Quantifying the Undiscovered Geothermal Resources of the United States

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Keywords

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ABSTRACT

In 2008, the U.S. Geological Survey (USGS) released summary results of an assessment of the electric power production potential from the moderate- and high-temperature geothermal resources of the United States (Williams et al., 2008a; USGS Fact Sheet 2008-3082; http://pubs.usgs.gov/fs/2008/3082). In the assessment, the estimated mean power production potential from undiscovered geothermal resources is 30,033 Megawatts-electric (MWe), more than three times the estimated mean potential from identified geothermal systems: 9057 MWe. The presence of significant undiscovered geothermal resources has major implications for future exploration and development activities by both the government and private industry. Previous reports summarize the results of techniques applied by the USGS and others to map the spatial distribution of undiscovered resources. This paper describes the approach applied in developing estimates of the magnitude of the undiscovered geothermal resource, as well as the manner in which that resource is likely to be distributed among geothermal systems of varying volume and temperature. A number of key issues constrain the overall estimate. One is the degree to which characteristics of the undiscovered resources correspond to those observed among identified geothermal systems. Another is the evaluation of exploration history, including both the spatial distribution of geothermal exploration activities relative to the postulated spatial distribution of undiscovered resources and the probability of successful discoveries from the application of standard geothermal exploration techniques. Also significant are the physical, chemical, and geological constraints on the formation and longevity of geothermal systems. Important observations from this study include the following. (1) Some of the largest identified geothermal systems, such as The Geysers vapor-dominated system in northern California and the diverse geothermal manifestations found in Yellowstone National Park, are unique in North America and highly unlikely to have counterparts with equivalent characteristics among the systems comprising the undiscovered resources. (2) Historical geothermal exploration has been limited in both the effectiveness of techniques employed and spatial coverage, since most exploration has targeted areas associated with surface thermal manifestations in the most easily accessible lands. (3) As noted by other investigators, in general, the hottest and largest geothermal systems are those with heat sources arising from recent magmatic activity. Consequently, a

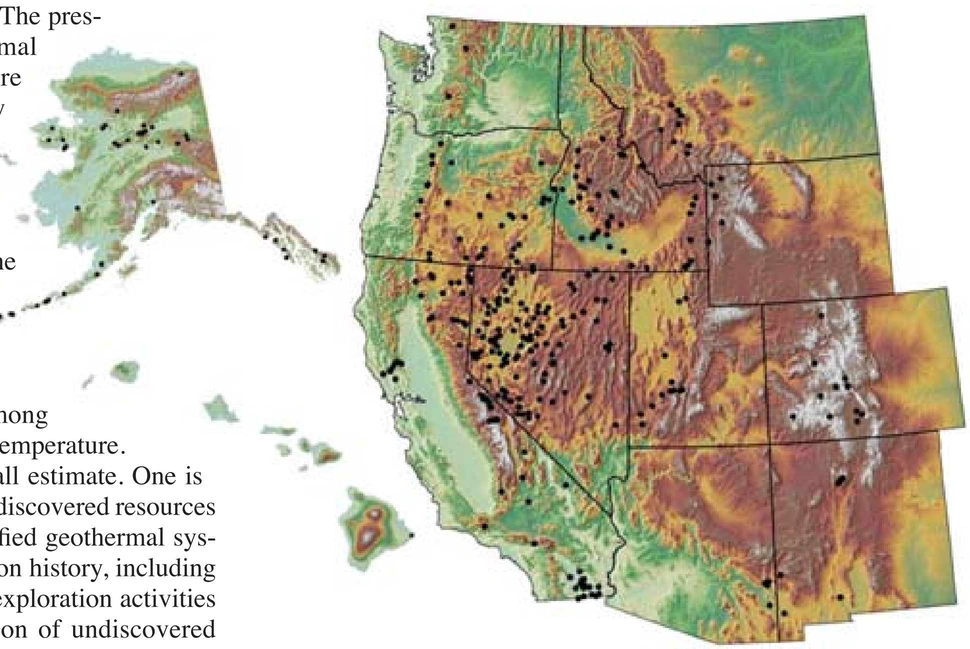

Figure 1. Map showing the location of identified moderate-temperature and high-temperature geothermal systems in the United States. Each system is represented by a black dot.

larger fraction of the undiscovered resource is associated with those areas favorable to the formation of this type of geothermal system, including some relatively remote areas, such as the Aleutian volcanic arc in Alaska.

Introduction

As part of the Energy Policy Act of 2005, the U.S. Geological Survey (USGS) has been 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, summarized in USGS Fact Sheet 2008-3082 (Williams et al., 2008a,b), provides an estimate of the geothermal electric power generation potential from identified and undiscovered resources and includes a provisional evaluation of the potential impact of Enhanced Geothermal Systems (EGS) technology. A key part of the assessment is characterizing undiscovered geothermal resources in type, magnitude and spatial distribution. This paper describes the approach used to derive estimates of undiscovered geothermal resources, utilizing information on relationships between characteristics of the identified geothermal resources compared to the undiscovered, geologic constraints on the formation of geothermal systems, observations of the spatial coverage of geothermal exploration to date, and evaluations of the effectiveness of those exploration efforts.

Comprehensive efforts to assess the geothermal resources of the United States began in the early 1970s, and the USGS produced three national geothermal resource assessments in the years following, USGS Circular 726 - *Assessment of Geothermal Resources of the United States-1975* (White and Williams, 1975), USGS Circular 790 - *Assessment of Geothermal Resources of the United States–1978* (Muffler, 1979) and USGS Circular 892 - *Assessment of Low-temperature Geothermal Resources of the United States–1982* (Reed, 1983). These reports evaluated various methodologies for geothermal resource assessments and provided estimates of potential electric power generation that have continued to guide long-term geothermal planning (e.g., Green and Nix, 2006).

The last national assessment of moderate-temperature (90 to 150ºC) and high-temperature (greater than 150ºC) geothermal resources, USGS Circular 790 (Muffler, 1979), estimated the potential for approximately 23,000 Megawatts-electric (MWe) of power generation from identified high-temperature (>150ºC) geothermal systems at depths less than 3 km in the western United States. Estimates of potential power production from undiscovered resources ranged from 72,000 to 127,000 MWe. Circular 790 listed nine western states (Alaska, Arizona, California, Hawaii, Idaho, Nevada, New Mexico, Oregon and Utah) with the potential for at least 100 MWe of electrical power generation per state from identified geothermal systems.

The results of the new national assessment for geothermal power generation potential yield a mean total of 9057 MWe with a 95% probability of 3675 MWe and a 5% probability of 16,457 MWe from 240 identified geothermal systems located in 13 states (Figure 1; Williams et al., 2008a). We assessed undiscovered geothermal resources for the same states in which the identified moderate- and high-temperature geothermal systems are located, with the spatial distribution based on a series of Geographic Information Systems (GIS) statistical models for the spatial correlation of geological factors that facilitate the formation of geothermal systems. The mean estimated power production potential from undiscovered resources located on private and accessible public lands is 30,033 MWe, with a 95% probability of 7917 MWe and a 5% probability of 73,286 MWe.

Characteristics of Identified Geothermal Systems

A key aspect of the evaluation of undiscovered geothermal resources is relating potential reservoir volumes, temperatures, and spatial distribution to the characteristics of identified geothermal systems. Figure 2 shows the distribution of temperature, volume, and electric power production potential for the moderate- and high-temperature geothermal systems identified in the assessment. As with other geologic resources, such as petroleum reservoirs, there are many more smaller volume, lower temperature geothermal systems than larger volume, higher temperature systems, and the resulting power potential is well-described by a truncated log-normal distribution (Attanasi and Charpentier, 2002). When fit to a log-normal distribution, the mean power production potential for these systems is 24.4 MWe, with 95% and 5% intervals of 1.4 MWe and 87.8 MWe, respectively.

As a further refinement, the entire set can be 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 (e.g., Hulen et al., 1994). Prominent examples of magmatic geothermal systems in the United States are The Geysers, Salton Sea, and Yellowstone. Amagmatic, or deep circulation, systems are those that acquire high temperatures through the circulation of water to great 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. As noted by others (e.g., Coolbaugh and Shevenell, 2004) magmatic systems on average are characterized by higher temperatures and larger volumes than amagmatic systems, and this is reflected in the means for the distributions. For the amagmatic systems, the mean temperature, volume and power production potential are 116 °C, 1.9 km^3, and 14.0 MWe, and for the magmatic systems these quantities are 154 °C, 4.8 km^3, and 76.2 MWe.

Observations from petroleum assessments indicate that the characteristics of undiscovered resources typically differ from reserves, as larger reservoirs tend to be discovered first with smaller, harder to find reservoirs following as exploration programs evolve and geologic understanding of the local structural and stratigraphic controls on petroleum accumulation mature (Figure 3; Stoker et al., 2006; Morton, 1998). Although the geologic processes responsible for petroleum accumulations generally differ significantly from those associated with the formation of geothermal reservoirs, the geophysical anomalies associated

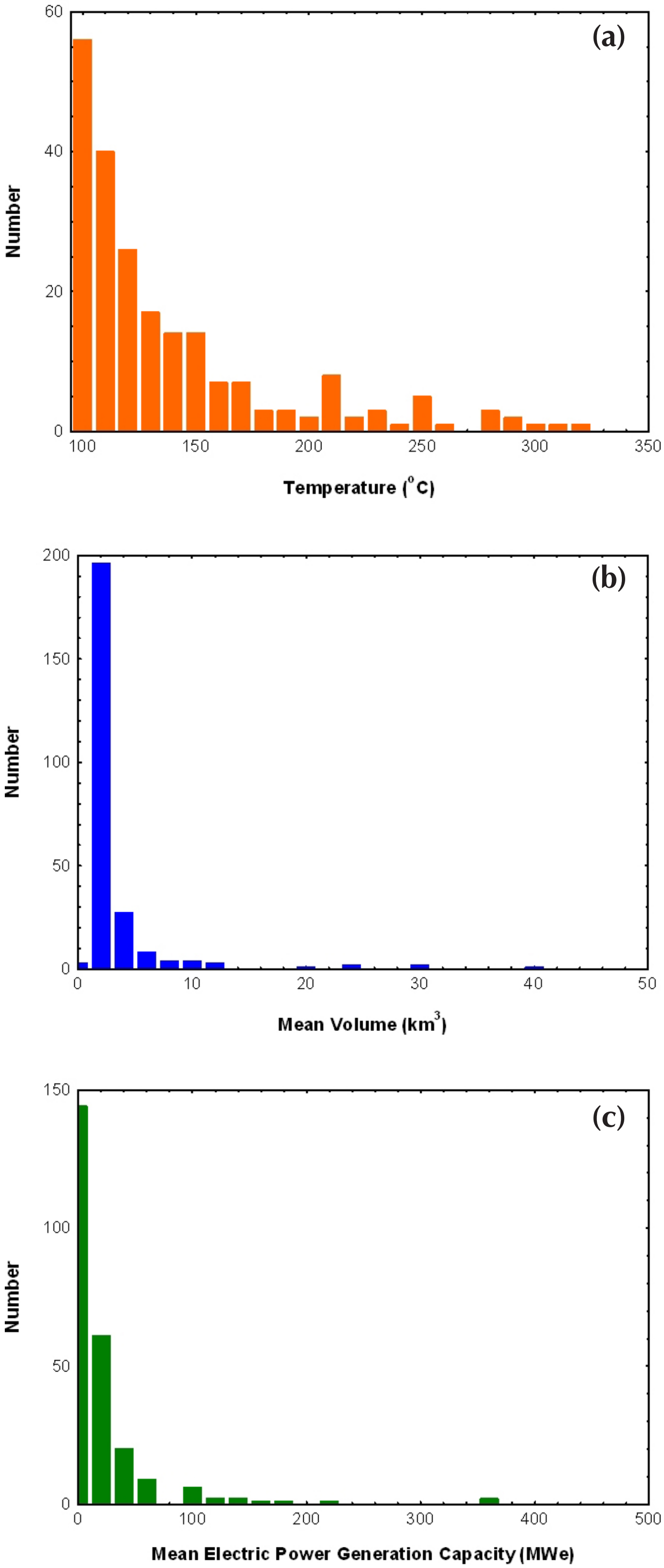

Figure 2. (a) Distribution of temperatures for moderate- and high-temperature geothermal systems included in the new resource assessment. (b) Distribution of estimated mean reservoir volumes for the geothermal systems included in the assessment. (c) Distribution of estimated mean electric power generation capacity for the assessed geothermal systems.

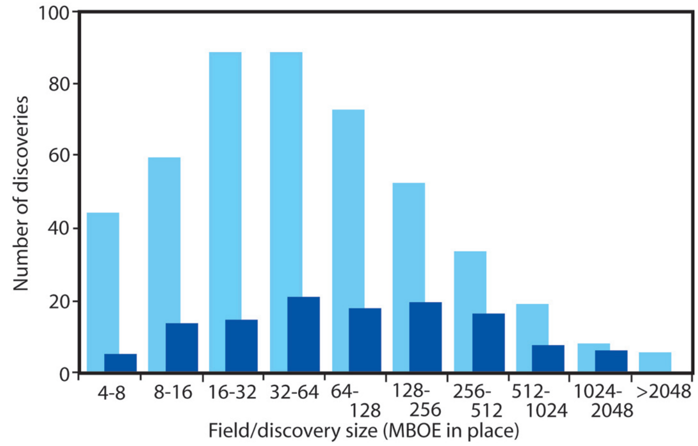

Figure 3. Histogram showing a hypothetical difference in the size distribution of petroleum reservoirs between historical discoveries (dark blue bars) and undiscovered resources (light blue bars). Modified from Stoker et al. (2006).

with larger geothermal reservoirs, such as the spatial extent of an associated heat flow anomaly, are more easily discovered by reconnaissance-level exploration. Given the relatively limited state of geothermal exploration and development, quantitative relationships equivalent to those used in the characterization of undiscovered petroleum resources cannot yet be derived from geothermal exploration history, but some analogous observations are available from both the geologic settings of geothermal occurrences and their surface manifestations.

Specifically, in the assessment analysis we note that the three largest identified geothermal systems in the United States – Yellowstone, The Geysers, and the Salton Sea – are associated with unique hydrothermal manifestations of volcanic and tectonic processes. The Yellowstone hydrothermal system, which as part of a national park is not included in the resource calculations for identified geothermal systems, is the result of high heat flow from recent extrusive and intrusive volcanic activity of the associated hot spot track (Morgan, 2007). In the case of The Geysers, the young volcanic activity responsible for its formation is found over a relatively large area in the northern California Coast Ranges, but the conditions that give rise to a large vapor-dominated reservoir are restricted to the shallow subsurface (White et al., 1971). Consequently, we consider it highly unlikely that equivalently large vapor-dominated reservoirs remain to be discovered in the United States. The young magmatic heat source for the Salton Sea geothermal field is not unusual among identified geothermal systems, as young magmatic heat sources are responsible for hydrothermal systems across the western United States and in the Aleutians and Hawaii. What is unique about the Salton Sea field is the association of magmatism with the highly porous and permeable young sediments of a deep, rapidly subsiding basin (Hulen et al., 2002). In our analysis, the potential for large, high-temperature geothermal reservoirs sharing the characteristics of the Salton Sea geothermal field is confined to the Imperial Valley of southern California.

Favorability Maps

As part of the effort to characterize the spatial distribution of undiscovered geothermal resources, the new national assess-

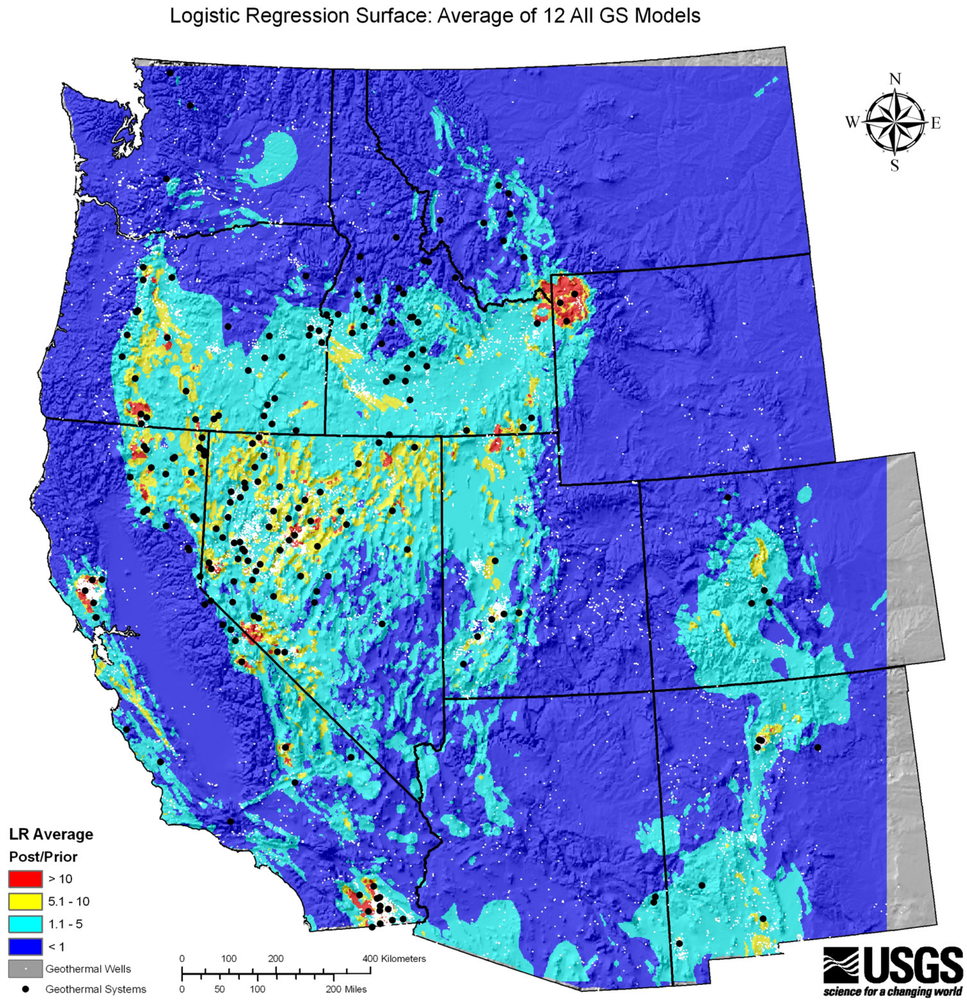

Figure 4. Map showing the ratio of posterior to prior probability for the occurrence of geothermal systems from an average of 12 logistic regression models as described by Williams and DeAngelo (2008). Black dots indicate the locations of identified moderate- and high-temperature geothermal systems. White dots indicate the locations of wells with heat flow and/or temperature gradient measurements.

ment incorporates a series of weights-of-evidence and logistic regression maps through which geothermal potential is modeled using a weighted combination of evidence layers derived from mappable geologic and tectonic features available in digital databases (Williams and DeAngelo, 2008). 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.

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). 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, the resulting posterior probability surface can be used only as a qualitative map highlighting areas of favorability (e.g., Coolbaugh et al., 2005), unless the results can be corrected or calibrated to account for the effects of conditional dependence (Singer and Kouda, 1999; Coolbaugh et al., 2007).

In order to move toward a quantitative evaluation of geothermal potential, we also performed logistic regression analysis, which does not require conditional independence among the evidence layers, on those evidence layers identified as having a statistically significant correlation with the presence or absence of geothermal systems. We produced a total of 28 weights-of-evidence and logistic regression models for geothermal favorability based on the analysis of the correlated evidence layers for heat flow, Quaternary magmatism, Quaternary faulting, seismicity, and tectonic stress (Williams and DeAngelo, 2008). 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 (Figure 4).

The resulting maps are useful for illustrating relative variations in the favorability for the occurrence of geothermal systems but do not provide complete quantitative estimates for the total number of systems comprising the identified and undiscovered resources. In order to quantify the number of undiscovered geothermal systems, the results must be calibrated by developing models comparing the characteristics of the identified systems to the undiscovered resources, evaluating the spatial coverage and effectiveness of geothermal exploration techniques, and through evaluation of constraints on the true number of geothermal systems in well-explored subregions of the model. In the sections below we address these issues as illustrated by three types of undiscovered resources: those with flow from thermal springs or wells, those with no surface or near-surface discharge but with significant thermal anomalies, and those deep systems with modest or undetectable thermal anomalies.

Geothermometers and Unrecognized Moderate and High Temperature Geothermal Systems

Geothermal reservoir temperatures can best be determined from in situ measurements in exploration and production wells where available, and chemical geothermometers can be applied as proxies when in situ temperature measurements are not available. The use of chemical geothermometers rests on the assumption that some relationship between chemical or isotopic constituents in the water was established at higher temperatures and this relationship has persisted when the water cools as it flows to the surface. The calculation of subsurface temperatures from chemical analyses of water and steam collected at hot springs, fumaroles, geysers, and shallow water wells is a standard tool of geothermal exploration, and the use of geothermometers is a key component in the assessment of identified geothermal systems (Reed and Mariner, 2007; Williams et al., 2008b). Although calculations of geothermometers are easily made from chemical analyses of thermal waters, reliable interpretation of the calculated temperatures requires knowledge of the most likely reactions to have occurred between the water and the surrounding rocks. In addition, charge-balance errors arise from unreliable and/or incomplete analyses. In the new assessment, analyses were generally discarded if the charge-balance error is over 10 percent.

Most geothermal systems never reach chemical equilibrium in the reservoir because most of the reaction rates are dependent on the concentrations of components in solution (Barton, 1984). The flow of hydrothermal fluids through a geothermal reservoir is constantly changing the concentrations of components in solution, and the geothermometers reflect a steady-state condition that exists at high temperature between the circulating water and enclosing rock. The reaction rates for mineral solubility are dependent on temperature as well as several other variables in a hydrothermal system. For example, the approximate times to reach equilibrium between the feldspar minerals and fluid for the Na-K-Ca geothermometer varies from tens of hours at 500°C to nearly 100 years at 150°C, and the solution - mineral equilibrium for the quartz geothermometer takes from tens of hours at 250°C to tens of years at 100°C (Barton, 1984). As the geothermal water cools on its way to the surface, the reaction rates become more sluggish. A secondary assumption is that the flow of hydrothermal water to the surface is rapid with respect to the rates of reactions at near-surface temperatures.

On the basis of these considerations, we note that an unknown number of thermal springs and wells are producing waters for which the quality of the water chemistry measurements is not sufficient for accurate geothermometer calculations or for which the geothermometers do not reflect true reservoir temperatures, either as a result of mixing with nonthermal waters or unusually slow flow of thermal water from depth, perhaps through an intermediate reservoir. Although oxygen isotope shifts can identify mixing between high-temperature geothermal fluids and cooler groundwater, these shifts are difficult to detect for mixing with moderate-temperature fluids. In addition, stable isotope measurements are lacking for water samples from many thermal springs. The common result of all these possibilities is to leave some known geothermal systems unrecognized as moderate- or high-temperature systems. These are part of the undiscovered resources until improved geochemical studies and/or in situ temperature measurements resolve the true reservoir temperatures.

The Spatial Coverage and Effectiveness of Geothermal Exploration

In the absence of thermal springs or other surface manifestations, the discovery of geothermal systems depends on recognition of other signatures, typically a near surface thermal anomaly recognized and characterized through subsurface temperature gradient/heat flow measurements. Important issues with respect to the magnitude of undiscovered geothermal resources are the extent to which these thermal exploration techniques have covered areas of significant geothermal potential and the effectiveness of geothermal exploration techniques in general, and thermal measurements in particular. The spatial coverage of geothermal exploration relative to the distribution of geothermal potential is relatively easy to evaluate. In the course of collecting data for the assessment, we compiled the results from boreholes in which subsurface temperature gradients (and often heat flow) had been measured. More than 11,000 of these are located in the 11 western states of the contiguous United States in which identified geothermal systems are concentrated (Williams, et al., 2008a,b). Despite the large number of measurements, a significant portion of the accessible lands in the western United States with high geothermal potential remains relatively unexplored.

Figure 4 shows the locations of identified geothermal systems and heat flow/temperature gradient holes relative to the average results of 12 logistic regression models for geothermal favorability in the western United States as a ratio of the posterior (or model-derived) probability of occurrence over the prior probability of occurrence (the probability of occurrence of a geothermal system simply based on the number of identified systems divided by the size of the study area; Williams and DeAngelo, 2008). Figure 5 shows the distribution of temperature gradient and/or heat flow measurements within 6 km of each 2km by 2km cell that comprises

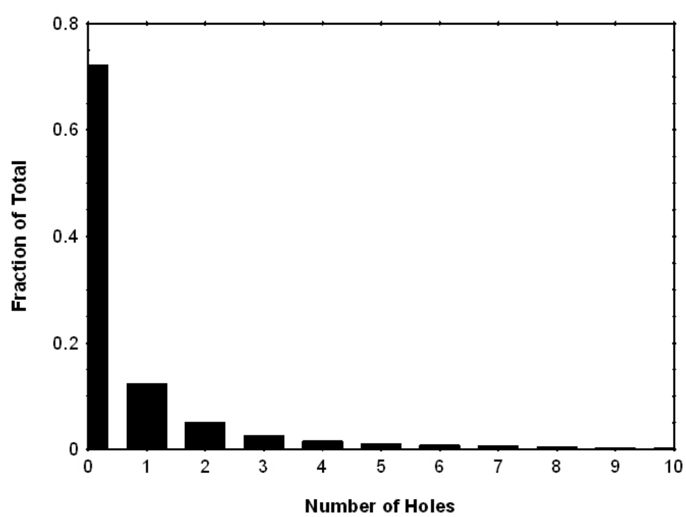

Figure 5. Distribution of the number of temperature gradient/heat flow measurements located within 6 km of cells from the logistic regression model shown in Figure 4 for which the ratio of posterior to prior probability is greater than 5.

the logistic regression model and for which the ratio of posterior to prior probability exceeds 5. There are no measurements within 6 km of 72% of these cells with elevated geothermal potential and only one measurement within 6 km of another 12%. Consequently, even if the varied measurements that constitute the temperature gradient and heat flow database were 100% effective in identifying subsurface geothermal systems, nearly three-quarters of the regions with elevated geothermal potential as a result of recent magmatism, active faulting, a favorable state of stress, and high regional heat flow (Williams and DeAngelo, 2008) are essentially unexplored with respect to geothermal systems that are not associated with surface manifestations. (The relative pattern of results holds for alternate values of both the probability ratio and the distance between the cells with elevated probability ratios and the nearest measurement.)

The Effectiveness of Geothermal Exploration

In recent years some attempts have been made to estimate the effectiveness of various types of exploratory drilling to locate and characterize geothermal systems (e.g., Coolbaugh et al., 2006, 2007), but a detailed evaluation for the western United States requires a comprehensive examination of the history and results of geothermal exploration activities that was not possible within the timeframe and budget of the 2008 national assessment. However, it is possible to use some observations regarding the nature of geothermal systems and the challenges of exploring for them to draw some general conclusions regarding the resources that may remain undiscovered in areas where standard exploration techniques, such as shallow temperature-gradient hole measurements, have been applied.

Perhaps the single most significant challenge in exploring for geothermal systems is the potential thermal disturbance from groundwater flow. Rapid flow in local and regional aquifer systems, such as the carbonate aquifer in central and eastern Nevada (Lachenbruch and Sass, 1978; Coolbaugh and Shevenell, 2004), the Snake River Plain aquifer in Idaho (Blackwell, 1989), and the “rain curtain effect” encountered in the Cascades of Washington, Oregon, and California (Hulen and Lutz, 1999), can suppress shallow temperature gradients and mask the presence of hydrothermal activity. According the Coolbaugh and Shevenell (2004), groundwater flow through the Nevada carbonate aquifer system may mask the presence of a number of geothermal systems. Even such basic hydrologic features as deep water tables have a significant influence on the surface manifestations associated with geothermal systems (Coolbaugh et al., 2005). In these environments exploratory drilling must reach beneath the shallow hydrologic disturbances at depths significantly greater than typical for temperature gradient/heat flow hole drilling in order to identify and characterize geothermal reservoirs.

Deep Geothermal Systems

In addition to those geothermal systems lacking obvious surface manifestations due to the effects of shallow groundwater flow, there is the question of the occurrence of deep geothermal systems. Specifically, are there significant numbers of geothermal systems for which the top of the reservoir is deep enough that the associated thermal anomaly is difficult to detect with standard shallow temperature-gradient measurements? For example, in the northern Great Basin, where regional heat flow can exceed 100 mW/m^2, conductive temperatures can exceed 100 °C at depths greater than 3 km (Lachenbruch and Sass, 1978). Geothermal systems at these depths, whether characterized by closed convection cells at temperatures elevated relative to the conductive gradient by tens of degrees or intermittent connections to the surface over geologic time, could be viable resources for electric power generation yet would have little or no surface thermal expression.

According to Ingebritsen and Manning (1999), crustal permeability in active tectonic regions follows a general exponential decrease with depth. If the temperature in each amagmatic hydrothermal system is taken to represent temperatures at the maximum depth of fluid circulation, an estimated depth of circulation can be derived from the regional geothermal gradient (Lachenbruch and Sass, 1978). On the other hand, given their lower anomalous heat flow, the thermal energy balance for deeper geothermal reservoirs is significantly different from the balance for the more easily identified shallow reservoirs. The high heat flow from a shallow reservoir mines a large amount of heat very rapidly from the surrounding crust and shortens the duration of high reservoir temperatures unless renewed by magmatic heat input. Deep reservoirs require less additional heat to maintain high temperatures and should be longer-lived (Williams, 2005). The results of an earlier analysis (Williams and Reed, 2005) suggest that the maximum depth of fluid circulation follows a distribution similar to that for crustal permeability and that the number of identified systems with circulation depths greater than 4 km may be underrepresented relative to the shallower systems by a ratio of approximately 0.65.

Undiscovered Geothermal Resource Estimates

Our interpretation of the issues summarized above leads to the following conclusions regarding the potential differences between the identified and undiscovered geothermal resource distributions. With the absence of The Geysers and Salton Sea geothermal systems, the best log-normal fit to the distribution of the electric power production potential of the remaining identified systems yields a mean 21.1 MWe, with 95% and 5% confidence intervals of 1.5 MWe and 73.4 MWe, respectively. We expect those geothermal systems that remain undiscovered due to uncertain or absent water chemistry or insufficient temperature gradient/heat flow measurements to follow the same distribution. We observe that deep, convective geothermal systems are likely to be higher in temperature but smaller in volume (due to restrictions on the vertical extent of circulation required to limit the magnitude of the corresponding surface heat flow anomaly). In the absence of other constraints, we assume that the two trends of higher temperature and smaller volume are approximately balanced among deep undiscovered systems, yielding a power distribution consistent with the values given above.

Given a power-potential distribution for the undiscovered systems and a range of spatial distributions from the logistic-regression models, the remaining issue is the ratio of the number of undiscovered to identified systems. If exploration were 100% effective in finding geothermal systems, the logistic regression models for the entire western United States can be calibrated using training sets from well-explored areas. For this analysis we evaluated northwestern Nevada, the Imperial Valley, The Geysers-Clear Lake area, and the regions surrounding Medicine Lake volcano, Klamath Falls and Newberry volcano. Applying the results from these areas to all 28 models yielded estimates of the ratio of number of undiscovered to identified geothermal systems ranging from 0.4 to 3.0, with a mean value of 1.6. Combining these results in a statistical summation with the ratios derived from the analysis of the potential for deep geothermal systems and the limited spatial coverage of geothermal exploration yielded a distribution of ratios for the number of undiscovered to identified geothermal systems outside of the Imperial Valley with a mean value of 3.6, and 95% and 5% limits equal to 1.6 and 6.7, respectively. This translates into estimates of 17,020 MWe for undiscovered resources over this area.

Within the Imperial Valley, we estimate the potential for undiscovered systems based on the distribution of subsurface temperatures derived from a new heat-flow map of the region (Williams et al., 2007), maps of sediment thickness derived from seismic and gravity studies (Kohler and Fuis, 1986), and distributions of permeable sediments derived from lithologies encountered in deep exploration wells (Hulen et al., 2002). The results are a mean power-production potential of 8790 MWe, with 95% and 5% confidence intervals of 1534 MWe and 22,424 MWe, respectively. In Hawaii, we apply only those calibrated logistic regression models for magmatic geothermal systems and estimate the mean undiscovered potential at 2435 MWe, with 95% and 5% confidence intervals of 822 MWe and 5438 MWe. In Alaska, our estimates combine magmatic models for the Aleutians and Alaska Peninsula with amagmatic models for lower temperature systems found in the interior, with a resulting mean of 1788 MWe, 95% confidence interval of 537 MWe, and 5% confidence interval of 4256 MWe.

Conclusions

In the 2008 USGS national geothermal resource assessment, the mean power production potential from undiscovered geothermal resources is 30,033 Megawatts-electric (MWe), more than three times the mean estimated potential from identified geothermal systems: 9057 MWe. The presence of significant undiscovered geothermal resources has major implications for future exploration and development activities by both the government and private industry. A number of key issues constrain the overall estimate. Taking into account the geologic and tectonic constraints on the formation of the largest geothermal systems, the prospects for identifying additional moderate and high temperature geothermal systems from among potentially misclassified geothermal systems, the limited spatial coverage of geothermal exploration over the portions of the western United States with significant geothermal potential, the constraints on the effectiveness of geothermal exploration relative to the masking effects of regional groundwater flow, the muted signature of deep geothermal systems, and the potential for formation of deep geothermal systems at deeper levels of the crust characterized by lower permeability but higher average temperatures, we developed a range of models for the magnitude of geothermal resources in the western United States. Overall results indicate that in the western United States outside of the Imperial Valley region, there are approximately 3.6 undiscovered geothermal systems for each identified geothermal system. As noted above, the exclusion of some of the largest identified geothermal systems, such as The Geysers vapor-dominated system and Yellowstone geothermal system, from the distribution of power production potential for the systems comprising the undiscovered resources reduces the estimated mean potential from 24.4 MWe to 21.1 MWe (approximately 14%). Consequently, the ratio of the power potential from undiscovered resources to the power potential from identified systems is reduced by the same factor to 3.2 in this broad region of the western United States. This equates to an estimated total of 17,020 MWe. Estimates totaling an additional 13,013 MWe comprise the undiscovered resources of Alaska, Hawaii, and the Imperial Valley of California.

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