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PRELIMINARY GEOTHERMAL POTENTIAL AND EXPLORATION ACTIVITY IN NEVADA

by

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SUMMARY

The geothermal potential and geothermal exploration activity in Nevada are represented here on two maps. The map on the right, *Geothermal Exploration Activity*, consists of site-specific evidence of geothermal activity. This information includes the location of hot springs, hot wells, Quaternary silicic volcanic rocks, existing geothermal power plants, and cold and warm springs whose chemistry suggests the possible presence of geothermal waters at depth. Geothermal exploration activity is indicated by past and present geothermal leases and lease applications

The map on the left, *Geothermal Potential*, identifies, on a broad regional basis, those areas of the state most likely to contain relatively high temperature geothermal resources. Hidden geothermal systems (those without hot springs) could occur in areas identified as having relatively high regional geothermal potential. The Geothermal Potential map was derived using some of the data on the Geothermal Exploration Activity map, as well as other data and information described below.

On the Geothermal Potential map, the geothermal energy producing potential of Nevada is divided into four ranks or categories: 1) *high local potential for geothermal systems ≥150°C*, 2) *regional potential for geothermal systems with temperatures ≥150°C*, 3) *regional potential for geothermal systems with temperatures ≥100°C*, and 4) *lower regional potential*. Areas ranked as category 1 have direct evidence in the form of hot springs or hot wells with temperatures near or exceeding the surface boiling point (~92°C at the average surface elevation of most geothermal systems in Nevada), demonstrating that geothermal system(s) do in fact exist. These areas are favorable places to search for high-temperature fluids (normally ≥150°C but sometimes as low as 100°C) that could support electric power production. Areas ranked as category 2 do not have direct evidence in the form of boiling springs or wells, but have other geological or geographical characteristics in common with areas in the state known to host relatively high-temperature (≥150°C) geothermal activity. Areas ranked as category 3 also do not have direct evidence of high subsurface temperatures at shallow depths, but share geological or geographical characteristics with other areas in the state where geothermal systems have temperatures that exceed the surface boiling point. Areas ranked as category 4 do not fit into any of the preceding categories and are considered less favorable for hosting high-temperature geothermal systems. The process of creating these map-based rankings is described below.

APPROACH

Three fundamentally different types of information were used to create this map. The first type consists of direct evidence of geothermal activity in the form of hot springs and hot wells. The second type of information is indirect evidence in the form of geological or geophysical features known to be associated with geothermal activity. Such features include felsic Quaternary volcanic rocks, Quaternary faults, earthquake epicenters, high temperature gradients, and high rates of crustal strain. The third type of information consists of areas in proximity to known geothermal systems. Many of the active geothermal systems in Nevada occur in regions, belts or trends, and these areas are consequently favorable areas to search for new resources.

These three types of information have an interesting parallel in gold exploration. The first type of information is analogous to information on gold mines and gold prospects. The second type of information is analogous to searching for gold mineralization within geologic formations known to host important gold deposits, such as the Roberts Mountains Formation in eastern Nevada. The third information type would be analogous to searching for gold deposits within a known mineral belt such as the Carlin trend.

Each of these information types has its strengths and weaknesses, which is why we combined their predictive powers. Known hot springs and wells are the most definitive evidence of geothermal activity, but wells have not been drilled everywhere (or may not be deep enough to hit hot water), and hot springs do not always form above geothermal reservoirs. In areas where springs and wells are not present, indirect evidence must be used to estimate geothermal favorability. Such indirect evidence includes the presence or absence of geological, geophysical, and geochemical features commonly associated

with geothermal activity. The disadvantage of using these physical features is that each geothermal system forms under somewhat different conditions so that physical features are imperfect predictors. Secondly, the manner in which physical variables combine to allow geothermal systems to form is incompletely understood. Furthermore, the digital data used to represent these physical variables is typically incomplete (e.g., not all Quaternary faults have been recognized or mapped).

An additional method of estimating geothermal potential involves a proximity analysis…"How close are the nearest known geothermal systems and how many occur nearby"? Many geothermal systems in Nevada occur in clusters or along discrete linear trends or belts that are imperfectly understood in terms of the known physical features mentioned above, so a proximity analysis has relevance in predicting geothermal potential. Our proximity analysis consists of a regional map of the distribution of maximum temperatures of known geothermal systems in the state, and its creation is described below. Not all geothermal systems occur in clusters or trends; however, so it is important to combine this type of analysis with the other approaches described above to produce a geothermal potential map that considers all the available evidence.

INPUT DATA

Hot Springs and Wells

Temperature and location data for hot springs and wells were taken from the Great Basin Groundwater Geochemical Database available on-line at www.unr.edu/geothermal/GeochemDB.htm. This database includes data from the Nevada Bureau of Mines and Geology, the Geo-Heat Center (Boyd, 2002), and the National Water Information System (NWIS) groundwater database (U.S. Geological Survey, 2005). Additional spring and well data were taken from the Nevada Well Drillers Database (Nevada Division of Water Resources, 2006) and the Southern Methodist University geothermal database (Blackwell and Richards, 2007).

For the purposes of geothermal modeling, these springs and wells were separated into two classes; those with temperatures ≥92°C and those with temperatures between 50°C and 92°C. The 92°C threshold represents the approximate surface boiling point of water in Nevada, which because of altitude is lower than 100°C. The 50°C threshold represents the approximate lower limit at which thermal waters are readily used in industrial direct use applications (www.geothermal.marin.org). Springs and wells above 20°C (slightly above average ambient surface temperature in Nevada) are also shown to designate waters that probably contain a geothermal component (Shevenell and Garside, 2005). Hot wells were included only if the temperatures in those wells at the specified depth exceeded a regional temperature gradient of 25°C/km.

Areas in Nevada that lie near hot springs and wells have an elevated potential for producing geothermal energy, but two questions are: 1) how close is "near" and 2) is the "nearness" parameter the same for all directions (i.e. is an elliptical or circular search preferred)? The first question was addressed by compiling distances between hot springs/wells and known geothermal systems in Nevada. These distances are often significant, measured in terms of kilometers, as documented by Benoit and others (1982) for Desert Peak, Nevada, Coolbaugh and others (2006b) for Salt Wells, Nevada, and Coolbaugh and others (2007) for the Desert Queen area, Nevada. Cumulative frequency plots were employed to statistically assess these distances and define radii for buffer zones containing areas of elevated geothermal potential. A buffer radius distance of 7 km around boiling (92+°C) springs and wells (n = 65) was chosen on the basis that 90% of those springs and wells lie within 7 km of their associated geothermal system (figure 1).

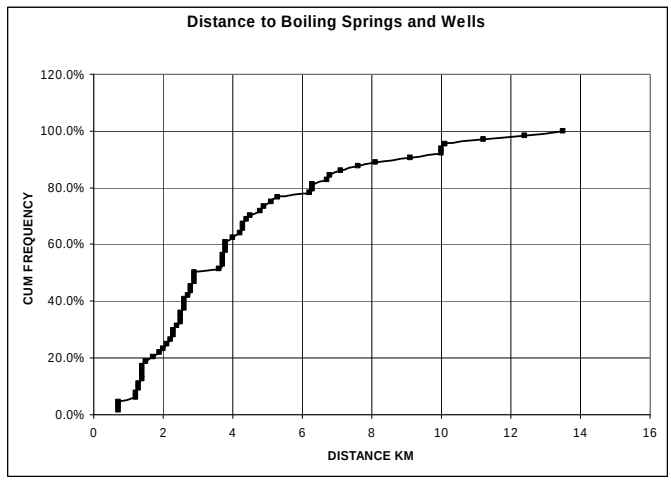

Figure 1. Cumulative frequency plot of the maximum distance to boiling (92+°C) springs and wells from their associated geothermal system, n = 65. The y-axis represents the fraction of all known geothermal systems in the state whose associated 92+°C spring and well temperatures all occur at distances less than or equal to the distance on the x-axis. A 7-km buffer contains 90% of the geothermal systems.

It could be argued that this buffering parameter should not be isotropic: for example, that a "nearness" buffer should be larger when looking parallel to a range front fault than when looking perpendicular to such a fault. Although this might be true on a case-by-case basis in well-studied areas, there are inherent risks in using non-isotropic buffers. In many cases, shallow thermal waters flow down-gradient away from the near-surface portions of thermal upwelling zones. If the thermal upwelling zone is controlled by a range-front fault, this down-gradient flow will usually be perpendicular to the strike direction of the controlling fault(s) instead of parallel to it, so that the shortest distance from a hot spring to an underlying upwelling zone may be perpendicular to the strike of range-bounding faults that control thermal flow in the deeper subsurface. Hot wells might be located in almost any direction relative to a hidden geothermal reservoir. In any case, the structural controls on underlying geothermal reservoirs are often poorly characterized, and in the absence of specific data, a circular buffer distance is the simplest and most all-inclusive assumption.

Spring and Well Geothermometry

In some cases, thermal waters rising from depth will either cool to ambient temperatures or mix with cool groundwater before reaching the surface or before being intercepted by wells. Often these cooled thermal waters will contain telltale concentrations of dissolved constituents indicative of their thermal histories, as in the case of springs at Salt Wells (Edmiston and Benoit, 1984), Desert Peak (Eagle Salt Works Spring, Mariner and others, 1983), Astor Pass (Coolbaugh and others, 2006a), and the Fish Lake Valley (Shevenell and Coolbaugh, 2007). In the examples referenced above, the quartz and Mg-corrected Na-K-Ca geothermometers of cold or warm springs and wells exceed 100°C.

Since geothermometer temperatures are a good indirect indicator of high reservoir temperatures, we considered areas close to springs and wells having geothermometer temperatures ≥100°C as favorable. Two separate estimates of geothermometer temperatures were calculated and averaged. First, an overall silica geothermometer temperature was estimated using the algorithm of Mariner and others (1983) which combines the results of the quartz (no steam loss) and chalcedony geothermometers developed by Fournier (1977, 1981). Second, a Mg-corrected Na-K-Ca geothermometer was calculated using the algorithms of Fournier and Truesdell (1973) and Fournier and Potter (1979). Cumulative frequency plots were used to determine the best buffer distance: 90% of springs and wells with ≥100°C average geothermometer temperatures (average of the above described silica and Mg-corrected Na-K-Ca geothermometers) lie within 8 km of their associated geothermal systems (figure 2). Thus, an 8 km buffer distance was chosen around springs and wells with geothermometer temperatures ≥100°C (n = 84).

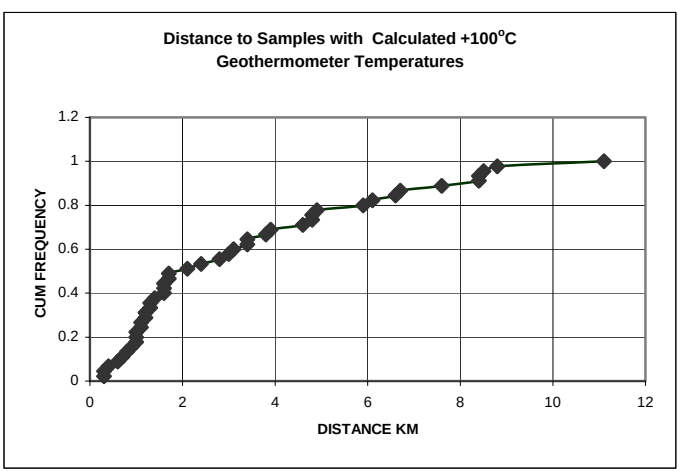

Figure 2. Cumulative frequency plot of the maximum distance to 100+°C spring and well geothermometer temperatures from their associated geothermal system, n = 84. The y-axis represents the fraction of all known geothermal systems in the state whose associated 100+°C spring and well geothermometer temperatures all occur at distances less than or equal to the distance on the x-axis. An 8-km buffer contains 90% of the geothermal systems.

Quaternary Silicic Volcanics

Exclusive of actual hot springs and wells, the best local predictor of geothermal activity on the margins of the Great Basin is the presence of Quaternary silicic volcanic rocks (Coolbaugh and others, 2003). In the Great Basin, this predictor works in the positive sense, but not in the negative sense. That is, Quaternary silicic volcanic rocks are a highly favorable indicator for geothermal activity, but a lack of these rocks does not imply a low potential for geothermal resources. The presence of Quaternary silicic volcanic rocks is favorable because it usually suggests there is a potential for a shallow crustal source of heat for groundwater. However, geothermal systems with temperatures ≥150°C occur throughout a large part of Nevada, and most are not known to be associated with Quaternary silicic volcanic activity. Instead, they are associated with active extensional/transtensional tectonics and high heat flow (Koenig and McNitt, 1983; Wisian and others, 1999).

A circular buffer distance of 5 km around Quaternary silicic volcanic rocks was chosen as a threshold distance for classification. At that distance, all six of the known geothermal systems in the Great Basin that are associated with young silicic volcanic rocks would be correctly classified as lying in favorable geothermal terrain. As an example, the geothermal reservoir at Roosevelt Hot Springs in Utah lies roughly 4 km from the nearest Quaternary rhyolite dome, in a direction roughly perpendicular to the range front of the Mineral Mountains.

Regionally Distributed Geological and Geophysical Features

Although Quaternary felsic volcanic rocks are important predictors of geothermal activity, their distribution in Nevada is limited to the extreme west-central portion of the state north and northeast of Carson City (adjacent to the Steamboat Springs geothermal system). Other more regionally distributed geological and geophysical features can be used to estimate geothermal favorability in other parts of the state. These features include horizontal gravity gradients, crustal strain rates as determined from geodetic measurements of global positioning satellite system (GPS) station movements and Quaternary fault offsets, temperature gradients, and earthquake magnitudes and epicenters. High horizontal gravity gradients are useful for predicting geothermal activity because, in places, these gradients define the locations of major faults that facilitate the deep circulation and heating of groundwater. High rates of crustal strain are favorable because they can reveal areas where faults are most likely to remain open to deep fluid flow. Earthquakes indicate areas of active crustal motion along faults, which helps to maintain fracture permeability. Areas with high temperature gradients are favorable because circulating waters can reach higher temperatures at relatively shallower depths, where fractures are more likely to remain open due to lower confining pressures. Coolbaugh and others (2005b) used weights of evidence and logistic regression to assess the correlation of each of these regional features with

geothermal activity and combine them into an overall map-based favorability index for ≥150°C geothermal systems (see map inset 1). On that map, geothermal favorability is subdivided into five broad probability rankings of "most favorable," "very favorable," "favorable," "marginally favorable," and "permissive." These rankings have been adopted for use in the current geothermal map of Nevada, and the manner in which they have been integrated with the other input predictive data is described below.

Geographic Location Relative to Known Geothermal Systems (Regionally Smoothed Maximum Temperatures of Known Geothermal Systems)

Several regional alignments and clusters of geothermal systems are present in Nevada, as is evident from examination of a surface interpolation map of maximum temperatures of known geothermal systems (see map inset). First published by Coolbaugh and others (2005a), that map has been updated here to incorporate the results of several recent geothermal discoveries. Temperature contours of 100°C and 150°C from this trend map were used to help define geothermal energy potential rankings on the Geothermal Potential map.

This regional trend surface was interpolated from a set of points representing all geothermal systems >37°C in the Great Basin for which both subsurface temperatures and geothermometer temperature estimates are available. After some experimentation to identify an interpolation algorithm compatible with the density of point data, inverse distance was chosen using a power of 1 and the five nearest neighbors. Each geothermal system was represented as a single point along with its maximum temperature. That maximum temperature was defined as the greater of 1) the highest measured temperature, or 2) the average of the silica and Mg-corrected Na-K-Ca geothermometer temperatures. The procedure for calculating geothermometer temperatures is the same as that described in the section on spring and well geothermometry. A minimum distance of 10 km between geothermal systems was required. Non-geothermal wells deeper than 500 meters were excluded from the analysis to minimize the inherent bias of higher temperatures associated with greater depths.

Method of Combining Data to Produce Rankings

The highest rank of geothermal energy potential (*high local potential for geothermal systems ≥150°C*) is restricted to areas with direct evidence of geothermal activity as defined by boiling or near-boiling temperatures in springs and wells (≥92°C). A 7 km circular buffer around all such springs and wells was used to define these areas (see section on "Hot Springs and Wells" above for details). This includes all geothermal power plants operating or under construction in the state. Four percent of the state falls into this highest rank.

In lieu of direct evidence in the form of high temperatures, the second and third ranks of geothermal potential were defined with indirect indicators. The second highest rank *(regional potential for geothermal systems with temperatures ≥150°C*) consists of areas outside the highest rank where one or more of the following criteria apply: 1) Quaternary felsic volcanic rocks occur within a distance of 5 km, 2) a spring or well with a temperature of 50-92°C occurs within 8 km, 3) a spring or well with an average geothermometer temperature ≥100°C occurs within 8 km, 4) the regional potential for ≥150°C geothermal systems is considered to be "most favorable" or "very favorable" according to regional geological and geophysical criteria assembled by Coolbaugh and others (2005b), or 5) temperatures on the regional trend map of maximum known geothermal temperatures are ≥150°C. The selection of buffer distances is explained in the preceding section on "Input Data." This second rank comprises 18% of the state.

The third rank of geothermal potential (*regional potential for geothermal systems with temperatures ≥100°C*) consists of areas exclusive of ranks one and two where temperatures on the regional trend map are ≥100°C or where the regional criteria of Coolbaugh and others (2005b) indicate "favorable" potential for geothermal systems ≥150°C. Thirty-nine percent of the state falls into this third rank. Hence, 61% of the state is favorable for geothermal resources suitable for electrical power generation.

Portions of the state not classified in the first three rankings are considered to have "*lower regional potential*" (rank 4). Because the prediction of hidden geothermal resources is an inexact science, it is likely that some geothermal resources occur in this lowest ranking area, even though the likelihood per unit area is considerably less than for other parts of Nevada. As described by Coolbaugh and others (2005b), all of Nevada is considered to be at least permissive for the occurrence of geothermal systems, because the entire state is located in an area of elevated heat flow in North America (Blackwell and Richards, 2004), and the entire state is also experiencing an elevated level of tectonic activity compared to most of the rest of North America. This final category encompasses 39% of the state.

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DISCLAIMER

This information should be considered preliminary. It has not been thoroughly edited or checked for completeness or accuracy. Although the published databases that are used in this report have been checked, experience has shown us that there are occasional errors, particularly in the locations of specific points on the map. Users should therefore double check information and locations, preferably on the ground, before making critical decisions.