The USGS National Geothermal Resource Assessment: An Update

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Keywords

Geothermal, heat flow, resource assessment, reservoir, electric power, permeability, fractures, faults, geothermometers, stress, ground water, tectonics, magmatism

ABSTRACT

The U. S. Geological Survey (USGS) is working with the Department of Energy's (DOE) Geothermal Technologies Program and other geothermal organizations on a three-year effort to produce an updated assessment of available geothermal resources. The new assessment will introduce significant changes in the models for geothermal energy recovery factors, estimates of reservoir volumes, and limits to temperatures and depths for electric power production. It will also include the potential impact of evolving Enhanced Geothermal Systems (EGS) technology. An important focus in the assessment project is on the development of geothermal resource models consistent with the production histories and observed characteristics of exploited geothermal fields. New models for the recovery of heat from heterogeneous, fractured reservoirs provide a physically realistic basis for evaluating the production potential of both natural geothermal reservoirs and reservoirs that may be created through the application of EGS technology. Project investigators have also made substantial progress studying geothermal systems and the factors responsible for their formation through studies in the Great Basin-Modoc Plateau region, Coso, Long Valley, the Imperial Valley and central Alaska. Project personnel are also entering the supporting data and resulting analyses into geospatial databases that will be produced as part of the resource assessment.

Introduction

Under the mandate of the Energy Policy Act of 2005, and with receipt of appropriated funds starting in Fiscal Year 2006, the United States Geological Survey (USGS) is conducting a new assessment of the moderate-temperature (90 to 150 °C) and high-temperature (>150 °C) geothermal resources of the United States. The assessment is focused on the western United States, including Alaska and Hawaii, and will highlight geothermal energy resources located on public lands. It will be the first comprehensive national geothermal resource assessment since 1979 (USGS Circular 790 - Muffler, 1979). Supporting documentation and databases will be published in the months following assessment release. The new assessment will present a detailed estimate of the geothermal electrical power generation potential from identified and undiscovered resources and include an evaluation of the major technical challenges for increased geothermal development. The assessment will also explain the significant changes in the models for geothermal energy recovery since the last assessment, and include both the characteristics of known geothermal systems and the potential impact of evolving geothermal production technology. An important component will be a comprehensive evaluation of Enhanced Geothermal Systems (EGS) techniques for extracting geothermal energy from low permeability rock units.

As summarized by Williams and Reed (2005), a number of changes are being incorporated in the new resource assessment. Improvements include: (1) a change in the method for determining recovery factors, (2) independent evaluations of permeability using reservoir models and other indicators, (3) a minimum temperature for electric power production of approximately 100 °C, (4) a maximum depth for geothermal reservoirs of at least 5 km, (5) revised quantitative models for the extent of undiscovered resources, and (6) the potential impact of mature EGS technology.

This paper provides an update of USGS activities in support of the assessment project, involving work on assessment methodology, site-specific characterization of known geothermal systems, and regional studies to better constrain the extent of undiscovered resources. The assessment effort also involves partnerships with other USGS programs and external organizations, including the Department of Energy (DOE), the Bureau of Land Management (BLM), other Federal agencies, national laboratories, universities, state agencies and the geothermal industry. Significant collaborators among the national laboratories and universities include the Idaho National Laboratory (INL), Lawrence Berkeley National Laboratory LBNL), the Earth and Geoscience Institute at the University of Utah (EGI), and the Great Basin Center for Geothermal Energy at the University of Nevada –Reno (UNR).

Geothermal Resource Assessment Methodology Studies

An important aspect of geothermal resource assessment methodology is the development of geothermal resource models consistent with the production histories of exploited geothermal fields. The primary method applied in past USGS assessments was the volume method, as developed by Nathenson (1975), White and Williams (1975), Muffler and Cataldi (1978) and Muffler (1979), in which the recoverable heat is estimated from the thermal energy available in a reservoir of uniformly porous and permeable rock using a thermal recovery factor, R_g, for the producible fraction of a reservoir's thermal energy. The volume method was established as the standard approach, and recent assessments of geothermal resources in parts of the United States rely on modified versions of the USGS volume method (e.g., Lovekin, 2004).

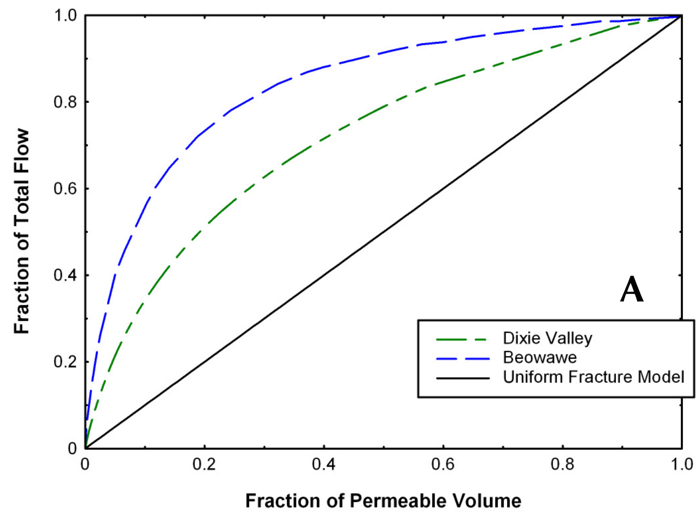
The geothermal recovery factor, R_g, is defined as the ratio of the amount of thermal energy that can be extracted from the reservoir at the wellhead, q_{WH}, to the thermal energy, q_R, present in the reservoir.

$$R_g = q_{WH} / q_R \qquad (1)$$

Once the reservoir fluid is available at the wellhead, the thermodynamic and economic constraints on conversion to electric power are well known. The challenge in the resource assessment lies not only in understanding the thermal energy and size of a reservoir but also on the constraints on extracting that thermal energy as represented by R_g.

With respect to thermal energy, when in situ temperature measurements are not available, chemical geothermometers can be applied as proxies. Reed and Mariner (this volume) present an overview of geothermometers that are being used in the new USGS assessment. Developing accurate estimates for the volumes of unexploited geothermal reservoirs is a more difficult problem. Production experience, tracer tests in active geothermal fields, and variations in recorded flow rates from producing fractures clearly indicate significant variations in permeability and path length among fractures connecting injection and production wells (Shook, 2005; Reed, 2007; Williams, 2007). Analysis of the first temporal moment, or mean residence time, of chemical tracer tests yields information on the swept volume and fluid velocity between production and injection well pairs that can be used to better characterize geothermal reservoirs. Based on the results of these analyses, variability of flow in a reservoir can be plotted as a curve relating flow capacity to storage capacity, or the productivity of each portion of the reservoir.

As part of the USGS assessment effort, Reed (2007) extended the temporal moment analysis technique developed and applied by Shook (2005) in the Beowawe, Nevada, geothermal field to the records of tracer tests in the Dixie Valley, Nevada, geothermal field. Examples from the Beowawe and Dixie



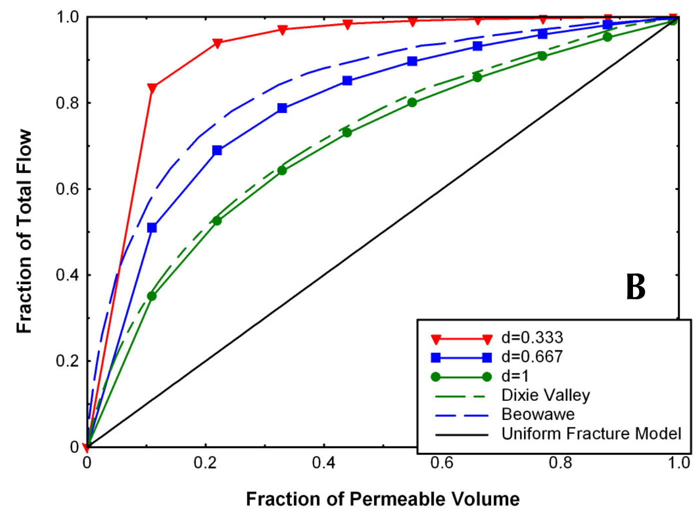


Figure 1. (a) Distribution of flow capacity across the reservoir permeable volume for the fractured reservoir model of Bodvarsson and Tsang (black) and the Beowawe (Shook, 2005) and Dixie Valley (Reed, 2007) geothermal fields. Variations in recovery factor with fracture spacing for model incorporating planar fractures with uniform flow properties. (b) Distribution of flow capacity from (a) with the predictions of self-similar models with three different fractal dimensions (after Williams, 2007).

Valley analyses are shown in Figure 1a. In the Beowawe field approximately 50% of the flow comes from the most productive 10% of the permeable fractures, and in the Dixie Valley field approximately 35% of the flow comes from the most productive 10% of the permeable fractures. The spatial distributions and hydraulic properties of real fracture networks are highly heterogeneous, and the heterogeneity manifests itself in the fundamental production characteristics yielded by the moment analysis of tracer tests. Any accurate characterization of injection and production from fractured reservoirs must be able to account for this heterogeneity.

Models for the recovery of heat from uniformly porous, homogeneous, and single-phase reservoirs indicate that R_g can reach values of 0.5 or higher (e.g., Nathenson, 1975; Garg and Pritchett, 1990; Sanyal and Butler, 2005). In order to allow for uncertainties in the distribution of permeability in a producing geothermal reservoir, the resource estimates in Circular 790 were based on a constant value for R_g of 0.25 (Muffler et al., 1979). More recent analyses of data from the fractured reservoirs commonly exploited for geothermal energy indicate that R_g is closer to 0.1, with a range of approximately 0.05 to 0.2 (Lovekin, 2004; Williams, 2004, 2007). In general this apparent discrepancy in R_g reflects the contrast in thermal energy recovery from complex, fracture-dominated reservoirs compared to the uniform, high-porosity reservoirs considered in the early models.

The original values for R_g were derived from models of the effects cooling in a geothermal reservoir due to reinjection or natural inflow of water colder than pre-existing reservoir temperatures (e.g., Nathenson, 1975; Bodvarsson and Tsang, 1982; Garg and Pritchett, 1990; Sanyal and Butler, 2005). This is consistent with the optimal extraction of thermal energy from a reservoir, as in general it is possible to produce many times the original volume of fluid from the reservoir in order to recover the thermal energy from the reservoir rock. Consequently, any estimate of reservoir production potential should evaluate longevity from the perspective of injection and eventual thermal breakthrough. The challenge is to extend these results to evaluate the thermal effects of injection and production in reservoirs ranging from those containing a few isolated fracture zones to those that are so pervasively fractured as to approach the idealized behavior of uniformly porous reservoirs.

The analytical model of Bodvarsson and Tsang (1982) for the thermal effects of injection into a geothermal reservoir formed of uniformly spaced fractures highlights the sensitivity of thermal energy recovery to average fracture spacing. (The greater the fracture spacing, the larger the fraction of thermal energy in the formation that is bypassed by cooler water moving along fast fracture paths.) Unfortunately, the models for uniform fracture permeability and spacing (Figure 1a) do not replicate some important characteristics of producing geothermal reservoirs, such as the varying flow capacity-storage capacity behavior demonstrated by the chemical tracer studies of Shook (2005) and Reed (2007).

Williams (2007) investigated the use of self-similar fracture distributions in a modification of the Bodvarsson and Tsang (1982) model as a means of better representing the actual fracture flow characteristics and variations in R_g observed in producing reservoirs. One simple and effective way of characterizing this heterogeneity has been through the use of models that characterize fracture properties such as permeability through a self-similar distribution (e.g. Watanabe and Takahashi, 1995). If, for example, the productivity of fractures intersecting a production well follows a self-similar distribution, this distribution is described by

$$N_k = C_k k^{-d_k} \quad (2)$$

where k is a reference permeability, N_k represents the number of fractures intersecting the well with permeability greater than or equal to k, C_k is a constant, and d_k is the fractal dimension. Although there is some direct evidence for fractal dimensions of properties that are relevant to permeability, such as fracture aperture, fracture length, and fracture density, the fractal dimensions for permeability may vary over a wide range (e.g., Watanabe and Takahashi, 1995; Dreuzy et al., 2001).

Figure 1b compares flow capacity/storage capacity curves from self-similar models for three different fractal dimensions with the Beowawe, Dixie Valley and uniform fracture model curves from Figure 1a. (For details see Williams, 2007.) The distribution of flow for the Dixie Valley field is consistent with the modeled distribution for d=1, and the distribution for the Beowawe field is consistent with the modeled distribution for d=0.667. The smaller value for d in the Beowawe field reflects the dominance of a single fracture or fracture system in the permeability tapped by the chemical tracer test. Like the uniform fracture model, the self-similar fracture flow models yield a range of values for R_g that depends both on average fracture spacing and on the dimensionality of the spatial distribution of fractures (Figure 2).

Models for the effects of injection within reservoirs of self-similar distributions of fracture permeability reproduce both the observed range of R_g and the flow capacity/volume capacity characteristics of producing fractured geothermal reservoirs. Although these analytical models are not intended as replacements for detailed numerical reservoir models, they do provide a physically realistic justification for applying a range of potential recovery factors to an unexploited reservoir in order to reflect the heterogeneous character of fracture permeability. Because EGS technology depends on developing a reservoir through the creation and stimulation of fractures, a similar recovery factor analysis may be applicable to evaluating the EGS resource.

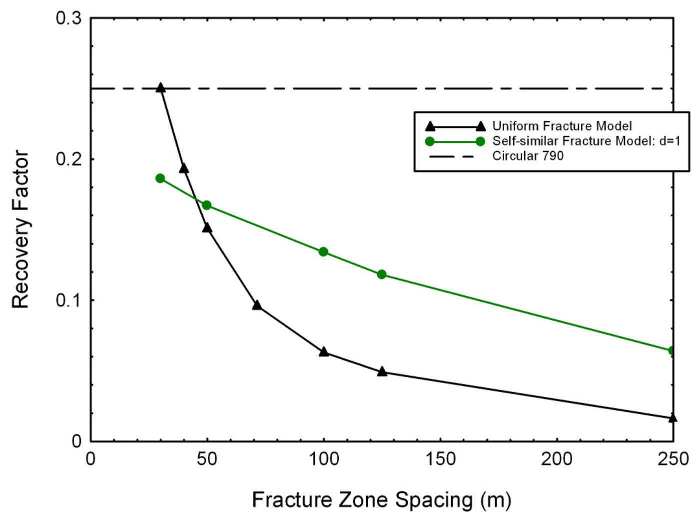


Figure 2. Variations in recovery factor with fracture spacing for example models incorporating planar fractures with uniform flow properties (black) and a self-similar distribution of flow properties among the producing fractures (green) (after Williams, 2007).

Regional and Site-Specific Studies

A second important part of the new assessment is a program of targeted site-specific and regional studies to characterize and constrain the nature and distribution of identified and undiscovered geothermal resources. This section highlights some of the ongoing investigations, most of which are being conducted in collaboration with other USGS programs and outside investigators.

Surprise Valley and the Great Basin-Modoc Plateau Transition

Located at the transition between the Great Basin and the Modoc Plateau, Surprise Valley in northeastern California is an unexploited geothermal system located in northeastern California and was assigned a power generation potential of 1400 MW in Circular 790. Tilden et al. (2005) reported on new gravity and magnetic data collected along a regional profile passing through Surprise Valley. In a follow-up effort in 2005 and 2006, USGS staff acquired precision temperature logs from exploratory geothermal wells in the Lake City area of Surprise Valley, conducted gravity and magnetic surveys throughout the region, and measured the physical properties of drill cores. In addition, 2006 saw the release previously unpublished geophysical data from the Crump's Geyser area of southeastern Oregon (Plouff, 2006) and new geophysical data from the Smoke Creek Desert of northwestern Nevada (Ponce et al., 2006). These geophysical studies will support an investigation of the factors responsible for the formation of geothermal systems in the northwestern Great Basin and Modoc Plateau as well as a detailed look at the known geothermal resources in Surprise Valley and Warner Valley. USGS investigators have also incorporated previously unpublished temperature-gradient data from the Susanville/Honey Lake geothermal areas of northern California in a GIS database and are using the data to better characterize the potential geothermal resource.

The Great Basin

The USGS is evaluating the potential for concealed geothermal resources within the area of low heat flow (Eureka Low) covered by the carbonate aquifer in eastern and central Nevada. USGS staff have completed a preliminary report on heat flow in Railroad Valley, Nevada, site of the major geothermal manifestation in the carbonate aquifer system (Williams and Sass, 2006). The results of the Railroad Valley study yielded the first clear constraints on the dimensions of the geothermal reservoir as well as the heat flux out of the system. Heat-flow measurements reveal a complex interaction of cooling due to shallow ground-water flow, relatively low (~50 to 75 mW m^{-2}) conductive heat flow at depth in most of the basin, and high (up to ~235 mW m^{-2}) heat flow associated with the 125 °C geothermal system that encompasses the Bacon Flat and Grant Canyon oil fields. The presence of the Railroad Valley geothermal resource within the Eureka Low may indicate that ground-water flow is not sufficiently vigorous to sweep heat out of the basin. If true, this suggests that other areas in the carbonate aquifer province may contain deep geothermal resources that are masked by ground-water flow.

Project personnel are investigating the deep thermal regime of the Great Basin through the analysis of aeromagnetic data to constrain the depth of the Curie temperature isotherm under parts of the Great Basin and thus evaluate whether thermal conditions at depth under the carbonate aquifer province are equivalent to those in northwestern Nevada. USGS investigators have also published new heat flow measurements from the Great Basin (Sass et al., 2005) and are conducting new studies of the chemical and isotopic characteristics of geothermal fluids following on a similar study of thermal springs in the Idaho batholith (Mariner et al., 2006). Collaboration with Mark Coolbaugh of the UNR Great Basin Center for Geothermal Energy is providing an updated look at the potential for undiscovered resources from geospatial analyses (Coolbaugh et al., 2006).

Long Valley

In Circular 790, the Long Valley area was characterized as having large geothermal resource potential (2100 MW) produced by heat flow from a massive magma body inferred to underlie the caldera. Subsequent work has indicated that the central magmatic system is cooled and that most of the geothermal heat is associated with the smaller Mono-Inyo volcanic chain that cuts through the western moat of the caldera (e.g., Hildreth, 2004). Revising the assessment for Long Valley is a major priority. USGS geothermal staff and research partners are working to integrate the geothermal resource assessment at Long Valley caldera with ongoing USGS volcano hazards studies. They have collected new temperature data and fluid samples from 10 geothermal wells in the caldera as a first step toward an integrated heat and fluid transport model that is being coordinated with a helium isotope study by Mack Kennedy of LBNL. New fault mapping between Long Valley and Mono Lake to the north will characterize the controls on fluid circulation and permeability along the Mono-Inyo chain and the results will be part of a new geospatial database being developed for the area.

Coso

USGS geothermal staff have also been working with Peter Rose of the University of Utah Energy and Geoscience Institute (EGI) and other colleagues on a series of DOE- and US Navy-funded investigations of the potential for developing and applying EGS technology at the Coso geothermal field in southern California. Results of the study have not only advanced the understanding of EGS potential but have also yielded significant insights into the nature and evolution of fracture permeability in hydrothermal systems. Davatzes and Hickman (2005) presented a comprehensive overview of the relative roles of stress, deformation and mineralization in determining the spatial and temporal distribution of permeability at Coso and other geothermal fields. In a follow-up paper, Davatzes and Hickman (2006) summarized the results of geologic mapping, in situ stress measurements, and fracture characterization studies to develop a geomechanical model for the Coso field in support of the EGS stimulation strategy.

Imperial Valley

The substantial geothermal resources concentrated in the Salton Sea/Imperial Valley region of southern California make it an important area of focus for the geothermal resource assessment project. In order to better delineate the thermal regime of the region and highlight identifiable geothermal manifestations, project staff have collected and digitized dozens of previously unpublished shallow and deep temperature-gradient and heat-flow measurements. A preliminary map of heat flow derived from the data analysis is shown in Figure 3 along with the locations of known geothermal systems and active fault zones. The mapped heat-flow contours provide much greater detail and coverage compared to earlier studies (Lachenbruch et al., 1985) and constrain the spatial extent and thermal budget associated with know geothermal reservoirs. The irregular spatial distribution of exploration drilling leaves large regions of uncertain potential, particularly under the central Salton Sea itself.

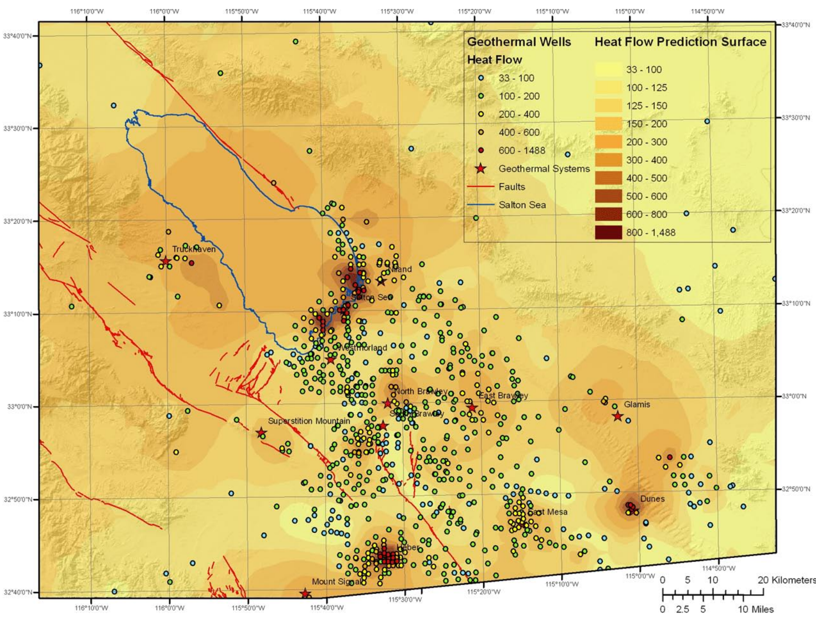


Figure 3. Preliminary heat-flow map of the Imperial Valley region, California.

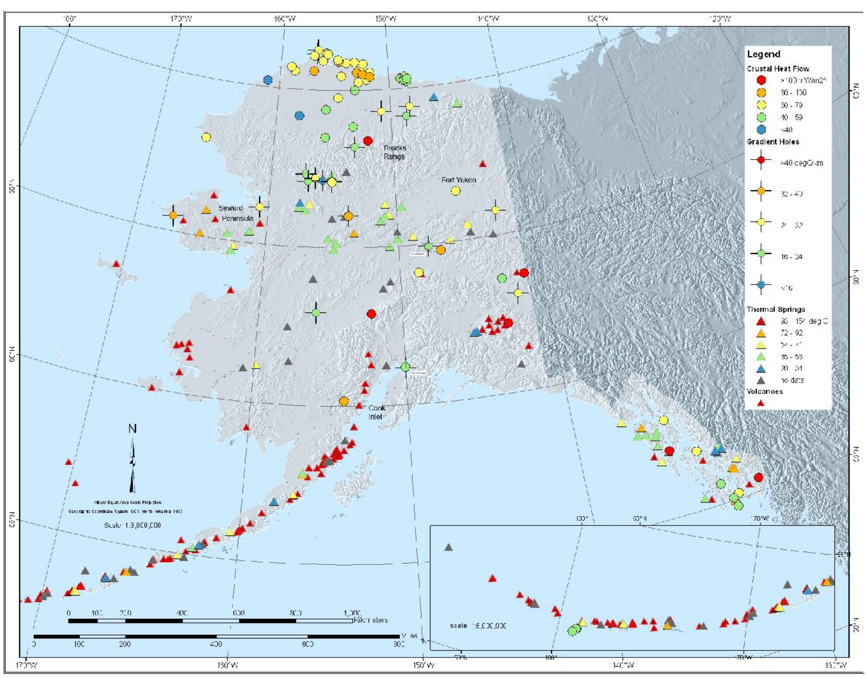


Figure 4. Updated heat-flow map of Alaska (after Williams et al., 2006).

Heat Flow and Geothermal Resources of the Alaskan Interior

In order to better characterize the thermal regime of central Alaska and the degree to which crustal heat flow influences the formation of hydrothermal systems, USGS staff have collected and analyzed new and previously unpublished conductive heat flow measurements at 11 sites in the Alaskan interior from the Brooks Range in the north to Cook Inlet in the south (Williams et al., 2006; Figure 4). The heat flow values range from 44 to 130 mW m^{-2} with a mean of 88 mW m^{-2}. Geothermal manifestations in central Alaska are dominated by the belt of thermal springs that extends along an east-west trend from the Canadian border to the Seward peninsula. Five of the heat flow measurements cover the portion of this trend from Fort Yukon in the east to the base of the Seward peninsula in the west and average 77±7 mW m^{-2}. Limited temperature gradient data from the Seward peninsula itself are consistent with a higher background heat flow. The 77 mW m^{-2} average for central Alaska is elevated relative to average continental heat flow but is significantly lower than the 85+ mW m^{-2} contours mapped by Blackwell and Richards (2004) based on a smaller dataset. Simple thermal models indicate that central Alaska is favorable for the formation of low to moderate temperature (up to 150 °C) hydrothermal systems from the deep circulation of water along fault zones or within permeable strata (Williams and Reed, 2005), and geothermometer estimates of temperatures for hydrothermal systems located in the same area are consistent with this result (Muffler, 1979; Reed et al, 1983). Large, high temperature hydrothermal systems are unlikely to be found outside of areas of Quaternary magmatic activity, but comparisons with other thermally active regions indicate that the identified thermal springs and manifestations in central Alaska may be only a fraction of the number likely to be found with more extensive exploration.

Summary

The USGS is conducting a new assessment of the moderate- and high-temperature geothermal resources of the United States. This new assessment will present a detailed estimate of electrical power generation potential and an evaluation of the major technological challenges and environmental impacts of increased geothermal development. The assessment effort involves partnerships with the DOE, BLM, national laboratories, universities, state agencies and the geothermal industry. The new assessment will introduce significant changes in the models for geothermal energy recovery factors, estimates of reservoir permeability, limits to temperatures and depths for electric power production, and include the potential impact of evolving EGS technology.

USGS assessment project personnel are evaluating thermal energy recovery from geothermal reservoirs through analysis of production histories, reservoir models, and chemical tracer tests. Researchers are also conducting a number of regional and site-specific studies, with the results being incorporated in geospatial databases. Areas of study discussed in this paper include the Great Basin-Modoc Plateau region, Coso, Long Valley, the Imperial Valley and central Alaska. Future publications will report on progress with studies in additional areas.

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