Mapping Geothermal Potential in the Western United States

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ABSTRACT

The U. S. Geological Survey (USGS) is conducting an updated assessment of geothermal resources in the United States. An important component of the assessment is the estimate of the spatial distribution and quantity of undiscovered geothermal resources. Weights of evidence and logistic regression models have been applied through a Geographic Information System (GIS) framework to produce maps of geothermal favorability. These maps provide the basis for characterizing the undiscovered geothermal resource base and could guide future exploration and land use decisions. A total of 28 weights-of-evidence and logistic regression models were developed using varied evidence layers for heat flow, Quaternary magmatism, Quaternary faulting, seismicity, and tectonic stress. The results highlight and quantify the strong correlation of geothermal systems with active tectonic deformation, magmatism, and elevated heat flow. Regions with significant geothermal potential, but few identified geothermal systems, include northeastern Nevada, western Utah, eastern Oregon, and parts of New Mexico, Colorado, and southern Idaho. Ongoing research is directed towards the transformation of these favorability maps to quantitative estimates of the magnitude of undiscovered geothermal resources.

Introduction

As part of the Energy Policy Act of 2005, the United States Geological Survey (USGS) is conducting a new national assessment of geothermal resources capable of producing electric power, with a focus on the western United States, including Alaska and Hawaii. The new assessment will provide a detailed estimate of the geothermal electric power generation potential from identified and undiscovered resources and include a provisional evaluation of the potential impact of Enhanced Geothermal Systems (EGS) technology. This assessment effort is moving forward in partnership with the Department of Energy (DOE), the Bureau of Land Management (BLM), other Federal agencies, National Laboratories, universities, State and Local agencies, and the geothermal industry.

More than 250 identified geothermal systems will be included in the new assessment effort, which is incorporating improved understandings of the thermal, chemical, and mechanical processes that lead to the formation of productive geothermal systems. Additional products will include online geospatial databases of regional and system-specific geological, geophysical, geochemical and hydrological information relevant to geothermal resources. The assessment and associated databases will be augmented with a series of research publications describing scientific advances and improved assessment methodologies. A key part of the assessment is characterizing undiscovered geothermal resources in type, magnitude and spatial distribution. This paper reports on application of the weights-of-evidence approach through a geographic information system (GIS) to creating geothermal favorability maps for the western United States. Subsequent reports will address the extension of these results to quantitative estimates of undiscovered geothermal resources.

The weights-of-evidence approach employs Bayesian probability factors to determine the probability of correlation among spatial databases. This quantitative measure of correlation is derived from analysis of pairs of spatially distributed data sets to produce a map of the favorability of correlation between the features represented by the two data sets. The technique as applied in the field of geological sciences is a statistical modeling method used to study the spatial relationship of deposits to evidence layers, such as lithologic units, faults, or other measureable or observable features (Goodacre et al., 1993; Bonham-Carter, 1994). The weights-of-evidence technique was first utilized on conjunction with Geographic Information Systems (GIS) in the context of mineral exploration (e.g., Bonham-Carter et al., 1989; Raines, 1999). This was followed by applications in other fields in which geospatial data can be used to investigate the spatial correlation between occurrences of interest and other observable features (e.g., Goodacre et al., 1993). The technique was applied to geothermal resources by Coolbaugh and colleagues in Nevada and subsequently in the Great Basin (Coolbaugh et al., 2007; Coolbaugh and Bedell, 2006; Coolbaugh et al., 2006; Coolbaugh et al., 2005; and Coolbaugh and Shevenell, 2004), and these earlier studies serve as examples for this study.

Weights-of-evidence is a data driven approach that can be used to assess spatial variations in probability through GIS via ArcSDM, a software module that works with the ArcGIS program (Raines et al., 2000). The GIS is used to manipulate the spatial databases, to establish the spatial extent for the analysis of correlation between the training set of known occurrences and to produce a map of the resulting predictions. In this paper, we summarize a weights-of-evidence approach through which geothermal potential is modeled using a weighted combination of evidence layers derived from mappable geologic and tectonic features available in digital databases. The spatial variations in probability for the presence of a geothermal system are determined by mapping the presence or absence of various indicators comprising evidence layers that are weighted for their influence on the feature of interest.

In Bayesian statistical theory, the prior probability is derived from knowledge that is present before a particular observation is made, and the posterior probability is derived from knowledge developed from reasoning once the outcome of the observation is taken into account. As a reference quantity, prior probability for the occurrence of a geothermal system in the study area is calculated as the ratio of the area occupied by geothermal systems divided by the study area. Using a Bayesian statistical model, the weighted evidence layers are the "observations" that are combined with the prior probability to produce a posterior probability map showing the spatial distribution of geothermal potential. Spatial associations between pattern and occurrence are determined through positive and negative weights, W+ and W-, which represent the degree of correlation. Derivation of the weights can be made through a binary analysis of an evidence layer (e.g., the presence or absence of a feature, such as proximity to a mapped fault zone) or with a multiclass analysis. In either case, the analysis can also be based on categorical data, in which the evidence layer is divided into classes that are descriptive (e.g., lithologic units) or quantitative (e.g., contoured values of heat flow). The posterior probability derived from the weights-of-evidence analysis represents the sum of the prior probability and the weights assigned to the evidence layers, yielding probabilities higher than the prior in promising areas and less than the prior in less likely areas. (For a more complete description of the weights-of-evidence technique, see Bonham-Carter et al., 1989; Goodacre et al., 1993; Bonham-Carter, 1994; Singer and Kouda, 1999; Raines et al., 2000).

One formal requirement in a quantitative application of the weights of evidence technique is the conditional independence of the evidence layers (Bonham-Carter, 1994; Singer and Kouda, 1999). When conditional dependencies exist the posterior probability map will overpredict occurrences in locations where the conditionally dependent evidence layers coincide (Singer and Kouda, 1999). Consequently, where dependence exists among the evidence layers, the resulting posterior probability surface can be used only as a qualitative map highlighting areas of favorability (e.g., Coolbaugh, 2005), unless the results can be corrected or calibrated to account for the effects of conditional dependence (Singer and Kouda, 1999; Coolbaugh, 2007). In order to supplement the weights of evidence evaluation of geothermal potential, logistic regression analysis, which does not require conditional independence among the evidence layers, was performed on the same evidence layers described below. Because the results of the logistic regression analysis are qualitatively similar to the weights-of-evidence models, they are not included in this paper. A future publication will describe the combined use of weight-of-evidence and logistic regression to quantify the potential number of undiscovered geothermal systems in the western United States.

Evidence Layers

At the most basic level, a geothermal reservoir requires high temperature and high permeability. There must also be some sort of seal or barrier on the reservoir, either physical, such as a cap rock, or hydraulic, such as elevated geothermal fluid pressures relative to surrounding cooler ground water. The heat source can be related to magmatism or simply elevated background heat flow due to active tectonic processes such as crustal extension. Permeability that allows for water or steam to circulate, extract heat from reservoir rocks, and be produced for electric power generation can be tied either to the intrinsic porosity of the reservoir rock (such as in sandstone or porous volcanic rocks) or fracture permeability, which is the most important form of permeability in geothermal reservoirs because of the need for high flow rates (e.g., Williams, 2004; Williams et al., 2007). Both elevated heat flow and fracture permeability are transient phenomena on geologic time scales, and hydrothermal circulation is most likely to be present where the tectonic processes responsible for providing the necessary heat source and permeability are either active or relatively recent. Such observations have been part of geothermal exploration and assessment for decades.

For this work, the focus is on moderate and high-temperature geothermal systems capable of producing electricity, which for the western conterminous United States constitutes those systems with temperatures above 90ºC (Williams and Reed, 2005; Williams et al., 2007). Three different training sets of known geothermal systems were developed. The first is an updated list of all identified moderate and high-temperature geothermal systems. The second and third are subdivisions of the first, divided into magmatic and amagmatic (also known as deep circulation) geothermal systems. Magmatic systems are those with a direct spatial association with magmatic activity that represents a shallow crustal heat source, with the partially cooled extrusive and/or intrusive rocks produced by magmatism serving as reservoir host rocks in some cases. Prominent examples of magmatic geothermal systems in the United States are The Geysers, Salton Sea, and Yellowstone. Amagmatic, or deep circulation, systems are those which acquire high temperatures through the circulation of water to depth in regions of elevated crustal heat flow, such as in the highly extended Great Basin. To some degree, the distinction between magmatic and amagmatic geothermal systems is imperfect. For example, in the Imperial Valley of California, extensive regional magmatism has raised background heat flow and fostered the formation of moderate temperature geothermal systems (e.g., Heber, East Mesa) that are otherwise equivalent to amagmatic geothermal systems. However, overall errors in classification are likely to be minor and covered by the wide range of results produced by having developed three sets of favorability maps for all geothermal systems, magmatic geothermal systems, and amagmatic geothermal systems, each set with a number of different weights of evidence models.

Weights of evidence is a data-driven technique, which in its ideal form is applied through an unbiased analysis of spatial correlations, but some knowledge-based aspects come into play in the choice and interpretation of evidence layers used in the analysis. In the application of this technique for geothermal resources in the western US, we focused on two basic criteria. First, that the evidence layer represents a measured or mapped geologic quantity or property that is plausibly significant in the formation of hydrothermal systems. Second, that the data making up the evidence layer are available in comprehensive and consistent databases over the entire study area of the western US. The imperfections of the databases are probably the single greatest source of uncertainty in this analysis.

The evidence layers used in this study were assembled from datasets covering the 13 states with identified conventional geothermal systems with temperatures greater than 90°C: Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. Due to geographic separation, these datasets were combined into three model domains covering the 11 conterminous western states, Alaska, and Hawaii. The results for the western states are described in this report. The following are the datasets utilized in the weights-of-evidence models.

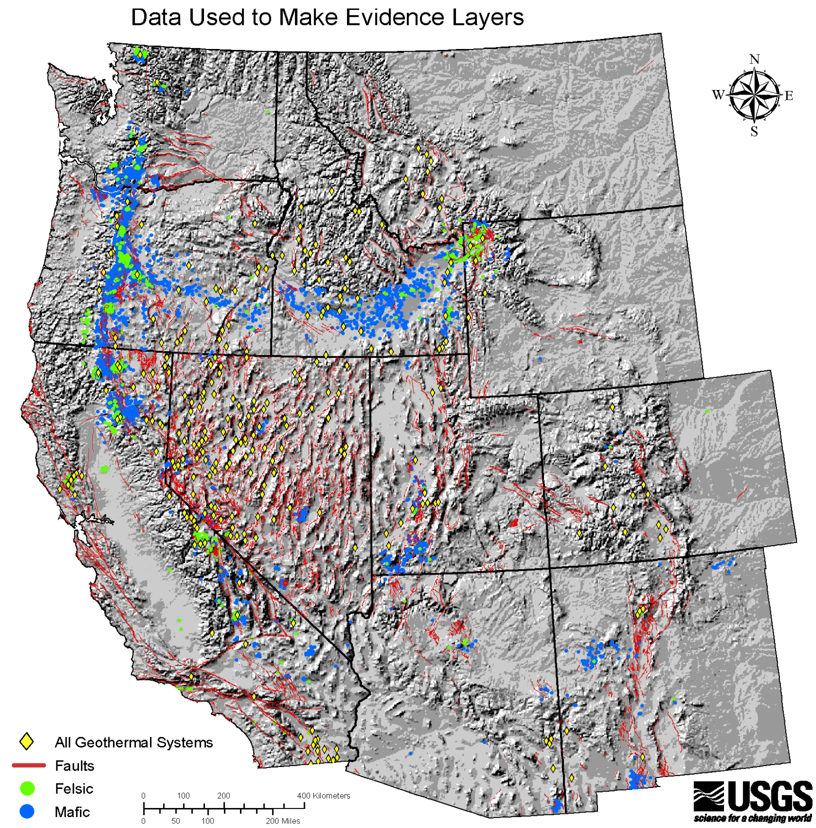

Figure 1. Map showing spatial distribution of Quaternary magmatic and fault activity used in the weights-of-evidence and logistic regression models, along with locations of identified geothermal systems used as training points in the analysis.

1. Quaternary magmatic activity –Data on magmatic activity in the western United States were compiled from a number of sources. The principal source, the Western North American Volcanic and Intrusive Rock Database (NAVDAT) (Walker et al., 2006), includes detailed information on the age and chemistry of volcanic and intrusive rock samples, and provides a basis for evaluating the correlation of geothermal occurrences with variations in the age and composition of magmatic activity. However, NAVDAT is incomplete in some areas and had to be supplemented with detailed maps of Quaternary vents and cinder cones (Hildreth, 2007; Donnelly-Nolan, 1988; MacLeod et al., 1995). The combined dataset lacks detailed age and composition information beyond the identified Quaternary age of activity and whether the predominant composition is felsic or mafic, but the spatial coverage is more complete, particularly in the Cascades Range of Washington, Oregon and California (Figure 1). In general, young felsic magmatism characterized by relatively shallow crustal magma chambers should correlate more consistently with known geothermal systems (e.g., Smith and Shaw, 1975). Analysis showed that Quaternary felsic magmatic activity has a stronger spatial correlation with geothermal systems than mafic magmatic activity, but both show strong positive correlations within a 10 km distance buffer around each magmatic center. This is due in some degree to the complex histories of composition, timing and volume of extrusion and intrusion at major magmatic centers. Surprisingly, a separate analysis of only the NAVDAT data by age did not yield a statistically significant weight correlation between more recent magmatism and geothermal occurrences.Possible reasons for this include significant spatial separation between geothermal manifestations and their heat sources due to lateral water flow, incomplete information on the spatial distribution of young magmatic activity, and misclassification of some geothermal systems as magmatic in origin.

2. Heat flow – Two maps were used for evaluating the relationship between heat flow and geothermal resources in order to represent different interpretations of the thermal state of the crust under major regional aquifers. The first map is taken directly from the recently published heat flow map of North America (Blackwell and Richards, 2004). This map has been used as a basis for evaluating crustal thermal conditions for EGS studies (Tester et al., 2006), and represents a mix of data-driven interpolation of measurements and knowledge-driven interpretation where the data coverage is limited or evidence suggests deep temperatures do not reflect shallow heat flow measurements (Blackwell and Richards, 2004). This interpretive aspect of the heat flow map is particularly relevant to evaluating geothermal potential because the authors take the position that cool ground-water flow in many major regional aquifers of the western United States, such as the Snake River Plain aquifer of Idaho and the Carbonate aquifer of eastern Nevada and western Utah, masks higher temperature gradients and heat flow at depth. As an alternative interpretation,

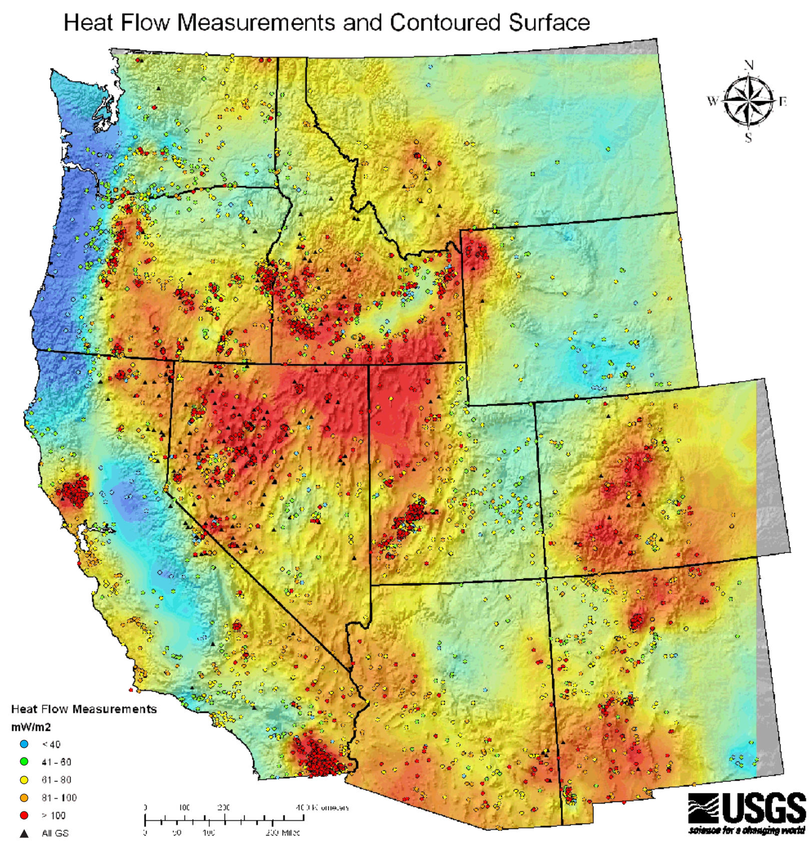

Figure 2. Map showing heat flow measurements and resulting contours for the western United States used in the weights of evidence and logistic regression models as an alternative to the Blackwell and Richards (2004) map. Note moderate and low values of heat flow in southern Nevada and the Snake River Plain.

a second map was prepared through radial basis function contouring of published and unpublished heat flow data in the western United States compiled for this project (Figure 2, Williams et al., 2007). On this contour map the major aquifers remain as regions of low or moderate heat flow. The two maps were used as evidence layers in separate weights of evidence analyses, and, as expected, in both cases there is a strong positive correlation between higher heat flow and the presence of both magmatic and amagmatic geothermal systems.

3. Quaternary Faults - The USGS Quaternary fold and fault database (Machette et al., 2003; Figure 1) was evaluated to determine relationships between focused deformation in the upper crust and the formation of geothermal systems. As with the databases of Quaternary magmatic activity, information on the timing and sense of the most recent slip is available for only a subset of the faults in the database, so it was not possible to examine in detail the relationship between geothermal occurrences and the age or style of faulting. However, even with these limitations there is a strong correlation between geothermal occurrences and all Quaternary faults, with a strong statistical significance for the correlation within 4 km distance of the mapped surface traces.

4. Seismicity - In order to supplement the limited information on tectonic deformation available from the Quaternary fault database, a number of other data sets related to active tectonics were evaluated for spatial association with geothermal systems. The USGS catalogue of earthquakes of magnitude (M) greater than 3.0 since the year 1965 demonstrated a significant correlation with all geothermal systems, whether characterized in terms of the rate of seismic deformation through summed moment release or simply in terms of the spatial density of events (Figure 3).

5. Stress - Information on the orientations and relative magnitudes of tectonic stresses in the western United

6. States was derived from the World Stress Map Project (Reinecker et al., 2005). A stress evidence layer

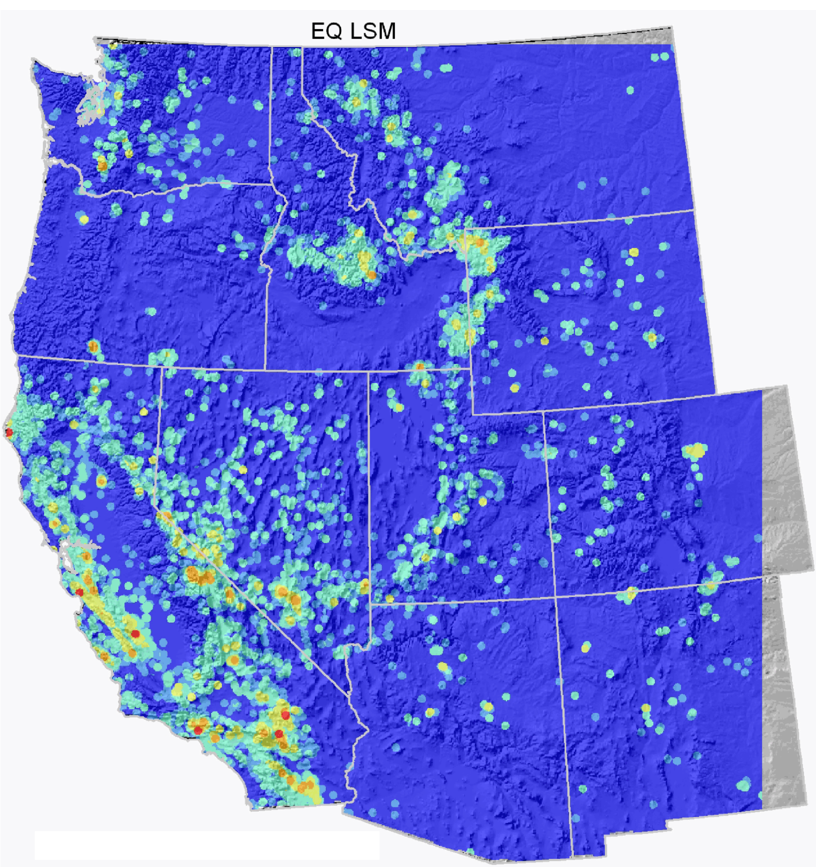

Figure 3. Example of seismicity evidence layer used in the weights of evidence and logistic regression models. The map shows the logarithm of the summed moment release for earthquakes with M>3.0 for the period 1965 to 2007.

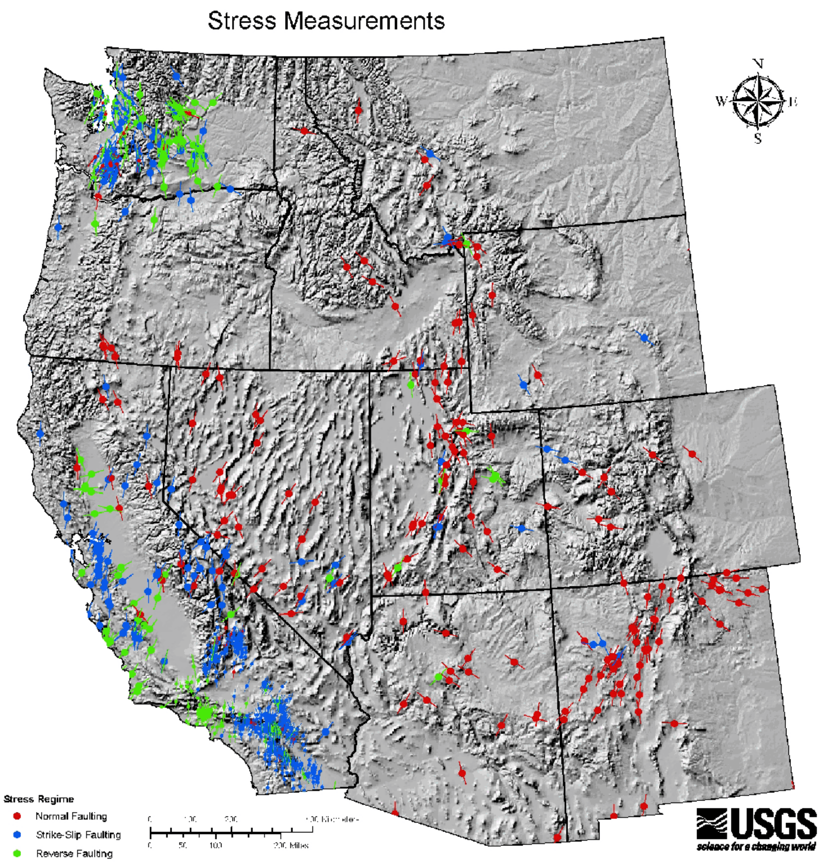

Figure 4. Map showing stress measurements in the western United States derived from the World Stress Map database (Reinecker et al., 2005). Note the wide distribution of normal faulting (extensional stress) outside of Washington and California.

was developed by estimating the magnitude of the maximum horizontal stress for each stress data point by applying a Coulomb failure criterion to the observed mode of faulting (normal, reverse or strike-slip) with an assumed friction coefficient of 0.6. Analysis of the resulting contour map showed a significant positive correlation of extensional stress with amagmatic geothermal systems, particularly in the Great Basin, but extensional stress did not correlate with magmatic geothermal systems (Figure 4). This may be indicative of local stress perturbations associated with active volcanic centers that are not consistent with the dominant regional stress regime. The correlation of extensional stress with amagmatic systems may be due to the association of lower horizontal principal stresses with higher fault zone permeability and to the tendency for extensional faulting to thin the lithosphere and raise regional heat flow.

Modeling Results

A total of 28 different weights-of-evidence geothermal occurrence models were constructed for the western conterminous United States using the evidence layers described above, with 12 for all geothermal systems, 12 for magmatic geothermal systems, and 4 for amagmatic geothermal systems. (Geothermal occurrence models for Alaska and Hawaii are in preparation.) For each weights-of-evidence model, an equivalent logistic regression model was run on the same sets of evidence layers. Limited space does not allow for a detailed discussion of all the results, so three representative weights of evidence models are described in this paper. Maps of posterior probability for these three models are shown in Figures 5, 6 (overleaf), and 7 (overleaf).

Model 1 (Figure 5) evaluates all geothermal systems (magmatic and amagmatic) and combines evidence layers for Quaternary faults, Quaternary magmatic activity (both felsic and mafic), summed earthquake moment release, and the contoured heat flow map shown in Figure 2. Overall patterns of geothermal favorability are consistent with the distribution of geothermal systems across the western

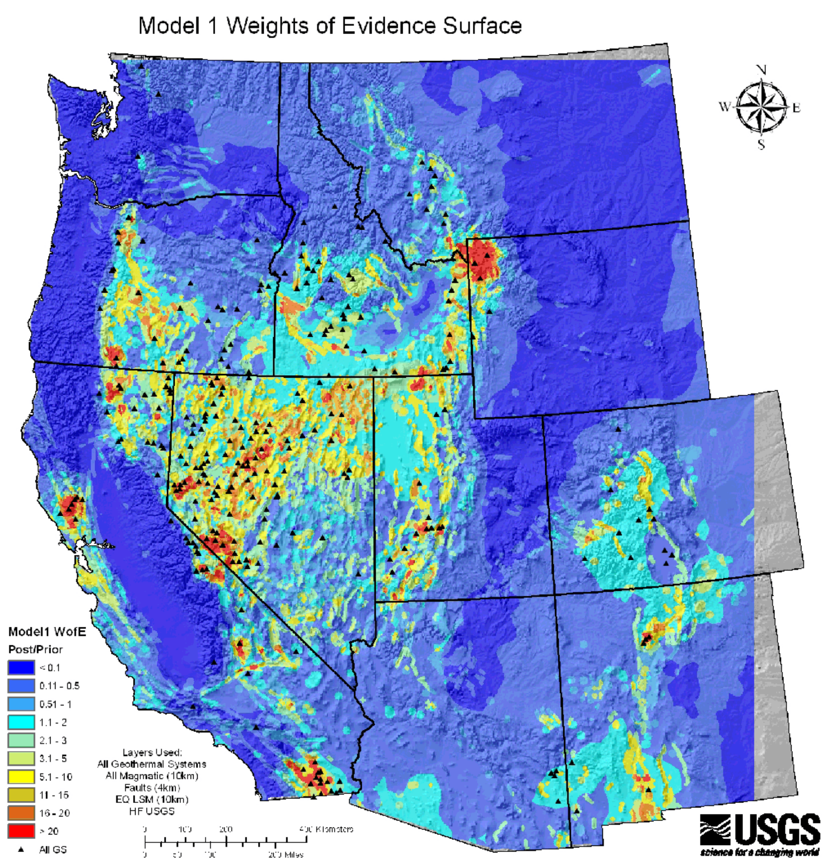

Figure 5. Map showing the results from Model 1 of the weights-of-evidence analysis, for which the probability of occurrence for all identified geothermal systems is determined from a combination of magmatic, fault, earthquakes and heat flow evidence layers. The color scale represents the posterior probability of geothermal occurrence as a ratio relative to the prior probability, which is calculated as the ratio of the area occupied by identified geothermal systems divided by the study area.

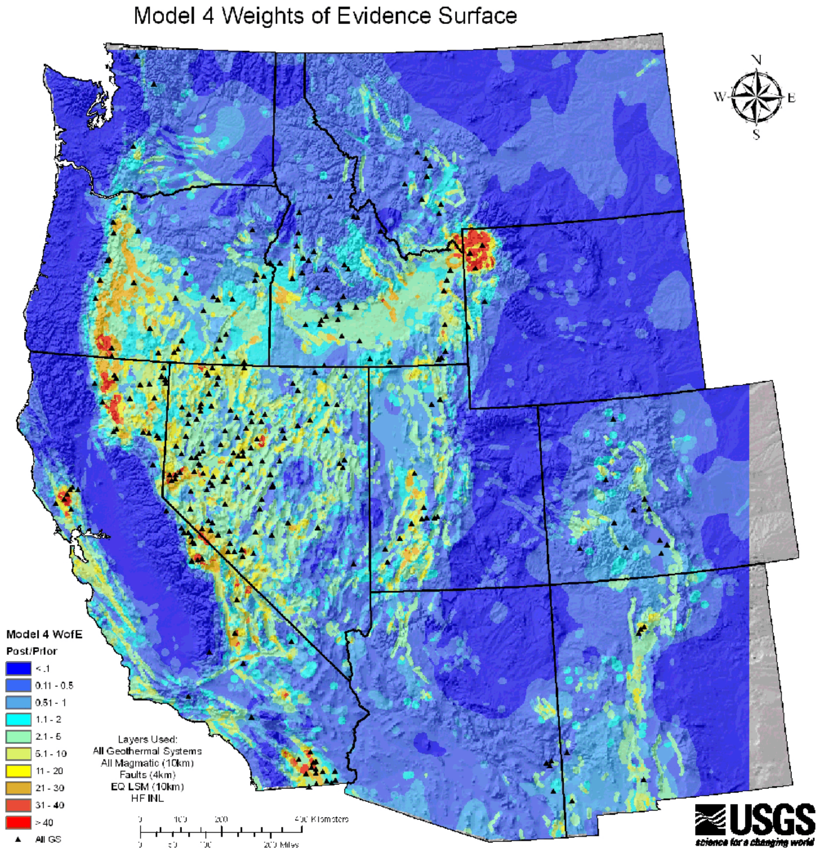

Figure 6. Map showing the results from Model 4 of the weights-of-evidence analysis. In contrast with Model 1 (Figure 5), an evidence layer derived from the Blackwell and Richards (2004) heat flow map was substituted for the heat flow contour map shown in Figure 2.

United States, with concentrations of high potential tied to areas of known abundant geothermal resources, such as Yellowstone, The Geysers, and the Imperial Valley. Regions of high potential are also concentrated at major centers of magmatic activity, as well as along faults and within regions of elevated heat flow. An example of the effect of introducing an alternative evidence layer can be seen in Figure 6, the posterior probability map for Model 4, in which the heat flow layer used in Model 1 is replaced by the heat flow map of Blackwell and Richards (2004). Although this change does not alter the general pattern of geothermal favorability, it does introduce significant increases in posterior probability in the areas covered by regional aquifers, such as the Snake River Plain. Alternative modeling approaches like this provide results that can be used to derive meaningful statistics on the range of viable estimates of the number and likely locations of undiscovered geothermal resources.

Results from Model 13, a weights of evidence model focused exclusively on amagmatic systems, are shown in Figure 7. Evidence layers of heat flow, faults, summed seismic moment, and stress were used in deriving the final posterior probability map. Although, in comparison to the models for all geothermal systems, the results emphasize potential in the northern Great Basin, the presence of critical factors such as high heat flow and active faulting still highlight some of the regions containing magmatic geothermal systems, even though this model does not utilize any evidence layer directly associated with magmatic activity.

Although the weights-of-evidence modeling is successful in generating maps of relative geothermal favorability, conditional dependence among many of the evidence layers rules out a straightforward estimate of the number of undiscovered geothermal systems from the estimates of posterior probability (see discussion in Singer and Kouda, 1999). In order to quantify the number of undiscovered geothermal systems, the results must be calibrated through application of constraints on the true number of geothermal systems in well-explored sub-regions of the model. Preliminary analyses indicate that there may be two to five times as many undiscovered geothermal systems in the western United States as identified geothermal systems. How these undiscovered systems may be distributed by size, location and temperature is still under investigation.

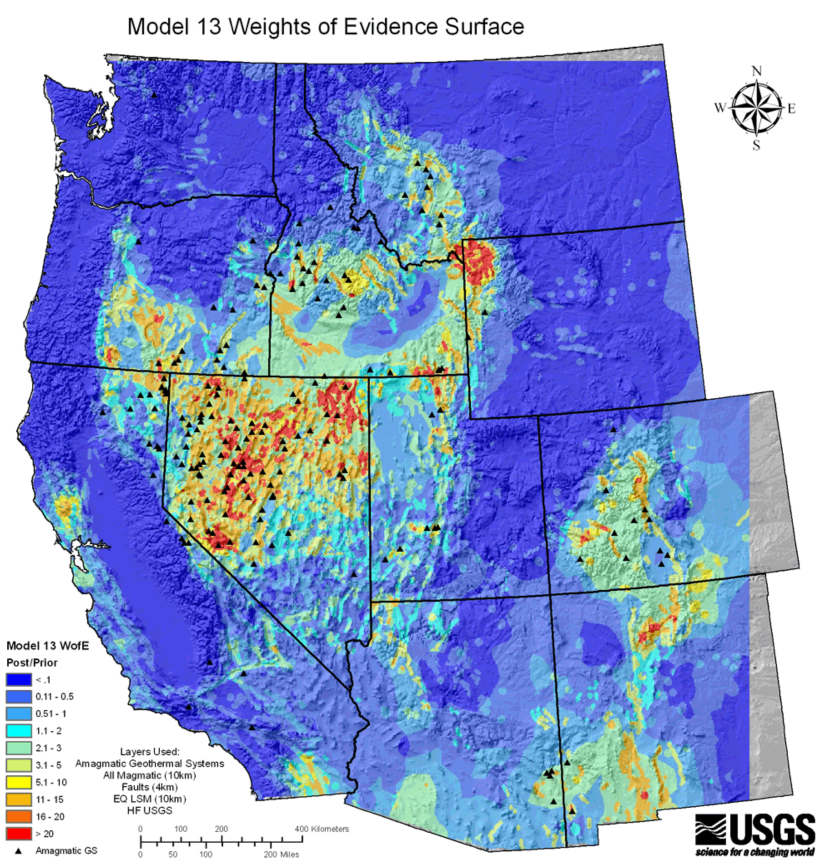

Figure 7. Map showing the results from Model 13 of the weights-of-evidence analysis, for which the probability of occurrence for amagmatic geothermal systems is determined from a combination of faults, stress, earthquakes, and heat flow evidence layers.

Summary

Maps of geothermal favorability have been produced from weights-of-evidence and logistic regression models for the occurrence of geothermal systems through the analysis of the spatial distribution of correlated evidence layers. These maps provide the basis for characterizing the undiscovered geothermal resource base and could guide future exploration and land use decisions. A total of 28 weights-of-evidence and logistic regression models were developed using varied evidence layers for heat flow, Quaternary magmatism, Quaternary faulting, seismicity, and tectonic stress. The results highlight and quantify the strong correlation of geothermal systems with active tectonics, magmatism, and elevated heat flow. Regions with significant geothermal potential but few identified geothermal systems include northeastern Nevada, western Utah, parts of southern Idaho, eastern Oregon, and parts of New Mexico and Colorado. Ongoing research is directed towards the transformation of these favorability maps to quantitative estimates of the magnitude of undiscovered geothermal resources.

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