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Thermal Regime of the Great Basin and its Implications for Enhanced Geothermal Systems and Off-Grid Power

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ABSTRACT

The Basin and Range Province of the Western United States covers most of Nevada and parts of adjoining states. It was formed by east-west tectonic extension that occurred mostly between 50 and 10 Ma, but which still is active in some areas. The northern Basin and Range, also known as the Great Basin, is higher in elevation, has higher regional heat flow and is more tectonically active than the southern Basin and Range which encompasses the Mojave and Sonoran Deserts. The Great Basin terrane contains the largest number of geothermal power plants in the United States, although most electrical production is at The Geysers and in the Salton Trough. Installed capacities of electrical power plants in the Great Basin vary from 1 to 260 MW_e. Productivity is limited largely by permeability, relatively small productive reservoir volumes, available water, market conditions and the availability of transmission lines.

Accessible, in-place heat is not a limiting condition for geothermal systems in the Great Basin. In many areas, economic temperatures (>120 °C) can be found at economically drillable depths making it an appropriate region for implementation of the concept of "Enhanced Geothermal Systems" (EGS). An incremental approach to EGS would involve increasing the productivity and longevity of existing hydrothermal systems. Those geothermal projects that have an existing power plant and transmission facilities are the most attractive EGS candidates. Sites that were not developed owing to marginal size, lack of intrinsic permeability, and distance to existing electrical grid lines are also worthy of consideration for off-grid power production in geographically isolated markets such as ranches, farms, mines, and smelters.

Introduction

The Great Basin of the southwestern United States (Figure 1) was the focus of concerted exploration and leasing activity by the geothermal power industry beginning in the 1970's. Phillips Petroleum Company and Chevron Geothermal together evaluated more than 75 geothermal prospects with a potential for accessible temperatures of 150 °C or greater. More than 25 additional sites were assessed by other companies, bringing the total number of potentially high-temperature sites evaluated by industry to more than 100. The majority of the thermal data from the Chevron/Phillips projects is now in a data base held jointly by the Idaho National Environmental and Engineering Laboratory (INEEL) and USGS. These data provide much of the information upon which our assessments and conclusions are based.

By 1985, more than 16 geothermal systems and reservoirs were discovered in the Great Basin with measured temperatures of >150 °C (Edmiston and Benoit, 1985; Benoit and Butler, 1983). In the ensuing decade beginning in the early 1980's, fourteen hydrothermal power plants with a combined installed capacity of over 500 MW_e came on-line (Benoit, 1994). Since then, market conditions and deregulation have combined to severely limit new plant construction, and some projects are experiencing declines in reservoir pressures.

With the completion of the Fenton Hill "Hot Dry Rock" (HDR) project, the U.S. Department of Energy (DOE) has shifted its emphasis from engineered reservoirs in impermeable rock to an incremental approach that will first demonstrate how to enhance the productivity/longevity of the marginal and nonproductive parts of hydrothermal systems. A new definition, "Enhanced Geothermal Systems" (EGS), has been introduced by DOE to characterize all but the highest productivity parts of these systems (Carwile and Entingh, 1998). In practice, EGS provides the opportunity to combine elements of DOE's HDR and Reservoir Technology programs. Another term, "Hot Fractured Rock" (HFR) is being used to describe all geothermal systems for which injection is an integral part of the energy-production cycle (Shell International Exploration and Production B.V. Geothermal Team, personal communication). In this paper, we examine the thermal regime of the Great Basin to provide a regional context within which to identify appropriate HFR and EGS prospects.

Thermal Regime of the Southwestern United States

Figure 1 is a generalized map of heat flow in the Great Basin and surrounding areas. The region is one of generally high heat flow with large areas of both low (<60 mW m^{-2}) and very high (>100 mW m^{-2}) heat flow relative to the modal value of about 80 mWm^{-2} for the southwestern United States (Sass *et al.*, 1996). The Sierra Nevada range represents a transient heat sink related to Miocene subduction beneath the range. The Eureka Low (EL Figure 1) is a hydrologic heat sink resulting from inter-basin flow of water in the carbonate rocks of east central Nevada (Lachenbruch and Sass, 1977; Winograd and Thordarson, 1975).

More than 200 determinations of regional heat flow have been made in the Great Basin (Figure 2). There are some significant gaps in thermal coverage (e.g., northeastern Nevada), but the overall regional picture is reasonably well documented. The regional heat flow control of the Great Basin was augmented in 1998, by the acquisition of data from more than 500 thermal gradient holes acquired from CalEnergy by the DOE through the Idaho National Environmental and Engineering Laboratory (INEEL). The discussion that follows is based on a combination of regional heat flow data previously assembled by the USGS and others (Blackwell *et al.*, 1991; Sass *et al.*, 1996) and a preliminary interpretation of data recently acquired from CalEnergy and other industry sources which can be found on a USGS Internet site, the address of which will be available at the GRC Annual Meeting.

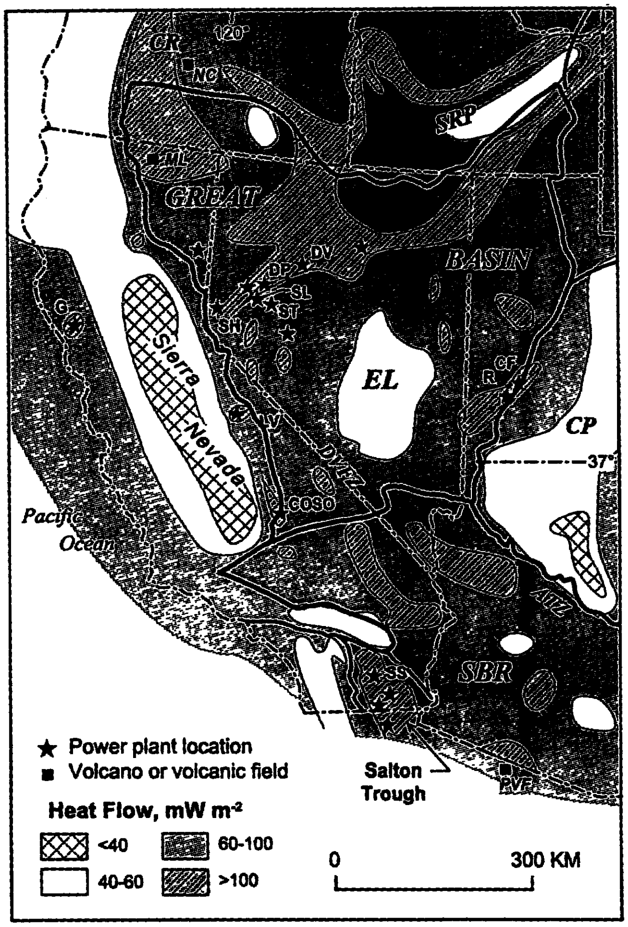

Figure 1. Heat flow of the Great Basin and surrounding thermal provinces. Abbreviations: CR, Cascade Range; SRP, Snake River Plain;EL, Eureka Low; SBR, southern Basin and Range; CP, Colorado Plateau; ATZ, Arizona Transition Zone; DVFZ, Death Valley fault zone; NC, Newberry Crater; ML, Medicine Lake Volcano; G, the Geysers; SS, Salton Sea; PVF, Pinacate Volcanic Field; Great Basin power plant abbreviations as in Table 2.

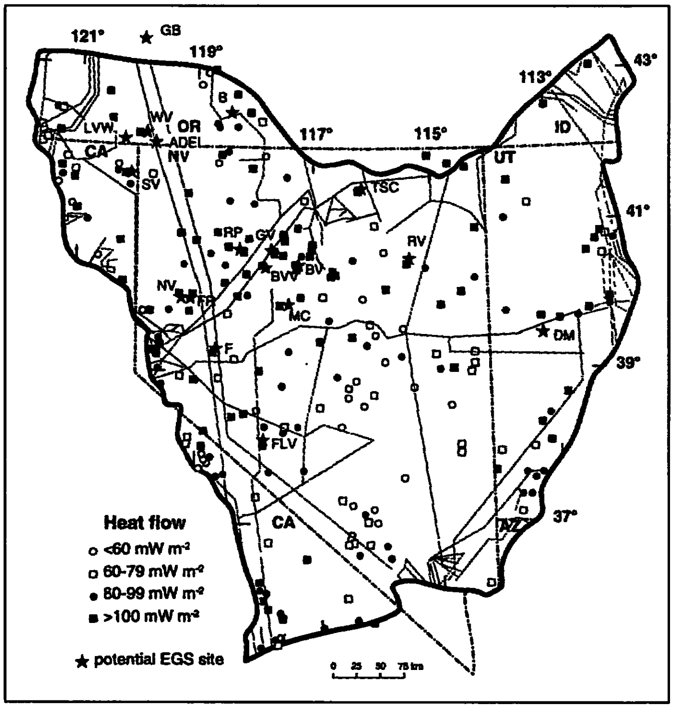

Figure 2. Sites of regional heat-flow determinations in the Great Basin. Screened lines show power grid. Labeled stars are locations of potential EGS sites presently not developed. Abbreviations as in Table 3 and the text.

Table 1. Mean Heat Flows from the Basin and Range Province

Province	Number of Sites	Mean Heat Flow, mW m-2	Mean Elevation m
Entire Basin & Range	440	92±4	1214±57
Great Basin	223	100±7	1614±64
Southern Basin & Range	217	83±4	910±62

The southern Basin and Range (SBR, Figure 1) is a granitic basement terrane of low relief and elevation compared to the Great Basin (Sass *et al.*, 1994: Lachenbruch *et al.*, 1994). Its mean heat flow is significantly lower (Table 1) than the Great Basin and it has been tectonically quiescent for the past 10 million years. All of the operating geothermal power plants in the Basin and Range Province are in the Great Basin (Figure 1). All of the active prospects are also found in the Great Basin, but there are three areas in the southern Basin and Range that may hold some prospect for geothermal development, particularly of the HFR-EGS variety. These include: the boot-shaped high heat flow area forming the southern extension of the Death Valley fault zone (DVFZ, Figure 1); the high heat flow zone associated with the western part of the transition zone between the Sonoran Desert and the Colorado Plateau (ATZ); and the high heat flow associated with the Pinacate Volcanic field (PVF) in Sonora, Mexico.

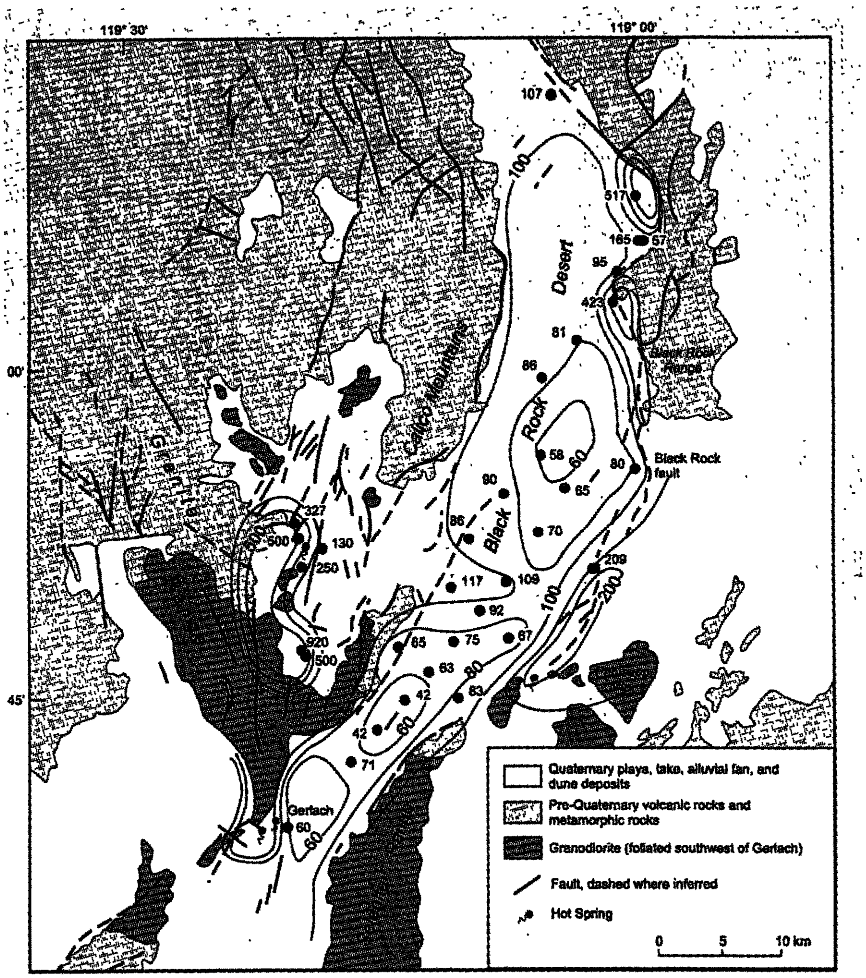

Figure 4. Heat Flow (in mW m^{-2}) near the Black Rock Desert, northwest Nevada (from Mase and Sass, 1980)

The high heat flow areas of the Great Basin have sufficiently high temperatures at drillable depths to provide fluids to geothermal power plants given sufficient permeability. The temperature profiles of Figure 3 are highly idealized in that they assume a uniform conductive heat flow from both basement rock and valley sediments. They are nevertheless useful in defining the range of average temperatures to be expected at a given depth, depending on the sediment thickness. Economics currently limit the depth of accessible reservoirs to about 3 km (~10,000 ft). Under those circumstances, temperatures of between 150 and 250°C in many areas of the Great Basin are accessible (Figure 3).

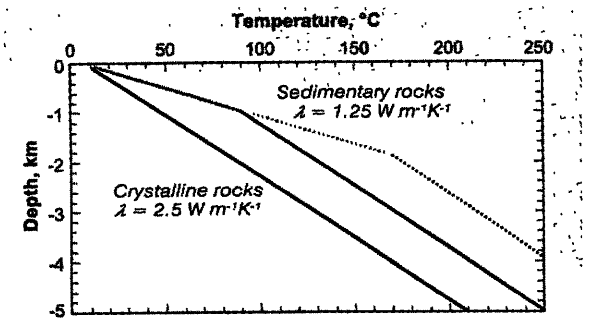

Figure 3. Idealized Temperature Profiles for average Great Basin heat flow of 100 mW m^{-2} (see Table 1). Leftmost curve is for outcrop; to the right are temperature profiles for 1 km (solid lines) and 2 km (dotted lines) of sediments (Conductivity 1.25 W m^{-1} K^{-1}), respectively.

The local heat flow situation in the Great Basin is often much more complicated than that suggested by Figure 3. Within most of the alluvial basins, the conductive thermal regime is modified by convection of both thermal and cold meteoric waters in the valley sediments, the underlying basement rocks, and the normal faults that bound the ranges. An example of a well-studied area is the Black Rock Desert (Mase and Sass, 1980). The complicated, shallow thermal regime of the Black Rock Desert is typical of other basins within the Great Basin. Here, the lowest shallow heat flow is in the central portions of the valleys and associated with the convection of cold meteoric waters. The highest shallow heat flow is adjacent to the range fronts and their associated faults up which thermal water is rising. Within and adjacent to the 100 mW m^{-2} contour (Figure 4), which characterizes regional heat flow, are heat-flow lows and highs with lateral dimensions of 5 to 10 km. The localized highs, which approach 1 W m^{-2}, provide targets for further exploration and assessment.

High Heat Flow and Extensional Tectonics

Lachenbruch and Sass (1978) analyzed the heat flow in the Basin and Range province in terms of extensional processes involving a combination of stretching and both underplating and intrusion of continental lithosphere by basaltic magma. Steady-state extensional models indicated that elevated heat flows were associated with extension rates of several percent per million years, consistent with observed displacements on normal faults and other indicators of extension. The fact that most Great Basin geothermal power plants are found in areas of high heat flow (Figure 1) and tectonic extension is not accidental. The high heat flow provides high temperatures at relatively shallow depths, and extension provides fracture permeability that allows concentration of geothermal fluids by convective processes (Wisian *et al.*, 1999). Active extension over much of the northern Great Basin also provides a mechanism for maintaining productive fractures by breaking rocks that would otherwise be healed by the precipitation of secondary minerals, primarily calcite and silicates, from circulating hydrothermal fluids.

It is noteworthy that there is a rotation of the azimuths of the ranges and tectonic trends within the Great Basin from north-south in eastern Nevada to northeast-southwest in northwestern Nevada. The largest number of geothermal areas in the western US are roughly aligned along a geothermal "fairway" between Steamboat, Nevada and the northeast corner of Nevada (Figure 1). This "fairway" is within the northeast-trending tectonic terrane and marginal to the transition between the north-south and northeast-southwest tectonic terranes (see e.g., Zoback, 1989).

Criteria for Selecting Enhanced Geothermal Systems

Based on a series of workshops since 1994, there is a strong consensus among industry, academic and government geothermal groups that geothermal technology and research should evolve in an incremental manner that takes advantage of efficiencies in all aspects of geothermal development. The competitive position of geothermally generated electric power can be enhanced by a combination of cost-effective drilling strategies and technology, improved conversion efficiency, and the use of injection to extend both the productivity and longevity of hydrothermal systems. We have demonstrated that many areas of the Great Basin are suitable for geothermal development, but the consensus approach demands that early EGS extend what has already been achieved by industry and its research partners. At an EGS workshop held in conjunction with the annual DOE Geothermal Program Review in April 1998, a general list of site-selection criteria was developed. Those criteria were summarized and discussed by Sass and Robertson-Tait (1998) and by Robertson-Tait and Sass (1999). They are:

Proximity to established resources – The experiment should be performed at a site with an existing generating facility and transmission line access to a market, enabling any enhancement of the resource to be translated immediately into available power, even if it simply makes up for a declining resource.

Commercial viability – To demonstrate the competitiveness of EGS, the site should be one from which additional power would find a ready market.

Accessibility – The site should be close to major roads, commercial services and housing, to lower startup and project costs, and to facilitate participation by a variety of interested parties, including operators of other potential EGS sites and international observers.

Availability of existing, low productivity wells – A major cost factor at existing hydrothermal plants is the relatively large number of wells, or legs of wells that do not have commercial grade permeability. One of the primary aims of EGS is to find ways to turn these liabilities into assets.

Availability of water for injection: This is particularly important in the arid conditions characteristic of the Great Basin. Any hot fractured rock system will require that produced water be replenished and supplemented to enhance the natural productivity of the system.

Well-characterized reservoir: Early, public-private partnerships in EGS should endeavor to establish general principles widely applicable to other sites. The first sites should not be overly complex or unique, geologically and structurally. Their hydrologic and stress regimes should also be well-characterized. Large amounts of geological, geochemical, geophysical, and reservoir test data are already in the public domain for the EGS sites listed in Table 2 (Benoit and Butler, 1983). Much of the proprietary data for most of the undeveloped, prospective sites in Table 3 could be made available at modest cost.

Extensional stress regime – The engineering problems associated with enhancing permeability of natural systems, particularly breakdown and injection pressures required, are much less daunting in an extensional tectonic environment than in compressional or strike-slip regimes. For the Great Basin, no other stress regime is likely to be encountered.

Table 2. Power Plant Sites with EGS Potential in the Great Basin

Reservoir	Net MW	Area> 150 mW m^{-2}(km^2)	q_{max}(mW m^{-2})
Coso	260	120	800
Cove Fort (CF)	10	160	800
Desert Peak (DP)	12	300	300
Dixie Valley (DV)	56	250	330
Long Valley (LV)	40	80	500
Roosevelt (R)	23	100	1000
Soda Lake (SL)	12.5	100	2500
Steamboat (SH)	42.5	80	800
Stillwater (ST)	12	120	850

Potential EGS Sites

Shallow and intermediate-depth temperature gradient holes (100 – 500m.) are the most direct means of determining if a high-temperature geothermal reservoir is present. All high-temperature geothermal sites in the Great Basin have been delineated or discovered by this method. The problem is that the presence of a high conductive heat flow above a reservoir does not nec-

Table 3. EGS and off-grid geothermal power prospects in the Great Basin

Prospect	Area> 150 mW m^{-2} (km^2)	q_{max} (mW m^{-2})
Borax Lake (B)	50	1000
Buffalo Valley (BV)	200	500
Buena Vista Valley (BVV)	40	280
Drum Mountains (DM)	500	400
Fallon NAS (F)	150	1000
Fireball Ridge (FR)	40	250
Fish Lake Valley (FLV)	100	300
Glass Buttes (GB)	200	500
Grass Valley (GV)	40	1000
McCoy (MC)	75	500
North Valley (NV)	80	600
Ruby Valley (RV)	30	400
Rye Patch (RP) (Humboldt House)	100	250
Surprise Valley (SV)	50	300
Tuscarora (TSC)	100	400
Warner Valley (WV)	50	700

essarily delineate the high temperature reservoir at depth. A problem with most of the Great Basin geothermal sites is that high-temperature water rises along range front faults and discharges into adjacent valley sediments creating a shallow and broad thermal plume that, if misinterpreted, greatly exaggerates the size of the potential high-temperature reservoir. Temperature reversals at depths less than 300m are common below geothermal discharge plumes. Therefore, distinguishing between a shallow discharge plume and a deep, high-temperature source requires information in addition to that which is widely available today.

In their paper outlining the thermal setting of The Geysers, Walters and Combs (1992) identified an area of some 750 km^2 with heat flow greater than 4 HFU (168 mW m^{-2}) as the Geysers-Clear Lake thermal anomaly. The producing Geysers well field encompasses about 10% of the thermal anomaly and where the electrical power plants are located, the heat flow exceeds 300 mW m^{-2} with 500 mW m^{-2} or higher being typical. Many other highly productive geothermal fields, including Coso and the Salton Sea, typically have heat flow of 400 mW m^{-2}or more within the productive portion of the reservoir. An evaluation of 15 commercially producing geothermal fields throughout the world (M. A. Walters, unpublished analysis) indicates that sustained (10-year) production rates of 10 to 30 MW$_e$ km^{-2} are produced from the developed well fields in these systems. While there is no simple relation between the area of elevated heat flow and the size of the potential resource, the heat-flow data afford an objective basis for the comparison of individual sites. Thus, for the sites that we discuss and present in Tables 2 and 3, a summary of the area and magnitude of elevated heat flow based on information now in the public domain indicates that these sites have a potential to produce commercially viable amounts of energy. It should be emphasized that proprietary data still held by operators or others could change these numbers significantly. We slightly changed the baseline used at The Geysers by adopting the value of 150 mW m^{-2} as the outer limit of a thermal anomaly. Because the production field within any developed geothermal area is small compared to the thermal area, and because no small thermal anomaly is known to be commercially viable, the size of a thermal anomaly surrounding a commercially productive geothermal system is large. If only 5 to 10% of the area in each of geothermal sites listed in Tables 2 and 3 with heat flow values exceeding 300 mW m^{-2}, were productive, the electrical generation from any well field would exceed 25 MW$_e$ (M.A.Walters, unpublished).

As part of site specific studies in the Great Basin, Imperial Valley, and the Great Central Valley of California, the USGS acquired several hundred values of thermal conductivity for sedimentary basins. These were high-quality determinations either *in situ* (Sass *et al.*, 1981), or using the line source "needle probe" (Sass *et al.* 1984) on fresh cores in the field. A remarkably consistent data set was obtained. In summary, conductivity values from clay-rich playa sediments averaged about 1.1 W m^{-1} K^{-1}, while those from alluvial valleys averaged about 1.4 W m^{-1} K^{-1}. This allowed us to convert temperature gradients obtained by industry sources in these lithologies to plausible estimates of heat flow. The first step was to convert the gradients in °F/100 ft to °C/km by multiplying by 18.22. To convert temperature gradient to heat flow in mW m$^{-2,}$ we further multiplied by the average thermal conductivity. We used rounded numbers 20 and 25 as conversion factors from gradient (°F/100 ft) to heat flow (mW m^{-2}) for playas and alluvial valleys respectively (1 °F/100 ft =18.22 °C/km X 1.1 ~20, X1.4 ~25). At those localities where data were available, we used the measured thermal conductivity to estimate heat flow.

In Table 2, we have limited the initial EGS site selection to those sites that have a significant potential as indicated by their present installed capacity (a minimum of ~10 MW), where most of the criteria enumerated above are satisfied, and where the areal size of the thermal anomaly together with the maximum heat flow indicate yet undeveloped geothermal resources. Apart from the size criterion, uniquely complex sites like Beowawe and Brady's were omitted from consideration. Brief comments on individual sites follow:

Coso, California – This is one of the Great Basin hydrothermal systems that is clearly and unequivocally derived from an intrusive heat source and its wells produce associated magmatic gas. Presently producing about 260 MW after almost ten years of production, it accounts for about half of the electricity generated from geothermal sources in the Great Basin. Sustaining long-term production at Coso is partially dependent upon injection strategies that maximize the return of spent brine from injection wells at the periphery. Several DOE-sponsored studies of fracture orientation and tracer returns are now underway in an attempt to determine how peripheral injection benefits the production portion of the well field.

Cove Fort, Utah – The Cove Fort field is located near the east-central margin of the Great Basin. Hot wells have been drilled into impermeable zones there, which make it a candidate for EGS.

Desert Peak, Nevada – The Desert Peak system was the first commercial "blind" geothermal area. It was discovered primarily on the basis of thermal gradient drilling. The size and intensity of the near-surface thermal anomaly (Benoit and Butler, 1983) compared to the size of the developed production field make it an excellent candidate for expansion and an EGS candidate.

Dixie Valley – The Dixie Valley field is located in a seismic gap between two major 20th Century earthquakes in the Nevada Seismic zone. There is evidence that continued movement along the Stillwater fault zone (within which the reservoir resides) is responsible for the high productivity of some fractures encountered by production wells. Interspersed among productive wells and on the margins of the known field are high temperature wells and well legs with low permeability. The Dixie Valley field is the object of a cooperative industry/government/university study of stress and fractures (Barton *et al.*, 1997; Hickman and Zoback, 1997) and injection tracer studies (Rose *et al.*, 1997) which may lead to the design of an EGS strategy for increasing productivity. In addition, the operator is injecting shallow ground water to boost reservoir pressure.

Long Valley, California – This is a classic silicic caldera associated with contemporary seismic and historic volcanic activity. The current power plants are near Casa Diablo Hot Springs, and exploit a shallow moderate-temperature aquifer associated with lateral flow from the west moat of the caldera. Both commercial and scientific drilling on the resurgent dome have failed to reveal a high temperature energy source there. The lack of hydrothermal manifestations associated with zones of presumed magmatic activity indicate low-to-no permeability and promise an opportunity for EGS if a shallow heat source is discovered. The consensus of most investigators is that further commercial geothermal development will come from the western part of the caldera, where there is evidence of shallow magma.

Roosevelt, Utah – The reservoir here is within a large area of elevated heat flow on the east side of range-bounding NNE-trending normal faults. The heat source may be intrusive and associated with nearby Quaternary rhyolite domes. Permeabilities in the footwall block of the fault are low as in most fault-controlled geothermal systems. Permeability enhancement and injection into the hot, low permeable portions of the fault footwall should be considered.

Soda Lake, Nevada – This is a reservoir in which the natural temperature enhancement seems to be accomplished primarily by deep circulation beneath an insulating layer of playa-type sediments. A narrow NNE-trending graben apparently controls upwelling thermal fluids and Quaternary basalt eruptions. As at Desert Peak, the resource was initially defined by temperature-gradient holes. High-temperature, low permeability wells within this reservoir provide opportunities for enhancement.

Steamboat, Nevada – The Steamboat reservoir is another reservoir that seems to be associated with a young-to-contemporary igneous intrusion, although the actual heat source remains enigmatic. Here, non-productive wells interspersed among those providing fluid for the power plants indicate a good potential for reservoir enhancement. Faults appear to control the location of the known reservoir.

Stillwater, Nevada – The large size of the thermal anomaly (Morgan, 1982) indicates a substantial potential for enhancement. As previously discussed, a large thermal anomaly appears to be a prerequisite for a commercial geothermal system, and given the large size of the Stillwater anomaly alone, this site deserves consideration as a candidate for enhancement.

Other Prospective EGS and Off-Grid Geothermal Project Sites

Deregulation of the electric power industry has discouraged development of new power plants. For the foreseeable future, it is apparent that new power generation facilities will be constructed close to the existing electrical transmission grid system and sell power at rates competing with all sources of energy including gas and coal. Those geothermal projects described above and in Table 2 were constructed and amortized during a period of guaranteed premium prices, can deliver power at competitive rates now, and could sell additional power if it were available. Almost certainly the initial systematic reservoir enhancement projects in the Great Basin will occur within this group of existing facilities. On the other hand, there are prospects that have not been developed because of marginal size relative to economies of scale or productivity. If the permeability or reservoir size can be enhanced significantly using what is learned from initial EGS studies, some of these prospects can be brought on line in the future. The major hurdle in most cases will be the availability of water. Deregulation and improvements in geothermal technology (e.g.; slim holes, modular power units) also brings with it the possibility that small, off-grid geothermal power plants will achieve competitive status in remote areas against alternatives such as diesel power in specific markets in the Great Basin similar to those envisioned for developing nations.

CalEnergy Operating Co.(now a MidAmerican subsidiary) recently announced the construction of a metals recovery project from its geothermal brines at the Salton Sea. Here, a portion of the geothermal power from a new 49 MW power plant will be used to power the zinc recovery program. This represents an off-grid use of geothermal power for a very localized market and demonstrates the synergy in the use of geothermal systems in producing power for mining and smelting. Several proprietary studies made for industry in the mid-1980's show that there are local markets for geothermal power, especially for mining projects scattered throughout the Great Basin. There is a spatial relationship between the occurrence of gold deposits, oil shows and geothermal areas (e.g.; Hulen *et al.*, 1999). Examples include the Florida Canyon gold mine in the Humboldt House prospect (see Table 3) where shallow warm geothermal water is already used to improve leaching efficiency (Alex Schriener, oral communication), and the Blue Mountain prospect spatially associated with an active geothermal system (Parr and Percival, 1991). Future gold and other mines in the Great Basin might benefit from off-grid power from local geothermal developments. With deregulation, geographically isolated agricultural areas and towns may also benefit from geothermal power as the low-cost alternative. Other localized markets include military installations, and during the MX Missile siting program temperature gradient holes were routinely drilled. Figure 2 and Table 3 indicate prospects with high heat flow and their location relative to the existing Western States Power Grid. Two additional sites not tabulated because of lack of data in our possession (Figure 2) are Lakeview (LVW) and Adel in southern Oregon (Dick Benoit, personal communication). It remains to be seen how many of these can be developed, but new technology and a changing market structure should eventually result in many of them realizing their thermal power potential.

Conclusions

Accessible, in-place heat is not a limiting condition for geothermal systems in the Great Basin. The sites listed in Tables 2 and 3 should be further studied and assessed for their EGS potential so that when market conditions improve, these sites will be available for bringing additional power on-line. Here there are numerous existing developments and explored prospects that could add as much as 1000 MW to the US geothermal portfolio. At the very least, application of appropriate EGS technology can slow or even reverse production declines at some sites.

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Endnote

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