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POTENTIAL FOR "ENHANCED GEOTHERMAL SYSTEMS" IN THE WESTERN UNITED STATES

John H. Sass
U.S. Geological Survey
Flagstaff, Arizona 86001 USA

Ann Robertson-Tait
GeothermEx, Inc.
Richmond, California 94804 USA

Abstract

Most presently active or contemplated hot dry rock (HDR) projects vary significantly from the original HDR concept of creating an engineered reservoir in an effectively impermeable medium. Instead, they form part of a spectrum of geothermal resources that exhibit less-than-commercial productivity, but are not completely impermeable. A new working definition, "Enhanced Geothermal Systems" (EGS), is now being used to describe all but the high-grade hydrothermal portion of the geothermal resource spectrum. To promote the commercial development of these lower permeability and/or fluid-deficient resources, EGS research and development in the U.S. during the next few years is likely to include field experiments that target hot, low permeability zones within or near the margins of commercially developed hydrothermal systems. These systems are located in areas of elevated regional heat flow (Cascade Range, Basin and Range Province, Salton Trough, California Coast Ranges and Rio Grande Rift Zone), where temperatures of 250°C can be reached at depths of 4 km or less. Potential sites for EGS experiments were identified with the objective of yielding immediate benefits to the geothermal industry while also contributing to the commercial development of an incrementally broader range of geothermal resources. On the basis of certain resource, infrastructure and social criteria, The Geysers, Salton Sea, Coso, Dixie Valley, Soda Lake, Steamboat and Roosevelt were identified as the most promising locations for increasing heat recovery by reservoir enhancement. Sites of secondary interest are Heber, East Mesa, Newberry, Medicine Lake, Puna and Cove Fort. These existing systems represent only a small fraction of the U.S. geothermal resource base but provide a unique opportunity to further the development of EGS.

Introduction

Recovering the vast reserves of geothermal energy which exist at economic drilling depths in the western U.S. is presently limited in many locations by naturally low permeability and/or low fluid content. Overcoming these natural barriers by enhancing subsurface conditions is part of the focus of geothermal research undertaken by the U.S. Department of Energy (DOE). Creating the world's first artificial geothermal reservoir in hot, impermeable basement rock at Fenton Hill, New Mexico was the focus of Hot Dry Rock (HDR) research in the United States for approximately 20 years. Given the unfavorable economics of developing a full-scale, commercial HDR project in the U.S., DOE is re-focusing its efforts to develop technology which will enable the more challenging geothermal resources to be exploited in the long term, while also achieving results immediately useful to the U.S. geothermal industry. Such "Dual-Use" research or technology may include pure research, paper studies and field experiments.

In pursuing these goals, DOE is now studying a permeability-fluid continuum of geothermal resources that range from the traditional, commercial-grade hydrothermal reservoir, through marginal hydrothermal systems, fluid-deficient systems and finally to hot dry rock (Figure 1). A new term, "Enhanced Geothermal Systems" (EGS), is now used to describe all but the commercial-grade hydrothermal portion of the continuum. As the name implies, EGS resources require enhancement to render them commercially viable.

An incremental approach to the development of EGS has been recommended by the U.S. geothermal industry. A logical step in this process would be to artificially enhance low-permeability or fluid-

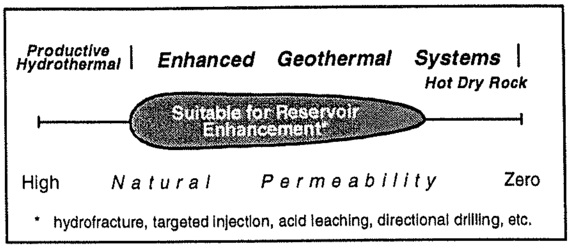

Figure 1. Diagram illustrating the fluid-permeability continuum for commercial and potentially commercial (EGS) resources.

depleted zones of presently developed geothermal systems, enabling a significant amount of previously inaccessible heat to be recovered. By performing a series of field experiments to enhance known geothermal systems, a body of knowledge will be developed which will be crucial to the advancement of EGS and the ultimate commercialization of the full range of accessible geothermal resources in the United States.

In this paper, we review the geologic setting for EGS resources, present initial criteria used for site selection, and identify and describe some of the most promising sites for EGS experiments.

Regional Heat Flow in the Southwestern United States

The entire southwestern part of the U.S. (Figure 2) is characterized by heat flow higher than 60 mW m^{-2}, with the exception of zones of low heat flow caused by tectonic transients (*e.g.*, the Sierra Nevada) or regional hydrologic transport (*e.g.*, the Eureka Low). The zones of highest heat flow are generally associated with extensional tectonics and associated magmatic activity (Lachenbruch and Sass, 1978). Some high heat flow areas are clearly associated with young-to-contemporary volcanism, whereas others probably reflect mid-to-lower crustal magmatism related to recent or active extension. The high heat flow zones of Figure 2 will afford conductive gradients that result in formation temperatures exceeding 150°C at economically drillable depths (Figure 3). At actual or prospective hydrothermal sites, these conductive gradients are often enhanced by convective heat flux in fault zones or permeable strata.

All of the presently operating geothermal power

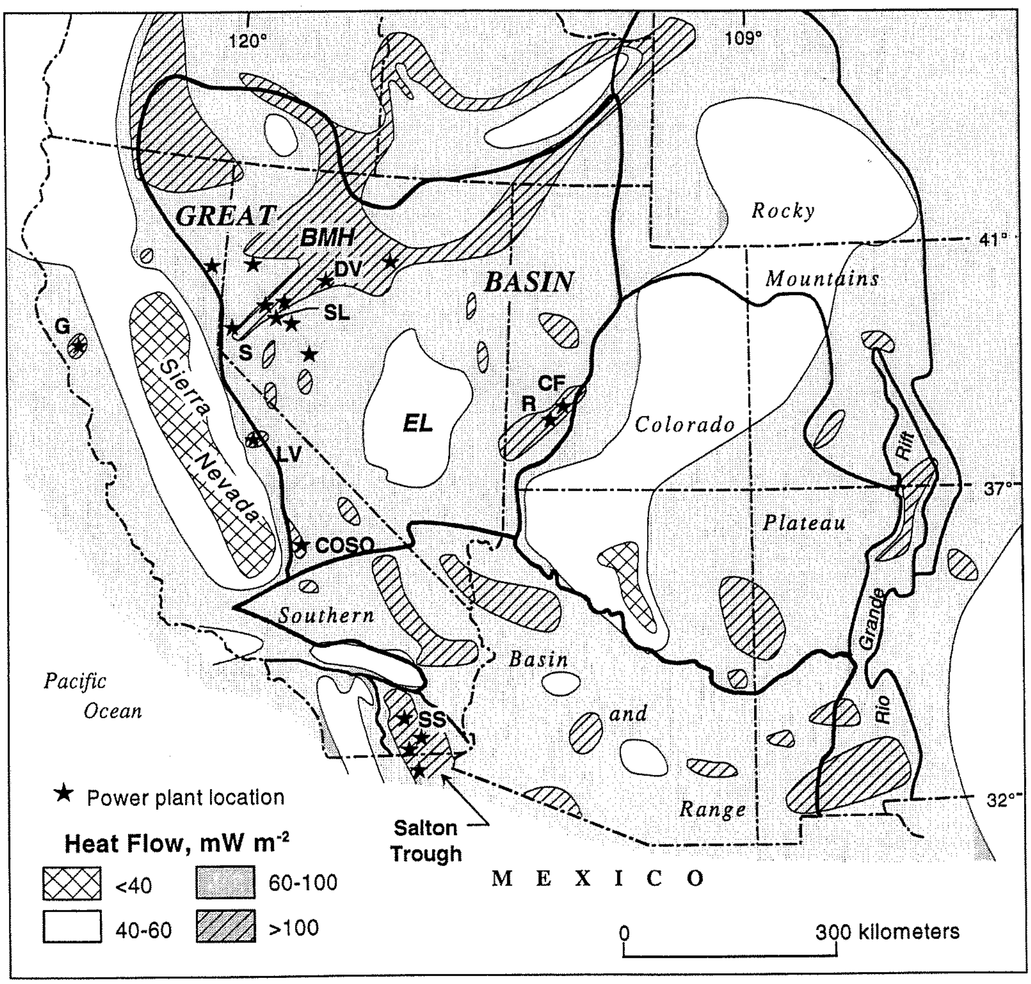

Figure 2. Heat flow in the Great Basin and surrounding terrains together with locations of presently operating power plants. Locations discussed in the text are identified. BMH, Battle Mountain High; EL, Eureka Low; DV, Dixie Valley; SL, Soda Lake; S, Steamboat; G, The Geysers; LV, Long Valley; CF, Cove Fort; R, Roosevelt; SS, Salton Sea.

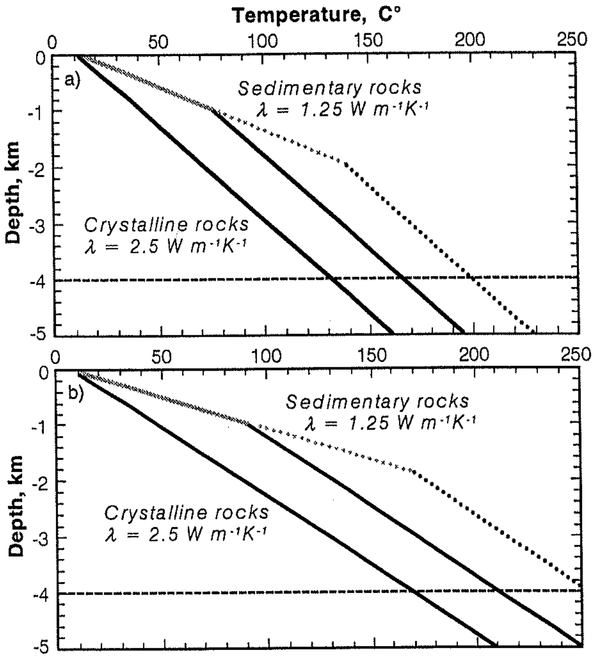

Figure 3. Idealized conductive temperature profiles for the Great Basin, illustrating the thermal blanketing effect of 1 and 2 km thicknesses of Basin sediments. λ, conductivity. (a) Background heat flow (80 mW m^{-2}); (b) Battle Mountain High (BMH, Fig. 2, heat flow of 100 mW m^{-2}).

plants in the United States are located in or near areas of high regional heat flow (> 100 mW m^{-2}) in California, Nevada, and Utah (Figure 2), and in Hawaii. Typically, the sites are also characterized by local shallow heat-flow anomalies with values reaching 500 mW·m^{-2} or more. Although the greatest number of geothermal-supplied power plants are found in the Great Basin, most of the power generated from geothermal resources comes from The Geysers (G, Figure 2) and the Salton Trough.

Criteria for Site Selection

An EGS Dual-Use workshop was held at the annual DOE Geothermal Program Review in April 1998 to identify EGS research and development directions. Among the topics discussed was EGS site selection criteria. Some of the criteria are resource-related, and others involve either infrastructure or social issues. By far, the most important of the social issues is support for the project from the public at large and the geothermal industry, to ensure that the short- and long-term goals of the EGS program are being met, and that the public perceives the societal benefit.

In developing the selection criteria, the assumption was made that a stand-alone EGS project is not economically feasible in the U.S. at this time. Therefore, in order to use the heat recovered as a result of the EGS experiment, some infrastructure must be present. The infrastructure criteria include:

- Proximity to an established hydrothermal resource with an existing generating facility and transmission line access, enabling the additional heat recovered to be immediately useful.
- Commercial relevance; *i.e.*, a site from which additional power or hot water could be sold at competitive prices.
- Accessibility by road, with nearby commercial services and housing.

Resource-related criteria include:

- Low permeability; *i.e.*, a system in which low productivity wells or legs are interspersed with productive ones.
- Availability of water for injection, as injected water will be the means of recovering additional heat from the reservoir.
- Availability of existing wells for experimentation. The need to drill new wells could be obviated by using dry holes drilled during exploration, perhaps at the margins of the reservoir, or dry legs of wells within the reservoir proper which were later successfully redrilled.
- A well-characterized reservoir, preferably of a single lithology, with well defined hydrology, boundaries and stress / fracture regimes.
- An extensional stress regime, which would provide lower breakdown and injection pressures than compressional or strike-slip regimes. However, the difficulties of the extensional regime include containing injected fluid (far field losses) and avoiding short circuits to existing production areas.

Based on these criteria, it is likely that the first candidates for EGS field experiments will be geothermal fields with existing power plants. We have categorized potential sites as primary (those which meet all of the above criteria) and secondary (those which meet most). It is envisaged that the field operator would propose an EGS experiment and share the costs of experimentation with DOE. Jointly, DOE and field operator would develop criteria to measure the benefit of enhancement, and the results would be incorporated into a database of information that would be used to further the development of EGS in the U.S. and around the world.

Descriptions of Primary Sites

The Geysers, California

The Geysers steam field in northen California is the longest operating and most productive geothermal development in the U.S. In the láte 1980s, after 30 years of production, developers discovered that although the pressure and productivity of the reservoir was declining, most of the *in situ* heat remained. The reservoir was slowly becoming a fluid-deficient EGS, and industry responded by enhancing production through augmented injection.

Unocal was the first to augment injection on a large scale by injecting water withdrawn from creeks and rivers during the rainy winter season. Operators routinely collect and inject surface water runoff from their respective plant sites. More recently, a pipeline was completed to transport 2.7 million pounds per hour (340 kg/s) of treated wastewater and Clear Lake water up to The Geysers. The water is divided among three geothermal operators (Unocal, Calpine and NCPA), who inject it to their mutual benefit into depleted zones of the reservoir. Since the completion of the pipeline in September 1997, fieldwide injection into The Geysers has increased from about 30 or 40% to more than 60% of the mass withdrawn. A second such project (injection of treated wastewater from the City of Santa Rosa) is presently being planned.

In addition, as most non-productive wells drilled at The Geysers are redrilled, there are dry holes or dry legs within the field that could be artificially stimulated, creating hydraulic connections to nearby

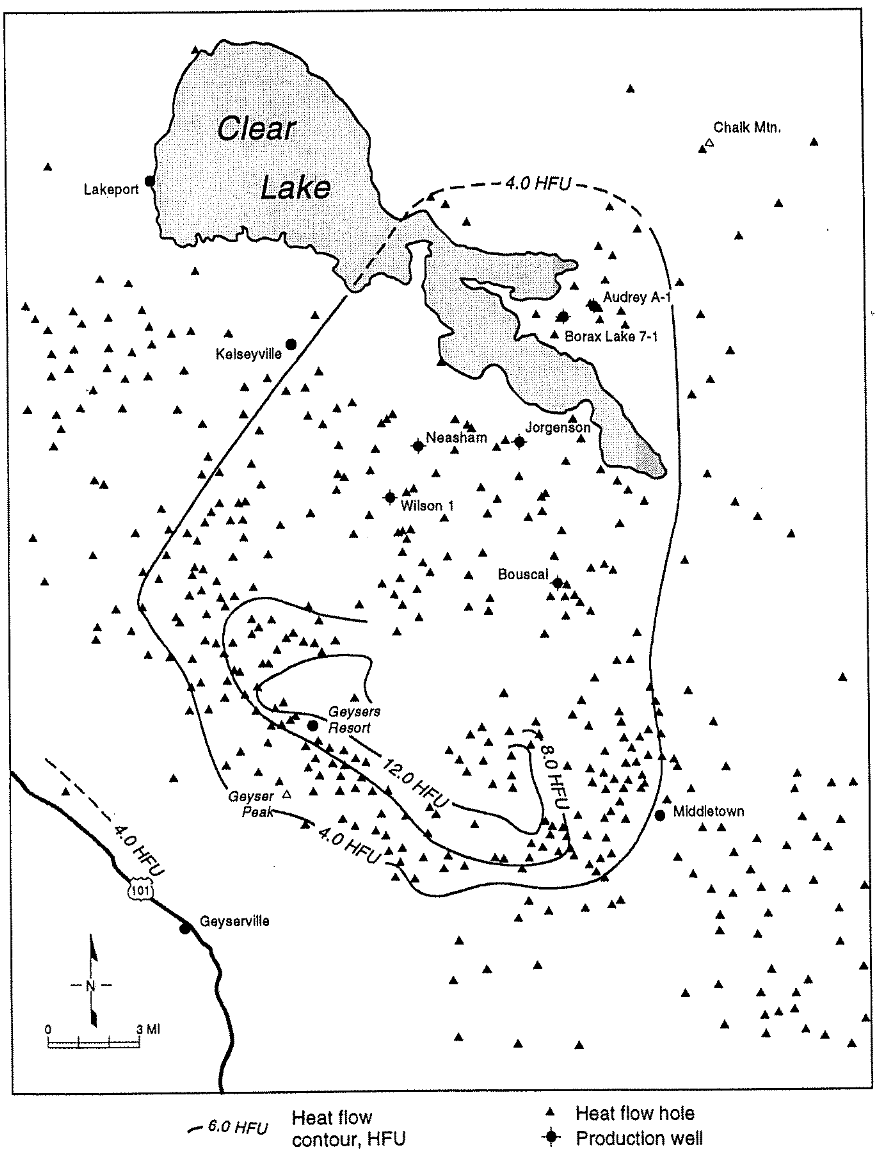

Figure 4. Map showing shallow wells (triangles) and selected deep wells from which conductive heat flow values were calculated [redrawn from Walters and Combs (1992)]. Heat flow contoured at 4 HFU (168 mW m^{-2}) intervals.

wells. Additional heat recovered from injection in these areas could be used directly in existing power plants.

Heat flow is very high in a large area around the field (Figure 4, modified from Walters and Combs, 1992), and there are numerous dry, peripheral holes which could be used for EGS stimulation experiments. In fact, the presence of two such wells near the city of Clearlake prompted a proposal to develop an HDR project in the early 1990s (Burns and Potter, 1993). As a stand-alone development would violate the criteria relating to existing power generation facilities, it has a lower priority than other types of EGS experiments at The Geysers. However, a benefit to existing facilities could be realized by stimulating and injecting into an appropriately located hot, dry well on the periphery of the field, which would be consistent with the selection criteria presented herein.

Salton Sea, California

The Salton Sea field represents a very large heat flow anomaly, with the recoverable reserves of geothermal energy estimated to be more than 1,000 MW. A present, about 280 MW have been installed, and most of the wells supplying the existing facilities are highly permeable, producing fluids from metamorphosed shales and sandstones. However, as in most geothermal fields, there are peripheral areas of the Salton Sea field which are hot but have significantly lower permeability than the geothermal reservoir area. Most of the wells in these areas remain unused or have been abandoned.

EGS experimentation in the Salton Sea might involve injecting under pressure to either create additional permeable zones or enhance low permeability zones near the periphery of the existing reservoir. There are several idle wells and active injection wells which could potentially be used for this purpose. It should be noted that there are untapped areas of the field with conditions appropriate for hydrothermal projects, and it is likely that additional field development would occur in those areas before ant major EGS work was done at Salton Sea.

Coso, California

As in the Salton Sea, the reserves of geothermal energy exceed the installed capacity in this hot, granitic geothermal reservoir, and there are wells in the field which would certainly benefit from stimulation. Although located in an arid area, CalEnergy (the field operator) has indicated that separated brine could be used for EGS experimentation, and has already had some success in thermally stimulating some Coso wells (Alex Schreiner, personal communication). As this reservoir closely approximates many hot, low permeability reservoirs throughout the U.S., Coso would be an ideal place to further the reservoir creation/enhancement concept.

Steamboat Springs, Nevada

There are two developments at Steamboat: the upper, high-temperature area, where Caithness Energy owns and operates a 12 MW flash plant; and the lower Steamboat area, where Far West owns and operates more than 40 MW of binary capacity (Figure 5). Commercial permeability is found in either basement (granitic and metamorphic rocks) or Tertiary volcanic units. Upflow of high-temperature fluid occurs beneath the area developed for the flash plant, whereas the binary development taps the outflow zone (Mariner and Janik, 1995). As in most geothermal systems in the Basin and Range province, Steamboat fits the selection criteria relating to stress regime and reservoir simplicity.

At Upper Steamboat, production is associated with a zone of enhanced permeability along a normal fault. Although most of the Caithness wells penetrate this structure, two were not commercially productive. Both of these wells are located within 200m of the nearest active producer and are completed in basement rock, making them ideal candidates for artificial enhancement.

Dixie Valley, Nevada

Dixie Valley is a classic Basin and Range geothermal system with a reservoir associated with a major range-bounding normal fault. Wells drilled to intercept this fault zone have had a relatively high success rate, but some dry holes or legs exist (Figure 6). Permeability sometimes extends a short distance away from the fault zone in certain competent geologic units. As summarized by Plank (1995), a number of wells with temperatures high enough for power generation have been unsuccessful in penetrating zones of commercial permeability. These wells occur both between other successful wells and outside the area of known production. An EGS experiment here might be devised to either stimulate a dry hole or leg which is known to penetrate the fault zone, increase the area of

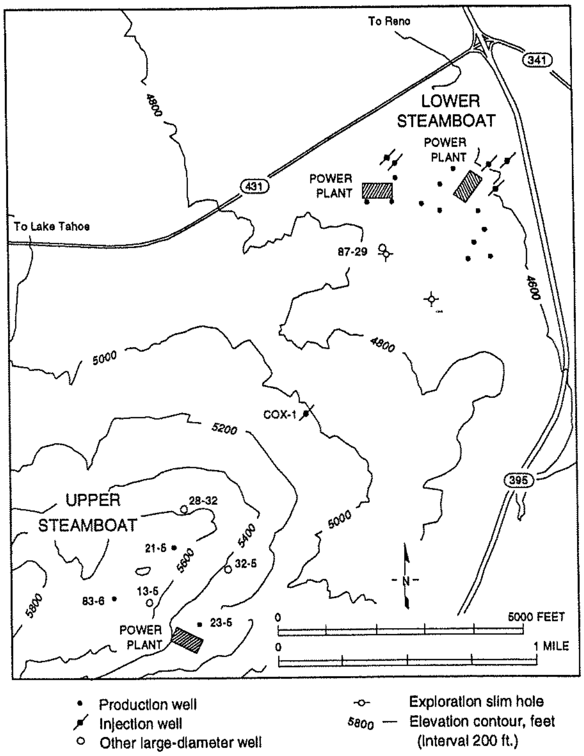

Figure 5. Map showing locations of power plants and various wells at Steamboat, Nevada.

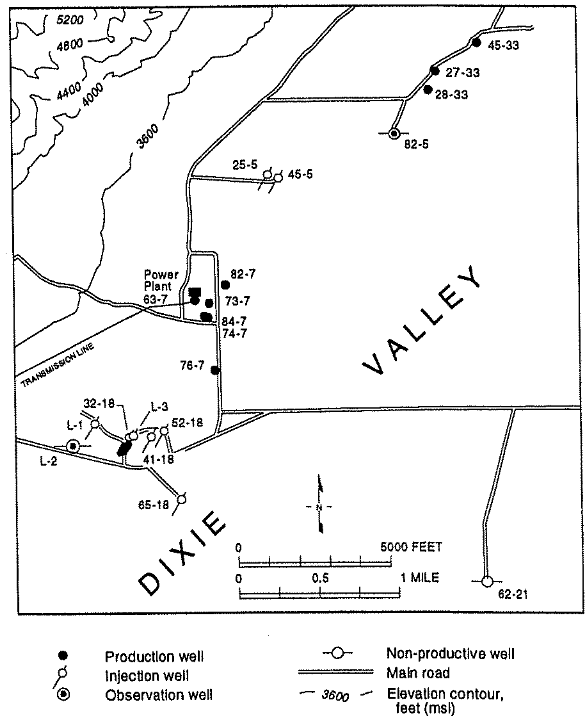

Figure 6. Map showing location of power plant and various wells at Dixie Valley, Nevada.

circulation in competent units adjacent to the fault zone, or stimulate a high-temperature area beyond the region of known production.

DOE-supported work to characterize the stress field at Dixie Valley is presently underway (Hickman *et al.*, 1998), with the ultimate goal of stimulating the non-productive well 82-5, which intercepts the fault zone and is located between other productive wells (Figure 6). This type of work would be highly useful for characterizing the behavior of enhanced Basin and Range systems, and sets the stage for other, similar experiments in fault-controlled geothermal systems.

Soda Lake, Nevada

The Soda Lake field lies within the Carson Sink, a major basin in north-central Nevada (Figure 2). Although located in the Basin and Range province, production in the geothermal system at Soda Lake is not associated with a major range-bounding fault zone, but is controlled by a combination of stratigraphic and structural features (McNitt, 1990). The fluid is derived from deep in the Carson Sink, and is inferred to flow updip in a coarse, pumice tuff unit at the base of the Truckee Formation into a structural and gravity high, where it is intercepted by the Soda Lake production wells. The static temperature in the production zone is approximately 180°C, but temperatures in excess of 200°C have been measured in a well which penetrates the Mesozoic basement (granite, metavolcanic and metasedimentary rock). Furthermore, successful and unsuccessful wells are interspersed in the field.

EGS experiments at Soda Lake could be of two types: 1) stimulation of the basement rock beneath the producing reservoir; or 2) stimulation of an unsuccessful well which penetrates the pumice tuff zone.

Roosevelt, Utah

A 20 MW flash power plant has been operating at Roosevelt since 1984, supplied by wells drilled into fractured Tertiary volcanic and Precambrian metamorphic rocks on the east side of a major NNE-trending fault called the Dome Fault (Figure 7). To the west of the Dome Fault, temperatures are high, but permeability is limited to the zone immediately adjacent to the fault. As indicated in Figure 7, well 9-1 was a dry hole, and the Participating Area for production was delineated on the basis of the distribution of known producers. However,

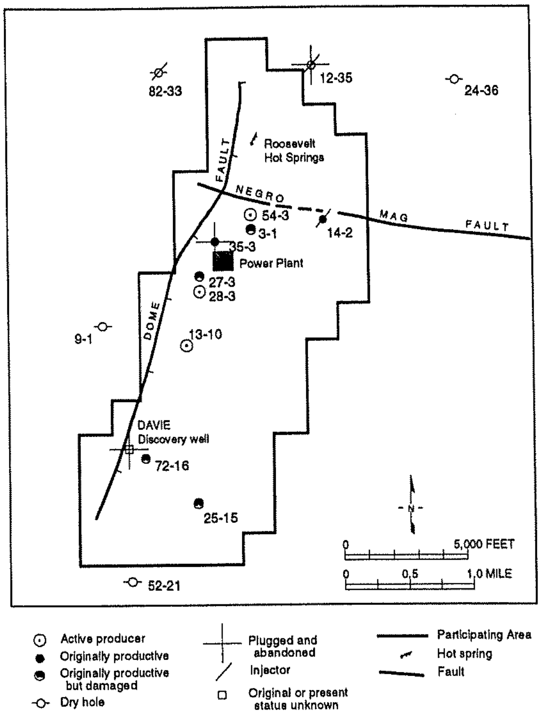

Figure 7. Map showing locations of power plant and various wells at Roosevelt, Utah.

enhancement by fracture stimulation could extend the reservoir into the footwall block, where temperatures as high as 200°C have been measured.

Descriptions of Secondary Sites

Salton Trough, California

In addition to the Salton Sea field, other areas in the Salton Trough are potential candidates for EGS experiments, including Heber and East Mesa. At both fields, production was successful at shallow depths, but some deeper wells, particularly those located near the margins of the fields, had relatively low permeability and productivity, but high temperature. These deep, peripheral, low permeability wells could be the subject of enhancement experiments; however, the availability of water for injection may be a problem.

Newberry Crater, Oregon

Two core holes and two full-sized wells, completed in Tertiary volcanic rocks and pre-Tertiary granitic basement rock, were drilled in 1995 on the western flank of Newberry Crater (Spielman and Finger, 1998). All had relatively low permeability (~0.3 md) and high temperatures (>315°C), making them ideal candidates for EGS experiments. Because there is presently no infrastructure (power generation facility or transmission access) at Newberry, it is a secondary choice. However, experimentation at Newberry would yield very useful information about the fracture characteristics of young volcanic rocks, which host many geothermal systems throughout the world.

Medicine Lake, California

Little is published about the characteristics of wells at Medicine Lake, but, like most geothermal fields, there are probably hot, low-permeability areas which could benefit from enhancement. As for Newberry, Medicine Lake volcano is dominantly basalt, secondarily rhyolite, and has subordinate andesite. Although no infrastructure exists at present, both CalEnergy and Calpine are planning to develop power projects in this area; therefore, it is a potential EGS candidate for the near future.

Puna, Hawaii

The Puna geothermal reservoir is one of the hottest in the world (>315°C) and presently supplies about 30 MW to a hybrid (flash-binary) power plant. Zones of high productivity are closely associated with intrusions from the 1955 fissure eruption, which transects the Puna Geothermal Venture (PGV) project area from SW to NE (Figure 8). Full-sized wells and slim holes have been drilled on the margins of the fissure eruptions, encountering lower temperature and permeability than in the central zone. Wastewater from the PGV project is injected into some of these peripheral wells, and enhancement might involve increasing the recovery of heat from the existing reservoir by targeting injection and/or increasing the extent of the reservoir by enhancing permeability in peripheral zones. The reason this site is classified as secondary relates to the political difficulty in developing geothermal projects in Hawaii.

Cove Fort, Utah

Cove Fort geothermal field is located in a transition zone between the Basin and Range and Colorado Plateau geologic provinces in southwestern Utah. Power production began in 1984, when a 3 MW binary power plant was installed, supplied by relatively shallow wells drilled into a low pressure steam zone in a Paleozoic sandstone unit. Later, a 2 MW topping cycle was added to better utilize the

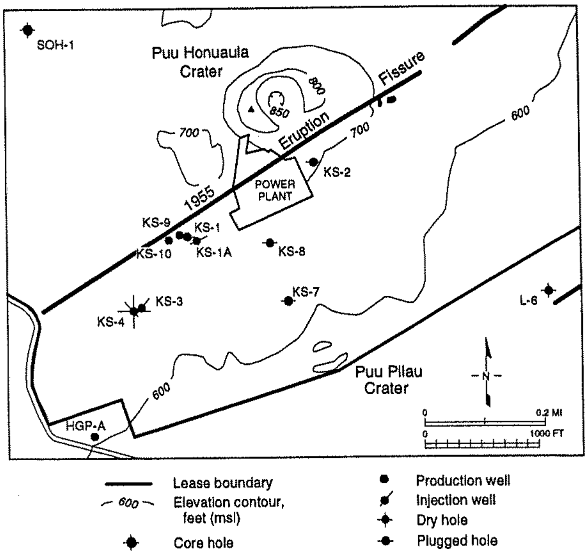

Figure 8. Map showing the locations of power plant and various wells at Puna, Hawaii.

energy of the produced steam and in 1990, an 8.5 MW flash steam unit was added, bringing the total installed capacity to 13.5 MW (gross). Pressure decline in the steam zone led the operator to explore for the hot water resource presumed to underlie the steam zone, and the next well to be drilled encountered a liquid-dominated zone in Paleozoic limestone beneath the steam reservoir. Deeper still, this well penetrated Tertiary quartz monzonite, which was hot but had limited permeability (Huttrer, 1992).

Based on geophysical evidence, the monzonite is postulated to be quite extensive and therefore represents a significant EGS opportunity. However, as the only well to have penetrated the monzonite is used for production, Cove Fort fails to meet the criteria of having wells available for experimentation.

Summary and Conclusions

Enormous subsurface heat reserves exist at economically accessible depths in the western United States but often cannot be recovered because of permeability and/or fluid limitations. Although existing hydrothermal developments represent only a small fraction of this resource base, they provide a unique opportunity to incrementally further the development of EGS. Through small-scale experimentation, reservoir enhancement could be accomplished in a variety of geologic environments. At numerous sites in the U.S., stranded assets could be recovered by stimulating marginally productive or non-productive wells drilled in areas with sufficient infrastructure to immediately utilize the additional heat recovered. EGS experiments such as the ones discussed above would not only yield short-term benefits to the U.S. geothermal industry, but would also move the U.S. further along the geothermal permeability-fluid continuum toward future commercialization of the full range of systems which comprise the significant geothermal resource base in the United States.

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References

Burns, K., and R.M. Potter, 1993. Potential geothermal development near the City of Clearlake, California. Transactions, Geothermal Resources Council, Volume 17, pp. 317 - 323.

Goranson, C., and J. Combs, 1995. Characterization of injection wells in a fractured reservoir using PTS logs, Steamboat Hills geothermal field, Nevada, USA. Proceedings, 20th Workshop on Geothermal Reservoir Engineering, Stanford University, pp. 47 - 53.

Hickman, S., J. Sass, C. Williams, R. Morin, C. Barton, M. Zoback and D. Benoit, 1998. Fracture permeability and *in situ* stress in the Dixie Valley, Nevada, geothermal reservoir. Federal Geothermal Research Program Update, Fiscal Year 1997, March 1998, pp. 4 -189 to 4 -196.

Huttrer, G.W., 1992. Geothermal exploration at Cove Fort - Sulphurdale, Utah, 1972 - 1992. Transactions, Geothermal Resources Council, Vol. 16, pp. 89 - 95.

Lachenbruch, A.H., and J.H. Sass, 1978. Models of an extending lithosphere and heat flow in the Basin and Range Province. Geological Society of America, Memoir 152, 209-250

McNitt, J.R., 1990. Stratigraphic and structural controls of the occurrence of thermal fluid at the Soda Lakes geothermal field, Nevada. Transactions, Geothermal Resources Council, Vol. 14, pp. 1507 - 1512.

Plank, G.L., 1995. Structure, stratigraphy and tectonics of the Dixie Valley geothermal site, Dixie Valley, Nevada. Transactions, Geothermal Resources Council, Vol. 19, p. 215.

Spielman, P.B. and J.T. Finger, 1998. Well test results of exploration drilling at Newberry Crater, Oregon in 1995. Proceedings, 23rd Workshop on Geothermal Reservoir Engineering, Stanford University, January 1998.

Walters, M.A. and J. Combs, 1992. Heat flow in The Geysers - Clear Lake geothermal area of northern California, USA. In: Claudia Stone, editor, Geothermal Resources Council Special Report 17, Monograph on The Geysers Geothermal Field, pp. 43 - 53.