CHAPTER 2

Geothermal Resource-Base Assessment

2.1 Introduction

Previous analyses have suggested that the amount of thermal energy available for Enhanced Geothermal System (EGS) development is enormous (Armstead and Tester, 1987; Rowley, 1982; Mock et al., 1997; Tester et al., 1994; Sass, 1993). However, these earlier works did not use detailed geologic information – and, as a result, the methodologies employed and resulting resource estimates were, by necessity, somewhat simplified. This study utilizes published geologic and geophysical data for the United States to calculate the stored thermal energy (or "heat in place") on both a national and state level, at depths from 3 to 10 km. The methodology, resource types considered, and the resource-base calculations are included in this chapter. Recoverability, or useful energy, is discussed in Chapter 3 of this report. A depth of 3 km was selected as a cutoff for upper depth because, outside of the periphery of active magmatic and hydrothermal systems, temperatures in excess of 150°C at less than that depth are rare.

Several classes of geothermal resources are discussed in this chapter (Table 2.1). In earlier analyses – USGS Circular 726 (White and Williams, 1975), USGS Circular 790 (Muffler and Guffanti, 1979), and USGS Circular 1249 (Duffield and Sass, 2003) – the geothermal resource was divided into four major categories: hydrothermal, geopressured, magma, and conduction-dominated (Enhanced Geothermal Systems or Hot Dry Rock). The resource classes that are discussed in this report include 1) sedimentary Enhanced Geothermal Systems (EGS), 2) basement EGS, 3) geopressured-geothermal systems, and 4) coproduced fluids (hot aqueous fluids that are produced during oil and gas production). Brief mention is also made of supercritical/volcano (i.e., igneous) geothermal systems. There is overlap of some of these categories, which will be explained in the discussion that follows.

Table 2.1 Geothermal resource categories.

Category of Resource	Reference
Conduction-dominated EGS	
Sedimentary EGS	This study, basins > 4 km
Basement EGS	This study
Volcano Geothermal Systems	USGS Circular 790 + new data
Hydrothermal	USGS Circulars 726 and 790
Coproduced fluids	McKenna et al. (2005)
Geopressured systems	USGS Circulars 726 and 790

Conventional hydrothermal resources, presumed to exist at depths of 3 km or less, are specifically excluded. A team at the United States Geological Survey (USGS) (Williams, 2005) is currently reevaluating these resources. Also not included, because of their relatively small geographic size, are EGS resources on the periphery of hydrothermal systems in the Western United States. While these types of resources are certainly of high grade and can be viewed as near-term targets of opportunity, they are so small in area and site-specific that a regional study of this scale cannot quantitatively assess them. They are, in general, extensions of the hydrothermal resource and will be identified as part of the ongoing assessment of hydrothermal geothermal resources being conducted by the USGS. 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 discussion (see Section 2.3.5).

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 data set used in developing the resource assessment. The conterminous U.S. portion of the map is shown in Figure 2.1. In order to expand coverage from the earlier GSA-DNAG map (Blackwell and Steele, 1992; Blackwell et al., 1991) and early versions of this type of resource evaluation (Blackwell et al., 1993; Blackwell et al., 1994), extensive industry-oriented thermal data sets were used, as well as published heat flow data from research groups. To that end, a western heat-flow data set was developed, based on thermal gradient exploration data collected by the geothermal industry during the 1970s and 1980s (Blackwell and Richards, 2004c; Kehle, 1970; Kehle et al., 1970).

The basic information in this data set consists of temperature-depth/gradient information. However, thermal conductivity and heat flow were also determined for as many of the sites as possible, based on thermal conductivity estimates from geologic logs (where available), and geologic maps for other sites where there were 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 2.2, especially in western Nevada and southwestern Utah.

A second industry data set consisting of about 20,000 point bottom-hole temperature (BHT) measurements, compiled in the early 1970s and published in digital form (AAPG CD-ROM, 1994), was also 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. That process is described briefly in Section 2.2.2 and, in more detail, by Blackwell and Richards (2004b, c).

The heat flow varies from less than 20 mW/m^2 in areas of low heat flow to more than 150 mW/m^2 in areas of high heat flow. The causes of the variations and the distribution of heat flow in the conterminous United States are discussed in detail by Roy et al. (1968, 1972), Sass et al. (1971), Lachenbruch and Sass (1977), Reiter et al. (1986), Morgan and Gosnold (1989), Blackwell et al. (1991), and others. The value of surface heat flow is the building block for the temperature-at-depth calculation (see Figure 2.3). Individual sites have thermal conductivity (rock columns) that varies with depth and, thus, the average thermal gradient depends on the depth interval studied – whereas, heat flow does not. In this study, contours of measured heat flow are combined with regionally specific, depth-averaged thermal conductivity models to more accurately represent the larger-scale thermal regime (i.e., average gradients and temperatures as a function of depth).

To summarize, the values of heat flow used to produce the contours for the United States shown in Figure 2.1 were compiled from the following data sets: the SMU compiled 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 (approximately 2,000 points, see www.smu.edu/geothermal); and the AAPG BHT database (AAPG 1994). The various data site locations are shown in Figure 2.2 by data category. In addition, for completeness, hot and warm spring locations, and Pleistocene and Holocene volcanoes, were shown on the Geothermal Map of North America and on Figure 2.1.

2.2 EGS Resource-Base Calculation – Temperature-at-Depth Maps

Several data components are needed to calculate temperature at depth. The heat flow (Q) map is the starting point for the calculations. The thermal conductivity (K) and the geothermal gradient (∇T, $\partial T/\partial z$) complete the trio of quantities directly involved (see Figure 2.3). In addition to the thermal conductivity as a function of depth, the radioactivity of the crustal rocks (A), the thickness of the radioactivity layer (r), the regional heat flow (i.e., the heat flow from below the radioactive layer, Q_m) (Roy et al., 1972), and the average surface temperature (T_o) must be available at each point in the grid. The components of the analysis used are briefly described below.

The resource maps were prepared at a gridding interval of 5 minutes (5' = 5 minutes = 0.08333°) of latitude/longitude. This grid interval corresponds to points with an average spacing of about 8 km representing an area of about 64 km^2. A typical 250 MW_e 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. Power plant operations, of course, would be confined to a much smaller area, 3 km^2 or less. Thus, at the field level, focused exploration and evaluation will be necessary to select optimum sites in a given region, because the grid size used in the analysis is bigger than a reasonable field size.

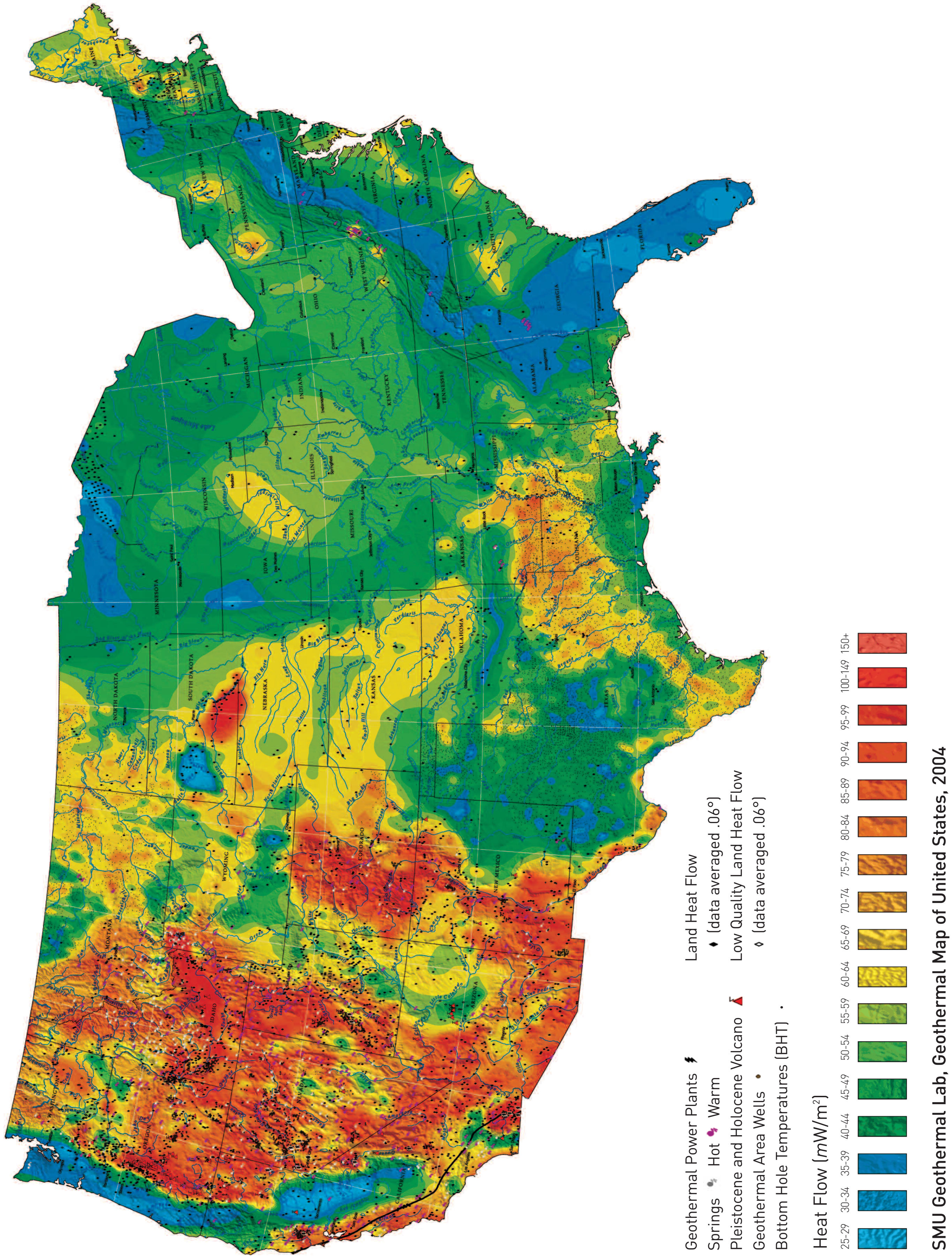

Figure 2.1 Heat-flow map of the conterminous United States – a subset of the geothermal map of North America (Blackwell and Richards, 2004)

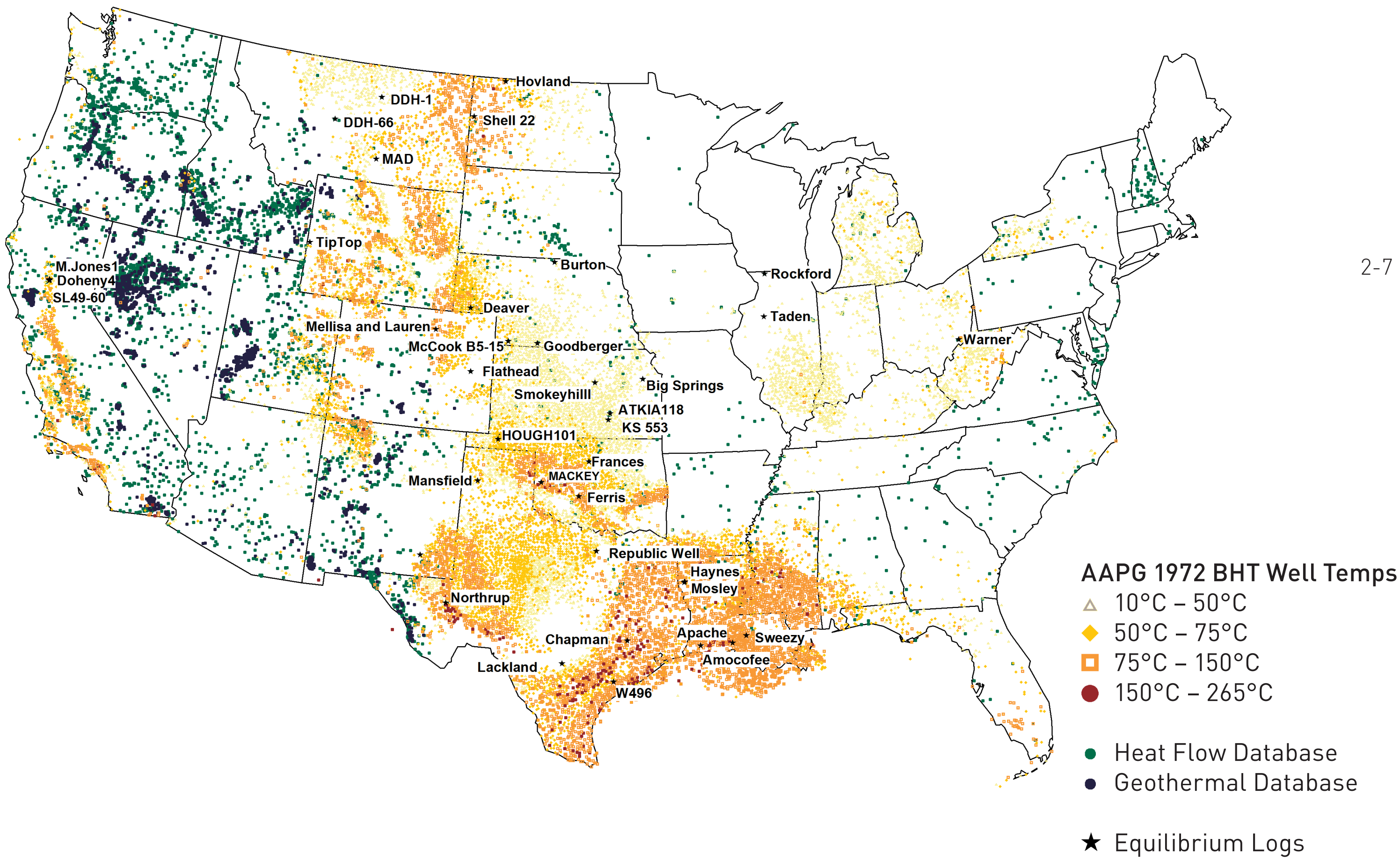

Figure 2.2 All BHT sites in the conterminous United States in the AAPG database. BHT symbols are based on depth and temperature (heat flow is not available for all of the sites, so some were not used for preparation of the Geothermal Map of North America). The named wells are the calibration points. The regional heat flow and geothermal database sites are also shown.

2.2.1 Heat flow

Before calculation of the heat-flow grid values, individual data points were ranked for quality, based on the uncertainty of the data points (see Blackwell et al., 1991, for a discussion of quality ranking). Hydrothermal system-influenced data (very high values, i.e., generally greater than 120 mW/m^2) were excluded from the contouring. All of the heat-flow values obtained from the regional data sets were then merged and contoured using a gridding interval of 5' (0.08333°) of latitude/longitude (about 8 km point spacing) with a minimum curvature algorithm. The resulting heat-flow grid (see Figure 2.1) is the starting point for all of the calculations described in this chapter.

Figure 2.2 illustrates that, at the present stage of the analysis, there are still large geographic areas that are under-sampled with respect to the 8 km grid interval, such that the contours are not well constrained in places where the data are sparse. For example, Kentucky and Wisconsin have no conventional heat-flow data at all (although there are some BHT data points), and there are large gaps in several other areas, especially the eastern part of the United States. Areas in the Appalachian basin may have low thermal conductivity and high heat flow (as is the case in northwestern Pennsylvania), but data are limited in this region. Heat flow for AAPG database BHT points in the eastern United States was not calculated, due to the small and generally scattered nature of the drilling there and limited thermal conductivity information. The deeper wells were used in the preparation of the temperature maps, however.

Although there are BHT data in some areas to depths of 6,000 m, the maximum depth used for the correction was 4,000 m, due to limited information on the drilling effect for deeper wells, and a lack of calibration wells at those depths. Generalized thermal conductivity models for specific geographic areas of the various 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.

Data from the Western Geothermal Database were also used to prepare the contour map. These are heat-flow measurements derived from thermal gradient exploration wells drilled primarily for geothermal resources exploration in the western United States, generally during the late 1970s and 1980s. The majority of these wells are 150 m or less in depth. The raw 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. 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 this data, on well-site geology maps.

The flow of the temperature-at-depth calculations is shown in Figure 2.3. There are discussions of each of the main parameters used in the following sections. The important parameters are the measured heat flow (this section), the thermal conductivity distribution (Section 2.2.3 and 2.2.4), the surface temperature (Section 2.2.5), and the distribution of heat due to radioactive elements in the crust (U, Th, K) (Section 2.2.6). In the calculations, Q_o is the measured heat flow, K is the thermal conductivity, Q_m is the mantle or tectonic component of heat flow (Section 2.2.6), A is the radioactive heat generation, r is the scaled depth of the radioactivity effect (10 km in these calculations, see Section 2.2.6), X is the depth of the temperature calculation, the subscript s indicates the sediment section, and the subscript b indicates the basement section of the calculation.

2.2.2 Geothermal gradients

The mean thermal gradient in the sedimentary section can be found by dividing the heat flow by the thermal conductivity (see Figure 2.3). The variation in the mean gradient is from less than 15°C/km to more than 50°C/km on a regional basis. Within an individual well, the geothermal gradient can vary by up to a factor of 5 or more, depending on the lithology in a particular depth interval. However, the whole sedimentary section is averaged in the approach used here.

Unlike thermal gradient maps produced from direct observations from individual wells (Kron and Stix, 1982; Nathenson and Guffanti, 1980; DeFord and Kehle, 1976), the gradients produced as described in this section and the subsequent temperature-at-depth calculations are not biased by the part of the sedimentary section in which the measurements were made. Thus, the geothermal gradient distribution used here is smoother and more regionally characteristic of the average geothermal gradient to depths below where direct measurements exist. This smoothing process produces a somewhat different temperature-at-depth result than would be obtained from extrapolation of existing gradient compilations that do not include thermal conductivity and heat-flow analyses.

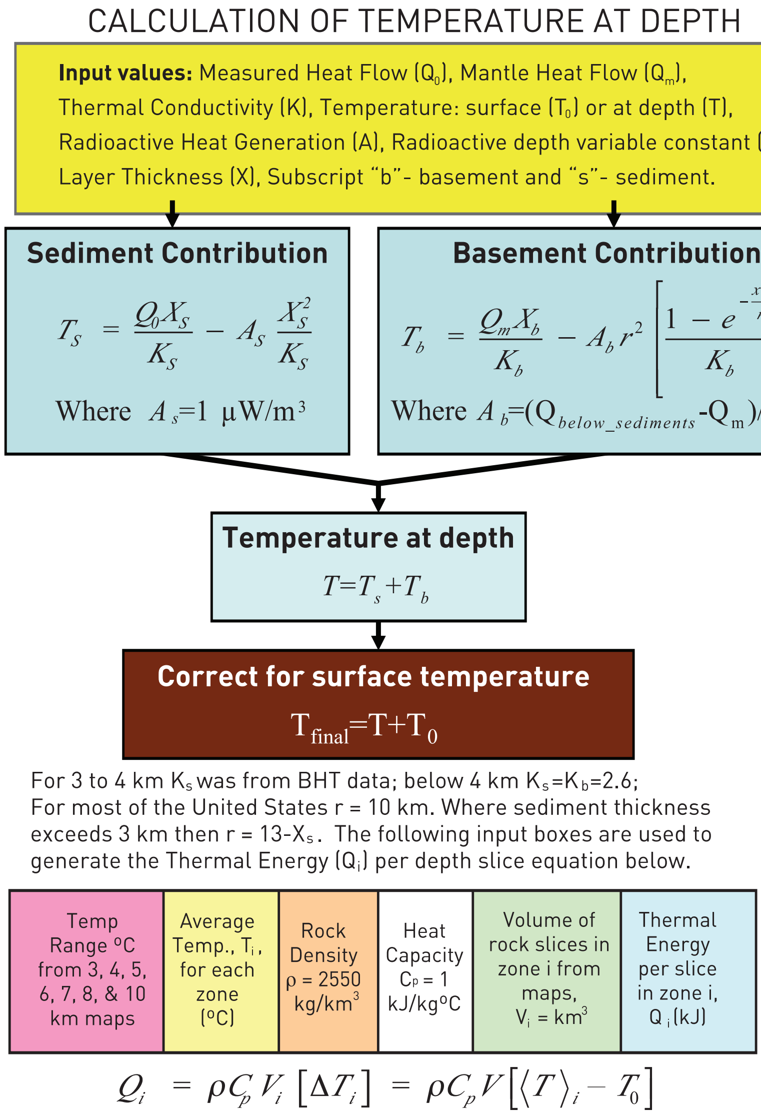

Figure 2.3 Flow chart for calculation of temperature and heat content at depth. Note: 1 kW-sec = 1 kJ and angle brackets denote depth-averaging.

Use of the extensive BHT data set is a new feature of the heat-flow map and this temperature-at-depth analysis used in previous studies. The BHT data were calibrated by 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; Blackwell et al., 1999). Data 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 et al. (1983). A secondary correction that is a function of the gradient was applied, so that a bias associated with average geothermal gradient in the well was removed. This correction was checked against the approximately 30 sites in the United States with accurate thermal logs (Figure 2.2). We contend the correction for the average gradient of a group of wells is accurate to about ± 10°C at 200°C, based on the direct comparisons described by Blackwell and Richards (2004b).

With the inclusion of the BHT data, there is a higher confidence level in the interpreted temperatures at depth. For geothermal resource potential purposes, the corrected BHT data can be used directly in many places, because many of these measurements are at 4 to 6 km depths. This additional data improves the definition of areas that qualify for further EGS evaluation.

2.2.3 Thermal conductivity

For the calculations of temperature at depth, the vertical thermal conductivity is sorted by depth into either one or two layers. The two-layer model for some of the areas is based on the effect of reduction of porosity and mineralogical changes in low-conductivity shale and in volcanic rock at temperatures above 60-80°C. A value of thermal conductivity of 2.6 W/m/K was assumed for the basement rocks. This value was based on the median of the values for basement rocks from the regional heat-flow database. For some of the sedimentary basins, an upper layer of lower thermal conductivity is assumed to overlie the 2.6 W/m/K value used for the deeper sedimentary rocks and the underlying basement.

A histogram of thermal conductivity for the wells in the regional heat-flow data set is shown in Figure 2.4. There is a peak in the distribution of thermal conductivity values at about 1.4 W/m/K. These low-conductivity values are characteristic of lithologies such as volcanic rock, shale, and unconsolidated valley fill. A value of 1.4 W/m/K was assumed for the Basin and Range valley fill and other high-porosity rocks where no measurements were available. 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.). The value of 2.6 W/m/K was used as the crustal value – instead of the 2.8-3.0 W/m/K peak – to partly take into account the effect of temperature on thermal conductivity, which ranges from 5% to 10% per 100°C change in temperature.

Regional values of thermal conductivity in the upper 2 to 4 km are based on generalized rock distributions. The peak at 1.4 W/m/K is related to the thermal conductivity of Late Cenozoic basin fill in the Great Basin. Parts of the Pacific Northwest and the Great Basin were assigned values of thermal conductivity of 2.0 W/m/K to a depth of 2 km, to approximate a mean of 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 was also 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 variations of almost 100% in the mean thermal conductivity within the sedimentary section. Therefore, detailed studies are necessary to identify the most favorable locations from the point of view of temperature and lithology. 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 such as in the Michigan, Illinois, Anadarko, and Delaware Basin regions. These areas were assigned the 2.6 W/m/K value starting at zero depth. Lower thermal conductivity values (< 2.0 W/m/K on a regional basis) are in areas where a significant part of the upper section is shale, such as in the Great Plains (Williston Basin, Cretaceous shales, Anadarko Basin, Paleozoic shales) and possibly in the northern Allegheny area (Paleozoic shales). 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 et al. (1998), Gosnold (1990), and Speece et al. (1985), for example.

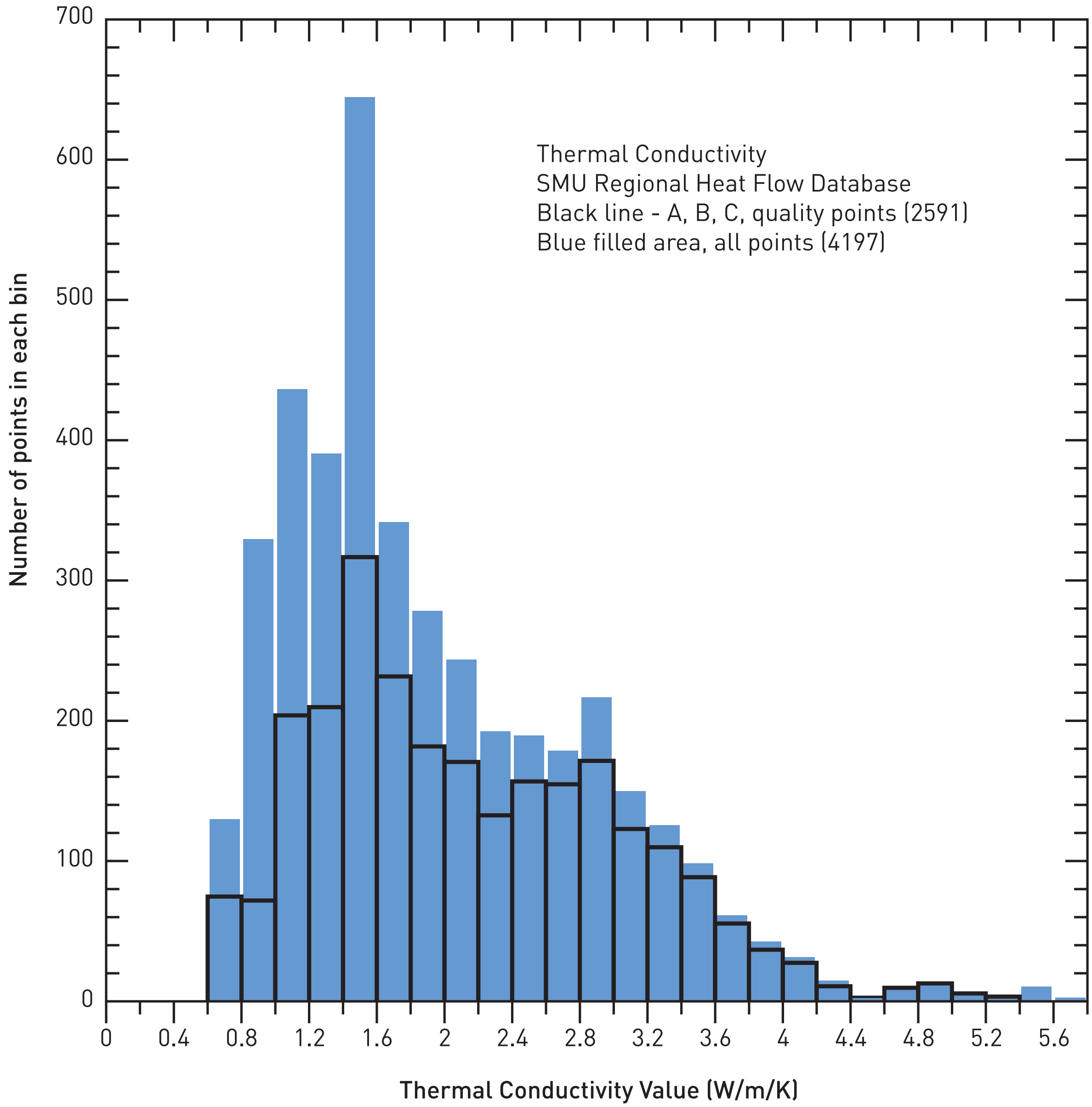

Figure 2.4 Histogram of *in situ* thermal conductivity, *K*, in the regional heat-flow database. Source: SMU Regional Heat Flow database at www.smu.edu/geothermal.

2.2.4 Sediment thickness

A map of the thickness of sedimentary cover was prepared by digitizing the Elevation of Basement Map published by the AAPG (1978). The basement elevation was converted to thickness by subtracting its value from the digital topography, resulting in the map shown in Figure 2.5. Sediment thickness is highly variable from place to place in the tectonic regions in the western United States (west of the Great Plains); and, for this reason, most of the areas of deformation in the western United States do not have basement contours on the AAPG map. Because of the complexity and lack of data, the sediment/basement division in the western United States 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. Local late extensional basins such as those in the Basin and Range and the Western Snake River Basin, are also not specifically represented on the sediment thickness map and were assigned a thickness of 2,000 m.

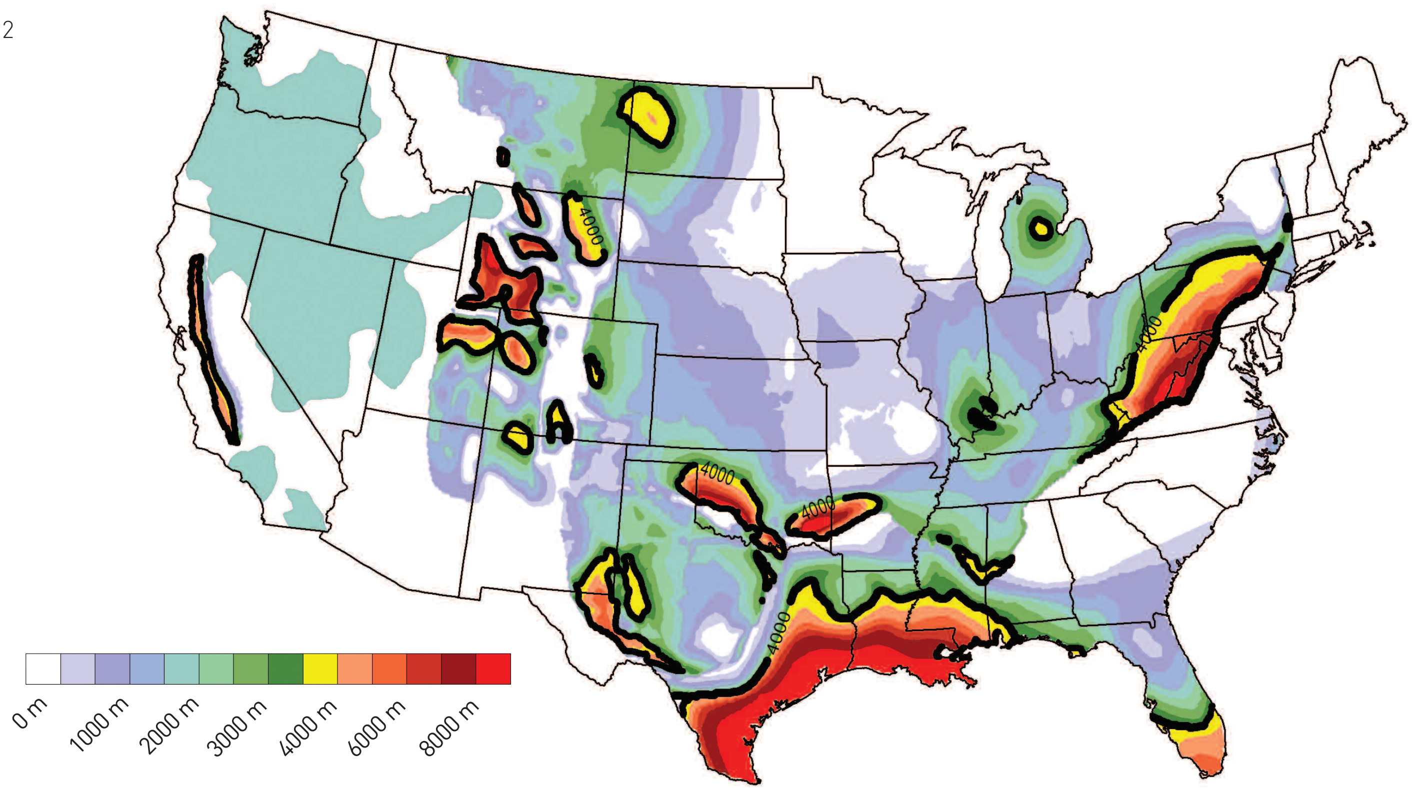

Figure 2.5 Sediment thickness map (in meters, modified from AAPG Basement Map of North America, 1978). The 4 km depth contour is outlined with a bold black line. The low-conductivity regions in the western United States are in blue/green.

In the Basin and Range and the Southern and Middle Rocky Mountains, there are smaller – but sometimes very 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.

The map in Figure 2.5 indicates areas that might be of interest for EGS development in the sediment section (the areas inside the 4 km sediment thickness contour), and areas of interest for basement EGS. 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 very localized regions in the area east of the Rocky Mountains. Thus, outside the areas identified by the heavy lines on Figure 2.5, development would have to be in basement settings (east of the Rocky Mountains).

2.2.5 Ground surface temperature

The ground surface temperature is shown in Figure 2.6. This temperature represents the lowest value of the average heat rejection temperature possible for any energy-conversion scheme. The values are from measurements of temperature in shallow groundwater wells (Gass, 1982). These temperatures can be used as shown in Figure 2.3 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).

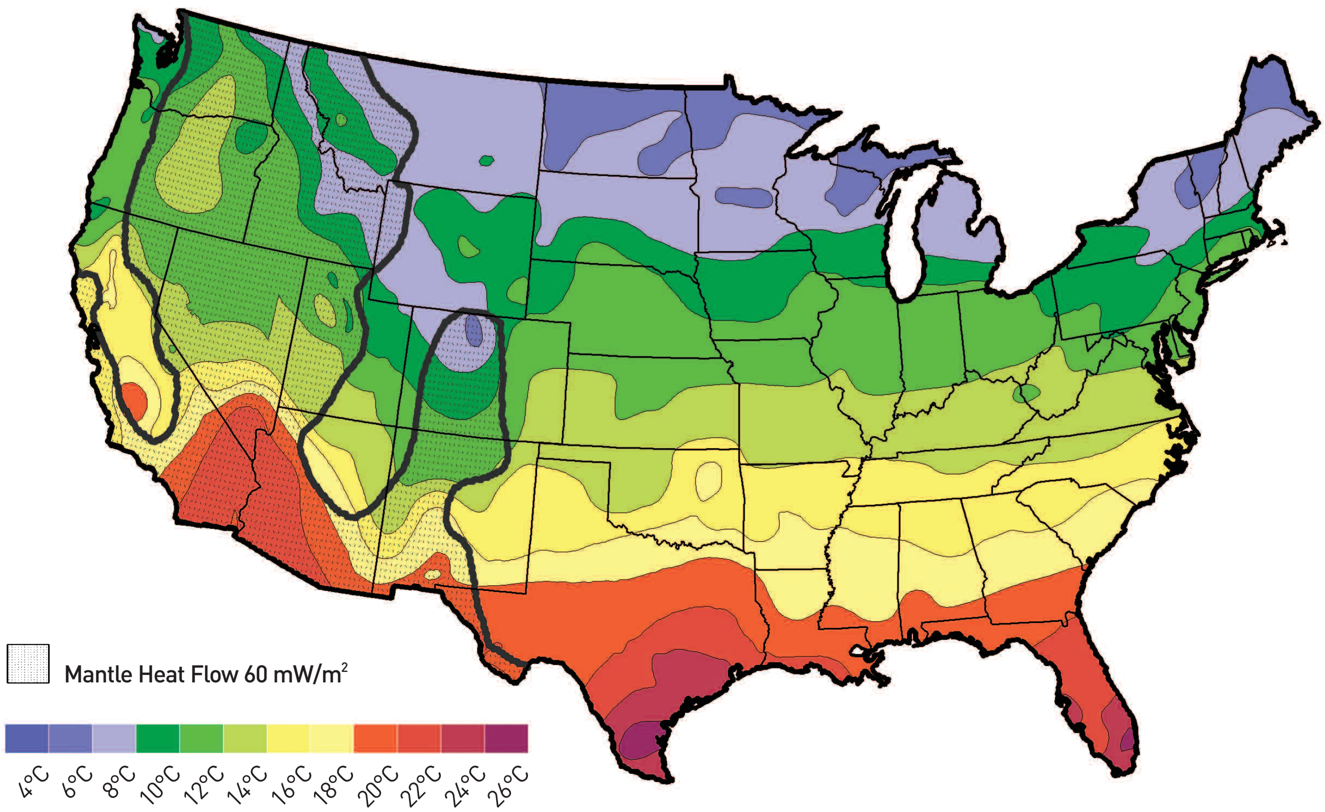

Figure 2.6 Map of surface temperature (colors, Gass, 1982) and generalized mantle heat flow for the conterminous United States (dotted area inside heavy black line is greater than 60 mW/m^2, the remainder of the area is 30 mWm^2).

2.2.6 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, i.e., the heat generated by radioactive elements in the crust and the tectonic component of heat flow that comes from the interior of the Earth (referred to here as the mantle heat flow). The radioactive component varies 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 about 10 km (Roy et al., 1972), so that most of the variation in heat flow from radioactivity is above that depth. This component can be large and is locally 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 (Birch et al., 1968). In contrast, in parts of the nearby Adirondack Mountains, the heat flow is only 30 mW/m^2, because the upper crustal rocks have very small radioelement content.

In the analysis of temperatures to 10 km, the heat flow from below the layer of radioactive elements providing a heat source in the continental crust must be known, because the depth-scale of the radiogenic contribution is similar to the depth of calculation. For the majority of the area covered by the analysis, two different "mantle" 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. The region of high mantle heat flow is shown as the dotted area inside the heavy black line in Figure 2.6. The high mantle heat flow is a result of the plate tectonic activity (subduction) that has occurred along the west coast of North America during the past 100 million years, and the hot spot activity along the Yellowstone/Snake River Plain track (Blackwell, 1989). Part of the Cascade Range in the Pacific Northwest (active volcanic arc) and part of the Snake River Plain (hot spot track) were assigned mantle heat flow values of 80 mW/m^2, because they are associated directly with geologically young volcanism. 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 et al., 1991). Transitions in heat flow between these different areas are generally sharp on the scale of the map, but are hard to recognize in some locations, because of the variable heat flow due to the upper crustal effects. Nonetheless, as deeper depths are considered, this regional factor becomes dominant.

2.3 EGS Resource Maps and Resource-Base Estimates – Lower 48 States

2.3.1 Heat (thermal energy) content

The results of the analysis described in the previous section are presented as temperature-at-depth maps and as thermal energy (or "heat") in place. The temperatures were calculated from the depths of 3 to 10 km at every km. The mean values at 0.5 km intervals were used in the recoverable resource analysis in subsequent chapters. Maps of the temperature at 3.5 km, 4.5 km, 5.5 km, 6.5 km, 7.5 km, and 10 km are shown in Figure 2.7. Heat-in-place was calculated and is listed in Table A.2.1 for 1 km x 1 km x 1 km blocks centered at depths of 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, and 9.5 km using the assumptions and equations shown in Figure 2.3. The values listed in Table A.2.1, and shown in the histogram in Figure 2.8, represent the geothermal resource base and not the 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 (8,980 km^2). It represents a large area of high temperature, and so its exclusion affects the resource-base calculation of areas at high temperature at shallow depths. The histogram in Figure 2.8 shows that there is a tremendous resource base of approximately 13 million EJ, between the depths of 3.5 to 7.5 km in the temperature range of 150°C to 250°C. Even if only 2% of the resource were to be developed, the thermal energy recovered would be 260,000 EJ. This amount is roughly 2,600 times the annual consumption of primary energy in the United States in 2006.

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 x 14 km wide x 1 km thick slice of rock below the ground surface, which is at an initial temperature of 250°C. Reasonable average values are 2,550 kg/m^3 and 1,000 J/kg°C, for the density (Ú) and heat capacity (C_p) of the rock, respectively. If this mass of rock is cooled through a temperature difference of 200°C to a final temperature of 50°C, then the heat removed is given by

$$Q = \rho C_p V \Delta T = (2550\text{kg/m}^3)(1000\text{J/kg}^\circ\text{C})(14\text{km} \times 14\text{km} \times 1\text{km})(250^\circ\text{C} - 50^\circ\text{C})$$
$$= 100 \times 10^{18}\text{J} \approx 100 \text{ quads.}$$

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 United States, which has a total land area close to 10 million km^2. This illustration demonstrates the substantial size of the U.S. geothermal resource. Of course, the size of the accessible resource is much smaller than implied by this simplistic analysis. Details relating to the development scenarios are described elsewhere in this report, including Chapter 3.

The validity of the calculations of temperature at depth is important. In the areas of hydrocarbon development, there are wells that have been drilled to 3 to 6 km (10,000 to 19,000 ft) depths, so that the predicted temperatures can be checked against measurements in deep wells. In the case of the areas represented in the AAPG BHT database, this 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.

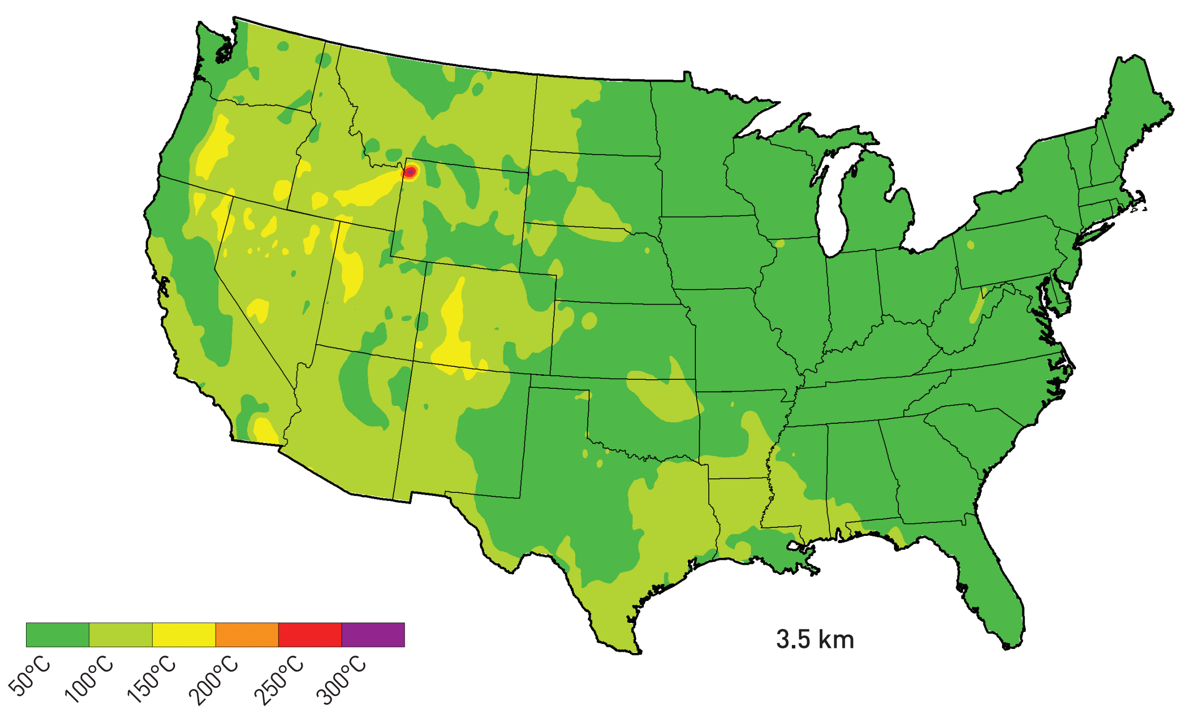

Figure 2.7a Average temperature at 3.5 km.

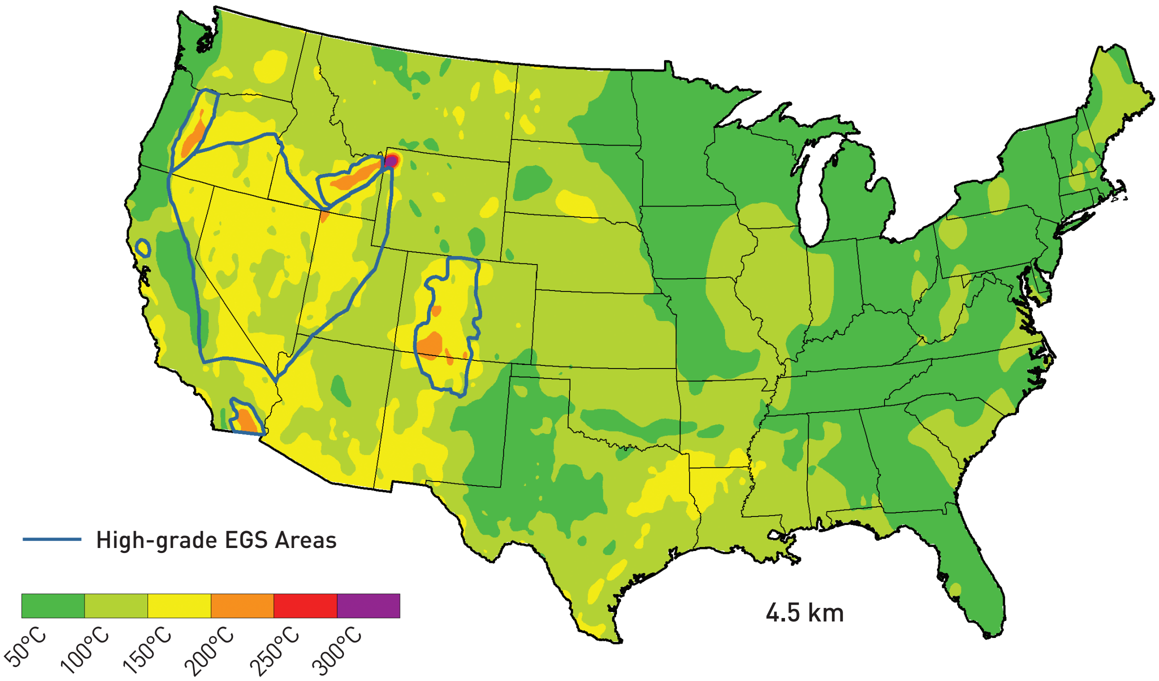

Figure 2.7b Average temperature at 4.5 km. Includes areas of special EGS interest outlined in blue and identified in Table 2.2.

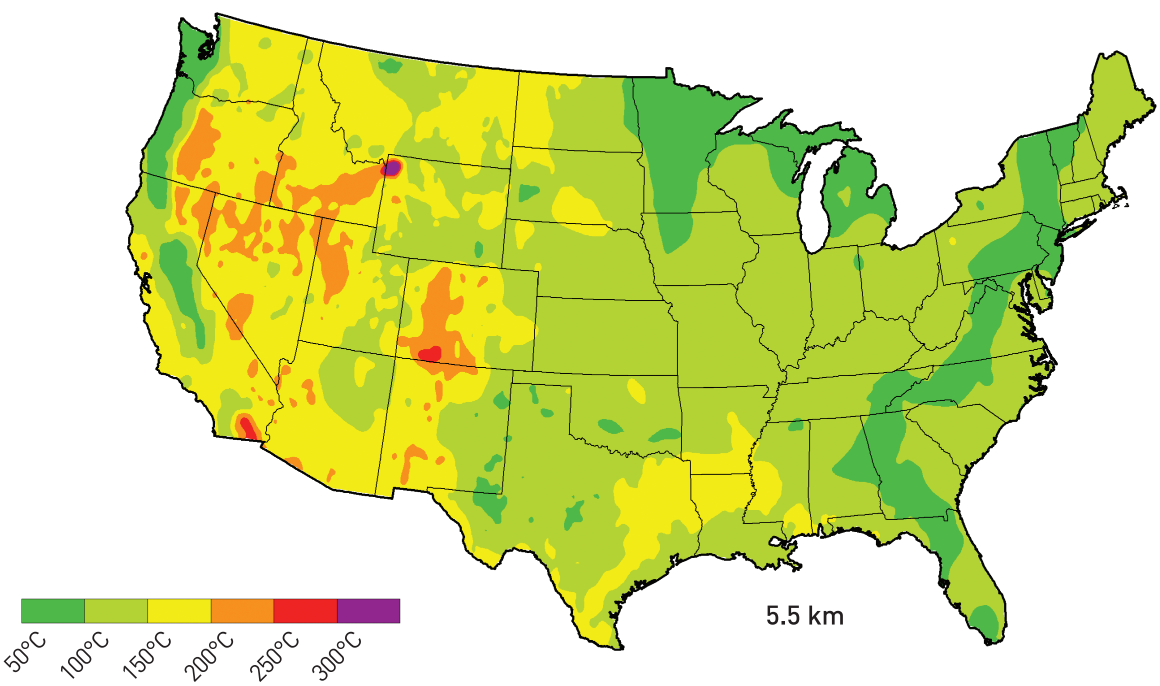

Figure 2.7c Average temperature at 5.5 km.

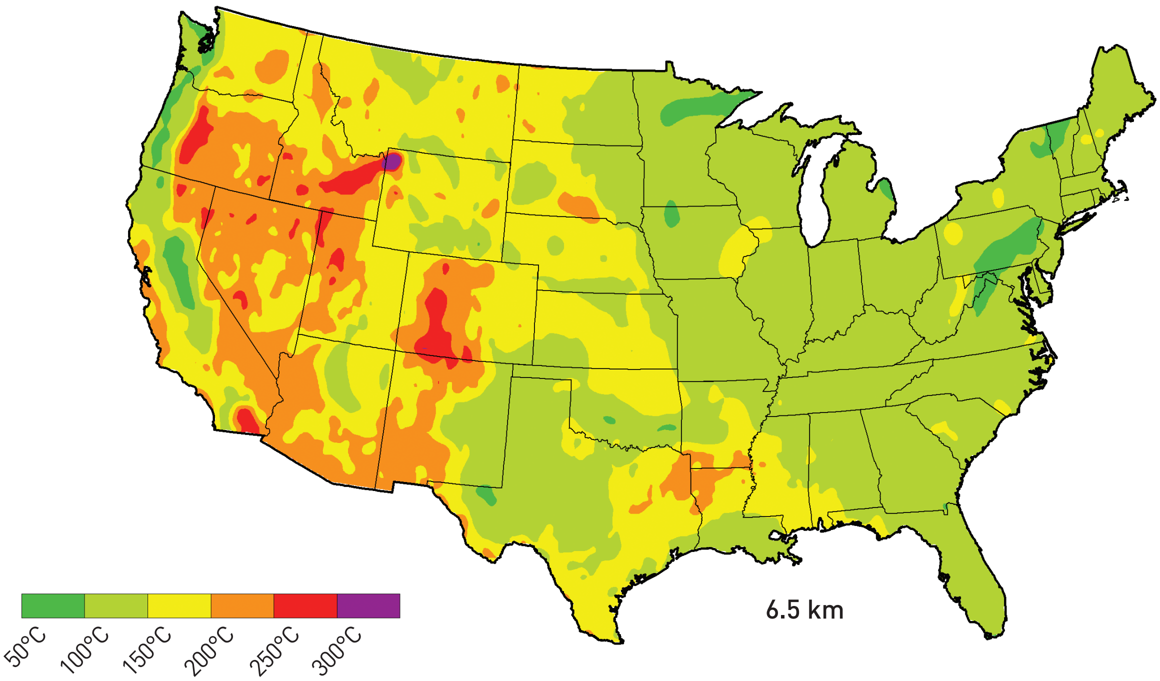

Figure 2.7d Average temperature at 6.5 km.

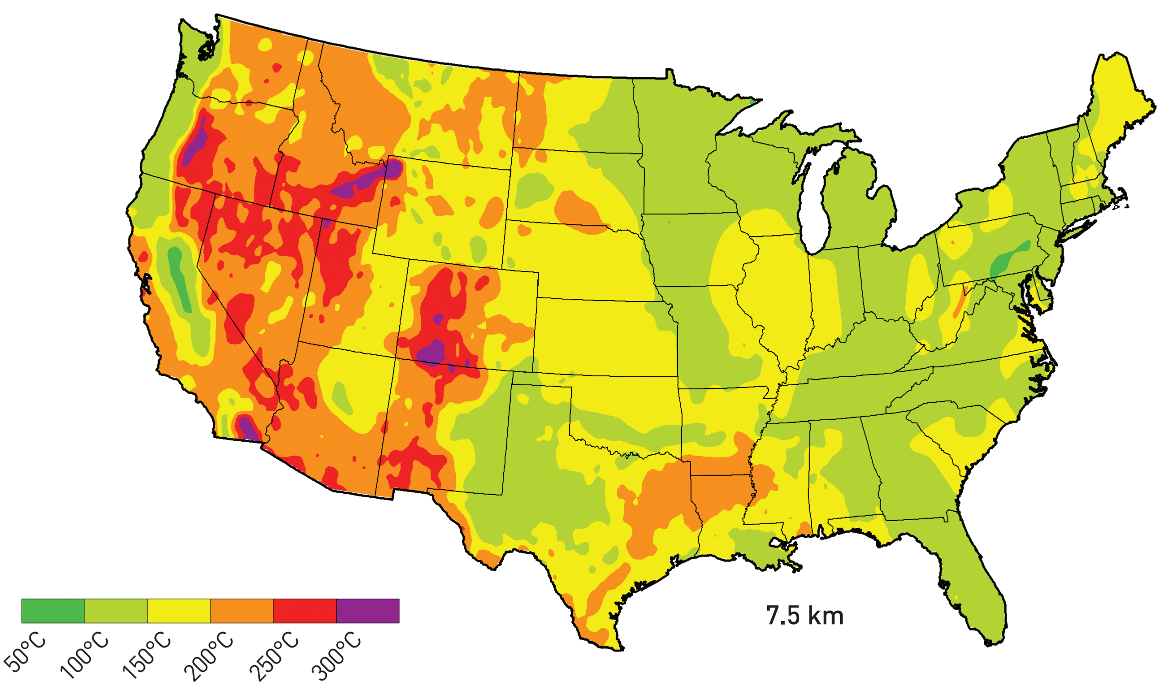

Figure 2.7e Average temperature at 7.5 km.

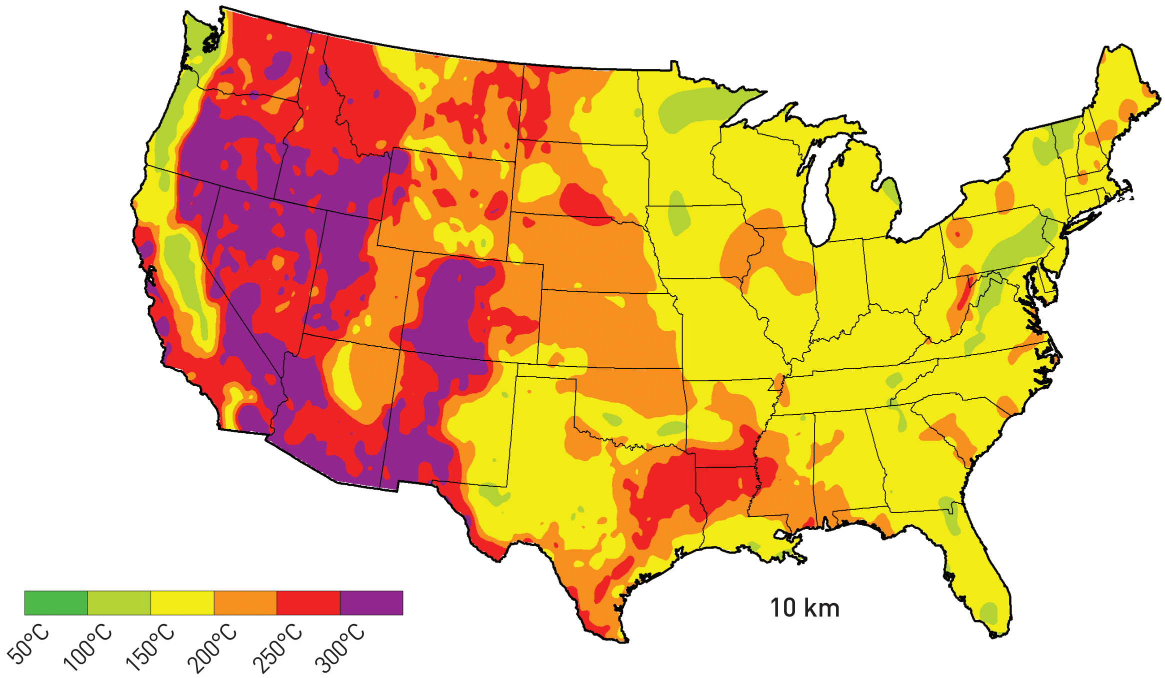

Figure 2.7f Average temperature at 10.0 km.

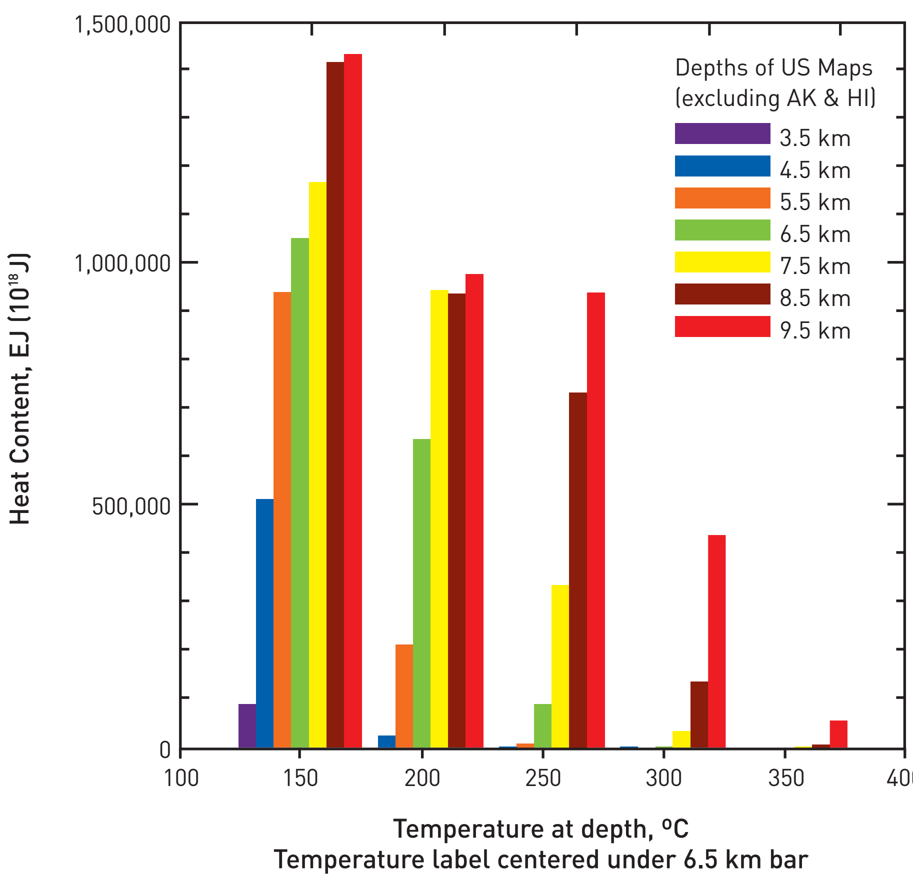

Figure 2.8a Histograms of heat content in EJ, as a function of depth for 1 km slices.

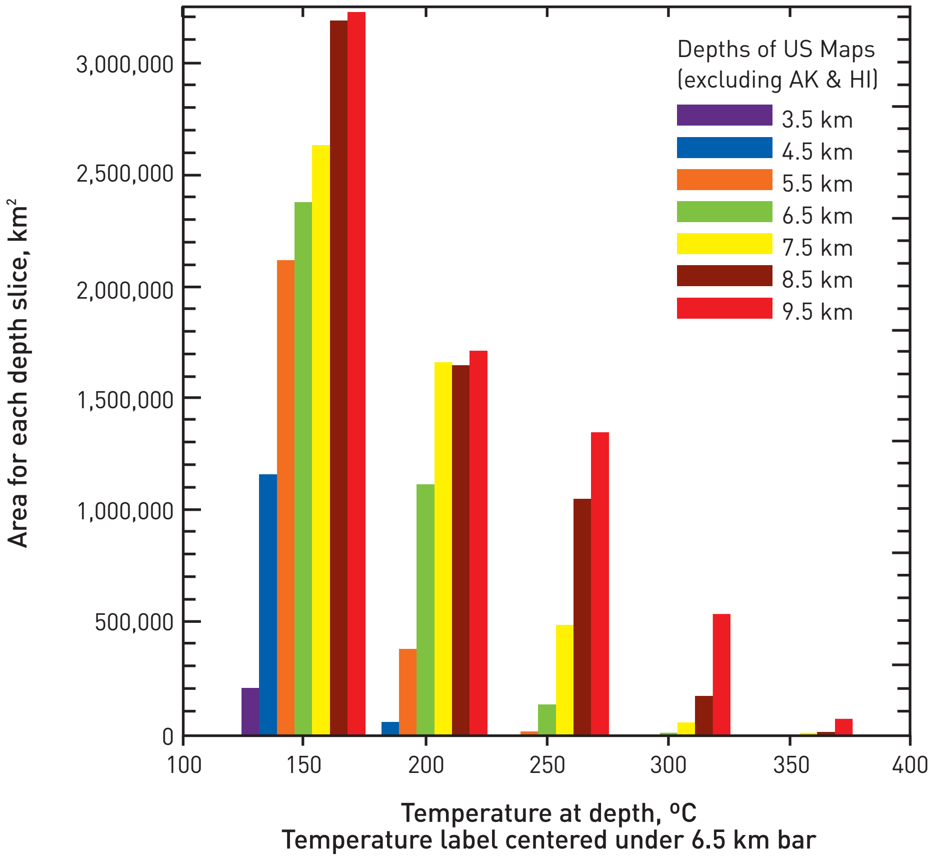

Figure 2.8b Histograms of United States area at a given temperature, as a function of depth for 1 km slices.

Although the EGS resource base is huge, it is not evenly distributed. Temperatures of more than 150°C at depths of less than 6 km are more common in the active tectonic regions of the western conterminous United States, but by no means are confined to those areas. 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 United States where the crustal radioactivity is high, such as the White Mountains in New Hampshire (Birch et al., 1968) and northern Illinois (Roy et al., 1989). However, the thermal conductivity in these areas is also high, so the crustal temperatures are not as high as areas with the same heat flow and low thermal conductivity, such as coastal plain areas or a Cenozoic basin in Nevada. The most favorable resource areas (e.g., the Southern Rocky Mountains) have a high tectonic component of heat flow, high crustal radioactivity (Decker et al., 1988), areas of low thermal conductivity (as in young sedimentary basins), and other favorable circumstances such as young volcanic activity.

There are also areas of low average gradient in both the eastern and western United States. In the tectonically active western United States, the areas of active or young subduction have generally 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 et al., 1991).

2.3.2 Crustal stress

Data on the state of stress are shown in Figure 2.9 (Zoback and Zoback, 1991; Zoback et al., 1991). All stress regimes are represented in the conterminous United States. The stress regime is extensional in areas such as the Basin and Range and the Gulf Coast; and compressional in parts of the eastern United States 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 still large areas that are not well-characterized; detailed resource evaluation in these areas will have to include stress studies.

There is not enough information to determine the optimum stress regime for EGS geothermal development. In Australia, the planned development in the Cooper Basin is in a highly compressive regime with geopressured conditions (Wyborn et al., 2005); while, at the Soultz area in Europe, the stress regime is extensional (Elsass et al., 1995). Because the stress regime determines drilling strategies (see Chapter 6); 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.

2.3.3 EGS geology

Much of the thermal energy resides in "basement" rocks below the sedimentary section. Because basement is usually defined as areas of metamorphic or igneous rocks, the composition and lithology of "basement" is actually extremely variable. The basement lithology below the sedimentary cover, where present, is as complicated as the surface exposures. While the generic description "granite" is used in this report, the lithology is not exactly specified. Quantification of the most favorable rock composition and structure for EGS development remains to be done. Most of the experimental EGS sites have been in granite (in a strict geologic sense), because of the expected homogeneity of the rock type. In fact, there may be situations where layered rocks might be equally or more favorable because the orientations of fractures might be easier to predict and the rock types may be more extensively fractured. From a more practical point of view, the lithology also affects the heat flow in the form of its radioactive content and the resulting heat flow. As has already been described above, areas of high radioactivity will have higher heat flow and so may have higher temperatures, all other factors being similar.

Some of the EGS resource resides in the sedimentary section, however. In general, as depth and temperature increase, the permeability and porosity of the rocks decreases. So, at depths of 3+ km and temperatures of 150+°C, the rocks are similar to basement in permeability and porosity. In many areas of the country, there is extensive drilling for gas at depths where temperatures are well within the EGS range because the gas deadline is on the order of 200+°C. In many of these areas, the rocks are "tight" and must be fractured to produce commercial quantities of gas (Holditch, 2006). In fact, much of the gas resource remaining in the United States is related to these types of formations. Examples are the Cretaceous sandstones in the Pieance Basin, Colorado (Mesa Verde and Wasatch Formations), and the East Texas Jurassic section (Bossier, etc.). These sandstones are "granitic" in bulk composition but still have some intrinsic porosity and permeability. Modeling by Nalla and Shook (2004) indicated that even a small amount of intrinsic porosity and permeability increases the efficiency of heat extraction, so that these types of rocks may be better EGS hosts than true granite. Thus, there is a natural progression path from the deep hot gas reservoir stimulation and production to EGS reservoir development in both technology and location. It seems likely that these areas might be developed early in the EGS history, because of the lower reservoir risk than in unknown or poorly known basement settings.

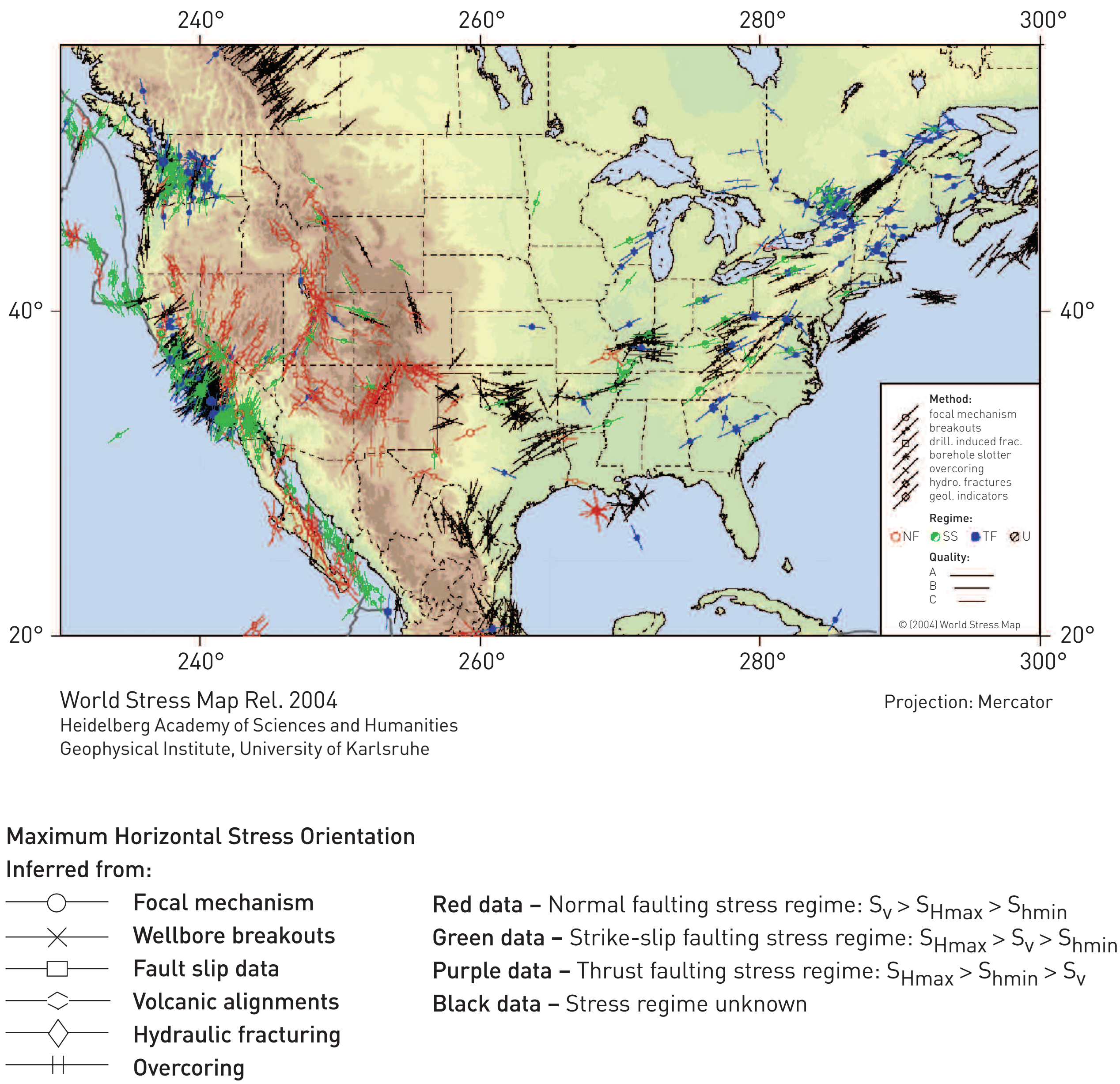

Figure 2.9 Subset of the Stress Map of North America (Zoback et al., 1991, World Stress Map, 2004).

2.3.4 Crustal permeability

Crustal permeability is a difficult parameter to characterize. 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. In general, permeability will decrease with depth. In sedimentary rocks, there is typically a relatively regular decrease due to compaction and diagenesis as depth and temperature increase. In basement rocks and deep sedimentary rocks, the primary permeability and porosity are related to the fracture and stress regime. General controls on and permeability of the crust have been discussed by Brace (1984), Davis (1981), Black (1987), among others. Ingebritsen and Manning (1999) have summarized a generalized distribution of crustal permeability as shown in Figure 2.10a. In the upper part of the crust, there is more than 8 orders of magnitude of permeability variation. However, by depths of 5 km, the variation is down to about 5 orders; and by 10 km, the range is closer to 2 orders of magnitude. Modeling of large-scale crustal fluid flow indicates a significant regime change over the permeability range of 10^{-17} to 10^{-15} m^2. At the smaller value, the crust is basically impermeable; while, at the larger value, large-scale fluid flow is possible with significant reconfiguration of the heat transfer and crustal temperatures (Wisian and Blackwell, 2004). Apparently, general large-scale crustal permeabilities are less than 10^{-16} m^2 in most areas, as evidenced by the lack of hot springs over large areas of the United States. Permeability vs. depth plots for the Pierre Shale of the mid-continent, and clastic sediments in the Uinta Basin are shown in Figure 2.10b (Bredehoeft et al., 1994). These measurements show that the Pierre Shale is essentially impermeable. In the case of the clastic sediments of the Uinta Basin, a "tight gas sand" area, the variation is from low to moderate permeability.

As a result of the range of variation and the uncertain controls on the type and nature of permeability, it is generally thought that most deep, hot regions of the crust away from tectonic activity will require extensive characterization and subsequent engineering of a reservoir to be produced. Existing and past studies of such situations are summarized in Chapter 4. This need to understand the rock characteristics and conditions is a major reason that areas of deep drilling for gas production may be the least expensive locations for initial EGS development.

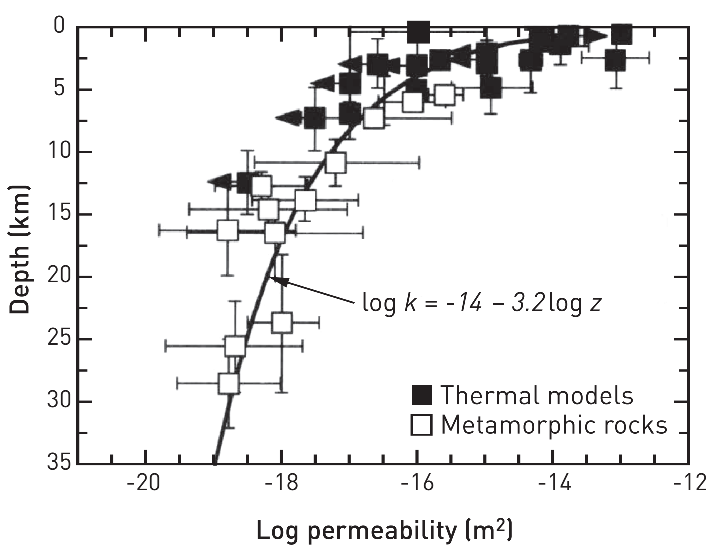

Figure 2.10a Permeability as a function of depth in continental crust (Ingebritsen and Manning, 1999).

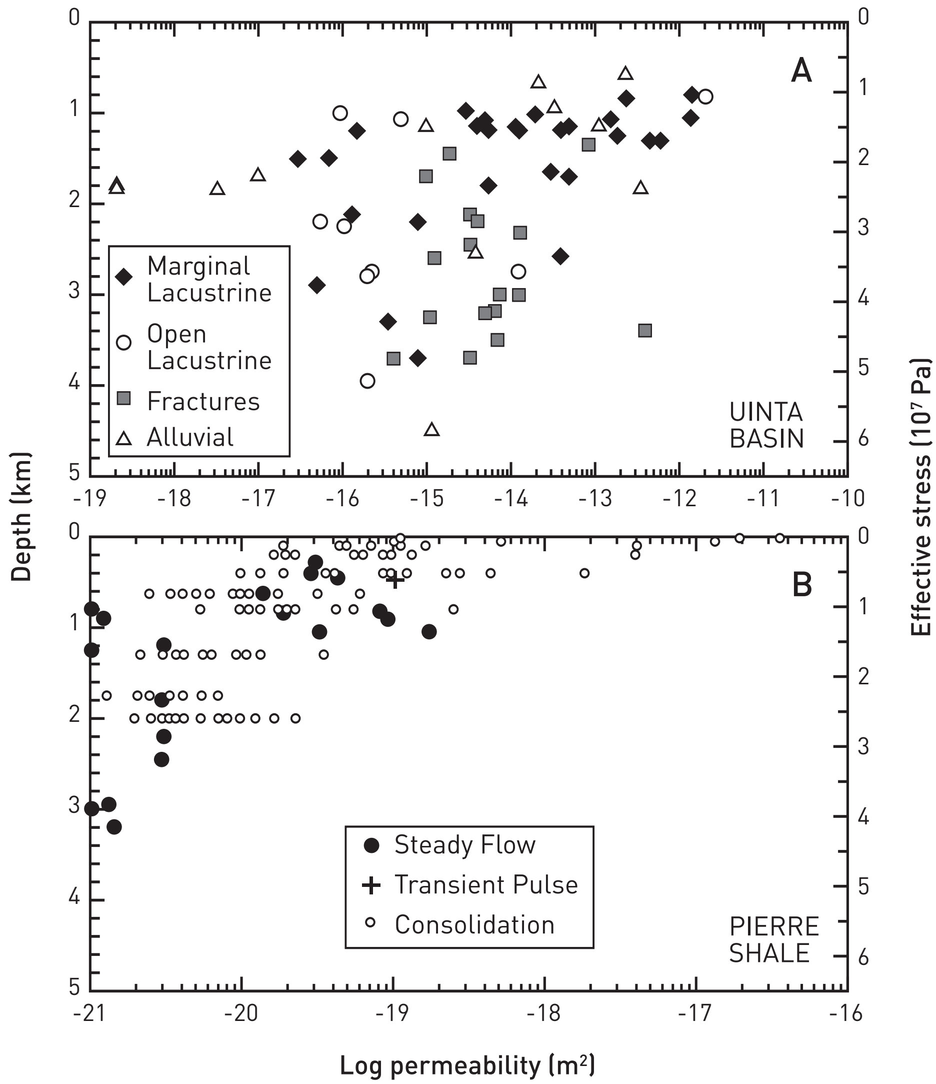

Figure 2.10b Permeability determined by direct hydraulic testing, as function of depth or effective stress in upper (<5km) crust (Bredehoeft et al., 1994). Results of drill-stem tests in sedimentary facies in Uinta Basin are shown in A; results of tests on core from Pierre Shale are shown in B.

2.3.5 High-grade EGS – targets for the near term (> 200°C at depths of about 4 km)

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 are generally in the western United States, 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 2.2. They include the Great Basin (Sass, 2001), the Snake River Plain, the Oregon Cascade Range, the Southern Rocky Mountains, the Salton Sea, and The Geysers/Clear Lake areas (see Figure 2.7b). In all these areas, detailed site studies could locate temperatures of more than 200°C at less than 4 km.

Table 2.2. High-grade EGS areas (>200°C at depths of about 4 km).

Region	Characteristics
Great Basin	30% of the 500 km x 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 x 500 km area is at temperatures > 200°C. Details of the geology at depths of 3-10 km unknown, probably volcanics and sediments overlaying 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 x 200 km area is at high, uniform temperatures and with similar geology (volcanic and intrusive rocks dominate). The margins of the area are accessible. 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 x 300 km area is at temperatures > 200°C. Geology is variable. Area includes the northern Rio Grande Rift and the Valles Caldera. 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 x 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 x 30 km area is at temperatures > 200°C (steam reservoir is 5 km x 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.

One area that has received some previous study is The Geysers/Clear Lake region in California (Stone, 1992). While 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. An interpretation of the temperatures at depth in the area is shown in Figure 2.11 (Erkan et al., 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 cross-hatched area in the first panel. Even outside this area and away from its periphery, temperatures are interpreted to exceed 200°C at 3 km over an area about 30 by 40 km. There may be an area almost as large, with temperatures of more than 350°C at 5 km. In this area, supercritical geothermal conditions might also exist.

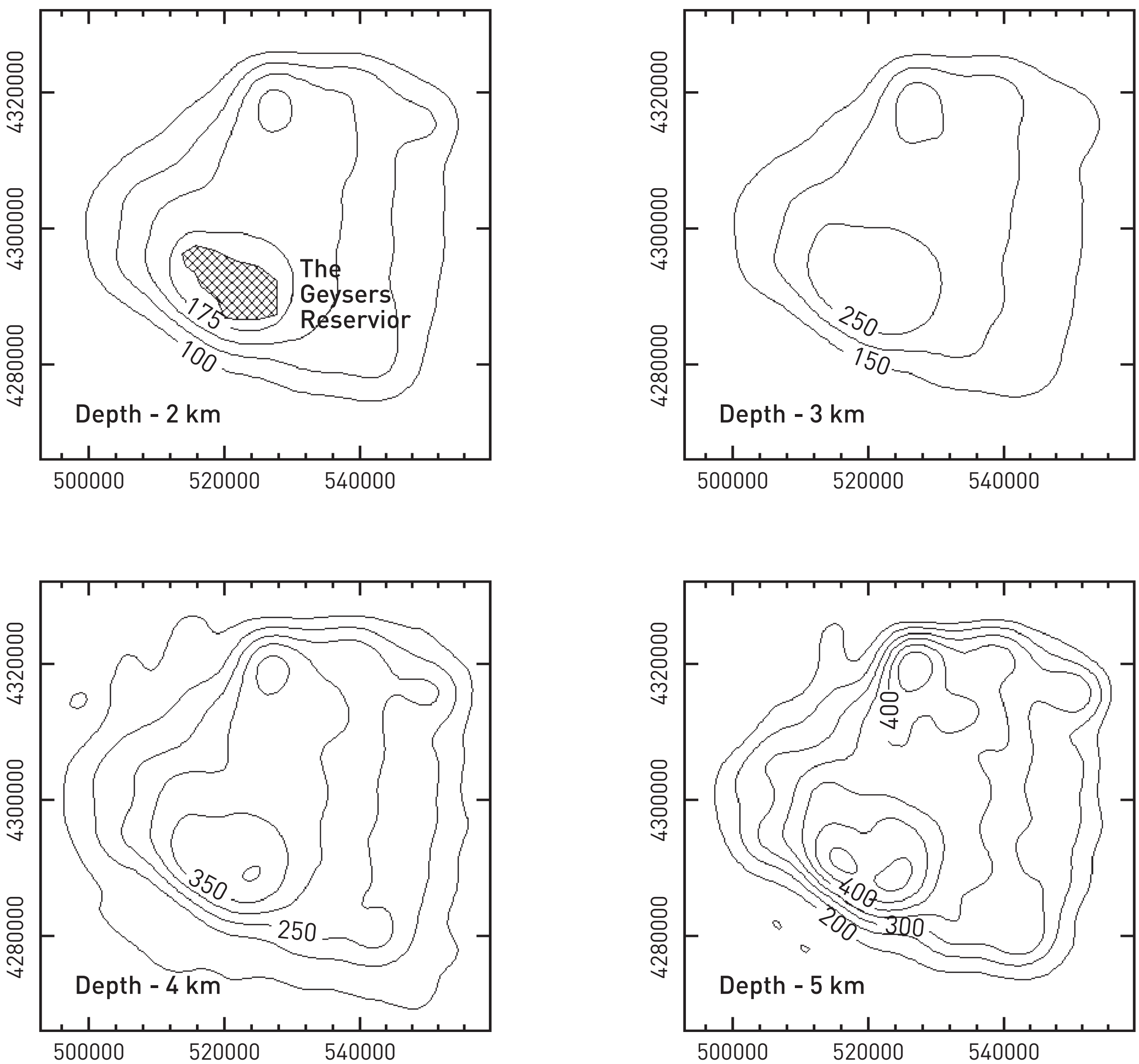

Figure 2.11 Temperatures at depths of 2 to 5 km in The Geysers/Clear Lake thermal area (Erkan et al., 2005).

2.4 EGS Potential of Alaska

There are all varieties of geothermal resources in Alaska. However, there is almost no information on the thermal regime except in very localized areas. Also, there is only a need for electrical generation development in localized areas, so for Alaska the questions are, first, how closely collocated are the resources with the demand; and, second, are there resources large enough to trigger new local development. The limited data available are shown in Figure 2.12 as a contour map of heat flow. Also included on the plot are the locations of volcanoes and hot springs. The EGS resource was estimated as in the case of the conterminous U.S. area described above. A thermal conductivity of 2.7 W/m/K was assumed everywhere, and the surface temperature was assumed to be 0°C. The heat content is shown in Table A.2.1 under column AK. This heat has not been added to the other U.S. values, however. The assessment of temperature at depth is diagrammatic only, because of the lack of data and the lack of collocation of information and electrical power need. There are possible conventional geothermal developments at several of the warm springs in central Alaska because of collocation situations. There is an active project at Chena Hot Springs near Fairbanks to develop 500 kW of power from a 165°F resource using binary power-generation equipment (Brasz and Holdmann, 2005). The first 250 kW unit went online in August 2006.

Coproduced fluids in the Cook Inlet gas developments (Shurr and Ridgley, 2002) are a possible future development scenario, but this area is part of the outer arc low heat-flow regime, and temperatures there are not particularly high.

2.4.1 Volcano systems

Electricity prices are high in Alaska, particularly in remote areas with only diesel-generating systems, typically greater than 25¢/kWh. In the longer term, electricity prices will depend partly on the future of oil and gas development on the North Slope, and on the location of a gas pipeline, if one is built. As a result of these and other factors, any long-term geothermal development scenario at this time is speculative. However, more than 40 volcanoes have been historically active, indicating there must be significant heat in a number of areas in Alaska. There are several of these volcanic centers relatively near the population center of Anchorage. Mt. Spurr and Mt. Dedoubt are close enough that geothermal power developed there might be transmitted to the load centers near Anchorage. The Wrangle Mountains are a huge volcanic complex almost certainly with associated geothermal systems. However, as a national park, geothermal energy recovery may not be possible, even if viable resources exist.

Smith and Shaw (1979) evaluated the igneous systems in Alaska for the 1978 resource assessment. They examined 27 volcanoes and estimated a resource base of about 2.5×10^{12} MWh for that set of sites. This estimate is certainly minimal, because there are more than 70 volcanoes that have erupted in the past 10,000 years along the Aleutian chain (www.UnivAlaska.edu). This is recent enough that there is a significant possibility that there is still heat associated with these areas.

Very high-grade EGS involving reservoir temperatures and pressures in the supercritical region ($T > 374$°C and $P > 220$ bar) are possible in Alaska, because of the many active volcanoes that are present along the Aleutian Island arc. If each one had a supercritical system associated with it, the resource could be quite large. The viability of such geothermal development has not been proven, but is under active research in Iceland (Valgardur, 2000; and Fridleifsson and Elders, 2004). The power from such systems in Alaska could be developed in the remote areas and converted to hydrogen for transport to load centers in future energy scenarios. Under the appropriate economic conditions, it is possible that several tens of thousands of megawatts could be developed. Efforts to initiate development are ongoing at the volcanoes Matushkin, on Unalaska, (Reeder, 1992; Sifford and Bloomquist, 2000); and Akutan, on the island of Akutan (Starkey Wilson, personal communication, 2005).

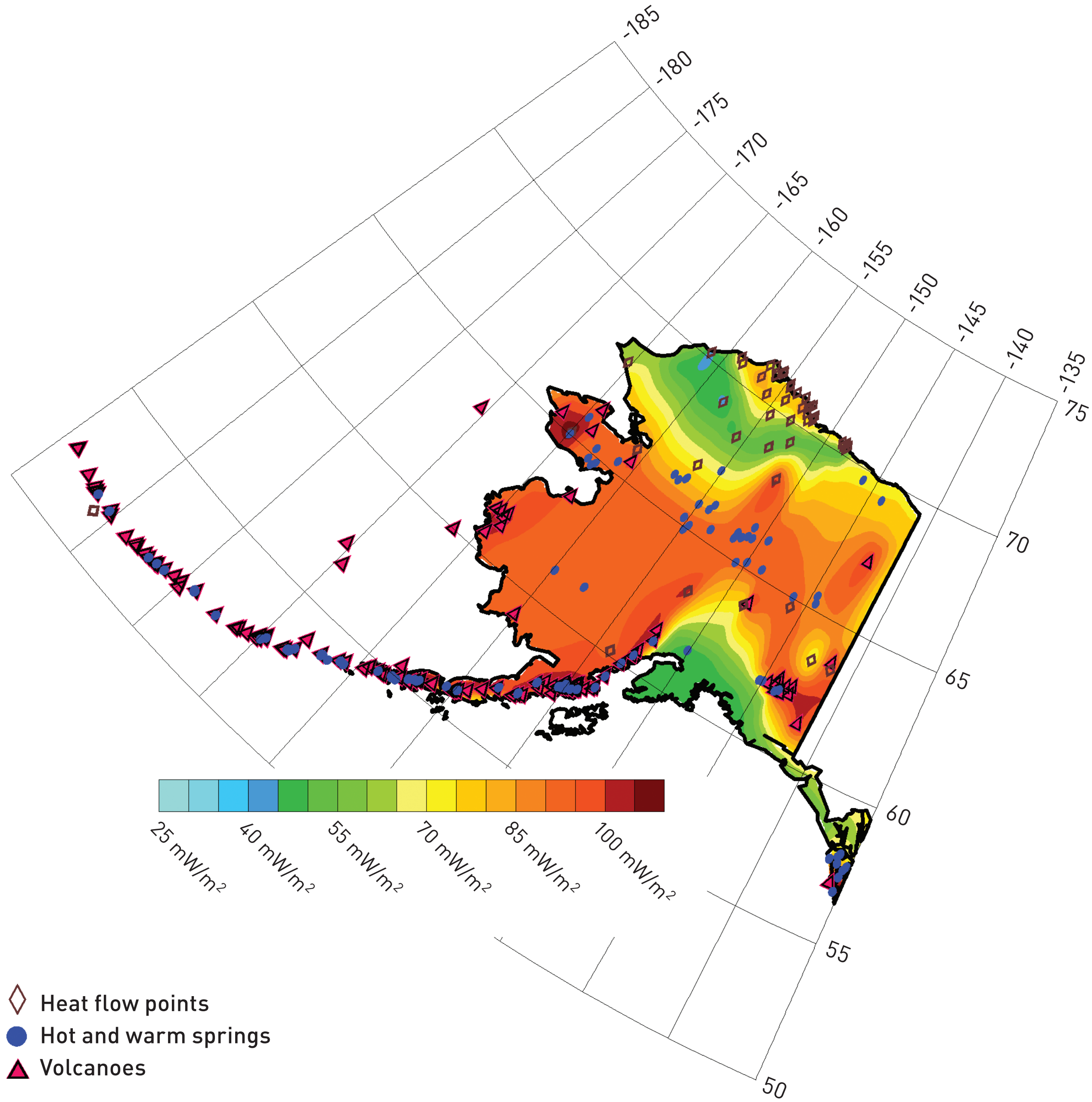

Figure 2.12 Heat-flow map of Alaska (from Blackwell and Richards, 2004).

2.5 EGS Potential of Hawaii

There is an existing power plant on the island of Hawaii along the east rift of the Kilauea volcano (Sifford and Bloomquist, 2000). The temperatures are high in this system of basaltic rift activity. There may be other resources in this area, but these are conventional hydrothermal resources. There is little subsurface information available outside of this area. The deepest drill hole on the Island of Hawaii, near Hilo (DePaolo et al., 2001), has a gradient of about 40°C/km below a depth of about 1.9 km and a BHT at 2.9 km of 42°C (Buttner and Huenges, 2003). There might be geothermal resources on Maui; but, on the other islands, geoelectric grade resources are not likely, due to the older age of volcanic activity there. There is little direct thermal information for these areas though, and the possibility of EGS development has not been ruled out. In a recent analysis of the geothermal potential of Hawaii, Lovekin et al. (2006) calculated resource estimates of 1,396 MW for the island of Hawaii (80% related to Kilauea volcano) and 139 MW for the island of Maui.

The island of Hawaii has the best possibility for the development of supercritical geothermal resources, 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).

2.6 Unconventional EGS Associated with Coproduced Fluids and Geopressured Fluids

2.6.1 Introduction

There are areas identified in the resource maps (Figure 2.7) where high temperatures are routinely being encountered in sedimentary rock during drilling for hydrocarbons. These temperatures typically reach 150°C (330°F) to more than 200°C (400°F). In some of these areas, significant porosity and permeability exists at depths of 3 to 6 km, and there is potential for large amounts of hot water either with or without stimulation of the reservoirs. In some of these cases, there may be the opportunity to stimulate fluid flows high enough to produce 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 are 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 be developed before the transition is made to pure, "start-from-scratch" EGS systems (McKenna et al., 2005). For the purpose of this report, these situations are divided into two categories: Coproduced Fluids and Geopressured Fluids. Thus, we have added coproduced hot water from oil and gas production 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.

2.6.2 Coproduced fluids: "conventional" geothermal development in hydrocarbon fields

Some areas of oil and gas development have relatively high temperatures at routinely drilled depths for hydrocarbon production. For example, parts of east and south Texas and northwest Louisiana are characterized by temperatures in excess of 150°C (300°F) at depths of 4 to 6 km (13,123 ft to 19,684 ft) (McKenna and Blackwell, 2005; McKenna et al., 2005) (see Figure 2.7). 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 east 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). Because *in situ* thermal conditions have been verified in these specific areas, the substantial areal extent of potential geothermal resources shown in Figure 2.7 is valid.

In addition to temperature requirements, a geothermal development requires large-volume flows of water, on the order of 1,000 GPM per MW (depending on the temperature). There are two typical types of existing situations associated with hydrocarbon development that are very 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 (Table 2.3). Curtice and Dalrymple (2004) show that coproduced water in the conterminous United States amounts to at least 40 billion barrels per year, primarily concentrated in a handful of states (Figure 2.13). In most mature hydrocarbon fields, the disposal of this coproduced water is an expensive problem (Veil et al., 2004).

Table 2.3 Equivalent geothermal power from coproduced hot water associated with existing hydrocarbon production in selected states (a complete listing is given in Appendix A.2.2).

State	Total Water Produced Annually, in 1,000 kbbl	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

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 100°C (212°F). Opportunities can be found in most of the basins in the continental United States. For example, Figure 2.13 shows the average total produced water as a byproduct of hydrocarbon production by state for 31 states (Curtice and Dalrymple, 2004). Oklahoma and Texas alone produce more than 24 billion barrels of water per year. In certain water-flood 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 relatively straightforward process; because, in some cases, 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 most of the need for expensive drilling and hydrofracturing operations, thereby reducing the risk and the majority 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 cases 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 2.3. Chapter 7 discusses this subject in more detail.

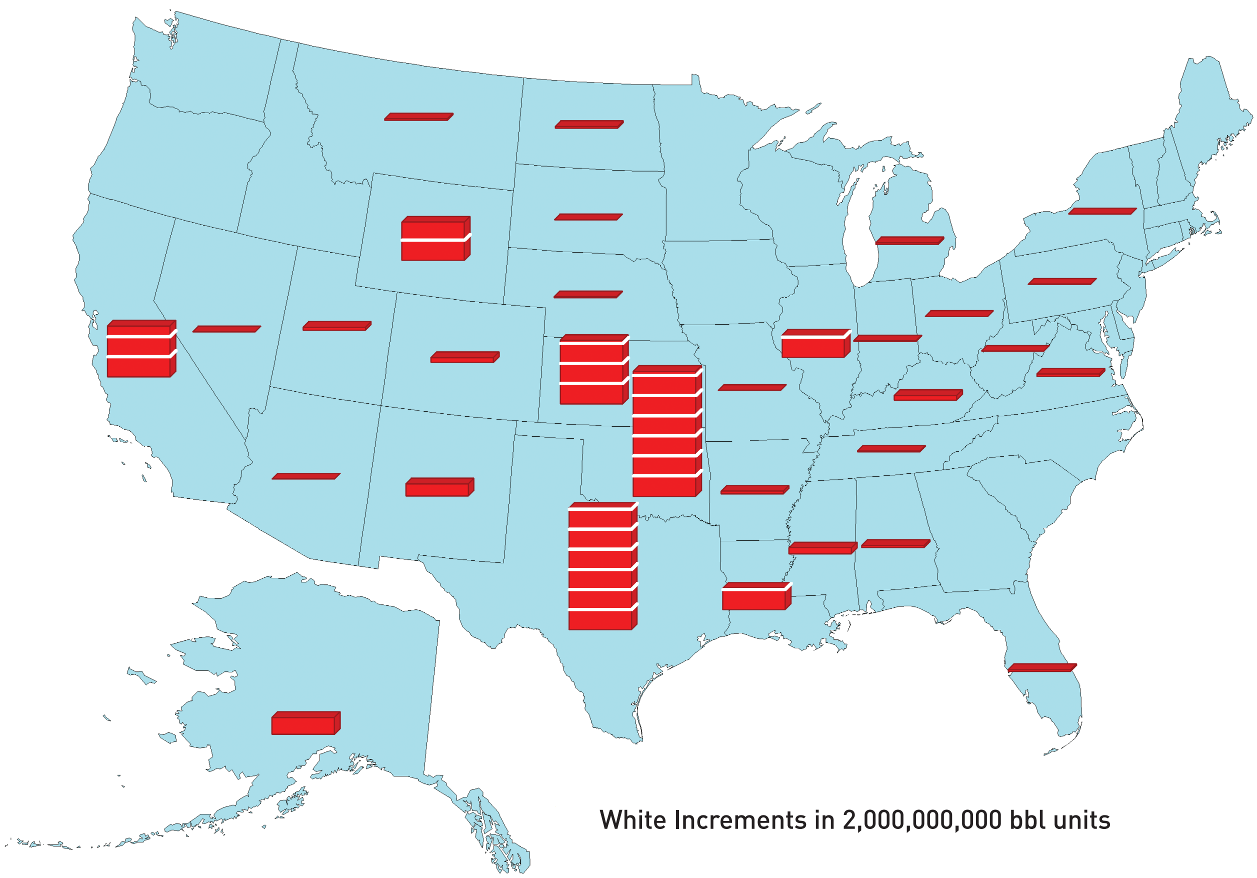

Figure 2.13 Water production from oil and gas wells (Curtice and Dalrymple, 2004).

Some of the fluid is produced from dispersed sites and may not be appropriate for 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 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 ultimately lowering the cost of some forms of hydrocarbon extraction. The figures for equivalent power in Table 2.3 represent an upper limit for electricial power generation that could be brought online with relatively low invested cost using all coproduced fluids (see also Chapter 9). The primary unknowns and, hence, limiting factors in these areas are the magnitude of the combined flow rates and the actual temperatures of the produced fluid in these existing hydrocarbon fields. In the case of two fields in Alabama, the temperatures appear to be more than 120°C (250°F), well within the range of binary generation capability.

2.6.3 Geopressured geothermal resources

The second category of systems in sedimentary rock is represented by the geopressured areas of deep basins where wells produce at pressures much higher than hydrostatic. The largest areas are in the young Gulf Coast sedimentary basin, but other 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 et al. (1975) and by Wallace et al. (1979). Papadopulos et al. (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 will also result in the recovery of significant amounts of natural gas that would otherwise be uneconomic.

Papadopulos et al. (1975) assessed the resource potential of geopressured-geothermal reservoirs within the onshore part of Tertiary sediments, 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 Figure 2.14). The assessment included only the pore fluids of sediments that lie in the interval between the top of the geopressured zones and the maximum depth of well control in 1975, i.e., 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. They did estimate that the potential of these additional geopressured reservoirs is about 1.5 to 2.5 times what was assessed in their study.

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. The area has been actively explored for oil and gas, and hundreds of thousands of wells have been drilled in search of petroleum deposits in the Texas and Louisiana Gulf Coast. The data presented by Papadopulos et al. (1975) represent general conditions in the various regions outlined. They believed 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 basis on which various data presented were determined, calculated, or assumed was discussed in the “Appendix” to their report (White and Williams, 1975).

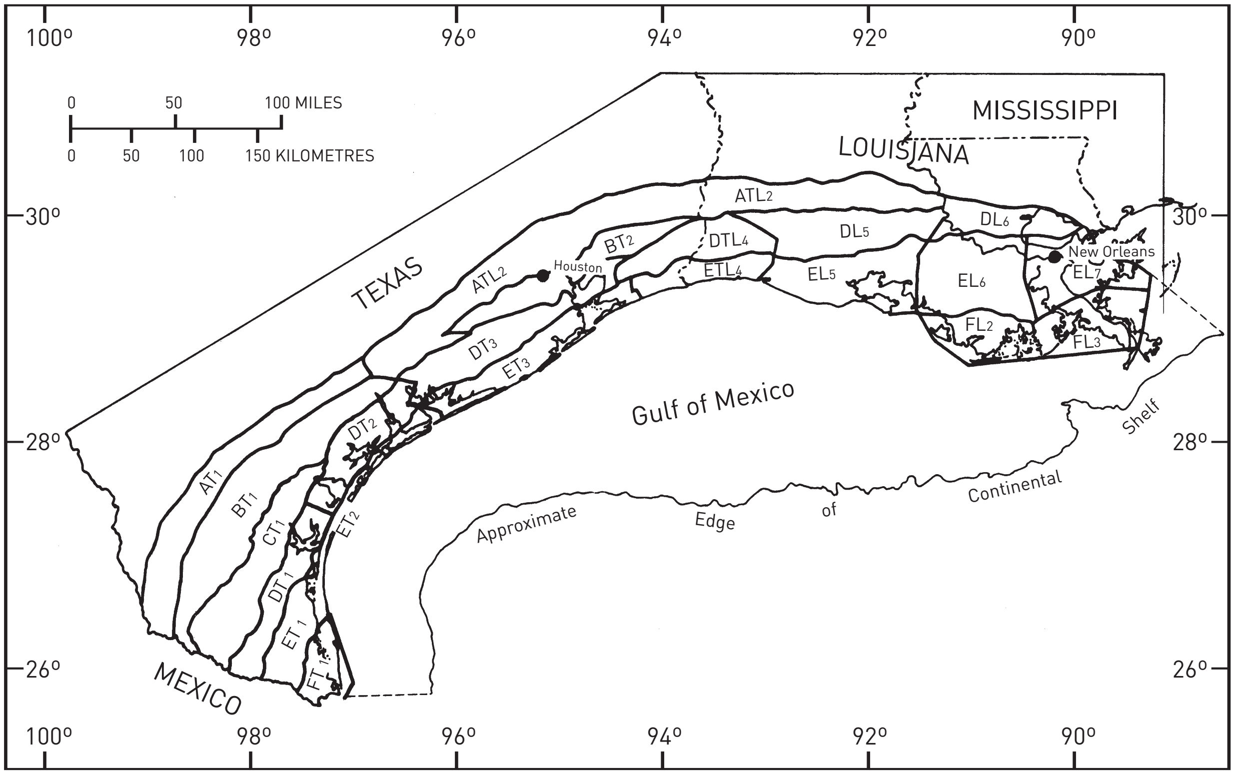

Figure 2.14 Location map showing the extent of the assessed geopressured zones and their division into subareas (AT1, BT1, etc.) (USGS Circular 726, 1975.)

The results of the assessment by Papadopulos et al. (1979) 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 x 10^{12} SCF, with a thermal equivalent of 25,000 EJ. The resource base, according to their calculations, is then about 1,000 MW for a century. Even their most conservative estimate of development was 46,000 EJ, excluding the chemical energy in the dissolved gas.

The Wallace et al. (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 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). As was the case for Papadopulos et al. (1975), they did not include the dissolved methane in their calculations. They estimated that the accessible resource was 110,000 EJ of dissolved methane, which was later reported by Wallace et al. (1979) to be about 59,000 x 10^{12} SCF or only about 60,000 EJ (see Table 2.5).

These numbers may be compared with the calculated thermal resource base for the Gulf Coast states calculated above. This value for the states of Louisiana, Mississippi, and Texas is 1.5 x 10^6 EJ. This number does not include the offshore areas of the Gulf of Mexico. The amount calculated by Wallace et al. (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. The Wallace et al. (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 A.2.1. This is because of the characteristics of the sedimentary basin resource. Wallace et al. (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 A.2.1. The ability to extract the methane for energy from these areas is also an additional resource.

Subsequent to these assessments, technologies for recovering geopressured energy were extensively studied by the U.S. DOE between 1979 and 1990. From late 1989 until early 1990, a 1 MW_e plant was operated on the Pleasant Bayou well in the Texas Gulf Coast near Houston, which produced hot water and 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 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, due to 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 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 much more favorable as pointed out in a recent study (Griggs, 2005).

2.6.4 EGS in sedimentary basins beneath hydrocarbon-bearing fields

Another scenario exists for geothermal development in many of the areas exploited for deep oil and gas production, especially in the Gulf Coast and mountain states regions. In these areas, EGS development in the deep, high-temperature part of the sedimentary section might be more cost-effective than basement EGS systems. Table 2.4 shows a comparison of needs for EGS-type development costs vs. 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 readily adapted to geothermal electrical power production.

Table 2.4 Comparison of cost components for "EGS" development (previous model for geothermal development vs. reality in oil patch situations).

Components of Direct EGS Development Cost	• Drill wells that reach hot temperatures.>150°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
Actual 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 cases, • 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.
Direct Costs to Develop a Gulf Coast EGS System	• Build power station, • Recomplete wells, in some cases, and test flow system, • Minor surface infrastructure upgrades (i.e., insulating collection pipes, etc.)

Future work 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 appears 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. These areas are clearly "EGS" types of systems but with known drilling and development costs and abundant water. Because of the thousands of wells drilled, the costs may be in some cases one-half to one-third of those for hard rock drilling and fracturing. A failed well in oil and gas exploration often means too much associated water production. In some areas, such as the Wilcox trend in south 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.

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). Production data from the hydrocarbon industry indicate that most of the hydrocarbon-bearing basins and Gulf Coast Plain in Texas, Louisiana, Mississippi, and Alabama host elevated temperatures and the potential for significant water flow (Erdlac and Swift, 2004). Currently, the oil and gas industry feels this is more of a problem than an asset. As an indication of the possibilities, research into the suitability of such basin-hosted geothermal resources has begun in the north German Basin (Zimmermann et al., 2005). In this area, low-formation permeability requires stimulating potential sandstone reservoirs, and/or significant lateral drilling. But those conditions have not deterred initial research.

The detailed size of this resource has not been calculated separately from the general EGS resource, which is mostly in basement rocks. The areas that are 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 2.5). Especially promising large areas are found in the Gulf Coast, the Appalachian Basin, the southern Midcontinent, and the Rocky Mountains. As described above, the thermal energy in such areas is at least equal to that in the geopressure-geothermal resource estimated for the Gulf Coast. Therefore, a very conservative figure of 100,000 EJ is listed in Table 2.5 for Sedimentary EGS systems. While this number may be a few percent of the total EGS value (10^5 quads, about 1% as listed in Table 2.5), the accessible fraction of the energy in a 10- to 25-year time frame may be equal to or greater than the basement EGS value (see Chapter 3). 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).

2.7 Concluding Remarks

Table 2.5 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 question of sustainability is not addressed in this chapter. However, the geothermal resource is large and is ubiquitous. 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.

Although the EGS resource base is huge, it is not evenly distributed. Temperatures of more than 150°C at depths of less than 6 km are more common in the active tectonic regions of the western conterminous United States, but by no means are confined to those areas. While the analysis in this chapter 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 United States, where the resource is almost ubiquitous, the local variations may not be as significant. In the central and eastern United States, however, there will be areas of moderate to small size that are much higher grade than the maps in Figure 2.7 imply; 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 lateral variations of almost 100% in the mean thermal conductivity within the sedimentary section. In addition, there are high heat flow areas in the eastern United States, due to the high crustal radioactivity, such as the White Mountains in New Hampshire (Birch et al., 1968) and northern Illinois (Roy et al., 1989). The most favorable resource areas in the eastern United States will have high crustal radioactivity, low average thermal conductivity, and other favorable circumstances (such as aquifer effects). Detailed exploration studies are necessary to identify the highest temperature locations, because the data density is lowest in the eastern United States, where smaller targets require a higher density of data points.

Table 2.5 Summary of nonhydrothermal U.S. geothermal resource-base estimates.

Source and Category		Thermal Energy, in 10^{18}J = EJ	Volume of Methane, x 10^{12} SCF*	Total Gas + Thermal Energy, in 10^{18}J = EJ
Geopressured (Papadopulos et al.,1975).		46,000	23,700	71,000
Geopressured (Wallace et al.,1979).		110,000	59,000	170,000
Coproduced 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		
- Volcanic EGS	Excluding Yellowstone and Alaska	65,000 (high)		
	Alaska – 26 systems	9,000 (low)		
	Hawaii – 2 systems	1,535 MW		
- Alaska – all EGS		3,200,000		
- Hawaii		N/A		

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

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Appendix A

A.2.1 Geothermal Resource-Base Data

Table A.2.1 Geothermal resource base (in exajoules = 10^{18}J) for selected states, and the total conterminous United States. Some northeastern states are combined at the end of the table.

Depth	AK[1]	AL	AR	AZ	CA[2]	CO	FL	GA
3.5 km								
150°C	0	0	0	499	10,950	17,845	0	0
200					316			
250					414			
300					275			
4.5 km								
150°C	39,588	34	6,361	49,886	53,068	45,890	0	0
200					4,734	8,413		
250					407			
300					796			
5.5 km								
150°C	387,597	1,046	16,077	82,432	79,100	55,161	1,032	0
200		8	125	8,960	23,029	36,890		
250					3,332	5,033		
300								
6.5 km								
150°C	361,688	9,148	20,725	52,335	54,243	54,667	4,339	95
200	187,722	60	6,373	74,305	70,941	51,170	2	
250				473	9,186	24,029		
300					176	1,077		
7.5 km								
150°C	139,800	20,603	33,674	38,005	35,806	37,983	7,535	9,827
200	503,829	150	16,045	85,611	85,336	52,511	14	
250	4,556		115	26,972	36,940	47,984		
300					5,204	10,517		
350								
8.5 km								
150°C	66,880	32,605	38,944	28,284	37,742	19,225	10,324	15,797
200	218,770	2,038	21,847	45,502	57,201	55,299	1,205	
250	471,901		1,196	95,001	84,389	53,729		
300				1,363	11,419	34,801		
350					3,627	4,269		
9.5 km								
150°C	14,408	39,537	32,749	13,959	36,234	6,260	31,540	32,705
200	175,463	10,425	20,115	36,486	36,780	54,748	4,503	
250	576,921		14,743	94,872	91,626	46,846		
300	54,703			42,529	48,111	55,326		
350					7,079	18,765		
Total	**3,203,825**	**115,655**	**229,089**	**777,471**	**888,460**	**798,437**	**60,494**	**58,424**

Depth	IA	ID	IL	IN	KS	KY	LA	ME
3.5 km								
150°C	0	15,845	0	0	0	0	0	0
200		138						
250								
300								
4.5 km								
150°C	0	36,008	0	0	0	0	11,455	0
200		7,218						
250		112						
300								
5.5 km								
150°C	0	61,467	0	0	266	0	19,920	0
200		31,035						
250		415						
300		90						
6.5 km								
150°C	10,729	35,257	2,005	0	57,556	0	15,280	785
200		53,875					11,028	
250		19,510						
300		359						
7.5 km								
150°C	17,070	4,770	60,518	20,997	85,427	2,728	16,380	30,136
200		71,735					23,859	
250		36,102						
300		11,323						
350		303						
8.5 km								
150°C	40,477	0	61,118	35,957	86,027	42,443	18,265	33,809
200		33,742	381		7,233		24,313	
250		75,531					4,171	
300		28,026						
350		771						
9.5 km								
150°C	43,724	0	59,015	39,003	32,540	42,930	20,828	32,849
200	14,099	5,812	3,086		76,639		12,123	1,547
250		82,886					23,396	
300		44,226						
350		17,411						
Total	**126,100**	**673,966**	**186,123**	**95,956**	**345,689**	**88,100**	**201,019**	**99,126**

Depth	MI	MN	MO	MS	MT	NC	ND	NE
3.5 km								
150°C	0	0	0	0	13	0	0	0
200								
250								
300								
4.5 km								
150°C	0	0	0	1,512	8,373	0	3,845	848
200								
250								
300								
5.5 km								
150°C	0	0	0	17,227	107,436	150	25,288	6,705
200				65	150		96	
250								
300								
6.5 km								
150°C	0	0	84	31,807	123,860	2,036	36,938	60,446
200				1,158	13,265		2,534	1,018
250					25			
300								
7.5 km								
150°C	0	0	25,081	31,467	62,006	7,728	31,332	77,730
200				10,863	109,931	74	22,289	4,053
250				58	114		27	
300					5			
350								
8.5 km								
150°C	4,581	3,331	75,279	24,382	35,340	22,597	39,481	70,168
200				30,334	143,166	181	38,193	17,414
250				3	18,204		183	136
300					136			
350								
9.5 km								
150°C	40,271	32,458	76,217	18,161	25,945	36,425	36,731	16,489
200			22	37,958	90,470	2,247	40,190	85,119
250				4,534	101,691		12,630	1,809
300				0	109			
350					74			
Total	**44,852**	**35,789**	**176,684**	**209,528**	**840,312**	**71,437**	**289,756**	**341,935**

Depth	NH	NM	NV	NY	OH	OK	OR	PA
3.5 km								
150°C	0	2,229	15,906	0	0	0	14,395	0
200								
250								
300								
4.5 km								
150°C	0	48,980	85,462	0	0	0	54,781	0
200		1,037	262				5,548	
250								
300								
5.5 km								
150°C	59	67,955	85,749	0	0	2,896	54,155	564
200		15,416	43,121				29,064	
250								
300								
6.5 km								
150°C	1,050	34,334	34,897	1,860	0	31,793	22,500	3,134
200		68,390	106,889				63,830	
250		3,447	9,585				15,248	
300								
7.5 km								
150°C	4,431	21,924	8,662	6,805	10,306	53,052	8,174	11,688
200		69,124	91,850			32	57,547	420
250		35,654	69,176				39,841	
300		1,126	18				8,110	
350								
8.5 km								
150°C	7,811	29,305	6	17,423	41,481	48,164	4,305	23,057
200	115	34,911	40,609			20,869	28,063	1,924
250		84,705	132,887				74,882	
300		5,884	14,815				21,944	
350								
9.5 km								
150°C	7,940	41,058	0	29,872	44,285	38,271	7,119	25,800
200	1,251	19,195	10,640	3,270		41,271	10,212	5,838
250		71,993	104,280			0	66,719	
300		52,671	91,908				47,698	
350		1,674	17				12,264	
Total	**22,657**	**711,011**	**946,738**	**59,230**	**96,071**	**236,347**	**646,397**	**72,424**

Depth	SC	SD	TN	TX	UT	VA	WA	WI
3.5 km								
150°C	0	0	0	74	10,371	0	24	0
200								
250								
300								
4.5 km								
150°C	0	8,051	0	32,528	36,521	0	9,796	0
200				14	1,160			
250								
300								
5.5 km								
150°C	0	18,442	0	83,934	52,362	0	41,967	0
200				354	20,480		185	
250								
300								
6.5 km								
150°C	2,712	32,029	431	117,096	50,085	991	44,388	1,733
200		8,979		21,659	44,178		13,290	
250					8,626			
300								
7.5 km								
150°C	18,126	44,780	4,212	120,075	35,496	7,876	17,087	9,177
200		17,494		80,165	46,958		47,972	
250				668	32,160		2,395	
300					1,369			
350								
8.5 km								
150°C	28,101	58,298	19,938	152,725	13,841	16,758	3,831	31,652
200		26,030		111,793	50,315		56,655	
250		2,711		13,340	49,693		15,087	
300					16,700			
350								
9.5 km								
150°C	30,597	45,838	39,322	159,675	2,540	23,827	3,728	56,882
200	3,020	39,180	398	114,015	47,367	1,344	22,915	2,711
250		14,239		59,693	48,600		56,683	
300				409	41,421		2,320	
350					1,956			
Total	**82,556**	**316,072**	**64,302**	**1,068,217**	**612,202**	**50,796**	**338,324**	**102,155**

Depth	WV	WY[3]	MA_CT_RI_VT	MD_NJ_DE	Continental USA[4]
3.5 km					
150°C	0	106	0	0	91,760
200					653
250					558
300					283
4.5 km					
150°C	0	6,795	0	0	518,041
200		203			29,930
250		8			734
300					965
5.5 km					
150°C	703	34,380	0	35	947,166
200		1,319			218,922
250		287			8,745
300					458
6.5 km					
150°C	3,367	68,411	183	468	1,062,065
200		7,132			641,638
250		334			94,405
300		177			1,854
7.5 km					
150°C	9,833	73,849	3,559	2,576	1,177,632
200	1,738	27,546		332	954,271
250		1,551			342,032
300		265			38,242
350		94			397
8.5 km					
150°C	19,425	51,926	15,198	6,760	1,426,245
200	3,834	58,148		538	944,568
250		8,809			739,995
300		445			140,961
350					8,673
9.5 km					
150°C	16,561	27,358	18,343	11,624	1,440,428
200	7,131	82,408	136	668	984,067
250	1,033	18,542		33	946,675
300		1,642			444,280
350		64			61,446
Total	**63,626**	**471,799**	**37,419**	**23,033**	**13,267,370**

1. Alaska does not include the Aleutians.

2. California had the addition of the Clear Lake and Salton Sea areas for 3.5 and 4.5 km.

3. Wyoming does not include Yellowstone National Park (8987 km^2).

4. Continental U.S. - not including Alaska or Hawaii, or Yellowstone National Park. It does include the addition of Clear Lake and the Salton Sea areas of California at depths of 3.5 and 4.5 km.

A.2.2 Coprocessed Water Associated with Oil and Gas Production

Table A.2.2 Water production (Curtice and Dalrymple, 2004) and potential power generation from oil and gas operations for selected states.

State	State	Total Processed Water, 2004, (bbl)	Water Production Rate, kGPM	Water Production Rate kg/s	Power, MW @ 100°C	Power, MW @ 140°C	Power, MW @ 150°C	Power, MW @ 180°C
AL	Alabama	203,223,404	18	1,026	18	47	64	88
AK	Alaska	1,688,215,358	153	8,522	153	389	528	733
AZ	Arizona	293,478	0.0265	1.4814	0.0267	0.0676	0.0918	0.1274
AR	Arkansas	258,095,372	23	1,303	23	59	81	112
CA	California	5,080,065,058	459	25,643	462	1,169	1,590	2,205
CO	Colorado	487,330,554	44	2,460	44	112	153	212
FL	Florida	160,412,148	15	810	15	37	50	70
IL	Illinois	2,197,080,000	199	11,090	200	506	688	954
IN	Indiana	72,335,588	7	365	7	17	23	31
KS	Kansas	6,326,174,700	572	31,933	575	1,456	1,980	2,746
KY	Kentucky	447,231,960	40	2,257	41	103	140	194
LA	Louisiana	2,136,572,640	193	10,785	194	492	669	927
MI	Michigan	188,540,866	17	952	17	43	59	82
MS	Mississippi	592,517,602	54	2,991	54	136	185	257
MO	Missouri	17,082,000	2	86	2	4	5	7
MT	Montana	180,898,616	16	913	16	42	57	79
NE	Nebraska	102,005,344	9	515	9	23	32	44
NV	Nevada	13,650,274	1	69	1	3	4	6
NM	New Mexico	1,214,796,712	110	6,132	110	280	380	527
NY	New York	1,226,924	0.1110	6.1931	0.1115	0.2824	0.3840	0.5326
ND	North Dakota	182,441,238	16	921	17	42	57	79
OH	Ohio	12,772,916	1	64	1	3	4	6
OK	Oklahoma	12,423,264,300	1,124	62,709	1,129	2,860	3,888	5,393
PA	Pennsylvania	18,571,428	2	94	2	4	6	8
SD	South Dakota	6,724,894	1	34	1	2	2	3
TN	Tennessee	62,339,760	6	315	6	14	20	27
TX	Texas	12,097,990,120	1,094	61,067	1,099	2,785	3,786	5,252
UT	Utah	290,427,704	26	1,466	26	67	91	126
WV	Virginia	2,235,240	0.2022	11.2828	0.2031	0.5145	0.6995	0.9703
VA	West Virginia	252,180,000	23	1,273	23	58	79	109
WY	Wyoming	3,809,086,632	344	19,227	346	877	1,192	1,654