GEOTHERMAL RESOURCE ANALYSIS AND STRUCTURE OF BASIN AND RANGE SYSTEMS, ESPECIALLY DIXIE VALLEY GEOTHERMAL FIELD, NEVADA

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Project Background and Status

This project is in the final year of a three calendar year study. The project was devised to bring into the public domain, and to the attention of geothermal developers, valuable thermal gradient and heat flow data collected during the extensive industry exploration episode in the 1970's and early 80's. In addition Caithness Corp. agreed to allow publication and interpretation of important exploration results in Dixie Valley obtained in 1993 and 1994. Obtaining, making public, and interpreting a significant and valuable block of previously proprietary data has been a key aspect of the project. Although industry has a keen interest in this project as evidenced by the commitment of proprietary data, the economic climate has not allowed them to perform this type of a study.

Project Objective

This project has had two main thrusts. The first is to develop a better understanding of the geology of Basin and Range extensional geothermal systems. This objective has been met by developing a detailed geologic model of a major Basin and Range geothermal system, to aid in the development of geothermal systems throughout the province. Dixie Valley, Nevada is the example for the model.

The second thrust is to use thermal techniques to better characterize the thermal resources of the Western United States. The second objective has been met by development and frequent updating of a data base of regional geothermal gradient/heat flow data for exploration use in the development of new geothermal resources using the world wide web as the publication medium (see www.smu.edu/geothermal). We have used this database to develop evaluation and resource estimation techniques for extensional geothermal systems.

Approach

The first project, characterizing extensional geothermal systems in the Basin and Range involves the following steps. First a detailed model of the Oxbow and DVPP sections of Dixie Valley, Nevada geothermal system, based on extensive thermal, seismic, drilling, geologic and potential field data, much of which was previously proprietary or was collected for this study, has been constructed (see Figures 1, 2, and 3). The extension of the characterization to other Basin and Range systems is a task in progress.

The second project is to assess the geothermal resource in place in the western US. A site specific heat flow/gradient/well database has been developed with over 5,000 wells included. These data are available via interactive pages on the Internet. The American Association of Petroleum Geologists (AAPG) as part of this project will publish a revised Geothermal Map of North America. These compilations/maps are a basic starting point for any work involving geothermal resources and are also a primary input to other areas such as tectonics/earthquake hazard assessment and petroleum generation. Distribution through the AAPG should greatly enhance awareness of geothermal resources in the economic geology community.

Research Results

Dixie Valley Model

The Dixie Valley, Nevada, geothermal field (Figure 1) has a rated output of approximately 62 MW and has been producing electrical power since 1988. This field represents the largest, hottest Basin and Range fault hosted, extensional, geothermal system. The thermal source is deep circulation along a part of the normal fault zone between the Stillwater Range and Dixie Valley. The last major event along this segment of the Dixie Valley fault was about 3,000 ya. North and south of this area are sections of the fault zone that have been historically active and produced major earthquakes (in 1954 a Ms 6.8 earthquake occurred on the fault zone about 30 km to the south, Bell and Katzner, 1987). The seismic interpretation was that the fault responsible for the earthquake dipped about 75° and the epicenter was at about 15 km (Doser, 1989). Fluid-entry temperatures in the producing geothermal wells range are 220 to 248°C (Benoit, 1992).

The Oxbow field has been described by Benoit (1992, 1999). It consists of two groups of production wells in sections 33 and 7 (Figure 1), with injection wells in between (section 5) and to the south (section 18). Two hot wells located several km to the southwest, 66-21 (218 °C) and 45-14, (195 °C) have a few lpm of artesian flow. The northern most well, 76-28 (Tmax of 162 °C at 2350 m) and the 62-21 well in the middle of the valley (Tmax of 184 °C at 3318 m) appear to approach background conditions. The producing zones in the Oxbow field are all at about the same depth and the wells are all about the same distance from the range front so that a reservoir model with a single, range bounding, normal fault dipping at about 54° satisfies the observations (Benoit, 1992).

In 1993 and 1994 Caithness Corp. (later joined with ESI to form Dixie Valley Power Partners, DVPP) drilled two deep exploration wells (62A-23 and 36-14) south of the Oxbow field. The temperature in 62A-23 (265°C) was higher than the production temperatures in the Oxbow field but the well had no flow capacity. More detailed results of the exploration have been described by Blackwell et al. (2000a, 2000b) and are briefly summarized. The initial exploration model of the geothermal system in the DVPP area (shaded area in Figure 1) was of a single range-bounding fault with a dip of about 54°. The drilling of the 62-23 and 62A-23 wells demonstrated that “the range bounding fault” at that location had to dip at an angle of 65° or steeper. However both legs of this well were completely tight with no evidence for a major fault in either leg. The 36-14 well was then drilled closer to the range front, but intersected basement at only 1 km, much too shallow for a single fault model. Consequently the well was deviated toward the range below about 1500 m. At 3,050 TVD the well intersected a permeable zone with over-pressured fluid at a temperature of 280°C.

Thus the wells have temperatures higher than in the producing field and the temperatures increase to the total depth of the wells. The wells are separated by over 1 km at a depth of 3 km. Hot water circulating along a single, range bounding, steeply dipping normal fault can not explain this thermal data. Thus the deep well data in the DVPP lease area require at least two major distinct thermal fluid structures to be present.

A two fault, finite difference, numerical thermal model was developed based on the temperature and geological constraints from the wells. The geometry inferred for the numerical model to fit the observed temperatures in the wells is shown in Figure 2. The boundary conditions included a surface temperature of 15°C and an assumed background heat flow of 80 mW/m^2. Two thermal conductivity values were assumed, one for the Cenozoic units (1.25 W/m/K) and one for pre Cenozoic rocks (2.5 W/m/K). The heat flow and thermal conductivity values are consistent with the thermal regime in the deep wells away from the geothermal system.

Heat transfer was assumed to be conductive except along the fault zones. The circulation of geothermal fluid along the fault controls the assumed temperature at a particular depth. The calculation shown was done for a period of existence of the system of 70,000 y. That time is long enough to reach near thermal equilibrium over an area on the order of the size of Figure 2. The temperature-depth curves from the deep wells suggest that major transient effects are not generally present.

Both the positions of the faults and the temperature distribution on the faults were varied to give a best match for the observed temperatures in the deep wells. The calculated temperatures along positions corresponding to the tracks of the wells were compared to the observed temperature-depth curves for 36-14 and 62A-23 until a close fit was obtained.

The thermal model and results of a gravity survey described by Blackwell et al. (1999) give a framework for understanding the structure of the geothermal system in the Dixie Valley area. The general model of the geothermal system is of deep meteoric water circulation and heating in the fractured Basin and Range basement rocks. The fluid flows upward along a complex, active, normal fault zone that bounds the Stillwater Range and Dixie Valley. Above 4,500 m the fault zone includes more than one strand having active geothermal fluid circulation along it. The data suggest that there are complex variations of fault structure along the strike of the range/valley contact, and require that the boundary be a series of faults rather than only one structure. For example there are piedmont faults along most of the contact that take up much of the displacement between the range-valley topographic contact and the valley. However, most of the topographic relief is due to a series of faults at the range/valley contact that in general have relatively little displacement of the valley fill. Finally the extension process is evident in the ubiquitous occurrence of antithetic faults forming grabens on the hanging wall (down thrown side) of the major faults, a detail not shown on Figure 2 but illustrated in the generalized model shown in Figure 3. The structure of the fault zone deduced here is similar to the structure of the fault zone in the area of the 1954 earthquake about 30 km to the south. The 1954 vicinity has a range bounding fault zone, a piedmont fault zone, and an antithetic graben system (see Bell and Katzner, 1987).

General Characteristics of Basin and Range Geothermal Systems

Some implications of the geometry of the normal fault system for geothermal exploration are clear from examination of Figures 2 and 3. For example the fault system along the range front has several targets for drilling, not just one range-front fault. Any thermal manifestations along the range front are not directly connected to the production zones in piedmont faults. Flow on the piedmont faults would be discharged into the valley fill considerably away from the range valley conflict. As an example discharge into the valley fill must have transpired before production allowing for the natural through flow along the fault zone that feeds the wells today in section 7, (Figure 1).

Deep drilling, temperature gradient exploration, and thermal manifestations together indicate most of the strands have some high temperature fluid flow in some places in the greater Dixie Valley geothermal system. The complexity offers challenges to the exploration and drilling, but it also offers reservoir opportunities and sizes that were not expected based on the single fault model.

In general the results from Dixie Valley show how complicated and indirect the thermal manifestations of Basin and Range systems can be. The low water tables and the multiple strands lead to these complicated patterns. Three scenarios for the surface manifestations associated with Basin and Range geothermal systems are shown in Figure 4. In turn the complicated patterns lead to complicated geochemical evolution of the shallow geothermal fluids. Often the samples of geothermal fluid come from these evolved waters and do not simply relate to the deeper geothermal fluids. Therefore the chemical geothermometers that have been used to evaluate deeper reservoir temperatures may not be valid in many cases. We believe the evidence suggests that a system with a spring temperature or a shallow well temperature of near boiling must be assumed to be much hotter at depth unless precluded by intermediate/deep drilling or deep geochemical sampling. Certainly temperatures in the range of 150 °C , suitable for binary power production, are possible. We compiled a first-cut list of such systems (Table 1) as a guide for thinking about the location of future Basin and Range resource development. There are 23 undeveloped systems on the list. Most of these systems are candidates for additional detailed resource evaluation.

Resource Evaluation of Basin and Range Systems

In developing geothermal resources, determining how much energy can be commercially extracted is always a major factor. The uncertainty in this factor has significant impact on the economics of development. What is needed is an indicator of production capacity that is available at an early stage - after a system has been defined, but before development. The variables involved are numerous and have large uncertainty: producible temperatures, finding producible permeability or fractures, drilling difficulties, long term temperature and pressure drawdowns, etc.

The need for an early stage resource assessment has been obvious since the industry began. The work has been along several lines: volume calculations, planar fracture flows, heat budgets, and surface heat fluxes. Volume calculations have been the most widely employed. They involve estimating the temperature, volume and recovery factor for a geothermal system. The idea is straight forward, but volume and recovery factors are subject to large uncertainty. A fundamental problem with this method is that it treats a geothermal system as a static entity and most geothermal systems are obviously dynamic systems. In these systems, there is no reservoir in the conventional meaning of the term (implying a defined body with negligible flux). Volume calculations are the source of most of the published assessments such as the USGS assessments for the United States (Muffler, 1979). The other volume techniques have been summarized elsewhere (Wisian et al., 2001).

The surface heat flux method has obvious attractions - heat flux is a major system parameter and relates directly to the strength of the geothermal system. Previously, the surface flux has been used as a starting point in calculating the total heat stored underground to which a recovery factor is then applied (as in the volume method) to determine the producible energy (Muffler and Cataldi, 1978). While this method is theoretically sound it has large uncertainties, similar to the other methods.

The study of Wisian et al. (2001) based on substantially more development experiences since the 1970's, shows that the surface heat flux approach (treating heat loss as the sum of the convective and conductive components) has substantial utility in estimating development potential of geothermal areas. Instead of establishing a direct calculation of heat in the system and then producible energy, an empirical correlation is sought between the two end points: heat loss and production capacity. Data summarizing the electric and thermal production from geothermal systems around the world are readily available (Lund, 2000). The site specific database of thermal wells (www.smu.edu/geothermal) has been used to generate heat flow maps for geothermal systems in the western US with enough data.

In addition values for selected systems worldwide were derived from published sources. Bibby et al. (1995) compiled heat loss values for the geothermal systems in the Taupo Volcanic Zone, New Zealand. Ndolo (2000) summarized the heat losses in the Northern Kenya Rift systems, but only one system, Olkaria, produces power, and thus provides a data point.

Conductive loss at the surface is only one component of the total heat loss. Heat is also lost by radiation (usually negligible) and by fluid/steam discharge. Discharge, particularly in visibly active systems, can be a significant percentage of the total heat loss, but appears to be less than 20% in most cases. Extensive tabulations of heat loss through spring discharge are available (i.e. Garside and Shilling, 1979, Renner et al., 1975) and where possible, these values are included in the total heat loss calculations.

The energy production and total heat loss values for geothermal systems in the US are shown in Figure 5. Total heat loss values are generally minimum values. In most cases the values are probably within a half order of magnitude of actual. Though the potential errors may seem large, they do not effect conclusions. Errors in generating capacity are negligible, although there is variation in reporting standards.

If only the high quality (1 or 2 rating) data are plotted as shown in Figure 5, no systems are found to produce more than 10 times the natural output. The worldwide data are consistent with this conclusion. The data points cover three orders of magnitude in generating capacity and almost two in total heat loss. Several systems produce at almost ten times their natural heat loss (Los Azufres, Mexico, Coso, and The Geysers in California). The majority of systems produce power at less than the natural heat loss rate.

Based on limited data, early studies suggested that heat could be withdrawn at a ratio of 4 to 100 times the natural rate (White, 1965; Suyama et al., 1975). With this expanded data set, a factor of 10 appears to be a well-defined, emperical limit to power production from a geothermal system. Implicit in this relation is a planned production life of 20-30 years. Higher production can be sustained for shorter periods.

The relationship can be used to predict the capacity of unexploited systems. In Figure 6 the possible generating capacity of a number of Basin and Range systems with heat loss estimates is plotted at an assumed value of 5 times the natural heat loss. These are currently undeveloped areas that have geothermal potential. One of the difficulties in determining a heat loss for areas with few wells is estimating the surface size of the system for the heat flow portion of the calculation. Some areas have more than one listing to represent diverse forecasts in size.

The above discussion assumes that the geothermal system is produced "as is", with no stimulation beyond the usual reinjection. Enhanced Geothermal System (EGS) techniques offer the potential to push production above the "normal" limit (Robertson-Tait and Lovekin, 2000).

This relationship has potential as a predictive tool early in the exploration or development phase of a geothermal project. Shallow temperature gradient surveys are relatively inexpensive, and are a direct measure of the target (heat). The ability to set at least an upper limit on production early in development can reduce the uncertainty and risk in an inherently risky business.

Technology Transfer/Collaborations

The results were presented at the GRC annual meeting, other national and international meetings and are being prepared for submission to other professional journals. The geothermal gradient/heat flow regional database can be downloaded from the web site www.smu.edu/geothermal. A total of almost 6,000 sites are in the geothermal database. Over 2,500 sites are contained in the regional thermal database.

The research phases so far have involved close industry collaboration. Initially interaction was with both Oxbow and Caithness Corp., who funded the geophysical studies that were the foundation for the early phases of this project. Close collaboration continues with Caithness Corp., now the sole owner of the larger Dixie Valley producing area.

During the past couple of years additional exploration has occurred in geothermal systems at Rye Patch, Nevada and Animas, New Mexico. Both these areas appear to structurally resemble Dixie Valley in unexpectedly close ways. Thus the Basin and Range model development described in this report has been extremely important in the success of activities associated with those projects.

Conclusions

There are reasons to be optimistic about the resource potential of the remaining geothermal areas to be explored in the western US, in spite of the lack of exploration and evaluation activity in the last 10+ years:

1. The “fault” reservoirs in Basin and Range systems are more complicated, i.e. larger than anticipated;

2. There is potential for higher temperatures than realized and the geochemical temperatures for many systems, if they are even available, are minimums;

3. There are many systems with shallow temperatures of > 80 °C but no intermediate or deep drilling;

4. The Basin and Range systems are hard to find because of the confusing surface and shallow subsurface evidence (illustrated in Figure 4) so there probably remain many undiscovered/ underevaluated systems at this time.

5. The discovery of the close correlation between heat loss in a geothermal system and the electrical power produced from it could be used as a better way to evaluate the geothermal potential of Basin and Range systems. The USGS Circular 790 approach using estimates of geochemical temperature, reservoir volume and the recovery factor has not proved very accurate and useful for exploration or resource planning and needs to be updated after 20 years.

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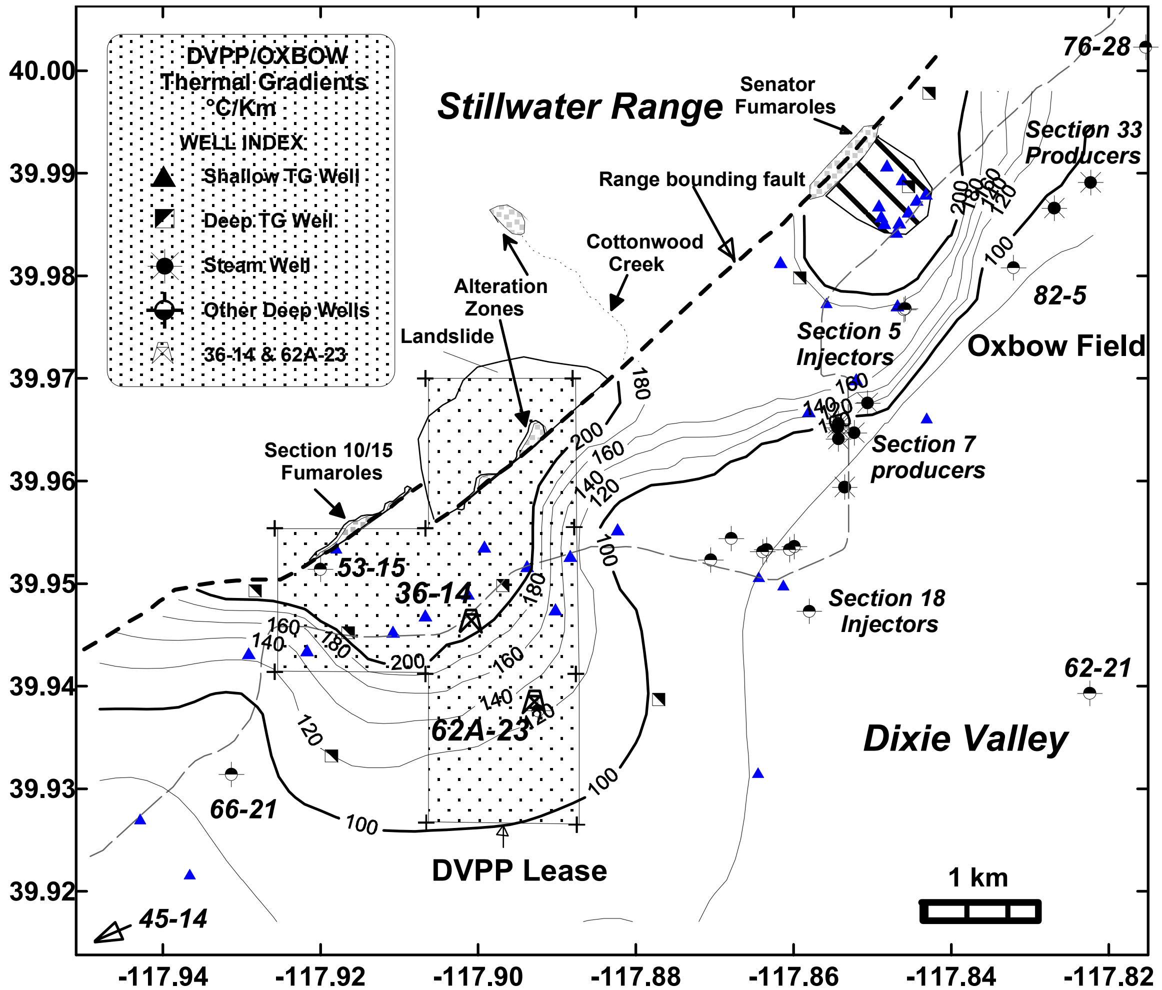

Figure 1. Index map of the Dixie Valley geothermal field. The shaded area represents the Dixie Valley Power Partners lease. The light dashed line is the county road.

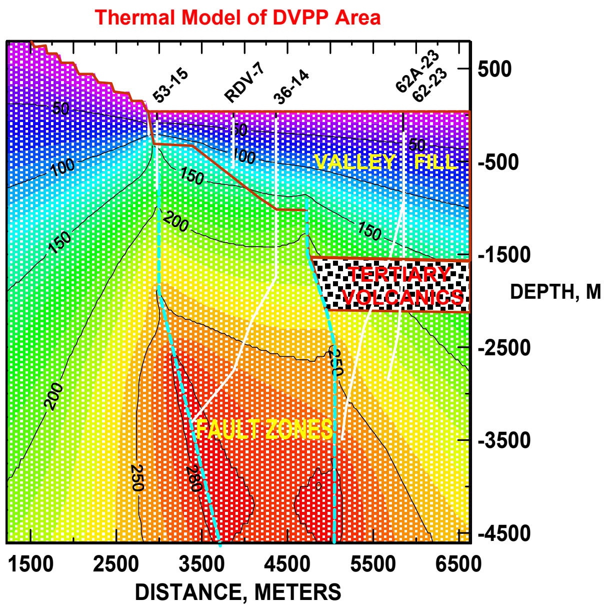

Figure 2. Thermal model resulting from Caithness exploration in Dixie Valley in 1993-1994 (Blackwell et al., 2000a, 2000b).

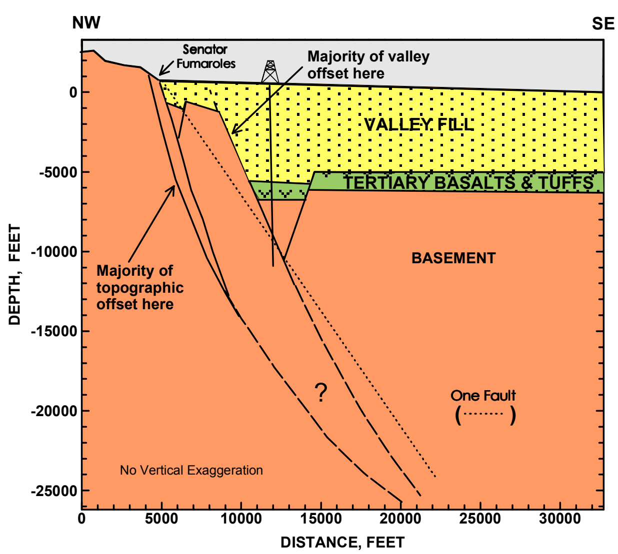

Figure 3. Idealized Dixie Valley structure model based on gravity, seismic and well data (Blackwell et al., 1999, 2000a, 2000b). The general existence of piedmont faulting (major faults outboard of the topographic scarps) and graben fractures result in larger and more complicated reservoirs then expected based on a single fault model (the dotted line).

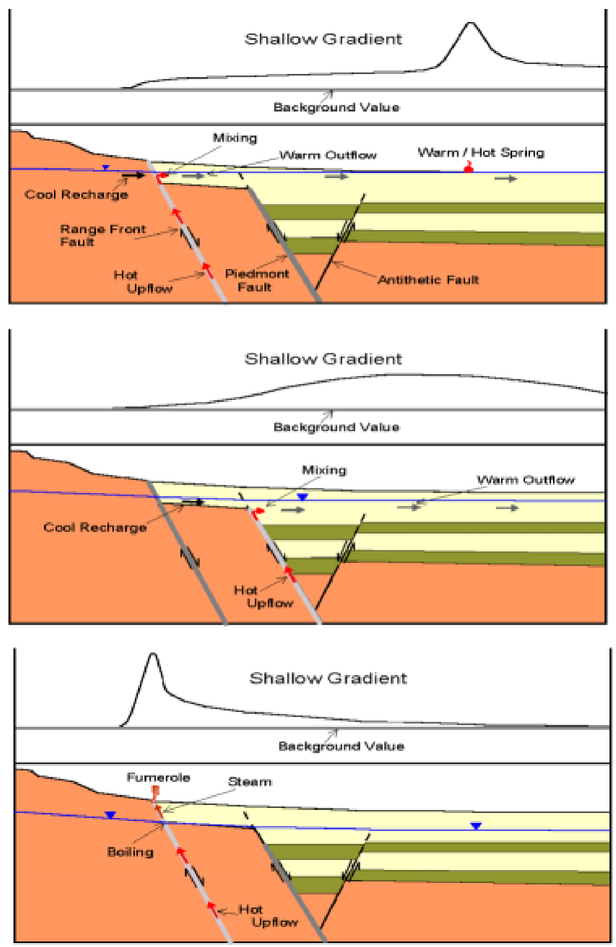

Figure 4. Characteristics of shallow thermal anomalies associated with Basin and Range geothermal systems.

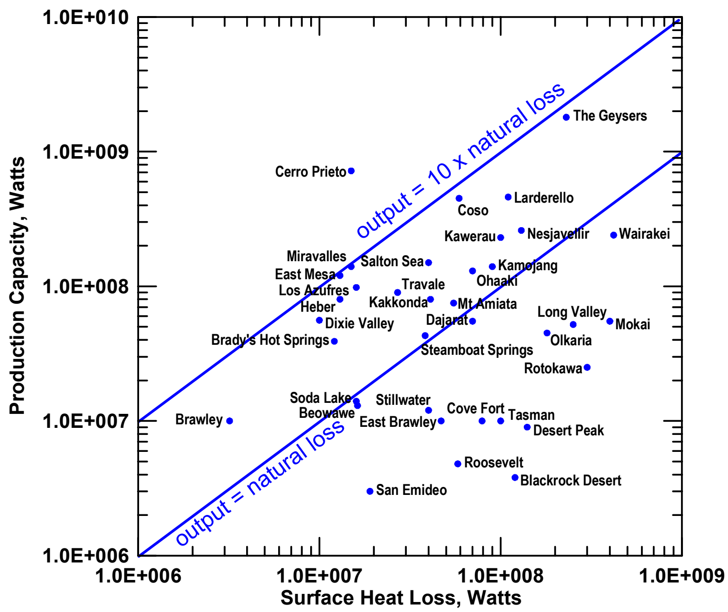

Figure 5. Comparison of heat loss and electrical power production. Cerro Prieto, Mexico is the only system above the 10X line.

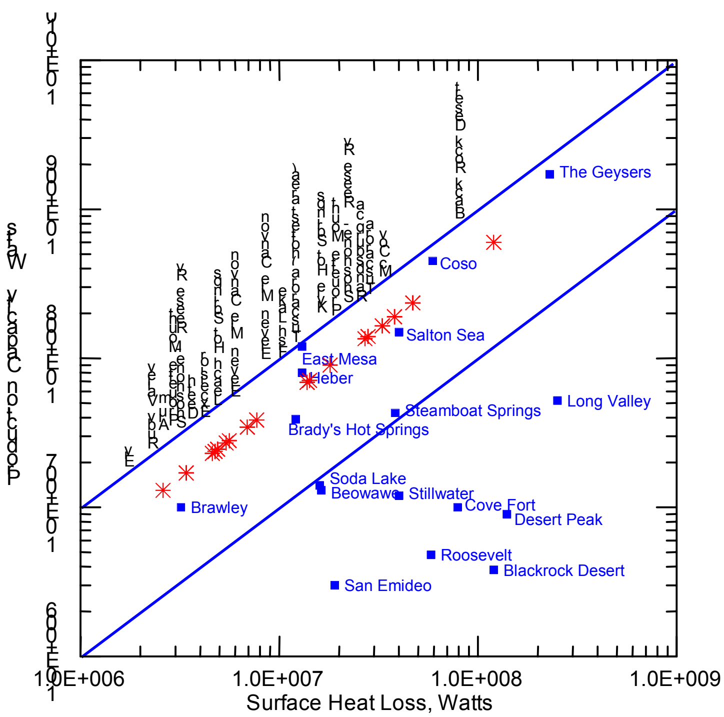

Figure 6. Predicted power production for some Basin and Range geothermal systems with heat loss numbers. A hypothetical 5X ratio is assumed. Black Rock Desert is actually a composite figure for several systems. Multiple listings of areas are from choosing different surface areas for the heat flow portion of the calculation.

Table 1. Systems in Regional Thermal Data Base with maximum temperature over 80°C. Based on the drilling results and the complicated surface manifestations in Basin and Range systems, all of the unexplored systems in the list, regardless of their geochemistry, merit additional exploration. Areas actually producing power at this time are in red.

AREA	STATE	MAX TEMP (C)	AREA	STATE	MAX TEMP (C)
Medicine Lake	CA	107	Humboldt House	NV	194
Geysers	***CA***	***360***	Leach Hot Spr.	NV	132
Salton Sea	***CA***	***355***	McCoy	NV	102
Bear RV	ID	111	Moana	NV	97
Driggs (AMS)	ID	210	Pirouette Mtn.	NV	87
Hailey (AMS)	ID	189	San Emidio Desert	NV	138
Pocatello (AMS)	ID	117	Shellbourne	NV	198
Preston (AMS)	ID	188	***Soda Lake***	***NV***	***216***
Raft RV	ID	150	***Steamboat Spr.***	***NV***	***179***
Texton	MT	90	***Stillwater***	***NV***	***177***
Marysville	MT	106	Tuscarora	NV	93
Albuquerque (AMS)	NM	343	Wells (AMS)	NV	115
Animas	NM	210	Breitenbush	OR	141
Alum	NV	91	Boise (AMS)	OR	110
Bacon Flat	NV	153	Borax Lake	OR	100
Baltazor	NV	128	Glass Butte	OR	94
Beowawe	***NV***	***216***	Klamath Falls (AMS)	OR	130
Black Rock Desert	NV	131	Lakeview	OR	103
Blue Mtn.	NV	81	Newberry Volcano	OR	344
Brady	***NV***	***212***	Vale	OR	136
Colado	NV	139	Vancouver (AMS)	OR	82
Desert Peak	NV	204	Best	UT	95
Dixie Valley	***NV***	***251***	***Cove Fort***	***UT***	***178***
Eleven Mile Canyon	NV	82	Crystal Hot Spr.	UT	83
Ruby Mtns.	NV	136	Newcastle	UT	127
Fallon	NV	191	***Roosevelt Hot Spr.***	***UT***	***268***
Fish Lake	NV	179	Thermex	UT	96
Hawthorne	NV	83			