Prediction and Discovery of New Geothermal Resources in the Great Basin: Multiple Evidence of a Large Undiscovered Resource Base

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ABSTRACT

Geothermal potential maps by themselves cannot directly be used to estimate undiscovered resources. To address the undiscovered resource base in the Great Basin, a new and relatively quantitative methodology is presented. The methodology involves three steps, the first being the construction of a data-driven probabilistic model of the location of known geothermal systems using weights of evidence. The second step is the construction of a degree-of-exploration model. This degree-of-exploration model uses expert judgment in a fuzzy logic context to estimate how well each spot in the state has been explored, using as constraints digital maps of the depth to the water table, presence of the carbonate aquifer, and the location, depth, and type of drill-holes. Finally, the exploration model and the data-driven occurrence model are combined together quantitatively using area-weighted modifications to the weights-of-evidence equations.

Using this methodology in the state of Nevada, the number of undiscovered geothermal systems with reservoir temperatures ≥100°C is estimated at 157, which is 3.2 times greater than the 69 known systems. Currently, nine of the 69 known systems are producing electricity. If it is conservatively assumed that an additional nine for a total of 18 of the known systems will eventually produce electricity, then the model predicts 59 known and undiscovered geothermal systems are capable of producing electricity under current economic conditions in the state, a figure that is more than six times higher than the current number. Many additional geothermal systems could potentially become economic under improved economic conditions or with improved methods of reservoir stimulation (Enhanced Geothermal Systems).

This large predicted geothermal resource base appears corroborated by recent grass-roots geothermal discoveries in the state of Nevada. At least two and possibly three newly recognized geothermal systems with estimated reservoir temperatures ≥150°C have been identified on the Pyramid Lake Paiute Reservation in west-central Nevada. Evidence of three blind geothermal systems has recently been uncovered near the borate-bearing playas at Rhodes, Teels, and Columbus Marshes in southwestern Nevada. Recent gold exploration drilling has resulted in at least four new geothermal discoveries, including the McGinness Hills geothermal system with an estimated reservoir temperature of roughly 200°C. All of this evidence suggests that the potential for expansion of geothermal power production in Nevada is significant.

Introduction

Last year (2005), the United States Geological Survey was funded to update a geothermal resource estimate for the United States. Because of budgetary limitations, both the quality and scope of the assessment depend on collaborative partnerships with research institutions and the geothermal industry. As part of this collaboration and in support of the mission of the Great Basin Center for Geothermal Energy, the current study examines the nature of undiscovered resources in the Great Basin. The primary thrust of the study is to demonstrate the feasibility of estimating undiscovered geothermal resources, by developing a methodology and then applying that methodology to an example region, which in this case is the state of Nevada. This methodology is designed to accept input from geothermal experts to interpret a variety of map-based evidence and build an exploration model. Data-driven spatial statistical techniques and mathematics are used to help constrain the interpolations within a computer-digital geographic information system (GIS).

The current approach builds on a previous study by Coolbaugh and Shevenell (2004), who estimated undiscovered geothermal resources by first calculating the density of occurrence (number of occurrences per unit area) of known geothermal systems. Differences in the density of occurrence between well-explored and poorly explored terrains were used to estimate the number of undiscovered systems. The current approach differs from that of Coolbaugh and Shevenell (2004) in several important aspects. First, instead of calculating the density of occurrence of geothermal systems, which was necessarily approximate in some cases, the probability of occurrence of geothermal systems is quantitatively calculated using geological and geophysical evidence in a data-driven weights-of-evidence model. Secondly, a more rigorous degree-of-exploration model was built, using fuzzy logic and more types of exploration evidence than used in the original study. Finally, the number of undiscovered geothermal systems was directly calculated by intersecting the degree-of-exploration model with the weights-of-evidence model using equations designed for that purpose.

The new methodology consists of three main steps, summarized below. For more details on the methodology and approach, the reader is referred to a paper being submitted to Natural Resources Research (Coolbaugh et al., 2006a).

Initial Weights-of-Evidence Model

An initial weights-of-evidence (WofE) model of geothermal potential was constructed for the state of Nevada, USA without considering any factors related to the degree of exploration. The geothermal systems used as training points were those with measured or calculated reservoir temperatures ≥100°C. A total of 69 such geothermal systems in Nevada were known to exist, and all were used as training sites.

Several types of geological, geophysical, and geochemical evidence are predictive of geothermal potential (Koenig and McNitt, 1983; Coolbaugh et al., 2002, 2005). For the initial weights-of-evidence model, this evidence was carefully selected for its ability to predict geothermal potential independently of the degree of exploration. For example, a map of water table depth was not used directly as an evidence layer, even though areas of shallow groundwater correlate with known geothermal activity. Areas with shallow groundwater tend to have surface indications of geothermal activity that would attract exploration efforts.

Four evidence layers were used; these were derived from 1) earthquakes catalogs (Pancha et al., 2006; Coolbaugh et al., 2005), 2) crustal strain rates from global positioning system station velocities and slip rates from Quaternary faults (Machette et al., 2003; Coolbaugh et al., 2005), 3) the isostatically corrected gravity field (Singer, 1996), and 4) the total horizontal derivative of gravity (derived from regional gravity data compiled by Gary Oppliger, University of Nevada, Reno). Weights of evidence for the model are listed in Table 1a.

The training site unit cell size was 9 km^2 and the conditional independence (C.I.) ratio (Bonham-Carter, 1996) was 0.95. This ratio equals the total number of geothermal systems predicted by the model divided by the number of known geothermal systems used in the modeling, and ideally, at this stage of the modeling process, this ratio should equal 1 (undiscovered deposits are predicted in a later section of this paper). Values of the C.I. ratio that are within 10 to 15% of unity suggest that conditional dependencies among the input evidence layers relative to the training sites (geothermal systems) is minimal and that the model is a good predictor of the total number of geothermal systems.

The posterior probability map (Figure 1a) was moderately successful in classifying the training sites; 77% fell within the upper 55% of the probability rankings (weighted by area) and 40% fell in the upper 90% of the probability rankings. Perfect predictability is never achieved in practice, and reasons for falling short include limitations in the availability of digital geologic, geophysical, and geochemical data, and uncertainties in the true physical location of geothermal reservoirs relative drill holes and surface indicators such as hot springs.

Additional information on the use of data-driven models such as weights of evidence is provided by Bonham-Carter (1996), Bonham-Carter et al. (1988) and Raines et al. (2000). More detailed descriptions of the use of such models for predicting geothermal favorability can be found in Coolbaugh et al. (2002, 2005).

Table 1a. Initial Weights of Evidence, without Degree of Exploration

	Pattern 1		Pattern 2		Pattern 3			
Evidence Layer	Weight	Stan. Dev.	Weight	Stan. Dev.	Weight	Stan. Dev.	Contrast	Confidence
Gravity Gradient	1.3739	0.2899	0.5895	0.2299	-0.3775	0.1623	1.75	5.27
Crustal Strain	0.8362	0.2005	0.3338	0.2003	-0.7510	0.2295	1.59	5.21
Earthquakes	0.3030	0.1350	-0.7065	0.2674			1.01	3.37
Isostatic Gravity	0.2558	0.1669	-0.2201	0.1742			0.48	1.97

Table 1b. Revised Weights of Evidence, with Degree of Exploration

	Pattern 1		Pattern 2		Pattern 3			
Evidence Layer	Weight	Stan. Dev.	Weight	Stan. Dev.	Weight	Stan. Dev.	Contrast	Confidence
Gravity Gradient	1.1760	0.2926	0.4692	0.2309	-0.3407	0.1627	1.52	4.53
Crustal Strain	0.6473	0.2016	0.2828	0.2011	-0.6700	0.2299	1.32	4.31
Earthquakes	0.2603	0.1356	-0.6420	0.2678			0.90	3.01
Isostatic Gravity	0.1967	0.1675	-0.1782	0.1747			0.37	1.55

Table 1c. Percent Change, Expored vs. Initial Model

	Pattern 1		Pattern 2		Pattern 3			
Evidence Layer	Weight	Stan. Dev.	Weight	Stan. Dev.	Weight	Stan. Dev.	Contrast	Confidence
Gravity Gradient	-14.4	0.9	-20.4	0.4	-9.7	0.2	-13.4	-14.0
Crustal Strain	-22.6	0.5	-15.3	0.4	-10.8	0.2	-17.0	-17.3
Earthquakes	-14.1	0.4	-9.1	0.1			-10.6	-10.8
Isostatic Gravity	-23.1	0.4	-19.0	0.3			-21.2	-21.5

Table 1. Weights-of-evidence statistics. Confidence equals contrast divided by its standard deviation. The term "evidence layer pattern" is equivalent to the term "evidence layer class".

Degree-of-Exploration Model

Exploration for geothermal systems in Nevada is far from complete, partly because the

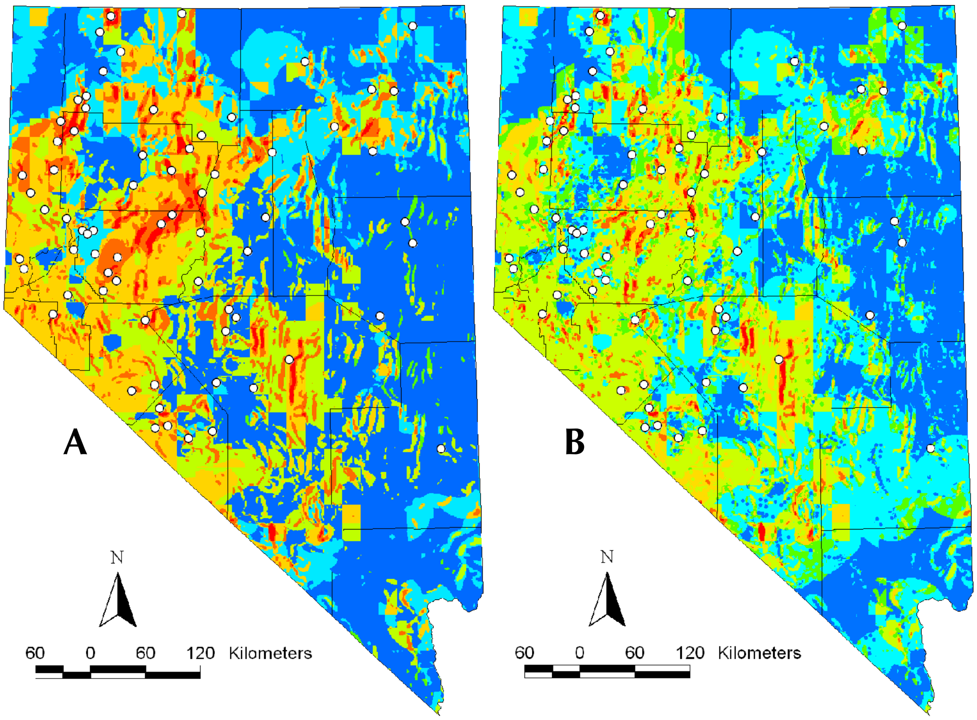

Figure 1. Geothermal potential for the state of Nevada, USA. The initial weights-of-evidence posterior probability map for known resources (a) was created without consideration of the degree of exploration. Figure 1b depicts the potential for undiscovered geothermal systems after intersecting the initial weights-of-evidence model with the degree-of-exploration model (Figure 2). Progressively warmer colors on both maps represent progressively higher probability levels, using 7 natural breaks. White circles are geothermal training sites.

entire state of Nevada is permissive for the occurrence of geothermal systems (Coolbaugh et al., 2005), and also because many geothermal systems have no surface expression. The presence of deep water tables, cold water aquifers, and near-surface impermeable cap rocks often prevent thermal groundwaters from reaching the surface, and where they do reach the surface, they have often been cooled and/or diluted with near-surface groundwaters that disguise the geothermal signature. Of the 69 geothermal systems used as training points, 24 (35%) are not associated with hot springs and thus can be considered concealed.

There are many ways to look for geothermal systems, including searching for hot and warm springs, water geochemical sampling, geologic mapping, gravity, magnetic, seismic surveys, and well drilling. The effectiveness of each of these techniques, and where they have been employed in the state, is a matter for debate. A variety of approaches for building a degree-of-exploration model are possible, employing a variety of statistical relationships. The fairly simple method presented here is not a unique solution, but serves as an example of how such a model might be built.

Fuzzy logic and expert knowledge were used to build a degree-of-exploration model scaled from 0 representing 0% efficiency (no exploration and no geothermal systems found), to 1 representing 100% efficiency (all geothermal systems discovered). Four types of evidence were used: 1) temperature gradient and geothermal wells, 2) other (non-geothermal) wells, 3) depth to the water table, and 4) presence of a carbonate aquifer. Temperature gradient and geothermal wells were compiled from databases at Southern Methodist University (http://www.smu.edu/geothermal/) and the Nevada Division of Minerals (http://minerals.state .nv.us/) and total 6,671 in number. Non-geothermal wells were compiled from the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/nwis/), the Nevada Division of Water Resources well log database (http://water.nv.gov/Engineering /wlog /wlog.cfm), and a Nevada Bureau of Mines and Geology oil and gas well database (Hess, 2001), and total 161,753 wells. Tim Minor of the Desert Research Institute, Reno, Nevada, generated a depth-to-water table map using approximately 40,000 NWIS water well records. Prudic et al. (1995) provided a carbonate aquifer map.

Well-drilling is one of the more effective methods of geothermal exploration. Deep wells are more likely than shallow wells to encounter thermal waters, and consequently a higher degree of exploration was assigned to areas with deeper wells (Table 2). The presence of geothermal and/or temperature gradient wells is believed more indicative of serious geothermal exploration than the presence of non-geothermal wells, because geothermal drilling is often accompanied by other types of exploration, and also because water temperature is often not reported in non-geothermal wells, so it is unclear if geothermal waters were encountered in them. For this reason, for a given well depth, higher degrees of exploration were assigned to geothermal-related wells than to non-geothermal wells (compare equivalent cells in Table 2a and Table 2b).

Table 2a.				
Geothermal and Temperature Gradient Wells				
Distance	Drilling	Water Table Depth (ft)		
from Well (km)	Depth (ft)	0 - 50	50 - 200	> 200
> 2 (6,560 ft)	None	0.30	0.25	0.18
≤ 2 (6,560 ft)	0 - 50	0.70	0.60	0.50
≤ 2 (6,560 ft)	50 - 200	0.70	0.60	0.50
≤ 2 (6,560 ft)	200 - 1000	0.80	0.70	0.65
≤ 2 (6,560 ft)	> 1000	0.90	0.85	0.81
Table 2b.				
Non-Geothermal Wells				
Distance	Drilling	Water Table Depth (ft)		
from Well (km)	Depth (ft)	0 - 50	50 - 200	> 200
> 2 (6,560 ft)	None	0.30	0.25	0.18
≤ 2 (6,560 ft)	0 - 50	0.35	0.30	0.23
≤ 2 (6,560 ft)	50 - 200	0.40	0.38	0.28
≤ 2 (6,560 ft)	200 - 1000	0.45	0.43	0.34
≤ 2 (6,560 ft)	> 1000	0.50	0.48	0.42

Table 2. Degree-of-exploration estimated for areas outside the carbonate aquifer, under the specified conditions of distance to wells, type and depth of drilling and water table depth. Values for the carbonate aquifer were estimated at 10% less than the values shown here.

All wells were assigned a 2-km circular radius of influence. Five of seven newly recognized geothermal systems in Nevada (unpublished data, 2005, Great Basin Center for Geothermal Energy (GBCGE), Reno, Nevada) occur within 2 km of existing wells, suggesting that at greater distances, the presence of a well is not an effective exploration guide.

Geothermal systems are less likely to be concealed, and consequently will be better explored for, in areas where the water table is shallow. Koenig and McNitt (1983) and Coolbaugh et al. (2002) documented a correlation between shallow water tables and the location of hot springs and known geothermal systems in the Great Basin. Surface exploration techniques (such as looking for hot springs) are more effective when the water table is shallow. Complicating this relationship is the fact that geothermal systems in Nevada also correlate with low topographic elevations (which in turn are associated with active range-bounding faults). Shallow water tables and low topographic elevations often occur in the same areas and it was found difficult to separate the effects of the two quantitatively. Instead, a more qualitative method based on observed field relationships in known geothermal areas was used to assign degrees of exploration to water table depth. The water table map was classified into 3 categories: 0-50 ft, 50-200 ft, and >200 ft (Table 2). For mountain ranges, where water wells are often lacking, water depths were assumed to fall within the ">200 ft" category. Shallow groundwaters are locally present in mountain ranges, but they often occur in perched water zones that do not provide useful information on the deeper geothermal potential. The WofE contrast statistic was useful in picking a threshold depth of 50 ft, at which a maximum statistical distinction occurs between shallow waters that correlate with geothermal systems, and deeper waters that do not.

Fewer known geothermal systems than expected occur in areas underlain by regional aquifers, such as the carbonate aquifer in Nevada (Coolbaugh et al., 2005). It is hypothesized that aquifers sometimes capture and entrain rising thermal fluids before they reach the surface. Consequently, these areas are considered less well explored than non-aquifer areas, when other exploration factors are equal. For the carbonate aquifer, the degree of exploration was reduced by 10% relative to equivalent categories outside the aquifer.

To produce a degree-of-exploration map, the exploration evidence was combined together to form a unique conditions map grid, and for each unique condition, degree-of-exploration values (exploration efficiency) were assigned as shown in Table 2 (Figure 2). Unique conditions for exploration efficiency include the presence or absence of drilling (i.e., ≤2 km from a well or >2 km from a well), the type of drilling, depth of drilling, depth to the water table, and presence or absence of the carbonate aquifer. A fuzzy "OR" statement was used when multiple types and depths of wells are present, such that the well with the highest ranked degree of exploration was used.

Intersection of the Weights-of-Evidence Model with the Degree-of-Exploration Model

The simplest case of intersecting a degree-of-exploration model with a data-driven predictive model occurs when the exploration map is binary: that is, composed of perfectly explored and unexplored areas. In this case, a revised WofE model can be calculated using the reduced area of the perfectly explored area, and then the revised prior probability and revised weights of the explored area can be extrapolated into the unexplored area using the unique conditions table of evidence patterns to estimate undiscovered deposits. (The unique conditions table lists all of the overlapping combinations of geological and geophysical evidence that occur on the map. Points on the map that have the same combination of geological and geophysical evidence will have the same geothermal potential.)

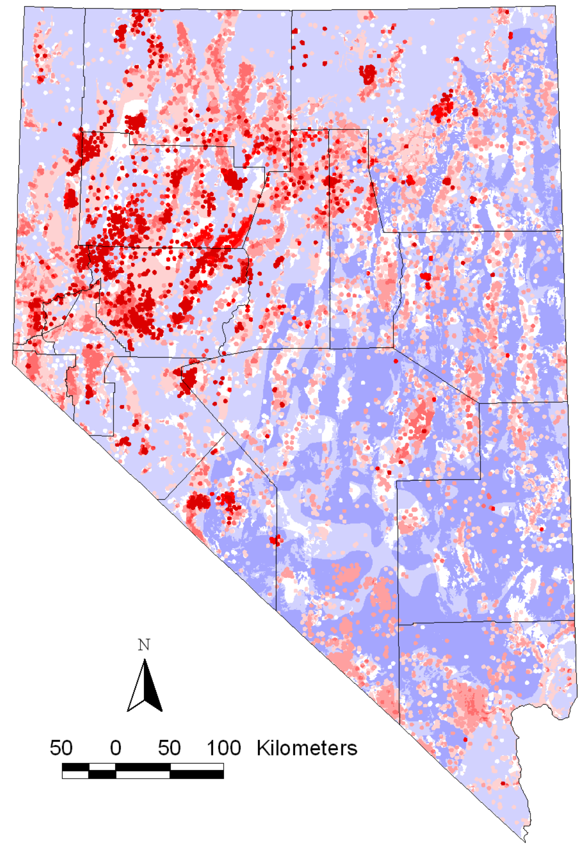

Figure 2. Degree-of-Exploration model for geothermal systems in Nevada. Progressively greater degrees of exploration are represented by the progression of colors from dark blue to light blue, to white, to light red and finally dark red.

A more general case occurs when degree of exploration is not binary but is instead scaled from 0 to 1, as is the case here. The approach adopted is to resolve the scaled degree-of-exploration model into perfectly explored and perfectly unexplored equivalent fractions, both of which fall into co-extensive study areas. For example, a polygon considered 40% explored (0.40 in Table 2) would have 40% of its area assigned to a "completely explored" study area, and 60% assigned to a "completely unexplored" study area, even though it is not possible to determine exactly which cells in the polygon are the explored ones and which are the unexplored ones. All training sites belong to the "completely explored" fraction, since it would be impossible to discover them without some type of exploration. In these circumstances, the total area of the initial study (i.e., the state of Nevada in this example) would equal the sum of the areas of the completely explored fraction and completely unexplored fraction study areas.

The calculation of a revised WofE posterior probability for the explored fraction study area can then proceed using only the "completely explored" study area in the calculations. There are some tricks involved with this computation, however, because the average degree of exploration for the entire study area will inevitably differ from the average degree of exploration associated with each evidence layer class or pattern. But by separately calculating the amount of explored area associated with each evidence class or pattern, the revised weights for the completely explored study area can be calculated. A full set of equations for accomplishing this are provided by Coolbaugh et al. (2006a).

Using the revised weights and prior probability, the posterior probability for the explored fraction study area can be determined using the weights-of-evidence formulas of Bonham-Carter et al. (1988). Since this revised posterior probability has been calculated only for the fully explored fractions of areas, it can be considered equal to the total density or frequency of occurrence of the resources being modeled. The probability of finding an undiscovered resource (P_U) or deposit then depends on the degree of exploration, as follows:

$$\text{(1) } P_U = P_{Epost} * (1 - f_E)$$

where P_{Epost} = the total probability of finding a geothermal system (either known or undiscovered) and f_E = the degree of exploration. When the degree of exploration is 1 (100%), the probability of an undiscovered deposit is 0, and when the degree of exploration is 0, the probability of an undiscovered deposit = P_{Epost}.

Results—Undiscovered Deposits

Using the approach outlined above, an "undiscovered" geothermal potential map was created (Figure 1b) that reveals which portions of Nevada have the best potential for harboring undiscovered geothermal systems. After correcting for a modest C.I. ratio of 0.92, a total of 157 undiscovered geothermal systems (with reservoir temperatures ≥100°C) are predicted, which is 3.2 times greater than the number of known systems (69). Currently, nine of the 69 known systems are producing electricity. If it is conservatively assumed that an additional nine of the known systems will eventually produce electricity (several are already being developed for power production or have a demonstrated capability of producing power, including Salt Wells, Fish Lake Valley, Rye Patch, Blue Mountain, and the Fallon Naval Base), and assuming the same ratio of power-producers to non-power-producers for undiscovered geothermal systems, the model predicts a total of 59 geothermal systems (known and undiscovered) are capable of producing electricity under current economic conditions in the state, a figure which is more than six times higher than the current number, and somewhat greater than the 40 such systems predicted by Coolbaugh and Shevenell (2004) using more approximate methods. Many additional geothermal systems could become economic if wholesale electricity prices increase or if techniques of stimulating reservoir fluid flow improve (enhanced geothermal systems).

Recent Discoveries of Geothermal Systems

Recent discoveries of a number of previously unknown geothermal systems in Nevada suggest that a large undiscovered resource base does in fact exist. Examples include two, and possibly three, moderate to high-temperature geothermal systems recently identified on the Pyramid Lake Paiute Reservation (PLPR) in west-central Nevada (Coolbaugh et al., 2006b). At two of these areas on the PLPR (at Pyramid Rock and in the Smoke Creek Desert), exploration during 2005 identified springs and wells than were hotter than those previously reported, and chemical analyses of thermal waters (not previously done) yielded estimates of reservoir temperatures in excess 150°C. The third newly recognized geothermal system on the PLPR, located east of Astor Pass, is completely blind and is currently being tested with shallow temperature gradient holes that have intersected waters with temperatures of up to 86°C within 60 m of the surface.

Evidence of three blind geothermal systems has recently been uncovered near borate-bearing playas at Rhodes, Teels, and Columbus Marshes in southwestern Nevada (Coolbaugh et al., 2006c, Kratt et al., 2006). In each of these playas, cold and warm springs and wells are spatially associated with bo-

Figure 3. White tincalconite and borax crusts adjacent to a 21.6°C artesian well on the southeast side of Rhodes Marsh. The water yields geothermometer temperatures of 162 and 155°C (quartz and cation respectively) and contains 319 mg/l boron (Coolbaugh et al., 2006c).

rate-rich Quaternary playa evaporate deposits. These well and spring waters have anomalous geothermometer temperatures suggesting the presence of concealed geothermal activity at temperatures >150°C in the case of Rhodes (Figure 3) and Teels Marshes, and >120°C at Columbus Marsh. Reconnaissance exploration of these marshes by the Great Basin Center for Geothermal Energy has only just begun. These three marshes are similar to the Fish Lake Valley in the sense that they occur in a broad, right-stepping transfer zone of strike-slip faults in the central Walker Lane (Wesnousky, 2005). Unlike the Fish Lake Valley however, these three borate marshes have seen no deep geothermal, oil, or mineral exploration drilling of the type that led to the geothermal discoveries in the Fish Lake Valley.

Another important source of recent geothermal discoveries comes from gold (and other mineral) exploration drilling. The authors know of at least 4 places where gold exploration holes drilled in the last few years have encountered hot water and/or steam in Nevada, and undoubtedly more instances exist. One of those areas occurs at the McGinness Hills, located approximately 18 km northeast of Austin, Nevada near Lander County road 21. Drilling of 300-meter-deep exploration holes underneath a 3 to 2 Ma sinter cap (Figure 4, Casaceli et al., 1986) by Newcrest Resources, Inc. in 2004 intercepted near boiling waters (up to 88°C) with some geysering action observed in one hole. Recognizing the significance of the discovery for geothermal exploration, Newcrest geologists had samples of artesian hot water collected from two holes, which yielded quartz geothermometer (no steam loss, Fournier, 1977, 1981) temperatures of 151° and 193°C and K-Na-Ca-Mg geothermometers (Fournier and Potter, 1979; Fournier and Truesdell, 1973) of 209° and 214°C.

As the above example from the McGinness Hills shows, these discoveries are not limited to the lower temperature end of the binary power plant spectrum. Other examples include Blue Mountain, where 160+°C waters were intercepted during drilling in 2004 (Figure 5) that yielded geothermometer temperatures greater than 200°C (Niggemann et al., 2005), and the Fallon Naval Air Station, where a geothermal well flow-tested in 2005 produced waters with temperatures estimated to equal or exceed a downhole measured static temperature of 202°C (Stu Johnson, personal communication, 2006). Also interesting, even though slightly lower temperatures are involved, is the Hot Creek geothermal area in north-central Nye County, Nevada. A reinterpretation of older chemical analyses, and acquisition of new chemical analyses, both indicate a possible reservoir temperature of roughly 160°C (Benoit and Blackwell, 2006). Because Hot Creek lies outside the Humboldt Structural Zone and Walker Lane where most geothermal power plants in Nevada are found, these results are significant because they suggest that geothermal systems capable of producing electricity could occur over a larger portion of the state.

Figure 5. Drilling of the Blue Mountain No. 2 well by Nevada Geothermal Power, Inc. in 2004. Measured fluid temperatures exceeded 160°C and geothermometer temperatures are >200°C (Niggemann et al., 2006).

Figure 4. Chalcedonic sinter from the McGinness Hills (foreground), Lander County, Nevada. Geothermometry suggests reservoir temperatures approaching 200°C.

Discussion

A series of grass-roots geothermal discoveries in the Great Basin have recently been made in spite of the exploration for such resources that took place in the 1970s, 1980s, and early 1990s. The fact that these discoveries have been made without a sustained and concrete grass-roots geothermal exploration effort suggests that a significant undiscovered resource base exists in the Great Basin, which might be tapped if grass-roots exploration efforts were increased. Spatial statistical modeling using weights of evidence and a "degree-of-exploration" model similarly predicts that relatively large numbers of potentially economic power-producing geothermal systems remain undiscovered.

The quantity of undiscovered geothermal systems predicted by the spatial statistical model is dependent on the degree-of-exploration model, which, as presented here, is partly qualitative in nature and requires expert guidance for its construction. It is argued nonetheless, that the concept of a degree-of-exploration model represents a step forward in efforts to model undiscovered resources, because it provides a mechanism for beginning to quantify the role that exploration plays in such estimates. Most past resource estimations have often only implicitly dealt with the role of exploration, if at all.

Although an effort was made to use the most reasonable values possible in the degree-of-exploration model, the authors do not consider themselves the final experts in assigning those values. Instead, the main effort of this paper is to present a viable methodology for calculating undiscovered resources within a computerized GIS framework. Within this framework, it becomes possible to rapidly explore multiple scenarios and competing models of "degree-of-exploration" to assess the effect that different perspectives have on the inferred undiscovered resource base.

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