localized areas of the Columbia Basin and South Cascades (Plate, Fig. A; Fig. 6B). Many of the areas that show high values in the resource potential model (such as Cascade Range volcanoes) were eliminated after favorability input models were combined. Transmission line proximity and elevation restrictions have a large effect on geothermal favorability (Fig. 6), as is evident in the comparison between the resource potential model (Fig. 6A) and the final favorability model (Fig. 6B). For example, the broad region of high resource potential in the South Cascades near Goat Rocks and East Canyon Ridge (areas 2 and 3 on Fig. 6) loses all favorability when proximity to the regional power grid is considered. Similarly, in much of the Cascade Range, especially at stratovolcanoes such as Mount Adams and Mount St. Helens, elevation restrictions result in a severe decrease in favorability.

Other regions in the Cascade Range, including some areas designated by the USGS as KGRAs, are not modeled as high potential or high favorability. This is likely due in part to the lack of geothermal gradient measurements in much of the Cascade Range and the increased weight given to geothermal gradient in our model. Additionally, the ‘rain curtain’ effect, which refers to a zone of hydrologic disturbance where cool meteoric water percolates downward and spreads laterally, is likely masking the surface expression of geothermal activity in much of the Cascade Range. This phenomenon can severely complicate exploration activities by diluting hot springs and yielding isothermal temperature gradients to depths in excess of a kilometer; it has proven problematic for understanding the geothermal systems in the Cascade Range (Swanberg and others, 1988).

In both the resource potential and favorability models, there are also widespread, moderately elevated values throughout much of the Columbia Basin, concentrated primarily in the Yakima Fold Belt (Fig. 6). These areas of elevated temperature-gradient measurements are associated with low-temperature geothermal resources (Schuster and Bloomquist, 1994). The low-temperature geothermal waters have potential for direct-use applications such as district heating, agriculture, or other industrial applications, but it is unlikely that temperatures are high enough for utility-scale power production.

Six areas were modeled as having high geothermal resource potential (Fig. 6): (1) Mount Baker/Kulshan Caldera, (2) Goat Rocks, (3) East Canyon Ridge, (4) Mount St. Helens, (5) Wind River, and (6) Roosevelt; however, only Wind River and Roosevelt were modeled as having corresponding high geothermal favorability. These six areas are discussed in detail below.


A. Geothermal Resource Potential

B. Geothermal Favorability

Figure 6. Comparison of the geothermal resource potential model (**A**) and geothermal favorability model (**B**) highlighting areas discussed in the text: (1) Mount Baker/Kulshan Caldera, (2) Goat Rocks, (3) East Canyon Ridge, (4) Mount St. Helens, (5) Wind River, and (6) Roosevelt. Physiographic provinces of Washington shown for reference.

Mount Baker / Kulshan Caldera

Mount Baker is a Quaternary stratovolcano on the western front of the North Cascades (Fig. 6, area 1). It is located within the Mount Baker–Snoqualmie National Forest, much of which is designated a national wilderness area. The Mount Baker volcano and surrounding area have received considerable attention due to the presence of thermal features and young volcanic centers. Exploration activities have included detailed geologic mapping, spring sampling, geophysical surveys, soil mercury measurements, and limited temperature gradient drilling (Korosec, 1984). Chemical geothermometry of Baker Hot Springs suggests that reservoir equilibrium temperature of this system may reach as high as 150° to 170°C (Korosec, 1984). In 1983, a 140-meter-deep (460 ft) temperature-gradient well was drilled near Baker Hot Springs. It had a bottomhole temperature of 48°C and a geothermal gradient between 200° and 309°C/km (Czajkowski and others, 2014c). However, this gradient is likely affected by hot spring circulation and may not represent a typical background value for the area.

Our modeled geothermal resource potential values near the Mount Baker/Kulshan Caldera suggest elevated resource potential, most notably in the area surrounding Kulshan Caldera (Fig. 6A) where no geothermal exploration has been performed to date. Kulshan Caldera is an oblate ~13-square-mile Pleistocene volcanic center located ~3.75

miles to the northeast of Mount Baker. Several Pleistocene andesite to rhyodacite vents and domes are located within the margins of the caldera, and late Pliocene to Pleistocene silicic intrusions are common in the surrounding area (Hildreth and others, 2003). However, our geothermal favorability model suggests that exploration for geothermal resources in this area would be unfavorable once transmission line proximity and elevation restrictions are considered (Fig. 6B). Further, much of the area with elevated resource potential lies within the Mount Baker Wilderness Area and is likely protected from any type of development (Plate, Fig. H).

Goat Rocks Volcanic Complex

The Goat Rocks volcanic complex, approximately 15 miles north of Mount Adams volcano, is located within the Goat Rocks Wilderness Area and in the Yakama Indian Reservation (Fig. 6, area 2). It is underlain by Pliocene to Pleistocene basalt and andesite lava flows, Pliocene rhyolite tuffs and flows, and numerous Pliocene to Pleistocene intrusions of intermediate composition, ranging from minor, narrow dikes to shallow plutonic bodies several kilometers in diameter (Williams and Finn, 1987; Swanson and Clayton, 1983). Younger intrusions are generally unaltered but are locally marked by areas of hydrothermal activity evidenced by quartz veins and propylitic, phyllic, and pyritic alteration (Swanson and Clayton, 1983). Gravity and magnetic data suggest the presence of a shallow, 16- by 7-mile pluton that may have been the magma source for the Goat Rocks volcano 1- to 2-million-year eruptive history (Williams and Finn, 1987). Furthermore, there is a zone of increased seismicity along an inferred northwest-trending active fault transecting this area (Plate, Fig. D).

Much of this region of elevated resource potential (Fig. 6A) is designated Goat Rocks Wilderness, restricting any type of geothermal exploration or development at present. Furthermore, when proximity to transmission lines is considered, favorability for exploration and development of any geothermal resources is significantly reduced for the entire area (Fig. 6B).

East Canyon Ridge

The region of high modeled geothermal resource potential centered on East Canyon Ridge, southwest of Goat Rocks Wilderness and northwest of Mount Adams Wilderness (Fig. 6, area 3), is part of the Gifford Pinchot National Forest. Numerous Quaternary basalt and dacite eruptive centers are mapped in the area (Swanson, 1994). Temperature-gradient measurements range from 55.7°C/km to 67.8°C/km (Plate, Fig. C). Water chemistry from Orr Creek Warm Springs indicates equilibrium reservoir temperatures ranging from 78°C to as much as 231°C, depending on which geothermometer formula is considered (Korosec and others, 1980). Several faults of unknown age transect this area

Although the area has elevated geothermal resource potential and is not located on protected lands, when proximity to transmission lines is considered, favorability for exploration and development is significantly reduced (Fig. 6B). Any resources developed in this area would likely be restricted to local use and not be economic for utility-scale interconnection with the regional power grid.

Mount St. Helens and Vicinity

Mount St. Helens, an active stratovolcano on the western crest of the southern Washington Cascade Range, lies within Mount St. Helens National Volcanic Monument and is a designated KGRA (Burkhardt and others, 1980) (Fig. 6, area 4). The volcano is the site of ongoing geothermal activity, with numerous hot springs and fumaroles at the central crater, along the north flank, and in the pumice plain north of the 1980 flank collapse. Geothermometer estimates of source temperatures range from 155°C to 185°C, but are unreliable due to disequilibrium of water with host rocks (Shevenell and Goff, 1995) and significant post-eruption decreases in measured spring temperatures (Bergfeld and others, 2008). In addition, a well-defined northwest-trending fault zone expressed as a linear band of concentrated seismicity extends across the volcano.

The area has a relatively high resource potential (Fig. 6A), but its elevation and distance from transmission lines contribute to its low overall geothermal-favorability score (Fig. 6B). The national volcanic monument status of the volcano also restricts any exploration or development of geothermal resources in this area (Plate, Fig. H). The northwest-trending seismic zone extends beyond the national monument boundary, and further study could be directed in these areas.

Wind River Valley

The Wind River valley on the crest of the southern Washington Cascade Range is a northwest-trending drainage that joins the Columbia River near Carson, Wash. (Fig. 6, area 5). Both the resource potential and favorability models identify the area as relatively favorable. There are numerous thermal and mineral springs and seeps along and adjacent to this valley, several of which are now or were previously developed into resorts such as Bonneville and Saint Martins (Carson) Hot Springs. Chemical geothermometry from hot springs suggests reservoir equilibrium temperatures from 53°C to 108°C (Korosec and others, 1983). Several temperature-gradient wells drilled in the early 1980s yielded gradients as high as 160°C/km (Czajkowski and others, 2014c). Detailed investigations with emphasis on the geothermal resources of the Wind River valley include Berri and Korosec (1983) and Czajkowski and others (2014a). Czajkowski and others (2014a) identified multiple intersecting fault zones that control thermal fluid upflow in the area.

The Wind River valley is one of two promising areas identified in the geothermal favorability model (Fig. 6B). It is in close proximity to transmission lines and infrastructure and lies at an elevation below 3,500 feet. Land is predominantly privately owned, with WADNR-managed resource lands and national forest in the uplands. Although considerable efforts have been made to understand the geothermal systems in the valley, no deep exploration wells have been drilled to date.

Roosevelt

An area with both elevated geothermal resource potential and modeled favorability is centered near the town of Roosevelt, Wash., in eastern Klickitat County just north of the Columbia River (Fig. 6, area 6). Numerous wells produce warm irrigation water from relatively shallow depths, with temperature gradients ranging from 43.3° to 53.8°C/km (Plate, Fig. C)(Czajkowski and others, 2014c). South of the Columbia River in Oregon, several wells have gradients ranging from 57° to as much as 78°C/km (not shown)(Blackwell, 2010). In addition, several active or potentially active faults are mapped through this area. Aside from shallow temperature-gradient well drilling in the 1980s, no geothermal studies have been performed in this area; additional data would be required to better understand this prospect.

The Roosevelt area is identified as having relatively high geothermal favorability, due in part to proximity to transmission lines and low elevation. Land ownership consists of a checkerboard pattern of WADNR-managed resource lands, USBLM-managed lands, and privately owned land, suggesting limited exploration and development restrictions.

CONCLUSIONS

This GIS-based multi-criteria analysis of geothermal favorability in Washington State integrates numerous geologic, infrastructure, and land-use data sets. As such, the model is limited by the quantity, distribution, and quality of available data. The model structure allows for update and refinement as new data is collected or if attributes or underlying assumptions change.

The model illustrates the challenges of developing geothermal resources in Washington State—most areas of the state with potential resources are remote, with little infrastructure or accessibility. Proximity to transmission lines, elevation, and land-use restrictions significantly impact geothermal favorability, rendering potential resource areas unfavorable for exploration and (or) development, including most of the thermal areas along the crest of the Cascade Range. The potential for local, small scale geothermal power production, however, remains an option for some remote locations.

The Wind River valley remains the most favorable area in Washington State for development of moderate- to high-temperature resources. It is important to note that while the Wind River area is favorable relative to the remainder of Washington State, further data and model integration are necessary to compare this favorability assessment to one with a regional scale and scope, such as the assessment by Williams and DeAngelo (2008).

The widespread low-temperature geothermal resources in the Columbia Basin and elsewhere have considerable potential for direct-use applications in district heating, agriculture, and industry. This resource remains a viable option for geothermal development in Washington State. Recent coupled groundwater and heat flow modeling (Burns, 2013) suggests that, due to variations in near-surface heat flow caused by patterns of groundwater flow, more of the Columbia Basin could be characterized by temperatures of geothermal interest than previously thought. Continued efforts to understand the nature and distribution of low-temperature geothermal resources could help reduce exploration costs and make development for direct-use applications economically attractive over large areas of the state.

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Appendix A. Parameters for Temperature Gradient Kriging Interpolation

Table A1. Parameters for temperature-gradient kriging interpolation.

method	kriging
type	simple
output type	prediction
trend type	none
transformation	normal score transformation
approximations	direct
searching neighborhood	smooth
type	smooth
smoothing factor	0.2
angle	0
major semiaxis	342,946.975 ft
minor semiaxis	342,946.975 ft
variogram	covariance
number of lags	12
lag size	42868.372
nugget	0
measurement error %	100
shift on	no
model type	stable
parameter	0.2
range	342946.975
anisotropy	no
partial sill	1.447

Appendix B. Glossary of Terms

The following terms, defined as they pertain to the report, are modified from the following sources:
[1] McGraw-Hill Professional Publishing, 2005
[2] ESRI, 2012a
[3] Oxford University Press, 2003
[4] Jackson, 1997
[5] ESRI, 2012b
[6] U.S. Department of Energy, 2004
[7] Williams and others, 2008b

Analytic hierarchy process (AHP) – A systematic procedure for representing the elements of any problem that breaks down the problem into its smaller constituents and then calls for only simple pairwise comparison judgments to develop priorities at each level.[1]

Bilinear resampling – (GIS) Determines the new value of a raster cell based on a weighted distance average of the four nearest input cell centers.[2]

Bottomhole temperature – The temperature of the fluid measured near or at the bottom of a borehole.[4]

Buffer – (GIS) A zone around a map feature measured in units of distance or time. A buffer is useful for proximity analysis.[5]

Buffering – (GIS) A process used to create a buffer.

Caldera – A large, basin-shaped volcanic depression, more or less circular or cirquelike in form, the diameter of which is many times greater than that of the included vent or vents, no matter what the steepness of the walls or form of the floor.[4]

Cataclasite – A fine-grained, cohesive cataclastic rock, normally lacking a penetrative foliation or microfabric, formed during fault movement.[4]

Cataclastic – Pertaining to clastic rocks, the fragments of which have been produced by the fracture of pre-existing rocks by Earth stresses.[4]

Conduction – The transport of heat in static ground water, controlled by the thermal conductivity of the geologic formation and the contained ground water and described by a linear law relating heat flux to temperature gradient.[4]

Convection – The transfer of heat by flowing ground water.[4]

Damage zone – A volume of fractured rock on either side of a fault plane.

Digital elevation model (DEM) – (GIS) The representation of continuous elevation values over a topographic surface by a regular array of z-values, referenced to a common datum. DEMs are typically used to represent terrain relief.[5]

Direct-use geothermal – Low- to moderate-temperature water from geothermal reservoirs used to provide heat directly to buildings or other applications that require heat. Generally, the water in the geothermal reservoirs withdrawn for direct use is between 20°C to 150°C. In addition to residential, commercial, and industrial buildings, homes, pools and spas, greenhouses, and fish farms use of geothermal resources directly for heat.[6]

Distance rasters – **(**GIS) See Euclidean distance analysis.

Euclidean distance – The straight-line distance between two points.[3]

Euclidean distance analysis – GIS spatial raster processing that calculates straight-line distance between multiple points.

Feature class – (GIS) Homogeneous collections of common features, each having the same spatial representation, such as points, lines, or polygons, and a common set of attribute columns. The four most commonly used feature classes are points, lines, polygons, and annotations.[2]

Fuzzy 'OR' overlay – (GIS) A raster overlay method that returns the maximum value of the overlain rasters at the cell location.

Fuzzy 'OR' raster – (GIS) A raster created from a fuzzy linear transformation.

Fuzzy linear transformation – (GIS) A function that reclassifies or transforms the input data to a 0 to 1 scale based on the possibility of being a member of a specified set. 0 is assigned to those locations that are definitely not a member of the specified set, 1 is assigned to those values that are definitely a member of the specified set, and the entire range of possibilities between 0 and 1 are assigned to some level of possible membership (the larger the number, the greater the possibility). Input values are transformed linearly on the 0 to 1 scale, with 0 being assigned to the lowest input value and 1 to the largest input value. All the in-between values receive some membership value based on a linear scale, with the larger input values being assigned a greater possibility, or closer to 1.[2]

Geographic information system (GIS) **–** An integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information so that it can be displayed and analyzed.[5]

Geothermal **–** Pertaining to the heat of the interior of the Earth.[4]

Geothermal energy **–** Energy that occurs naturally in the Earth and can be extracted from the Earth's internal heat. Geothermal energy is usable for a wide range of temperature and volume, for example, nonelectric use (direct use of geothermal water via geothermal heat pumps to heat homes and businesses, etc.) and electric use (using geothermal steam or hot water via generators to produce electricity).[4]

Geothermal gradient **–** The rate of change of temperature in the Earth with depth, measured in °C/m or °C/km. The gradient differs from place to place, depending on the heat flow in the region and the thermal conductivity of the rocks. The average geothermal gradient in the Earth's crust approximates 25°C/km.[4]

Geothermal reservoir **–** Water trapped in porous rock capable of providing hydrothermal (hot water and steam) resources.[4]

Geothermal resource **–** That portion of the accessible resource base that can be recovered as useful heat under current and potential economic and technological conditions. Includes ***high temperature***—both liquid- and vapor-dominated systems with temperatures greater than 150°C, viable for electric power generation; ***moderate temperature***—predominantly liquid-dominated systems between 90° and 150°C, viable for electric power generation; and ***low temperature***—liquid-dominated systems less than 90°C, generally viable only for direct-use applications.[7]

Geothermometry (chemical) **–** A method used to estimate reservoir temperatures for geothermal systems based on temperature-dependent, water–rock reactions that control the chemical and isotopic composition of the thermal water.[7]

Grid resolution **–** (GIS) The dimensions represented by each cell or pixel in a raster.[5]

Heat flow measurement **–** Measurement of the amount of heat leaving the earth. It involves measuring the geothermal gradient of rocks by accurate resistance thermometers in drill holes (preferably more than 300 meters deep) and the thermal conductivity of rocks (usually in the laboratory on samples from the drill holes).[4]

Hydrothermal **–** Of or pertaining to hot water, to the action of hot water, or to the products of this action, such as a mineral deposit precipitated from a hot aqueous solution, with or without demonstrable association with igneous processes; also said of the solution itself. "Hydrothermal" is generally used for any hot water but has been restricted by some to water of magmatic origin.[4]

Interpolation **–** The estimation of surface values at unsampled points based on known surface values of surrounding points.[5]

Intersect analysis **–** (GIS) A geometric integration of spatial datasets that preserves features or portions of features that fall within areas common to all input datasets.[5]

Kernel density **–** (GIS) Analysis that calculates the density of point features around each output raster cell. Conceptually, a smoothly curved surface is fitted over each point. The surface value is highest at the location of the point and diminishes with increasing distance from the point, reaching zero at the search radius distance from the point. Only a circular neighborhood is possible. The density at each output raster cell is calculated by adding the values of all the kernel surfaces where they overlay the raster cell center. The kernel function is based on the quadratic kernel function described in Silverman (1986, p. 76, equation 4.5).[2]

Kriging – (GIS) An interpolation technique in which the surrounding measured values are weighted to derive a predicted value for an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points. Kriging is unique among the interpolation methods in that it provides an easy method for characterizing the variance, or the precision, of predictions. Kriging is based on regionalized variable theory, which assumes that the spatial variation in the data being modeled is homogeneous across the surface. That is, the same pattern of variation can be observed at all locations on the surface.[5]

Meteoric water **–** Pertaining to water of recent atmospheric origin.[4]

Normalize – Adjustment of values to a standard

Raster **–** (GIS) A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates. Unlike a vector structure, which stores coordinates explicitly, raster coordinates are contained in the ordering of the matrix. Groups of cells that share the same value represent the same type of geographic feature.[5]

Raster algebra **–** (GIS) A set of operations in a geographic information system (GIS) that allows two or more raster layers of similar dimensions to be combined on a cell-by-cell basis using algebraic operations such as addition, subtraction, etc.

Reclassify – (GIS) Geoprocessing that changes the value of cells in a raster based upon a characteristic

Schema **–** (GIS) The structure or design of a database or database object, such as a table, view, index, stored procedure, or trigger. In a relational database, the schema defines the tables, the fields in each table, the relationships between fields and tables, and the grouping of objects within the database. Schemas are generally documented in a data dictionary. A database schema provides a logical classification of database objects.[5]

Search radius – (GIS) In kernel density analysis, it is the maximum distance in coverage units a feature can be from the current point for consideration as the closest feature.[5]

Spatial data – (GIS) Information about the locations and shapes of geographic features and the relations between them, usually stored as coordinates and topology.[5]

Temperature gradient – *See* geothermal gradient.

Thermal conductivity – A measure of the ability of a material to conduct heat. It is a basic property of rocks that changes depending on the porosity, pore medium, composition, and geometry of the rock matrix.[4]

Thermal spring – A spring whose water temperature is appreciably higher than the local mean annual atmospheric temperature.[4]

Vector – (GIS) A coordinate-based data model that represents geographic features as points, lines, and polygons. Each point feature is represented as a single coordinate pair, while line and polygon features are represented as ordered lists of vertices. Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.[5]

Weighted sum – (GIS) A method that combines multiple raster inputs representing multiple factors, incorporating weights or relative importance.[2]

WASHINGTON STATE DEPARTMENT OF
Natural Resources
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Division of Geology and Earth Resources
David K. Norman - State Geologist

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
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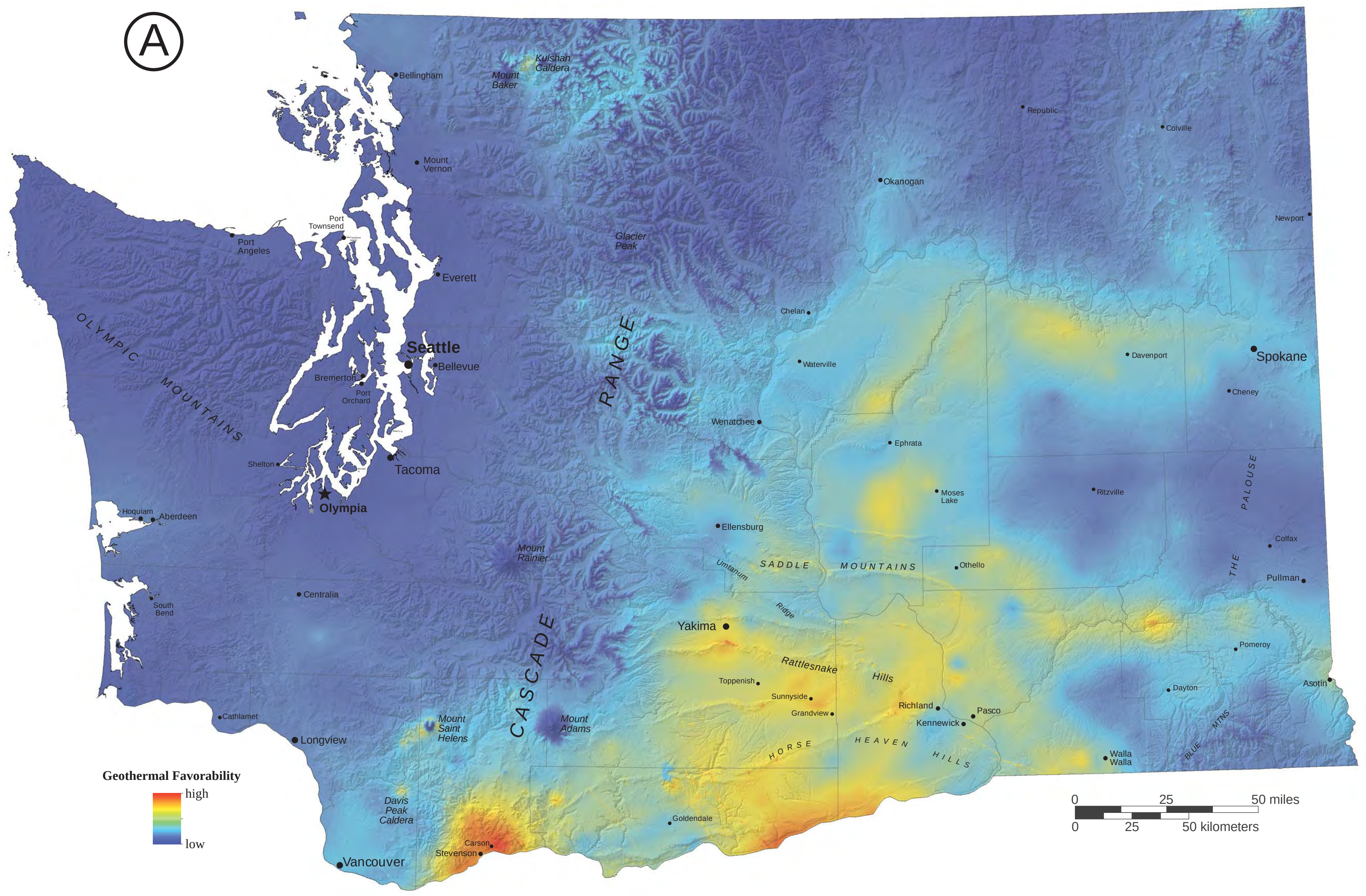
Geothermal Favorability Model of Washington State
July 2014
Pamphlet accompanies plate

Geothermal Favorability Model of Washington State

by Darrick E. Boschmann, Jessica L. Czajkowski, and Jeffrey D. Bowman

July 2014

Geothermal Favorability Model



In the early phases of geothermal exploration, many important geological details are unknown. A regional exploration model based on available data and exploratory principles can identify areas where it would be most beneficial to obtain more detailed data.

In 2011, the U.S. Department of Energy funded a three-year effort by state geological surveys to compile and collect all varieties of new and existing geothermal-related data and information for inclusion in the National Geothermal Data System (NGDS; geothermaldata.org). In support of this effort, the Washington State Department of Natural Resources (DNR), Division of Geology and Earth Resources (DGER), developed and (or) revised numerous datasets of existing geothermal and geological data in Washington State.

Using this newly compiled and collected data, a Geographic Information System (GIS)-based analysis of relevant spatial datasets was used to determine the spatial association between various geologic and thermal features, infrastructure, and land-use to gain a broad understanding of geothermal resource potential and favorability for development in Washington State.

The geothermal favorability model of Washington State was constructed by first performing multiple iterative ArcGIS processes (various methods of density and proximity analyses, interpolation, and data combination) on volcanic vents, young silicic intrusive rock bodies, thermal/mineral springs, temperature gradients in wells, faults, earthquakes, electric transmission lines, and elevation (Figs. C–G). Detailed data processing methods and further discussion of model results are found in the accompanying pamphlet.

The geothermal favorability model shows relatively high favorability in localized areas of the Columbia Basin as well as areas within the South Cascades (Fig. A and pamphlet Fig. 6B). The model also illustrates the challenges of developing geothermal resources in Washington State—most areas of the state with potential resources (Fig. F) are remote, with little infrastructure or accessibility. Proximity to transmission lines (not shown), elevation (Fig. G), and land-use restrictions (Fig. H) significantly impact geothermal favorability, rendering potential resource areas unfavorable for exploration and (or) development, including most of the thermal areas along the crest of the Cascade Range (see pamphlet, Fig. 6). However, the potential for local, small-scale geothermal power production remains an option for some remote locations.

The widespread low-temperature geothermal resources in the Columbia Basin and elsewhere have considerable potential for direct-use applications in district heating, agriculture, and industry; continued efforts to understand the nature and distribution of low-temperature geothermal resources could reduce exploration costs and make development for direct-use applications economically attractive over large areas of the state.

Model outputs are intended to supersede the geothermal resource map of Washington State (Korosec and others, 1981). The model results represent an assessment of geothermal resource potential and favorability on a statewide scale, and are not intended for site-specific evaluation of geothermal development potential. The modeling incorporates the most complete and accurate data compilations to date, but is nevertheless limited by the quantity, quality, and sparse or irregular distribution of available data.

Geothermal Favorability Model Structure

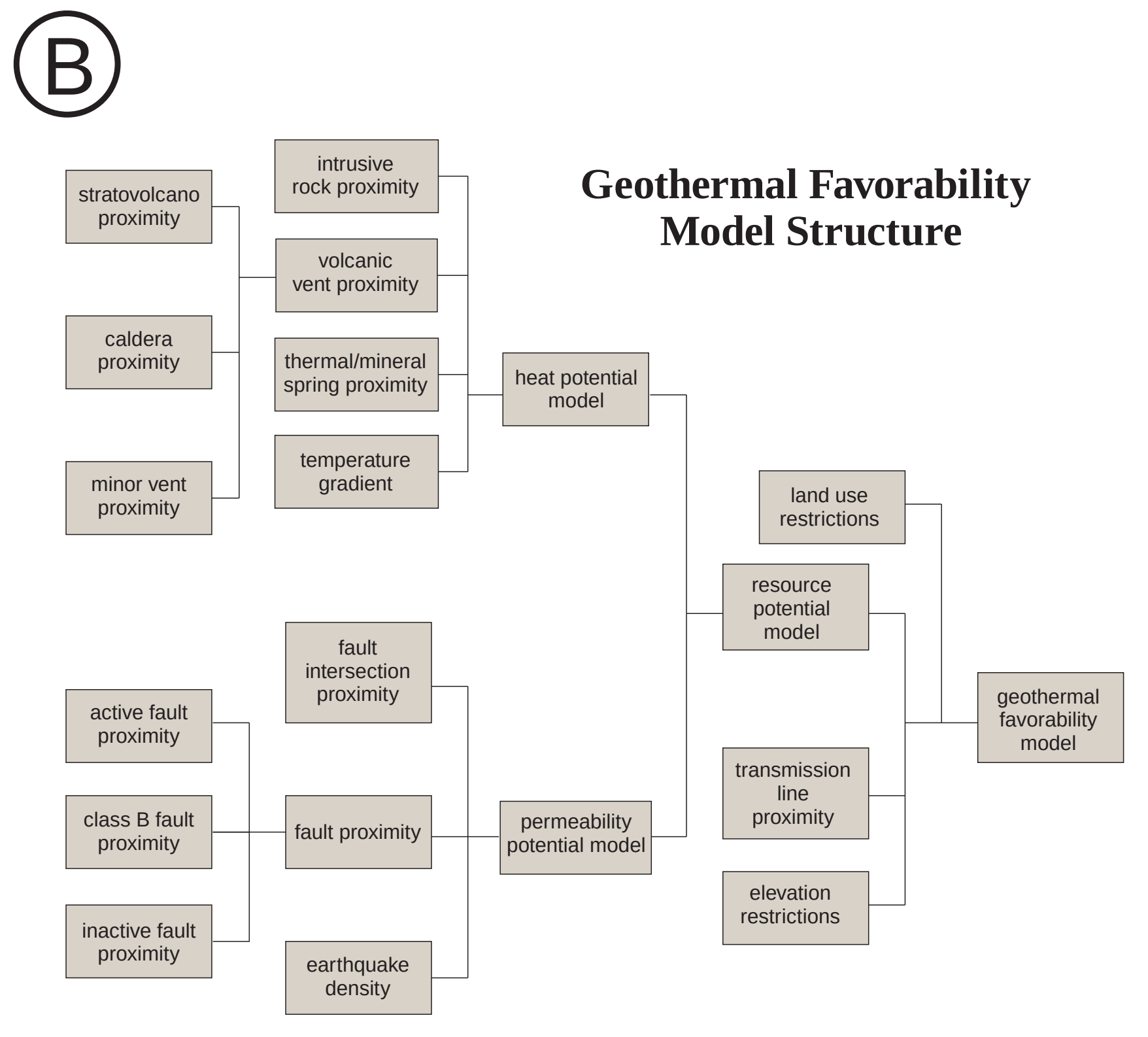


Figure B. Schematic of geothermal favorability model inputs and data organization. See the accompanying pamphlet for a detailed description of methodology, assumptions, and processing steps.

Heat Potential Model

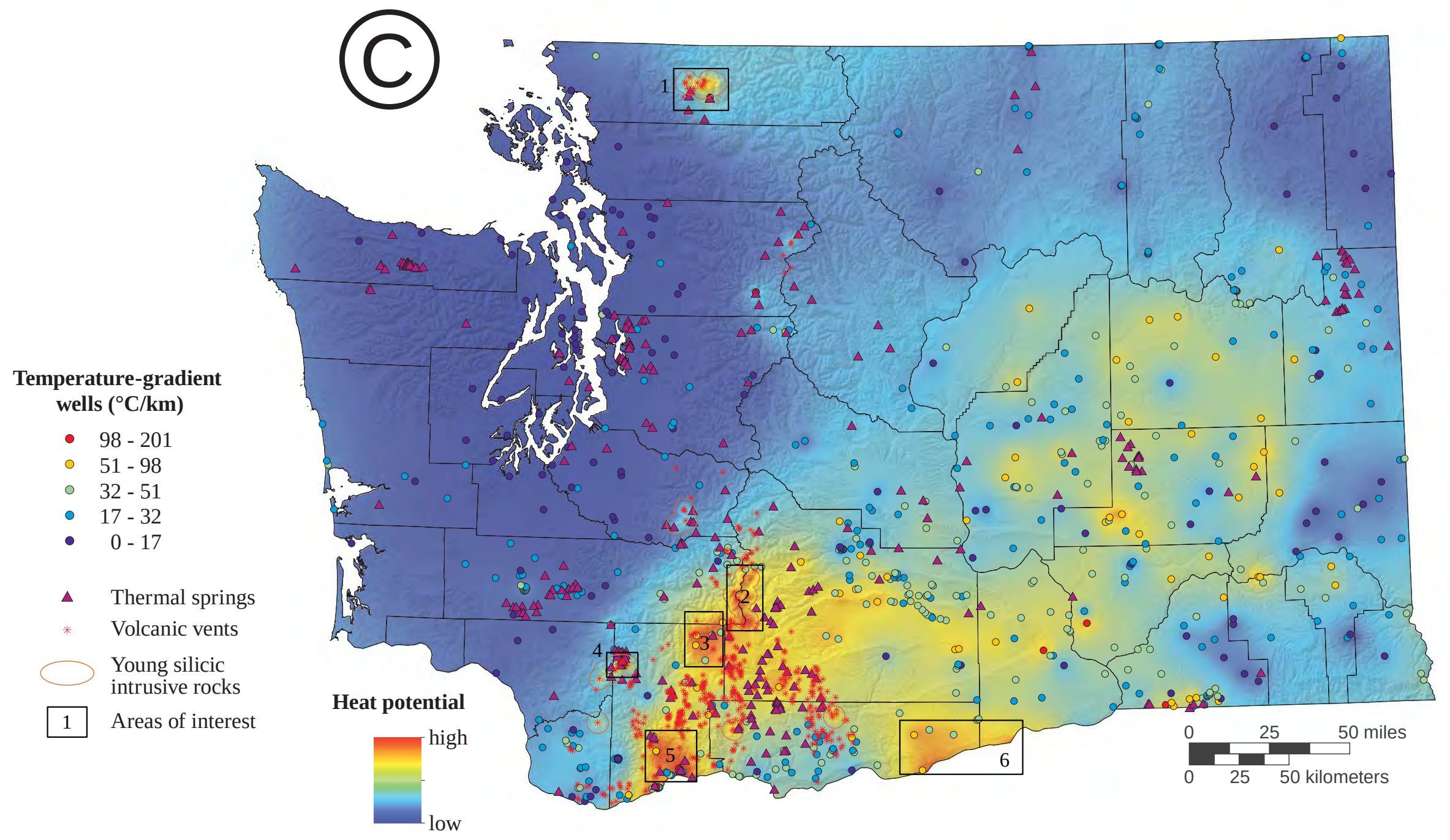


Figure C. Crustal heat at depths accessible by modern drilling technologies is a basic requirement for development of geothermal resources. The geothermal heat potential model represents the modeled shallow crustal heat potential in Washington State based on the spatial distribution of temperature gradient, thermal/mineral springs, volcanic vents, and young intrusive rocks. The highest modeled heat potential is in the southern Cascade Range, with isolated areas of elevated heat potential in the North Cascades and a broad region of scattered moderate potential across much of the Columbia Basin. Areas west of the Cascade Range, including the Puget Lowland and Olympic Mountains, generally have the lowest modeled heat potential. Areas of interest: area 1, Mount Baker/Kulshan Caldera; area 2, Goat Rocks; area 3, East Canyon Ridge; area 4, Mount St. Helens; area 5, Wind River; and area 6, Roosevelt.

Resource Potential Model

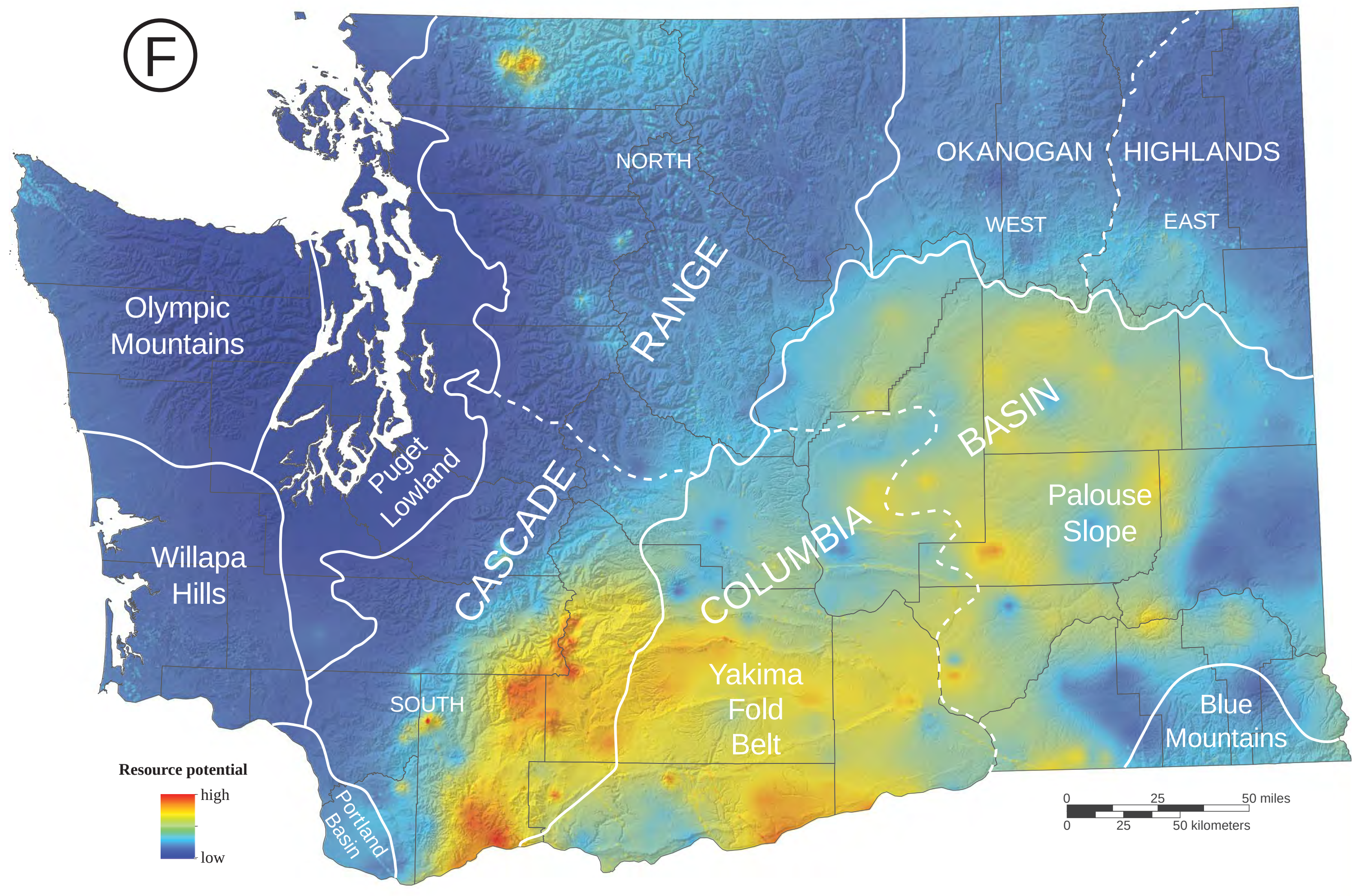


Figure F. The resource potential model represents the relative geothermal potential in Washington State based on the permeability and heat potential models. The model is intended to highlight areas of elevated potential for the presence of moderate- to high-temperature geothermal systems. This model represents geothermal resource potential without consideration of regulatory restrictions, land-management restrictions, or economic viability. The general trend of the resource potential model is similar to that of the heat potential model. Locally, areas with elevated modeled permeability potential moderately increase the relative resource potential. See accompanying pamphlet for a detailed discussion of model results.

Permeability Potential Model Input Data

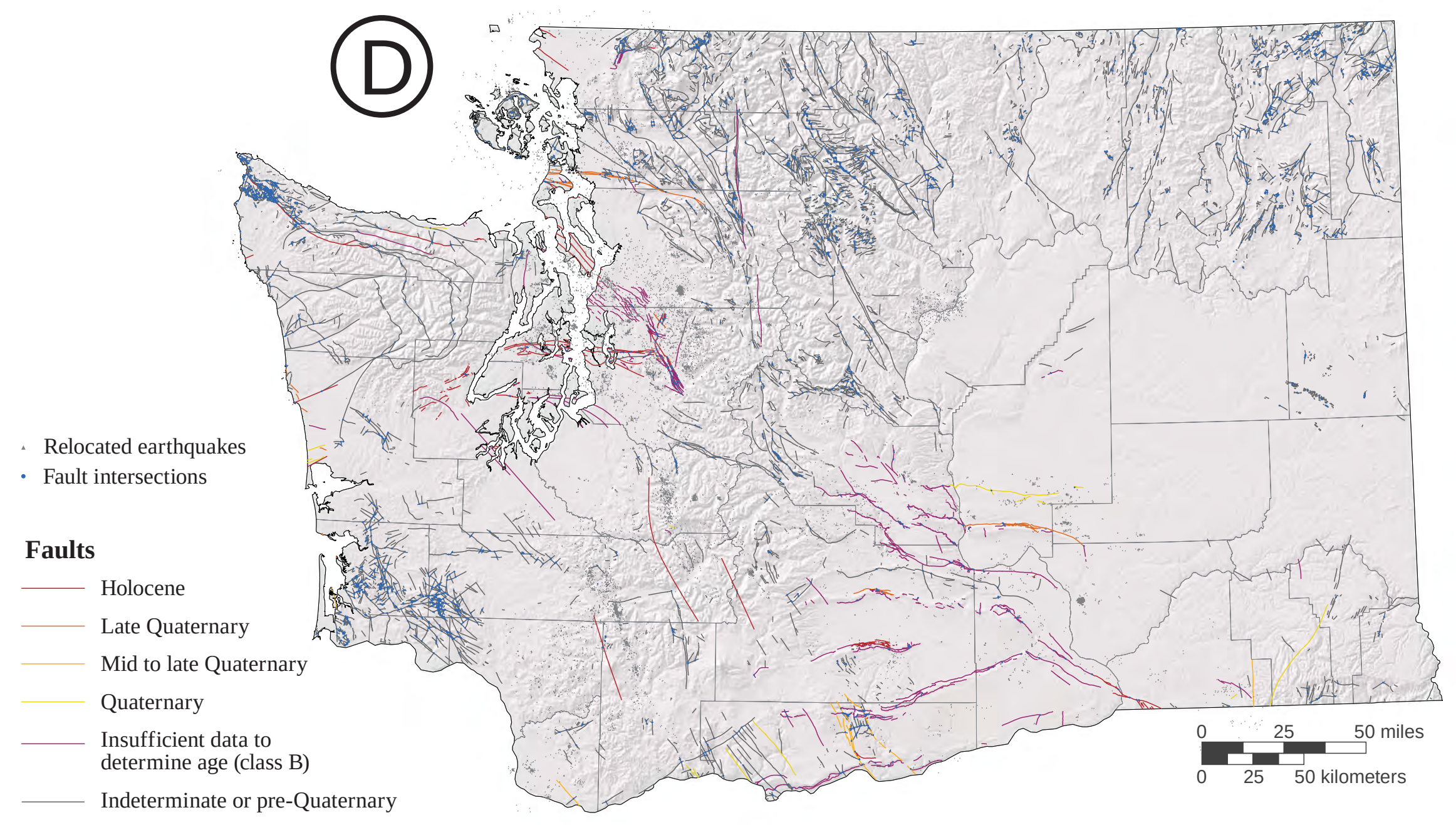


Figure D. The permeability potential model uses input data including faults, fault intersections, and earthquake locations. Fault data consist of mapped faults compiled from 1:250,000-scale, 1:100,000-scale, and active fault digital data. The earthquake density calculation was performed on relocated earthquakes greater than magnitude 1 and at less than 30 km depth.

Permeability Potential Model

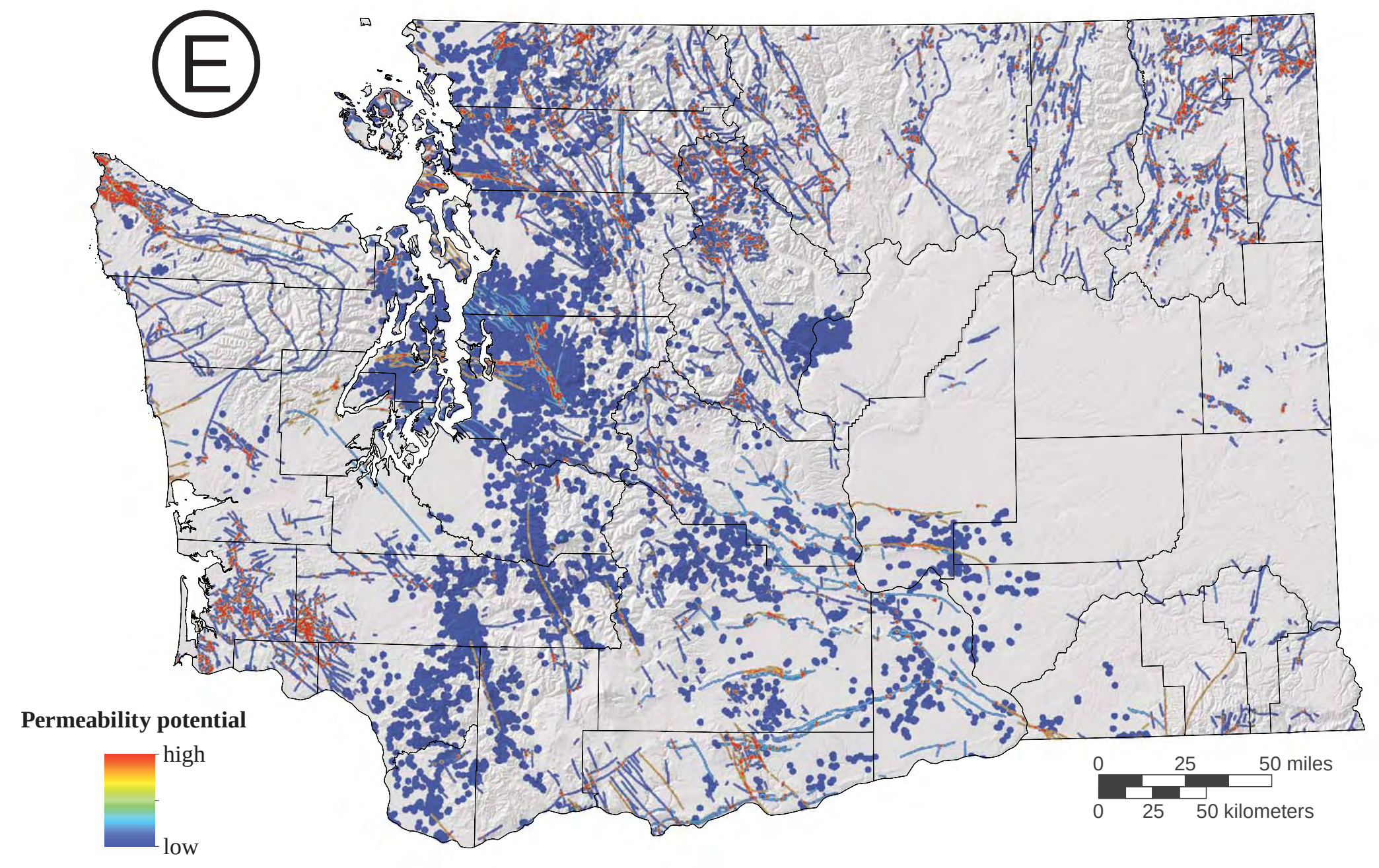


Figure E. Conventional geothermal-resource production requires significant reservoir permeability to enable thermal fluids to migrate freely through a reservoir and into the wellbore. The permeability potential model is based on the spatial distribution of known faults, fault intersections, and recorded seismic activity. The highest modeled permeability potential is found in areas of dense fault intersection, such as the northwest corner of the Olympic Peninsula and the southern Willapa Hills. Mapped fault-density variation is likely due in part to the scale and scope of fault mapping as well as the variable emphasis placed on faults by different investigators. Broad regions with recorded seismic activity are distributed widely along the western front of the Cascade Range, with isolated high density regions occurring across much of the state.

Elevation Restrictions

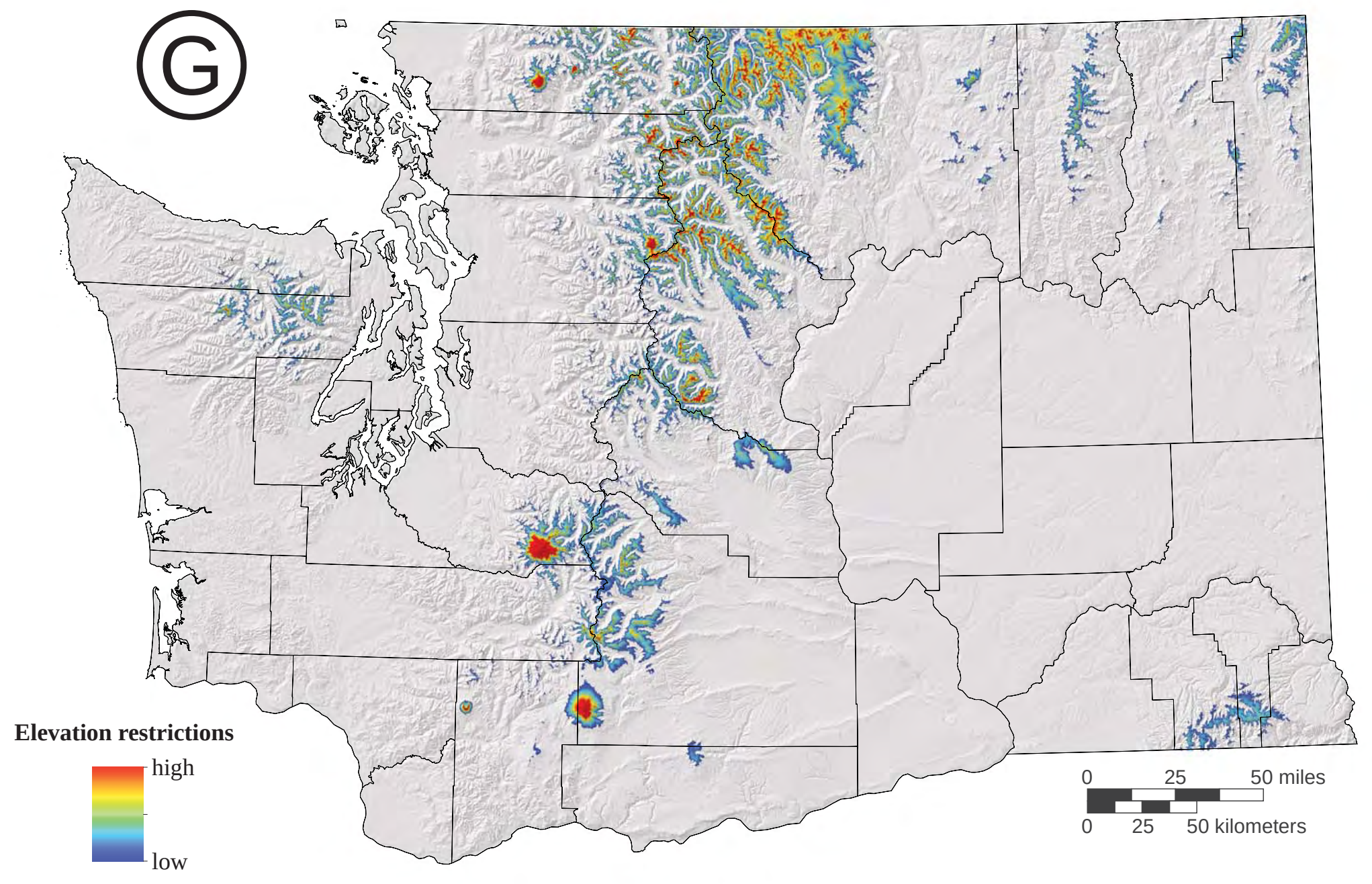


Figure G. High elevations can be restrictive to development because of logistic and climatic conditions, especially in the Cascade Range where annual snowfall can exceed 80 feet at elevations as low as 4,200 feet (Leffler and others, 2001). Most high-elevation areas are also remote, have little existing infrastructure, and may be inaccessible during several months of the year. Many areas thought to have high heat flow, such as Mount St. Helens volcano, a "Known Geothermal Resource Area" (KGRA)(Burkhardt and others, 1980), are at high elevations, making these areas challenging for geothermal-resource development. While extreme elevation and climate do not necessarily preclude development of geothermal resources, the model assumes favorability will decline with increasing elevation above 5,000 feet, and that elevations above 8,000 feet will prohibit any development activity.

Land-Use Restrictions

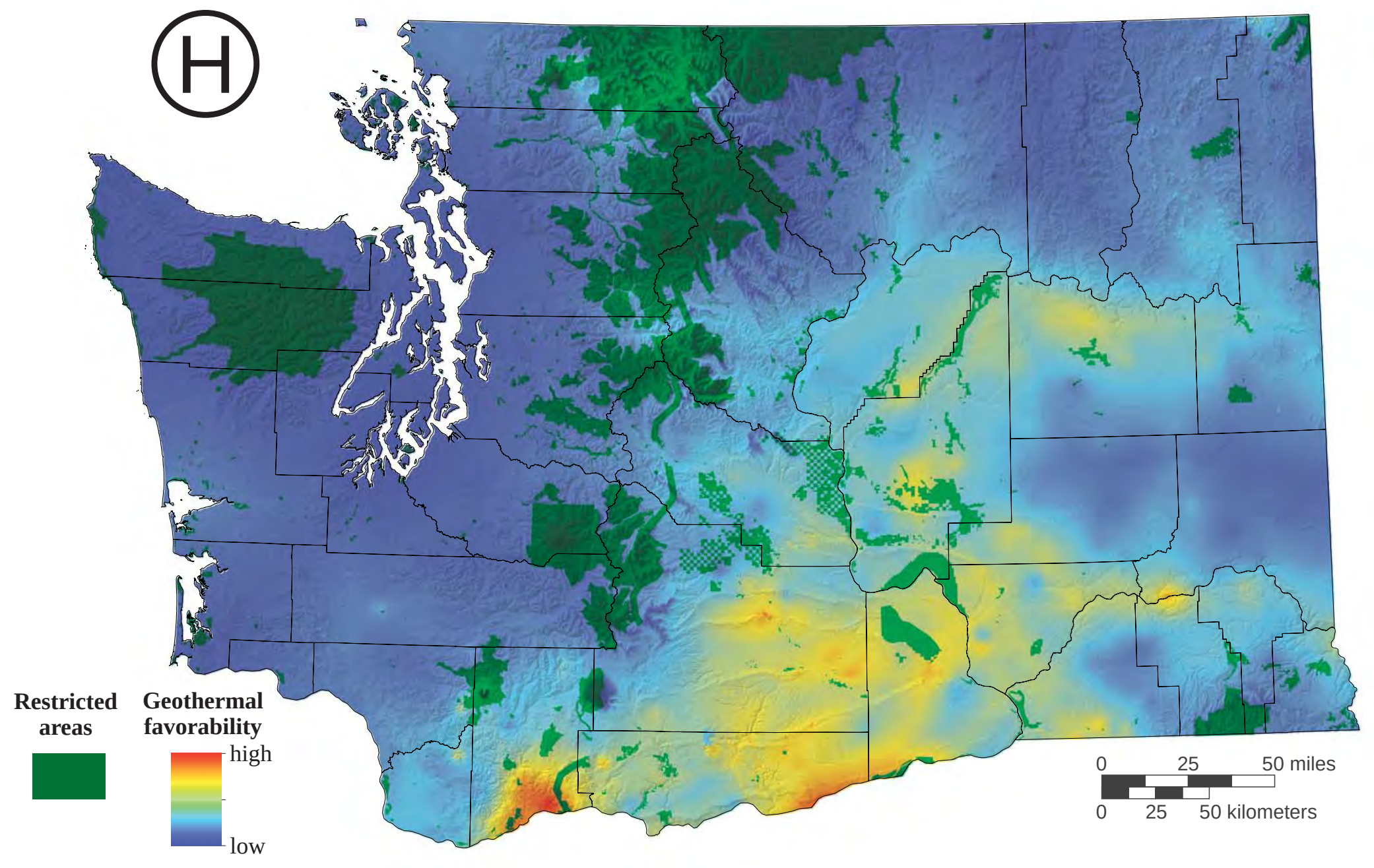


Figure H. Land-use restrictions include public and private lands managed for the conservation of biological diversity and other natural, recreational, and cultural uses that may, through legal or other effective means, restrict the exploration and development of geothermal resources. These lands include national parks, national wilderness areas, wildlife refuges, private conservations lands, and areas of critical environmental concern. Land-use restricted areas are widespread in the Cascade Range, especially in the North Cascades where much of the uplands is designated federal wilderness area. The South Cascades and Olympic Mountains also have significant land-use restrictions, and widely distributed restrictive parcels are located throughout the state. In total, just over 10,000 square miles (~14%) of land in Washington State are designated as restrictive for the purposes of this report. Much of this land is located in areas with elevated resource potential, and thus, land-use restrictions are a major obstacle for exploration and development of geothermal resources in Washington State.

http://www.dnr.wa.gov/geology/