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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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=$9.485\text{x}10^{-4}$ British thermal unit (Btu)
	1 J=$2.777\text{x}10^{-4}$ watt-hour (W·hr)
	10^{18} J=0.9485 quad (10^{15} Btu)
	1 MW_t for 30 yr=$9.461\text{x}10^{14}$ J
Power or work:	1 watt (W)=1 J/s
	1 megawatt (MW)=$3.154\text{x}10^{13}$ J/yr
Heat flow:	1 mW/m^2=$2.390\text{x}10^{-8}$ cal/cm·s
	1 mW/m^2=$2.390\text{x}10^{-2}$ 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.

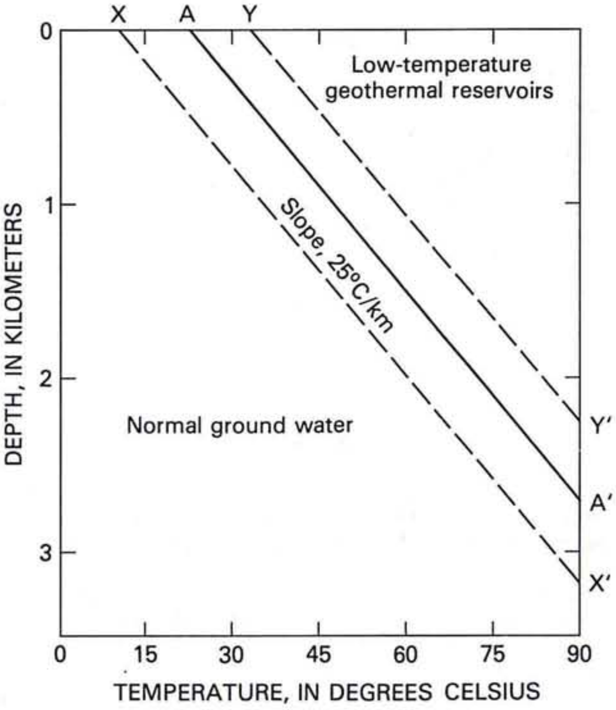

Figure 1.--Temperature-versus-depth relation used to define low-temperature geothermal resources. Upper temperature limit is 90°C, following usage of Muffler (1979); lower temperature limit is defined as 10°C above the mean annual air temperature at the surface, increasing by 25°C/km with depth. Dashed 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

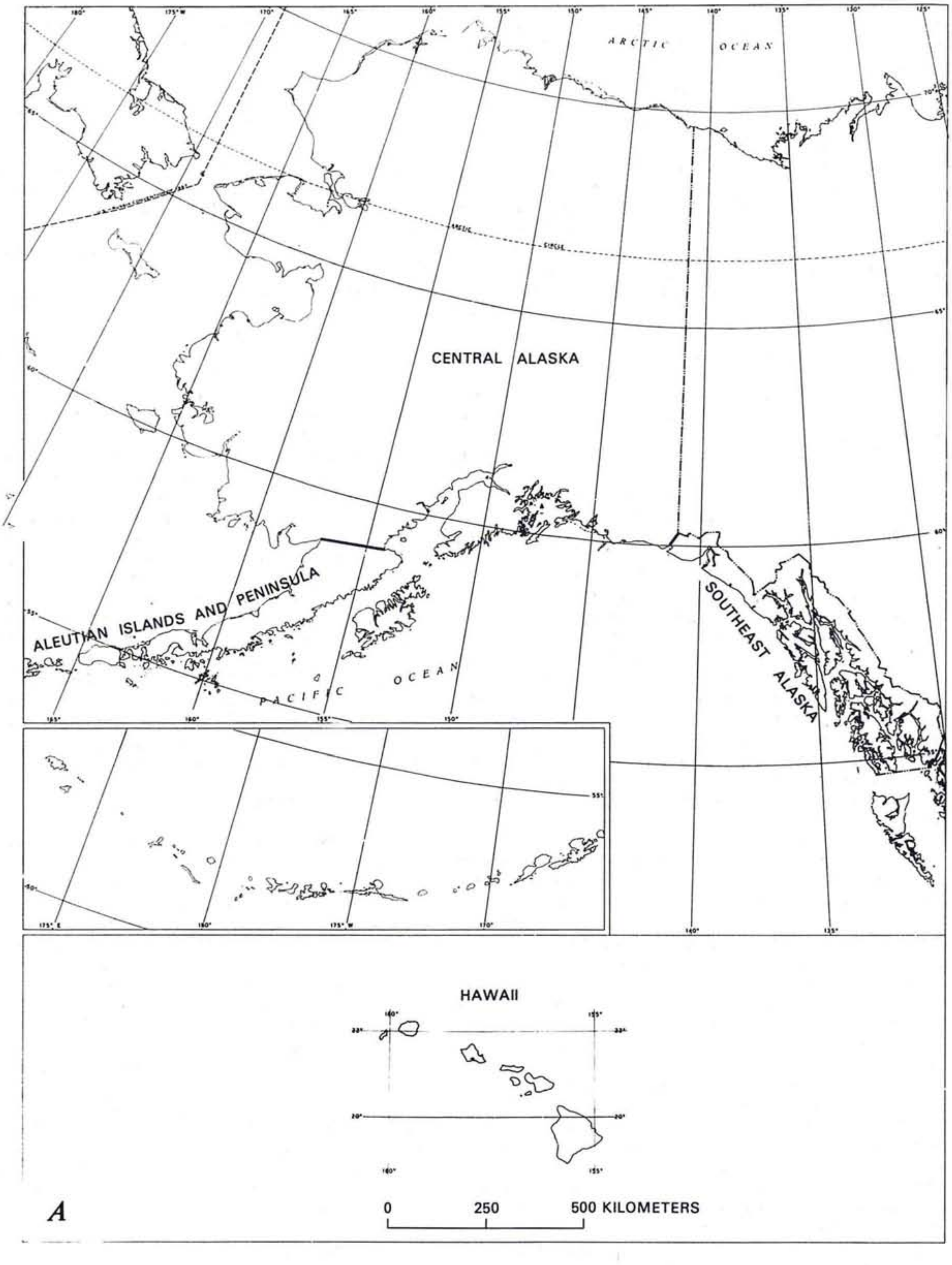

Figure 2.—Major geologic provinces of the United States (modified from the physiographic provinces of Fenneman, 1946), showing division of the country into three regions for discussion in this assessment. A, Alaska and Hawaii (western region). B, Conterminous United States (western, central, and eastern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

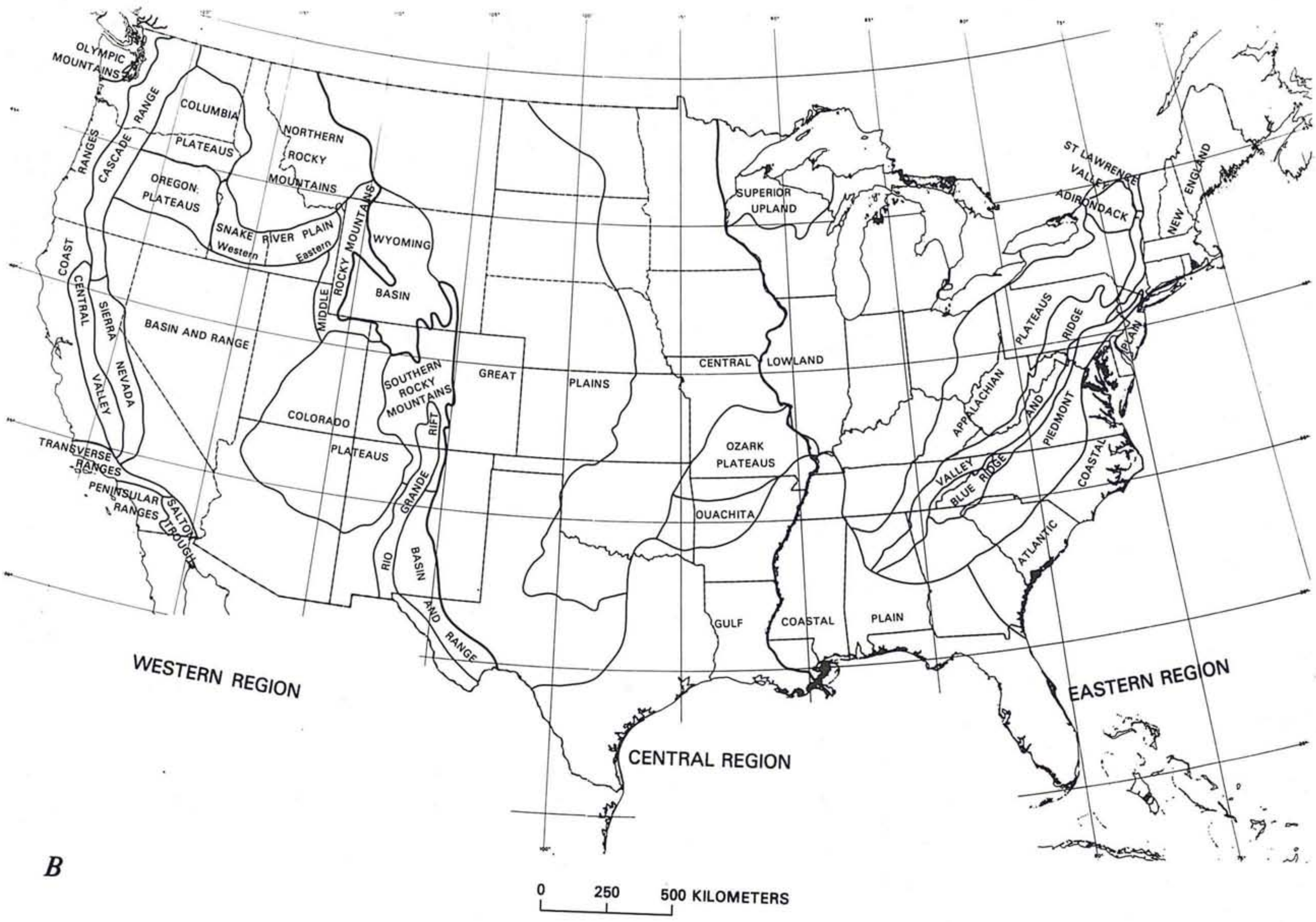

Figure 2.--Continued

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

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

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:

$$q=q_r+DA, \qquad (2)$$

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 μW/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

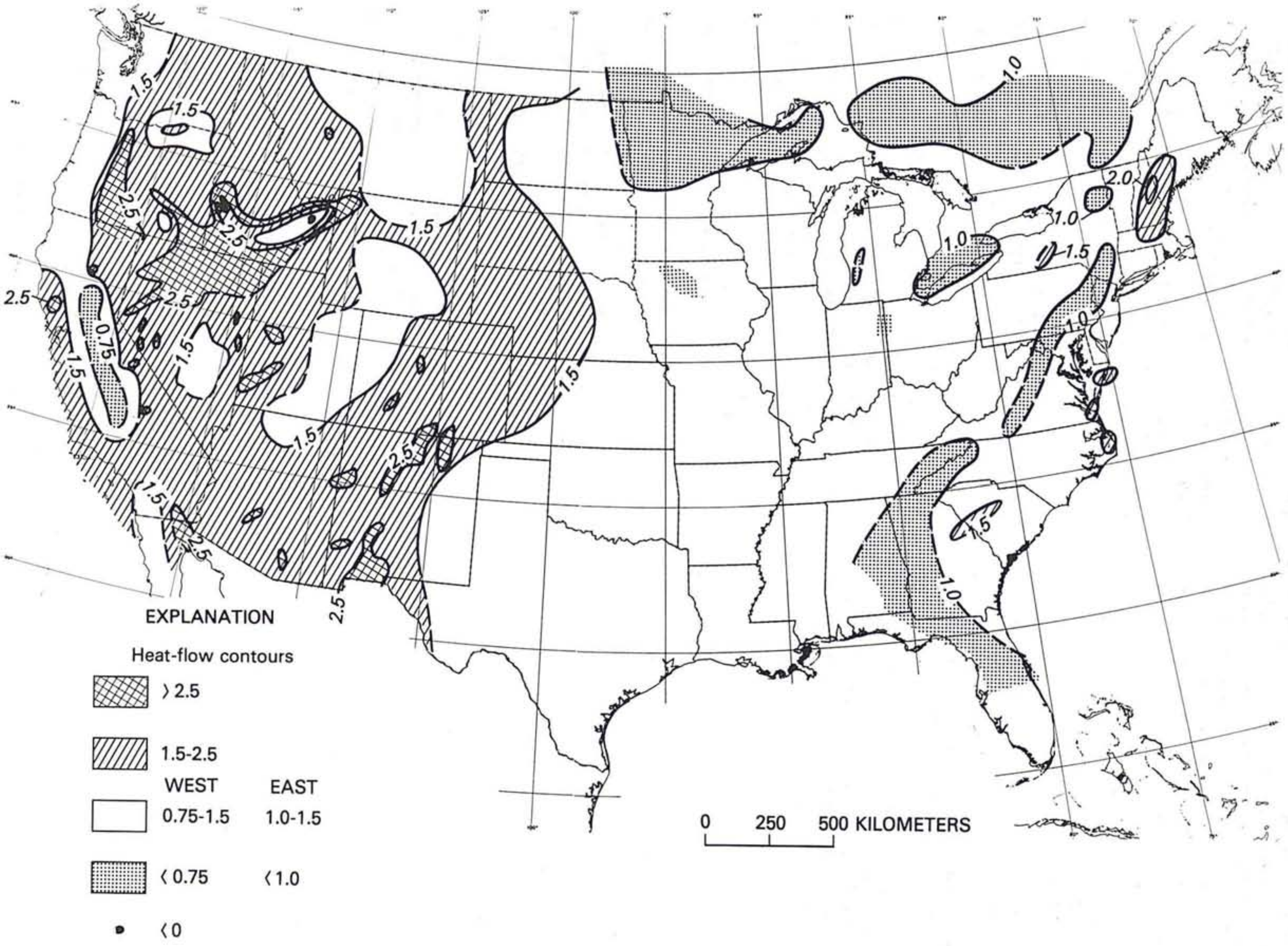

Figure 4.--Heat-flow map of the conterminous United States (from Sass and others, 1981, fig. 13.4). Contours are in heat-flow units.

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 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).

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

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

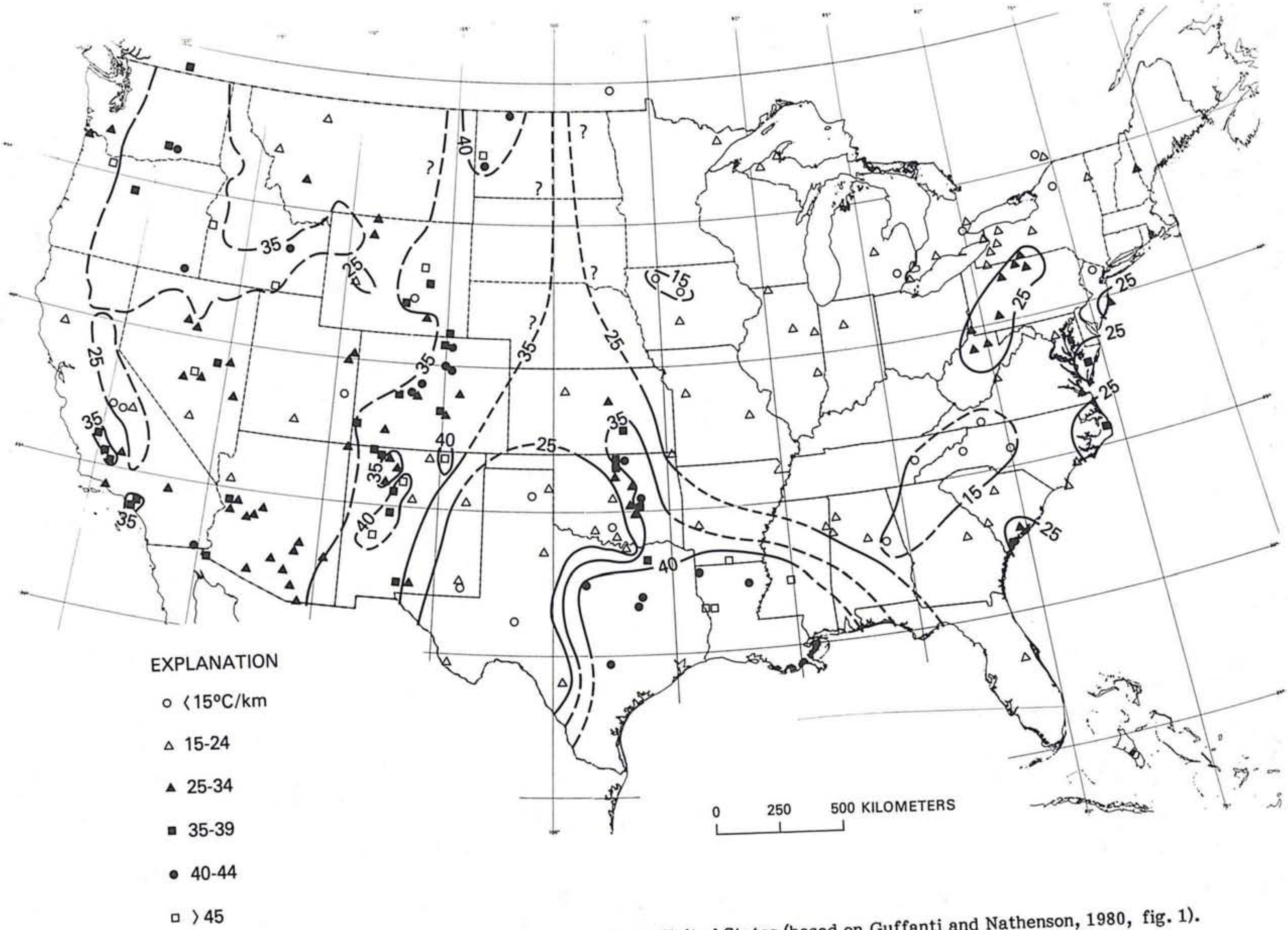

Figure 5.—Temperature-gradient map of the conterminous United States (based on Guffanti and Nathenson, 1980, fig. 1).

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

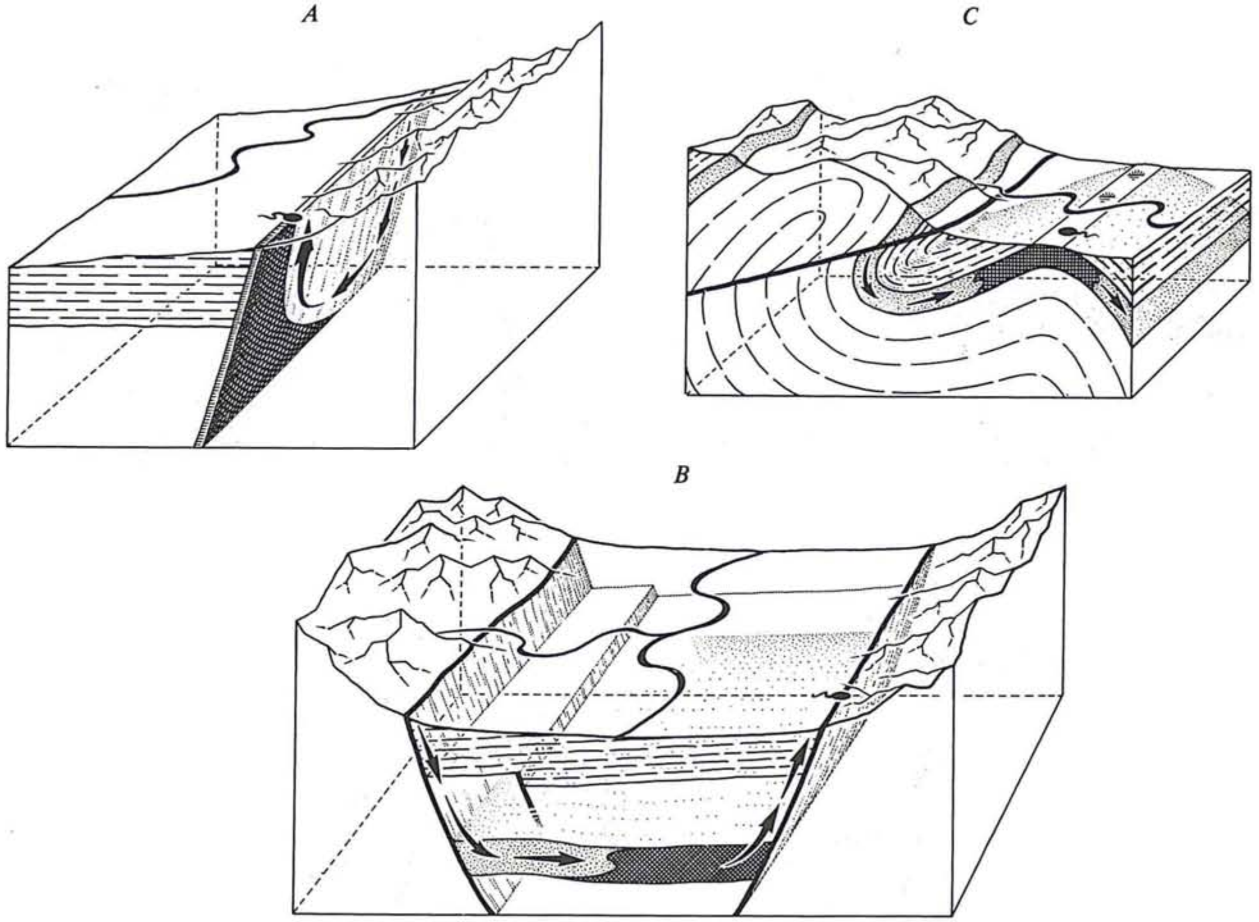

Figure 6.—Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal-resource areas in category 1 (isolated thermal springs and wells) occur. A, Fault plane. B, Deep reservoir. C, Margin of anticline. Arrows indicate direction of fluid circulation; shading shows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

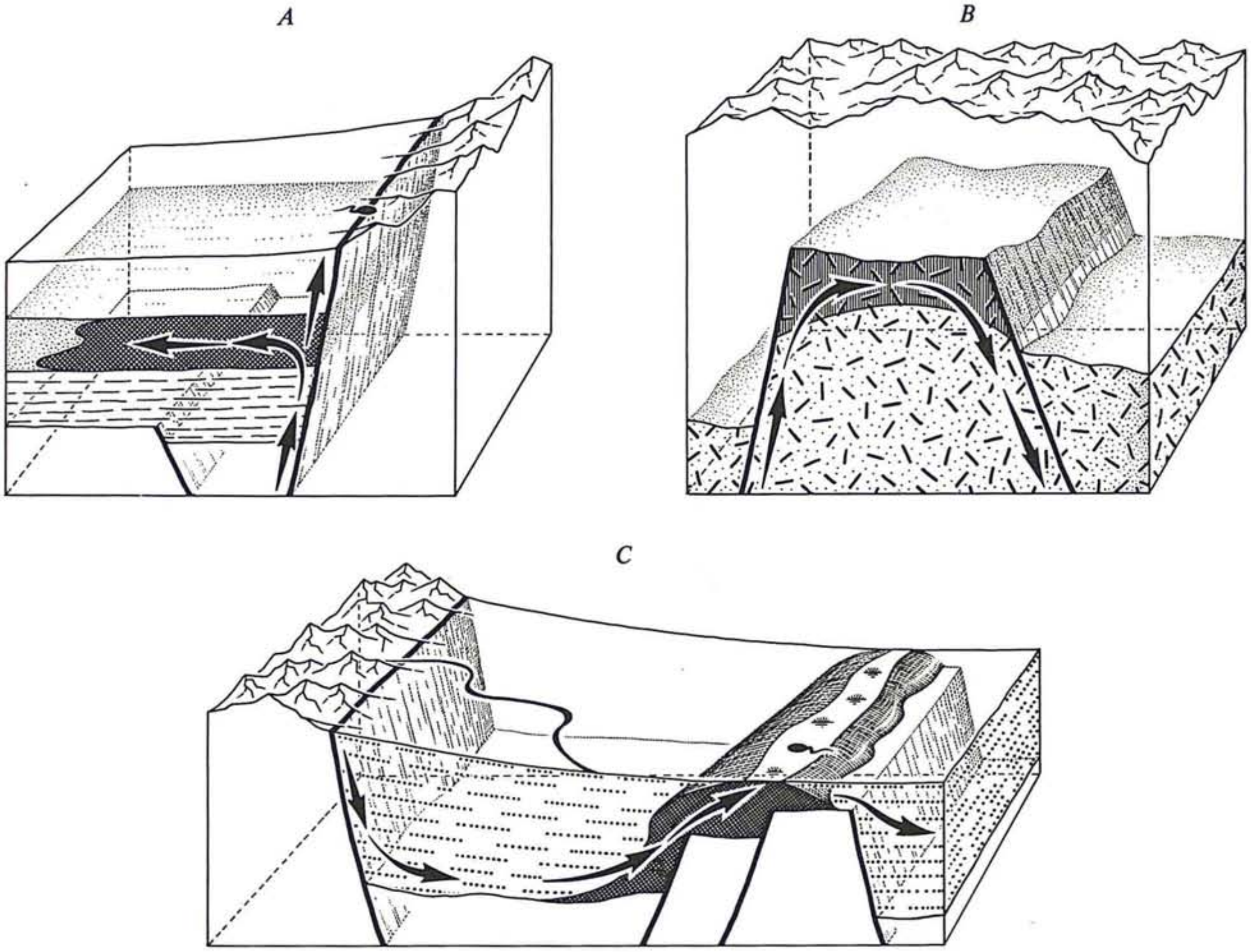

Figure 7.—Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal-resource areas in category 2 (delineated thermal reservoirs) occur. A, Lateral leakage. B, Bedrock high. C, Basin constriction. Arrows indicate direction of fluid circulation; shading shows location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

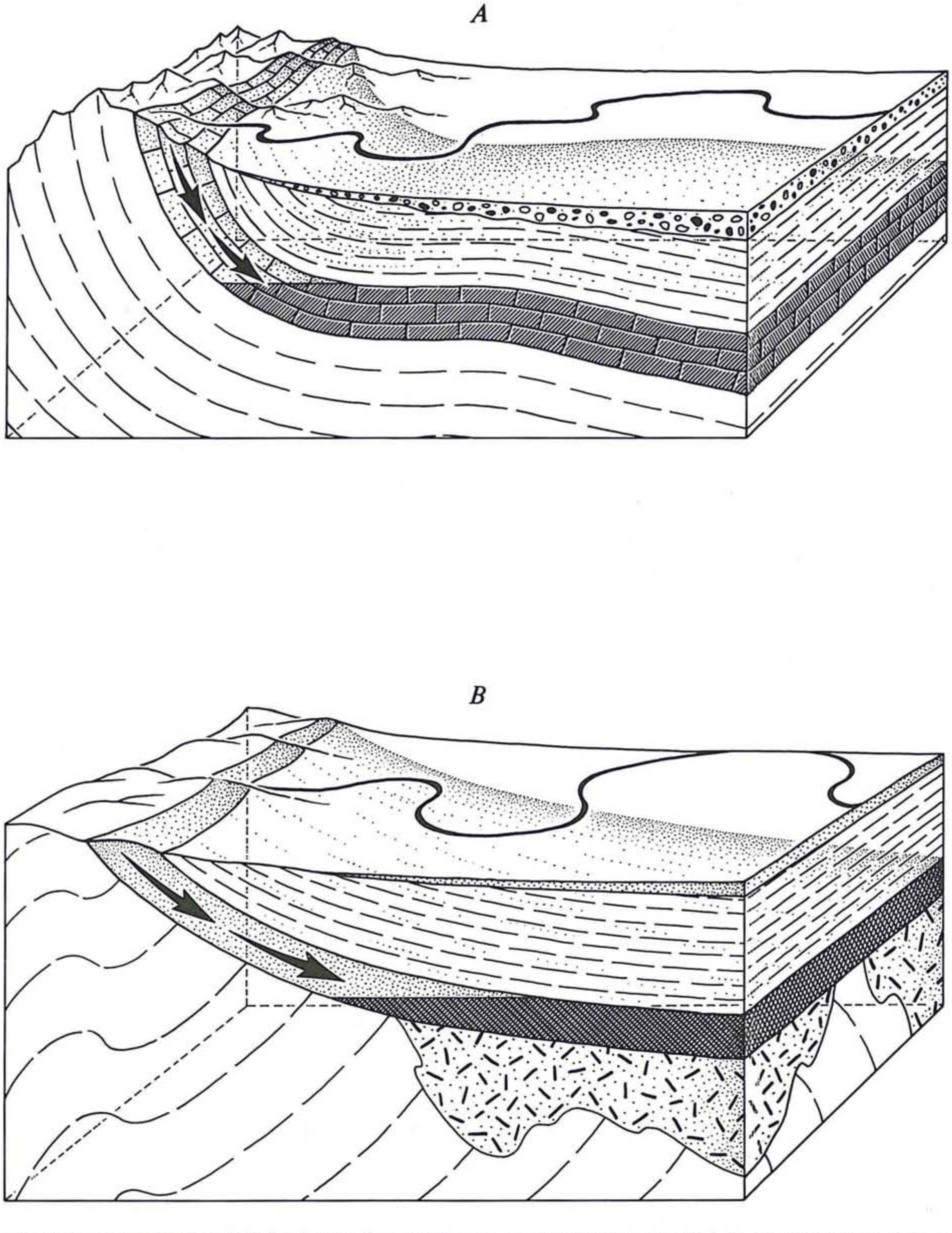

Figure 8.—Conceptual models for types of conduction-dominated systems in which low-temperature geothermal-resource areas in category 3 (sedimentary basins, A) and category 4 (coastal plains, B) occur. Arrows indicate direction of fluid circulation; shading shows location of reservoir containing low-temperature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

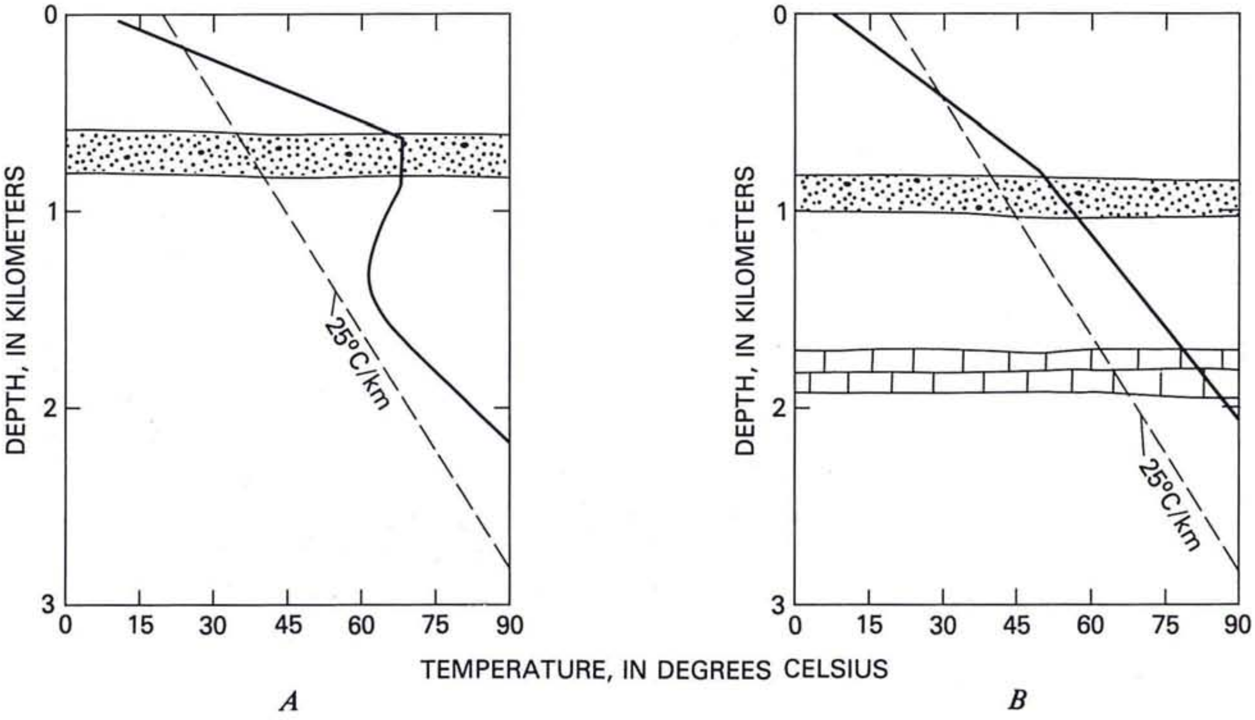

Figure 9.--Idealized temperature profiles in hydrothermal-convection systems with lateral leakage (A) and within sedimentary basins (B). Identified low-temperature geothermal resources exist where temperatures in aquifers exceed the minimum-temperature criterion (10°C above mean annual temperature plus 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 r_e. This approach was followed in previous assessments of intermediate- and high-temperature hydrothermal-convection systems, using 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 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

$$q_{WH}=(\rho c)_f NQP(t-t_{ref}), \qquad (3)$$

where q_{WH} is the resource, $(\rho c)_f$ is the volumetric specific heat of the fluid (4.1 J/cm^3·°C), N is the number of production wells, Q is the average volumetric discharge of each production well, and 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 N and 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 a to the area per well 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 a_w less than the optimum, cumulative drawdown at the center of the reservoir exceeds 152 m; for values of 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 T is the product of the hydraulic conductivity 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 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 $S=10^{-4}$ 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 (S_s) for each confining bed; the specific storage equals the storage coefficient divided by the thickness of the confining bed. Although values of 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

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

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.

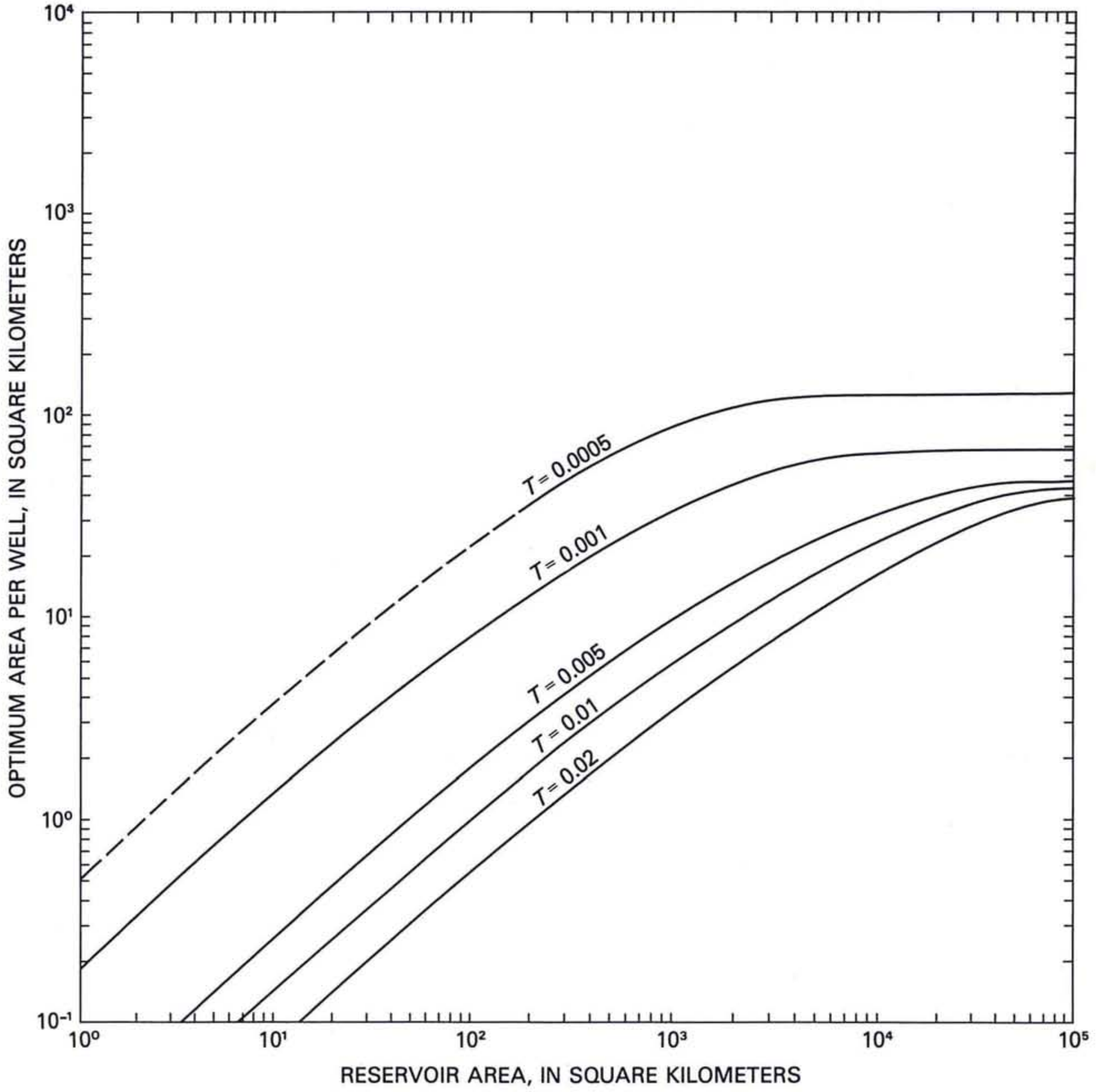

Figure 10.--Reservoir area $\underline{a}$ versus optimum area per well $\underline{a}_w$ for reservoirs with leaky confining beds, based on a production plan involving evenly spaced wells producing for 30 years at 31.5 L/s with a cumulative drawdown of 152 m. $\underline{T}$, reservoir transmissivity (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.

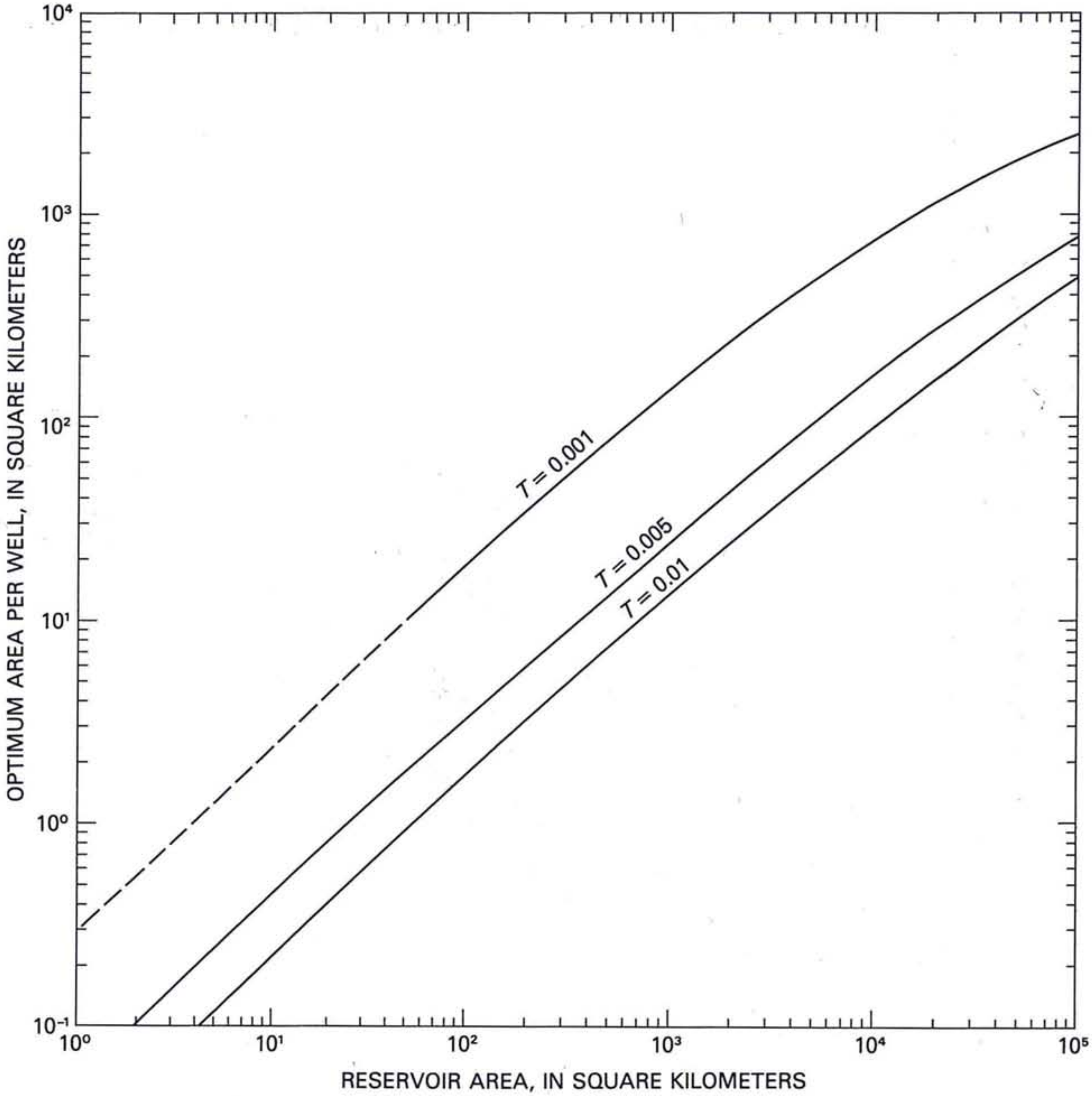

Figure 11.--Reservoir area a versus the optimum area per well a_w for reservoirs with nonleaky confining beds, based on a production plan involving evenly spaced wells producing for 30 years at 31.5 L/s with a cumulative drawdown of 152 m. T, reservoir transmissivity (in square meters per second); dashed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

$$\bar{q}_{ben} = (\rho c)_f (\bar{k}\bar{a}/\bar{a}_w) QP\Delta t, \tag{5}$$

where q_{ben} is the thermal energy (in MW_t for 30 years), $(\rho c)_f$ is the volumetric specific heat of water, Q is the mass produced, P is the duration of the development period, and Δt 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 $58^\circ - 35^\circ = 23^\circ C$.

To establish the dependence of the usable Δt 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 Δt'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

$$\Delta t = 0.6(\bar{t} - 25^\circ C). \tag{6}$$

The upper end of this line is constrained by the data, whereas the intercept at $\Delta t = 0^\circ C$ 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 Δt-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 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.

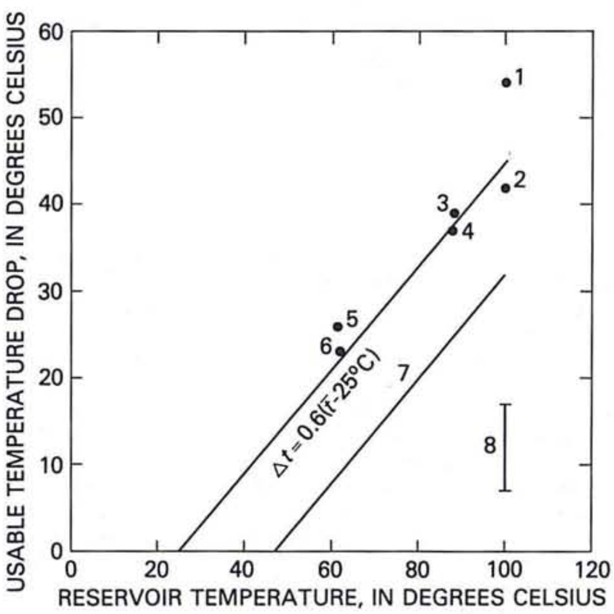

Figure 12.—Usable temperature drop t versus reservoir or input temperature t for various direct-use applications, showing empirically derived line used in this assessment for effective temperature drop as a function of reservoir temperature. 1, Reykjavik, Iceland, municipal heating system (Pálmason and 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 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

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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

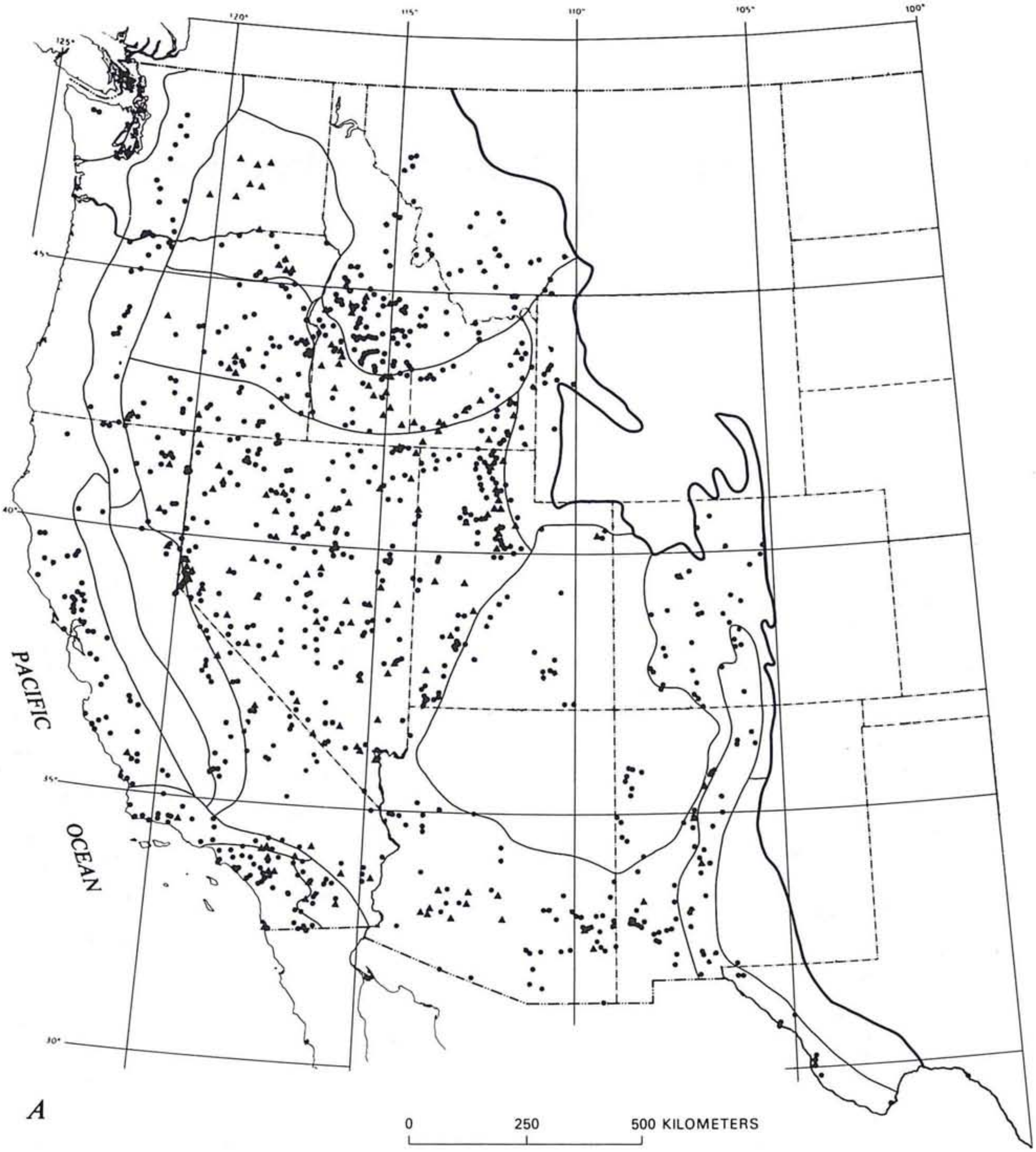

Figure 13.--Low-temperature geothermal systems in the Western United States. Major geologic provinces are identified in figure 2. Dots, isolated systems; triangles, systems with delineated areas. A, Conterminous United States. B, Alaska and Hawaii.

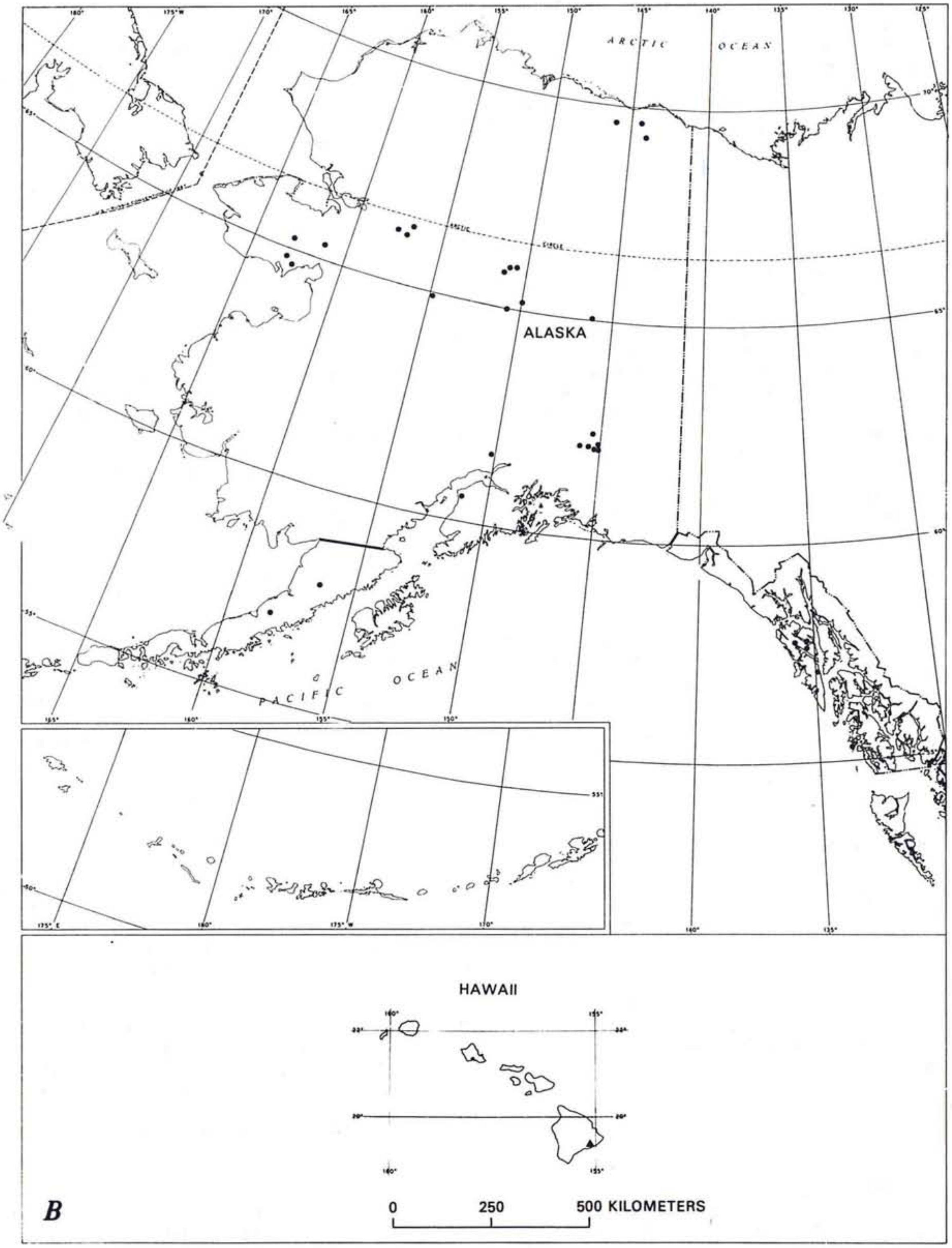

Figure 13.—Continued

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