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Assessment of Low-Temperature Geothermal Resources of the United States—1982

Prepared in cooperation with the U.S. Department of Energy

Assessment of Low-Temperature Geothermal Resources of the United States—1982

Marshall J. Reed, *Editor*

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The first quantitative estimation of the thermal energy recoverable from low-temperature (less than 90° C) geothermal systems within the United States

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CONVERSION FACTORS

Length:	1 centimeter (cm)=0.3937 inch (in.) 1 meter (m)=3.281 feet (ft) 1 kilometer (km)=0.6214 mile (mi)
Area:	1 m^2=10.76 ft^2 1 km^2=0.3861 mi^2
Volume:	1 liter (L)= 0.2642 gallon (gal) 1 km^3=0.2399 mi^3
Mass:	1 kilogram (kg)=2.205 pounds (lb)
Flow rate:	1 L/s = 15.85 gal/min
Temperature:	degrees Celsius (°C)=5/9(degrees Fahrenheit [°F]-32) Kelvins (K)=°C+273.15
Temperature gradient:	1°C/km=0.05486°F/100 ft
Energy:	1 joule (J)=0.2390 calorie (cal) 1 J=9.485x10^{-4} British thermal unit (Btu) 1 J=2.777x10^{-4} watt-hour (W·hr) 10^{18} J=0.9485 quad (10^{15} Btu) 1 MW_t for 30 yr=9.461x10^{14} J
Power or work:	1 watt (W)=1 J/s 1 megawatt (MW)=3.154x10^{13} J/yr
Heat flow:	1 mW/m^2=2.390x10^{-8} cal/cm·s 1 mW/m^2=2.390x10^{-2} heat-flow unit (HFU)
Thermal conductivity:	1 W/m·K=2.390 mcal/cm·s·°C

Introduction

By Marshall J. Reed

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ABSTRACT

The geothermal-resource assessment presented here is the first quantitative estimation of the thermal energy recoverable from low-temperature (less than 90°C) geothermal systems within the United States. This assessment, based on data available through April 1982, includes estimates of accessible resource base (geothermal energy in the ground), resource (energy that might be recoverable at the surface), and beneficial heat (energy that might be usable in a specific application). The minimum temperature for low-temperature geothermal resources was defined as 10°C above the mean annual air temperature at the surface and increasing by 25°C/km with depth. Systematic variations in heat flow and temperature gradient permitted the division of the United States into western, central, and eastern regions; within each of these regions, the low-temperature geothermal resources were divided into hydrothermal-convection and conduction-dominated systems.

Quantitative estimates were made for the geothermal energy available in undiscovered as well as identified systems, and the results are tabulated by region, State, and geologic province. Identified low-temperature geothermal systems in the United States contain an accessible resource base of 27×10^{21} J, a resource of 87×10^{18} J, and a beneficial heat of 41 GW_t for 30 years. Undiscovered low-temperature geothermal systems are estimated to contain an additional accessible resource base of 7.2×10^{21} J, a resource of 66×10^{18} J, and a beneficial heat of 30 GW_t for 30 years.

BACKGROUND

Resource assessment is the estimation of the amount of a given raw material that might be produced from the Earth and used economically at a future time. The present assessment of geothermal resources in the United States estimates the thermal energy that might be recoverable from low-temperature (less than 90°C) geothermal reservoirs. Using a newly developed uniform methodology applied to the most accurate data available through April 1982, this assessment provides a scientific basis for decisions about national energy policy and offers some guidance for resource-development strategy. The overall goal of this assessment is to provide a comprehensive framework for future geothermal-resource development.

This is the first quantitative assessment of low-temperature geothermal resources to be conducted by the U.S. Geological Survey (USGS). An earlier (1978) geothermal assessment included a qualitative discussion of low-temperature geothermal waters in the United States (Sammel, 1979); however, the data available at that time were not adequate for a quantitative assessment. The present geothermal-resource assessment is an extension and expansion of the inventory by Sammel and of the discussions of conduction-dominated thermal regimes by Diment and others (1975) and Sass and Lachenbruch (1979).

In 1978, the Division of Geothermal Energy of the U.S. Department of Energy began to fund studies, covering all the States, to investigate low- and intermediate-temperature geothermal systems; information gathered in these studies was provided to the USGS. The list of additional references at the end of this chapter includes a series of State geothermal-resource maps and the major reports of the State studies. Other studies, primarily carried out within the Geothermal Research Program and the Regional Aquifer Systems Analysis Program of the USGS, have provided additional information on low-temperature geothermal systems. Information on water chemistry, temperature, flow rate, and other parameters measured at many low-temperature geothermal sites was stored in the computer-based GEOTHERM information system (Teshin and others, 1979) maintained by the USGS. The GEOTHERM system enabled the assessment team to manipulate the data in various ways for the more than 2,500 geothermal systems that were considered.

TERMINOLOGY

The terminology used in this report is based on the review by Muffler and Cataldi (1978). "Resource base" is defined as the total geothermal energy in the Earth's crust. "Accessible resource base" is defined as all the geothermal energy between the Earth's surface and a specified depth in the crust. "Resource," or recoverable energy, is defined as that part of the accessible resource base that is producible at the wellhead under reasonable assumptions of future economics and technology (Muffler and Guffanti, 1979). The energy calculations for accessible resource base and resource were made for a reference temperature of 15°C (standard reference temperature of White and Williams, 1975, and Muffler, 1979), which is the average of the mean annual air temperatures in the United States. "Beneficial heat" is defined as that part of the resource that is usable in a specific application; beneficial heat is a function of the temperature drop within the application system, and an empirical relation between temperature drop and reservoir temperature is used in this report to calculate beneficial heat.

Use of the term "accessible resource base" is limited in this report to porous and permeable geothermal reservoirs that can produce water to carry thermal energy to the surface. This same limitation was applied by Brook and others (1979) in their assessment of hydrothermal-convection systems at temperatures equal to or greater than 90°C. Adoption of this limitation reflects a judgment that only low-temperature geothermal systems with high permeability will be economically competitive in the foreseeable future. In this assessment, depth to the resource is limited by the minimum-temperature function, defined as 10°C above the mean annual air temperature at the surface and increasing by 25°C/km with depth. Thus, this assessment considers the geothermal energy to a maximum depth of 3.2 km. For example, in an area with a mean annual air temperature of 12°C, spring-water temperature must exceed 22°C, and water temperature at a depth of 1 km must exceed 47°C (22°+25°). Figure 1 illustrates these relations.

Adoption of the lower temperature limit excludes from consideration an enormous amount of shallow ground water in the United States; average ground-water temperatures from 5 to 15 m deep are 5° to 7°C above the mean annual air temperature (Gass and others, 1979, fig. 1). It is recognized that such shallow waters may be useful as a source of thermal energy in specific applications, but these cases are judged to be exceptional. Similarly, the definition of the lower temperature limit at depth virtually restricts this assessment to areas having anomalous concentrations of heat associated either with hydrothermal-convection or with conduction-dominated systems within deep sedimentary basins or beneath coastal plains.

METHODOLOGY

Nathenson and others (this volume) discuss regionally significant temperature-gradient measurements to depths of 2 km and present a map showing the regional variation of these gradients (see fig. 4). Delineation of the regional variations in temperature gradients and in heat flow provides a background against which to recognize anomalous concentrations of thermal energy that may include low-temperature geothermal systems. These temperature-gradient and heat-flow data exhibit a systematic variation across the United States and provide a basis for division of the country into western, central, and eastern regions for a discussion of geothermal resources.

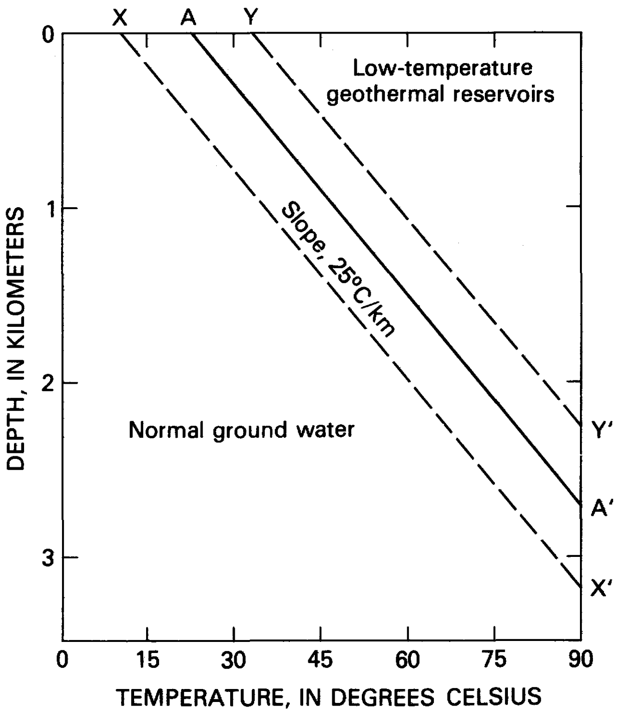


Figure 1.—Temperature-versus-depth relation used to define low-temperature geothermal resources. Upper temperature limit is 90°C, following usage of Muffler (1979); lower temperature limit is defined as 10°C above the mean annual air temperature at the surface, increasing by 25°C/km with depth. Dashed lines X-X' and Y-Y' show minimum geothermal-resource temperatures required for mean annual air temperatures of 0° and 23°C, which are the limits for air temperatures considered in this assessment. For example, for a mean annual air temperature of 12°C, the minimum surface-spring temperature is 22°C (point A), and the line A-A' gives the minimum temperature at any depth. Mean annual air temperatures are from Kincer (1941, p. 703), supplemented by information for Alaska from Johnson and Hartman (1969, pl. 35) and for Hawaii from Blumenstock and Price (1978).

Low-temperature geothermal systems can be divided into two types, hydrothermal convection and conduction dominated, on the basis of the major mechanism of heat transfer (Sorey, Nathenson, and Smith, this volume). Both types of geothermal systems occur in each region. Relatively small volume hydrothermal-convection systems predominate in the western region (Mariner and others, this volume); the Western States also contain all the intermediate- and high-temperature hydrothermal-convection systems identified in previous assessments (Nathenson and Muffler, 1975; Renner and others, 1975; Brook and others, 1979). In the central region, a few conduction-dominated low-temperature geothermal systems of relatively large volume account for the bulk of the Nation's low-temperature identified accessible resource base (Sorey, Reed, and others, this volume). A few small-volume low-temperature geothermal systems of both types are identified in the eastern region (Sorey, Reed, and others, this volume). Figure 2 shows the regions and geologic provinces used for this assessment.

The detailed assessment methodology is presented by Sorey, Nathenson, and Smith (this volume). The calculation of identified accessible resource base uses a volumetric method. For low-temperature geothermal systems with only limited information available, a standard minimum reservoir volume of 1 km^3 was assumed; this assumption reflects a judgment about the average size of a system that supplies only a few isolated springs or wells.

Calculation of the resource determines the energy recoverable from a low-temperature reservoir over a period of 30 years without fluid injection into the reservoir. The resource value depends on the number of evenly spaced wells that can maintain production at a constant flow rate for a 30-year period with a maximum drawdown of 152 m. A similar approach was used for an assessment of geopressured geothermal systems (Papadopulos and others, 1975; Wallace and others, 1979). In the analysis here, the proportion of the accessible resource base that is recoverable as a resource increases as the resource calculation, the proportion of the accessible resource base recoverable from a reservoir in 30 years ranges from a minimum of 0.1 percent for regional aquifers in large sedimentary basins (Sorey, Reed, and others, this volume) to a maximum of 25 percent for small-area reservoirs. The upper limit of 25-percent recovery from the accessible resource base is derived from the heat-sweep analysis by Nathenson and Muffler (1975).

Calculations of the beneficial heat are based on an analysis of recently published information that provides measured energy-utilization factors and heat-rejection temperatures. A reservoir temperature of 25°C (10°C above the average mean annual air temperature of 15°C) is the lower limit considered in these calculations; values are in watts thermal (W_t). The United States has a broad range in the climatic conditions that control some of the uses of geothermal energy. Mean annual air temperature ranges from -12°C in northern Alaska (0°C is the lowest air temperature considered in this report) to 23°C in southern Texas and Hawaii; in addition, the central region has extremely large seasonal variations in air temperature. It is possible that water below 25°C can be used economically in certain localities and at certain times of the year, even though water of lower temperatures is omitted here from the calculations of beneficial heat.

Uncertainties in the energy estimates of this assessment are expressed as standard deviations. The uncertainty in the identified accessible resource base results from uncertainties in estimates of the temperature, area, and thickness for each reservoir. Minimum, maximum, and most likely values were assumed for each of these parameters to create a triangular probability density from which the mean and standard deviation were calculated analytically (Brook and others, 1979, fig. 4); this calculation assumes that temperature, area, and thickness are statistically independent variables (Nathenson, 1978, app. 1). In the calculations of resource and beneficial heat, however, additional nonlinear parameters are used, and the standard deviation cannot be calculated analytically; thus, only the mean values are listed (see tables 4, 7, and 8). To determine the mean and standard deviation for the totals of identified accessible resource base, resource, and beneficial heat in the summary tables (5, 9, 10, and 12), a Monte Carlo computer simulation was used that created 400 random values of each parameter within the triangular probability density. The simpler analytical result was well suited to the calculation of energies for individual systems, but for the summary of energies by temperature category or region the more complex Monte Carlo calculations were necessary to obtain standard deviations. The values for identified accessible resource base from the Monte Carlo calculations differ slightly from those calculated analytically, but the differences are not significant (well within the standard deviation). Estimates of the minimum, maximum, and most likely values of the distributed parameters for each system have been made by Reed and others (1983).

RESOURCE UTILIZATION

Anderson and Lund (1979) discussed many specific legal and economic factors related to the development of low-temperature geothermal energy in the United States. A similarly detailed discussion is beyond the scope of this report; our assessment presents only an estimate of the resource that will be available in the foreseeable future within an undefined framework of legal and economic factors.

Direct use of low-temperature geothermal water can supply the energy needs of many processes that now depend on fossil fuels, as shown in figure 3. Some of these uses involve direct consumption of thermal water rather than an exchange of heat, and so the method of calculation of beneficial heat does not apply. Three low-temperature geothermal reservoirs in China currently provide energy for electrical generating plants (Reed and Bliss, 1983), but this use of low-temperature geothermal water is not considered at present to be economical in the United States.

In the past, the use of geothermal water in the United States was primarily for hot-water baths and pools (balneology). After 1920, however, the abundance of inexpensive natural gas for heating baths and pools caused a rapid decline in the use of natural

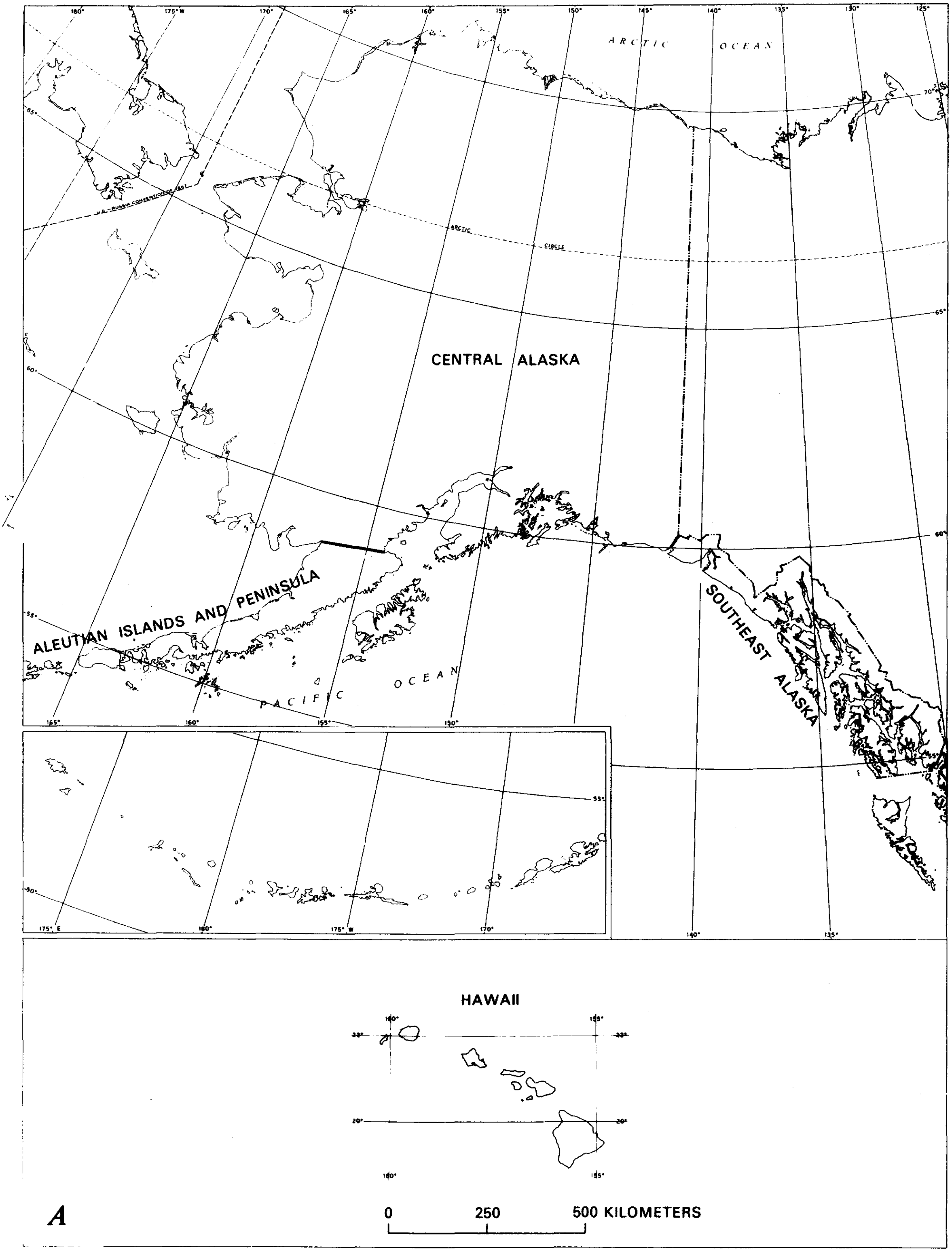
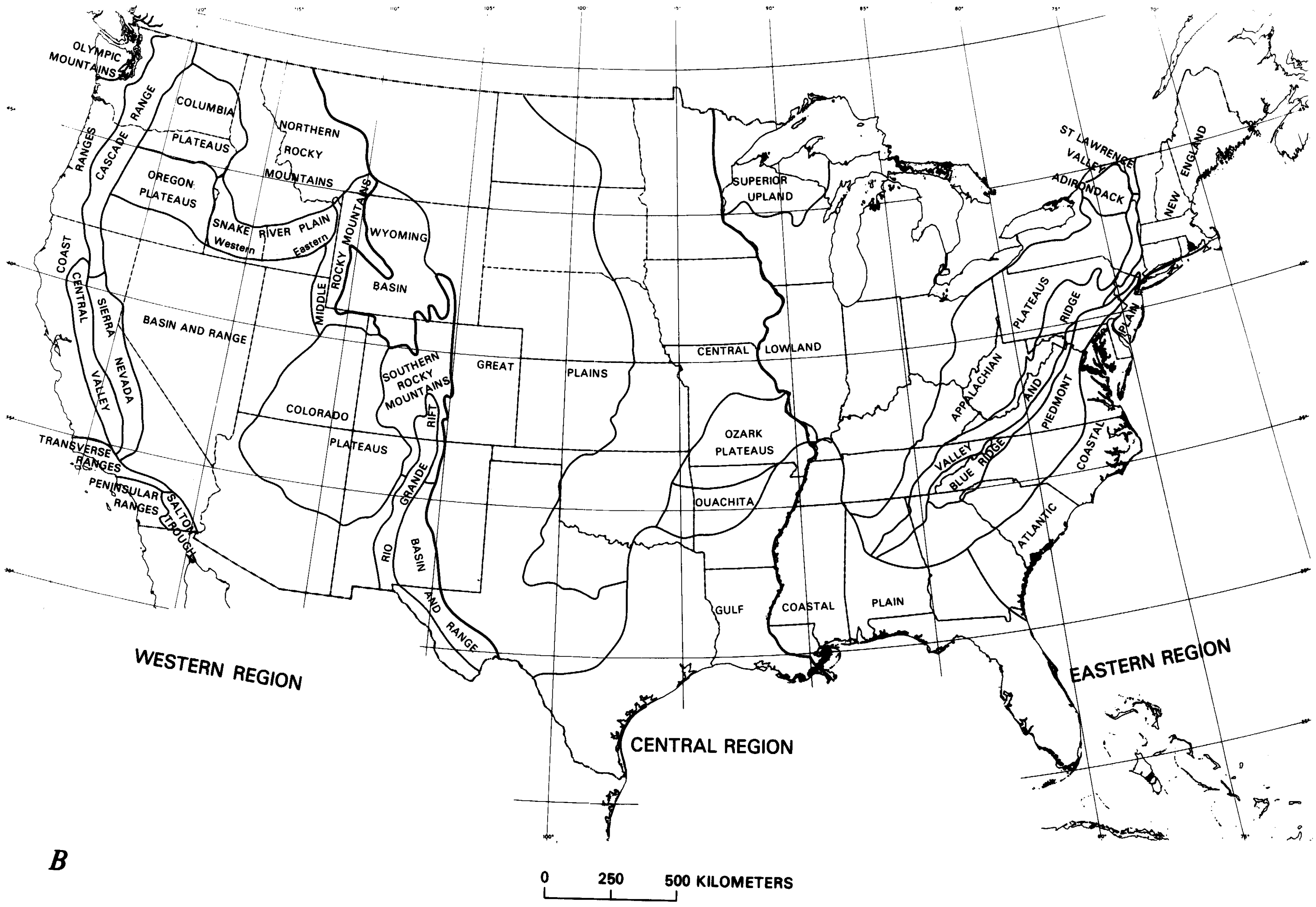


Figure 2.—Major geologic provinces of the United States (modified from the physiographic provinces of Fenneman, 1946), showing division of the country into three regions for discussion in this assessment. A, Alaska and Hawaii (western region). B, Conterminous United States (western, central, and eastern regions).



B

Figure 2.—Continued

hot water. Some use of geothermal water for space heating dates from before 1890 in such areas as Boise, Idaho, but interest in this application has been rather slight until the 1970's.

This assessment estimates that identified low-temperature geothermal systems in the United States contain an accessible resource base of 27×10^{21} J, a resource of 87×10^{18} J, and a beneficial heat of 41 GW_t for 30 years; undiscovered low-temperature geothermal systems are estimated to contain an additional accessible resource base of 7.2×10^{21} J, a resource of 66×10^{18} J, and a beneficial heat of 30 GW_t for 30 years. The current estimated use of low-temperature geothermal energy requires only a small part of the identified beneficial heat. Installed uses in the United States at the end of 1980 consisted of 790 MW_t for enhanced oil recovery in Montana, North Dakota, and Wyoming; 1 MW_t for balneology; and 110 MW_t for agricultural, residential, and industrial needs (estimated from Oliver, 1981, and M. J. Reed, unpub. data, 1981). From a 1980 survey, the use of geothermal energy with reservoir temperatures less than 90°C in countries other than the United States is estimated at 2.2 GW_t for balneology and 1.7 GW_t for all other needs (from Gudmundsson and Pálmason, 1981).

Temperature (°C)	Uses
90	Drying of stock fish Intense deicing operations
80	Space heating Greenhouse heating and milk pasteurization
70	Refrigeration (lower limit) Vacuum distillation of ethanol
60	Animal husbandry Combined space and bed heating of greenhouses
50	Mushroom growing
40	Enhanced oil recovery (lower limit) Soil warming
30	Water for winter mining in cold climates Balneology and deicing (lower limit)
20	Fish hatching and fish farming

Figure 3.—Temperatures required for uses of geothermal water (from Líndal, 1973).

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Regional Heat Flow and Temperature Gradients

By Manuel Nathenson, Marianne Guffanti,
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CONTENTS

ABSTRACT

To assess the potential for low-temperature geothermal resources in regional conductive thermal environments, a knowledge of temperature gradients to depths of about 2 km is required. Regional variations in temperature gradient, which reflect corresponding regional variations in heat flow, thermal conductivity, or both, result in some uncertainties in the derivation of deep thermal-gradient data from near-surface (100-250-m depth) heat flows. A contour map of regional heat flow in the conterminous United States shows that heat flow in the West is generally higher than in the East. A temperature-gradient map, based on data from 240 drill holes generally deeper than 600 m, indicates the same sort of first-order variation in geothermal-resource potential as does the heat-flow map, although there also are some important differences between these two maps. Large areas are without data on both maps, but either map can be used to identify promising geothermal-resource areas or areas where more reconnaissance work is needed.

INTRODUCTION

For the assessment of low-temperature geothermal resources in the United States, regional heat flow and temperature gradients assume a much greater importance than for intermediate- and high-temperature resources. For low-temperature geothermal energy, a favorable combination of high regional heat flow, low thermal conductivity, and a good aquifer can result in an exploitable resource at depths of 2 km or less. However, the depths of occurrence for high-temperature geothermal energy derived from conductive thermal gradients without hydrothermal convection are so great that economical extraction becomes unlikely.

This chapter briefly reviews heat flow and temperature gradients to provide a background for presentation of maps of heat flow and deep temperature gradients in the United States and of a table of thermal conductivities. These maps help to delineate areas favorable for the occurrence of low-temperature geothermal resources and have been used to assign average temperature gradients for the estimation of reservoir temperatures for some geothermal systems (Sorey, Reed, and others, this volume).

BACKGROUND

The vertical conductive heat flow q given by

$$q=k\left(\frac{dT}{dz}\right), \tag{1}$$

where k is the conductivity and dT/dz is the vertical temperature gradient. The temperature gradient is determined by measuring the temperature at various depths in a drill hole and calculating a gradient (for example, Sass and others, 1971). Thermal conductivities, which are commonly measured in the laboratory on core or cuttings, generally range from 1.7 to 3.5 W/m K for consolidated rocks, although values as low as 0.8 W/m K and as high as 8 W/m K also occur (Roy and others, 1981). Table 1 lists typical values for regional heat flow and temperature gradients in the United States.

Birch and others (1968) showed that for granitic plutonic rocks in the Northeastern United States, a plot of the measured surface heat flow q versus the measured radioactive heat production A defines a straight line:

$$q=q_r+DA, \tag{2}$$

where D is the slope of the line, in units of depth. The reduced heat flow q_r is the heat flow obtained by extrapolating the plot of q versus A to zero radioactive heat production. Typical values for

Table 1.—Typical values of heat flow and temperature gradient in parts of the conterminous United States

[All values assume a thermal conductivity of 2.5 W/m·K and a radioactive heat production of 2.1 $\mu W/m^3$ (after Lachenbruch and Sass, 1977)]

Region	Reduced heat flow (mW/m^2)	Heat-production thickness (km)	Heat flow (mW/m^2)	Temperature gradient (°C/km)
Sierra Nevada----------	17	10	38	15
Eastern United States--	34	7.5	49	20
Basin and Range--------	67	10	88	35
Battle Mountain high (part of the Basin and Range)	84	10	105	42

radioactive heat production in felsic crystalline-basement rocks range from 1 to 3 W/m^3, although values as high as 8 W/m^3 are also known. The q-A relation was interpreted by Birch and others (1968) to indicate that the heat flow measured at the surface is made up of one component of heat flow q_r from the mantle and lower crust and another component of heat flow DA due to the radioactivity of the upper crust. The parameter D can be related to the thickness of a layer of rock with constant heat production A below which heat flow is constant and equals the reduced heat flow q_r. Other distributions of radioactivity with depth also satisfy equation 2; a model in which A decreases exponentially with depth was proposed to maintain the validity of equation 2 under the effects of differential erosion (Lachenbruch, 1968, 1970).

Different regions have been found to have characteristic values of q_r and D (for example, Roy and others, 1968a, b; Lachenbruch, 1968), and on this basis the conterminous United States can be divided into regions of characteristic heat flow. Table 1 lists the values of q_r and D for these regions (Lachenbruch and Sass, 1977). Within most such regions, q_r remains constant, whereas the measured surface heat flow may vary from place to place owing to variations in radioactive heat production of the crust. The value used in table 1 for radioactively generated heat flow in the Eastern United States is 16 mW/m^2, which represents a substantial fraction of the measure surface heat flow. For the tectonically young parts of the Western United States, the data for q are quite high on the average, and the q-A data show considerable scatter (Lachenbruch and Sass, 1977), so that a linear q-A relation cannot be defined. Some of the heat flow in all the regions is attributable to crustal radioactivity, but other large-scale processes also are involved. The high mean value is most likely related to deep-seated tectonic processes, such as crustal extension and associated magmatism, whereas the large scatter is probably due to hydrothermal convection in the uppermost few kilometers of the crust, and to associated hot-spring activity.

DISTRIBUTIONS OF HEAT FLOW AND TEMPERATURE GRADIENTS IN THE UNITED STATES

The temperature-versus-depth relation in the upper 2 km of the crust can be estimated from either heat-flow or temperature-gradient data. In many areas, heat flows have been determined from data collected in drill holes less than 150 m deep, and although the measured gradients may appear to be conductive, some heat flows are probably affected by hydrothermal convection and ground-water flow below the drill hole. If, however, the conductive heat flow is representative of the region and if a model can be developed for the variation in thermal conductivity with depth, then temperatures to depths of 2 km can be predicted from shallow heat-flow measurements alone. In most of the conterminous United States, however, it is difficult to fulfill both these requirements, owing to an insufficient number of internally consistent heat-flow determinations or to incomplete knowledge of the thermal conductivity to the required depths.

A more direct method of estimating deep subsurface temperatures is by extrapolating measured gradients. However, if the depths of interest lie significantly below the depth for which temperature measurements are available, this extrapolation becomes uncertain, and variation in conductivity must be accounted for. When the thermal conductivity has not been measured or cannot be estimated with confidence, the temperature data should be from drill holes sufficiently deep that any changes in thermal conductivity between the bottom of the hole and the target depth will not be significant.

The heat-flow map (fig. 4) of Sass and others (1981, fig. 13.4) shows contours of surface heat flow based on more than 1,000 determinations. The specific data are not shown, but a map of them together with a fairly complete reference list may be found in Sass and others (1981). The United States east of the 100th meridian is generally characterized by a heat flow of 40 to 60 mW/m^2, with some local regions of higher heat flow in New England and on the Atlantic Coastal Plain. Heat flow west of the 100th meridian appears to vary more and to be higher overall than in the East; the mean heat flow in the West is about 80 mW/m^2. Within the West, areas of relatively low heat flow occur in the western Sierra Nevada, southern Nevada, and parts of the Colorado Plateaus, whereas heat flow greater than 100 mW/m^2 characterizes the Southern Cascade Mountains, the Battle Mountain high, and the Rio Grande Rift. On a regional scale it is unlikely that conductive heat flow can exceed 150 mW/m^2, and higher values indicate some form of hydrothermal convection.

An empirical approach to predicting heat flow in areas of little or no conventional heat-flow data was developed by Swanberg and Morgan (1978, 1980; see Sass and others, 1981), who discovered a statistical correlation between the silica geotemperature of ground waters and heat flow within 1-degree blocks of latitude and longitude for which silica geotemperature and heat flow are both well documented and have small scatter. They extended this empirical relation

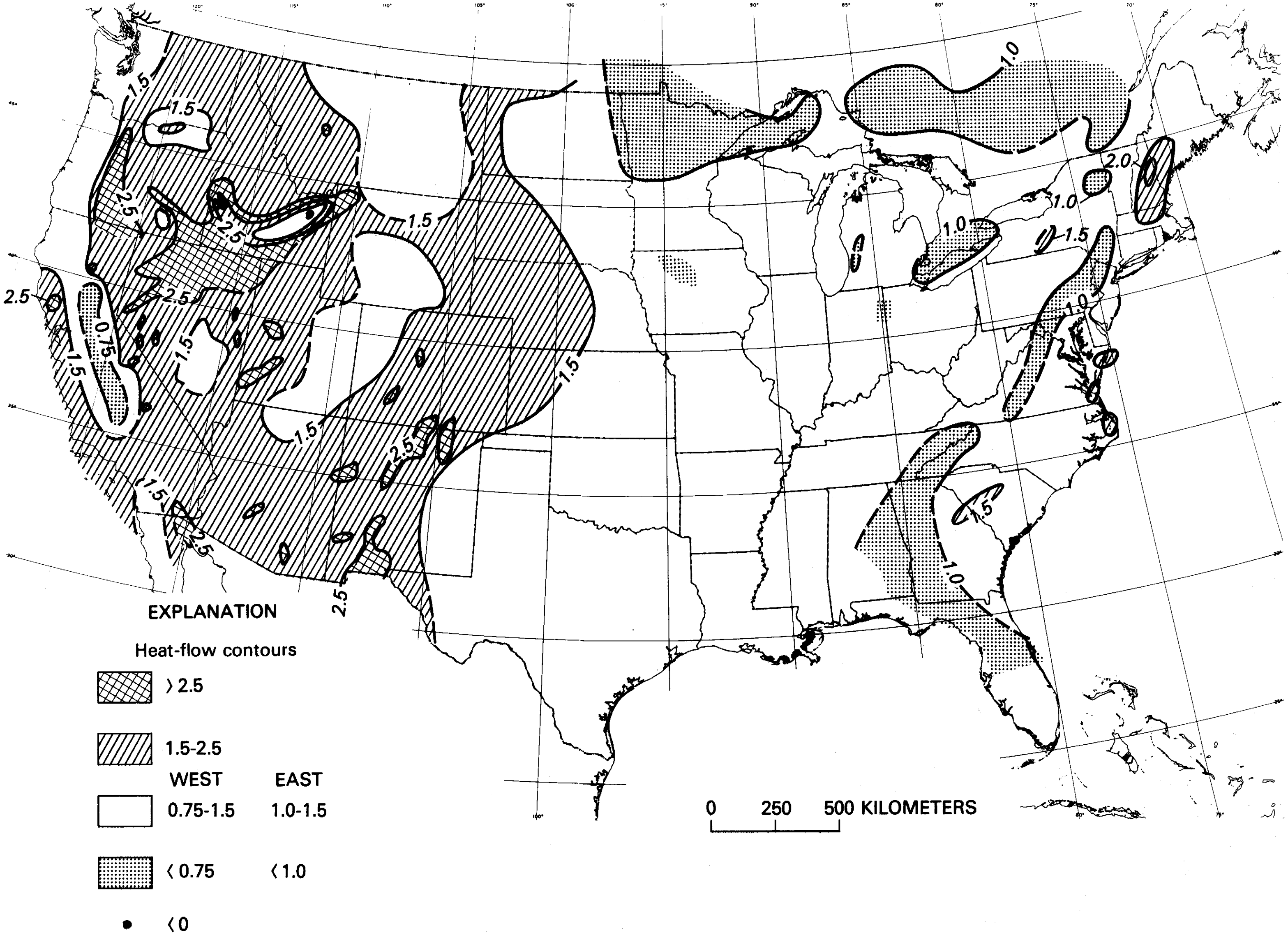

Figure 4.--Heat-flow map of the conterminous United States (from Sass and others, 1981, fig. 13.4). Contours are in heat-flow units.

to areas with few heat-flow measurements and predicted heat-flow anomalies for several such areas. Some of their predictions—namely, on the Atlantic Coastal Plain, in southeastern Utah, and in parts of Nebraska—have been confirmed by subsequent heat-flow measurements, whereas others (for example, in the Central Valley of California) appear to represent something other than high heat flow (see J. K. Costain, in Sass and others, 1981, p. 533-539; C. A. Swanberg and Paul Morgan, in Sass and others, 1981, p. 540-544). The silica-geotemperature/heat-flow relation has thus had some success in predicting heat-flow anomalies on a regional basis, and the anomalies predicted by this method are worth investigating with conventional techniques. However, because the method relies on a statistical approach involving data averaged over 1-degree blocks of latitude and longitude or larger areas, and because the physical basis of the relation has yet to be established, the silica-geothermometer/heat-flow method probably has only a limited applicability to reconnaissance exploration for low-temperature geothermal resources.

If thermal conductivities were more or less uniform or well known on a regional scale, the heat-flow map in figure 4 could be used to characterize

Table 2.—Thermal conductivities of common rock types

[All values in watts per meter-Kelvin]

Rock type	Range	Mean
Andesite	1.35-4.86	3.7
Basalt	1.12-2.38	1.8
Dolomite	4.0-5.9	4.5
Gabbro	1.80-3.60	2.6
Gneiss	1.69-5.75	3.7
Granitic rocks	2.1 -5.0	3.6
Limestone	1.30-5.80	3.6
Marble	2.02-6.52	4.3
Quartzite	2.33-7.45	4.9
Rhyolite	1.58-4.33	3.0
Rock salt	5.3-7.2	5.4
Sandstone	1.5-4.3	2.9
Shale	1.2-2.9	2.0
Tuff	.91-3.20	2.1

temperature gradients. Table 2 lists representative values of the thermal conductivities of water-saturated rocks in various parts of the United States. The ranges and means are only approximate and have been generalized from various sources, including Clark (1966), Roy and others (1981), and J. H. Sass and R. J. Munroe (unpub. data, 1982).

Several observations should be made in relation to the data listed in table 2:

1. For most rock types, the thermal conductivity varies enormously. For some rock types in a given locality or region, however, most values may fall within a relatively narrow range of about 20 to 30 percent of the mean. Mean values commonly vary from region to region, and so the literature values used for estimates of heat flow and for derivation of temperature gradients must be chosen with care.
2. For quartz-rich rocks, the bulk thermal conductivity varies widely with the content of such low-conductivity minerals as feldspars and with the porosity, and so it is difficult to generalize regional means.
3. Literature values for shale are unreliable. Argillaceous sedimentary rocks represent possibly the most difficult media for the measurement of thermal conductivity. They are fissile and, in many places, poorly consolidated, and it is almost impossible to maintain them in their natural physical state after removal from the ground. They also are anisotropic, and so measurements of thermal conductivity on crushed samples or drill cuttings (the most common current method) will generally be in error because such measurements represent a geometrically weighted average conductivity rather than the actual vertical conductivity. Blackwell and others (1981) discussed some of the implications of this type of error to measured heat-flow values from the Great Plains. In the context of low-temperature geothermal resources, suspect literature values for the thermal conductivity of shale are irrelevant if the temperatures of interest are entirely within a shale section; however, if gradients are extrapolated from sand to shale or vice versa, the predicted temperatures can be greatly in error.
4. Generalized literature values of thermal conductivity can be used to estimate the variation in conductivity with depth and thus, as mentioned previously, to facilitate extrapolation of temperature gradients for most crystalline terranes and a restricted class of sedimentary terranes. For carbonate rocks, the ratio of limestone to dolomite in a given section must be known. In sand-shale sections, an accurate estimate of the sand/shale ratio is required, and in sedimentary basins where the sand/shale ratio varies laterally, gradients in these sections may vary by a factor of 2 for the same regional heat flow.

Several maps of temperature gradients in the United States have been constructed. The American Association of Petroleum Geologists and U.S.

Geological Survey (1976) prepared a map of gradients calculated primarily from temperature measurements at a single depth in oil, gas, and water wells and from assumed values of the mean annual air temperature (see Guffanti and Nathenson, 1980, fig. 2). Vaught (1980) used the data for Michigan to point out various problems with the accuracy of this data set in that area and thus showed that the map must be interpreted with care. Kron and Heiken (1980a, b) used data from the heat-flow literature for drill holes deeper than 50 m to construct a map of temperature gradients. Although they omitted data for any drill hole with temperatures that were obviously disturbed, some shallow drill holes with either high or low temperature gradients are most probably influenced by underlying hydrothermal convection. Although meaningful estimates of thermal budgets and deep temperatures can be obtained from groups of such shallow heat-flow data (for example, Sass and others, 1971; Brott and others, 1976), simple linear extrapolation of thermal gradients from such data generally is misleading.

Guffanti and Nathenson (1980, fig. 1) constructed a temperature-gradient map based on data from drill holes generally deeper than 600 m, using data that appeared to represent conductive heat transfer, to obtain a representation of regional, background thermal gradients. Data from drill holes at sites in or adjacent to known hydrothermal-convection systems were omitted. In drill holes where the gradient varied with depth, an overall gradient was chosen as the average of straight-line segments, approximately weighted by depth interval. Although, this value may not exactly reflect the temperatures at all depths, it can be a good approximation of these temperatures, provided the temperature-gradient contrasts over large depth intervals are not too great. As part of their study, Guffanti and Nathenson (1981) made a systematic search of the compilation by Spicer (1964) to extract the deepest, least disturbed, and most areally representative temperature logs.

Figure 5 shows the map of Guffanti and Nathenson (1980) but with added data from Blackwell and Steele (1981), Dashevsky and McClung (1980), M. C. Gardner (written commun., 1981), Hodge and others (1981), Jessop and Judge (1971), Judge and Beck (1973), W. S. Keys and D. E. Eggers (written commun., 1980), Leonard and Wood (1980), McClung (1980), Perry and others (1980), Roy and others (1980), Sass and others (1981), J. H. Scott and J. J. Daniels (written commun., 1980), Shearer (1979), and Urban and others (1978). An important characteristic of these deep temperature gradients is that few of the high gradients shown on the map by Kron and Heiken (1980b) are confirmed by the deeper data. In part, this difference reflects the smaller number of deep drill holes used by Guffanti and Nathenson (1980), but it also reflects the improbability of very high gradients persisting to depths of 600 m except in geothermal areas, as well as the local-areal extent of most high-temperature thermal anomalies. It should be emphasized that the map (fig. 5) is highly generalized and that in areas between temperature-gradient contours, both higher and lower values may be measured on a local scale, especially at shallow (less than 300 m) depths.

The temperature-gradient map (fig. 5) reflects the combined effects of heat flow and thermal conductivity. Comparison with the heat-flow map (fig. 4) shows a general coincidence of temperature gradients with heat flow. Gradients less than 25°C/km and heat flow less than 63 mW/m^2 (1.5 HFU) predominate east of the 100th meridian, whereas gradients greater than 25°C/km and a heat flow greater than 63 mW/m^2 are common in the West. Within the East, part of the southern Appalachians region stands out as a thermal low in terms of both heat flow and temperature gradients, whereas in parts of the Atlantic Coastal Plain, higher than average heat flow is expressed by higher temperature gradients. High temperature gradients in the Northwestern United States and in parts of Colorado and Wyoming approximately correspond to areas of high heat flow. Virtually no heat-flow determinations exist on which a comparison can be based in western Texas, where temperature gradients are low, or in the Gulf Coastal Plain, where inland gradients are high.

This general correspondence between heat flow and temperature gradients suggests that thermal conductivities cluster around some average value on a regional scale, despite smaller scale variations in lithology. Some variations in conductivity, however, are related to regional geologic features, and some temperature-gradient anomalies mirror geologic environments but not heat flow. For example, relatively high temperature gradients occur in western Pennsylvania and West Virginia, primarily owing to the low thermal conductivity of the thick sequence of Devonian shale in those States; however, this is not a region of high heat flow except for a small area in south-central New York. Some anomalous temperature gradients are related to local thermal-conductivity extremes that are not significant on a regional scale; for example, a 13°C/km gradient in eastern Utah relects the local presence of high-conductivity salt.

LOW-TEMPERATURE GEOTHERMAL-RESOURCE ASSESSMENT

Low-temperature geothermal resources are defined partly in relation to regional background values of heat flow and temperature gradient. The low-temperature geothermal resources assessed in this volume occur in permeable aquifers that have temperatures greater than those defined by a minumum of 10°C above the local mean annual air temperature at the surface, increasing by 25°C/km with depth to a maximum of 90°C (see Reed, this volume, fig. 1). The value of 25°C/km corresponds to the temperature gradient based on an average heat flow of 63 mW/m^2 and a thermal conductivity of 2.5 W/m·K for felsic crystalline rocks. This thermal regime is appropriate for stable continental environments and is an upper limit for large areas of the Eastern United States, as depicted on the temperature-gradient map (fig. 5).Gradients higher than 25°C/km occur in regions of high heat flow and in areas of normal heat flow containing a thick sequence of such low-conductivity rocks as shale and basalt. The low-temperature limit used in this assessment screens from consideration geologic environments with

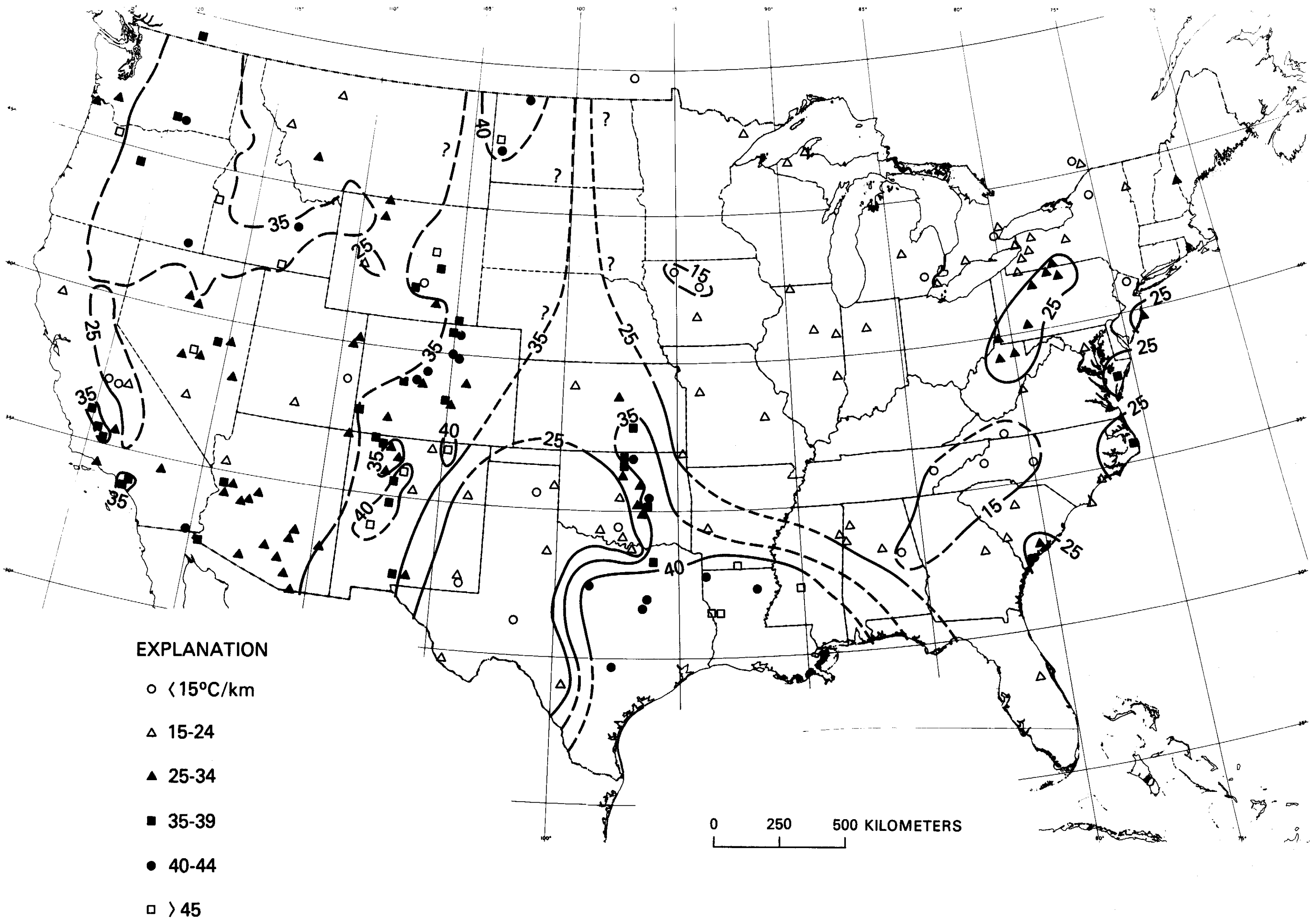

Figure 5.—Temperature-gradient map of the conterminous United States (based on Guffanti and Nathenson, 1980, fig. 1).

normal heat flow and average conductivity, and thus excludes areas containing vast amounts of relatively cool shallow ground water; it also constrains to reasonable values the drilling depths required to reach adequate temperatures for nonelectrical uses.

The temperature-gradient map (fig. 5) broadly highlights areas with gradients greater than 25°C/km where useful temperatures can be found at drillable depths. East of the 100th meridian, an area in western Pennsylvania, parts of the Atlantic Coastal Plain, and areas inland of the Gulf of Mexico coast all have higher than average temperature gradients. Much of the West has high gradients, although depths to basement are shallow in many places; obvious exceptions are the San Joaquin Valley and the Los Angeles basin in California, the Williston basin in North Dakota, and smaller basins in Wyoming, Colorado, and New Mexico.

To be considered a resource, not only must the temperatures be adequate, but also there must be indication of sufficient permeability to supply long-term production (Sorey, Nathenson, and Smith, this volume). Mariner and others (this volume) and Sorey, Reed, and others (this volume) survey the available hydrologic data to estimate reservoir thicknesses, transmissivities, and confining-bed properties for aquifers that exceed the minimum-temperature criterion. For most aquifers, actual temperature data were used; however, for some areas the data shown on the temperature-gradient map (fig. 5) were used to assign average gradients for an estimation of reservoir temperatures.

Superimposed on the regional gradients are anomalies caused by hydrothermal convection. The low-temperature resources identified by Mariner and others (this volume) include some that have hot springs at the surface and are clearly associated with hydrothermal-convection systems. Other resources are defined by high temperatures in wells; for these resources, the heat-flow and temperature-gradient maps (figs. 4, 5) are useful for deciding whether the system reflects regional conductive heat flow and temperature gradients, or is likely to require convection to give the temperatures measured in wells at the depth shown.

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Methods for Assessing Low-Temperature Geothermal Resources

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CONTENTS

ABSTRACT

Low-temperature geothermal resources exist in systems dominated by hydrothermal convection and by heat conduction. Most identified low-temperature geothermal-resource areas occur in hydrothermal-convection systems that were delineated solely on the basis of a single thermal spring or well, and for resource-assessment purposes a standard reservoir volume was assigned to these areas. Other types of low-temperature geothermal-resource areas for which actual reservoir volumes could be determined occur in hydrothermal-convection systems and in conduction-dominated systems within sedimentary basins and beneath coastal plains. In this assessment, mean values for the thermal energy stored in each identified low-temperature reservoir were obtained from estimates of triangular probability densities for the reservoir area, thickness, and temperature. Mean values of the thermal energy recoverable at the surface depend on estimates of the number of production wells each reservoir can support over a period of 30 years. An assumed development plan, with evenly spaced wells producing at 31.5 L/s at a maximum drawdown of 152 m, was used to generate curves that relate reservoir area and hydrologic properties to the optimum well spacing. The optimum well spacing is shown to increase with reservoir area but to be relatively insensitive to the length of the development period and the fraction of time during a given period that fluid production actually occurs. Finally, estimates of the amount of recoverable energy that can be used in applications at the surface were obtained as a function of reservoir temperature.

INTRODUCTION

Assessment of geothermal resources involves determination of the location, size, and geologic characteristics of each resource area to calculate the accessible resource base (thermal energy stored in the reservoir) and the resource (thermal energy recoverable at the wellhead). Identified low-temperature geothermal-resource areas must meet the criteria that a reservoir with sufficient permeability to supply long-term production exists and that reservoir temperatures exceed a defined temperature-depth relation (see fig. 1). In this chapter, the types of hydrothermal-convection and conduction-dominated systems within which low-temperature geothermal-resources occur are discussed, and the methods used to estimate accessible resource base, resource, and beneficial heat (recovered thermal energy usable in applications at the surface) are described. A rationale is also presented for estimating undiscovered geothermal resources in various geologic environments.

The statistical basis for resource estimates in this assessment is similar to that used by Brook and others (1979), with minor exceptions as noted. In contrast to the work of Brook and others (1979), however, in which recoverable thermal energy was determined by using a fixed recovery factor of 25 percent of the stored thermal energy, the methodology used in this assessment involves estimation of the number of production wells a reservoir can support for a period of 30 years with a maximum drawdown of 152 m. Recovery factors based on this methodology are less than 25 percent except for small-volume reservoirs.

Identified low-temperature geothermal resources occur mostly in areas where subsurface temperatures in permeable rock layers are above the normal or background temperatures at corresponding depths. At any given locality, one or more of the following factors may give rise to such a geothermal resource: (1) high regional heat flow, (2) young

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magmatic intrusions, (3) a thick sequence of low-thermal-conductivity rocks overlying an aquifer, (4) upward circulation of thermal fluid along faults, or (5) updip flow within areally extensive aquifers. In areas where these factors are unimportant, the temperature gradient is generally so low that drilling to resource temperatures is either uneconomical or impractical.

A useful distinction can be made between a geothermal reservoir and a geothermal system. A "geothermal reservoir" is considered to be a geometrically defined volume of permeable rock from which thermal energy in water can be extracted. Reservoirs containing low-temperature (and high-temperature) geothermal resources commonly are surrounded by cooler rocks that are also permeable and hydraulically connected to the reservoir; thus, water may flow between the reservoir and surrounding rocks in the natural state. Such reservoirs exist as parts of larger "geothermal systems" involving circulation of meteoric water downward from recharge areas and upward toward discharge areas, commonly with lateral leakage of thermal water into permeable formations adjacent to the upflow conduits. In the broadest sense, a geothermal system could also be construed to include a heat source of either magmatic or nonmagmatic origin. Although the reservoir is the producible part of the geothermal system, the response of the reservoir to development may be significantly affected by the nature of its connection with the rest of the geothermal system.

CATEGORIES OF LOW-TEMPERATURE GEOTHERMAL-RESOURCE AREAS

Low-temperature geothermal resources occur in two types of geothermal systems—hydrothermal convection and conduction dominated. In hydrothermal-convection systems, upward circulation of water transports thermal energy to reservoirs at shallow depths or to the surface. These systems commonly occur in regions of active tectonism and above-normal heat flow, such as much of the Western United States. In conduction-dominated systems, upward circulation of fluid is less important than the existence of high vertical temperature gradients in rocks that include aquifers of significant lateral extent. These conditions occur beneath many deep sedimentary basins throughout the United States.

For each type of geothermal system, two categories of low-temperature geothermal-resource areas are recognized (table 3). Each low-temperature geothermal-resource area identified in this assessment is assigned to one of these four categories to convey additional information about resource characteristics. Figures 6 through 8 illustrate conceptual models of geothermal systems related to all these categories. Additional discussions of the various types of geothermal systems, including those in which low-temperature geothermal resources occur, were presented by Muffler and others (1979).

Table 3.—Categories of low-temperature geothermal-resource areas

Category	Setting	Example
	Hydrothermal-convection systems	
1	Isolated thermal springs and wells	Pagosa Springs, Colorado
2	Delineated thermal reservoirs	Klamath Falls, Oregon
	Conduction-dominated systems	
3	Sedimentary basins	Powder River Basin, Wyoming
4	Coastal plains	Delmarva Peninsula, Virginia

Most of the identified low-temperature geothermal-resource areas associated with hydrothermal-convection systems fall into category 1 (isolated thermal springs and wells). In such areas, the only evidence that a geothermal reservoir exists at depth is a single thermal spring or group of closely spaced springs, or a well that produces thermal water. In the Western United States, thermal springs commonly occur along normal faults, whereas in the Eastern United States, thermal springs occur in regions of folded and thrust-faulted rocks. Figure 6 shows three possible models of fluid circulation in such areas; other models were presented by Breckenridge and Hinckley (1978) and Hobba and others (1979). Although reservoir volumes and associated thermal energies may vary greatly from area to area, for localities where data on subsurface conditions are too few or absent, a standard reservoir volume of 1 km^3 was assigned.

Low-temperature geothermal-resource areas in category 2 (delineated thermal reservoirs in hydrothermal-convection systems) are generally characterized by the upflow of thermal water along faults and its subsequent lateral movement into aquifers at relatively shallow depths (fig. 7). There may or may not be an associated discharge of thermal springs at the surface, and the shallow thermal aquifer may be underlain by a hotter reservoir at greater depths. Temperature profiles in wells drilled in such areas generally show high gradients above the thermal aquifer and temperature reversals below; figure 9A illustrates such a temperature profile along with the 25°C/km minimum-gradient criterion used in this assessment to identify low-temperature geothermal-resource areas. For resource areas in category 2, reservoir volumes were estimated from available data on reservoir areas and thicknesses; such data were provided by test drilling, geophysical surveys, or simply by the distribution of thermal springs within the same geologic province.

The lateral-leakage model (fig. 7A) is applicable to many low-temperature geothermal-resource areas in the Basin and Range province and the Snake River Plain, for example, near Klamath Falls, Oregon, and Boise, Idaho. Test drilling near Marysville, Montana, has delineated an intermediate-temperature hydrothermal-convection system related to a bedrock high (see fig. 7B) within a stock in the Boulder batholith (Blackwell and Baag, 1973). Although detection of systems of this type is hampered by absence of surface manifestations, many such occurrences are likely within the Boulder and Idaho batholiths and in parts of central Alaska where thermal springs are associated with granitic plutons (Miller and others, 1975). This bedrock-high model is also applicable to areas within the Basin and Range province, such as Grass Valley, Nevada, where heat-flow data and exploratory drilling indicate that low-temperature geothermal reservoirs exist in fractured-bedrock highs just below the contact with the overlying less permeable valley fill (Welch and others, 1981).

Additional models of hydrothermal-convection systems in which low-temperature geothermal resources occur may be developed as data from future exploration become available. For example, the basin-constriction model (fig. 7A) has been suggested for geothermal areas in the Rio Grande Rift in New Mexico (Morgan and others, 1981), although none of these areas has been adequately drilled and tested as yet.

Low-temperature geothermal resources in conduction-dominated systems occur within sedimentary basins (category 3) and beneath coastal plains (category 4). Identified geothermal-resource areas in category 3 exist in the Central United States within the Great Plains and Wyoming Basin geologic provinces, where thick layers of low-thermal-conductivity shale and relatively high temperature gradients occur above regionally continuous carbonate and sandstone aquifers (fig. 8A). An idealized temperature profile within a sedimentary basin (fig. 9B) illustrates that aquifers must occur at depths sufficient for temperatures to exceed the minimum-temperature criterion. Thus, many basins east of the Great Plains are not identified as containing low-temperature geothermal resources because either the thickness of the sediment is insufficient or its thermal conductivity is too high to produce aquifer temperatures above our minimum-temperature criterion. In contrast, within some parts of the Great Plains, such as the Denver Basin in western Nebraska, ground-water flowing updip in a regional aquifer results in high conductive temperature gradients and heat flow in the overlying sediment, so that aquifer temperatures exceed the minimum-temperature criterion at relatively shallow depths (Gosnold and Eversoll, 1981).

Low-temperature geothermal-resource areas in

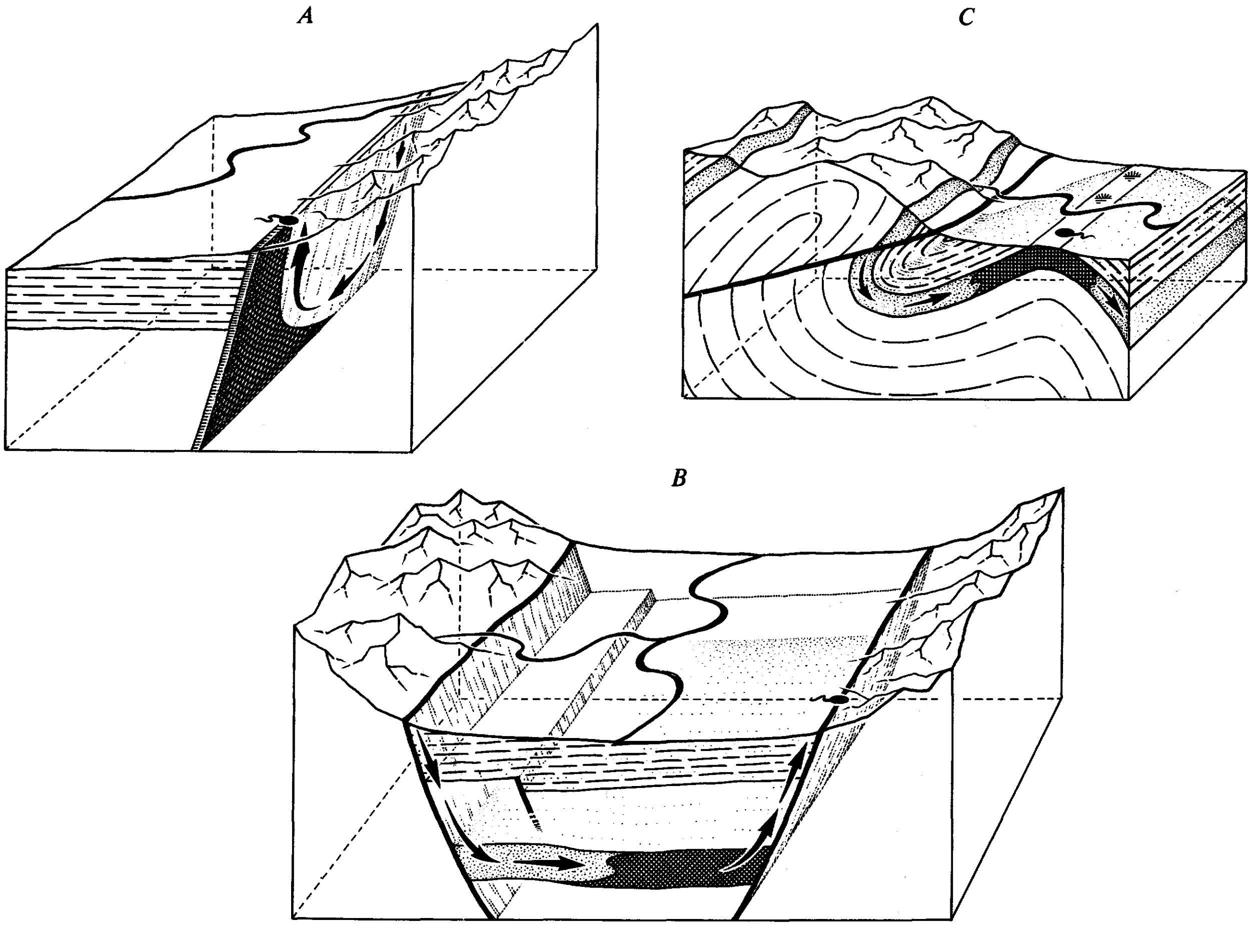

Figure 6.—Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal-resource areas in category 1 (isolated thermal springs and wells) occur. A, Fault plane. B, Deep reservoir. C, Margin of anticline. Arrows indicate direction of fluid circulation; shading shows location of reservoir containing low-temperature geothermal resources.

category 4 have been identified along the Atlantic and Gulf Coastal Plains. The conceptual model shown for this category (fig. 8B) involves a thick sedimentary layer underlain by an intrusive body that generates an elevated heat flow by radioactive decay. Although widespread occurrence of such intrusive bodies along the Atlantic coast has been proposed (Costain and others, 1980), delineation of such areas is limited by an absence of deep drill holes. Within the Gulf Coastal Plain, identified low-temperature geothermal-resource areas along the Balcones/Ouachita structural trend in central Texas are not associated with buried intrusive bodies but may involve a component of thermal water derived from updip migration from deeper zones.

DETERMINATION OF ACCESSIBLE RESOURCE BASE

The accessible resource base for each geothermal system inventoried in this report is given by

$$q_R = \rho c a d (t - t_{ref}), \qquad (1)$$

where q_R is the accessible resource base, ρc is the volumetric specific heat of rock plus water (2.6 J/cm$^3\cdot$°C), a is the reservoir area, d is the reservoir thickness, t is the reservoir temperature, and t_{ref} is the reference temperature (15°C). The volumetric specific heat of 2.6 J/cm$^3\cdot$°C is a weighted average value calculated for the rock types and porosities found in low-temperature geothermal-resource areas. The reference temperature of 15°C is used for the entire United States.

The statistical methods outlined by Brook and others (1979) were used to quantify the uncertainties in calculations of accessible resource base, resource, and beneficial heat. The use of triangular probability densities, involving estimates of the minimum, maximum, and most likely values for reservoir temperature, area, and thickness, enables calculation of the mean and standard deviation of the accessible

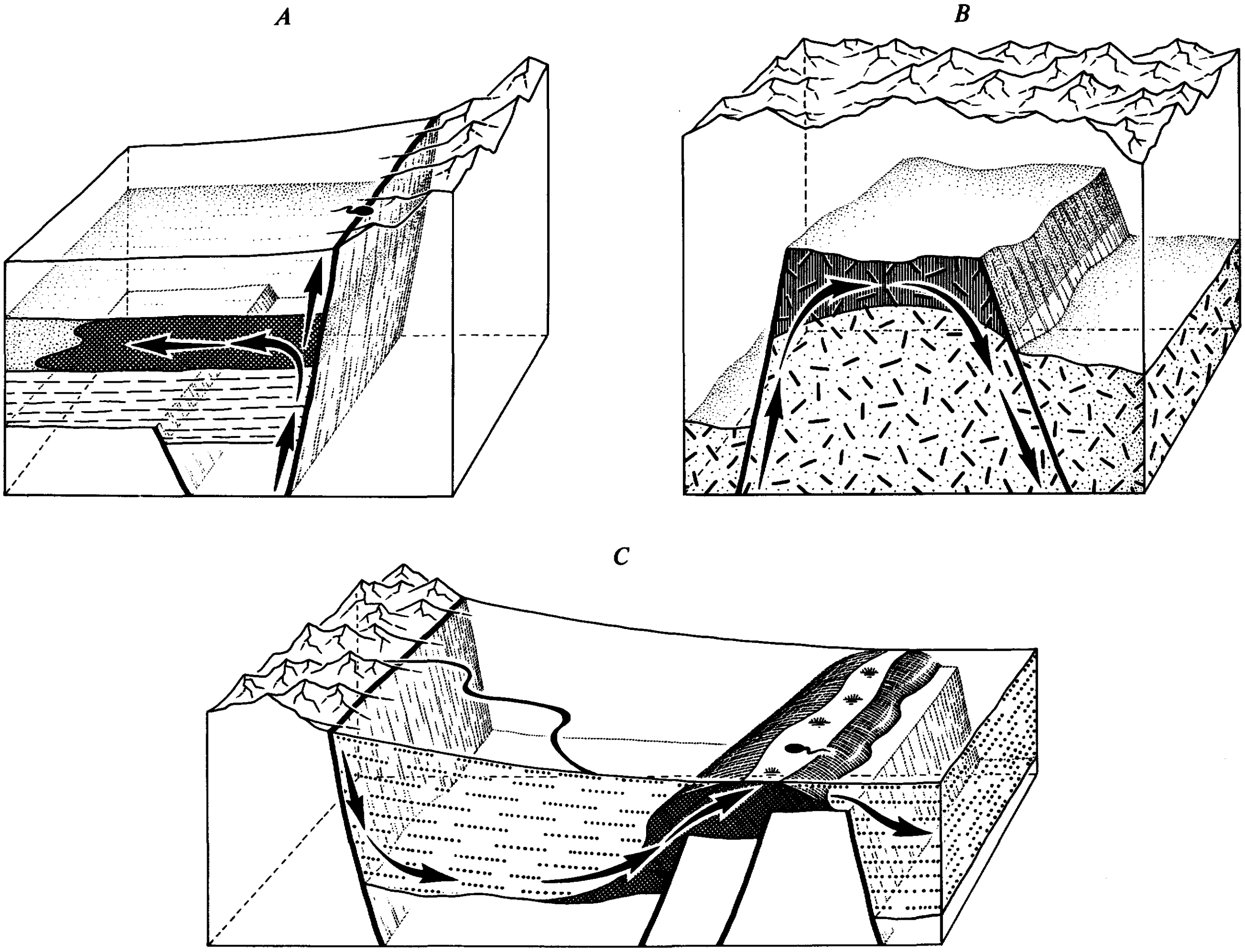

Figure 7.—Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal-resource areas in category 2 (delineated thermal reservoirs) occur. A, Lateral leakage. B, Bedrock high. C, Basin constriction. Arrows indicate direction of fluid circulation; shading shows location of reservoir containing low-temperature geothermal resources.

A

B

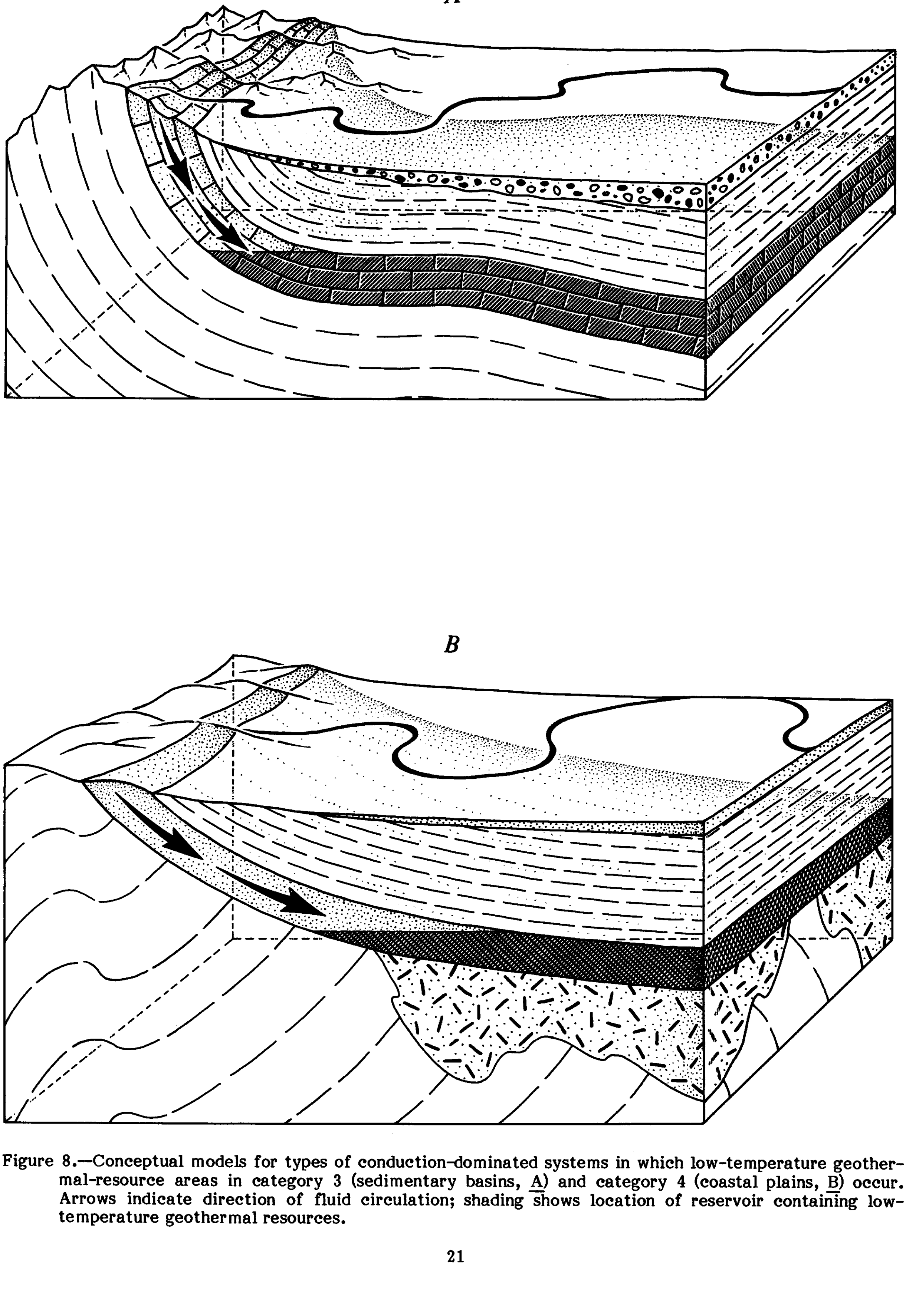

Figure 8.—Conceptual models for types of conduction-dominated systems in which low-temperature geothermal-resource areas in category 3 (sedimentary basins, A) and category 4 (coastal plains, B) occur. Arrows indicate direction of fluid circulation; shading shows location of reservoir containing low-temperature geothermal resources.

resource base for individual areas and for all resource areas to be calculated. These estimates were also used to calculate probability distributions for the total accessible resource base, resource, and beneficial heat, using a Monte Carlo computer program similar to that described by Nathenson (1978). Such probability distributions establish confidence limits for each energy total.

The mean identified accessible resource base for each low-temperature geothermal area is calculated by substituting the mean values into equation 1:

$$\bar{q}_R = \rho c \bar{v} (\bar{t} - t_{ref}), \qquad (2)$$

where $\bar{v} = \bar{a}\bar{d}$. The mean value of each variable, which is calculated as the arithmetic average of the minimum, maximum, and most likely values, is not necessarily equal to the most likely value. Equations for determining the standard deviation of each variable and for the accessible resource base weregiven by Nathenson (1978). The identified accessible resource base for all areas equals the sum of the values of $\bar{q}_R$ for each area. The overall standard deviation equals the square root of the sum of the squares of the individual standard deviations.

Methods of estimating the reservoir area, thickness, and temperature for the various categories of low-temperature geothermal-resource areas are discussed by Mariner and others (this volume) and Sorey, Reed, and others (this volume). The mean value of 1.0 km^3 for the standard reservoir volume applied to resource areas in category 1 was calculated from minimum, maximum, and most likely estimates of 0.01, 2.0, and 1.0 km^3, respectively, which reflect limiting values for reservoir volumes in the models discussed previously for these categories. Although actual reservoir volumes in most low-temperature geothermal-resource areas where this standard volume is applied will probably differ from the mean value used here, it was assumed that the total identified accessible resource base for all such areas can be estimated by using the standard volume for each area.

DETERMINATION OF RESOURCE

The "resource" is that part of the accessible resource base that can be produced at the wellhead under reasonable assumptions of future economics and technology (Muffler and Cataldi, 1978). Thus, the methodology used to make resource estimates should be based on assumptions regarding development schemes that could reasonably be followed now or in the foreseeable future. No attempt is made in this assessment to estimate "reserves," which represent that part of the identified geothermal resource that can be extracted legally and economically at present (Muffler and Cataldi, 1978), because the required

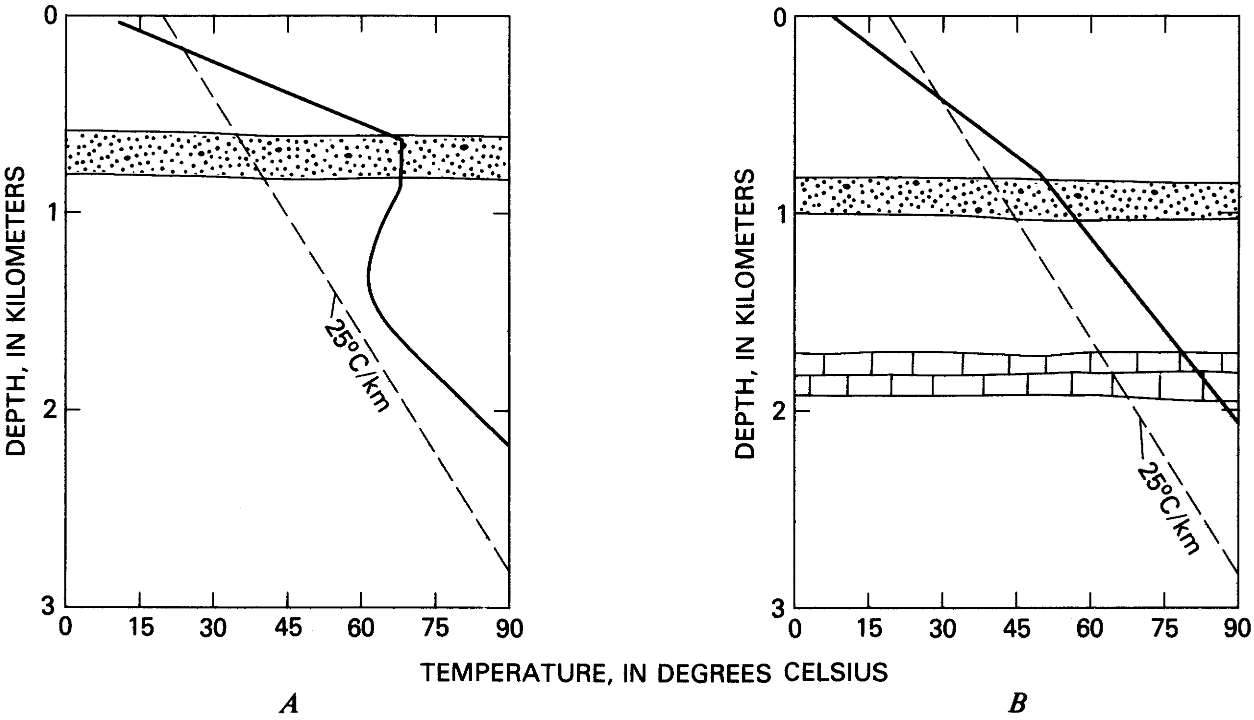

Figure 9.--Idealized temperature profiles in hydrothermal-convection systems with lateral leakage (A) and within sedimentary basins (B). Identified low-temperature geothermal resources exist where temperatures in aquifers exceed the minimum-temperature criterion (10°C above mean annual temperature plus 25°C/km) used in this assessment, as shown by straight lines.

specifications of reservoir, production, and economic data are beyond the scope of this report.

The simplest procedure for estimating the resource in each identified low-temperature geothermal-resource area is to multiply the accessible resource base by a fixed recovery factor $\underline{r}_e$. This approach was followed in previous assessments of intermediate- and high-temperature hydrothermal-convection systems, using $\underline{r}_e$=0.25, a value based on an energy-recovery process involving injection of cold water into the reservoir to replace the hot water withdrawn during production. Nathenson (1975) estimated that as much as 50 percent of the thermal energy in a uniformly permeable reservoir is recoverable in such a heat-sweep process but suggested using $\underline{r}_e$=0.25 to account for permeability variations, including the parts of a reservoir that may be unproductive. Resource determinations based on this method do not depend on the time scale over which development occurs.

The method used here to calculate recoverable energy involves estimation of the number of wells each reservoir can support over a development period of 30 years, assuming that cold water will not be injected into the reservoir. Although injection of produced fluids after surface utilization may be legally required to protect the environment in certain areas, lower reservoir temperatures and larger reservoir areas make injection schemes for energy recovery less likely in low- than in intermediate- and high-temperature geothermal-resource areas. The method used in this resource assessment allows for induced recharge of water from permeable regions surrounding each thermal reservoir as reservoir pressure declines. Thus, the recovery factor approaches 0.25 over 30 years for small-area reservoirs.

The resource is given by

$$\underline{q}_{WH}=(\rho\underline{c})_f\underline{NQP}(\underline{t}-\underline{t}_{ref}), \qquad (3)$$

where $\underline{q}_{WH}$ is the resource, $(\rho\underline{c})_f$ is the volumetric specific heat of the fluid (4.1 J/cm^3·°C), $\underline{N}$ is the number of production wells, $\underline{Q}$ is the average volumetric discharge of each production well, and $\underline{P}$ is the development period. Fluid temperatures at the wellhead are assumed to equal the corresponding reservoir temperatures; the reference temperature is 15°C.

To determine optimum values of $\underline{N}$ and $\underline{Q}$, several reservoir parameters must be known, and economic and engineering aspects of the process for which the resource is to be used must be considered. A detailed analysis of well-field design for each reservoir is beyond the scope of this assessment. Instead, a simplified production plan was considered for which the optimum value of the number of production wells can be determined for each reservoir by specifying a limited number of reservoir parameters.

The production plan assumed here consists of regularly spaced wells on a square grid, discharging at 31.5 L/s for 30 years, with a cumulative drawdown at the center of the production field of 152 m; these conditions are representative of the well performances required for commercial development. The specified drawdown of 152 m applies to a decline in water level within a well or a decrease in wellhead pressure corresponding to a decline of 152 m in the piezometric surface for a flowing well. On the basis of this production plan, the number of wells that would produce a drawdown of 152 m at the center of the reservoir after 30 years is given by the ratio of the reservoir area $\underline{a}$ to the area per well $\underline{a}_w$. The area per well is the square of the distance between adjacent wells.

For a given reservoir area and well spacing, the cumulative drawdown at the center of the area is the sum of the drawdowns due to each interfering well. For values of $\underline{a}_w$ less than the optimum, cumulative drawdown at the center of the reservoir exceeds 152 m; for values of $\underline{a}_w$ greater than the optimum, cumulative drawdown at the center of the reservoir is less than 152 m. Determination of the optimum well spacing depends on the specified ratio of discharge to drawdown; discharge-drawdown combinations with the same ratio yield the same optimum well spacing.

Drawdown calculations are based on the exponential integral solutions developed by Theis (1935) for artesian aquifers with nonleaky confining beds and by Hantush (1960) for artesian aquifers with leaky confining beds. Similar calculations were discussed by Papadopulous and others (1975) and Wallace and others (1978) for assessments of geopressured geothermal resources in the northern Gulf of Mexico Basin. In contrast with Papadopulous and others (1975), however, it was assumed in this assessment that the lateral boundaries of low-temperature geothermal reservoirs are connected hydraulically to adjacent regions of permeable rock. Strictly speaking, the resource calculations in this assessment apply to reservoirs whose areas are square; application of the methodology to reservoirs of markedly different shape requires some adjustments, as noted below.

Reservoir parameters that affect the calculation of optimum well spacing include the area, transmissivity, and compressibility. Reservoir transmissivity $\underline{T}$ is the product of the hydraulic conductivity $\underline{K}$ and the thickness; hydraulic conductivity, in turn, is a function of the permeability of the rock and the density and viscosity of the thermal fluid. The effects of reservoir compressibility and fluid compressibility can be included in the dimensionless storage coefficient $\underline{S}$, which ranges from about 10^{-5} to 10^{-3} for most confined (artesian) aquifers (Lohman, 1972). To reduce the required number of calculations for this analysis, a constant value for $\underline{S}=10^{-4}$ was used throughout because changes in this parameter were found to have only a second-order effect on determinations of the optimum well spacing.

Production from a reservoir can induce leakage of fluid into the reservoir from adjacent confining beds. The rate of induced leakage is related to the product of the hydraulic conductivity and specific storage ($\underline{S}_s$) for each confining bed; the specific storage equals the storage coefficient divided by the thickness of the confining bed. Although values of $\underline{K}$

and S_s range over several orders of magnitude for different rock types, the product KS_s is more tightly constrained. In this assessment, confining beds adjacent to geothermal reservoirs consist primarily of shale, clay, or pyroclastic rocks. Data on KS_s values for confining beds in most identified low-temperature geothermal-resource areas are absent except for those within sedimentary basins in the northern Great Plains, for which modeling studies of regional aquifer systems yield values for the predominantly shale confining beds (Konikow, 1976; Woodward-Clyde Consultants, 1980; Downey, 1982). Values of KS_s from these studies and values for nonindurated fine-grained deposits typical of confining beds in some identified low-temperature geothermal-resource areas (Johnson, 1968) range from approximately 10^{-15} to 10^{-13} s^{-1}; less indurated sedimentary rocks generally have higher KS_s values.

Two sets of curves that relate the optimum area per well to reservoir area and transmissivity are presented in figures 10 and 11. As discussed above, for a given reservoir area and transmissivity, the corresponding value of a_w indicates the spacing of wells producing at 31.5 L/s for which the cumulative drawdown at the center of the reservoir after 30 years would be 152 m. The curves in figure 10 are for the case of induced leakage from confining beds above and below the reservoir; the curves in figure 11 are for the case of impermeable confining beds. Comparison of these two sets of curves indicates that optimum well spacing is significantly smaller for reservoirs with leaky confining beds than for those with nonleaky confining beds. However, additional calculations carried out for other values of confining-bed properties indicate that for reservoir areas of less than about 1,000 km^2, optimum well spacing is insensitive to variations in KS_s within the range noted in the previous paragraph. Identified low-temperature geothermal-resource areas with reservoirs larger than about 1,000 km^2 occur only in sedimentary-basin environments for which the parameters indicated in figure 10 are applicable. Accordingly, the curves in figure 10 were used to estimate optimum well spacings for all reservoirs with leaky confining beds.

Transmissivities for which well-spacing curves were determined range from 0.0005 to 0.02 m^2/s for reservoirs with leaky confining beds and from 0.001 to 0.01 m^2/s for reservoirs with nonleaky confining beds. Measured and estimated T values for reservoirs in resource areas identified in this assessment fall within this range. For T less than about 0.0005 m^2/s for reservoirs with leaky confining beds and 0.001 m^2/s for reservoirs with nonleaky confining beds, the drawdown due to a single well approaches the 152-m limit after 30 years of production. Transmissivity values for each reservoir area were selected on the basis of available hydrologic and geologic data, as discussed by Mariner and others (this volume) and Sorey, Nathenson, and Smith (this volume).

Resource estimates for each identified low-temperature geothermal reservoir are based on use of the curves in figures 10 and 11 to determine the optimum area per well (a_w) from specifications of reservoir area (a), transmissivity (T), and the presence or absence of leaky confining beds. The corresponding estimate of the number of production wells (N) is given by a/a_w. Methods used to quantify the uncertainty in resource determinations follow those used for determination of the accessible resource base in that triangular probability densities were calculated from minimum, maximum, and most likely estimates for a, a_w, and t. An additional source of uncertainty in these resource estimates relates to the validity of the assumption that permeable connection exists throughout the reservoir. Although the areas over which aquifer temperatures meet the minimum-temperature criterion can be reasonably well delineated, not enough is known about the associated hydrologic conditions in most places to be certain that the entire low-temperature geothermal-reservoir area is sufficiently permeable to yield fluid at rates close to that assumed in the development plan. Therefore, a procedure was followed similar to that used with the recovery-factor approach of Brook and others (1979) of introducing a constant k to adjust for nonuniform transmissibility, including unproducible regions within each reservoir. The corresponding probability density for k was based on minimum, maximum, and most likely values of 0, 1.0, and 0.5, respectively. The effects of this factor are to decrease estimates of the number of wells each reservoir can support and to increase the confidence limits on estimates of the resource and beneficial heat.

The mean number of wells each reservoir can support is given by $\bar{k}\bar{a}/\bar{a}_w$, and the mean resource from equation 3 becomes

$$\bar{q}_{WH} = (\rho c)_f (\bar{k}\bar{a}/\bar{a}_w) QP(\bar{t} - t_{ref}). \qquad (4)$$

Equation 4 was used in resource calculations for the identified low-temperature geothermal-resource areas in categories 2 through 4 for which actual reservoir areas could be estimated. A different method was used to estimate the resource for areas in category 1. For these areas, the standard reservoir volume of 1.0 km^3 was assumed, and the resource was calculated as 25 percent of the corresponding accessible resource base.

For the production plan assumed here, the number of wells each reservoir can support does not increase in proportion to the reservoir area because the optimum area per well increases as the reservoir area increases owing to drawdown interference between wells. This increase results in considerably lower recovery factors for large- than for small-area reservoirs. As reservoir area decreases, however, induced recharge of water from surrounding regions becomes more important, and breakthrough of cold water in production wells rather than drawdown interference may limit recovery factors. To allow for this effect, the upper limit of the recovery factor q_{WH}/q_R is assumed to be 0.25. Thus, recovery factors are at or near 0.25 for the smallest area reservoirs in this assessment, which occur in hydrothermal-convection systems, and are near 0.001 for the largest-area reservoirs, which occur within sedimentary basins.

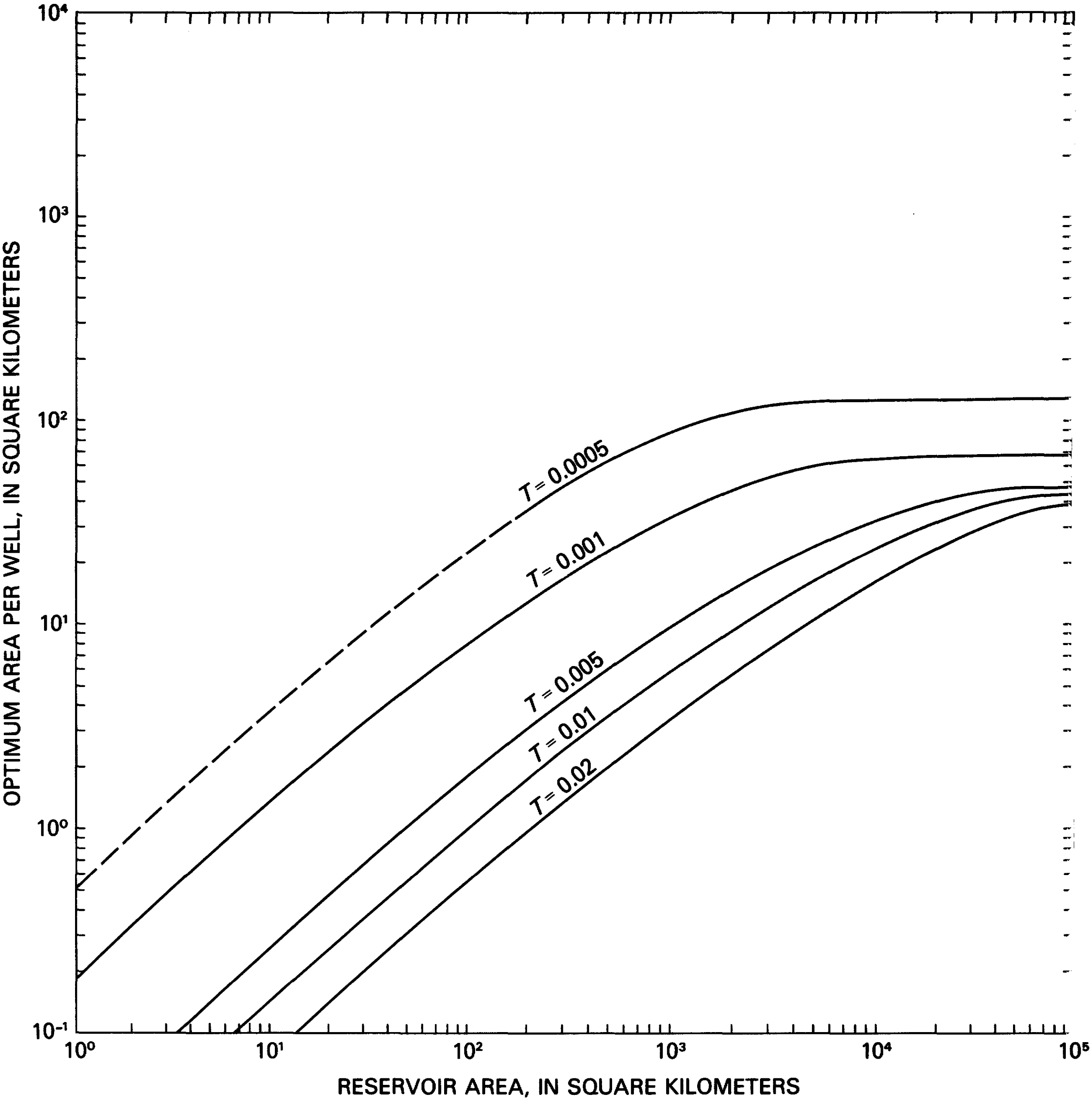

Figure 10.--Reservoir area $\underline{a}$ versus optimum area per well $\underline{a}_w$ for reservoirs with leaky confining beds, based on a production plan involving evenly spaced wells producing for 30 years at 31.5 L/s with a cumulative drawdown of 152 m. $\underline{T}$, reservoir transmissivity (in square meters per second); dashed portion of curve for $\underline{T}$=0.0005 m^2/s involves fewer than five wells to produce the allowable drawdown. Drawdown computations were based on a reservoir storage coefficient $\underline{S}$ of 10^{-4} and a value for the product of hydraulic conductivity and specific storage $\underline{KS_s}$ of $6x10^{-15}$ s^{-1} for each of two confining beds.

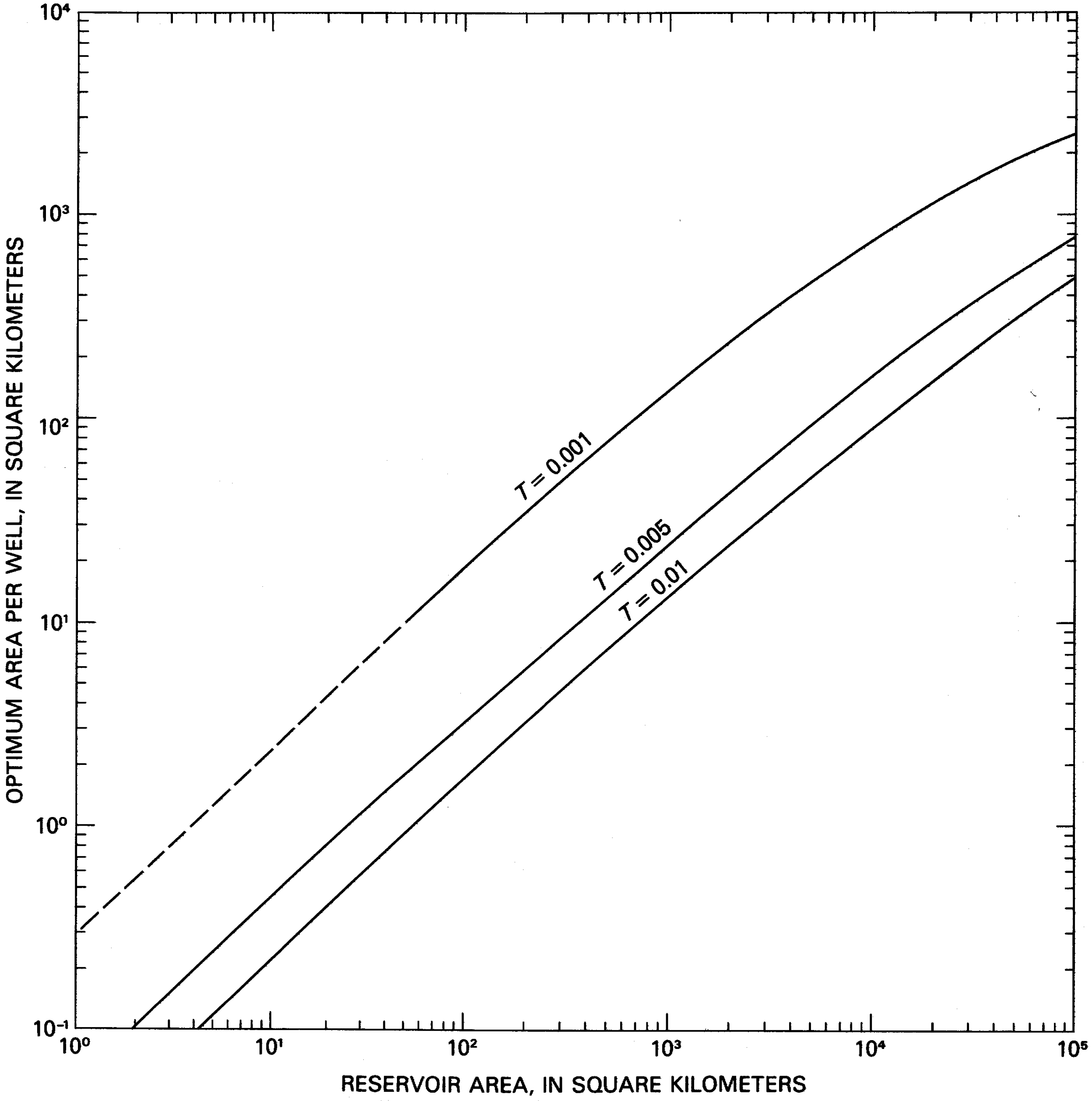

Figure 11.--Reservoir area $\underline{a}$ versus the optimum area per well $\underline{a}_w$ for reservoirs with nonleaky confining beds, based on a production plan involving evenly spaced wells producing for 30 years at 31.5 L/s with a cumulative drawdown of 152 m. $\underline{T}$, reservoir transmissivity (in square meters per second); dashed portion of curve for $\underline{T}$=0.001 m^2/s involves fewer than five wells to produce allowable drawdown. Drawdown computations were based on a reservoir storage coefficient $\underline{S}$ of 10^{-4} and a value for the product of hydraulic conductivity and specific storage $\underline{KS_s}$ of 0 for each of two confining beds.

Several additional factors can be noted in regard to the resource determinations in this assessment. The first factor is that, for small-area reservoirs, the effects of lateral-boundary conditions may be important. These boundaries were assumed to connect the reservoir to additional regions of permeable rock. It may be that in some areas the reservoir boundaries are impermeable or behave as constant-pressure sources, as in the case of a fault conduit that connects a shallow with a deep reservoir (Benson and others, 1981). Although these conditions could be allowed for in specific areas by adjusting the value of $\underline{a}_w$ upward for impermeable boundaries and downward for constant-pressure boundaries, we have not done so here because reservoir boundaries have not yet been adequately tested in any low-temperature geothermal-resource area.

For reservoirs whose areal configuration is elongate rather than square, well-spacing determinations based on an assumption of evenly spaced wells in a square grid encompassing the same total area can lead to overly conservative estimates of the optimum well spacing. Allowance must be made in some areas for greater distances between wells and the center of the reservoir and, thus, for less interference. Such an allowance was made for some reservoirs within sedimentary basins by adjusting the values of $\underline{a}_w$, estimated from the curves in figure 10 downward by a factor of 2.

The resource estimates obtained by the method used in this assessment depend on the assumed development period of 30 years. For a given reservoir, the number of wells that yield a specified maximum drawdown would not differ greatly for develpment times somewhat longer or shorter than 30 years because the rate of drawdown caused by each well decreases rapidly over time. Therefore, the method used here defines an optimum rate of energy recovery that is drawdown dependent but that could be sustained for periods longer or shorter than 30 years.

Fluid production from low-temperature reservoirs for many direct-heat applications is carried out in a cyclic pattern corresponding to variations in the energy demand at the surface. This procedure introduces a load factor that represents the fraction of time during a given period when energy production and use occur; load factors are ordinarily integrated over significant periods of time (commonly 1 year). For the same installed energy-production capacity, the total energy produced at the wellhead over a period of 30 years is less for small than for large load factors. The method used in this assessment for resource estimates assumes a load factor of 1.0. A limited number of drawdown computations were carried out for load factors less than 1.0. Results of these computations and other theoretical considerations indicate that resource estimates equal to those in this assessment would be obtained for load factors less than 1 if the drawdown specification of 152 m were assumed to represent the average drawdown at the center of the reservoir between discharge and recovery cycles, because the drawdown at each well is proportional to the discharge rate. Thus, production schemes with different load factors that yield the same total fluid production over a given period will cause the same average reservoir drawdown.

DETERMINATION OF BENEFICIAL HEAT

For geothermal resources, it is important to distinguish between thermal energy above some reference state and thermal energy comparable to that from another fuel. For resources above 150°C, the amount of wellhead thermal energy convertible to electricity can be calculated as a function of the resource temperature (for example, Nathenson, 1975; Brook and others, 1979), and the values can then be compared with the amount of electricity produced from fossil fuels. For low- and intermediate-temperature geothermal resources, the concept of beneficial heat was introduced by Nathenson and Muffler (1975); "beneficial heat" is the energy applied by a user to a specific process. Brook and others (1979) calculated the beneficial heat as a fixed fraction of the wellhead thermal energy. Because of the importance of this quantity for assessments of low-temperature geothermal resources, the basis for this calculation is refined here.

The mean beneficial heat $\underline{q}_{ben}$ is given by

$$\bar{\underline{q}}_{ben}=(\rho \underline{c})_f(\underline{k}\bar{a}/\bar{\underline{a}}_w)\underline{Q}\underline{P}\Delta\underline{t}, \qquad (5)$$

where $\underline{q}_{ben}$ is the thermal energy (in MW_t for 30 years), $(\rho \underline{c})_f$ is the volumetric specific heat of water, $\underline{Q}$ is the mass produced, $\underline{P}$ is the duration of the development period, and $\Delta\underline{t}$ is the usable temperature drop that occurs as energy is extracted in some process, such as home heating. For example, in the geothermal heating system at Lavey, Switzerland, the water comes out of the production well at 62°C, enters a heat exchanger at 58°C, and leaves it at 35°C (Rybach, 1979). Because the heat transferred from the geothermal fliud to the exchanger is the same as the heat transferred to the heating system on the other side of the exchanger, the usable temperature drop for calculating the beneficial heat is 58°-35°=23°C.

To establish the dependence of the usable $\Delta\underline{t}$ on the resource temperature, the data for five direct-use applications are plotted in figure 12 as a function of reservoir temperature. The bar marked "8" is for the downhole heat exchangers used at Klamath Falls, Oregon, in closed-loop residential heating systems; the usable temperature drop is low relative to the other applications because flow rates are high enough at low $\Delta\underline{t}$'s to supply all the energy needed. The line marked "7" is for a relation proposed by Engen (1978) for the temperature change obtainable from a heat exchanger used for home heating under reasonable economic assumptions. The available data indicate that Engen's line underestimates beneficial-heat temperature drops; a better fit is given by a line with the equation

$$\Delta\underline{t}=0.6(\bar{\underline{t}}-25°C). \qquad (6)$$

The upper end of this line is constrained by the data, whereas the intercept at $\Delta\underline{t}$=0°C at a resource temperature of 25°C is determined by the nationwide average mean annual temperature of 15°C plus the 10°C required for a spring at the surface to be considered a resource. If equation 6 were used for a specific location, the parameters would have to be adjusted for the local mean annual temperature; this degree of detail is beyond the scope of this assessment.

Few data are available to characterize the $\Delta\underline{t}$-$\underline{t}$ relation over the range 25°-60°C. Uses other than home heating are mentioned by Reed (this volume); however, no data are readily available to plot in figure 12. Point 3, for a greenhouse project, does conform to

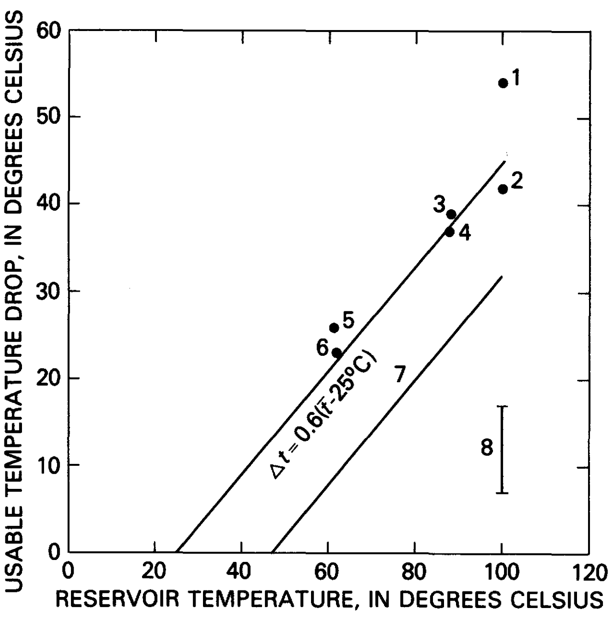

Figure 12.—Usable temperature drop $\underline{t}$ versus reservoir or input temperature $\underline{t}$ for various direct-use applications, showing empirically derived line used in this assessment for effective temperature drop as a function of reservoir temperature. 1, Reykjavik, Iceland, municipal heating system (Pálmason and Zoëga, 1970); 2, proposed U.S. district heating using waste heat from central generating station (Karkheck and others, 1977); 3, Susanville, California, greenhouse (Boren, 1979); 4, Oregon Institute of Technology, Klamath Falls, Oregon, heating system (Purvine, 1974); 5, Mont de Marson, France, heating system (supplemental energy is added when outside temperature falls below 6°C; Huxtable and others, 1980); 6, Lavey, Switzerland, heating system (Rybach, 1979); 7, estimated temperature change for economic heat exchanger to be used for home heating (Engen, 1978); 8, Klamath Falls, Oregon, downhole heat exchanger (Culver and Reistad, 1978).

the data available for home heating. At the lower temperatures, geothermal energy can be used in combination with a heat pump for home heating. By using the hotter source water, the electricity needed to drive the heat pump can be decreased (Reistad and Means, 1980a, b). Another method involving a heat pump is the use of geothermal energy for heating down to a certain outside temperature (and heating load) and use of the heat pump in combination with the geothermal energy below this temperature (Jaud, 1980). Both of these schemes enable the use of lower temperature water; however, it is difficult to assign a usable temperature drop to the geothermal water to provide data for the lower temperatures in figure 12.

The units for reporting beneficial heat are megawatts thermal (MW_t) for 30 years, and the values obtained represent energy that might actually be used in applications at the surface. For comparison with other forms of energy, the overall efficiency of those other forms in direct-use applications should be considered. The overall efficiency for a fossil fuel is the energy inputted to the process divided by the heating value of the fuel. For natural gas, about 50 percent of the energy in the gas is actually available for space heating (Beller, 1975); for electric-resistance heating, the efficiency is nearly 100 percent in the heater, but the overall efficiency is lower because the central-station efficiency is about 33 percent for a modern fossil-fueled plant (Beller, 1975). Thus, 100 MW_t of beneficial heat from a geothermal system is equivalent to 100 megawatts electric (MW_e) if electricity were used for heating.

In assessing the benefits available from low-temperature geothermal resources, the potential benefits from cascading high-temperature waters were not included. Karkhek and others (1977) proposed adjusting the condensation temperatures of central generating stations to 100°C, so that energy could be made available for district heating; similar schemes could be developed for multiple use of a geothermal resource. Quantifying the benefits of such schemes is possible only when some have actually been built, and no attempt is made to calculate the benefits here.

UNDISCOVERED GEOTHERMAL RESOURCES

The "undiscovered accessible resource base" represents the accessible thermal energy stored in reservoirs that are inferred to exist but as yet undiscovered. It includes: (1) Thermal energy in aquifers within sedimentary basins and beneath coastal plains, where the existing data are insufficient to allow any quantitative assessment; (2) additional thermal energy due to upward revisions of reservoir volume and temperature estimates for identified low-temperature geothermal-resource areas; and (3) thermal energy in systems whose locations are as yet unknown. The undiscovered accessible resource base for various geologic and physiographic provinces is estimated below, along with the undiscovered resource and beneficial heat.

For many of the sedimentary basins within which low-temperature geothermal resources were identified in a particular regional aquifer, corresponding undiscovered resources were assumed to exist in another aquifer or group of aquifers within the same basin. For example, in the Denver Basin in northeastern Colorado, low-temperature geothermal resources were identified in sandstone of the Cretaceous Dakota Group because sufficient data on temperature gradient, stratigraphy, and transmissivity exist to make a quantitative assessment. Undiscovered resources in this basin were inferred to exist in deeper Paleozoic aquifers for which fewer temperature and hydrologic data are available. In such areas, estimates of the undiscovered accessible resource base, resource, and beneficial heat were made by multiplying the corresponding estimates for the associated identified low-temperature geothermal resources by an assumed ratio of undiscovered to identified reservoir areas.

Along the Gulf and Atlantic Coastal Plains, undiscovered resources are inferred to exist on the basis of limited evidence of favorable conditions, such as high measured temperature gradients, thick sequences of low-conductivity sediment, or geophysical evidence for buried intrusive bodies that may have radiogenic heating. Particularly in the Gulf Coastal Plain in parts of Texas, Louisiana, and Mississippi, available temperature-gradient information suggests that large areas containing low-temperature geothermal resources in sandstone aquifers may exist, but additional data are required to confirm and delineate individual reservoirs.

Undiscovered resources in regions characterized by the occurrence of hydrothermal-convection systems are estimated as multiples of the corresponding identified resources. Where identified low-temperature geothermal-resource areas in category 1 (standard reservoir volume assumed) occur, undiscovered resources could exist in similar systems whose locations are unknown and in known systems whose temperature or volume is larger than assumed. Upward revision of reservoir temperature is possible where the measured spring temperature was used instead of geothermometric calculations. Upward revision of reservoir volume is possible if both a deep circulation system and a zone of shallow lateral leakage or circulation within bedrock highs exist. In regions containing identified low-temperature geothermal-resource areas in category 2, similar undiscovered resources are inferred to occur in areas with similar geologic conditions.

No estimates are included here of low-temperature geothermal resources available in the form of waste water from powerplants utilizing water from higher temperature geothermal systems. This omission avoids overlap or double counting with respect to the resource estimates in previous assessments. Although the magnitude of low-temperature geothermal energy potentially available from such sources is not likely to be quantitatively significant, the costs of utilizing these resources are likely to be relatively low where powerplants already exist.

ACKNOWLEDGMENTS

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Low-Temperature Geothermal Resources in the Western United States

By Robert H. Mariner, Charles A. Brook, Marshall J. Reed, James D. Bliss, Amy L. Rapport, and Randolph J. Lieb

CONTENTS

ABSTRACT

Most of the 1,084 low-temperature (less than 90°C) geothermal systems identified in the Western United States are characterized by hydrothermal convection; conduction-dominated systems are identified only in the Columbia Plateaus (8 systems) and the Salton Trough (1 system). The identified accessible resource base for all low-temperature geothermal systems in the Western United States is about 310×10^{18} J. The resource associated with these identified thermal reservoirs is about 31×10^{18} J, corresponding to a beneficial heat of 13.7 GW_t for 30 years. Hydrothermal-convection systems account for 96 percent of this resource; conduction-dominated systems contain approximately a third of the identified accessible resource base, and about 1 percent of this energy can be extracted as a resource under the proposed development plan. The undiscovered accessible resource base is estimated at 480×10^{18} J; thus, the total accessible resource base available from identified and undiscovered low-temperature geothermal systems in the Western United States is 790×10^{18} J.

INTRODUCTION

The assessment of low-temperature geothermal systems in the Western United States (fig. 13) is presented in this chapter in terms of the accessible resource base, resource, and beneficial heat. To be included in this assessment, springs or free-flowing wells must discharge water at least 10°C warmer than the mean annual air temperature for a given locality (see Reed, "Introduction," this volume), and nonflowing wells must have a water temperature at depth that exceeds the sum of 10°C above mean annual air temperature plus the product of the depth and the gradient 25°C/km. The GEOTHERM computer file (Teshin and others, 1979) maintained by the U.S. Geological Survey in Menlo Park, California, formed

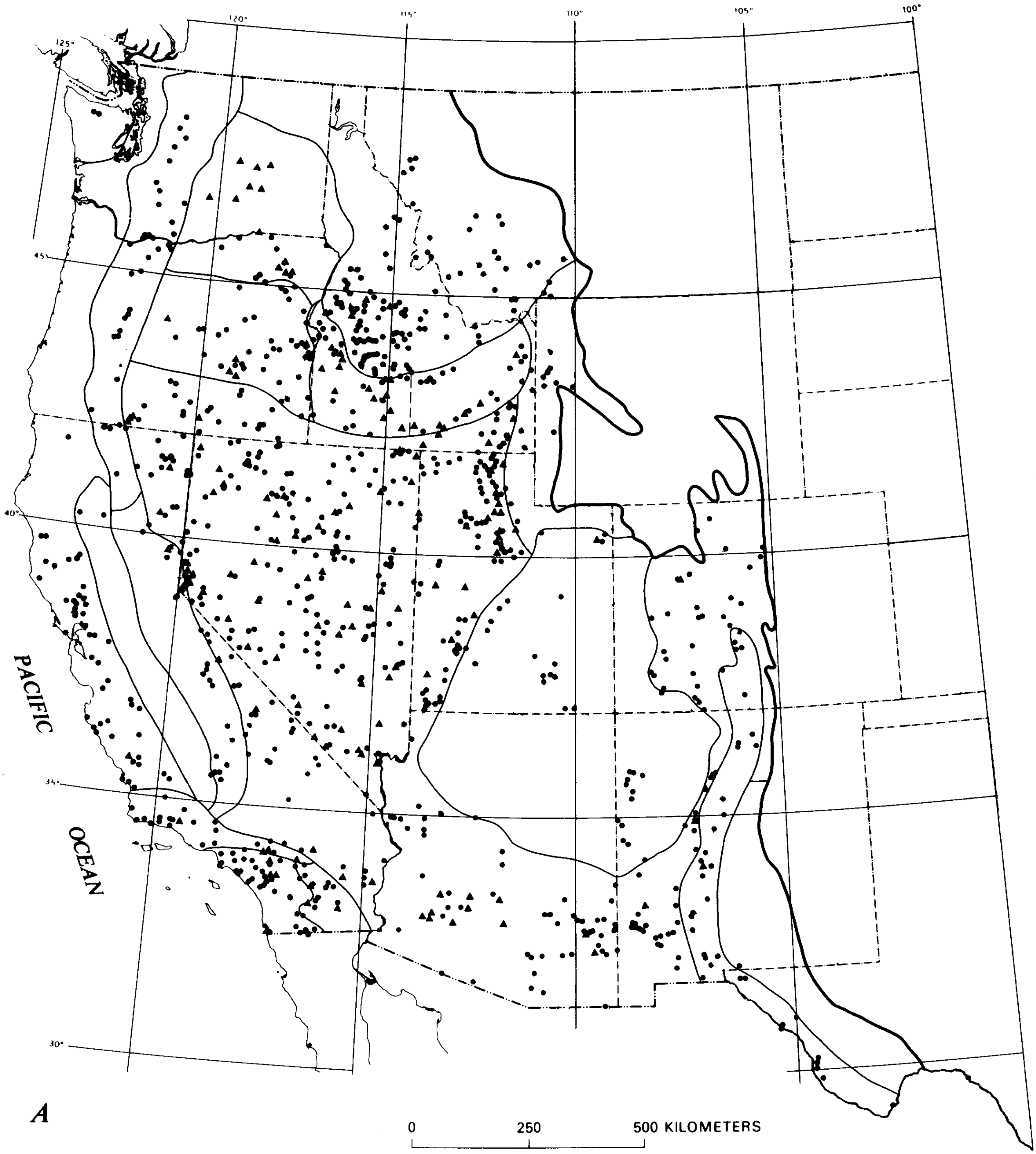

Figure 13.—Low-temperature geothermal systems in the Western United States. Major geologic provinces are identified in figure 2. Dots, isolated systems; triangles, systems with delineated areas. A, Conterminous United States. B, Alaska and Hawaii.

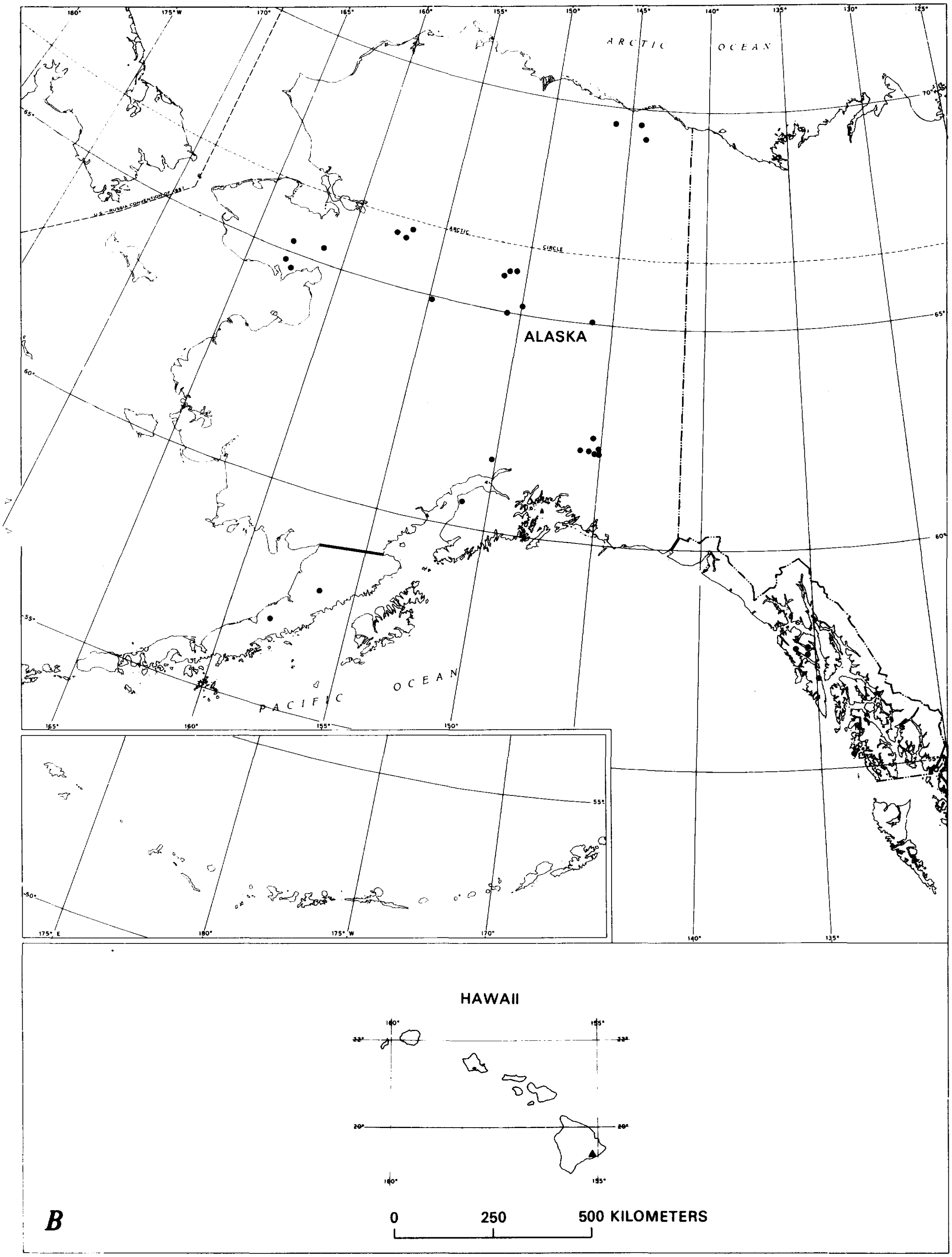

Figure 13.—Continued

the data base for this assessment. A total of 2,000 records were identified for low-temperature geothermal occurrences in the Western United States; about 46 percent (927) of these records were ultimately considered to represent isolated systems (reservoir volume, 1 km^3), whereas the remaining 54 percent are distributed among 157 systems of large area (reservoir volume, more than 1 km^3). The distribution of low-temperature geothermal systems was determined by plotting the locations of thermal springs and wells on maps at a scale of 1:250,000. Point sources or clusters of springs or wells distributed over an area of 4 km^2 or less are considered to be associated with an isolated system. All isolated systems are assigned reservoir volumes of 1 km^3; groups of wells or springs distributed over areas of more than 4 km^2 are assumed to represent systems having reservoir volumes of more than 1 km^3. A total of 1,084 low-temperature reservoirs were thus identified. Hydrothermal-convection systems predominate in the Western United States; fewer conduction-dominated systems have been identified here than in the Central and Eastern United States (Sorey, Reed, and others, this volume).

Extrapolation of a curve of cumulative frequency versus reservoir temperature for hydrothermal-convection systems with reservoir temperatures above 90°C (Brook and others, 1979, fig. 11) indicates that 902 hydrothermal-convection systems should be present in the temperature range 20°-90°C. The number of observed hydrothermal-convection systems (1,075) differs from the number of predicted systems (902) for several reasons. Data on approximately 20 new systems with reservoir temperatures slightly above 90°C, identified during this assessment, were not included in this curve. The addition of these systems to the lower temperature end of the curve would increase its slope and thus increase the number of systems expected in the low-temperature range. At least 25 of the intermediate- and high-temperature reservoirs assessed by Brook and others (1979) have low-temperature aureoles that are evaluated in this assessment. If these systems are subtracted from the observed low-temperature system total, the number of identified low-temperature hydrothermal-convection systems is reduced to 1,041—still 139 more than predicted from an extrapolation of the curve. This difference is due in part to the shortage of identified thermal reservoirs in the temperature range 90°-100°C (Brook and others, 1979) and may also indicate that some of the reservoirs listed as isolated in this assessment are parts of larger reservoirs.

DISTRIBUTION AND GEOLOGIC SETTING OF LOW-TEMPERATURE GEOTHERMAL SYSTEMS

Geothermal systems are widely distributed throughout the Western United States and occur in diverse geologic settings. Much of the region is characterized by active tectonism and volcanism and generally has higher than normal heat flow; these conditions are favorable for the occurrence of geothermal systems. For simplicity of discussion, the western region is divided into geologic provinces, as shown in figures 2 and 12.

Central Alaska

Most of the thermal springs in central Alaska are situated in an east-west-trending zone between latitudes 64° and 68° N. They are thought to result from deep circulation along faults in or associated with Mesozoic and Tertiary granitic plutons (Miller and others, 1975). A total of 15 intermediate- and high-temperature systems were identified in the province by Brook and others (1979); 25 isolated low-temperature hydrothermal-convection systems are identified in this assessment.

Southeastern Alaska

Thermal springs in southeastern Alaska are associated with faults and thus are believed to result from deep circulation. One high- and six intermediate-temperature geothermal systems were identified in the province by Brook and others (1979); five isolated low-temperature geothermal systems are identified in this assessment.

Aleutian Islands and Peninsula

Although numerous hydrothermal-convection systems would be expected in association with the active Alaskan volcanoes, only six high-temperature systems were identified by Brook and others (1979). More recently, Motyka and others (1981) sampled springs associated with 18 additional hydrothermal-convection systems and reported that 15 of these systems have reservoir temperatures of more than 90°C and that at least seven additional thermal springs may exist in the province. We have identified only three isolated low-temperature geothermal reservoirs in the province, but many systems may be masked by near-surface cold water.

Hawaii

Geothermal resources in the Hawaiian province have been identified only at the crater and along the East Rift Zone of Kilauea Volcano on the Island of Hawaii (Brook and others, 1979). The one low-temperature geothermal resource identified in the Kapoho area of the East Rift Zone is apparently associated with the underlying high-temperature hydrothermal-convection system. Undiscovered low-temperature geothermal resources in the province may occur in other rift zones associated with the shield volcanoes on Hawaii and Maui. The repeated emplacement of basaltic dikes in the rift zones may provide local near-surface heat sources. Several potential low-temperature geothermal sites have been studied (Thomas and others, 1982).

Olympic Mountains

The Olympic Mountains of northwestern Washington consist of late Mesozoic to Tertiary sedimentary and volcanic rocks that have been complexly deformed and weakly metamorphosed (Tabor and Cady, 1978). A complex assemblage of mostly gneissic amphibolite and quartz diorite forms the basement. Heat flow is low, and only two isolated hydrothermal-convection systems are identified in the province. Geothermal systems in the province are probably confined to faults and fractures.

Cascade Range

The Cascade Range is an active volcanic chain that overlies a subduction zone along the Pacific Northwest. The mountains consist of a thick pile of dominantly andesitic flows, overlain locally by large stratovolcanoes (Hammond, 1979). In the northern Cascades, Mesozoic and older crystalline basement is exposed at the surface over extensive areas and is overlain only locally by large Quaternary stratovolcanoes. In the central Cascades, the volcanic rocks are underlain locally by Eocene marine sedimentary rocks and Mesozoic sedimentary and volcanic rocks that in some places include serpentinite. In the southern Cascades, the pre-Cenozoic crystalline basement is overlain by Miocene to Quaternary basalt flows and andesitic to dacitic stratovolcanoes. Small granodiorite plutons have intruded and created metamorphic aureoles in early Tertiary volcanic rocks in the northern and central Cascades.

A total of 36 isolated low-temperature hydrothermal-convection systems are identified in the province; 13 intermediate- and high-temperature systems were identified by Brook and others (1979).

Coast Ranges

The Coast Ranges of central and northern California consist of Mesozoic and Cenozoic sedimentary rocks that have been folded and faulted into northwest-trending mountains (Page, 1966). The Clear Lake volcanic field, adjacent to the producing steam field at The Geysers, has been the center of silicic volcanic activity during much of the Quaternary (Donnelly-Nolan and others, 1981). The province contains 46 identified isolated geothermal systems and two systems with reservoir volumes of more than 1 km^3.

Central Valley

The Central Valley of California is a deep asymmetric basin filled with Cenozoic sediment. Only two isolated low-temperature geothermal systems have been identified in the province. The province appears to have little geothermal potential, although geopressured-geothermal systems may occur in the deeper parts of the basin.

Sierra Nevada

The Sierra Nevada is a westward-tilted fault block consisting mostly of Mesozoic granitic rocks. Of the 20 identified geothermal systems in the province, 19 are isolated and appear to be limited to fractures.

Transverse Ranges

The Transverse Ranges consist of various rock types that have been thrust faulted and folded into east-west-trending ranges of mountains. Thermal springs and wells in the eastern part of the province occur in a granitic and metamorphic basement complex and are apparently restricted to faults and fractures. In contrast, thermal waters in the western part of the province occur predominately in clastic sedimentary rocks and, for the most part, do not occur along faults. There are 23 isolated and three larger area low-temperature geothermal systems identified in the province.

Peninsular Ranges

The Peninsular Ranges of southern California are dominated by granitic and metamorphic terranes. A total of 29 isolated low-temperature geothermal reservoirs are probably confined to faults and fractures in the crystalline rock, and 3 of the 4 larger systems are small in volume (2.5 km^3 or less). The large-volume (38 km^3) reservoir in the San Jacinto Valley is poorly defined.

Salton Trough

The Salton Trough of southern California includes the Imperial and Coachella Valleys. This province, which marks the transition from the divergent plate boundary of the East Pacific Rise to the transform plate boundary of the San Andreas fault system (Fuis and others, 1982), is characterized by active tectonism, recent volcanism, and high heat flow. A total of 10 intermediate- and high-temperature hydrothermal-convection systems have been identified in the province (Brook and others, 1979). A conduction-dominated low-temperature geothermal system, with an estimated reservoir area of 800 km^2, occupies the east third of the Imperial Valley. In addition, a total of 18 hydrothermal-convection systems are identified, of which 3 have reservoir volumes of more than 1 km^3.

Basin and Range

Much of the Western United States lies within the Basin and Range geologic province, which has a heat flow generally higher than normal (Sass and others, 1981) and is characterized by extensional tectonism (Atwater, 1970; Scholz and others, 1971). The combination of range-front faults and sediment-filled basins is favorable for the occurrence of geothermal systems (Sorey, Nathenson, and Smith, this volume). Young silicic volcanic centers along the east and west margins of the province provide localized heat sources for hydrothermal-convection systems.

Most thermal waters in the province result from deep circulation. Normal faults provide near-surface conduits for the circulating waters and thus control the positions of most of the identified hydrothermal-convection systems (figs. 5, 6). Basin-fill sediment may act as a thermal blanket that traps heat in relatively shallow aquifers beneath large areas of some of the basins. Leakage away from fault conduits is probably the source of the thermal waters in these aquifers.

Numerous geothermal systems, widely distributed throughout the northern part of the Basin and Range province, reflect the active seismicity of the region. Hydrothermal-convection systems are generally localized along faults, and lateral leakage appears to be limited owing to the relatively narrow basins and thin basin fill. In contrast, lateral leakage is more common in the southern part of the province, where the basins are much larger and generally deeper. A total of 471 low-temperature hydrothermal-convection systems are identified in the Basin and Range, of which 376 are isolated systems.

Oregon Plateaus

The Oregon Plateaus province is structurally transitional between the Basin and Range on the south and the Columbia Plateaus on the north. Rocks exposed in the province range from late Paleozoic and Mesozoic marine strata and Mesozoic intrusive rocks to late Tertiary volcanic and volcaniclastic rocks (Baldwin, 1981). The 40 low-temperature geothermal systems identified in the province appear to be controlled by normal faults and probably reflect deep circulation in a region of near-normal heat flow. Only five systems in this province were identified as having reservoir volumes greater than 1 km^3.

Columbia Plateaus

The Columbia Plateaus province of Washington and Oregon is constructed of flood basalt of Miocene to Pliocene age. The basalt flows have a maximum thickness of about 2 km and are mantled by Pleistocene sediment, as much as 350 m thick (Swanson and others, 1979). Although the regional heat flow is normal for the Western United States and shallow ground waters are cold, deep wells in eastern Washington have penetrated warm water in aquifers at two depth intervals. The shallower aquifer, which occurs at depths of 300 to 700 m, appears to be restricted in area; the subsurface extent of the deeper aquifer, which occurs between depths of 800 and 1,500 m, is unknown. Thermal waters in the Washington part of the province appear to be conductively heated. Besides the 8 conduction-dominated systems identified in Washington, 15 hydrothermal-convection systems are identified along the south edge of the province in Oregon. Preliminary, unpublished data collected for the U.S. Department of Energy indicate that the Hanford area identified in this assessment may be significantly larger than was estimated here.

Western Snake River Plain

The Snake River Plain of southern Idaho is divided into a western and an eastern province on the basis of distinct geologic settings. The western province is a northwest-trending grabenlike structure, partly filled with late Tertiary silicic volcanic rocks and clastic sedimentary rocks (Malde and Powers, 1962). The province has higher than normal heat flow, and 32 low-temperature geothermal systems are identified. Most of the thermal waters apparently rise along normal faults and spread laterally into the basin fill; 13 geothermal systems with reservoir volumes of more than 1 km^3 are recognized.

Eastern Snake River Plain

The Eastern Snake River Plain province is a broad northeast-trending downwarp, partly filled with young basalt flows. Heat-flow values measured in shallow (less than 200 m) wells in the eastern Snake River Plain are low (less than 20 mW/m^2) because of cold-water movement in the extensive Snake Plain aquifer (Brott and others, 1976). The abundance of young basalt, however, suggests that thermal anomalies may exist at least locally. A total of 20 low-temperature geothermal systems are identified in the province; 16 of these are isolated systems.

Northern Rocky Mountains

The Idaho batholith in central Idaho and the Boulder batholith in southwestern Montana together make up most of the Northern Rocky Mountains province. The province contains 135 isolated low-temperature geothermal systems that are probably controlled by fault and joint patterns in the crystalline rocks and six larger area systems.

Middle Rocky Mountains

The Middle Rocky Mountains are characterized by diverse and complex geology; thrusting, normal faulting, and folding are all recognized. A total of 25 widely scattered low-temperature geothermal systems are identified in the province. These systems are apparently structurally controlled, and all but one system are probably of limited extent. Heat flow is normal, and water temperatures are determined by circulation depths.

Southern Rocky Mountains

The Southern Rocky Mountains of Colorado and New Mexico consist of a wide variety of rocks, ranging from Precambrian crystalline basement to Cenozoic volcanic rocks. The province has a normal heat flow and is not seismically active. Of the 34 identified geothermal systems, 33 are isolated, and the province does not appear to have much geothermal potential.

Colorado Plateaus

The Colorado Plateaus province is an area of relatively undeformed Paleozoic and Mesozoic sedimentary rocks. The province is seismically inactive and has low heat flow. Low-temperature geothermal systems are identified only in that part of the province in Utah; a total of 30 such systems, of which 29 are isolated, are recognized. Although young volcanic features in northern Arizona and New Mexico are possible geothermal targets, the province has little identified geothermal potential.

Rio Grande Rift

The Rio Grande Rift, as used here, extends from western Texas to the upper Arkansas Valley of Colorado. The province, particularly in New Mexico, has high heat flow and contains several thermal anomalies. It is divided into several interconnected partly filled structural basins. Harder and others (1980) and Morgan and others (1981) proposed that these thermal anomalies are the result of forced convection driven by ground-water flow through the interconnected basins. Thermal springs and surface heat-flow anomalies are thought to occur where the ground-water flow is constricted at the discharge areas of the basins. Temperatures within individual geothermal systems are determined by the depths of water circulation and the geothermal gradient. A total of 44 isolated and four larger area low-temperature geothermal reservoirs are identified in the province.

DETERMINATION OF ACCESSIBLE RESOURCE BASE, RESOURCE, AND BENEFICIAL HEAT

The methodology used here in determining the identified accessible resource base for low-temperature geothermal systems in the Western United States is essentially the same as that used by Brook and others (1979, equations 1, 1a) in evaluating intermediate- and high-temperature hydrothermal-convection systems. This methodology requires that minimum, maximum, and most likely values be determined for reservoir temperature, area, and thickness. These three estimated values for each reservoir variable are assumed to fit a triangular probability density and are used to calculate a mean and standard deviation. These mean values are used, in turn, to calculate the identified accessible resource base, resource, and beneficial heat; uncertainties associated with the magnitudes of these quantities are expressed in terms of standard deviations.

The resource (wellhead thermal energy) for each identified thermal reservoir is calculated either (1) by assuming a 25-percent recovery factor for those reservoirs with a standard volume of 1 km^3, or (2) by estimating the number of production wells that a reservoir with a larger than standard volume can support for 30 years with a cumulative drawdown of 152 m. The number of production wells is determined by the reservoir area and the optimum well spacing, which, in turn, is a function of reservoir transmissivity and the properties of the confining beds. For most reservoirs, the existence of leaky confining beds can reasonably be inferred, although measured transmissivity values are unavailable. Transmissivity values are estimated principally on the basis of the discharge rates of springs and wells. Systems with springs or wells that individually discharge less than 3.3 L/s are assigned a transmissivity of 0.0025 m^2/s, those with discharges of a few hundred to a few thousand liters per minute a transmissivity of 0.005 m^2/s, and those with greater discharges a transmissivity of 0.01 m^2/s; a few systems that have wells with very large discharges are assigned transmissivities of 0.02 m^2/s. If flow rates are unavailable, a transmissivity of 0.005 m^2/s is assumed.

Beneficial heat is calculated by applying equation 6 of Sorey, Nathenson, and Smith (this volume), who also give a detailed discussion of the methodology and all the assumptions and equations used in calculating the identified accessible resource base and resource.

ESTIMATION OF TEMPERATURES

Minimum, maximum, and most likely reservoir temperatures are estimated from the temperatures measured in springs or wells and from calculated subsurface temperatures based on geothermometry. The mean temperature is considered to be characteristic of the entire reservoir, although both cooler and warmer temperatures may occur locally within the reservoir. For isolated geothermal systems and for a few systems with reservoir volumes only slightly larger than 1 km^3, the minimum temperatures are the measured temperatures, whereas the maximum and most likely values are from geothermometric calculations. For reservoirs of larger than the standard volume (greater than 1 km^3), the minimum, maximum, and most likely temperatures are generally the temperatures measured in wells.

Where the basic assumptions of water-rock equilibrium on which geothermometry is based (Fournier and others, 1974) are not satisfied, the maximum and most likely temperatures are inferred from geologic information. For reservoirs with insufficient data and for those with geothermometric temperatures below the measured temperatures, the maximum and most likely temperatures are set equal to the spring or well temperature.

The geothermometers used in this assessment are the Na-K-Ca, quartz conductive, and chalcedony. Although these geothermometers may not be reliable at low temperatures, owing to slow rates of water-rock reaction, these data were used as the best available estimates in the absence of measured reservoir temperatures. Selection of the appropriate Na-K-Ca temperature followed the rules given by Fournier and Truesdell (1973). A magnesium correction (Fournier and Potter, 1978) was applied to the Na-K-Ca geothermometer where a correction of more than 1°C was indicated. Precise rules for selection of the quartz or chalcedony geothermometer in all terranes are not available. Arnórsson (1975) demonstrated that, in basaltic terranes in Iceland, chalcedony controls dissolved-silica concentrations in reservoirs with temperatures below 130°C, whereas quartz limits dissolved-silica concentrations in reservoirs with temperatures above 180°C. Between 130° and 180°C, either quartz or chalcedony could be the mineral that controls the dissolved-silica concentration. In granitic terranes the solubility of quartz apparently limits the dissolved-silica concentration down to 80°C, whereas the solubility of chalcedony limits dissolved-silica concentrations at lower temperatures (R.O. Fournier, oral commun., 1981). Thermal-spring waters discharged from granitic terranes generally have Na/Ca weight ratios of more than 20, whereas ratios of less than 20 are characteristic of most other terranes. For this assessment, the quartz geothermometer is used only where the Na/Ca ratio in thermal water equals or is greater than 20 and where the Na-K-Ca geothermometer indicates a temperature above 80°C.

Interpretation of the temperatures estimated from silica geothermometers is further complicated by the increased solubility of silicate minerals at high pH (greater than 8.5). This is a common problem for thermal waters discharging in granitic terranes. The solubility of quartz or chalcedony is a function of both temperature and pH. At a pH between 4 and 8, the solubility of quartz or chalcedony is almost solely a function of temperature, and the effects of pH are negligible. At a pH greater than 8.5, however, the solubility of quartz or chalcedony increases sharply with rising pH at any given temperature. The equations that relate dissolved-silica concentrations to the temperature of quartz-water or chalcedony-water equilibrium (Fournier, 1977) are valid only for waters of near-neutral pH. In high-temperature geothermal reservoirs, thermal waters are buffered at near-neutral pH by silicate-mineral/water reactions. At low temperatures, however, the water is not buffered, and the pH may exceed 9 or even 10. Accordingly, the dissolved-silica concentration of alkaline waters cannot be used directly in silica geothermometers; instead, a computer program is used to calculate the pH at successively higher temperatures until equilibrium with quartz or chalcedony is theoretically achieved; these equilibrium temperatures are then used in place of the temperatures calculated from quartz or chalcedony geothermometers. This method generally gives temperatures near those estimated from the Na-K-Ca geothermometer.

ESTIMATION OF AREA AND THICKNESS

The mean volume of a geothermal reservoir is the product of the mean estimated area and the thickness. Reservoir areas for large geothermal systems are based predominately on the distribution of thermal springs and wells as plotted on 1:250,000-scale maps. Mean reservoir thickness is assumed to be 0.25 km unless the data indicate otherwise; this mean thickness is based on estimated minimum, maximum, and most likely permeable thicknesses of 0.1, 0.4, and 0.25 km, respectively.

Isolated geothermal reservoirs are assigned a mean standard volume of 1 km^3 on the basis of theoretical calculations by M. L. Sorey (oral commun., 1981). This standard volume is obtained from minimum, maximum, and most likely volumes of 0.01, 2, and 1 km^3, respectively. This approach probably overestimates the volume of reservoirs in granitic or other low-permeability rock in which the thermal fluids are restricted to narrow faults or fractures, but underestimates the volume of isolated geothermal reservoirs in sedimentary and basin-fill terranes.

USE OF TABLES

Table 4 lists mean values for the reservoir parameters temperature, area, and thickness, and calculated values for the accessible resource base, resource, and beneficial heat, for identified low-temperature geothermal systems in the Western United States. The table is arranged by State, and large-volume systems are listed individually. Isolated geothermal systems are not listed individually; instead, the accessible resource base, resource, and beneficial heat for these systems are given as totals for the respective geologic provinces in each State. Complete chemical data and estimates of the reservoir temperature, area, thickness, transmissivity, well spacing, and type of system have been reported by Reed and others (1983). The range of total dissolved solids is included in the "Comments" to table 4 as a guide to environmental planning associated with water disposal after the usable heat has been extracted. Slightly to highly saline waters are discharged by approximately 30 percent of the large-volume low-temperature hydrothermal-convection systems in the Western United States.

All identified low-temperature geothermal-resources areas are classified according to the categories of Sorey, Nathenson, and Smith (this volume, figs. 5-7; table 3). Systems associated with fault zones (fig. 5) have been identified in all geologic settings and are by far the most common type of low-temperature geothermal system in the Western United States. Lateral-leakage systems (fig. 6) are particularly common in the Basin and Range province, the Snake River Plain, the Rio Grande Rift, and the Salton Trough. Conduction-dominated systems (fig. 7) have been identified only in the Columbia Plateaus and the Salton Trough.

UNDISCOVERED ACCESSIBLE RESOURCE BASE

Sammel (1979) listed areas favorable for the discovery and development of low-temperature geothermal resources. Many of these same areas are evaluated in this assessment; however, several areas remain unevaluated because the data are insufficient. Unevaluated areas make up part of the undiscovered accessible resource base, the rest of which is assumed to be either in identified thermal reservoirs that may be larger or warmer than determined here, or in reservoirs with no surface discharge. The undiscovered accessible resource base was estimated for each geologic province by multiplying the identified accessible resource base of that province by factors of 1, 2, 3, 5, or, rarely, 10; our estimates are listed in table 5. The factor for each province was based on geologic and hydrologic characteristics, the number of systems identified in the province, and our own judgment; we recognize that large uncertainties may be associated with these estimates. The resource and beneficial heat were estimated by assuming the same ratio of resource (or beneficial heat) to accessible resource base as that determined for identified geothermal reservoirs in the region.

SUMMARY

The identified accessible resource base for both hydrothermal-convection and conduction-dominated low-temperature geothermal systems in the Western United States is $310x10^{18}$ J (table 6). Of this total, $75x10^{18}$ J is contained in hydrothermal-convection systems with standard reservoir volumes, $128x10^{18}$ J is in hydrothermal-convection systems with larger than standard reservoir volumes, and $102x10^{18}$ J is in

Table 5.—Summary of the identified and undiscovered accessible resource base in geologic provinces of the Western United States

[All values calculated analytically. All values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

Geologic province	Accessible resource base (10^{18} J)	
	Identified	Undiscovered
Aleutian Islands and Peninsula	0.35	3.5
Central Alaska	2.60	13.0
Southeastern Alaska	.58	2.9
Basin and Range	107	210
Cascade Range	3.5	10.5
Coast Ranges	3.7	11.1
Colorado Plateaus	1.56	1.56
Columbia Plateaus	78	78
Central Valley	.094	.094
Hawaii	1.70	5.1
Olympic Mountains	.29	.29
Oregon Plateaus	6.1	12.2
Peninsular Ranges	5.7	5.7
Rio Grande Rift	5.4	27
Southern Rocky Mountains	3.1	3.1
Middle Rocky Mountains	1.80	1.80
Northern Rocky Mountains	15.4	15.4
Salton Trough	29	29
Sierra Nevada	3.6	3.6
Eastern Snake River Plain	5.7	11.4
Western Snake River Plain	28	28
Transverse Ranges	2.7	2.7
Total	310	480

conduction-dominated systems. Table 6 lists the distribution by temperature range of the identified resource and beneficial heat. Hydrothermal-convection systems account for only 65 percent of the identified accessible resource base but for 97 percent of the identified resource and beneficial heat. The total identified resource is 31×10^{18} J, and the total beneficial heat is 13.7 GW_t.

The undiscovered accessible resource base for low-temperature geothermal systems is 480×10^{18} J, on the basis of our judgment guided by geologic and hydrologic factors and by the distribution of identified geothermal systems. Assuming the same ratios of resource to accessible resource base and of beneficial heat to accessible resource base as observed in the identified systems, the undiscovered resource is 48×10^{18} J, and the beneficial heat in the undiscovered component is 21 GW_t. Thus, the total low-temperature accessible resource base, resource, and beneficial heat in the Western United States are 790×10^{18} J, 79×10^{18} J, and 35 GW_t, respectively.

Table 6.—Summary of energies for low-temperature geothermal systems in the Western United States

[Systems in national parks are omitted. All means and standard deviations calculated by the Monte Carlo method. All values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

Type of system	Number of systems	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial heat (MW_t for 30 yr)
Identified				
Hydrothermal convection				
Delineated areas				
less than 50°C	---	---	4.6±0.42	1,600±181
50° to 70°C	---	---	5.3±0.55	2,600±280
70° to 90°C	---	---	1.18±0.192	620±105
Subtotal	148	128±5.1	11.1±0.72	4,800±350
Isolated Systems				
less than 50°C	---	---	6.3±0.189	1,950±81
50° to 70°C	---	---	7.9±0.31	3,900±157
70° to 90°C	---	---	4.8±0.27	2,500±149
Subtotal	921	75±1.26	19.0±0.45	8,400±230
Conduction dominated				
less than 50°C	---	---	.62±0.139	210±57
50° to 70°C	---	---	.25±0.170	120±93
70° to 90°C	---	---	.32±0.149	166±78
Subtotal	9	102±16.7	1.19±0.27	500±134
Total	1,078	310±17.5	31±0.89	13,700±440
Undiscovered	---	480	48	21,000

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TABLE 4

Table 4.--Estimated reservoir values and thermal energies of identified low-temperature geothermal resources in the Western United States

[Systems in national parks have been excluded from calculations of resource and beneficial heat. All means and standard deviations calculated analytically. All values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value. See table 3 for the categories of low-temperature geothermal systems. TDS, total dissolved solids: (1) Less than 1,000 mg/L; (2) 1,000 to 10,000 mg/L; (3) more than 10,000 mg/L. $\underline{T}$, assumed reservoir transmissivity; $\underline{a}_w$, area per well for equally spaced production wells]

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
					ALASKA			
Aleutian Islands and Peninsula province								
Isolated systems----------	1	--	--	--	0.35±0.098	0.088	43	3 systems.
Central Alaska province								
Isolated systems----------	1	--	--	--	2.6±0.26	.65	320	25 systems.
Southeastern Alaska province								
Isolated systems----------	1	--	--	--	.58±0.116	.145	71	5 systems.
					ARIZONA			
Basin and Range province								
Isolated systems----------	1	--	--	--	4.8±0.35	1.21	550	51 systems.
Agua Caliente-------------	2	48	22	.25	.47±0.162	.106	47	5 wells, no depth data; TDS (1,2), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1 km^2.
Bowie---------------------	2	42	113	.25	1.96±0.86	.172	68	Poorly defined system: 4 wells, no depth data or flow rates; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1.8 km^2.
Buckeye Valley------------	2	40	150	.25	2.4±0.80	.149	58	3 wells: 1 well 84°C and 214 m deep; other 2 wells: saline (1,000 mg/L), cooler, and lack depth data; $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1.6 km^2.
Buckhorn------------------	2	55	53	.25	1.39±0.66	.23	110	2 wells; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1 km^2.
Cactus Flat---------------	2	53	33	.25	.83±0.35	.180	84	12 wells: 1 well, 489 m deep; TDS (2), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1 km^2.
Chandler------------------	2	58	220	.25	6.1±1.97	.30	147	8 wells (30°-62°C), to 914 m deep; TDS (1,2), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=2.3 km^2.
Gila Bend-----------------	2	55	27	.25	.69±0.33	.157	74	2 wells, no depth data; TDS (2), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1 km^2.
Harquahala Plain----------	2	50	100	.25	2.3±0.95	.20	90	3 wells, no depth data; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1.8 km^2.
Hyder Valley--------------	2	53	200	.25	5.0±1.96	.25	115	11 wells, 31 to 162 m deep; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=2.3 km^2.
Palomas Plain-------------	2	53	100	.25	2.5±0.98	.22	102	9 wells: 2 wells are 73 and 145 m deep; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1.8 km^2.
Rainbow Valley------------	2	48	100	.25	2.2±1.04	.193	84	3 wells, no depth data; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1.8 km^2.
Sulphur Springs Valley----	2	55	100	.25	2.6±1.04	.23	107	Poorly defined system: 2 wells, 412 and 670 m deep; TDS (1), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1.8 km^2.
					CALIFORNIA			
Basin and Range province (northern)								
Isolated systems----------	1	--	--	--	1.03±0.15	0.26	101	16 systems.
North of Likely-----------	2	65	5.0	.25	.161±0.069	.038	19	2 wells and 1 spring (maximum 44°C): wells, 34 and 61 m deep; TDS (1), $\underline{T}$=0.0025 m^2/s, $\underline{a}_w$=1 km^2.
Susanville----------------	2	68	6.7	.25	.23±0.086	.054	28	Numerous shallow wells (36°-63°C), 90 to 180 m deep; TDS (1), $\underline{T}$=0.0025 m^2/s, $\underline{a}_w$=1 km^2.
Basin and Range province (southern)								
Isolated systems----------	1	--	--	--	1.95±0.21	.49	200	26 systems.
Desert Center-------------	2	35	123	.25	1.60±0.45	.063	20	5 wells (30°-35°C), 69 to 183 m deep; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=2.33 km^2.
Eastern Long Valley-------	2	40	33	.50	1.08±0.66	.042	16	Springs east and southeast of Hot Creek, leakage from high-temperature system; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.2 km^2.
McCoy Wash----------------	2	32	19.3	.25	.21±0.098	.046	12	Wells (31°-33°C), 84 to 178 m deep; no chemical data, $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Saline Valley-------------	2	56	7.3	.25	.194±0.059	.046	22	4 springs on northeast side of valley; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Twentynine Palms----------	2	55	63	.25	1.65±0.83	.089	42	5 wells (40°-67°C), no depth data; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.8 km^2.
Cascade Range province								
Isolated systems----------	1	--	--	--	.71±0.24	.179	88	6 systems.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
Central Valley province								
Isolated systems----------	1	--	--	--	0.094±0.028	0.024	6.6	2 systems.
Coast Ranges province								
Isolated systems----------	1	--	--	--	3.5±0.28	1.56	370	46 systems.
Agua Caliente-------------	2	43	3.7	.25	.068±0.024	.016	6.5	3 springs (38°-46°C); no chemical data, $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Paso Robles---------------	2	72	4.3	.25	.160±0.058	.038	20	3 springs (39°-43°C); TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Peninsular Ranges province								
Isolated systems----------	1	--	--	--	2.4±0.21	.59	250	29 systems.
Diamond Valley------------	2	42	5.7	.25	.099±0.054	.023	9.2	1 well, 27 m deep; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Domenigoni Valley---------	2	53	5.7	.25	.141±0.060	.033	15.6	3 wells (37°-49°C), 6 to 34 m deep; TDS (1,2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Palm City-----------------	2	52	10.0	.25	.24±0.103	.052	24	2 wells (36°C); TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
San Jacinto Valley--------	2	45	150	.25	2.9±1.19	.094	40	Springs (38°-43°C) and wells (26°-49°C), depths to 186 m; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=2.08 km^2.
Salton Trough province								
Isolated systems----------	1	--	--	--	1.21±0.154	.30	129	15 systems.
Desert Hot Springs--------	2	67	32	.25	1.06±0.38	.120	61	14 wells, 5 to 69 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.17 km^2.
Eastern Imperial Valley---	3	57	800	.30	26±10.4	.23	109	Numerous wells (30°-55°C), some artesian, 100 to 300 m deep; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=9.03 km^2.
Lower Borrego Valley------	2	42	27	.25	.46±0.138	.062	25	9 wells (31°-38°C), 45 to 102 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.07 km^2.
Northwestern Salton Sea---	2	43	30	.25	.55±0.187	.062	26	Numerous wells (32°-43°C), only one well depth available (118 m); TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.08 km^2.
Sierra Nevada province								
Isolated systems----------	1	--	--	--	1.78±0.20	.41	188	19 systems.
Sierra Valley-------------	2	50	78	.25	1.78±0.88	.050	23	Wells (25°-35°C), 7 to 335 m deep; TDS (1), (1 well 94°C, has 1,370 mg/L), $\underline{T}$=0.0025 m^2/s, $\underline{a}_w$=3.33 km^2.
Transverse Ranges province								
Isolated systems----------	1	--	--	--	1.78±0.179	.44	187	23 systems.
Urbita Hot Springs--------	2	45	10.7	.25	.21±0.063	.045	19.1	7 wells (41°-51°C), 53 to 297 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Harlem Hot Springs--------	2	50	9.0	.25	.20±0.074	.048	22	3 wells (43°-54°C), 42 to 152 m deep; no chemical data, $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Ojai Springs--------------	2	68	15.3	.25	.53±0.196	.094	48	5 springs (39°-51°C); TDS (1,2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
					COLORADO			
Rio Grande Rift province								
Isolated systems----------	1	--	--	--	0.39±0.101	0.098	44	5 systems.
Southern Rocky Mountains province								
Isolated systems----------	1	--	--	--	3.0±0.26	.75	340	33 systems.
Glenwood Springs----------	2	51	5.0	.25	.117±0.039	.028	12.6	Several springs (32°-51°C); TDS (3), $\underline{T}$=0.01 m^2/s, $\underline{a}_w$=1 km^2.
					HAWAII			
Hawaiian province								
Kapoho--------------------	2	48	78	.25	1.70±0.57	0.054	24	2 springs near sea level (33° and 36°C) and 3 wells (37°-52°C), 44 to 96 m deep; TDS (1,2), $\underline{T}$=0.0025 m^2/s, $\underline{a}_w$=2.93 km^2.
					IDAHO			
Basin and Range province								
Isolated systems----------	1	--	--	--	1.28±0.189	0.32	153	12 systems.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
Goose Creek-Oakley--------	2	63	67	0.25	2.1±0.71	0.138	69	1 spring (47°C) and 5 wells (32°-47°C), some artesian, 259 to 326 m deep; TDS (1), T=0.005 m^2/s, a_w=1.55 km^2.
Lower Raft River----------	2	40	62	.25	1.01±0.61	.20	77	5 wells (32°-40°C), depths to 352 m; TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Malad City----------------	2	33	41.0	.25	.49±0.31	.075	21	3 springs (25°-27°C), poorly defined reservoir; TDS (2), T=0.005 m^2/s, a_w=1 km^2.
Marsh Creek---------------	2	60	8.3	.25	.24±0.100	.057	28	Springs and 1 well (60°C and 136 m deep); TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Raft River----------------	2	47	220	.25	4.5±1.72	.183	79	Numerous wells (generally 20°-40°C), 50 to 200 m deep: 1 well (77°C) 1 km deep; TDS (1,2), T=0.005 m^2/s, a_w=2.3 km^2.
Soda Springs--------------	2	59	5.7	.25	.163±0.087	.038	18.9	2 CO_2-charged springs, system temperatures speculative; TDS (2), T=0.005 m^2/s, a_w=1 km^2.
Middle Rocky Mountains province								
Isolated systems----------	1	--	--	--	.33±0.139	.082	37	4 systems.
Northern Rocky Mountains province								
Isolated systems----------	1	--	--	--	10.1±0.49	2.5	1,220	94 systems.
Boiling Springs-----------	2	80	6.0	.25	.25±0.087	.060	32	6 springs (32°-86°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Cascade-------------------	2	67	11.7	.25	.39±0.168	.076	39	2 springs (39°-71°C) and 1 well (43°C) 15 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Holdover Hot Springs------	2	62	7.0	.25	.22±0.071	.051	25	2 springs (46°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Midvale-------------------	2	52	14.3	.25	.34±0.170	.067	31	1 spring (50°C) and 2 wells (28°C), depths to 316 m; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Punkin Corners------------	2	48	11.7	.25	.25±0.115	.055	24	2 wells (26°-35°C), 58 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Sunflower-Riverside-------	2	75	5.0	.25	.195±0.068	.046	24	4 springs (43°-65°C), along both sides of Middle Fork, Salmon River; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Eastern Snake River Plain province								
Isolated systems----------	1	--	--	--	1.22±0.172	.30	130	16 systems.
Newdale-------------------	2	57	57	.25	1.54±0.60	.117	57	Wells (21°-37°C), 56 to 200 m deep, in area extending across Teton River; TDS (1), T=0.005 m^2/s, a_w=1.39 km^2.
Rock Creek-Artesian City--	2	53	108	.25	2.7±0.98	.127	60	Many wells (23°-41°C), 24 to 335 m deep; TDS (1), T=0.005 m^2/s, a_w=1.80 km^2.
South American Falls------	2	30	7.7	.25	.075±0.028	.018	3.7	Wells (27°-33°C), depths to 164 m; TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Tyhee---------------------	2	35	9.3	.25	.121±0.049	.029	9.1	6 wells (20°-41°C), 60 to 152 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Western Snake River Plain province								
Isolated systems----------	1	--	--	--	1.28±0.165	.32	134	17 systems.
Boise Front---------------	2	67	57	.25	1.90±0.84	.186	95	More than 25 wells, most are 100 to 450 m deep; 1 well 90°C and 1,174 m deep; TDS (1), T=0.005 m^2/s, a_w=1.13 km^2.
Bruneau-Grandview---------	2	40	750	.25	12.2±3.8	.23	88	More than 100 high-discharge wells (20°-84°C); TDS (1), T=0.01 m^2/s, a_w=5.94 km^2.
Buhl----------------------	2	45	58	.25	1.14±0.49	.099	42	Springs (to 70°C) and wells (28°-63°C), 34 to 332 m deep; TDS (1), T=0.005 m^2/s, a_w=1.19 km^2.
Clover Creek--------------	2	68	21	.25	.72±0.26	.135	70	1 spring (27°C) and 3 wells (43°-47°C), 50 to 256 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Dry Creek-----------------	2	43	6.7	.25	.123±0.048	.029	11.9	5 wells (25°-30°C), 90 to 120 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Emmett Valley-------------	2	24	12.3	.25	.072±0.034	.015	0	2 wells (24°C), 9 to 54 m deep; no chemical data, T=0.005 m^2/s, a_w=1 km^2.
Glenns Ferry-King Hill----	2	35	37	.25	.48±0.176	.028	8.9	Wells (23°-38°C), 73 to 396 m deep; TDS (1), T=0.0025 m^2/s, a_w=1.64 km^2.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
Mt. Bennett Hills---------	2	72	30	0.25	1.10±0.35	0.145	76	Springs (57°C) and wells (36°-68°C), to 483 m deep; TDS (1), T=0.005 m^2/s, a_w=1.08 km^2.
Murphy-Givens-------------	2	35	150	.25	1.95±0.69	.063	19.8	Springs and wells (25°-56°C): wells 39 to 457 m deep; TDS (1), T=0.005 m^2/s, a_w=2.27 km^2.
Nat-Soo-Pah---------------	2	43	26	.25	.47±0.175	.103	42	Springs and wells near 36°C, depths to 236 m; TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Salmon Falls Creek--------	2	33	17.7	.25	.21±0.085	.050	14.3	Wells (25°-30°C), 150 to 250 m deep; no chemical data, T=0.01 m^2/s, a_w=1 km^2.
West Snake River Plain----	2	32	570	.25	6.1±2.0	.078	19.8	Numerous irrigation wells, near 25°C, 100 m deep; TDS (1), T=0.005 m^2/s, a_w=7.42 km^2.
					MONTANA			
Middle Rocky Mountains province								
Isolated systems----------	1	--	--	--	0.29±0.072	0.074	30	4 systems.
Northern Rocky Mountains province								
Isolated systems----------	1	--	--	--	3.6±0.28	.91	411	41 systems.
					NEVADA			
Basin and Range province								
Isolated systems----------	1	--	--	--	11.9±0.31	3.0	1,310	143 systems.
Abel-Chimney Springs------	2	47	54	.25	1.11±0.51	.081	35	4 springs (37°-66°C) and 1 artesian well (60°C) 522 m deep; TDS (1), T=0.005 m^2/s, a_w=1.2 km^2.
Alkali Springs------------	2	58	6.7	.25	.188±0.070	.044	22	Several springs (37°-60°C); TDS (2), T=0.005 m^2/s, a_w=1 km^2.
Arnoldson Spring----------	2	23	6.3	.25	.033±0.011	.008	0.0	3 springs (22°-23°C); no chemical data, T=0.01 m^2/s, a_w=1 km^2.
Artesia Lake--------------	2	83	20	.25	.88±0.40	.146	79	3 shallow wells (21°-28°C), 18 to 165 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Ash Meadows---------------	2	30	100	.25	.98±0.34	.083	17.6	More than 30 springs and shallow wells (26°-34°C): wells less than 200 m; TDS (1), T=0.01 m^2/s, a_w=1.27 km^2.
Ash Springs---------------	2	36	5.0	.25	.068±0.024	.016	5.3	2 high-discharge springs (32° and 36°C); TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Bartine Hot Springs-------	2	57	6.7	.25	.182±0.075	.043	21	1 spring (44°C) and 1 well (47°C) 148 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Beatty-Hicks--------------	2	72	16.7	.25	.61±0.24	.112	58	4 springs (26°-43°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Bennett's Spring----------	2	25	13.0	.25	.084±0.027	.016	0.0	2 springs (25°C) and 4 shallow wells (23°-28°C), depths to 100 m; no chemical data, T=0.005 m^2/s, a_w=1 km^2.
Black Canyon--------------	2	50	5.7	.25	.129±0.058	.030	13.7	Springs (25°-33°C); TDS (2), T=0.005 m^2/s, a_w=1 km^2.
Blue Eagle Spring---------	2	35	10.0	.25	.132±0.056	.031	10.0	3 springs (22°-28°C) and 1 well (22°C) 56 m deep; TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Caliente------------------	2	80	5.7	.25	.24±0.096	.056	30	1 spring (63°C) and 4 wells (42°-67°C), 15 to 41 m deep; TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Carlin--------------------	2	83	5.0	.25	.22±0.073	.052	28	1 spring (79°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Comstock------------------	2	77	5.3	.25	.22±0.066	.051	27	1 well (77°C), 914 m deep; no chemical data, T=0.005 m^2/s, a_w=1 km^2.
Dixie Valley--------------	2	25	53	.25	.35±0.161	.034	0.0	2 wells (22° and 23°C), 61 m deep; TDS (1), T=0.005 m^2/s, a_w=1.27 km^2.
Duckwater-----------------	2	44	7.7	.25	.146±0.056	.034	14.4	3 springs (32°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Elko----------------------	2	75	7.3	.25	.29±0.091	.067	36	2 springs; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Ely-Lackawana-------------	2	40	9.7	.25	.159±0.068	.035	13.3	2 springs (30° and 35°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Fallon South--------------	2	73	10.7	.25	.40±0.25	.088	46	1 artesian well (70°C), no chemical or depth data; T=0.005 m2/s, a_w=1 km2.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
Fish Lake Valley----------	2	27	42	0.25	0.33±0.182	0.043	3.9	Springs (25°-30°C); TDS (2), T=0.005 m^2/s, a_w=1.08 km^2.
Fly Ranch-----------------	2	58	21.7	.25	.61±0.26	.093	45	At least 5 shallow wells (20°-25°C), depths less than 100 m; T=0.005 m^2/s, a_w=1 km^2.
Gabbs---------------------	2	53	7.7	.25	.191±0.063	.045	21	3 wells (52°-68°C), depths to 139 m; no chemical data, T=0.005 m^2/s, a_w=1 km^2.
Gamble Ranch Spring-------	2	38	17.3	.25	.26±0.115	.050	18	2 springs (21° and 44°C) and 1 well (24°C) 64 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Golconda Hot Springs------	2	84	5.0	.25	.22±0.076	.053	29	Springs (74°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Goose Creek---------------	2	40	21.0	.25	.34±0.124	.057	22	4 springs and shallow wells (21°-43°C), to 75 m depth; TDS (1), T=0.005 m^2/s a_w=1 km^2.
Grass Valley--------------	2	67	20.0	.20	.54±0.171	.060	31	Low-temperature water leaking from Leach Hot Springs high-temperature system; TDS (1), T=0.0025 m^2/s, a_w=2.33 km^2.
Hawthorne-----------------	2	47	53	.25	1.10±0.46	.073	32	At least 6 shallow wells (23°-34°C), depths near 200 m: 1 well (51°C) with unknown depth; TDS (1), T=0.005 m^2/s, a_w=1.55 km^2.
Hill's Warm Spring--------	2	56	8.3	.25	.22±0.113	.052	25	2 springs (23° and 28°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Hobo Hot Spring-----------	2	60	5.3	.25	.157±0.053	.037	18.3	2 spring areas; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Hot Creek Canyon----------	2	53	13.3	.25	.33±0.167	.078	37	At least 5 springs (33°-82°C); TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Hot Springs Point---------	2	72	10.7	.25	.39±0.125	.085	45	1 spring area (55°-60°C) and 1 well (75°C) 125 m deep, may overlie high-temperature system; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Huffaker Narrows----------	2	52	40.0	.25	.95±0.40	.102	47	Springs and shallow wells, leakage from Steamboat Springs high-temperature system; TDS (2), T=0.005 m^2/s, a_w=1.27 km^2.
Humboldt Wells------------	2	48	6.3	.25	.137±0.051	.032	14.3	2 wells (36° and 57°C), no depth data; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Indian Springs------------	2	26	9.7	.25	.069±0.024	.015	0.9	4 springs (25°-26°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Las Vegas-----------------	2	26	21	.25	.150±0.085	.035	2.0	Marginally thermal (26°C), high-discharge wells; TDS (1), T=0.01 m^2/s, a_w=1 km^2.
Moana---------------------	2	55	25.7	.25	.67±0.32	.090	43	Many shallow wells in Reno (most are 30°-90°C), depths to 214 m: water used for space heating; TDS (1), T=0.005 m^2/s, a_w=1.07 km^2.
Moapa Springs-------------	2	47	10.3	.25	.22±0.082	.047	21	Springs (28°-32°C), subsurface temperatures are speculative; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Moniter-------------------	2	22	5.7	.25	.026±0.010	.006	0.0	2 wells (22°C), no depth data; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
North Dixie Valley--------	2	43	40.0	.25	.74±0.29	.068	28	5 springs (28°-78°C); TDS (1), T=0.005 m^2/s, a_w=1.27 km^2.
Panaca--------------------	2	32	12.0	.25	.133±0.047	.031	8.1	1 spring (32°C) and 3 wells (23°-24°C), 32 to 41 m deep; TDS (1), limestone aquifer, T=0.01 m^2/s, a_w=1 km^2.
Pinyon Hills--------------	2	50	15.0	.25	.34±0.105	.062	28	4 springs and wells, temperatures to 50°C; TDS (1,2), T=0.005 m^2/s, a_w=1 km^2.
Pleasant Valley-----------	2	30	17.3	.25	.169±0.055	.031	6.5	Shallow wells (22°-28°C), 5 to 51 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Preston Springs-----------	2	23	5.3	.25	.028±0.011	.007	0.0	2 wells (22° and 24°C), 120 and 124 m deep; TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Reese River Valley--------	2	59	10.3	.25	.30±0.101	.064	31	2 springs (50° and 53°C); TDS (1), T=0.005 m^2/s, a_w=1 km^2.
Rose Creek----------------	2	48	7.0	.25	.152±0.063	.036	15.8	Wells (28°C) 30 m deep; TDS (2), T=0.005 m^2/s, a_w=1 km^2.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
Soldier Meadows----------	2	64	11.7	0.25	0.30±0.107	0.075	38	Many springs (to 54°C), at northwest end of Black Rock Desert; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
South Las Vegas----------	2	30	72	.25	.70±0.23	.041	8.7	Marginally warm wells (25°-27°C), 100 to 150 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.7 km^2.
Wheeler Ranch------------	2	26	6.0	.25	.043±0.016	.010	0.6	2 wells (26°C), 61 m deep; no chemical data, $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
				NEW MEXICO				
Basin and Range province								
Isolated systems---------	1	--	--	--	1.78±0.177	0.45	185	26 systems.
Gila Hot Springs---------	2	47	63	.25	1.30±0.61	.092	40	Springs and shallow wells (27°-68°C); TDS (1), 1 well (32°C) 183 m deep, discharges Na-Ca-SO_4 type water with 2,400 mg/L TDS, $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.4 km^2.
Colorado Plateaus province								
Isolated systems---------	1	--	--	--	.55±0.084	.135	43	12 systems.
Rio Grande Rift province								
Isolated systems---------	1	--	--	--	1.93±0.21	.48	210	27 systems.
Laguna Pueblo------------	2	27	18.3	.25	.139±0.050	.025	2.3	Saline springs (20°-30°C); no detailed chemical analyses, $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
San Ysidro---------------	2	43	65	.25	1.20±0.52	.128	52	Springs (20°-30°C) and wells (maximum 61°C) 585 m deep; TDS (1,2,3), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.19 km^2.
Socorro Canyon-----------	2	38	17.7	.25	.27±0.152	.058	21	Springs in galleries (32°-43°C); TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2. Warm wells north of Socorro are barely nonthermal by our temperature-depth criterion.
Soda Dam-----------------	2	75	6.0	.25	.23±0.093	.055	29	Springs (48°-50°C), water is probably leaking from the Valles Caldera high-temperature system; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
				OREGON				
Basin and Range province								
Isolated systems---------	1	--	--	--	1.34±0.163	0.33	132	22 systems.
Klamath Basin------------	2	30	117	.25	1.14±0.66	.062	13.2	Wells (21°-90°C), 25 to 344 m deep: 2 wells (90°C) 127 m deep, (22°C) 344 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.8 km^2.
Klamath Falls-Olene Gap---	2	60	32	.25	.93±0.36	.122	60	Springs (65°-74°C) and wells (21°-89°C), to 550 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.07 km^2.
Klamath Hills------------	2	53	20	.25	.51±0.23	.092	43	Wells (22°-93°C), temperatures do not change uniformly with depth, 2 wells (93°C) 86 m deep, (30°C) 235 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Warner Valley------------	2	58	40	.25	1.13±0.63	.104	51	20 springs and wells (20°-93°C), depths to 285 m; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1.14 km^2.
Cascade Range province								
Isolated systems---------	1	--	--	--	1.82±0.23	.45	230	15 systems.
Columbia Plateaus province								
Isolated systems---------	1	--	--	--	.95±0.155	.24	107	11 systems.
Cove---------------------	2	43	7.3	.25	.135±0.052	.032	13.0	Springs and wells (20°-42°C); TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Hot Lake-----------------	2	67	7.3	.25	.25±0.097	.058	23	Springs (30°-80°C) and wells (25°-82°C): no depth data; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
La Grande----------------	2	71	13.7	.25	.50±0.21	.101	53	Wells (26°-28°C), no depth data; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.
Rhinehart-Imbler---------	2	55	11.0	.25	.29±0.128	.062	30	Wells (22°-31°C), no depth data; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a}_w$=1 km^2.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
Oregon Plateaus province								
Isolated systems----------	1	--	--	--	2.5±0.22	0.63	260	35 systems.
Baker Spring--------------	2	45	7.7	.25	.151±0.059	.036	15.1	2 springs (21°C) and 1 well (23°C); TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Burns---------------------	2	52	14.0	.25	.34±0.145	.066	31	Wells (25°-30°C), some are artesian, depths about 30 m; $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Powell Buttes-------------	2	45	63	.25	1.24±0.55	.040	17.0	Marginal well temperatures (20°-32°C), no depth data; TDS (1), $\underline{T}$=0.0025 m^2/s, $\underline{a_w}$=2.55 km^2.
Southeast Harney Lake-----	2	55	30	.25	.78±0.32	.068	32	Springs (20°-51°C), possibly associated with high-temperature system; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1.08 km^2.
Warm Springs Valley-------	2	55	27	.25	.70±0.32	.104	50	Springs and artesian wells (20°-26°C), on northeast side of Harney Lake; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1.03 km^2.
Western Snake River Plain province								
Isolated systems----------	1	--	--	--	.25±0.082	.062	31	2 systems.
Vale Well-----------------	2	40	4.3	.25	.070±0.024	.017	6.3	2 wells (36° and 40°C), 212 m deep: possibly associated with a high-temperature system; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
					TEXAS			
Rio Grande Rift province								
Isolated systems----------	1	--	--	--	1.27±0.174	0.28	133	12 systems.
					UTAH			
Basin and Range province								
Isolated systems----------	1	--	--	--	4.4±0.29	1.11	400	80 systems.
Central Bear Valley-------	2	38	7.3	.25	.111±0.046	.025	9.1	2 wells (25° and 28°C), 91 and 155 m deep, near Great Salt Lake; TDS (3), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Crater-Saratoga Hot Springs	2	43	14.0	.25	.26±0.081	.030	12.4	2 springs (32° and 43°C) and 7 wells (21°-35°C), 15 to 27 m deep; TDS (2), $\underline{T}$=0.0025 m^2/s, $\underline{a_w}$=1 km^2.
Crystal Hot Spring--------	2	55	5.3	.25	.139±0.056	.033	15.5	1 spring (58°C) and 1 well (28°C) 251 m deep; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Delta---------------------	2	25	633	.25	4.1±1.95	.055	0.0	Marginally thermal wells (22°-29°C), 91 to 264 m deep; TDS (1,2), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=7.1 km^2.
Deseret Livestock---------	2	23	5.7	.25	.028±0.009	.007	0.0	3 springs (22°-24°C); TDS (1,2), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Goshen Valley-------------	2	50	11.7	.25	.26±0.139	.035	15.9	2 wells (23° and 26°C), no depth data; TDS (1), $\underline{T}$=0.0025 m^2/s, $\underline{a_w}$=1 km^2.
Granger-Mud Flats---------	2	25	100	.25	.65±0.22	.029	0.0	Springs (29°C) and wells (26°-28°C), 114 to 194 m deep; TDS (1,2,3), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1.63 km^2.
Kaysville-Farmington------	2	23	18.7	.25	.101±0.058	.022	0.0	Marginally thermal wells (24°-29°C), to 372 m deep; TDS (1), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Kennecott-Asarco Wells----	2	30	6.0	.25	.058±0.021	.014	2.9	6 wells (25°-31°C), no depth data; TDS (3), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Meadow-Hatton Hot Springs-	2	48	15.0	.25	.32±0.134	.059	26	5 springs (22°-41°C) and 1 well (67°C) 27 m deep; TDS (2), $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1 km^2.
Milford-------------------	2	33	48	.25	.58±0.29	.044	12.8	Area of marginally warm wells (to 26°C), approximately 20 km southwest of Roosevelt Hot Springs high-temperature system; $\underline{T}$=0.005 m^2/s, $\underline{a_w}$=1.39 km^2.
Newcastle-----------------	2	52	20	.25	.48±0.26	.112	52	3 wells (23°-95°C), 76 to 152 m deep; $\underline{T}$=0.01 m^2/s, $\underline{a}$ =1 km^2.

Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18}J)	Beneficial Heat (MW_t for 30 yr)	Comments
North Salt Lake City------	2	37	53	0.25	0.75±0.40	0.077	26	Springs (55°C) and 7 wells (21°-42°C), 35 to 305 m deep; TDS (1,2,3), T=0.005 m^2/s, a_w=1.17 km^2.
Ogden Flats---------------	2	30	350	.25	3.4±1.65	.031	6.6	Marginally thermal wells (20°-25°C), to 358 m deep; TDS (1), T=0.0025 m^2/s, a_w=10.3 km^2.
Southern Cache Valley-----	2	27	270	.25	2.0±1.22	.033	3.0	Marginally thermal wells from (21°C) 50 m deep to (49°C) 1,580 m deep; TDS (1), T=0.0025 m^2/s, a_w=5.8 km^2.
Tule Valley---------------	2	30	28.3	.25	.28±0.138	.050	10.6	5 springs (25°-28°C) and 1 well (31°C) 13 m deep; TDS (2), T=0.005 m^2/s, a_w=1 km^2.
Wendover (northeast)------	2	28	15.0	.25	.130±0.044	.031	4.8	4 wells (24°-28°C), 51 to 90 m deep; TDS (2), T=0.01 m^2/s, a_w=1 km^2.
Colorado Plateaus province								
Isolated systems----------	1	--	--	--	.65±0.083	.163	35	17 systems.
Ashley Valley-------------	2	45	18.3	.25	.36±0.125	.065	28	1 irrigation well (20°C) and 3 wells (44°-49°C), 1.3 km deep; TDS (1,2), T=0.005 m^2/s, a_w=1 km^2.
Middle Rocky Mountains province								
Isolated systems----------	1	--	--	--	.045±0.0132	.0111	0.41	2 systems.
Midway--------------------	2	52	10.0	.25	.24±0.096	.052	24	2 springs (39°C); TDS (2), T=0.005 m^2/s, a_w=1 km^2.
					WASHINGTON			
Cascade Range province								
Isolated systems----------	1	--	--	--	1.01±0.129	0.24	97	15 systems.
Columbia Plateaus province								
Connell-Cunningham--------	3	39	700	.15	6.5±2.4	.124	45	10 wells (25°-47°C), 300 to 760 m deep; T=0.005 m^2/s, a_w=8.2 km^2.
Ephrata-------------------	3	30	280	.27	2.9±1.17	.046	9.7	5 wells (25°-30°C), 140 to 360 m deep; T=0.005 m^2/s, a_w=5.7 km^2.
Hanford-------------------	3	72	700	.27	28±9.6	.30	155	Several test wells (60°-75°C), 800 to 1,700 m deep; T=0.005 m^2/s, a_w=8.2 km^2.
Moses Lake----------------	3	33	1,000	.25	11.9±3.7	.093	27	5 wells (28°-35°C), 150 to 300 m deep, and 1 oil test well (66°C) 1,343 m deep; T=0.005 m^2/s, a_w=12 km^2.
Odessa--------------------	3	33	280	.25	3.4±1.20	.056	16.2	4 wells (28°-35°C), 100 to 300 m deep; T=0.005 m^2/s, a_w=5.7 km^2.
Othello-------------------	3	48	280	.27	6.5±2.8	.101	45	5 wells (25°-54°C), 300 to 925 m deep; T=0.005 m^2/s, a_w=5.7 km^2.
Walla Walla River---------	3	39	320	.25	4.9±1.76	.073	27	1 spring (22°C) and 7 wells (25°-41°C), 250 to 470 m deep; T=0.005 m^2/s, a_w=6.3 km^2.
Yakima--------------------	3	34	930	.25	11.3±3.8	.089	26	More than 15 wells (25°-36°C), 300 to 480 m deep; T=0.005 m^2/s, a_w=12 km^2.
Olympic Mountains province								
Isolated systems----------	1	--	--	--	.29±0.090			2 systems.
					WYOMING			
Middle Rocky Mountains province								
Isolated systems----------	1	--	--	--	0.89±0.098	0.22	90	14 systems.

Low-Temperature Geothermal Resources in the Central and Eastern United States

By Michael L. Sorey, Marshall J. Reed, Duncan Foley[1], and Joel L. Renner[2]

CONTENTS

ABSTRACT

Identified low-temperature (less than 90°C) geothermal resources in the Central and Eastern United States occur primarily in regional aquifers within sedimentary basins in the Great Plains and in aquifers beneath the Gulf and Atlantic Coastal Plains. Additional resources occur in hydrothermal-convection systems associated with thermal springs in the Wyoming Basins and Ouachita geologic provinces and in the Appalachian Mountains. The total accessible resource base for identified low-temperature geothermal reservoirs in the Central and Eastern United States is estimated at 27×10^{21} J. The total identified resource is estimated at 55×10^{18} J, from which 28 GW_t for 30 years of beneficial heat could be obtained. Estimates of the total undiscovered accessible resource base, resource, and beneficial heat are 6.7×10^{21} J, 18×10^{18} J, and 9.2 GW_t for 30 years, respectively.

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INTRODUCTION

Within the Central and Eastern United States, low-temperature geothermal resources occur in various geologic settings. The central region, as outlined in figure 14, is bordered on the east by the Mississippi River and on the west by the Rocky Mountains. The Wyoming Basins geologic province is included in the central region because of the occurrence of geothermal resources within several sedimentary basins. The eastern region (fig. 15) lies east of the Mississippi River. Figure 2 shows the geologic provinces within these two regions.

This chapter provides a discussion of the general geothermal settings and the criteria used to identify low-temperature geothermal-resource areas in the Central and Eastern United States, and estimates the accessible resource base, resource, and beneficial heat for each geothermal reservoir. The methods used to obtain these estimates are discussed by Sorey, Nathenson, and Smith (this volume), and additional details are given here. Energy totals are presented for identified low-temperature geothermal reservoirs in hydrothermal-convectionand conduction-dominated systems over three ranges of reservoir temperature, as well as estimates of the undiscovered geothermal resource in various geologic provinces. Selected references to the maps and reports that provided the information utilized in this asssment are given by Reed ("Introduction," this volume). The stratigraphic nomenclature used in this chapter may not necessarily be that adopted by the U.S. Geological Survey.

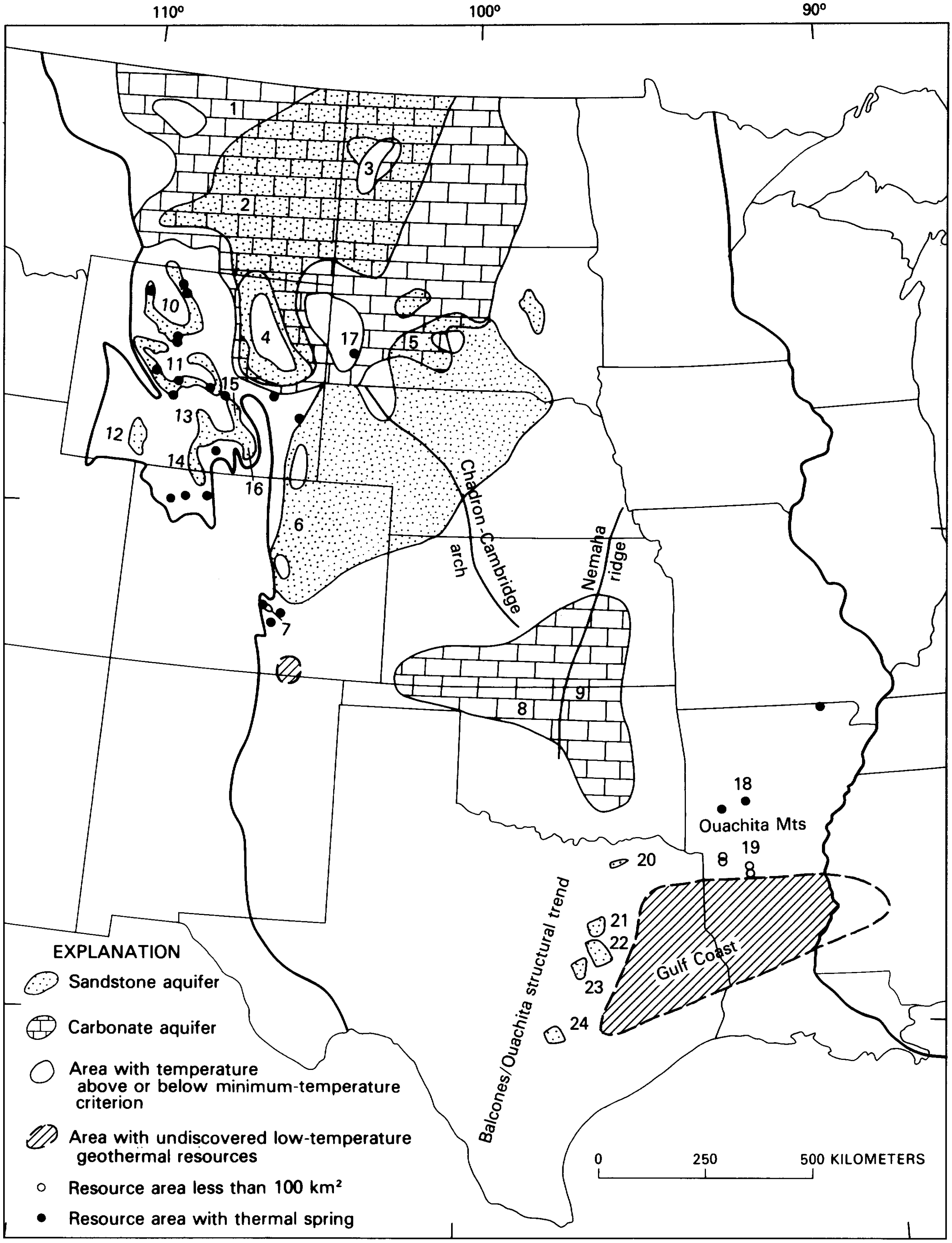

Figure 14.--Identified low-temperature geothermal-resource areas and areas containing undiscovered geothermal resources in the Central United States. Numbers refer to individual geothermal-resource areas listed in table 7; for sedimentary basins, numbers are positioned near deepest part of each basin.

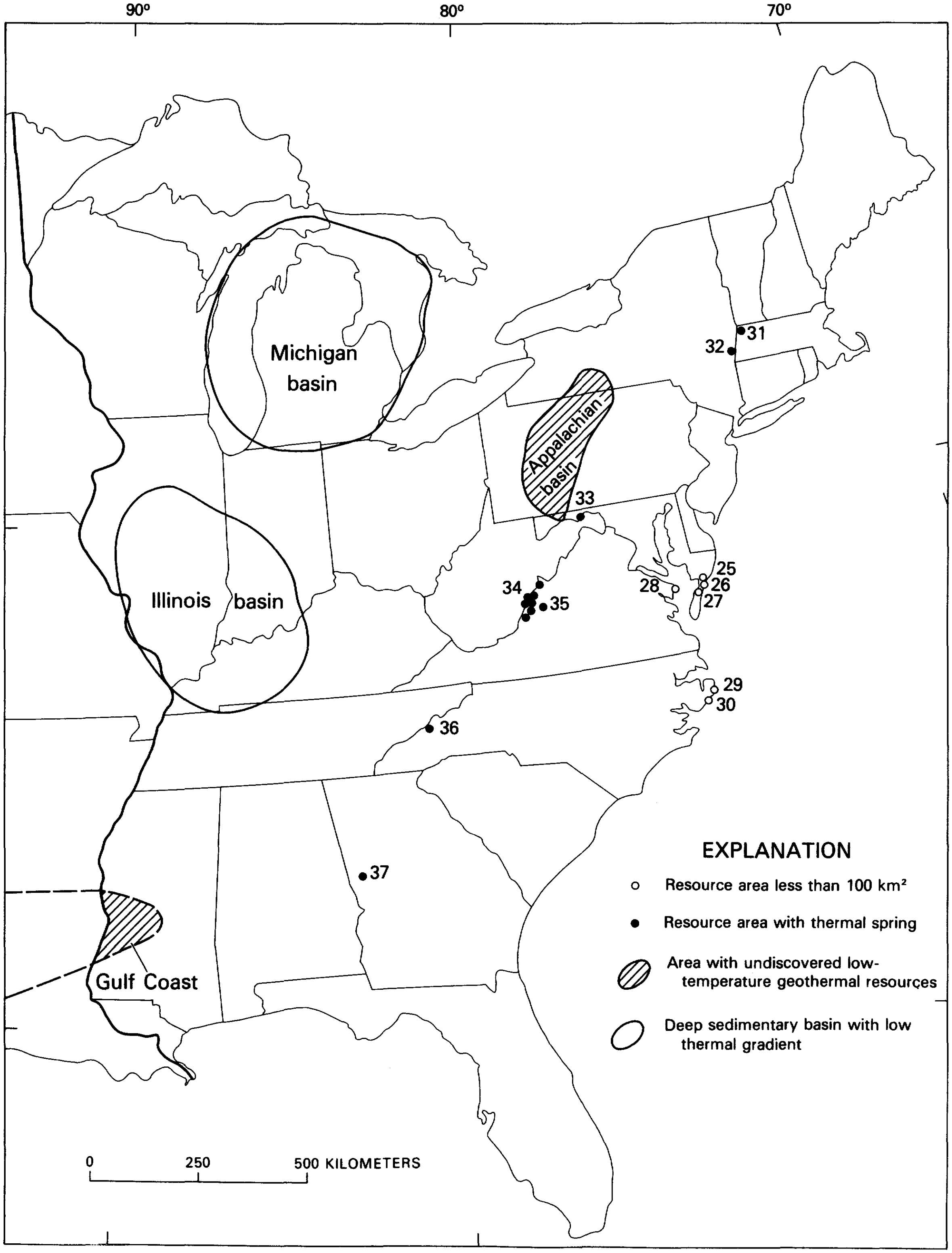

Figure 15.—Identified low-temperature geothermal-resource areas and areas containing undiscovered geothermal resources in the Eastern United States. Numbers refer to individual geothermal-resource areas listed in table 8.

LOW-TEMPERATURE GEOTHERMAL-RESOURCE AREAS IN THE CENTRAL UNITED STATES

The categories of low-temperature geothermal-resource areas identified in this assessment are discussed by Sorey, Nathenson, and Smith (this volume). Isolated thermal springs and wells (category 1, table 3) must meet the criterion that the estimated reservoir temperature be less than 90°C and at least 10°C above the local mean annual air temperature. For identified low-temperature geothermal-resource areas within sedimentary basins (category 3) and beneath coastal plains (category 4), a permeable reservoir with a temperature less than 90°C and greater than the minimum-temperature criterion given by Reed ("Introduction," this volume) must exist. Low-temperature geothermal-resource areas in each of these three categories occur in the Central United States.

The stratigraphic and hydrologic conditions within sedimentary basins of the Great Plains geologic province are complex. In most areas, water wells produce from numerous formations between the Upper Cretaceous shale and crystalline basement. For the purposes of this assessment, however, one or two regional aquifers are identified within each basin; these aquifers are considered to be a combination of one or more permeable formations that are hydraulically connected. Identified aquifers in Cretaceous rocks are denoted as sandstone of the Dakota Group, and in Paleozoic rocks as carbonates (limestone and dolomite) of the Madison Group or Arbuckle Group, except in the Bighorn and Wind River Basins in Wyoming, where we have identified Pensylvanian sandstone of the Tensleep Formation as the reservoir rock because of the relative abundance of data on its thermal, hydrologic, and chemical characteristics. Most of these data were collected during oil and gas exploration, and present-day production of thermal water from these sedimentary basins is used primarily in secondary oil recovery.

Selection of particular basins and related areas of thick sedimentary accumulations for geothermal-resource assessment was based primarily on evidence for temperature gradients greater than 25°C/km above the Lower Cretaceous and Paleozoic aquifers. Wherever possible, measured temperature gradients were used along with bottom-hole temperature data and lithologic information to assign average temperature gradients and to estimate aquifer temperatures in each area. In most areas, reservoir temperatures were assumed to increase linearly with depth, and a depth range over which reservoir temperatures meet the minimum-temperature criterion was established. For example, if the average vertical temperature gradient above a dipping aquifer is 35°C/km and the mean annual air temperature is 10°C, low-temperature geothermal resources would be assessed in this aquifer at temperatures of 45° to 90°C between depths of 1 and 2.3 km. Areas in which aquifer temperatures exceed 90°C at greater depths exist in most of our identified sedimentary basins.

Within much of the northern Great Plains province in Montana, Wyoming, North Dakota, and South Dakota, identified low-temperature geothermal resources exist in the Dakota and Madison aquifers at depths between approximately 0.5 and 3 km. These regional aquifer systems are recharged primarily in outcrop areas in the Black Hills and the Bighorn Mountains, and flow is continuous between the Powder River, Kennedy, and Williston basins. Hydraulic heads substantially above the land surface allow flowing wells to be completed in the Madison and Dakota aquifers; in parts of Montana and North Dakota, heads in the Madison aquifer are as much as 300 m above land surface. Although salinity generally increases with depth over most of the geothermal-resource area, the contents of total dissolved solids are less than 10,000 mg/L. In addition to usage in secondary oil recovery and potential usage for coal-slurry transmission, Madison aquifer water is currently being produced for geothermal applications at several places in South Dakota (for example, Martinez, 1981).

Abnormally high temperature gradients and heat flow exist in the Denver basin in western Nebraska and the Kennedy basin in South Dakota and north- central Nebraska. These conditions could reflect convective heat transfer associated with updip flow within a single aquifer and leakage of warm water from a deeper aquifer into a shallower one. Within the Denver basin in western Nebraska, temperature gradients as high as 60°C/km above the Dakota aquifer and conductive heat flows as great as 85 mW/m^2 have been measured (Gosnold and Eversoll, 1981). Theoretical analyses of heat and fluid flow suggest that ground water flowing updip in the Dakota aquifer at rates of about 1 m/yr could generate the measured thermal regime west of the Chadron-Cambridge arch. In north-central Nebraska and south-central South Dakota (east of the Chadron-Cambridge arch in the Kennedy basin), measured gradients above the Dakota aquifer exceed 100°C/km, and conductive heat flows of 100 mW/m^2 and higher have been determined. These data suggest that, in some parts of this area, warm water is leaking from the Madison into the Dakota aquifer through a subcrop connection (Schoon and McGregor, 1974; Gosnold and Eversoll, 1981).

In western Wyoming, identified low-temperature geothermal-resource areas are associated with both hot springs and sedimentary basins. Hot springs occur adjacent to major uplifts, in many places along small anticlinal folds on the flanks of the bordering mountain blocks (Breckenridge and Hinckley, 1978). In the Bighorn Basin, vertical flow over such anticlinal structures results in measured temperature gradients of 30° to 50°C/km above the Tensleep aquifer. In southern Wyoming, geothermal-resource areas are associated with regional uplifts, such as the Rock Springs and Rawlins uplifts; over most of the adjacent basins, depths to aquifers in Cretaceous and older sedimentary rocks are so great that the temperature exceeds 90°C.

In parts of Kansas and Oklahoma, geothermal resources were assessed within carbonate rocks of the Arbuckle Group of Cambrian and Ordovician age. Identified areas occur within the Anadarko and Hugoton basins and along the Nemaha ridge, a major crustal fracture zone along which relatively high temperature gradients have been measured (fig. 4; Blackwell and Steele, 1981). The Arbuckle Group contains significant oil and gas reserves and has been used as a reservoir to dispose of industrial liquid waste and saline water produced in conjunction with hydrocarbon production (U.S. Environmental Protection Agency, 1974). The Arbuckle contains no freshwater within the low-temperature geothermal-resource area outlined in figure 14.

Along the Balcones-Ouachita structural trend, as outlined by Woodruff and Caran (1981) in central Texas, the buried Ouachita Mountains are covered by a southeastward-thickening wedge of Mesozoic and Cenozoic sedimentary rocks. Cretaceous rocks form major stratigraphically controlled thermal aquifers (Woodruff and McBride, 1979). Two thermal regimes are postulated along the Balcones-Ouachita trend: A cooler, fresher water regime resulting from water moving downdip from recharge zones west of the thermal areas, and a warmer, more saline regime controlled by updip migration of water from deeper parts of the Gulf of Mexico coastal embayment. Five counties were identified as having low-temperature geothermal resources in Cretaceous sandstone aquifers. Additional resources may exist along the Balcones-Ouachita trend, but the data do not permit their delineation as identified low-temperature geothermal-resource areas.

In western Arkansas, identified low-temperature geothermal resources occur in areas of thermal springs and within coastal-plain sediment. Thermal springs in the Ouachita province, including those at Hot Springs National Park and Caddo Gap, are associated with tightly folded and thrust-faulted rocks. Studies by Bedinger and others (1979) and Steele and Wagner (1981) indicated that chemical compositions are similar in all the springs in this province and suggested that circulation systems feeding the springs occur largely in silica-rich sandstone and chert formations. Little is known, however, about the configuration of associated low-temperature geothermal reservoirs in these areas. In southwestern Arkansas, brines containing more than 4,000 mg/L bromide ion are present over an area of about 3,000 km^2 (Collins, 1974; Carpenter and Trout, 1978). Wells in this area produce hypersaline water from a highly permeable 20-m-thick oolitic limestone near the top of the Jurassic Smackover Formation. Low-temperature geothermal resources have been identified in seven fields containing brines with temperatures between 70° and 90°C at depths of 1.7 to 2.1 km. The Smackover Formation dips south, and in northern Louisiana and eastern Texas, temperatures in the formation are above our upper limit of 90°C.

In other parts of the Central United States, regional aquifers are known to exist within sedimentary basins or beneath coastal plains but were not identified as containing low-temperature geothermal resources. In such areas, either the depth of the aquifer is too shallow, or the corresponding temperature gradient is less than 25°C/km. Areas of relatively low thermal gradient (see fig. 5) occur in western Texas, Minnesota, Iowa, and Missouri. Low-temperature geothermal-resource areas may exist within the Gulf of Mexico coastal embayment in southeastern Texas and Louisiana, where temperature gradients are generally greater than 25°C/km and upward leakage of higher temperature brines from underlying geopressured zones may be occurring, as suggested by Sammel (1979). Because of the absence of data on specific reservoirs, this area is assumed to contain undiscovered low-temperature geothermal resources.

LOW-TEMPERATURE GEOTHERMAL-RESOURCE AREAS IN THE EASTERN UNITED STATES

Most of the Eastern United States is characterized by lower than average heat flow and by rocks of moderate to high thermal conductivity (crystalline rocks and quartz-rich sedimentary rocks). This combination of features limits the areas where low-temperature geothermal resources are likely to be found. As shown in figure 15, thermal waters meeting our minimum-temperature criterion were identified in two geologic settings—the Appalachian Mountains (in the Valley and Ridge, Blue Ridge, Piedmont, and New England geologic provinces) and the Atlantic Coastal Plain. The existing data base is small owing to limited exploration; future exploration may result in the identification of additional low-temperature geothermal resources in the Eastern United States.

Atlantic Coastal Plain

A sequence of nearly flat lying sedimentary rocks, ranging in age from Late Jurassic to Holocene, overlies metamorphic and igneous basement rocks beneath the Atlantic Coastal Plain (Brown and others, 1972, 1979). The sedimentary sequence generally thickens to the east, and its greatest thickness lies off shore. In the course of exploration for geothermal resources, more than 50 holes, drilled to depths of at least 300 m, have been used to determine heat flow and temperature gradient along the Atlantic Coastal Plain from New Jersey to Georgia (Lambiase and others, 1980). These widely spaced holes indicate that heat transfer through the sedimentary section is dominated by conduction and that convective heat transfer is restricted to near-surface zones of moderate vertical permeability. The available information was used to calculate the temperature at the top of bedrock (Lambiase and others, 1980), in order to determine areas that meet our minimum-temperature criterion. These areas have a thickness of sedimentary rock greater than 1 km and a moderate heat flow in the range 63-79 mW/m^2. At depths greater than 1 km, Cretaceous marine and continental sedimentary rocks with a significant shale content and a low thermal conductivity provide an increased temperature gradient. Water-saturated discontinuous sand lenses within these Lower Cretaceous sedimentary rocks are potential geothermal reservoirs.

Along the Atlantic Coastal Plain, four areas in Virginia and two areas in North Carolina have been identified as containing low-temperature geothermal resources. In each area, temperature gradients exceed 30°C/km, and the reservoir size was estimated from the inferred lithology of the basement rocks. Gravity and magnetic maps of the Atlantic Coastal Plain indicate that silicic plutonic rocks may underlie the geothermal-resource areas, and Costain and others (1980) suggested that radiogenic heat production in these rocks is the source of the anomalous temperature gradients and heat flow. On the basis of this model, the areas in Virginia were estimated to cover 50 km^2 each, and the areas in North Carolina 90 km^2 each. Schubert and Johnson (1980) suggested that geothermal-resource areas in this part of the Coastal Plain are larger and not restricted to zones over radiogenic plutons; however, evidence of lower heat flow and temperature gradients in wells between the identified areas indicate that the geothermal-resource areas are not regional in scale.

Appalachian Mountains

Thermal springs in the Eastern United States are associated with fault and fracture zones in several provinces of the Appalachian Mountains. Early descriptions of these springs dealt with their therapeutic and recreational values (Moorman, 1867; Crook, 1899; Fitch, 1927). Despite some inaccuracies in reported spring locations and characteristics, comparisons of these descriptions with more recent data indicate some changes in flow rate and temperature over time. Recent chemical analyses, available for most major springs in the Appalachian Mountains (Hobba and others, 1976, 1979), were used in this assessment.

The locations of these springs are controlled mostly by the structural setting and, to a lesser extent, by lithology. The springs occur in areas of steeply dipping folded rocks that are transected by nearly vertical east-west-trending fracture zones. Correlation of springs with topographic lows, or gaps, apparently results from the fact that easily eroded areas correspond to zones containing many fractures, which, in turn, provide the increased vertical permeability needed to establish a hydrothermal-convection system. The warm springs in the Appalachians that were considered in this assessment issue from sandstone or carbonate rocks exposed in the steeply dipping limbs of anticlinal folds (Hobba and others, 1979). Chemical analyses of the warm-spring waters issuing from carbonate rocks exhibit consistently low concentrations of dissolved silica and high concentrations of magnesium and calcium, which indicate that the flow of warm water is restricted to the carbonate rocks. Analyses of waters from springs issuing from fractured sandstone show higher concentrations of dissolved silica and lower concentrations of magnesium and calcium, which indicate that flow is restricted to the sandstone beds.

Geochemical considerations suggest that reservoir temperatures are not substantially higher than the measured surface temperatures at most eastern thermal springs; observed temperatures range from 18° to 41°C. The occurrence of these springs in areas of average heat flow and relatively low temperature gradients (Costain and others, 1976; Perry and others, 1979) indicates that the depths of hydrothermal circulation are generally between 1 and 3 km. A standard reservoir volume of 1 km^3 was assumed for each spring because of an absence of data on actual reservoir configurations.

Sedimentary Basins

Three large sedimentary basins (dashed lines, fig. 15) in parts of the Appalachian basin (in the Appalachian Plateaus geologic province) centered in western Pennsylvania may contain low-temperature geothermal resources because the basin is deep and contains a thick sequence of Devonian shale of low thermal conductivity. Average measured temperature gradients to a depth of 2 km range from 25° to 32°C/km in the region (fig. 5), although data are unavailable with which to delineate productive aquifers beneath the Devonian shale. Consequently, only undiscovered geothermal resources are estimated here for the Appalachian basin.

In the Michigan and Illinois basins, temperature gradients measured in deep wells are less than 25°C/km. Gradients greater than 30°C/km reported for some wells less than 1 km deep appear to be in error (Vaught, 1980a, b). The relatively low gradients in these basins apparently reflect low heat flow and the absence of thick accumulations of sediment of low thermal conductivity. Even though future exploration or adoption of a minimum-temperature criterion different from that used in this assessment could result in identification of aquifers in these basins containing low-temperature waters acceptable for energy development, no identified or undiscovered low-temperature geothermal-resource areas in these basins are included in this assessment.

CALCULATIONS OF ACCESSIBLE RESOURCE BASE, RESOURCE, AND BENEFICIAL HEAT

The mean accessible resource base for each identified low-temperature geothermal reservoir in the Central and Eastern United States was calculated from equation 2 of Sorey, Nathenson, and Smith (this volume). Estimates of the minimum, maximum, and most likely values for reservoir area, thickness, and temperature define the probability densities and mean values for these quantities, and the mean and standard deviation for the accessible resource base. For low-temperature geothermal-resource areas in category 1 (table 3), which includes isolated thermal springs in the northern Great Plains, Wyoming Basins, and Ouachita provinces and the Appalachian Mountains, a mean reservoir volume of 1.0 km^3 was assumed. For low-temperature geothermal-resource areas within large sedimentary basins (category 3), variations in temperature, salinity, and hydrologic properties necessitated division of the total reservoir areas into subareas to improve the accuracy in estimating stored and recoverable thermal energy.

Methods used to calculate the resource in each identified low-temperature geothermal reservoir are discussed by Sorey, Nathenson, and Smith (this volume). For low-temperature geothermal-resource areas in category 1, a recovery factor of 0.25 was applied to the accessible resource base to obtain the resource estimate. For identified low-temperature geothermal-resource areas in other categories, resource determinations involve estimates of the number of production wells each reservoir can support over a period of 30 years in the absence of fluid injection. A development plan is assumed, consisting of evenly spaced wells producing at 31.5 L/s for 30 years, with a cumulative drawdown at the center of the reservoir of 152 m. The number of production wells is given by the reservoir area divided by the optimum area per well ($\underline{a}_w$) for this development plan.

Estimates of the minimum, maximum, and most likely values of $\underline{a}_w$ were obtained from the well-spacing curves in figure 10, which relate optimum area per well to reservoir area and transmissivity. Most likely values of $\underline{a}_w$ correspond to estimates of the most likely values of transmissivity; minimum and maximum values of $\underline{a}_w$ correspond to estimates of the maximum and minimum values of transmissivity, respectively. Reservoirs in identified low-temperature geothermal-resource areas within sedimentary basins and beneath coastal plains are assumed to be bounded by leaky confining shale beds, for which the curves in figure 10 apply.

Most of the data on the hydrologic properties of regional aquifers within the sedimentary basins assessed in this volume were obtained from reports prepared by the U.S. Geological Survey as part of a program of regional-aquifer-system analysis. However, the degree of detail and the accuracy of the hydrologic information available for different areas vary considerably. The best data set for sedimentary basins exists for the Madison and Dakota aquifers in the northern Great Plains, where a large fraction of our estimated low-temperature geothermal resource occurs (Woodward-Clyde Consultants, 1980; MacCary and others, 1981; Downey, 1982). In other sedimentary basins for which data on aquifer transmissivity and confining-bed properties are more limited, it was necessary to rely partly on comparisons with similar formations in the northern Great Plains to obtain estimates of the required hydrologic parameters.

For aquifers in Cretaceous sand within the Balcones-Ouachita structural trend in Texas, adequate data exist from well tests to assign transmissivity values to each reservoir. For low-temperature geothermal-resource areas along the Atlantic Coastal Plain, results of well tests and laboratory measurements on cores from a 1-km-deep well drilled near Cambridge, Maryland (Harold Meisler, unpub. data, 1981), were used to assign a transmissivity value to each reservoir, assuming a composite reservoir thickness of 30 m in each area.

For low-temperature geothermal-resource areas that were divided into subareas because of variations in reservoir properties, separate estimates of the accessible resource base, resource, and beneficial heat were obtained for each subarea. In addition to reservoir area and transmissivity, two factors influenced the choice of values of $\underline{a}_w$ for each resource area or subarea: (1) For subareas that are connected hydraulically to adjacent subareas, the total connected reservoir area was used with the curves in figure 10 to estimate $\underline{a}_w$; (2) for subareas forming narrow bands around the margins of certain basins and bounded by permeable regions at temperatures above and below the minimum-temperature criterion, values of $\underline{a}_w$ were adjusted downward by a factor of 2 to reflect less interference between wells than would occur in square reservoirs with the same area.

Mean values of reservoir area, area per well, and temperature were used in equation 4 of Sorey, Nathenson, and Smith (this volume) to calculate the mean resource for each identified low-temperature geothermal-resource area. The correction factor ($\underline{k}$) in this equation accounts for the likelihood that these reservoirs are not uniformly permeable and may contain regions of low-permeability rock. Minimum, maximum, and most likely values of $\underline{k}$ are 0, 1.0, and 0.5, respectively. An example that demonstrates the need to consider such a correction factor is provided by the results of drilling and testing wells completed in the Madison aquifer in the Powder River basin of Wyoming. Wells that penetrate cavities associated with the paleokarst system developed near the top of the limestone show relatively high transmissivity and production, whereas wells that do not intercept cavities show relatively low transmissivity and production (Kelly and others, 1981).

The amount of a resource that can be utilized in applications on the surface is termed the "beneficial heat." Beneficial-heat estimates for each identified low-temperature geothermal reservoir were obtained from equations 5 and 6 of Sorey, Nathenson, and Smith (this volume). Equation 6 is based on an empirically derived relation between reservoir temperature and the temperature drop as energy is extracted from the geothermal water. The lower reservoir-temperature limit for beneficial-heat calculation is taken as 25°C for all resource areas.

Units of megawatts thermal for 30 years are used to report beneficial heat estimates, whereas both accessible resource base and resource are reported in units of 10^{18} J. For comparison, 1 MW_t for 30 years equals 9.461×10^{14} J. The use of units of megawatts thermal for 30 years for beneficial heat facilitates comparisons with equivalent thermal-energy requirements from other fuels.

ESTIMATES OF IDENTIFIED ACCESSIBLE RESOURCE BASE, RESOURCE, AND BENEFICIAL HEAT

Tables 7 and 8 list the results of our quantitative assessment of low-temperature geothermal resources in the Central and Eastern United States. Estimates of reservoir characteristics and thermal energy are listed by State; for each State, separate totals are given for areas within which a particular reservoir is continuous and for groupings of thermal springs within the same geologic province. For sedimentary basins that were subdivided into subareas, the area-weighted mean reservoir temperature is given along with the total mean reservoir area and the mean reservoir thickness; multiplication of these estimates yields the listed value for mean accessible resource base. For groupings of thermal springs, the range in mean reservoir temperature among the spring areas is listed, but no entry is made for reservoir area and thickness because a standard mean reservoir volume of 1.0 km^3 was assumed in each case. For all low-temperature geothermal-resource areas, the standard deviation for each estimate of the accessible resource base is specified.

Table 7.--Reservoir parameters and thermal energies of identified low-temperature geothermal resources in the Central United States

[All means and standard deviations calculated analytically. Values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value. Map numbers refer to locations in figure 13. Categories of low-temperature geothermal-resource areas are listed in table 3. For areas in category 1, a mean reservoir volume of 1.0 km^3 was assumed, and the resource was calculated as 25 percent of the accessible resource base. Resource and beneficial heat were calculated from equations 4 and 6 (Sorey, Nathenson, and Smith, this volume). Beneficial heat is assumed to be zero for reservoir temperatures less than or equal to 25,C. TDS, total dissolved solids: (1) Less than 1,000 mg/L; (2) 1,000 to 10,000 mg/L; (3) 10,000 to 50,000 mg/L; (4) more than 50,000 mg/L. Q, flow rate; T, reservoir transmissivity; G, average temperature gradient above reservoir; a_w, mean area per well]

Map No.	Geologic province / Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial Heat (MW_t for 30 yr)	Comments
	ARKANSAS								
	Ouachita province								
18	Isolated systems--------	1	--	--	--	0.151±0.031	0.038	7.4	4 systems, springs (25°-35°C); TDS (1).
18	Hot Springs National Park	1	--	--	--	.123±0.050	--	--	1 system, 47 spring orifices (58°-66°C); Q=40 L/s.
	Gulf Coastal Plain province								
19	Brine fields------------	4	89	60	.020	.23±0.015	.054	29	Permeable limestone reservoir in the Smackover Formation; TDS (4), G=33°C/km.
	COLORADO								
	Great Plains province								
14	Isolated systems--------	1	--	--	--	0.32±0.090	0.080	38	3 systems, springs (52°-58°C) in Washakie-Sand Wash basin; TDS (1,2), Q=0.8-10 L/s.
14	Washakie-Sand Wash basin	3	60	1,170	.152	21±4.3	.124	61	Reservoir in sandstone of the Dakota aquifer; TDS (2,3), G=30-35°C/km, T=0.001 m^2/s, a_w=26 km^2.
7	Isolated systems--------	1	--	--	--	.183±0.052	.046	16.5	3 systems, springs (25°-48°C) in Canon City embayment-Pueblo area; TDS (2), Q=0.3-1.6 L/s.
7	Canon City embayment----	3	40	260	.091	1.54±0.38	.024	9.2	Reservoir in sandstone of the Dakota aquifer; TDS (2), G=45°C/km, T=0.001 m^2/s, a_w=16.4 km^2.
6	Denver basin------------	3	77	56,000	.091	660±81	2.4	1,240	Reservoir in sandstone of the Dakota aquifer; TDS (2,3), G=35°C/km, T=0.001 m^2/s, a_w=70 km^2.
	KANSAS								
	Great Plains province								
6	Denver basin------------	3	40	2,900	0.091	17.4±3.0	0.064	24	Reservoir in sandstone of the Dakota aquifer; TDS (2,3), G=45°C/km, T=0.001 m^2/s, a_w=70 km^2.
8 9	Anadarko basin---------- Nemaha ridge	3	71	65,000	.173	1,640±260	3.2	1,660	Reservoir in carbonate rocks of the Arbuckle aquifer; TDS (4), G=30-40°C/km, T=0.001 m^2/s, a_w=70 km^2.
	MONTANA								
	Great Plains province								
1 2 3 4	North-central Montana--- Central Montana Williston basin Powder River basin	3	67	177,000	0.37	8,900±530	11.6	6,000	Reservoir in carbonate rocks of the Madison aquifer; TDS (2,3,4), G=30-35°C/km, T=0.005-0.02 m^2/s, a_w=49 km^2.
1 2 3 4	North-central Montana--- Central Montana Williston basin Powder River basin	3	61	115,000	.091	1,260±163	4.6	2,300	Reservoir in sandstone of the Dakota aquifer; TDS (2,3,4), G =30-40°C/km, T=0.001 m /s) a_w=70 km^2,

Map No.	Geologic province / Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial Heat (MW_t for 30 yr)	Comments
	Wyoming Basins province								
10	Big Horn Basin----------	3	40	620	.122	4.9±1.37	.037	14	Reservoir in sandstone of the Tensleep aquifer; TDS (2), G=35°C/km, T=0.001 m^2/s, a_w=26 km^2.
	NEBRASKA								
	Great Plains province								
6 5	Denver basin------------ Kennedy basin	3	50	112,000	0.091	930±64	3.4	1,550	Reservoir in sandstone of the Dakota Group; TDS(2,3), G=45-80°C/km, T=0.001 m^2/s, a_w=70 km^2.
	NORTH DAKOTA								
	Great Plains province								
3	Williston basin---------	3	63	128,000	0.366	5,800±470	7.5	3,800	Reservoir in carbonate rocks of the Madison aquifer; TDS (3,4), G=30-35°C/km, T=0.005-0.02 m^2/s, a_w=49 km^2.
3	Williston basin---------	3	62	57,000	.091	628±75	2.3	1,150	Reservoir in sandstone of the Dakota aquifer; TDS (2,3,4), G=30-40°C/km, T=0.001 m^2/s), a_w=70 km^2.
	OKLAHOMA								
	Great Plains province								
8 9	Anadarko basin---------- Nemaha ridge	3	87	62,000	0.31	3,600±620	3.9	2,100	Reservoir in carbonate rocks of the Arbuckle aquifer; TDS (4), G=30-35°C/km, T=0.001 m^2/s, a_w=70 km^2.
	SOUTH DAKOTA								
	Great Plains province								
3 5	Williston basin--------- Kennedy basin	3	51	86,000	0.183	1,490±154	3.9	1,790	Reservoir in carbonate rocks of the Madison aquifer; TDS (1,2), G=30-40°C/km, T=0.005-0.01 m^2/s, a_w=49 km^2.
3 5	Williston basin--------- Kennedy basin	3	50	55,000	.061	310±57	1.76	800	Reservoir in sandstone of the Dakota aquifer; TDS (2), G=35-80°C/km, T=0.001 m^2/s, a_w=54-70 km^2.
17	Isolated systems--------	1	--	--	--	.083±0.021	.021	2.5	3 systems, springs (22°-31°C) in the Black Hills; TDS (2), Q=57-670 L/s.
	TEXAS								
	Gulf Coastal Plain province								
20	Hunt County-------------	4	52	320	0.046	1.39±0.30	0.033	15.3	Reservoir in Woodbine Sands aquifer; TDS (1,2), G=37°C/km, T=0.001 m^2/s, a_w=22 km^2.
21	Navarro County----------	4	75	1,170	.091	16.7±2.6	.098	52	Reservoir in Woodbine Sands aquifer; TDS (1,2), G=48°C/km, T=0.001 m^2/s, a_w=44 km^2.
22	Limestone County--------	4	51	2,400	.076	17.1±3.2	.093	42	Reservoir in Woodbine Sands aquifer; TDS (1,2), G=43°C/km, T=0.001 m^2/s, a_w=57 km^2.
23	Falls County------------	4	64	1,230	.152	24±4.3	.176	89	Reservoir in Houston-Trinity Sands aquifer; TDS (1,2), G=51°C/km, T=0.003 m^2/s, a_w=22 km^2.
24	Caldwell County---------	4	63	1,290	.152	24±3.7	.182	92	Reservoir in Houston-Trinity Sands aquifer; TDS (1,2), G=43°C/km, T=0.003 m^2/s, a_w=22 km^2.

Map No.	Geologic province Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial Heat (MW_t for 30 yr)	Comments
				WYOMING					
	Great Plains province								
4	Isolated system---------	1	--	--	--	0.071±0.032	0.0178	7.2	1 system, spring (42°C) in Powder River basin; TDS (1), Q=50 L/s.
6	Isolated system---------	1	--	--	--	.035±0.0169	.0087	1.38	1 system, spring (28°C) in Denver basin; TDS (1), Q=1.4 L/s.
4	Powder River basin------	3	69	27,000	.152	580±64	4.1	2,100	Reservoir in carbonate rocks of the Madison aquifer; TDS (1,2), G=30-35°C/km, T=0.005-0.02 m^2/s, a_w=27 km^2.
4	Powder River basin------	3	70	24,000	0.091	310±55	2.1	1,070	Reservoir in sandstone of the Dakota aquifer; TDS (2), G=30-40°C/km, T=0.001 m^2/s, a_w=39 km^2.
6	Denver basin------------	3	80	8,800	.091	136±23	.90	480	Reservoir in sandstone of the Dakota aquifer; TDS (2), G=35°C/km, T=0.001 m^2/s, a_w=39 km^2.
	Wyoming Basins province								
10	Isolated systems--------	1	--	--	--	.33±0.090	.083	33	5 systems, springs (24°-64°C) in the Big Horn Basin, TDS (1,2), Q=25-270 L/s.
11	Isolated systems--------	1	--	--	--	.33±0.071	.082	28	6 systems, spring (24°-53°C) in the Wind River basin; TDS (1,2), Q=0.3-35 L/s.
13	Isolated systems--------	1	--	--	--	.35±0.103	.086	42	3 systems, springs (31°-87°C) near the Rawlins uplift and Shirley Basin; TDS (1,2), Q=6.3-140 L/s.
10	Big Horn Basin----------	3	43	6,000	.122	53±6.5	.39	158	Reservoir in sandstone of the Tensleep aquifer; TDS (2), G=30-60°C/km, T=0.001 m^2/s, a_w=26 km^2.
11	Wind River basin--------	3	65	7,300	.122	115±29	.86	430	Reservoir in sandstone of the Tensleep aquifer; TDS (2), G=35°C/km, T=0.001 m^2/s), a_w=26 km^2.
12	Rock Springs uplift-----	3	65	2,800	.152	56±12.4	.167	84	Reservoir in sandstone of the Dakota aquifer; TDS (2,3), G=35°C/km, T=0.001 m^2/s, a_w=52 km^2.
13 14 15 16	Rawlins uplift---------- Washakie-Sand Wash basin Shirley Basin Laramie basin	3	65	6,700	.152	133±32	.53	270	Reservoir in sandstone of the Dakota aquifer; TDS (2,3), G=35°C/km, T=0.001 m^2/s, a_w=40 km^2.

In the "Comments" to tables 7 and 8, additional information used to make estimates of the accessible resource base and resource is listed. For low-temperature geothermal-resource areas within sedimentary basins and beneath coastal plains, this information includes the formation name, the range in total dissolved solids, the range in assumed transmissivity, the range in average temperature gradient within the sedimentary section above each reservoir, and the range in mean values used for the area per well. For low-temperature geothermal-resource areas in category 1, the number of springs and the range in flow rate are also listed. Most of the source data and the results of intermediate calculations have been given by Reed and others (1983).

Mean values of the total resource and beneficial heat for each reservoir also represent summations over all subareas within each low-temperature geothermal-resource area. Corresponding standard deviations for the resource and beneficial heat are not listed because they were calculated for only a few individual reservoirs. Typical values of the standard deviations for the resource and beneficial heat in thermal-spring areas are 70 percent of the corresponding mean values. For low-temperature geothermal-resource areas within sedimentary basins and beneath coastal plains, the standard deviations for the resource and beneficial heat are about 50 percent of the corresponding means for undivided areas and 20 percent of the corresponding means for areas that were subdivided. These calculations show that the

Table 8.—Reservoir parameters and thermal energies of identified low-temperature geothermal resources in the Eastern United States

[All means and standard deviations calculated analytically. Values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value. Map numbers refer to locations in figure 13. Categories of low-temperature geothermal-resource areas are listed in table 3. For areas in category 1, a mean reservoir volume of 1.0 km^3 was assumed, and the resource was calculated as 25 percent of the accessible resource base. Resource and beneficial heat were calculated from equations 4 and 6 (Sorey, Nathenson, and Smith, this volume). Beneficial heat is assumed to be zero for reservoir temperatures less than or equal to 25,C. TDS, total dissolved solids: (1) less than 1,000 mg/L; (2) 1,000 to 10,000 mg/L; (3) 10,000 to 50,000 mg/L; (4) more than 50,000 mg/L. Q, flow rate; T, reservoir transmissivity; G, average temperature gradient above reservoir; a_w, mean area per well]

Map No.	Geologic province / Geothermal area	Category	Mean reservoir temperature (°C)	Mean reservoir area (km^2)	Mean reservoir thickness (km)	Mean accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial Heat (MW_t for 30 yr)	Comments
	GEORGIA								
	Piedmont province								
37	Isolated system--------	1	--	--	--	0.050±0.020	0.0124	3.7	1 system, spring (34°C); TDS (1), Q=57 L/s.
	MASSACHUSETTS								
	New England Province								
31	Isolated system--------	1	--	--	--	0.0156±0.0063	0.0039	0.0	1 system, spring (21°C); TDS(1),
	NEW YORK								
	New England province								
32	Isolated system--------	1	--	--	--	0.0183±0.0074	0.0046	0.0	1 system, spring (22°C); TDS (1), Q=6.7 L/s.
	NORTH CAROLINA								
	Blue Ridge province								
36	Isolated system--------	1	--	--	--	0.068±0.028	0.0170	6.6	1 system, spring (44°C); TDS (1), Q=0.4 L/s
	Atlantic Coastal Plain province								
29	Stumpy Point-----------	4	81	90	.030	.47±0.112	.070	38	Reservoir in Lower Cretaceous sandstone aquifers; TDS (3), G=37°C/km, T=0.002 m^2/s, a_w=5.2 km^2.
30	Englehard--------------	4	76	90	.030	.44±0.104	.065	35	Reservoir in Lower Cretaceous sandstone aquifers; TDS (3), G=37°C/km, T=0.002 m^2/s, a_w=5.2 km^2.
	VIRGINIA								
	Valley and Ridge province								
35	Isolated systems-------	1	--	--	--	0.31±0.044	0.077	13.2	10 systems, springs (22°-40°C), TDS (1), Q=3.8-200 L/s.
	Atlantic Coastal Plain province								
25	Oak Hall---------------	4	66	50	.030	.20±0.049	.047	24	Reservoir in Lower Cretaceous sandstone aquifers; TDS (3), G=31°C/km, T=0.002 m^2/s, a_w=3.3 km^2.
26	Wallops Island---------	4	77	50	.030	.24±0.059	.057	30	Reservoir in Lower Cretaceous sandstone aquifers; TDS (3), G=31°C/km, T=0.002 m^2/s, a_w=3.3 km^2.
27	Tasley-----------------	4	61	50	.030	.181±0.044	.042	21	Reservoir in Lower Cretaceous sandstone aquifers; TDS (3), G=31°C/km, T=0.002 m^2/s, a_w=3.3 km^2.
28	Smith Point------------	4	46	50	.030	.121±0.030	.028	12.2	Reservoir in Lower Cretaceous sandstone aquifers; TDS (3), G=31°C/km, T=0.002 m^2/s, a_w=3.3 km^2.
	WEST VIRGINIA								
	Valley and Ridge province								
	Isolated systems-------	1	--	--	--	0.089±0.0162	0.022	0.0	5 systems, springs (20°-23°C), TDS (1), Q=6.3-100 L/s.
33	Northeast springs								
34	Southeast springs								

standard deviations for resource and beneficial heat represent a larger fraction of the corresponding mean values than do those for the accessible resource base, a result that reflects the larger uncertainty in recoverable-energy estimates. This degree of uncertainty decreases, however, as the number of subareas or the number of individual thermal-spring areas grouped together increases. Similarly, the degree of uncertainty associated with the mean values of nationwide resource and beneficial-heat totals is significantly less than that associated with the mean values of these quantities for individual reservoirs.

Resource estimates for low-temperature geothermal-resource areas with isolated thermal springs or wells (category 1) average about 0.04×10^{18} J. For comparison, the spring-flow rate that would yield this amount of thermal energy over a 30-year period is 160 L/s (at 45°C). With few exceptions, total flow rates at individual spring areas in the Central and Eastern United States are much less than 160 L/s, and the resource estimates listed in tables 7 and 8 are larger than the energy that could be obtained by tapping only the natural spring flow.

Resource estimates for sedimentary basins are significantly larger than corresponding estimates for other types of low-temperature geothermal-resource areas. For example, for the Madison aquifer in eastern Montana, the total resource is 11.6×10^{18} J. Although this value represents a recovery of only about 0.1 percent of the stored thermal energy, approximately 1,800 wells spaced at distances of about 7 km would be required to realize this resource estimate. Obviously, no single development scheme would be considered on such a scale. An alternative development, however, involving well fields with closer spacings near each population center could result in similar total energy recovery. To accomplish this goal, well fields of 30 wells each would be required near approximately 60 towns located in the geothermal-resource area. Thus, the methods used in this assessment appear to yield realistic estimates of the thermal energy that could potentially be recovered from regional aquifers within sedimentary basins.

Tables 9 and 10 list the mean values and standard deviations of the total accessible resource base, resource, and beneficial heat for identified low-temperature geothermal-resource areas in the Central and Eastern United States; subtotals are listed for hydrothermal-convection and conduction-dominated systems. For resource and beneficial-heat estimates, subtotals are listed for three temperature ranges. The total resource in conduction-dominated systems of the Central and Eastern United States is 55×10^{18} J; 93 percent of this total is in thermal reservoirs at temperatures of 50° to 90°C. The mean value of the total resource in hydrothermal-convection systems is 0.60×10^{18} J; 34 percent of this total is in reservoirs at temperatures of 50° to 90°C. From the data listed in tables 7 and 8, it is clear that the dominant sources of low-temperature geothermal energy for areas east of the Rocky Mountains are regional aquifers within deep sedimentary basins in the Central United States. Although the thermal energy stored in such reservoirs is huge (27×10^{21} J), less than 1 percent of this energy is recoverable at the surface under the proposed

Table 9.—Summary of energies for identified low-temperature geothermal systems in the Central United States

[Systems in national parks are omitted. All means and standard deviations calculated by the Monte Carlo method. All values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

Type of system	Number of systems	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial heat (MW_t for 30 yr)
Hydrothermal convection				
Isolated Systems				
less than 50°C	---	---	0.25±0.038	73±16.3
50° to 70°C	---	---	.161±0.042	78±21
70° to 90°C	---	---	.046±0.30	25±17.0
Subtotal-----------	31	1.84±0.191	.46±0.064	176±32
Conduction dominated				
Sedimentary basins and coastal plains				
less than 50°C	---	---	4.3±0.78	1,630±330
50° to 70°C	---	---	32±3.3	15,800±1,640
70° to 90°C	---	---	19.0±2.5	10,300±2,100
Subtotal-------------	27	27,000±1,010	55±4.27	28,000±2,100
Total--------------------	58	27,000±1,010	55±4.27	28,000±2,100

Table 10.—Summary of energies for identified low-temperature geothermal systems in the Eastern United States

[Systems in national parks have been omitted. All means and standard deviations calculated by the Monte Carlo method. Values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

Type of system	Number of systems	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial heat (MW_t for 30 yr)
Hydrothermal convection				
Isolated Systems				
less than 50°C	---	---	0.138±0.022	24±6.5
50° to 70°C	---	---	---	---
70° to 90°C	---	---	---	---
Subtotal-----------	31	0.55±0.060	.138±0.022	24±6.5
Conduction dominated				
Coastal plains				
less than 50°C	---	---	.029±0.015	12.7±6.4
50° to 70°C	---	---	.096±0.035	48±17.4
70° to 90°C	---	---	.199±0.057	106±35
Subtotal-------------	6	1.63±0.175	.32±0.070	167±35
Total--------------------	25	2.2±0.150	.46±0.062	191±32

development plan. The total resource for the eastern region is significantly lower than for the central region, a difference that reflects an absence of exploration activity and the lower heat flow and higher thermal conductivity in most of the Eastern United States.

UNDISCOVERED GEOTHERMAL RESOURCES

Estimates of undiscovered low-temperature geothermal resources in the Central and Eastern United States were made for aquifers within some sedimentary basins and beneath coastal plains and for reservoirs associated with thermal-spring areas in the Appalachian Mountains. Although low-temperature geothermal energy may exist in these areas, additional information is needed to identify individual reservoirs and their characteristics. Favorable indications include measured or inferred temperature gradients greater than 25°C/km, thick sedimentary accumulations, evidence of upward leakage of thermal water in nearby areas, and geophysical evidence of radiogenic granitic intrusive bodies beneath aquifers.

Table 11 lists estimates of the undiscovered accessible resource base, resource, and beneficial heat for seven low-temperature geothermal-resource areas in the Central and Eastern United States. For each region, the basis for these estimates is a comparison of the reservoir areas and volumes considered favorable for the existence of low-temperature geothermal reservoirs with those of identified geothermal systems that are similar geologically. For sedimentary basins, undiscovered resources were estimated for many basins that also contain an identified low-temperature geothermal reservoir, and for the Appalachian basin in western Pennsylvania and the Raton basin in southeastern Colorado for which no corresponding estimates of the identified geothermal resource have been made. Estimates of the total undiscovered accessible resource base and resource in sedimentary basins are less than those for identified low-temperature geothermal resources within sedimentary basins and thus reflect the degree to which resource areas of this type can be delineated on the basis of existing data.

Undiscovered geothermal resources in the Balcones-Ouachita structural trend in Texas are estimated to be twice the identified resources. For the Gulf of Mexico coastal region in eastern Texas, Louisiana, and Mississippi, where temperature gradients (fig. 4) are greater than 35°C/km, resource areas totaling 12,000 km^2 were assumed in estimating undiscovered geothermal resources.

Geologic settings similar to those in identified warm-spring areas in the Appalachian Mountains occur elsewhere in each subprovince of this region. An extension of the valley-and-ridge style of folding also underlies the Champlain River valley in Vermont and New York. The absence of warm springs in nonmountainous areas of tightly folded rocks suggests that vertical fracture zones and hydraulic gradients imposed by topographic variations may be necessary for the occurrence of warm springs in the Appalachians. Undiscovered geothermal resources equal in magnitude to identified resources were estimated for the States where warm springs occur.

Table 11.--Estimates of undiscovered low-temperature geothermal resources in the Central and Eastern United States

[Values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

Resource area	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial heat (MW_t for 30 yr)
Central United States			
Denver basin	3,500	6.7	3,300
Raton basin[1/]	75	.34	174
Anadarko basin	1,900	5.0	2,700
Rawlins and Rock Springs uplifts; Washakie, Shirley, and Laramie basins	380	.70	350
Balcones-Ouachita structural trend	170	1.16	580
Gulf Coastal Plain[2/]	170	1.16	580
Eastern United States			
Atlantic Coastal Plain	4.9	.93	480
Appalachian Mountains	.56	.14	24
Appalachian basin[3/]	490	1.90	1,000
Total	6,700	18.0	9,200

1/ Estimates based on a total resource area of 2,100 km^2 containing aquifers in Cretaceous and Paleozoic sedimentary rocks, in comparison with resource areas in the Denver basin in Colorado.

2/ Estimates based on a total resource area of 12,000 km^2 dispersed within the area of 120,000 km^2 outlined in figure 13, in comparison with resource areas in the Balcones-Ouachita structural trend.

3/ Estimates based on a total resource area of 37,000 km^2 containing aquifers in Paleozoic sedimentary beneath Devonian shale, in comparison with resource areas in the Anadarko basin-Nemaha ridge in Kansas.

Along the Atlantic Coastal Plain, thick sediment and high temperature gradients are known to be present only in the areas of Stumpy Point, North Carolina, and the Delmarva Peninsula, Virginia. Undiscovered geothermal reservoirs were assumed to have more than 3 times the identified reservoir volume in each of those areas.

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Summary

By Marshall J. Reed

CONTENTS

ABSTRACT

This assessment of low-temperature geothermal resources in the United States presents a quantitative estimate of the energy available from identified and undiscovered reservoirs at temperatures less than 90°C. Changes in the world price of petroleum and the increasing price of natural gas have led to a growing interest in the use of low-temperature geothermal energy. Quantitative estimates made for the geothermal energy available in identified and undiscovered systems give an accessible resource base of $27x10^{21}$ J, a resource of $87x10^{18}$ J, and a beneficial heat of 42 GW_t for 30 years.

DISCUSSION

The principal source of thermal energy in the temperature range 10°-90°C within the United States is the burning of natural gas and No. 2 diesel oil; electrical resistance heating is also a common source of thermal energy in this temperature range. Changes in the world price of petroleum and the increasing price of natural gas have led to a growing interest in the use of low-temperature geothermal energy and have clearly indicated the need for an evaluation of low-temperature geothermal resources. Knowledge of the quantity, distribution, and potential of these resources is critical to their development. To determine these factors, the U.S. Geological Survey, with the support of the U.S. Department of Energy, has evaluated low-temperature (less than 90°C) geothermal resources in the United States on the basis of information available through April 1982. This assessment complements the earlier estimates of intermediate- and high-temperature geothermal resources by White and Williams (1975) and Muffler (1979).

The terminology and methodology used in this assessment make careful distinctions among the accessible resource base (energy stored in the ground), the resource (energy recoverable at the wellhead), and the beneficial heat (energy usable in a specific application). The resource, which is a factor of major significance in any assessment, is the quantity that can be most easily compared with other energy sources.

The accessible resource base for this assessment of low-temperature geothermal resources is restricted to the upper 10 km of the crust, as suggested by Muffler and Cataldi (1978). It is also constrained by a minimum-temperature criterion and by the requirement that the reservoirs be permeable (see Reed, "Introduction," this volume). Using this definition of accessible resource base, a total resource of $34x10^{21}$ J was calculated for identified and undiscovered low-temperature geothermal systems in the United States. From this energy in the Earth, a resource of $153x10^{18}$ J could be recovered in 30 years, and the resulting beneficial heat is 72 GW_t for 30 years.

THERMAL REGIMES

The discussion of heat flow, thermal conductivity, and temperature gradients in the United States identifies the thermal regimes within which low-temperature geothermal systems exist (Nathenson and others, this volume). Conductive heat transfer through rock is the dominant mechanism for the movement of thermal energy in the crust of the Earth. However, in parts of the crust where faults, fractures, or other high-permeability structures provide steeply dipping channels, warm water may move toward the surface, carrying thermal energy in hydrothermal-convection systems. The types of low-temperature geothermal systems have been divided into conduction dominated or hydrothermal convection, depending on the principal mode of heat transfer within them.

Maps of heat flow and thermal gradient (figs. 4, 5) show a systematic variation across the conterminous

United States that reflects differences in the underlying rocks and the level of tectonic and magmatic activity in different regions of the country. This assessment of low-temperature geothermal resources was conducted by dividing the country into western, central, and eastern regions so as to group the geothermal systems by similar geologic environments that reflect regional differences in the thermal structure of the crust. The map of temperature gradients (fig. 5) was combined with available geologic data to provide a basis for estimates of the range in depth for some identified geothermal systems and of the probable extent of undiscovered geothermal systems.

METHODOLOGY OF ASSESSMENT

The accessible resource base in low-temperature geothermal reservoirs was estimated by the volumetric method used previously for hydrothermal-convection systems greater than 90°C (Brook and others, 1979). Geothermal reservoirs identified only by isolated hot springs or thermal wells, or from limited subsurface information, were assigned an estimated volume of 1 km^3. New methods have been developed to calculate the resource and beneficial heat available from low-temperature geothermal reservoirs (Sorey, Nathenson, and Smith, this volume). The method for calculating the resource is based on a production model with equally spaced wells, producing at 31.5 L/s, for a 30-year period with a cumulative drawdown of 152 m. This production model assumes a natural recharge of water in the system as the reservoir pressure declines, but does not include injection of produced water after thermal energy has been extracted. Well spacings that result in the allowable drawdown are a function of the reservoir area and hydrologic properties. With this method of resource calculation, the proportion of the accessible resource base that can be recovered from a reservoir in 30 years ranges from a minimum of 0.001 for regional aquifers in large sedimentary basins (Sorey, Reed, and others, this volume) to a maximum of 0.25 for small-area reservoirs. The upper limit of the recovery factor, 0.25, from the accessible resource base is derived from the heat-sweep analysis of Nathenson and Muffler (1975).

The estimate of beneficial heat is based on an empirical relation derived from the characteristics of several low- and intermediate-temperature geothermal installations. This relation indicates that the usable temperature difference is approximately 60 percent of the difference between the reservoir temperature and 25°C (see Sorey, Nathenson, and Smith, this volume, equations 5 and 6).

WESTERN UNITED STATES

Cenozoic tectonic activity in the Western United States created many faults with a high vertical permeability that commonly have hydrothermal-convection systems associated with them. Little information is available on the reservoirs in 927 isolated hydrothermal-convection systems; these systems are here assigned a standard volume of 1 km^3. Six hydrothermal-convection systems in national parks were excluded from the calculations of resource and beneficial heat because they are not available for development; the resource for the 921 remaining reservoirs was calculated by using a recovery factor of 0.25 for a period of 30 years. Enough information is available for 157 systems in the Western United States to estimate the area of each reservoir individually. The resource for these areas was calculated by using the equally-spaced production-well method of Sorey, Nathenson, and Smith (this volume). Of these larger systems, most are hydrothermal-convection systems, but one in the Salton Trough province of California and eight in the Columbia Plateaus province of Washington are conduction-dominated geothermal systems. The nine conduction-dominated systems have nearly horizontal zones of high permeability where water moving laterally absorbs thermal energy from the surrounding rock.

For the 1,075 hydrothermal-convection systems identified by Mariner and others (this volume), an estimated resource of 30×10^{18} J could be recovered in 30 years from an accessible resource base of 200×10^{18} J. From the nine reservoirs in conduction-dominated systems, an estimated resource of 1.19×10^{18} J could be recovered in 30 years from an accessible resource base of 102×10^{18} J. The beneficial heat from all identified systems in the Western United States is 13.7 GW_t for 30 years from a total identified resource of 31×10^{18} J and a total identified accessible resource base of 310×10^{18} J (table 6).

The estimate of the undiscovered accessible resource base has a much greater uncertainty than that of the identified accessible resource base because so little information is available. Some identified geothermal reservoirs may be larger in volume than estimated in this assessment. An undiscovered component of energy in identified systems and the energy contained in undiscovered systems were estimated by geologic province in an attempt to partly reduce this uncertainty. Undiscovered systems were considered to be similar in geologic and hydrologic characteristics to the identified systems in the same province (table 5). The total accessible resource base, including identified and undiscovered components, for low-temperature geothermal resources in the Western United States is 790×10^{18} J.

CENTRAL UNITED STATES

The Central United States has had little tectonic activity during the Cenozoic, and few hydrothermal-convection systems are found there. The heat flow map (fig. 4) shows that the central region is transitional between the below-average to average (61 mW/m^2) heat flow in the East and the high heat flow in the West. The existence of low-temperature geothermal reservoirs in the central region depends primarily on the occurrence of rocks with low thermal conductivity. The Central United States includes many large basins containing thick sequences of Paleozoic and Mesozoic sedimentary rocks. Oil and gas exploration wells have been drilled into most of these basins, and several aquifers have been found that contain low-temperature geothermal water. Two very extensive conduction-dominated systems have been identified in this assessment (Sorey, Reed, and others, this volume): The Madison aquifer in Mississippian limestone and the Dakota aquifer in Cretaceous sandstone, which both have great areal extent within the basins of the northern and central Great Plains province. These large-area aquifers dominate the energy estimates for low-temperature geothermal resources in the United States.

An estimated resource of 55×10^{18} J could be recovered in 30 years from an accessible resource base of 27×10^{21} J in the reservoirs of the 23 conduction-dominated geothermal systems identified in the Central United States, and an estimated resource of 0.46×10^{18} J could be recovered in 30 years from an accessible resource base of 1.84×10^{18} J in the reservoirs of the 29 hydrothermal-convection systems in the same region. No estimate was made of the resource or beneficial heat available from the hydrothermal-convection system in Hot Springs National Park, Arkansas. The beneficial heat from all identified systems in the Central United States is 28 GW_t for 30 years from a total resource of 55×10^{18} J and a total accessible resource base of 27×10^{21} J.

The energy contained in undiscovered geothermal systems was estimated by comparing areas considered favorable for the existence of low-temperature geothermal reservoirs with identified geothermal systems that are similar in geologic and hydrologic characteristics (table 11). The total accessible resource base, including identified and undiscovered components, for low-temperature geothermal resources in the central United States is 34×10^{21} J.

In the course of this assessment, large amounts of thermal energy at reservoir temperatures above 90°C contained in deep aquifers of the Anadarko, Powder River, and Williston basins were excluded from consideration. This energy is in water with temperatures of between 90° and 150°C containing more than 100,000 mg/L total dissolved solids at depths greater than about 2.5 km (MacCary, 1981). The great depth and high concentration of dissolved solids make economical recovery of this energy unlikely.

EASTERN UNITED STATES

The Eastern United States had little tectonic activity during the Cenozoic, and the few hydrothermal-convection systems found in this region occur along areas of pre-Cenozoic folding and faulting in the Appalachian Mountains. The eastern region has below-average to average (61 mW/m^2) heat flow, and so the existence of conduction-dominated low-temperature geothermal reservoirs depends on the presence of thick sequences of rocks of low thermal conductivity. The eastern region, however, includes large areas of high-thermal-conductivity crystalline rock exposed at the surface or at shallow depth, and so the available area for low-temperature geothermal systems is greatly reduced. Oil and gas exploration wells have been drilled into the Atlantic Coastal Plain and into most of the sedimentary basins, but all the explored basins except the Appalachian basin fall below the minimum-temperature criterion. In the Appalachian basin, drilling has penetrated only about 2.2 km (Joel Renner, written commun., 1981), although stratigraphic information from outside the basin suggests that an undiscovered low-temperature geothermal reservoir may exist at greater depth in pre-Devonian sedimentary rocks.

An estimated resource of 0.32×10^{18} J could be recovered in 30 years from an accessible resource base of 1.63×10^{18} J in the six conduction-dominated geothermal systems identified in the Eastern United States, and an estimated resource of 0.138×10^{18} J could be recovered in 30 years from an accessible resource base of 0.55×10^{18} J in the 19 hydrothermal-convection systems in the same region. The beneficial heat from all identified low-temperature geothermal systems in the Eastern United States is 191 MW_t for 30 years from a total identified resource of 0.46×10^{18} J and a total identified accessible resource base of 2.2×10^{18} J.

Undiscovered geothermal systems were considered to be similar in geologic and hydrologic characteristics to identified systems (table 11). The undiscovered geothermal system anticipated in the Appalachian basin has no counterpart in the identified conduction-dominated systems of the eastern region, and so similarities are drawn to identified geothermal systems in the central region. The total accessible resource base, including identified and undiscovered components, for low-temperature geothermal resources in the Eastern United States is 490×10^{18} J (dominated by the undiscovered component in the Appalachian basin).

CONCLUSIONS

This assessment of low-temperature geothermal resources in the United States refines and extends the qualitative estimate by Sammel (1979). Extensive data collected by the State-cooperative projects of the U.S. Department of Energy, Division of Geothermal Energy (see "Additional References" in Reed, "Introduction," this volume), led to the identification of many more low-temperature geothermal systems within the favorable areas listed by Sammel (1979). Table 12 summarizes the identified low-temperature geothermal energy in each State.

Table 13 identifies the contributions from both hydrothermal-convection and conduction-dominated geothermal systems for the three regions of the country and summarizes the undiscovered component of low-temperature geothermal energy. Reservoirs in hydrothermal-convection systems make up the greatest proportion (97 percent) of identified low-temperature geothermal-resource areas, but the smaller average volume of these systems accounts for their contribution of only 1 percent to the accessible resource base. However, the small size of most reservoirs in hydrothermal-convection systems also leads to a relatively high average recovery factor (0.15), and they account for 36 percent of the identified resource. The beneficial heat calculated for hydrothermal-convection systems is 32 percent of the total identified beneficial heat, a proportion that reflects the lower average reservoir temperature of these systems. Although reservoirs in conduction-dominated systems are much less numerous, some are extremely large, and taken together they constitute 64 percent of the total low-temperature geothermal resource in the United States. Because use of the proposed development plan to calculate the resource results in lower recovery factors for larger area reservoirs, the average recovery factor for conduction-dominated systems is only 0.002. The greater depth to most of these reservoirs and the attendant higher average temperature explains their contribution of 69 percent of the total beneficial heat for identified geothermal systems.

Evaluation of low-temperature geothermal energy in the United States gives an estimated resource of 153×10^{18} J (table 13). This is much lower than the estimate of 2.4×10^{21} J for the total resource in hydrothermal-convection systems with reservoir temperatures above 90°C (Brook and others, 1979), primarily because of the lower recovery factors calculated in this assessment. The ratio of the undiscovered to the identified component for the accessible resource base in hydrothermal-convection systems is 5.0 for intermediate- and high-temperature systems (Brook and others, 1979) and 1.8 for low-temperature systems (table 13); this difference reflects the greater number of oil, gas, and water wells that have been drilled in areas with favorable geology for the discovery of low-temperature geothermal resources. However, areas with favorable geology for intermediate- and high-temperature geothermal resources have fewer wells and less information available, and so larger areas exist with the possibility for undiscovered systems. In the estimates of the accessible resource base for low-temperature geothermal energy, the higher ratio of the undiscovered to the identified component in hydrothermal-convection systems (1.8) than in conduction-dominated systems (0.25) also reflects the much greater drilling activity in and greater subsurface information on areas where undiscovered conduction-dominated systems may exist.

A total of 1,126 low-temperature hydrothermal-convection reservoirs are identified in this assessment. Water chemistry was evaluated for these systems, many of which have estimated geochemical

Table 12.—Summary of energies by State for identified low-temperature geothermal systems in the United States

[Systems in national parks have been omitted from calculations of the resource and beneficial heat. All means calculated analytically. Values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

State	Number of systems	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Benefical heat (MW_t for 30 yr)
Alaska	33	3.5	0.88	430
Arizona	63	33	3.6	1,640
Arkansas	6	.50	.092	36
California	203	54	5.6	2,000
Colorado	49	690	3.6	1,800
Georgia	1	.050	.012	3.7
Hawaii	1	1.70	.054	24
Idaho	171	55	6.1	2,800
Kansas	2	1,700	3.3	1,700
Massachusetts	1	.016	.004	.0
Montana	52	10,200	17.3	8,800
Nebraska	1	930	3.4	1,550
Nevada	191	28	5.5	2,400
New Mexico	70	7.4	1.32	580
New York	1	.018	.005	.0
North Carolina	3	.98	.152	80
North Dakota	2	6,400	9.8	5,000
Oklahoma	1	3,600	3.9	2,100
Oregon	99	15.0	2.7	1,200
South Dakota	5	1,800	5.7	2,600
Texas	17	84	.86	420
Utah	118	20	2.1	690
Virginia	14	1.05	.25	100
Washington	25	77	1.12	450
West Virginia	5	.088	.023	.0
Wyoming	34	1,400	9.5	4,800
Total	1,168	27,000	87	41,000

Table 13.—Summary of energies for identified and undiscovered low-temperature geothermal systems in the United States

[Omitted are seven hydrothermal-convection systems in national parks that contain an accessible resource base of 0.76×10^{18} J. All means and standard deviations calculated by the Monte Carlo method. Values are rounded to two significant figures or, if the first digit is 1, to three significant figures; this rounding represents a range of 0.5 to 5 percent in the accuracy of the total value]

Type of system	Number of systems	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Beneficial heat (MW_t for 30 yr)
Identified				
Hydrothermal convection				
Western region	1,069	200±5.3	30±0.85	13,200±420
Central region	31	1.84±0.191	.46±0.064	176±32
Eastern region	19	.55±0.060	.138±0.022	24±6.5
Subtotal	1,119	200±5.3	31±0.85	13,400±420
Conduction dominated				
Western region	9	102±16.7	1.19±0.27	500±134
Central region	27	27,000±1010	55±4.2	28,000±2100
Eastern region	6	1.63±0.175	.32±0.069	167±35
Subtotal	42	27,000±1010	56±4.2	29,000±2100
Total	1,161	27,000±1010	87±4.3	42,000±2100
Undiscovered	---	7,200	66	30,000
Grand total	---	34,000	153	72,000

temperatures above the measured reservoir temperatures. Difficulties exist in the interpretation of chemical geothermometers at low temperatures (see Mariner and others, this volume), and the estimates of maximum and most likely reservoir temperatures are subject to large errors. To evaluate the overall temperature distribution of hydrothermal-convection systems, the mean temperatures for the 220 intermediate- and high-temperature systems identified by Brook and others (1979) were combined with the mean temperatures of the systems in this assessment on a semilogarithmic plot of cumulative frequency versus temperature (fig. 16). The distribution of the 1,346 identified hydrothermal-convection systems shown in figure 16 approximates the equation $\underline{N} = \exp[(318.26-\underline{T})/41.49]$, where $\underline{N}$ is the total number of geothermal systems above a certain reservoir temperature and $\underline{T}$ is the temperature (in degrees Celsius). This equation (as determined by a least-squares fit to the data) is nearly identical to that for intermediate- and high-temperature systems alone (Brook and others, 1979, fig. 11). The natural distribution of a resource of this type could be expected to fit some kind of exponential equation; if the distribution of temperatures for the total population of geothermal systems is a similar exponential function, then the identified hydrothermal-convection systems are representative of that total population.

The 38 low-temperature conduction-dominated geothermal systems were evaluated similarly to the assessment of geopressured-geothermal systems in the northern Gulf of Mexico basin (Wallace and others, 1979). The recovery factors, based on similar methods of calculating the resource, are also comparable for geopressured-geothermal and low-temperature conduction-dominated geothermal systems.

The distribution of low-temperature geothermal energy as a function of reservoir temperature is important for the potential uses of this resource. The value of geothermal water depends strongly on its temperature because water near the higher limit of the temperature range (near 90°C) can be used for more applications and carries more energy per unit mass than water near the lower limit of temperature. Figure 17 summarizes the distribution of low-temperature geothermal energy in three temperature ranges. To determine the resource energy within these temperature ranges, a Monte Carlo computer simulation was performed. Values for the reservoir

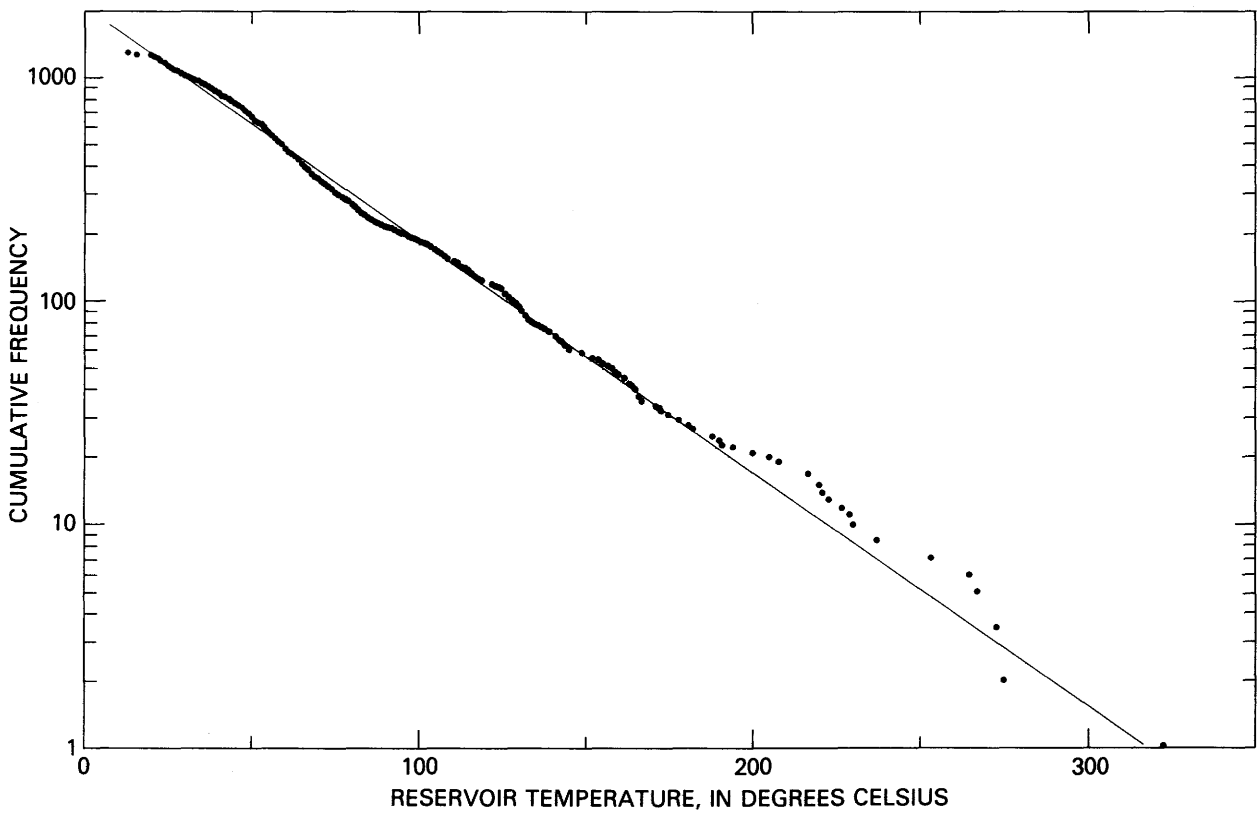

Figure 16.--Cumulative frequency versus reservoir temperature for 1,346 hydrothermal-convection systems in the United States, including 1,126 low-temperature geothermal systems in this assessment and 220 intermediate- and high-temperature systems from Brook and others (1979). Straight line is least-squares fit to data, described by equation given in text.

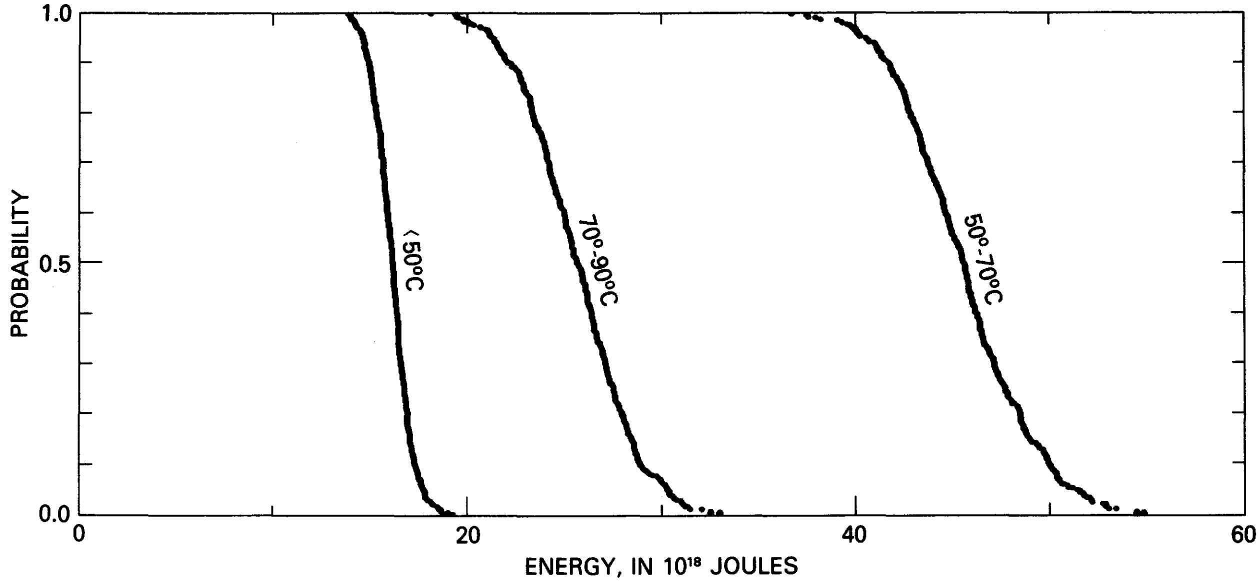

Figure 17.—Monte Carlo distribution of resource for low-temperature geothermal systems in the United States.

parameters of temperature, area, thickness, and production-well spacing were generated by using the minimum, maximum, and most likely values to simulate triangular probability distributions. The thermal energies listed in tables 6, 9, 10, and 13 were also calculated by the Monte Carlo method; these values are slightly higher than those calculated analytically, but both types of calculations agree within the standard deviations listed.

The standard deviations given in this assessment indicate the uncertainties associated with the estimated ranges of parameters that were allowed to vary. Some parameters were assumed to be constant for the calculations, but assignment of a distribution to these parameters would add to the overall uncertainty of the results. The totals for large numbers of systems have smaller associated uncertainties because the aggregation reduces the overall standard deviation. As in the assessments by White and Williams (1975) and Muffler (1979), the total-energy estimates are considered more reliable than the estimates for any one reservoir.

Important gains can be made in the use of low-temperature geothermal energy for suitable applications, and a significant contribution to the Nation's energy needs could result from increased use of this resource. Table 14 compares the energy available from the total (identified and undiscovered) beneficial heat of low-temperature geothermal resources with the calculated amounts from other

Table 14.—Comparison of the total beneficial heat from low-temperature geothermal systems with that from other energy sources

Energy source	Energy content per unit quantity	Burner efficiency (Beller, 1975)	Resource quantity needed to provide a beneficial heat of 27 GW_t for 30 years in a space-heating application
Natural gas--------	$3.7x10^7$ J/standard m^3	0.48	$3.8x10^{12}$ standard m^3
No. 2 diesel oil---	$4.4x10^7$ J/kg	.44	$3.5x10^{12}$ kg
Bituminous coal----	$3.0x10^7$ J/kg	.44	$5.2x10^{12}$ kg

energy sources needed to provide the same beneficial heat. Each process that involves transfer of this heat to air, water, or other substances will have an efficiency factor. To calculate the beneficial heat available from each energy source, the efficiencies for combustion in residential space heating were used (Beller, 1975); other applications may have much different efficiencies.

Future low-temperature geothermal-resource assessments will have the advantage of a longer history of exploration and development. The data base will be enlarged by future exploration, and a better understanding of the operating efficiencies of geothermal installations will refine our knowledge of beneficial heat. The resolution of existing uncertainties concerning reservoir temperature will require further investigations into chemical geothermometers and the measurement of equilibrium temperatures in available wells. It is anticipated that, as more information is acquired, State or regional agencies will wish to refine the estimates of geothermal energy within their own boundaries. With that possibility in mind, the authors of this volume have attempted to provide a basic methodology and examples of its application, so that future geothermal-resource assessments can build on this base.

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