Natural Resources Research (© 2007)
DOI: 10.1007/s11053-007-9028-7

Assessment of the Enhanced Geothermal System Resource Base of the United States

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Received 18 June 2006; accepted 21 November 2006

This paper describes an assessment of the enhanced geothermal system (EGS) resource base of the conterminous United States, using constructed temperature at depth maps. The temperature at depth maps were computed from 3 to 10 km, for every km. The methodology is described. Factors included are sediment thickness, thermal conductivity variations, distribution of the radioactive heat generation and surface temperature based on several geologic models of the upper 10 km of the crust. EGS systems are extended in this paper to include coproduced geothermal energy, and geopressured resources.

A table is provided that summarizes the resource base estimates for all components of the EGS geothermal resource. By far, the conduction-dominated components of EGS represent the largest component of the U.S. resource. Nonetheless, the coproduced resources and geopressured resources are large and significant targets for short and intermediate term development. There is a huge resource base between the depths of 3 and 8 km, where the temperature reaches 150–250°C. Even if only 2% of the conventional EGS resource is developed, the energy recovered would be equivalent to roughly 2,500 times the annual consumption of primary energy in the U.S. in 2006. Temperatures above 150°C at those depths are more common in the active tectonic regions of the western conterminous U.S., but are not confined to those areas. In the central and eastern U.S. there are identified areas of moderate size that are of reasonable grade and probably small areas of much higher grade than predicted by this analyses. However because of the regional (the grid size is 5′ × 5′) scale of this study such potentially promising sites remain to be identified.

Several possible scenarios for EGS development are discussed. The most promising and least costly may to be developments in abandoned or shut-in oil and gas fields, where the temperatures are high enough. Because thousands of wells are already drilled in those locations, the cost of producing energy from such fields could be significantly lowered. In addition many hydrocarbon fields are producing large amounts of co-produced water, which is necessary for geothermal development. Although sustainability is not addressed in this study, the resource is so large that in at least some scenarios of development the geothermal resource is sustainable for long periods of time.

KEY WORDS: Geothermal, geothermal resource base, renewable energy, heat generation, U.S. heat flow, temperature-at-depth, coproduced fluids, enhanced geothermal systems (EGS).

INTRODUCTION

Geothermal energy from areas with abundant hot water or steam has been developed extensively worldwide (Barbier, 2002). There is currently an installed capacity of more than 8,000 MW of hydrothermal geothermal energy with an average load factor exceeding 95%. Hydrothermal geothermal energy generally is considered to be developable if temperatures exceed 150°C and there is abundant producible water (or steam). It generally is assumed that such resources are exclusively related to areas

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of young volcanic activity and or high heat flow associated with active tectonism and most of the developments so far conform to this hypothesis. However, temperature increases with depth everywhere and so in theory geothermal energy could be developed almost anywhere. Of course, there are practical limits to the possible depth of exploitation. There are several classes of geothermal resources that might be considered possibilities for development in addition to the conventional hydrothermal ones, particularly in view of the relatively benign environmental effects, moderate cost of development, and ubiquity of possible locations compared to other renewable and nonrenewable systems capable of generating electrical power (DiPippo, 1991a, 1991b; Mock, Tester, and Wright, 1997). The concept of making an artificial reservoir and forming an artificial geothermal system, initially termed Hot Dry Rock geothermal energy has been investigated in many areas with ongoing activity in Europe and Australia (Tester and others, 2006). A more general term is Enhanced Geothermal System (EGS) implying a more general scenario of development.

Previous analyses have suggested that the amount of thermal energy available for EGS development is enormous (Armstead and Tester, 1987; Rowley, 1982; Mock, Tester, and Wright, 1997; Tester and others, 1994). However, these sources did not use detailed geologic information and, as a result, the methodologies employed were by necessity somewhat simplified. The primary focus of this paper is a detailed regional analysis of the heat content in the upper crust in the conterminous U.S. as a resource base evaluation of the potential for EGS energy development. Although the results generally are limited to the conterminous part of the U.S., Alaska, and Hawaii will be discussed briefly, in particular with respect to the potential of the volcanic systems.

This analysis is the resource basis of a detailed and complete study recently published (Tester and others, 2006) that considered in detail all aspects of EGS development from resource base to cost to environmental effects.

The various classes of geothermal development are listed in Table 1. Several categories of geothermal resources listed in Table 1 were evaluated in the 1970's by the U.S. Geological Survey (White and Williams, 1975; Muffler, 1979). In earlier USGS analyses the geothermal resource was divided into four major categories: hydrothermal, geopressured, magma, and conduction-dominated (Hot Dry Rock, HDR—now typically referred to as EGS). Table 1 also includes additional resource categories not mentioned in the earlier assessments. In this paper we specifically exclude detailed discussion of conventional hydrothermal resources, magma and geopressure geothermal resources. A resource evaluation for hydrothermal geothermal systems is in process by a team at the U.S. Geological Survey (Williams, 2005). The classes of resource that are discussed in detail in this paper are sedimentary and basement EGS.

Table 1. Geothermal Resource Categories. Modified from USGS Circulars 726 and 790

Resource Type	Reference
Conduction-dominated (EGS)	
Sedimentary EGS (SEGS)	This study, basins >4 km
Basement EGS	This study
Volcano Geothermal Systems	USGS Circular 790
Hydrothermal	USGS Circulars 726 and 790
Co-produced Fluids	McKenna and others (2005)
Geopressured Systems	USGS Circulars 726 and 790

Not included here because of their relatively small geographic size are "high grade" EGS Resources on the periphery of the conventional hydrothermal systems in the western U.S. Most of these types of targets are high grade and can be viewed as near-term targets of opportunity. These areas may be considered more properly part of the ongoing USGS hydrothermal resource assessment because of their association and small size. However, some larger basement EGS resource areas that might in some sense be considered marginal to hydrothermal systems, such as The Geysers/Clear Lake area in California and the High Cascades Range in Oregon, are included in this assessment because of their large size.

The primary object of this study is to calculate the stored thermal energy, or "heat" in place nationally and by state at depths from 3 to 10 km. The methodology, resource types considered, and the resource base calculations are included in this paper and follow Chapter 2 of Tester and others (2006). Recoverability, or useful energy, is not addressed in detail in this paper.

SOURCE OF DATA

The data set used to produce the *Geothermal Map of North America* published by the American Association of Petroleum Geologists (AAPG) (Blackwell and Richards, 2004a) is the basic thermal

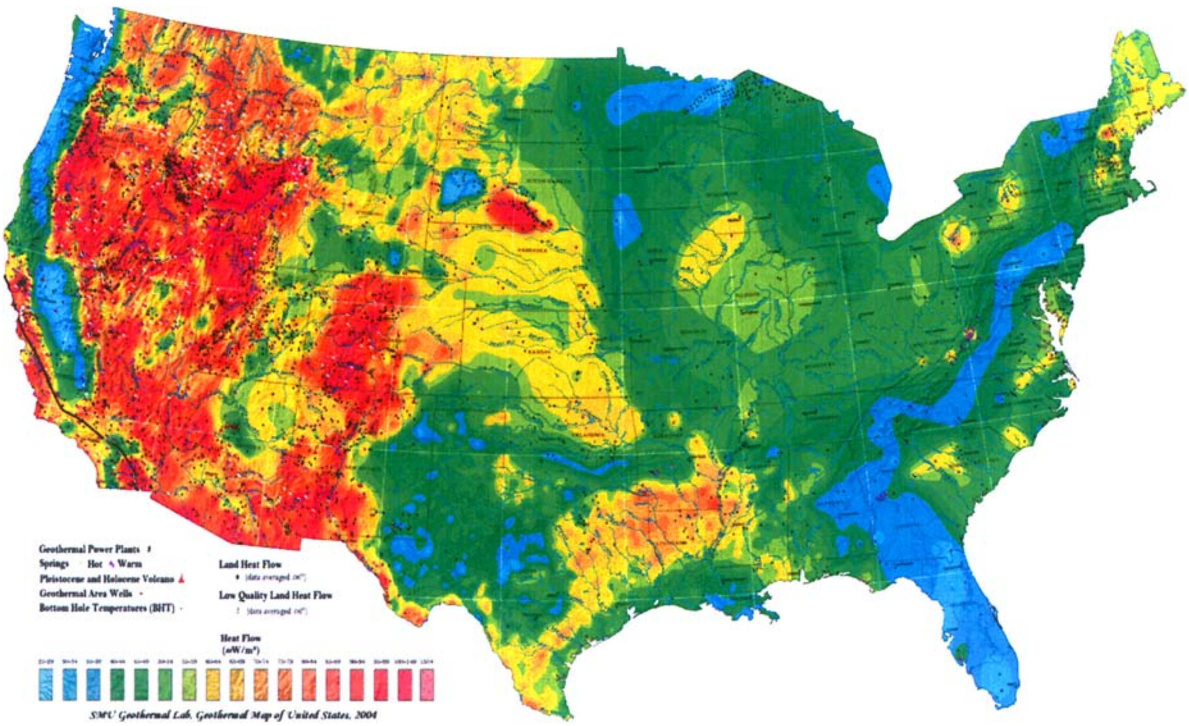

Figure 1. Heat Flow map of conterminous United States. Subset of Geothermal map of North America (Blackwell and Richards, 2004a).

data set used in developing this resource assessment. The conterminous U.S. portion of the map is shown in Figure 1. In order to expand coverage from the GSA-DNAG map (Blackwell and Steele, 1992; Blackwell, Steele, and Carter, 1991) and previous methods of resource evaluation (Blackwell, Steele, and Carter, 1993; Blackwell, Steele, and Wisian, 1994), extensive industry-oriented thermal data sets were used, as well as published heat-flow data from research groups. To that end a Western U.S. heat flow data set was developed, based on thermal gradient exploration data collected by the geothermal industry during the 1970's and 1980's (Blackwell and Richards, 2004c) and the 1974 AAPG Bottom Hole Temperature (BHT) data set (AAPG CD-ROM, 1994) was processed for temperature at depth and heat-flow determinations.

The basic information in the Western U.S. heat-flow data set consists of temperature-depth/gradient information. However, thermal conductivity and heat flow also were determined for as many of the sites as possible, based on thermal conductivity measurements, or estimates from geologic logs (where available) and geologic maps for locations with no well logs. About 4,000 points were used in the preparation of the map (of the 6,000 sites in the database). The focused nature of the drilling is shown by the clumps of data on Figure 2, especially in western Nevada and southwestern Utah.

A second industry data set consisting of about 12,000 bottom hole temperature measurements compiled in the early 1970's and published in digital form (DeFord and Kehle, 1976; AAPG CD-ROM, 1994) also was utilized. The AAPG BHT data set was augmented in Nevada by BHT data digitized from hydrocarbon exploration well logs in the files of the Nevada Bureau of Mines and Geology. Use of the BHT data required extensive analysis of the error associated with the determination of in situ equilibrium temperatures from these nonequilibrium data (Blackwell and Richards, 2004b, 2004c).

The heat flow ranges from less than 20 mW/m^2 in areas of low heat flow to above 100 mW/m^2 in areas of high heat flow. The causes of the variations and the distribution of heat flow in the conterminous U.S. are discussed by Blackwell, Steele, and Carter (1991) and Morgan and Gosnold (1989). The value of surface heat flow is the building block for the temperature at depth calculation. Figure 2 also illustrates that at the present stage of the analysis there are

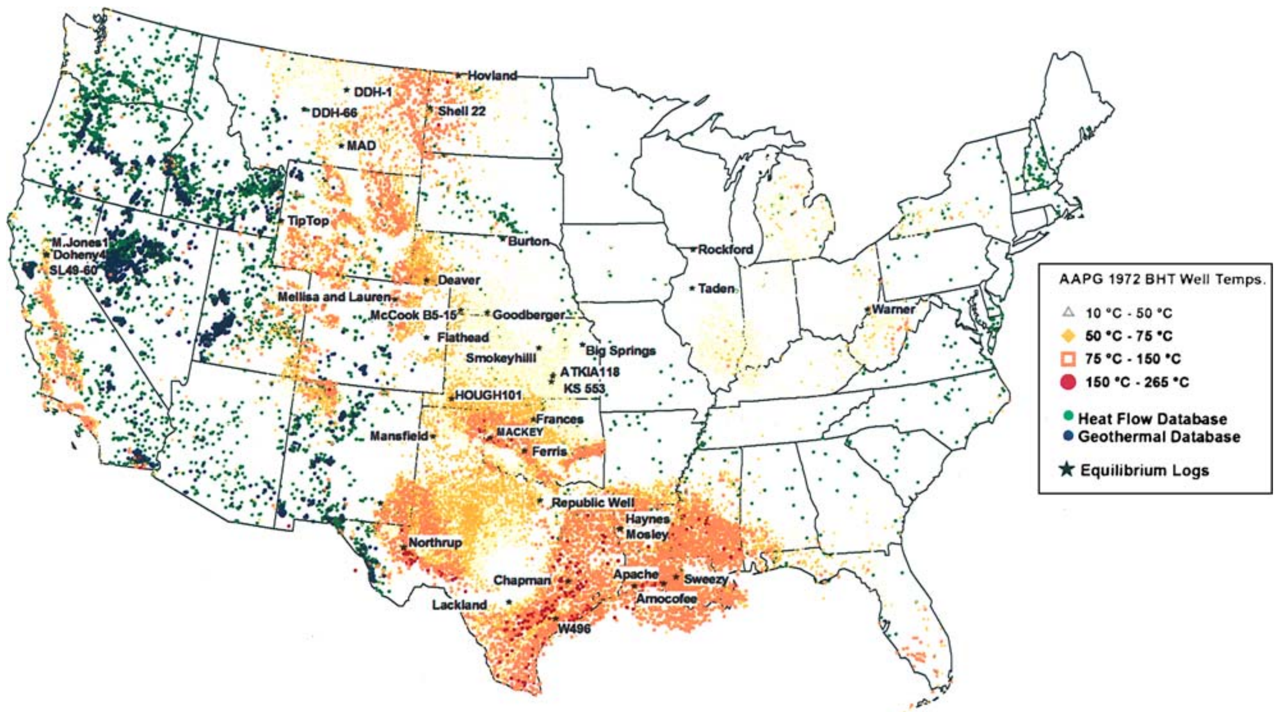

Figure 2. All BHT sites in the conterminous U.S. in the AAPG data base. BHT symbols are based on depth and temperature (not all of the sites were used for the Geothermal Map of North America). The named wells are the calibration points. The regional heat flow and geothermal database sites are also shown.

large geographic areas that are under-sampled with respect to the 5′ grid interval, such that aliasing locally is a problem that leads to uncertainty. For example, Kentucky and Wisconsin have no heat flow data at all and there are large gaps in several other areas, especially the eastern part of the U.S. Areas in the Appalachian basin may have low thermal conductivity and high heat flow, as is the situation in northwestern Pennsylvania, but there are limited data in this region. A typical 250 MWe (electrical) EGS plant might require about 5–10 km^2 of reservoir planar area to accommodate the thermal resource needed, assuming that heat removal occurs in a 1 km thick region of hot rock at depth. The power plant operations, of course, would be confined to a much smaller area, 3 km^2 or less (Tester and others, 2006, chapter 3). Thus, at the field level, specific exploration and evaluation activity will be necessary to select optimum sites in a given region.

To summarize, the values of heat flow used to produce the contours for the U.S. (shown in Fig. 1) were compiled from the following data sets: the SMU Western Geothermal database (includes the USGS Great Basin database, http://wrgis.wr.usgs.gov/open-file/of99-425/webmaps/home.html), the SMU compiled U.S. Regional Heat Flow database (www.smu.edu/geothermal), and American Assocation Petroleum Geologists BHT (AAPG CD-ROM, 1994). The various data site locations are shown in Figure 2 by data category. In addition, for completeness hot and warm spring locations, and Pleistocene and Holocene volcanoes, were shown on the North America Geothermal Map (Blackwell and Richards, 2004a). The data in each category are listed in Table 2.

Table 2. Data Sets for Geothermal Map of North America, 2004

TYPE	2004 DATA #	1992 DATA #
Land heat flow U.S.	2,815	1,629
Lower quality heat flow	246	0
BHT from oil and gas U.S.	12,211	0
Geothermal wells	4,047	95
Warm & Hot Springs	1,896	340
Volcanoes	454	454
Power Plants	36	0

RESOURCE BASE CALCULATION

Quantitatively, the temperature T at depth X for a basement terrain (granite or metamorphic rocks at the surface) can be written as:

$$T(x) = T_0 + Q_0 x/K + A_0 b^2(1 - e^{-x/b})/K$$

where $T(x)$ is the temperature at depth x, Q_0 is the surface heat flow, K is the average thermal conductivity from surface to depth X and A_0 is the radioactive heat contribution to the temperature from upper crustal rocks. Thus several components are needed to compute the temperature at depth. The surface heat-flow map (from the digital grid used to prepare the map in Fig. 1), the thermal conductivity, and the heat generation value of the upper crustal rocks are the starting point for the calculations. The details of the calculation and the thermal conductivity and radioactivity models are described in the Appendix and so the approaches are described only generally in this section.

Typically two depth distributions of the radioactive heat generation are considered: a constant heat generation and an exponential one (Birch, Roy, and Decker, 1968; Lachenbruch, 1968, 1970; Blackwell, 1971; Roy, Blackwell, and Decker, 1972). In addition the depth scale constant of the heat generation distribution must be known. For the situation of the exponential heat-generation distribution (assumed in the equation used), the scale parameter is the exponential decrement; for the constant heat generation model it is the thickness of the radioactive layer. In the computations made for the temperature at depth maps presented in this paper the exponential radioactivity model with a scale constant of 10 km was assumed, based on average parameters for the U.S. The temperatures at 10 km are about 10°C higher in the exponential model than in the constant model for the same radioactivity (assumed to be about 2 μW/m^3, see Blackwell, 1971), but this value and the uncertainty associated with it are not significant compared to the estimated 10% error of the combined temperature at depth calculations. The heat flow below the radioactive layer; that is, the "mantle heat flow" (Roy, Blackwell, and Decker, 1972) must be known and the determination of this parameter is discussed below.

In the situation of a sedimentary or volcanic rock cover over the basement the thickness, thermal conductivity, and the radioactive heat generation of the cover rocks must be known. The various components involved in the computation and their interactions are discussed below. The flow diagram of the computations is shown in Figure 3.

Surface Heat Flow

Before gridding of the heat-flow data for the U.S. map, heat flow was determined for as many of the thermal gradient locations in the three databases as possible. Because each data set is different, the heat-flow determination approach was somewhat different. For the regional heat-flow database individual data points in the original publications generally included measured thermal gradient, thermal conductivity, calculated terrain corrections, and error estimates. The heat-flow values for the regional data set were ranked for quality based primarily on the authors error estimates (see Blackwell, Steele, and Carter, 1991, for a discussion of quality ranking). Hydrothermal system-influenced data (high values, generally higher than 120 mW/m^2) were excluded from the gridding calculations. Clusters of data points within ±2 km of each other were averaged. Figure 1 shows the contoured conterminous U.S. heat flow gridded at an interval of 5 minutes.

Use of the extensive BHT data set distinguishes the 2004 Geothermal Map of North America from previous ones. The BHT data were calibrated by

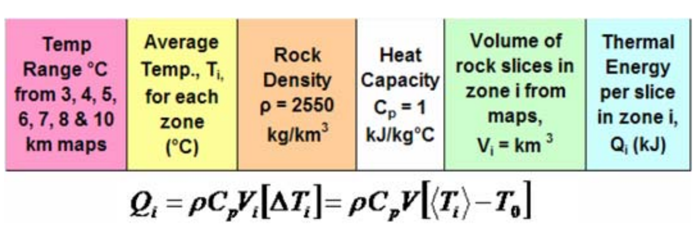

Figure 3. Flowchart for calculation of temperature and heat content at depth. *Note*: 1 kW-s = 1 kJ and angle brackets denote depth-averaging. See Appendix A for more details.

comparison to a series of precision temperature measurements made in hydrocarbon wells in thermal equilibrium and a BHT error was thus established (Blackwell and Richards, 2004b). Corrected temperatures up to a maximum depth of 3,000 m were used (4,000 m in southern Louisiana). The basic correction was similar to the AAPG BHT correction with modifications as proposed by Harrison and others (1983). A secondary correction that is a function of the local geothermal gradient was then applied so that a bias associated with the average geothermal gradient in the well was removed. This correction was checked against approximately 30 sites in the U.S. with accurate thermal logs. We believe the correction for the average gradient of a group of wells is accurate to about ±8°C at 100°C (corresponding to a gradient error of about 10%), based on comparison of the results to the measured equilibrium temperature logs.

Although there are BHT data in some areas to depths of 6 km, the maximum depth used for the correction was limited to BHT's from depths of less than 4 km because of limited information on the drilling effect for wells deeper than 4 km, and a lack of calibration wells at those depths. However, for geothermal resource potential purposes, the BHT data can be used qualitatively in places where measurements are at 4 to 6 km depths. These additional data improve the definition of areas that qualify for further EGS evaluation.

Generalized thermal conductivity models for specific geographic areas of several sedimentary basins were used to compute the heat flow associated with the BHT gradients. The results were checked against conventional heat-flow measurements in the same regions for general agreement. With the new analysis of the BHT data (Blackwell and Richards, 2004c) there is a higher confidence level in the interpreted BHT heat-flow values.

Data from the Western Geothermal Database also were used to prepare the heat-flow contour map. The heat-flow measurements were derived from thermal gradient exploration wells drilled primarily for geothermal resource exploration in the western U.S., in most situations during the late 1970's and 1980's. The raw thermal data were processed to calculate heat flow where there was sufficient information. There are site/well specific thermal conductivity data for about 50% of the sites. Estimated thermal conductivity was used for other sites (see next section).

Thermal Conductivity

For the calculation of temperature at various depths, the vertical thermal conductivity model was simplified into either one or two layers based on regional lithology. The thermal conductivity values used in the models were based on the databases described and regional basement/sedimentary maps. A histogram of thermal conductivity for the wells in the regional heat-flow data set is shown in Figure 4. The first peak in the distribution of thermal conductivity values is at about 1.4 W/m/K. This low conductivity value is characteristic of lithologies such as volcanic rock, shale, and unconsolidated material. The value of 1.4 W/m/K is dominated by the measured and assigned value for the Basin and Range valley fill wells and other high porosity rocks when no measurements were available. In the Basin and Range, most of the sites are in the valley fill. Thermal conductivity was assumed for these wells based on lithology logs or, in the absence of even these data, on well-site geology maps. There is another smaller peak in the distribution between 2.0–3.0 W/m/K. Rocks in the >2.2 W/m/K category are generally low porosity sedimentary rocks and basement lithologies (granite, metamorphic rocks, carbonates, sandstone, etc.). A value of 2.6 W/m/K was used as the crustal (basement, i.e., all rocks below the sedimentary and volcanic cover) value instead of the 2.8–3.0 W/m/K peak to partially take into account the effect of temperature on thermal conductivity, which ranges from 5 to 10% per 100°C change in temperature.

A one layer model was used for areas in the eastern U.S. with basement at the surface and for most of the Cordillera except as discussed. A 2-layer model was used for some areas based on the effect of reduction of porosity and mineralogical changes in general and especially for low-conductivity shale and in volcanic rock resulting from compaction and temperature effects above 60–80°C. A value of thermal conductivity of 2.6 W/m/K was assumed for the basement. This value was based on the median of the thermal conductivity values for basement rocks from the regional heat-flow database. In some of the sedimentary basins, an upper layer of low thermal conductivity underlain by the 2.6 W/m/K value, identical to the assumed basement value was assumed. The sedimentary basins where this model was applied are described next.

Within the two models, regional values of thermal conductivity in the upper 2 to 4 km are based

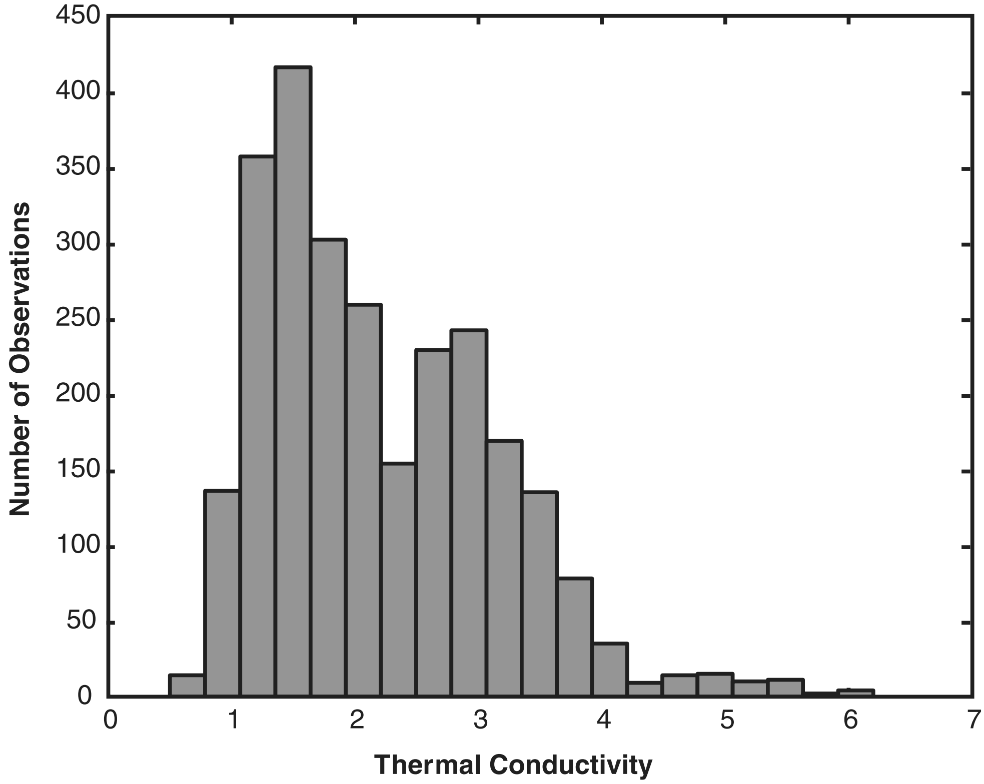

Figure 4. Histogram of the in situ thermal conductivity, *K* in the regional heat flow database. The data show a bimodal distribution, with peaks around 1.5 and 2.5–3 W/m/K, corresponding to mean conductivities for basin fill/volcanics and consolidated sediments/basement rocks respectively.

on generalized rock distributions. Parts of the Pacific Northwest and Great Basin were assigned values of thermal conductivity of 2.0 W/m/K to a depth of 2 km to approximate the mean value representative of combined basement, volcanic, and Cenozoic rift basin lithologies. In the areas of the Salton Sea/Imperial Valley and the Los Angeles Basin the upper 2 km of section also was assigned a thermal conductivity value of 2.0 W/m/K. Thus, the vertical thermal conductivity distribution in sedimentary and volcanic sections is considered only on a semiregional scale.

There are lateral and vertical variations of almost 100 % in the thermal conductivity within the sedimentary section. Typical thermal conductivity values for the different lithologies, based on measurements in the Midcontinent region, are given by Blackwell and Steele (1989), Gallardo and Blackwell (1999), Carter and others (1998), Gosnold (1990), and Speece and others (1985) for example. The highest thermal conductivity values (>3.4 W/m/K) for relatively thick intervals on a regional basis are associated with areas where Paleozoic carbonates and evaporates dominate the section in basin regions such as in the Michigan, Illinois, southern Anadarko, and Delaware basins. These details were beyond our ability to quantify at the scale of the gridding so some generalizations of the thermal conductivity structure were assumed.

Using the 2-layer model, high thermal conductivity areas were assigned a value of 2.6 W/m/K value starting at zero depth. Lower thermal conductivity values (<2.0 W/m/K on a regional basis) were assigned in areas where a significant part of the upper section is shale, such as in the Great Plains (Williston Basin) where there are thick Cretaceous shales, Anadarko Basin (central part) with thick Paleozoic shales sections and in the northern Allegheny area (Paleozoic shales). Because of these generalizations, detailed studies are necessary to identify the most favorable local locations from the point of view of temperature and lithology.

Geothermal Gradients

By dividing the thermal conductivity into the heat flow, mean gradients can be obtained. However, the approach used here to compute the specific depth temperatures does not require directly the use of geothermal gradients, although in some publications they are preferred because they are easier to understand than the heat flow. We start with the heat-flow value because in a single well the gradients can differ by as much as a factor of five or more depending on the thermal conductivity of the rocks, resulting in a lithologic (depth of measurement) bias. The gradients computed from the heat-flow map are smoother, appropriate with the scale of this study, and more regionally characteristic than some existing gradient compilations (Kron and Stix, 1982; Nathenson and Guffanti, 1980). On a regional basis those gradients can range from 15°C/km to more than 50°C/km, excluding of course the high gradients in hydrothermal areas.

Sediment Thickness

A map of the thickness of sedimentary cover was prepared by digitizing the elevation of the basement map published by the AAPG (1978). The basement elevation was converted to thickness by subtracting its value from the digital topography. The resulting map is illustrated in Figure 5. Sediment thickness is highly variable from place to place in the tectonic regions in the Western U.S. and, for this reason, most of the areas of deformation in the Western U.S. do not have basement contours on the AAPG map. Because of the complexity and lack of data, the sediment/basement division in the Cordillera is not shown, with the exception of the Colorado Plateau (eastern Utah and western Colorado), the Middle Rocky Mountains (Wyoming), and the Great Valley of California. The area of most uncertainty is the Northern Rocky Mountain/Sevier thrust belt of the Cordillera. In that area basement thermal conductivity was assumed.

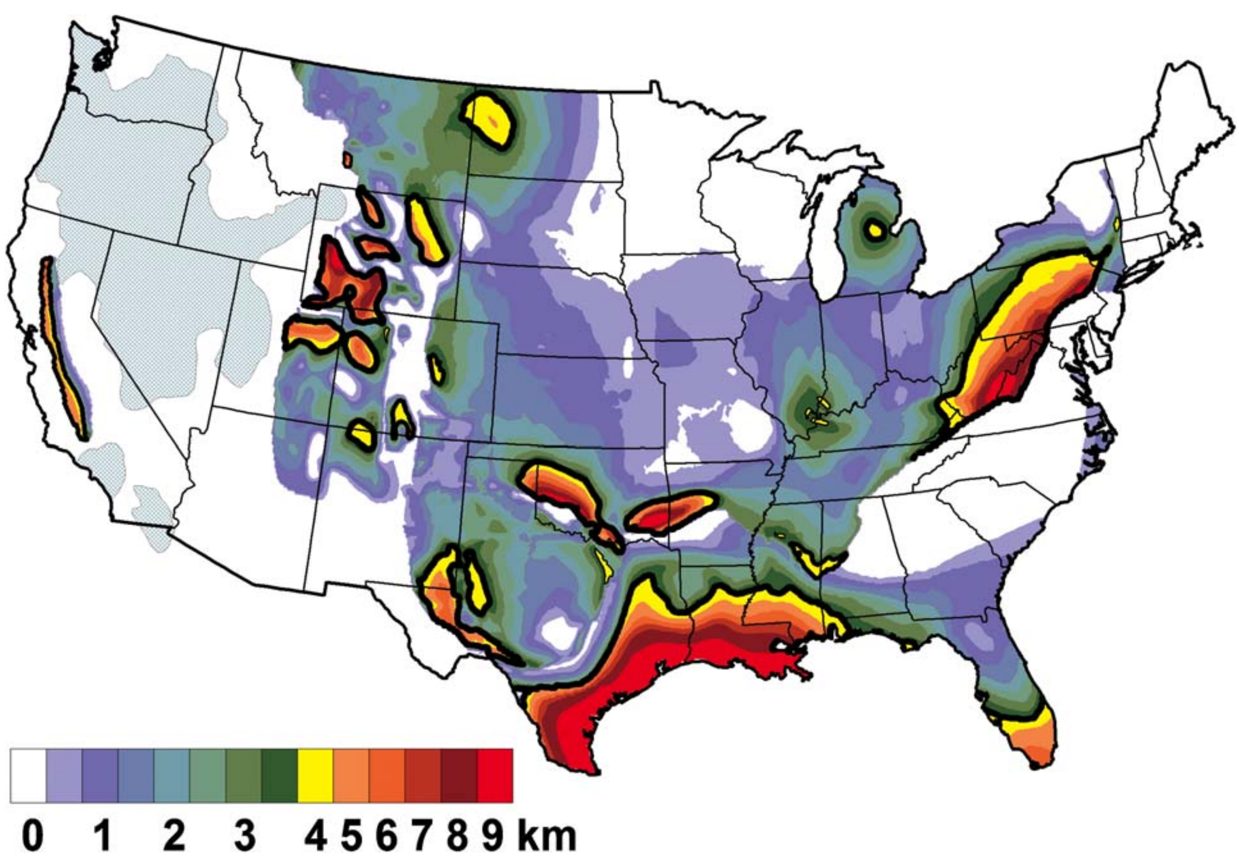

Figure 5. Sediment thickness map (in km, modified from AAPG Basement Map of North America, 1978). The 4 km depth contour is outlined with a bold black line. The low conductivity areas in the western U.S. are shown as patterned areas.

In the Basin and Range and the Southern and Middle Rocky Mountains there are smaller, but locally deep basins filled with low thermal conductivity material. The scale of this study is such that these areas are not examined in detail and considerable variations are possible in those regions, both hotter and colder than predicted. A more detailed map of the Great Basin and its margins was prepared at a gridding interval of 2.5′ for regional resource evaluation purposes (Coolbaugh and others, 2005a, 2005b).

The map in Figure 5 indicates regional scale areas that might be of interest for EGS development in the sediment section and areas of interest for basement EGS. East of the Rocky Mountains, with the exception of the Anadarko Basin, the Gulf Coast, and the eastern edge of the Allegheny Basin, sedimentary thickness does not exceed 4 km except in localized regions. Thus east of the Rocky Mountains and outside the areas identified by the heavy lines on Figure 5, EGS (or other geothermal) development would be in basement settings.

The sediment thickness influences the temperature calculations in two ways. First, as previously discussed in the conductivity section, the sedimentary rocks have in general lower conductivity than most of the basement rocks, and the geothermal gradients will be higher. The second effect is because of the radioactive heat distribution, and is discussed in the next section.

Tectonic and Radioactive Components of Heat Flow

The heat flow at the surface is composed of two main components that may of course be perturbed by local effects; that is, the heat generated by radioactive elements in the crust and the tectonic component of heat flow that comes from the interior of the Earth. The radioactive component ranges from 0 to more than 100 mW/m^2 with a typical value of about 25 mW/m^2. The characteristic depth of the radioelements (U, Th, and K) in the crust averages between 7 to 10 km (Roy, Blackwell, and Decker, 1972) so that most of the variation in heat flow caused by radioactivity variations is above that depth. This component can be large and locally is variable and thus there can be areas of high heat flow even in areas that are considered stable continent. For example in the White Mountains in New Hampshire the heat flow is as high as 100 mW/m^2 because of the extreme natural radioactivity of the granite there (Birch, Roy, and Decker, 1968). Also there is an area of high heat flow and basement radioactivity in northern Illinois (Roy, Rahman, and Blackwell, 1989). In contrast the surface heat flow is only 30 mW/m^2 in parts of the Adirondack Mountains because the upper crustal rocks there have small radioelement content.

In the analysis of temperatures to 10 km, the component of heat flow not related to crustal radioactivity must be known. Fortunately the discovery of the linear heat flow heat generation relationship allows a quantification of this parameter. For the majority of the area, two different heat-flow values were used: 60 mW/m^2 for the high heat flow regions in the west and 30 mW/m^2 for most of the rest of the map area (see Roy, Blackwell, and Decker, 1972; Morgan and Gosnold, 1989). The area of high mantle heat flow is shown as the shaded area in Figure 6. The high mantle heat flow is a result of the plate tectonic activity (subduction) that has occurred along the west coast of North America over the past 100 Ma. Part of the Cascade Range in the Pacific Northwest and part of the Snake River Plain were assigned mantle heat flow values of 80 mW/m^2 because they are associated directly with geologically young volcanism (Brott, Blackwell, and Mitchell, 1978; Blackwell and others, 1990a, 1990b). Finally part of the Great Valley/Sierra Nevada Mountains areas were given a mantle heat flow of 20 mW/m^2 compatible with the outer arc tectonic setting in those areas (see Morgan and Gosnold, 1989; Blackwell, Steele, and Carter, 1991). Transitions in heat flow between these different areas are generally sharp on the scale of the map but are difficult to recognize in some locations because of the variable heat flow resulting from the upper crustal effects. At the maximum depth of 10 km used in this study the relative effects of heat production and mantle heat flow on temperature are similar, but as deeper and deeper depths are considered the mantle heat flow factor become dominant.

The radioactivity value of the basement is highly variable and has only been measured in a few places. To determine the average radioactivity value appropriate at each calculation node is impractical. Therefore the Q-A model was assumed to hold and the radioactivity value for each node was assumed to be the surface heat flow (Q_0) minus the mantle (m) heat flow (Qm) divided by 10 km. Thus at each basement node the surface heat flow is assumed to be exactly on the Q-A line with a slope of 10 km and an intercept given by the mantle heat-flow value in Figure 6.

In general the radioactive heat generation is significant to a depth of 10 to 20 km. As modeled it was assumed to decay exponentially with depth in

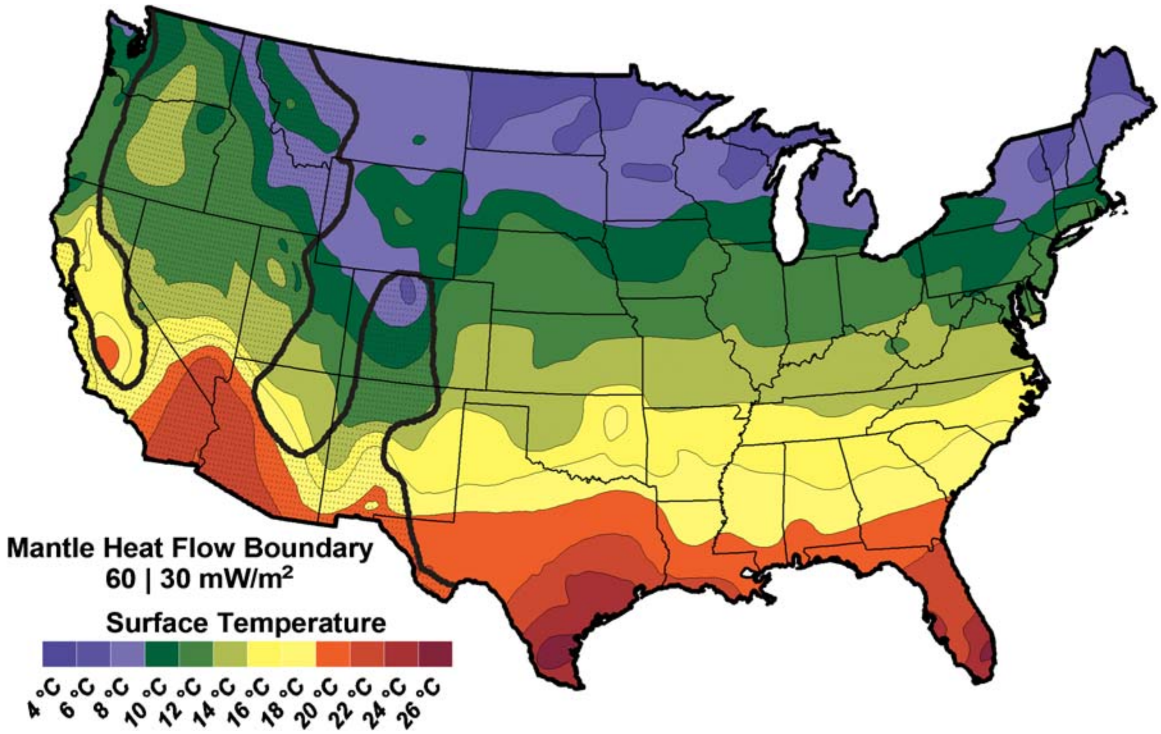

Figure 6. Map of surface temperature (Gass, 1982) and generalized mantle heat flow for the conterminous United States.

basement rocks, consistent with a general trend from granitic rocks at the surface to mafic or high-grade metamorphic rocks at depths. For sedimentary basins the radioactive heat is primarily a function of the thickness of shale in the sedimentary column. However for sedimentary basins a constant heat generation value was used for the complete sedimentary section (1 $\mu W/m^3$).

In the situation of thick sedimentary basins the radioactive scale constant in the underlying basement was assumed to be lowered in proportion to the thickness of the sedimentary section. If the sediment thickness exceeded 3 km, then the exponential factor of the layer with exponential distribution (b) was decreased below 10 km by 1 km for each km of sediment more than 3 km. More details are given in the Appendix.

Ground Surface Temperature

The mean ground surface temperature is shown in Figure 6. This temperature represents the lowest value of the average heat rejection temperature for any energy conversion scheme and the starting point for the temperature depth calculation. The values are from measurements of temperature in shallow groundwater wells (Gass, 1982). The mean ground surface temperature varies from over 26°C in south Texas to less than 4°C in North Dakota. These temperatures can be used as shown in Figure 3 to calculate maximum attainable temperature differences which can then be used to calculate the thermal energy content of a rock volume for any U.S. region (difference of the rock temperature at depth and the average surface temperature).

RESULTS

To calculate the total resources, various geological factors are needed: the heat content, the stress regime, the geology of the basement, and the permeability. The heat content is the primary objective of this paper and will be discussed in more detail.

Heat (Thermal Energy) Content

The results of the analysis are presented as temperature at depth and as thermal energy (or "heat") in place for the conterminous U.S. The temperatures were calculated from the depths of 1 to 10 km at every km. Maps of the temperature at 4 km, 6 km, and 10 km depths are shown in Figure 7. Heat-in-place was calculated and is listed in the Table 3 for 1 km × 1 km × 1 km blocks centered at depths of 4.5, 6.5, and 9.5 km using the assumptions and equations shown in Figure 3. A more detailed calculation at depths of 3.5, 4.5, 5.5, 6.5, 7.5, 8.5 and 9.5 km is included in Tester and others (2006). The values listed in Table 3 and shown in histogram form in Figure 8 represent the geothermal resource base and not the amount of electrical power that can be generated. For demonstration purposes, the values are shown in terms of stored thermal energy, namely, exajoules (EJ = 10^{18} J). The only area excluded from the calculation is Yellowstone National Park (8980 km^2) for the depths of 3.5 to 6.5 km. The Yellowstone region represents a large area of high temperature and so its exclusion affects the resource base calculation of areas with high temperatures at shallow depths.

The histogram in Figure 8 shows that there is a tremendous resource base between the depths of 3.0 to 10 km in the temperature range of 150 to 250°C. Even if only 2 % of the resource were to be developed, the thermal energy recovered would be 250,000 EJ. This amount is roughly 2,500 times the annual consumption of primary energy in the U.S. in 2006. The resource base of thermal energy is thus enormous and relatively widely distributed.

The accuracy of the calculations of temperature at depth is a factor in the analysis. In the areas of hydrocarbon development there are wells drilled from 3 km to more than 6 km (10,000 to more than 19,000 ft) depths, so that the predicted temperatures can be checked against measurements in deep wells. In the situation of the areas represented in the AAPG BHT database this comparison has been done and the agreement is within ±20°C in the 3 to 6 km depth range. In the areas of geothermal drilling there is some information outside of the immediate influence of geothermal systems and there are a few research wells that serve as data points at depth. This information has been compared to the calculated values with similar results to the BHT comparison. Of more practical relevance is the fact that the analysis is regional in the sense that the grid interval is 5′ × 5′ or approximately 25 km^2.

Crustal Stress and Permeability

Data on the state of stress are discussed by (Zoback and Zoback, 1991; Zoback and others, 1991). All varieties of stress regimes are represented in the conterminous U.S. For example the stress regime is extensional in areas such as the Basin and Range and the Gulf Coast, compressional in parts of the eastern U.S. and locally in the state of Washington. Strike-slip stresses are also typical of large areas such as along the transform plate in California. However, there are large areas that are not well-characterized; detailed resource evaluation in these areas will have to include stress studies. Because the stress regime determines drilling strategies, and because in opening fractures, the most favorable ones are along the direction of maximum shearing stress, it is important to have information on regional stress direction and magnitude in the planning of EGS geothermal development.

There is not enough information to determine the optimum stress regime for EGS geothermal system development (Tester and others, 2006, Chapter 3). In Australia the planned development in the Cooper Basin is in a highly compressive regime with geopressured conditions (Wyborn, de Graaf, and Hann, 2005) whereas at the Soultz area in Europe and the Fenton Hill, New Mexico sites the stress regime is extensional (Elsass and others, 1995; Duffield and others, 1981). In spite of the high shut-in pressure at the Australian site a subhorizontal reservoir several km^2 in area has been produced there.

Crustal permeability is the most difficult parameter to measure and is highly variable in distribution and value. Permeability may be in the form of pore space in a sedimentary rock such as in a sand or as fractures in any type of rock strong enough to fracture. The Hot Dry Rock concept originally focused on granite because of its supposed homogeneity. However fracture systems have proved hard to predict a priori. As discussed next silicic sedimentary rocks actually may have advantages over basement rocks. Actual field tests and experience are necessary to optimally plan the subsurface reservoirs.

Geology of the “Basement”

Because basement usually is defined as areas of metamorphic or igneous rocks, the composition and lithology of “basement” is extremely variable. The basement lithology below the sedimentary cover, where present, is as complicated as the surface exposures. Quantification of the most favorable rock composition and structure for EGS development remains to be done. Most of the experimental EGS sites have

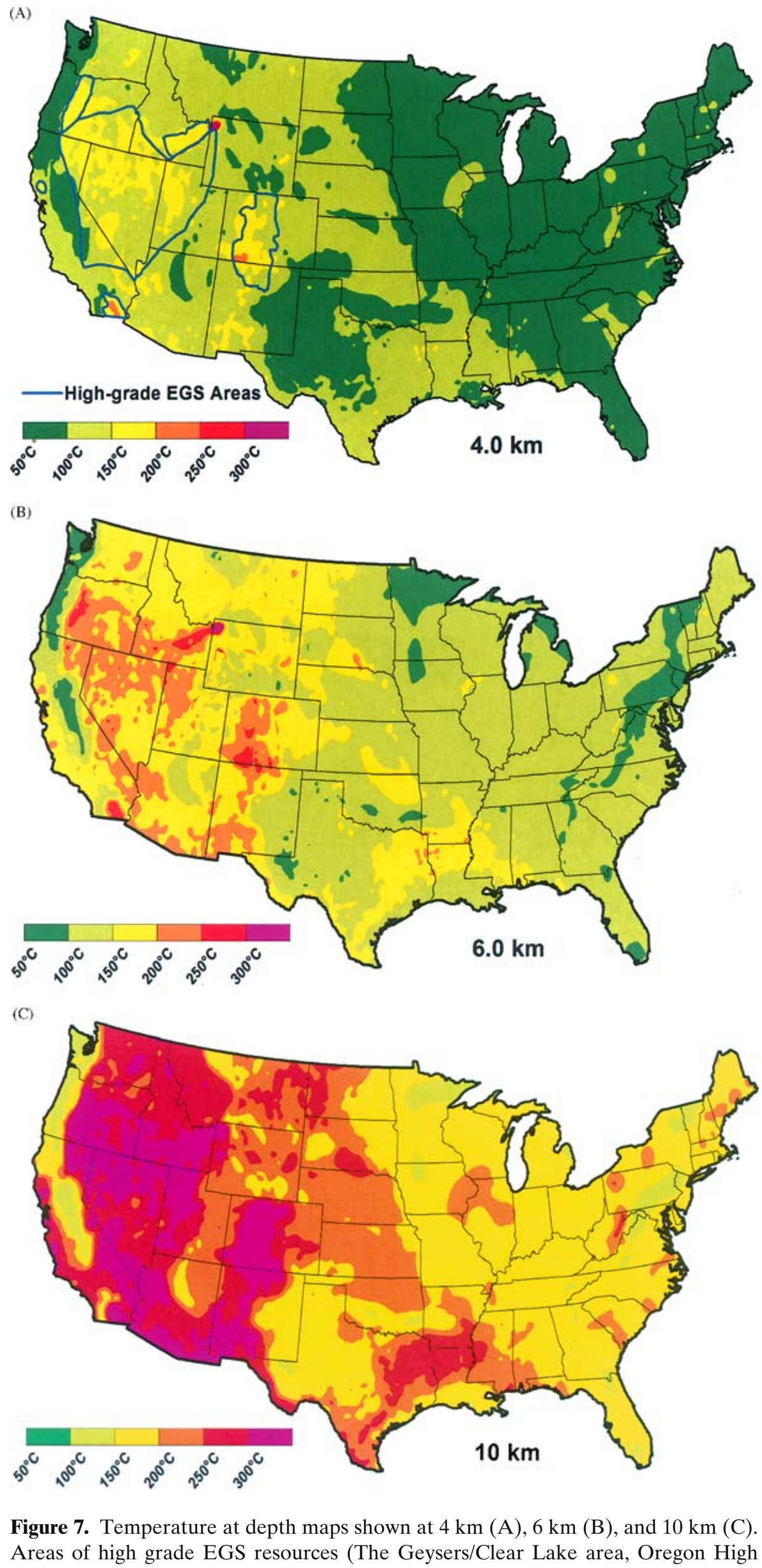

Figure 7. Temperature at depth maps shown at 4 km (A), 6 km (B), and 10 km (C). Areas of high grade EGS resources (The Geysers/Clear Lake area, Oregon High Cascade Range, Basin and Range, Southern Rocky Mountains, and Salton Trough) are outlined in blue on 7A.

Table 3. Heat in Place (Exajoules = 10^{18} J)

	AK[1]	AL	AR	AZ	CA[2]	CO	FL	GA	IA	ID	IL
4.5 km DEPTH											
Temp °C											
150	39,588	34	6,361	49,886	53,068	45,890	0	0	0	36,008	0
200		0	0	0	4,734	8,413	0	0	0	7,218	0
250		0	0	0	407		0	0	0	112	0
300		0	0	0	796		0	0	0	0	0
6.5 km DEPTH											
Temp °C											
150	361,688	9,148	20,725	52,335	54,243	54,667	4,339	95	10,729	35,257	2,005
200	187,722	60	6,373	74,305	70,941	51,170	2	0	0	53,875	
250		0	0	473	9,186	24,029	0	0	0	19,510	
300		0	0	0	176	1,077	0	0	0	359	
10 km DEPTH											
Temp °C											
150	25,073	42,643	26,260	9,922	36,089	4,316	48,062	57,485	43,425	0	40,906
200	122,877	16,317	25,125	39,467	31,336	47,131	6,019	3,571	16,970	2,346	26,368
250	520,597	111	18,635	64,525	73,812	45,614	5	0	0	71,702	
300	199,506	0	296	80,190	77,307	57,944	0	0	0	52,488	
350		0	0	1,500	12,844	33,251	0	0	0	28,138	
Totals	3,203,825	115,655	229,089	777,471	888,460	798,437	60,494	58,424	126,100	673,966	186,123

	IN	KS	KY	LA	ME	MI	MN	MO	MS	MT	NC
4.5 km DEPTH											
Temp °C											
150	0	0	0	11,455	0	0	0	0	1,512	8,373	0
200	0	0	0		0	0	0	0			0
250	0	0	0		0	0	0	0			0
300	0	0	0		0	0	0	0			0
6.5 km DEPTH											
Temp °C											
150	0	57,556	0	15,280	785	0	0	84	31,807	123,860	2,036
200	0		0	11,028	0	0	0	0	1,158	13,265	0
250	0		0		0	0	0	0		25	0
300	0		0		0	0	0	0			0
10 km DEPTH											
Temp °C											
150	39,003	18,783	42,897	20,773	26,757	56,156	66,215	74,394	14,621	22,297	45,834
200	0	94,326	41	10,147	9,379	0	0	2,366	38,876	72,761	6,103
250	0		0	27,943	0	0	0	0	9,192	128,534	33
300	0		0		0	0	0	0	50	2,803	0
350	0		0		0	0	0	0		52	0
Totals	95,956	345,689	88,100	201,019	99,126	44,852	35,789	176,684	209,528	840,312	71,437

Table 3. Continued

	ND	NE	NH	TX	UT	VA	WA	WI
4.5 km DEPTH								
Temp °C								
150	3,845	848	0	32,528	36,521	0	9,796	0
200	0	0		14	1,160	0		0
250	0	0			0	0		0
300	0	0			0	0		0
6.5 km DEPTH								
Temp °C								
150	36,938	60,446	1,050	117,096	50,085	991	44,388	1,733
200	2,534	1,018		21,659	44,178	0	13,290	0
250	0	0			8,626	0		0
300	0	0			0	0		0
10 km DEPTH								
Temp °C								
150	34,198	6,358	6,780	144,600	1,539	30,176	4,678	56,012
200	36,978	96,021	3,032	113,021	44,520	3,849	14,189	5,811
250	22,759	4,404		86,151	38,391	0	60,195	0
300	13	0		2,723	50,546	0	11,641	0
350	0	0			11,554	0		0
Totals	289,756	341,935	22,657	1,068,217	612,202	50,796	338,324	102,155

	WV	WY[3]	MA_CT_RI_VT	MD_NJ_DE	Continental U.S.A.[4]
4.5 km DEPTH					
Temp °C					
150		6,795	0	0	518,041
200		203		0	29,930
250		8		0	734
300		0		0	965
6.5 km DEPTH					
Temp °C					
150	3,367	68,411	183	468	1,062,065
200		7,132		0	641,638
250		334		0	94,405
300		177		0	2,268
10 km DEPTH					
Temp °C					
150	15,476	19,107	19,078	13,851	1,446,607
200	7,479	84,380	1,377	728	1,057,978
250	2,377	27,437		464	914,277
300		3,240		0	620,849
350		493		0	132,479
Totals	63,626	471,799	37,419	23,033	13,267,370

Note. Footnotes for Appendix
[1] Alaska does not include the Aleutians.
[2] California has the addition of the Clear Lake and Salton Sea areas for 4.5 km.
[3] Wyoming does not include Yellowstone National Park (8987 km^2).
[4] Continental U.S. - Does not include Alaska or Hawaii, as well as Yellowstone National Park.

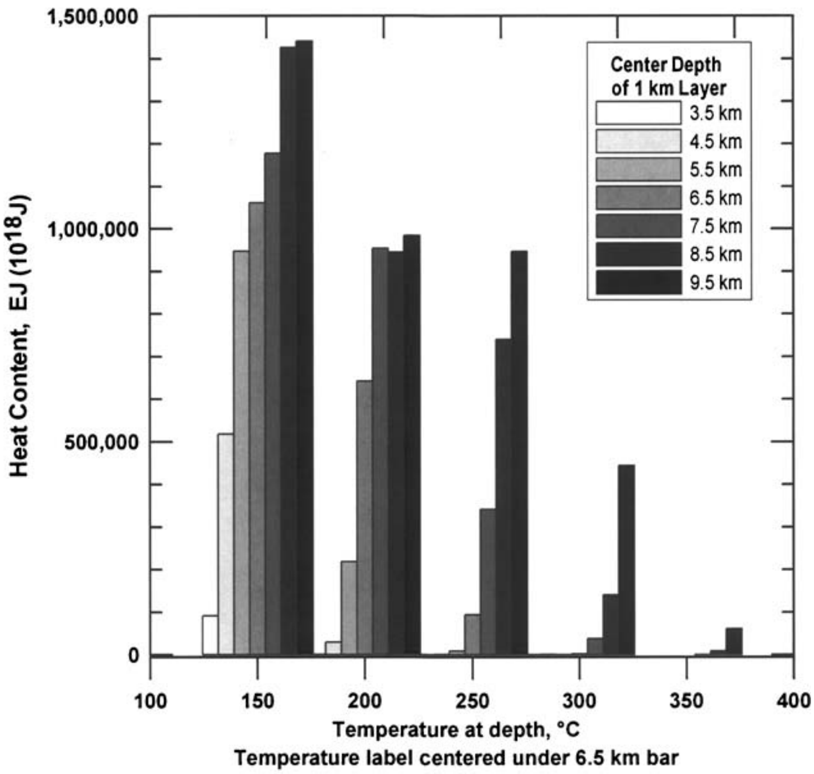

Figure 8. Histograms of heat content for conterminous U.S. as a function of depth for 1 km slices.

been in granite because of the expected homogeneity of the rock type. In fact there may be situations where layered rocks might be equally or more favorable as the orientations of fractures might be easier to predict and the rock types may be fractured more extensively in the natural condition. From another point of view, the lithology also affects the heat flow in the form of its radioactivity content and the resulting heat flow. As has already been described areas of high radioactivity will have higher heat flow and so may have higher temperatures, all other factors being similar.

Regional EGS Resource Areas

There are some large areas that have high temperatures at relatively shallow depths (3–5 km) that deserve special mention as near-term EGS development candidates. These generally are in the western U.S, but are not confined to the areas that are presently developed as conventional hydrothermal geothermal systems. The most prominent of these areas are listed in Table 4. They include the Great Basin, the Snake River Plain, the Oregon Cascade Range, the Southern Rocky Mountains, the Salton Sea, and the Geysers/Clear Lake areas (see Fig. 7). In all of these areas detailed site studies could locate large areas of temperatures of more than 200°C at less than 4 km.

One area that has received previous study is the Geysers/Clear Lake region in California (Stone, 1992). Although the Geysers steam field is part of the area, exploration for other steam deposits has identified a large area that is hot at shallow depth, but does not have enough permeability for conventional hydrothermal systems to exist. An interpretation of the temperatures at depth in the area is shown in Figure 9 (Erkan, Blackwell, and Leidig, 2005). Temperature maps at 2, 3, 4, and 5 km are shown based on the interpretation of more than 600 drill sites. The actual area of steam development (Stone, 1992) is shown as the hachure area in the first panel. Even outside this area and away from its periphery, temperatures are interpreted to exceed 200°C at 3 km from an area about 20 by 30 km. There may be an area almost as

Table 4. High-Grade EGS Areas (>200°C at Depths of About 4 km)

Region	Characteristics
Great Basin	30% of the 500 km × 500 km area is at temperatures >200°C. Highly variable geologic and thermal conditions with some drilling confirming deep conditions. Large-scale fluid flow both laterally and horizontally so extensive fracturing at depth in many areas. The stress regime is extensional. Rocks are highly variable with depths of 4–10 km mostly sedimentary with some granite and other basement rock types.
Snake River Plain and margins	75% of the 75 km × 500 km area is at temperatures >200°C. Details of the geology at depths of 3–10 km unknown, probably volcanics and sediments overlying granitic basement at 3–5 km, low permeability. The stress regime is unknown, existing fracturing may be limited.
Oregon Cascade Range	25% of the 50 km × 200 km area is at. High, uniform temps. & geology (volcanic and intrusive rocks dominate)-accessibility to the margins. The stratovolcanoes are excluded from the analysis. Conditions are more variable in California and Washington but some high-grade resources probably exist there as well.
Southern Rocky Mountains	25% of the 100 km × 300 km area is at temperatures >200°C. Geology is variable. Can have sediments over basement, generally thermal conditions in basement are unknown. Both high crustal radioactivity and high mantle heat flow contribute to surface heat flow. Probably highest basement EGS potential on a large scale.
Salton Sea	75% of the 25 km × 50 km area is at temperatures >200°C. Young sedimentary basin with very high heat flow, young metamorphosed sedimentary rocks at depth. There is extensive drilling in the existing geothermal systems and limited background data available from hydrocarbon exploration.
Clear Lake Volcanic Field	50% of the 30 × 30 km area is at temperatures >200°C (steam reservoir is 5 km × 10 km). Low permeability Franciscan sediments, may find granite at deeper depths. Possible access problems. Significant deep drilling with temperatures of 200°C at 2 km over a large area.

large, with temperatures more than 350°C at 5 km. In this area, supercritical geothermal conditions also might exist.

The island of Hawaii and the volcanoes of the Aleutian chain in Alaska have the best possibility for the development of supercritical geothermal resources (Tester and others, 2006) in the United States if the viability of such development becomes feasible. Extensive interest in such development exists in Iceland where drilling into such systems is planned in the near future (Fridleifsson and Elders, 2004). Supercritical systems and other volcanic/magmatic systems are not included in this discussion, however.

STRATEGIES FOR EGS DEVELOPMENT

Unnconventional EGS Associated with Co-produced Fluids and Geopressured Fluids

Several areas identified by the resource maps (Fig. 7) with temperatures in the development range (90 to 125°C with binary systems) are areas of extensive drilling for hydrocarbons. Temperatures typically reach 150°C and may reach more than 200°C (300°F to more than 400°F). For example, parts of eastern and southern Texas and northwestern Louisiana are characterized by temperatures in excess of 150°C (300°F) at depths of 4 to 6 km (13,000 ft to 19,700 ft) (McKenna and Blackwell, 2005; McKenna and others, 2005) (see Fig. 7). Data from BHT and high-resolution log segments in wells in south Texas indicate temperatures of more than 200°C (400°F) at 5 km (16,000 ft). In eastern Texas, temperatures are more than 150°C in the depth range of 3.5 to 4 km (11,000 to 13,000 ft). And, in northwest Louisiana, BHTs and equilibrium temperature logs document temperatures of 120–160°C at only 3 km (10,000 ft, Blackwell, Steele, and Carter, 1993). Because *in situ* thermal conditions have been verified in these specific areas, the substantial areal extent of potential geothermal resources in these areas shown in Figure 7 is clearly valid.

In these areas significant porosity and permeability exists at depths of 3 to 6 km and there is potential for the production of large amounts of hot water either with or without stimulation of the sedimentary rock reservoirs. In some of these examples, there may be the opportunity to produce fluid flows high enough to generate significant quantities of geothermal energy without having to create a new reservoir, or with relatively minor modifications of an existing oil or gas reservoir. So the distinction between an EGS system and a natural hydrothermal system is somewhat blurred. In these areas, there is also a developed infrastructure and an existing energy industry presence. Therefore, it seems possible that EGS or hybrid geothermal systems might

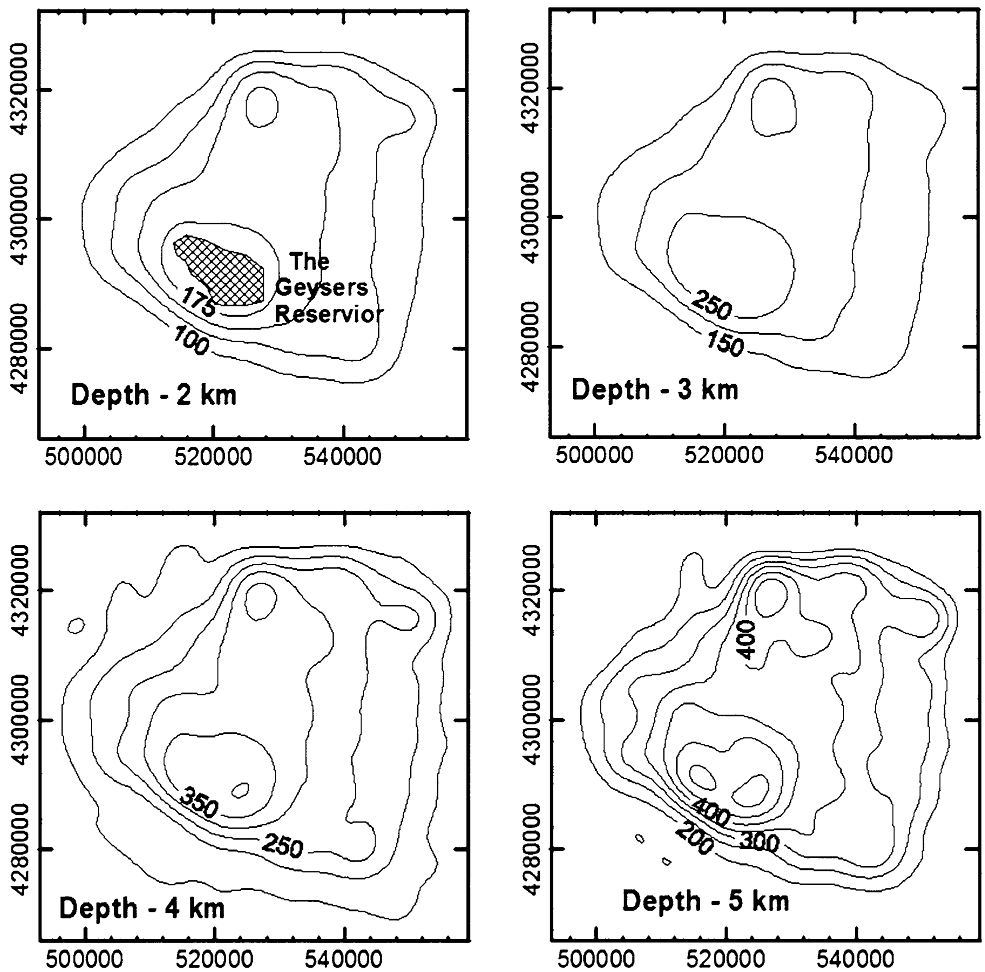

Figure 9. Temperatures in C° at depths of 2 to 5 km in The Geysers/Clear Lake thermal area (Erkan, Blackwell, and Leidig, 2005).

be developed in these types of areas before the transition is made to pure start-from-scratch EGS systems (McKenna and others, 2005). For the purpose of this report, these situations are divided into three categories, more or less in order of expense to develop: Co-produced Fluids, Geopressured Fluids, and Sedimentary EGS. In Table 5 coproduced hot water from oil and gas production has been included as an unconventional EGS resource type, because it could be developed in the short term and provide a first step to more classical EGS exploitation.

In addition to high temperature, a geothermal development requires large-volume flows of water, on the order of 500 to 1,000 gallons per minute (GPM) per MW (depending on the temperature). There are two typical types of existing situations associated with hydrocarbon development that are favorable for geothermal development. The first might be considered "conventional" hydrothermal development, in that high volumes of water are produced in some fields as a byproduct of hydrocarbon production. This situation exists, for example, in massive water-flood secondary recovery fields. Curtice and Dalrymple (2004) show that co-produced water in the conterminous United States amounts to at least 40 billion barrels per year, primarily concentrated in a handful of states (e.g. Texas, Oklahoma, California, Wyoming, Louisiana). In most mature hydrocarbon fields, the disposal of co-produced water is an expensive problem (Veil and others, 2004).

The factors required for successful geothermal electrical power generation are sufficiently high fluid flow rates for a well or a group of wells in relatively close proximity to each other, at temperatures in excess of about 100°C (212°F). Oklahoma and Texas alone produce more than 24 billion barrels

Table 5. Equivalent Geothermal Power From Co-produced Hot Water Associated With Existing Hydrocarbon Production in Selected States (A complete listing is given in Tester and others, 2006; modified from McKenna and others, 2005.) (bbl = 42 gallon barrels per day, GPM = gallons per minute)

State	Total Water Produced Annually, in 1,000 bbl	Total Water Production Rate, kGPM	Equivalent Power, MW @ 100°C	Equivalent Power, MW @ 140°C	Equivalent Power, MW @ 180°C
Alabama	203,223	18	18	47	88
Arkansas	258,095	23	23	59	112
California	5,080,065	459	462	1,169	2,205
Florida	160,412	15	15	37	70
Louisiana	2,136,573	193	194	492	928
Mississippi	592,518	54	54	136	257
Oklahoma	12,423,264	1,124	1,129	2,860	5,393
Texas	12,097,990	1,094	1,099	2,785	5,252
Totals	32,952,141	2,980	2,994	7,585	14,305

of water per year. In certain waterflood fields in the Gulf Coast region – particularly in northeastern Texas, southwestern Arkansas, and coastal Alabama/Mississippi – more than 50,000 barrels/day of fluid are produced, and paid for (in terms of pumping and disposal costs) by existing operations. Collecting and passing the fluid through a binary system electrical power plant could be a straightforward process; because, in some situations, the produced fluid already is passed to a central collection facility for hydrocarbon separation and water disposal. Hence, piggy-backing on existing infrastructure should eliminate the need for expensive drilling and hydrofracturing operations, thereby reducing the risk and major fraction of the upfront cost of geothermal electrical power production. There is not actual information available for the temperature of the waters available, so example calculations are shown for extreme situations of temperature. If the produced water is exploited for electric power production, the resulting power potential from contemporary binary plants is substantial as shown in Table 5.

Some of the fluid is produced from dispersed sites and may be too distributed for power use. However, these figures do give an idea of the absolute minimum of fluid that can be easily produced; and, if collected, could be a feedstock for existing EGS reservoirs or new EGS types of applications. Its use in this way would also mitigate the environmental problems associated with disposal, by introducing a beneficial use of the waste product and could ultimately lower the cost of some forms of hydrocarbon extraction. The figures for equivalent power in Table 5 represent an upper limit for electricity that could be brought online with relatively low invested cost using all co-produced fluids. The primary unknowns and limiting factors in existing hydrocarbon fields are the magnitude of the combined flow rates and the actual temperature of the produced fluid.

Geopressured Geothermal Resources

The second category of unconventional geothermal systems generally is in sedimentary rock and is represented by the geopressured areas of deep sedimentary basins where wells produce at fluid pressures much higher than hydrostatic. The largest areas are in the young Gulf Coast sedimentary basin, but other deep basins also have geopressured conditions. The geothermal potential of geopressured zones in the northern Gulf of Mexico basin was evaluated in some detail by Papadopulos and others (1975) and by Wallace and others (1979). Papadopulos and others (1975) noted, "Unlike other geothermal areas that are being considered for the development of energy, the energy potential of the waters in the geopressured-geothermal areas of the northern Gulf of Mexico is not limited to thermal energy. The abnormally high fluid pressures that have resulted from the compartmentalization of the sand and shale beds that contain these hot waters are a potential source for the development of mechanical (hydraulic) energy. In addition, dissolved natural gas, primarily methane, contributes significantly to the energy potential of these waters." So the development of this type of geothermal resource also will result in the recovery of significant amounts of natural gas that otherwise would be uneconomic.

Papadopulos and others (1975) assessed the resource potential of geopressured-geothermal reservoirs within the onshore part of Tertiary sediments,

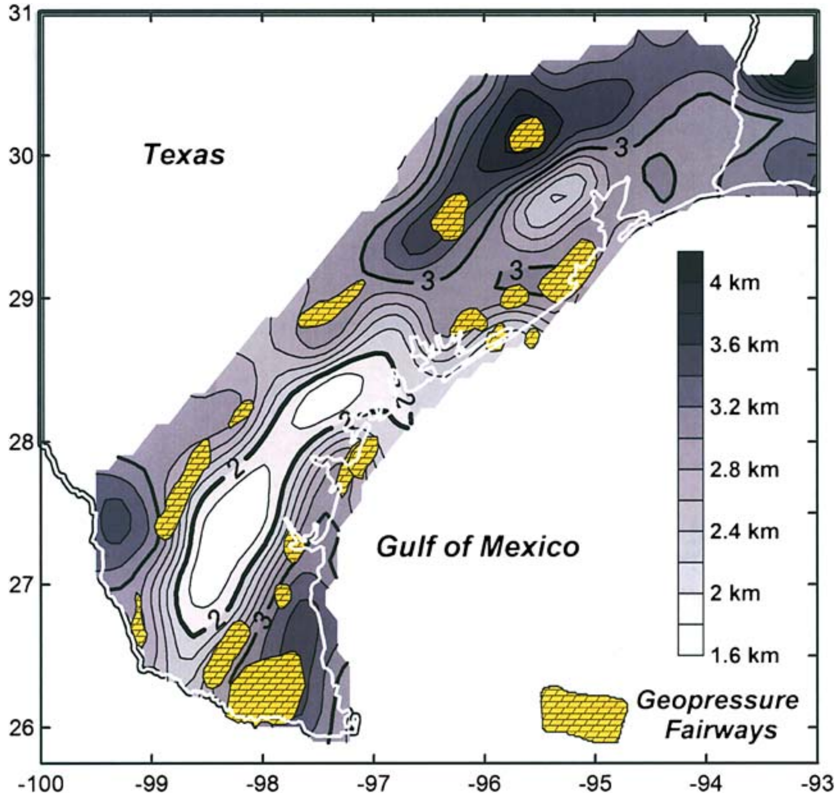

Figure 10. Location map showing the top of geopressured zones in km and geothermal "fairways" as defined by Gregory and others (1980).

under an area of more than 145,000 km^2 along the Texas and Louisiana Gulf Coast – this represents about half of the total area with geopressured conditions (see Fig. 10 where the depth to geopressure in the Texas Gulf Coast is contoured). The assessment included only the pore fluids of sediments in the interval between the top of the geopressured zones and the maximum depth of well control in 1975; that is, a depth of 6 km in Texas and 7 km in Louisiana. They did not include the resource potential of geopressured reservoirs within (i) onshore Tertiary sediments in the interval between the depth of maximum well control and 10 km, (ii) offshore Tertiary sediments, and (iii) Cretaceous sediments.

In contrast to geothermal areas of the western United States, subsurface information is abundant for the geopressured-geothermal area of the northern Gulf of Mexico basin. Hundreds of thousands of wells have been drilled in search of petroleum deposits in the Texas and Louisiana Gulf Coast. They stated that their information on geologic structure, sand thickness, temperature, and pressure were adequate for the purpose of their study. On the other hand, they noted a lack of sufficient data on porosity, permeability, and salinity.

The results of the assessment by Papadopulos and others (1975) were incorporated into the final conclusions of the overall geothermal resource assessment of Circular 726 (White and Williams, 1975). Based on their analysis, they assessed the thermal resource base to be 46,000 EJ and the methane volume to be 23,700 $\times$ 10^{12} SCF, with a thermal equivalent of 25,000 EJ. The resource base, according to their calculations, is then about 71,000 EJ.

The Wallace and others (1979) assessment extended the study to Cretaceous rocks north of, and beneath, the Tertiary sediments studied by the 1975 project for a total area of more than 278,500 km^2 (including offshore areas). The area they accessed extended from the Rio Grande in Texas northeastward to the vicinity of the mouth of the Pearl River in Louisiana; and from the landward boundary of Eocene growth faulting southeastward to the edge of the Continental Shelf, including unmapped

Table 6. Summary of Nonhydrothermal U.S. Geothermal Resource Base Estimates

Source & Category	Thermal Energy, in 10^{18} J = EJ	Volume of Methane, × 10^{12} SCF*	Total Gas + Thermal Energy, in 10^{18} J = EJ
Geopressured (Papadopulos and others, 1975)	46,000	23,700	71,000
Geopressured (Wallace and others, 1979)	110,000	59,000	170,000
Co-produced Resources	0.0944 – 0.451 (depends on water temperature)		
EGS			
Sedimentary EGS (lower 48 states)	100,000		
Basement EGS (lower 48 states)	13,300,000		
Volcanincs			
Hawaii	N/A		

Note. SCF: standard cubic feet of methane (ideal gas conditions) at 1 atm, 60°F.

Cretaceous sediments underlying the Tertiary sediments, extending farther inland. They assumed a depth limit of 6.86 km (22,500 ft) for development and a lower limit of temperature of 150°C (300°F). Wallace and others (1979) estimated a thermal energy of 110,000 EJ. The also estimated the accessible dissolved methane resource to be about 59,000 × 10^{12} SCF or 62,000 EJ (see Table 6).

Subsequent to these assessments, the resources and technologies for recovering geopressured geothermal energy were extensively studied by the U.S. DOE between 1979 and 1990 (Gregory and others, 1980; John, Maciasz, and Harder, 1998). Gregory and others (1980) identified a number of the most favorable areas in the Texas Gulf Coast for geopressure energy development and termed them "fairways." Locations of these fairways are shown on Figure 10. From late 1989 until early 1990, a 1 MWe plant was operated on the Pleasant Bayou well in the Texas Gulf Coast near Houston. The well produced hot water and dissolved natural gas. About half of the power was generated by a binary cycle plant running on the thermal energy of the water, and about half was generated by burning the gas in a reciprocating-engine-operated electric generator (Campbell and Hattar, 1990). The economics of the power generation at that time were not favorable, because of the low price of natural gas and oil, and the test was discontinued after the 6-month trial run. The well had been flow tested for a period of about 5 years with limited drawdown, so the geologic system seemed to be a success, and the reservoir sufficiently large to sustain production at about 3 MW for many years (Shook, 1992). With today's higher gas costs and increasing demand for natural gas, geopressured systems deserve to be reconsidered, because their economics in today's energy markets will be more favorable as pointed out in a recent study (Griggs, 2005).

EGS in Sedimentary Basins

Another scenario exists for geothermal development in many of the areas exploited for deep oil and gas production, especially in the Gulf Coast and in the mountain states region. In these areas, EGS development in the deep, high temperature part of the sedimentary section might be more cost-effective than basement EGS systems. Shown in Table 7 is a comparison of needs for EGS-type development costs versus reality in existing hydrocarbon fields. It is clear that many of the upfront reservoir costs have been reduced, and that the existing infrastructure can be adapted readily to geothermal electrical power production. As an indication of the possibilities, research into the suitability of such basin-hosted geothermal resources has begun in the north German Basin (Zimmermann and others, 2005). In this area, low-formation permeability requires stimulating potential sandstone reservoirs, and significant lateral drilling. But those conditions have not deterred activities.

Future research must be performed on the suitability of some of the wells/fields now being developed as deep, hot, tight, sandstone gas reservoirs; but, overall, it seems that large areas of the United States are suitable for future geothermal exploitation in the near term that have not been considered in the past. Many of these areas are hot, and most are being artificially stimulated (fractured), or horizontally drilled, or both, at the present time. These areas are clearly EGS types of systems but with known drilling and development costs and abundant water.

Furthermore theoretical modeling suggests that stimulations in sedimentary settings, where there is some intrinsic porosity and permeability, are more favorable than a fractured basement rock setting (Nalla and Shook, 2004).

The general size of this resource has been calculated separately from the general EGS resource, which is primarily in basement rocks. The areas that are considered to be in this EGS category are the areas of sedimentary section deeper than 4 km. The deep sections of sediments are present over many areas of the United States (see Figure 5). Especially promising large areas occur in the Gulf Coast, the Appalachian Basin, the southern Midcontinent, and the Rocky Mountains. Therefore, a conservative resource base figure of 100,000 EJ is listed in Table 6 for sedimentary EGS systems. Although this number may be a few percent of the total EGS value of 13,300,000 EJ (Table 6), the accessible fraction of the energy in a 10- to 25-year time frame may be equal to the accessible basement EGS value.

DISCUSSION

Table 6 provides a summary of resource base estimates for all components of the geothermal resource. By far, the conduction-dominated components of EGS represent the largest component of the U.S. resource. Nonetheless, the hydrothermal, coproduced resources, and geopressured resources are large and significant targets for short and intermediate term development.

The EGS resource base value for only the states of Louisiana, Mississippi, and Texas is 1.5×10^6 EJ. This number does not include the offshore areas of the Gulf of Mexico. In order to understand the magnitude of the thermal energy or heat content of the rock, it is useful to consider the following "thought experiment." Imagine a 14 km long $\times$14 km wide $\times$1 km thick slice of rock below the ground surface, which is at an initial temperature of 250°C. Reasonable average values are 2550 kg/m^3 and 1000 J/kg °C, for the density (ρ) and heat capacity (C_p) of the rock, respectively. If this mass of rock is cooled by 200°C, to 50°C, then the heat removed is given by

$$\begin{aligned} Q = \;& \rho C_P V \Delta T = (2550\,\mathrm{kg/m^3})(1000\,\mathrm{J/kg\,^\circ C}) \\ & \times (14\,\mathrm{km} \times 14\,\mathrm{km} \times 1\,\mathrm{km})(250\,^\circ\mathrm{C} - 50\,^\circ\mathrm{C}) \\ = \;& 100 \times 10^{18}\,\mathrm{J} = 100\,\mathrm{quads}. \end{aligned}$$

This quantity of thermal energy, which could potentially be released from a 200 km^2 area of rock, is equivalent to the total amount of energy consumed annually in the U.S., which has a total land area close to 10 million km^2. This illustration shows the substantial size of the U.S. geothermal resource. Of course, the size of the accessible resource is smaller than implied by this simplistic analysis. Details relating to the development scenarios are not the topic of this paper although there is a brief discussion given (see also Table 7).

The resource base value calculated by Wallace and others (1979) was 110,000 EJ. This value includes the stored thermal energy in both the on- and offshore geopressure areas, but does not include the energy stored in dissolved methane or the hydraulic energy resulting from the naturally high pressures of geopressured fluids. In considering these estimates, it is important to note that the EGS values in this report include the entire states of Texas, Louisiana, and Mississippi, and not just the geopressure areas.

Table 7. Comparison of Cost Components for "EGS" Development Versus Oil Patch Situations

Components of EGS Development Cost	• Drill wells that reach hot temperatures, i.e., 100°C (>300°F), • Fracture and/or horizontally drill wells to develop high water flow and/or acquire make-up water, • Install infrastructure, roads, piping, and power line routing, • Build power stations
Hydrocarbon Field Conditions	• Many wells with BHTs of more than 150°C (300°F) at 4,570 m (15,000 ft) or less, • Wells fractured or horizontally drilled in many situations, • Water available from the well or adjoining wells in fields or as externally supplied disposal water (paid for by disposer), • In-place infrastructure of power lines, roads, pipelines, • Continued production of gas and oil in otherwise marginally economic wells,
Gulf Coast Geopressure EGS System	• Build power station, • Recomplete wells, in some situations, and test flow system, • Minor surface infrastructure upgrades (i.e., insulating collection pipes, etc.)

The Wallace and others (1979) value for the specific geopressure value could be considered to add to the baseline EGS figures from the analysis of stored thermal energy reported in Table 6. This is because of the characteristics of the sedimentary basin resource. Wallace and others (1979) used a value of approximately 20% for the porosity of the sediments. Because the heat capacity of water is about five times larger than that of rock, the stored thermal energy is approximately twice what would be present in the rock mass with zero porosity as assumed in the analysis summarized in Table 6. The ability to extract the methane for energy from these areas is also an additional resource.

Because of the thousands of wells drilled, the costs may be in some situations one-half to one-third of those for hard rock drilling and fracturing. Plus, a failed well in oil and gas exploration may indicate too much water production. In some areas, such as the Wilcox trend in southern Texas, there are massive, high-porosity sands filled with water at high temperature. These situations make a natural segue way into large-scale EGS development. Thus, the main reason for emphasizing this aspect of the EGS resource is its likelihood of earlier development compared to basement EGS, and the thermal advantages pointed out by the heat-extraction modeling of Nalla and Shook (2004).

Although the EGS resource base is huge, it is not evenly distributed. Temperatures of over 150°C at depths of less than 6 km are more usual in the active tectonic regions of the western conterminous U.S., but not confined to those areas. Although this analysis gives a regional picture of the location and grade of the resource, there will be areas within every geological region where conditions are more favorable than in others, and indeed more favorable than implied by the map contours. In the western U.S. where the resource is almost ubiquitous the local variations may not be as significant. In the central and eastern U.S, however, there will be areas of moderate to small size that are much higher grade than the maps in Figure 7 imply and these areas would obviously be the initial targets of development.

The highest temperature regions represent areas of favorable configurations of high heat flow, low thermal conductivity plus favorable local situations. For example, there are high heat flow areas in the eastern U.S. where the crustal radioactivity is high, such as the White Mountains in New Hampshire (Birch, Roy, and Decker, 1968) and northern Illinois (Roy, Rahman, and Blackwell, 1989). However, the thermal conductivity in these two areas also is high as basement and high conductivity sedimentary rocks are present so the crustal temperatures are not as high as areas with the same heat flow and low thermal conductivity (such as a coastal plain area or a Cenozoic basin in Nevada).

Similarly there are areas of low average gradient and hence low EGS potential (because of the expense to develop these areas) in both the eastern and western U.S. In the tectonically active western U.S. the areas of active or young subduction generally have low heat flow and low gradients. For example areas in the western Sierra Nevada foothills and in the eastern part of the Great Valley of California are as cold as any area on the continent (Blackwell, Steele, and Carter, 1991).

The most favorable resource areas in the eastern U.S. will have high crustal radioactivity, below average thermal conductivity, and other favorable circumstances (such as aquifer effects). Detailed studies (exploration) are necessary to identify the highest temperature locations because the data density is lowest in the eastern U.S., where smaller targets require a higher density of data points than currently exist.

The question of sustainability is not addressed in this study. However, the geothermal resource is of large size and is ubiquitous in certain areas. The temperature of the cooled part of the EGS reservoir will recover about 90% of the temperature drop after a rest period of about 3 times the time required to lower it to the point where power production ceased (Pritchett, 1998). So development of an area 3 to 5 times the area required for the desired power output could allow cycling of the field and more than 100 years of operation. In areas where there are already large numbers of wells, this type of scenario might be practical and economical. Thus, in some scenarios of development, the geothermal resource is sustainable.

ACKNOWLEDGMENTS

The research for this paper was part of a larger research assessment titled: The Future of Geothermal Energy, Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, 2006. We would like to thank project coordinator Jefferson Tester of MIT, Susan Petty, and the other panel members for their contribution to this research. Funding for this project was from Battelle Energy Alliance, LLC (BEA) Subcontract No. 00050178 for the U.S. Department of Energy, under U.S. Government Contract NO. DE-AC07-05ID14517. The comprehensive report is available on the Internet at: http://geothermal.inel.gov and http://www1.eer.eenergy.gov/geothermal/egs_technology.html.

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Appendix A: Details of the Temperature-at-Depth Calculations

Several models of thermal conductivity and radioactive heat generation of the upper 10 km were used for the temperature at depth calculations. Shown in Figure A.1 are the geologic distributions over depth scale over which the temperature at depth was calculated.

Case A is in the simplest possible tectonic distribution. From surface to the 10 km the geology is represented by basement, with an assumed thermal conductivity of 2.7 W/m/K and a radioactive heat generation of A_b. For such a situation the temperature at any depth X is given by:

$$T = \frac{Q_m}{K} - A_b b^2 \frac{1 - e^{-\frac{X}{b}}}{K}, \quad \text{where } A_b = (Q_0 - Q_m)/b.$$

The quantities involved in this equation are: surface heat flow (Q_0), mantle heat flow (Q_m), thermal conductivity (K), and the scale depth of heat generation ($b = 10$ km).

Case B is for the areas represented by a layer of young volcanics/basin fill overlying the basement. Geographically such an area would be represented by Basin and Range for example. In this area a thermal conductivity of 2 W/m/K was assumed to a depth of 2 km, with the basement value of 2.7 W/m/K used below 2 km. The heat generation was assumed to be constant at 1 μW/m^3 for the upper 2 km, whereas below 2 km the distribution was assumed to be exponential as described in the text. The equations involved in the calculations are:

For $X = 0$–2 km

$$T_{2\,\text{km}} = \frac{Q_0 X}{K} - A_S \frac{X^2}{K},$$

where the quantities involved are: surface heat flow (Q_0), heat generation ($A_s = 1$ μW/m^3) and thermal conductivity $K = 2$ W/m/K.

For $X > 2$ km the temperature equation can be written as:

$$T = T_{2\,\text{km}} + \frac{Q_m}{K} - A_b b^2 \frac{1 - e^{-(\frac{X-2}{b})}}{K},$$

where the quantities are similar to those involved in Case A.

Case C is represented by a shallow $X < 3$ km sedimentary section overlying the basement. The conductivity of the sedimentary section is variable, but the basement conductivity is 2.7 W/m/K. In such a situation the equations necessary to compute the temperature at a specific depth are:

For $X = 0$–3 km

$$T_S = \frac{Q_0 X}{K} - A_S \frac{X^2}{K}$$

(note that $X = S$, in this particular example), where the thermal conductivity K is variable, and $A_s = 1$ μW/m^3.

For $X > 3$ km

$$T = T_S + \frac{Q_m}{K} - A_b b^2 \frac{1 - e^{-(\frac{X-S}{b})}}{K}.$$

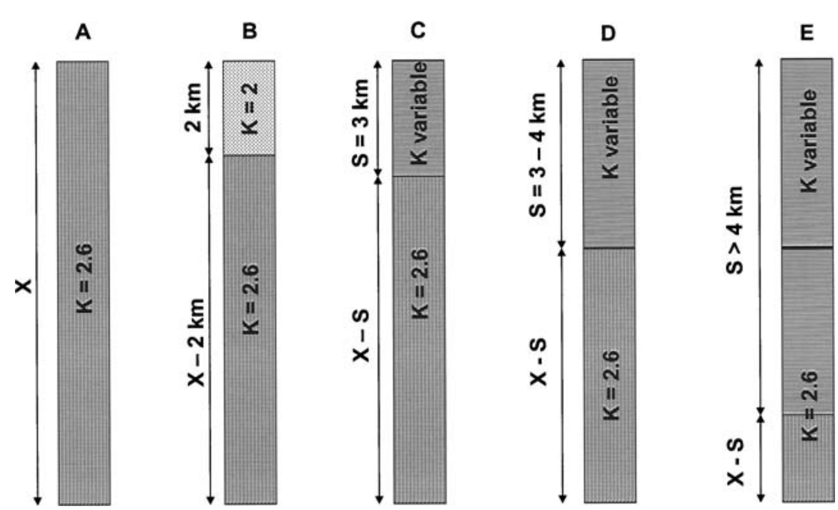

Figure A.1. Thermal conductivity and radioactivity models for temperature calculation.

Case D is relatively similar to the Case C. In this case the geology is represented by a sedimentary layer of thickness 3 to 4 km, overlying basement rocks. Again the conductivity distribution in variable for the sedimentary section, while the basement rocks have a conductivity of 2.7 W/m/K. The only difference from Case C is the depth scale of the heat generation (the value of b), which is variable. The value of b is selected so that $b = 13 - S$. The reasoning for this approach (and the similar one for Case E) is the assumption that a thick sedimentary basin would form only over attenuated or eroded continental crust. Thus the radioactive layer in the basement is assumed to be thinned in the situation of a thick sediment cover. The equation for the temperature up to 4 km is similar to Case C:

For $X = 0$–4 km

$$T_S = \frac{Q_0 X}{K} - A_S \frac{X^2}{K} (\text{again } X = S)$$

For $X > 4$ km

$$T = T_S + \frac{Q_m}{K} - A_b b^2 \frac{1 - e^{-\left(\frac{X-S}{b}\right)}}{K},$$

where b is variable ($b = 13\text{-}S$)

Case E is the most complicated. Geologically it is represented by a layer of sedimentary thickness larger that 4 km, overlying basement rocks. The conductivity of the rocks is variable for the upper 4 km, depending on the geological properties of the various sedimentary basins, whereas below 4 km the thermal conductivity was assumed to be 2.7 W/m/K no matter whether the rocks at the depths were the temperature is computed are basement or sediments. The equations involved in the computation are:

For $X = 0$–4 km

$$T_{4\,\text{km}} = \frac{Q_0 X}{K} - A_S \frac{X^2}{K},$$

where K is variable, $As = 1$ (in this situation $X \neq S$)

For $X = 4$ To S km (S being the bottom of sediments)

$$T_S = T_{4\,\text{km}} + \frac{Q_0 - 4A_S}{K} - A_S \frac{X^2}{K},$$

where $K = 2.7$ W/m/K

For $X > S$

$$T = T_S + \frac{Q_m}{K} - A_b b^2 \frac{1 - e^{-\left(\frac{X-S}{b}\right)}}{K},$$

where b is variable ($b = 13 - S$).