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Geothermal GIS Coverage of the Great Basin, USA: Defining Regional Controls and Favorable Exploration Terrains

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ABSTRACT

A geographic information system (GIS) of geothermal resources, built last year for the state of Nevada, is being expanded to cover the Great Basin, USA. Data from that GIS is being made available to industry, other researchers, and the public via a web site at the Great Basin Center for Geothermal Energy, Reno, Nevada. That web site features a search engine, supports ArcExplorer™ for on-line map construction, and provides downloadable data layers in several formats.

Though data collection continues, preliminary analysis has begun. Contour maps of geothermal temperatures, constructed using geothermometer temperatures calculated from a Great Basin geochemical database compiled by the Geo-Heat Center, reveal distinctive trends and patterns. As expected, magmatic-type and extensional-type geothermal systems have profoundly different associations, with magmatic-type systems following major tectonic boundaries, and extensional-type systems associating with regionally high heat flow, thin crust, active faulting, and high extensional strain rates.

As described by earlier researchers, including Rowen and Wetlauffer (1981) and Koenig and McNitt (1983), high-temperature (>100°C) geothermal systems appear to follow regional northeast trends, most conspicuously including the Humboldt structural zone in Nevada, the "Black Rock-Alvord Desert" trend in Oregon and Nevada, and the "Newcastle-Roosevelt" trend in Utah and Nevada. Weights-of-evidence analyses confirm a preference of high-temperature geothermal systems for young northeast-trending faults, but the distribution of geothermal systems correlates even better with high rates of crustal extension, as measured from global positioning system (GPS) stations in Nevada. A predictive map of geothermal potential based only on areas of high extensional strain rates and high heat flux does an excellent job of regionally predicting the location of most known geothermal systems in Nevada, and may prove useful in identifying blind systems.

Introduction

A geothermal GIS is being constructed at the Great Basin Center for Geothermal Energy (GBCGE) at the University of Nevada, Reno with the long-term objective of providing comprehensive data coverage over the entire Great Basin of geological, geochemical, and geophysical data useful in the exploration for, and development of, geothermal resources. During the first year of that effort, priority was given to developing a GIS for the state of Nevada and statistically analyzing relationships among the data (Coolbaugh et al., 2002). That initial study quantified relationships between geothermal activity and basaltic volcanism, groundwater geochemistry, and recent faulting, and led to sister research projects investigating regional crustal strain rates derived from GPS stations (Blewitt et al., 2002) and trace element geochemical tools for distinguishing magmatic from extensional-type geothermal systems (Arehart et al., 2002). Predictive models of geothermal potential were constructed for the state of Nevada, and tools were developed for assessing geothermal favorability in areas where groundwater characteristics were not permissive for the formation of hot springs. Groundwater characteristics precluding hot spring formation include deep water tables, which can make it difficult for thermal waters to reach the surface, and laterally flowing groundwater in aquifers, that can capture and entrain geothermal fluids.

The GIS is now being expanded to cover the entire Great Basin and accelerated efforts are being made to post this database on the web to make it accessible to interested stakeholders. By covering the entire Great Basin it becomes possible to analyze similarities and differences in the distribution of magmatic and extensional-type geothermal systems. A groundwater table map, originally constructed for the state of Nevada, is also being expanded to the boundaries of the Great Basin, to better recognize where geothermal systems could remain hidden (beneath deep water tables).
Software and Web Site Development

ArcView® GIS v. 3.3 software is currently being used for data integration. Spatial statistical analyses, including weights-of-evidence, logistic regression, and fuzzy logic, are performed with Arc-SDM, an ArcView® spatial data-modeling extension developed by the Geological Survey of Canada (GSC) and the United States Geological Survey (USGS; Kemp, et al., 2001).

In conjunction with a companion research project, “Geo-Powering the West”, GIS data are posted on the web site of the GBCGE for public access. New GIS data collected in the field and acquired from other databases, as well as thematic maps and illustrations generated by image-analysis and GIS software, are archived in a geodatabase on the GBCGE data server. This archive is linked to the GBCGE web site and contains a public portion for general information and published data and a proprietary part for collaborating researchers in on-going GBCGE projects. The purpose of this archive is to provide a means for the creation of georeferenced maps and other illustrations to assist in research and for preparation of publications and talks. Data are in a format for use in GIS programs such as ArcView® and ArcInfo®. Data are also in a format allowing for online preparation of maps and illustrations by means of selective extraction, overlaying, and viewing of data using ArcExplorer® and similar, GIS-capable freeware and Microsoft Access® and similar database software.

Great Basin Geochemistry Database

One of the first steps in building a geothermal GIS is development of a comprehensive geochemistry database, from which an inventory of known geothermal systems can be made. The Geo-Heat Center of Klamath Falls, OR. recently compiled thermal spring and well databases developed by individual states in the Great Basin and made them available on CD (Geo-Heat Center, 2002). To facilitate GIS analysis, those databases have been compiled into a single geochemical file and geothermometer estimates of reservoir temperatures have been added using Na-K-Ca-Mg and silica geothermometers. The compiled file together with metadata and geothermometer references is available in ArcView® shapefile and Excel spreadsheet formats at the GBCGE web site (www.unr.edu/geothermal).

For purposes of spatial statistical analyses, a second file consisting of an inventory of known geothermal systems has been created. This file differs from the more comprehensive database described above, in that each geothermal system (sometimes simply a hot spring) is represented by only one record or entry in the table, whereas multiple springs, wells, or analyses may be present in the more comprehensive Geo-Heat database. To minimize duplication, no two geothermal systems were allowed to lie within 10 km of each other. Geothermal fluids taken from oil wells deeper than 500 meters were not used, because in many such cases the regional background temperature gradient is not exceeded and such temperatures don’t necessarily represent a geothermal anomaly. The resulting “distilled” geothermal system file can be used as a “training set” for weights-of-evidence and other types of spatial statistics. Geothermal systems can be discriminated by temperature in the file, using either the maximum observed temperature or temperatures calculated from geothermometers.

The geothermal system inventory or training set file is available in multiple formats at the aforementioned GBCGE web site. Multiple sources of data were used; in addition to the Geo-Heat Center database (Geo-Heat Center, 2002), sources include state geochemistry databases from Nevada (Garside, 1994) and Utah (Blackett and Wakefield, 2002), the geothermal well database at Southern Methodist University (Blackwell, 2002), and geothermal resource maps of Arizona (Witcher, et al., 1982), California (Higgins and Martin, 1980), Idaho (Mitchell, et al., 1980), and Oregon (Peterson, et al., 1982).

An example application for the training set file is the creation of contoured maps of geothermal system temperatures (Figure 1). In this example, the temperature used for contouring was the greater of the directly measured temperature and the average of two geothermometers: the Na-K-Ca-Mg and silica geothermometers (using algorithms employed by Mariner, et al., (1983)). The contours were interpolated using the inverse distance weighting method with a power of 1. The Great Basin is clearly divided into zones of high and low geothermal temperatures, and a number of trends are evident. One challenge for GIS-based statistical modeling is to understand and predict geothermal trends based on underlying geological, geochemical, and geophysical parameters.

Figure 1. Contoured maximum geothermal temperatures in the Great Basin. See text for details on methods used.

Magmatic Versus Extensional Geothermal Systems

Two types of high-temperature geothermal systems are recognized in the Great Basin: the “magmatic-type,” which are believed to obtain their heat from shallow crustal magmas or cooling intrusions, and which occur on the margins of the Great Basin (e.g., Long Valley caldera), and the “extensional-type,” which are “amagmatic” and most commonly occur within the interior of the Great Basin (e.g., Dixie Valley; Koenig and McNitt, 1983; Wisian, et al., 1999). GIS coverages of the entire Great Basin...
provide the opportunity to analyze and compare the distributions and controls of these two system types.

Given that magmatic-type systems have magmatic-related sources of heat, it is not surprising that such systems correlate with the location of young silicic volcanic rocks (Figure 2), and the degree of correlation is strong. A peak weights-of-evidence contrast statistic of 6.6 for young silicic volcanics, which measures the likelihood of hosting geothermal power plants that are either in production or economically feasible, is not even closely matched by any other map-based parameter for any type of geothermal system in the Great Basin. Seventy-five percent of all silicic volcanic centers in the Great Basin either host currently producing geothermal power plants or are believed capable of doing so.

The only exceptions are the Big Southern Butte and China Hat domes in southeastern Idaho, though a similar exception could be ascribed to the Flagstaff-San Francisco Mountain region in northern Arizona (outside the Great Basin). In both southeastern Idaho (Smith, 2002; Fiesinger, 2002; Nash, 2002) and northern Arizona (Witcher et al., 1982), lateral flows of groundwater are believed to suppress the ability of geothermal fluids to reach the near-surface where they could be detected in water wells or thermal springs. If techniques can be developed for the remote detection of geothermal systems at depth, geothermal fluids capable of supporting power plants might be discovered in each of these areas.

The different affinities of magmatic and extensional-type geothermal systems are illustrated Figures 3 and 4, which are weights-of-evidence correlation plots of crustal thickness and seismic moment release (based on natural earthquakes). Magmatic systems occur along the tectonic margins of the Great Basin where earthquakes are more frequent and crustal thicknesses are greater compared to the relatively aseismic Basin interior with thinner crust. As additional data become available for the Great Basin, more complete statistical evaluations are becoming possible and predictive maps of each type of system can be prepared.

**Structure and Strain Rate Analysis**

Medium to high temperature geothermal systems ($\geq 100^\circ$C) in the Great Basin appear aligned along several broad-scale northeast trends (Koenig and McNitt, 1983), including the Humboldt structural zone in Nevada (Rowen and Wetlaufer, 1981), the "Black Rock-Alvord Desert" trend in Oregon and Nevada, and the "Newcastle-Roosevelt" trend in Utah and Nevada (Figure 2). In support of this observation, Coolbaugh et al. (2002) used weights-of-evidence analysis to identify a systematic preference of high-temperature geothermal systems ($\geq 160^\circ$C) for young northeast-trending faults in Nevada, and inferred that higher rates of crustal extension across those faults could permit greater depths of penetration of meteoric waters into the crust, where they could
be heated to higher temperatures. Crustal motion of the Sierra Nevada block in a northwest direction away from the Great Basin (Bennet et al., 1998) was invoked as the causative mechanism for higher extension rates across northeast-trending faults.

To further evaluate the postulated relationship between crustal extension and geothermal activity, Blewitt et al. (2002) modeled crustal strain rates across the Great Basin using geodetic measurements of plate motion derived from GPS stations. A digital grid of strain rates was then intersected with a map of Quaternary faults in Nevada compiled by Craig DePolof the Nevada Bureau of Mines and Geology (NBMG), and the rate of opening across those faults was calculated on a regional basis (Blewitt et al., 2003). The resulting map of extension rates normal to faults correlates much better with high-temperature geothermal resources than do northeast-trending young faults alone (peak weights-of-evidence contrast of 3.5 for GPS-based extension rates compared to 2.5 for northeast-trending faults alone), suggesting that GPS-based measurements of crustal strain could constitute an effective tool in regional and local geothermal resource assessment.

High temperature extensional-type geothermal systems have been postulated to form in regions of active extensional faulting and high heat flow (Koenig and McNitt, 1983; Wisian et al., 1999). To explore this hypothesis, a predictive map of geothermal potential based only on areas of high extensional strain rates (as determined by Blewitt et al., 2003) and high heat flux (modeled by D. Blackwell of Southern Methodist University) was created (Figure 5). This map does an excellent job of regionally predicting the location of most high-temperature extensional-type geothermal systems in Nevada, and helps explain why many geothermal power plants in Nevada are located west of the Battle Mountain Heat Flow high (because of higher extensional strain rates in western Nevada).

Conclusions

The development of a GIS for geothermal resources of the Great Basin is already yielding significant benefits. Improved data accessibility makes it easier to gather information in subsets to evaluate individual projects or watersheds. Data can be visualized more effectively and it is now possible to quantitatively analyze relationships among the data. Better analysis leads to increased understanding, as exemplified by the GPS-station-based geodetic strain research.

Continued positive results are expected as more data are compiled into the database. Much additional data remain for input and analysis in the coming months. That data will become accessible on the web for use by industry, researchers, and the public.

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