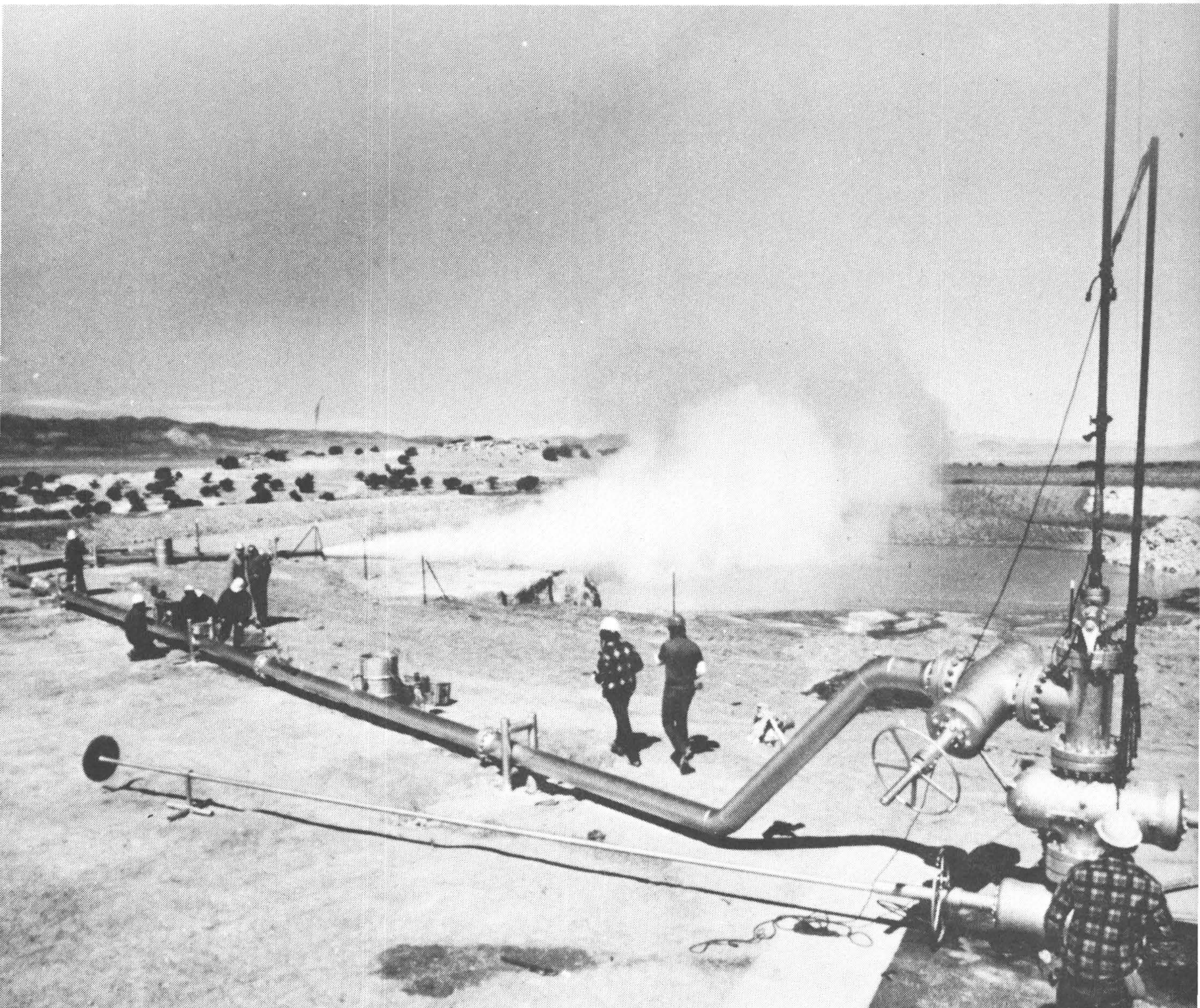
CIRC. 790

Assessment of Geothermal Resources of the United States—1978



GEOLOGICAL SURVEY CIRCULAR 790

Prepared in cooperation with the
Department of Energy

Cover: Utah State 72-16 geothermal well, Roosevelt area, Utah.
Taken by Nack Pavloff. Photograph used courtesy of Thermal Power Company.

Assessment of Geothermal Resources of the United States--1978

L. J. P. Muffler, Editor

GEOLOGICAL SURVEY CIRCULAR 790

1979

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CONTENTS

TABLES

ILLUSTRATIONS

Assessment of Geothermal Resources of the United States--1978

Introduction

By L. J. P. Muffler and Marianne Guffanti

ABSTRACT

The geothermal resource assessment presented in this Circular is a refinement and updating of USGS Circular 726. Nonproprietary information available in June 1978 is used to assess geothermal energy in the ground and, when possible, to evaluate the fraction that might be recovered at the surface. Five categories of geothermal energy are discussed:

a. Conduction-dominated regimes
b. Igneous-related geothermal systems
c. High-temperature (>150°C) and intermediate-temperature (90°-150°C) hydrothermal convection systems
d. Low-temperature (<90°C) geothermal waters
e. Geopressured-geothermal energy (both thermal energy and energy from dissolved methane).

Assessment data are presented on three colored maps prepared in cooperation with the National Oceanic and Atmospheric Administration.

BACKGROUND

Geothermal resource assessment is the estimation of the amount of thermal energy that might be extracted from the Earth and used economically at some reasonable future time. A resource assessment is regional or national in scope and thus provides a framework for long-term energy policy and strategy decisions by industry and government. A resource assessment is not intended to establish specific reserve figures for short-term investment and marketing decisions, but instead to give an overall perspective at a particular time, using uniform methodology and data.

The first systematic effort to estimate the geothermal resources of the entire United States was published in 1975 as U. S. Geological Survey Circular 726 (White and Williams, eds., 1975). This study used the data available in early 1975 to estimate the quantities of geothermal energy available in several categories: (a) regional conductive environments (Diment and others, 1975), (b) igneous-related geothermal systems (Smith and Shaw, 1975; Peck, 1975), (c) hydrothermal convection systems (Renner and others, 1975; Nathenson and Muffler, 1975), and (d) geopressured-geothermal systems (Papadopulos and others, 1975).

Any resource assessment should be periodically updated in response to new information, new assessment methodologies, greater understanding of resource characteristics, improved exploration, extraction, and utilization technologies, and changed economic and social conditions (Muffler and Christiansen, 1978). Such updating is particularly important in a rapidly developing field such as geothermal energy. Considered a novelty only a few years ago, geothermal energy is rapidly becoming a significant contributor to the energy economies of several countries. Particularly since the petroleum crisis of 1973, exploration and utilization of geothermal energy have taken a dramatic upswing throughout the world. This expansion can most easily be illustrated by the growth rate in electrical generating capacity from geothermal energy (fig. 1). Worldwide, the growth rate has been a steady 7 percent per year since about 1945. However, 1977-1978 installations and the installations expected by 1983 give a rate of about 19 percent per year. Even excluding The Geysers in northern California, the world's largest and most rapidly expanding geothermal electrical installation, the worldwide geothermal electrical capacity appears to be growing at about 16 percent per year.

Given this accelerated rate of use of geothermal energy and the attendant increases in exploration, technology development, and direct utilization, the U. S. Geological Survey (USGS) has reevaluated the geothermal resources of the United States in the light of nonproprietary data available June, 1978. This new geothermal resource assessment is essentially a refinement of USGS Circular 726 (White and Williams, eds., 1975), to which the reader is referred for background information and general statements on the nature of the various geothermal resource categories. Some support for both the 1975 and 1978 assessments was provided by the Department of Energy (DOE).

COMPARISON WITH CIRCULAR 726

The organization of Circular 790 is similar to that of Circular 726, but not exactly parallel (table 1). For example, the hydrothermal convection systems with reservoir temperatures of 90°C or more were discussed in two papers in Circular 726 (Renner and others, 1975, and Nathenson and Muffler, 1975), but are covered in

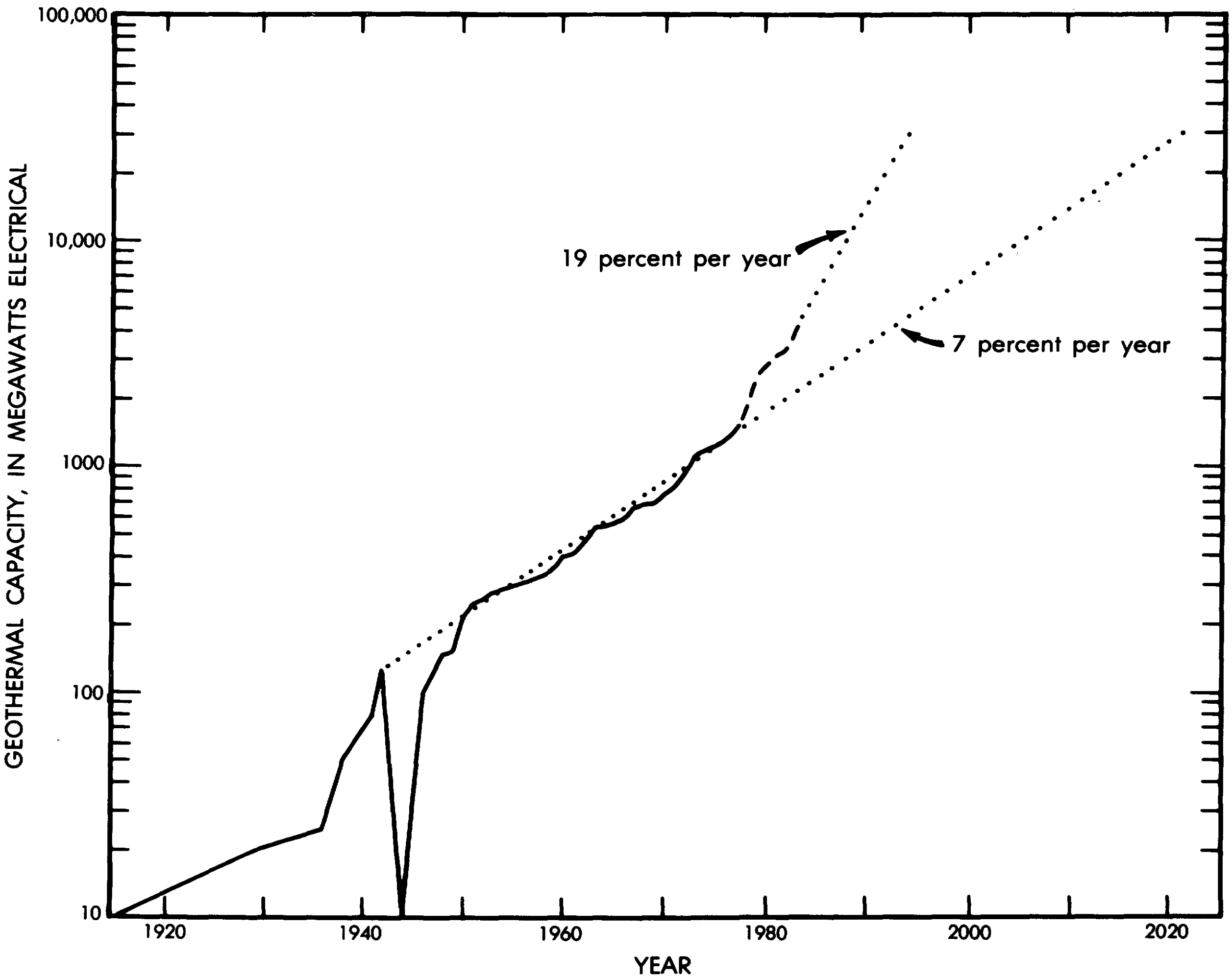

Figure 1.--Graph showing worldwide installed geothermal electrical capacity as a function of time. Dashed line indicates plants under construction or committed up to 1983. Data collated in great part by Donald E. White (written commun., 1978). The dotted extrapolations can be interpreted as upper and lower limits of expected growth.

one comprehensive paper in Circular 790 (Brook and others, this volume).

Where the analyses of Circular 726 are still valid, we have made no attempt to duplicate them in Circular 790. For example, the conclusions of Diment and others (1975) on the conduction-dominated regimes are not significantly changed by the refined heat-flow data available today (Sass and Lachenbruch, this volume), and the conclusions of Peck (1975) with regard to the recoverability of energy directly from magma are still valid in 1978. The analysis of igneous-related systems by Smith and Shaw (this volume) incorporates new data but is similar in scope to the previous analysis (Smith and Shaw, 1975).

The major new addition in Circular 790 is a report describing and depicting areas favorable for the discovery and development of low-temperature (<90°C) geothermal waters from depths less than 1 km (Sammel, this volume). This is the first time that such a nationwide evaluation has been attempted. However, owing to the differences in format, thoroughness, and reliability of the many data sets and to the paucity of reliable data over wide areas, thermal energies are not calculated. A more elaborate collation of data in individual states is being carried out by the Western States Cooperative Direct Heat Geothermal Program of the DOE Division of Geothermal Energy (Wright and others, 1978).

The report on hydrothermal convection systems with reservoir temperatures of 90°C or more (Brook and others, this volume) represents a significant refinement of Circular 726. Major changes include:

1. Revision of reservoir volumes and temperatures based on data accumulated since 1975 and on improvements of chemical geothermometers.

Table 1.--*Comparison of contents of USGS Circular 790 with contents of USGS Circular 726 (White and Williams, eds., 1975)*

Circular 790	Circular 726
Introduction, by L. J. P. Muffler and Marianne Guffanti	Introduction, by D. E. White and D. L. Williams
Heat flow and conduction-dominated thermal regimes, by J. H. Sass and A. H. Lachenbruch	Temperatures and heat contents based on conductive transport of heat, by W. H. Diment, T. C. Urban, J. H. Sass, B. V. Marshall, R. J. Munroe, and A. H. Lachenbruch
Igneous-related geothermal systems, by R. L. Smith and H. R., Shaw a. Supporting data in USGS Open-File Report 78-925 by R. L. Smith, H. R. Shaw, R. G. Luedke, and S. L. Russell	Igneous-related geothermal systems, by R. L. Smith and H. R. Shaw
(NO EQUIVALENT)	Recoverability of geothermal energy directly from molten igneous systems, by D. L. Peck
Hydrothermal convection systems with reservoir temperatures ≥90°C, by C. A. Brook, R. H. Mariner, D. R. Mabey, J. R. Swanson, Marianne Guffanti, and L. J. P. Muffler a. Supporting data in USGS Open-File Report 78-858 by R. H. Mariner, C. A. Brook, J. R. Swanson, and D. R. Mabey b. Statistical methodology in USGS Open-File Report 78-1003 by Manuel Nathenson	Hydrothermal convection systems, by J. L Renner, D. E. White, and D. L. Williams a. Supporting data in National Technical Information Service CRPU-76-16 by J. L. Renner and others Geothermal resources in hydrothermal convection systems and conduction-dominated areas, by Manuel Nathenson and L. J. P. Muffler a. Recoverability methodology in USGS Open-File Report 75-525 by Manuel Nathenson
Occurrence of low-temperature geothermal waters in the United States, by E. A. Sammel	(NO EQUIVALENT)
Assessment of geopressured-geothermal resources in the northern Gulf of Mexico basin, by R. H. Wallace, Jr., T. F. Kraemer, R. E. Taylor, and J. B. Wesselman a. Methane energy calculations based on USGS Open-File Report 78-1004 by J. L. Haas, Jr.	Assessment of onshore geopressured-geothermal resources in the northern Gulf of Mexico basin, by S. S. Papadopulos, R. H. Wallace, Jr., J. B. Wesselman, and R. E. Taylor
Summary, by L. J. P. Muffler	Summary and conclusions, by D. E. White and D. L. Williams

2. Incorporation of statistical methods into the calculations of thermal energies of identified systems.
3. Tabulation of available work.
4. Estimation of the undiscovered accessible resource base by geologic province.

The geopressured-geothermal assessment (Wallace and others, this volume) is substantially expanded in scope from Circular 726. Evaluation has been extended to the continental shelf of the northern Gulf of Mexico basin and to the Upper Cretaceous deposits onshore. Data from over 3000 wells were analyzed, compared to only 250 in 1975. In addition, Circular 790 estimates the amount of methane likely to be found in solution in the geopressured-geothermal waters.

Finally, a major addition in Circular 790 consists of three multicolored maps depicting the data and conclusions presented in the Circular. Map 1 is of the conterminous Western United States (at a scale of 1:2,500,000), map 2 is of Alaska (at 1:5,000,000) and Hawaii (at 1:2,500,000), and map 3 is of the northern Gulf of Mexico basin (at 1:1,000,000). These maps were prepared by the National Geophysical and Solar-Terrestrial Data Center of the National Oceanic and Atmospheric Administration (NOAA) under the direction of Paul J. Grim.

Circular 790 and Circular 726 are both supported by Open-File Reports giving important data too voluminous to be included in the Circulars themselves. These Open-File Reports (see table 1 and References Cited) should be considered as integral parts of the resource assessment and may be purchased from the Open-File Services Section, Branch of Distribution, U. S. Geological Survey, Box 25425, Federal Center, Denver, CO 80225.

TERMINOLOGY

The terminology used in this Circular is similar to that used in Circular 726, with one important modification. Following the proposal of Muffler and Cataldi (1978), we substitute the term accessible resource base for the term resource base used in Circular 726. Resource base is thus restored to its original definition given by Schurr and Netschert (1960, p. 297) and reiterated by Schanz (1975): "Resource base is all of a given material in the earth's crust, whether its existence is known or unknown and regardless of cost considerations." The accessible resource base for geothermal energy is that part of the resource base shallow enough to be reached by production drilling in the forseeable future. Muffler and Cataldi (1978) further describe the accessible resource base as all of the geothermal energy between the Earth's surface and a specified depth in the crust, beneath a specified area and referenced to mean annual temperature. This definition can be applied exactly to the conduction-dominated environments (Sass and Lachenbruch, this volume; Diment and others, 1975) and to the thermal energy remaining in and around igneous systems (Smith and Shaw, 1975; this volume), in both cases with a depth cut-off of 10 km. For hydrothermal convection systems with reservoir temperatures of 90°C or more (Brook and others, this volume), the term accessible resource base is restricted to the thermal energy contained in rock and fluid between the specified top and bottom of a reservoir; in most cases the bottom is taken to be 3 km, and no estimates are made to deeper levels. The rationale for this cutoff is that there is virtually no direct information at depths greater than 3 km, the current limit of production drilling in hydrothermal convection systems. For geopressured-geothermal energy, Wallace, Kraemer, Taylor, and Wesselman (this volume) do not evaluate the accessible resource base. Instead they evaluate only the accessible fluid resource base, defined as the thermal energy, mechanical energy, and energy from dissolved methane contained in pore fluid of sandstone and shale at depths greater than the depth to the top of the geopressured zone but less than 22,500 ft (6.86 km). Because mechanical energy was shown by Papadopulos, Wallace, Wesselman, and Taylor (1975) to be negligible, it is not calculated by Wallace, Kraemer, Taylor, and Wesselman (this volume).

In both Circular 790 and Circular 726 a careful distinction is made between the thermal energy in the ground (the accessible resource base of Circular 790 and the resource base of Circular 726) and the thermal energy that could be extracted and used at some reasonable future time (the useful accessible resource base, or resource). In a manner analogous to other resources (for example, petroleum or mineral deposits), the geothermal resource represents the thermal energy that could be extracted at costs competitive with other forms of energy at a forseeable time, under reasonable assumptions of technological improvement and economic favorability (Muffler and Cataldi, 1978). With regard to these assumptions, any resource assessment tends to be optimistic.

In both Circular 726 and Circular 790, the accessible resource base is divided into identified and undiscovered components. Adapted from the general definition of the U. S. Geological Survey (1976, p. A3), identified refers to specific concentrations of geothermal energy known and characterized by drilling or by geochemical, geophysical, and geologic evidence. Undiscovered refers to unspecified concentrations of geothermal energy surmised to exist on the basis of broad geologic knowledge and theory.

In contrast to Circular 726, Circular 790 makes no attempt to specify what fraction of the geothermal resource might be considered as a geothermal reserve (that is, that part of the geothermal resource that is identified and also can be extracted legally at a cost competitive with other commercial energy sources at present; Muffler and Cataldi, 1978). Specification of reserves would require reservoir, production, and economic data beyond the scope of this report.

Geothermal resource terminology has been summarized by Muffler and Cataldi (1978) on a McKelvey diagram (fig. 2). The vertical axis refers to the degree of economic feasibility, and the horizontal axis describes the degree of geologic assurance.

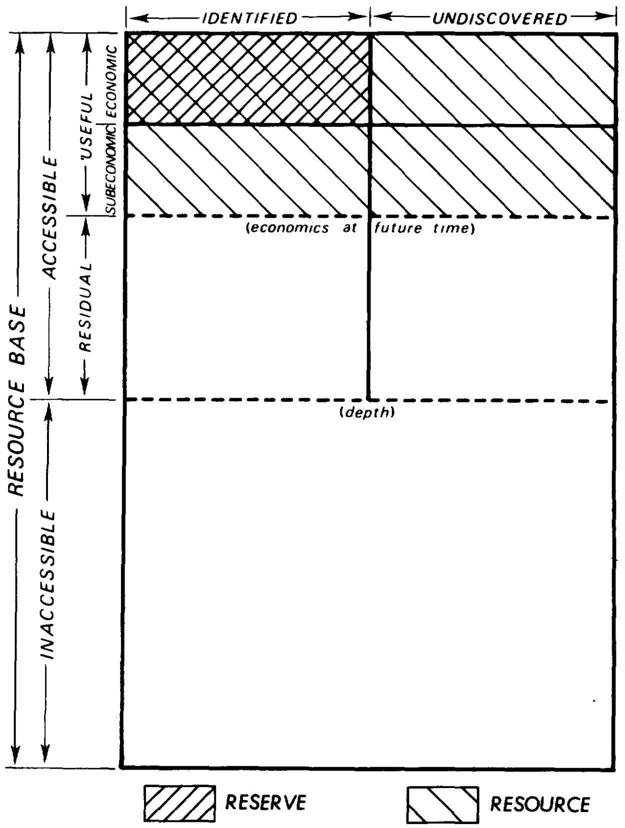

Figure 2.--McKelvey diagram for geothermal energy, showing derivation of the terms resource and reserve (from Muffler and Cataldi, 1978). Vertical axis is degree of economic feasibility; horizontal axis is degree of geologic assurance.

UNITS

The International System of Units (SI) is used where possible throughout this report, following the recommendations of the National Bureau of Standards (Page and Vigoureux, 1972). Conversions to other common units are given in table 2. Note particularly that energies in Circular 790 are in joules (J), whereas in Circular 726 energies are in calories (1 calorie = 4.186 J). All energies reported in Circular 790 are given in units of 10^{18} J because 10^{18} J is approximately 10^{15} British thermal unit (Btu), which in turn equals one quad (a quadrillion Btu).

Following Muffler and Cataldi (1978), we adopt the convention of specifying electrical power or capacity in megawatts electrical, abbreviated MWe. Electrical energy is thus given in megawatts electrical for a specified time (for example, MWe for 30 yr). When thermal power is expressed in megawatts, the abbreviation is MWt to avoid any confusion with electrical power or capacity.

ACKNOWLEDGMENTS

This Circular represents the cooperative work of many contributors from government, private industry, and academic institutions. Without the unselfish help of innumerable persons, the job could not have been done. To all those who have willingly given their help, data, advice, and criticism, we express our deepest thanks.

A large part of the data that have been incorporated in this assessment comes from the USGS Geothermal Research Program, an interdisciplinary research effort carried out in Geologic and Water Resources Divisions of the USGS and by extramural grants and contracts (Muffler and Christiansen, 1978). In addition, we have drawn heavily on nonproprietary data in Conservation Division and have been aided greatly by personnel in district offices of Water Resources Division. We are indebted to numerous State agencies for assistance in compilation of data relating to hydrothermal convection systems and to low-temperature geothermal waters. We also wish to acknowledge the cooperation of many private companies in supplying data on hydrothermal convection systems and on geopressured-geothermal waters.

Several individuals contributed greatly to this resource asesssment in ways that are not explicitly recognized or apparent in the text. Manuel Nathenson was an invaluable guide, major contributor, perceptive critic, and sympathetic advisor throughout the entire effort. Paul J. Grim of the NOAA National Geophysical and Solar-Terrestrial Data Center and George W. Berry of the Earth Science Laboratory of the University of Utah Research Institute were reliable and flexible colleagues in the preparation of the maps, particularly in providing many trial versions and in incorporating many last-minute changes in data and organization. James A. Swanson provided invaluable computer support, not only in the organization of the data on hydrothermal convection systems, but also in trial depictions of a variety of data for the low-temperature evaluation. Duncan Foley of the Earth Science Laboratory of the University of Utah Research Institute enthusiastically helped compile and interpret data on low-temperature geothermal waters.

We also wish to thank our advisory group, consisting of Robert L. Christiansen, Robert G. Coleman, Robert O. Fournier, Donald W. Klick, Arthur H. Lachenbruch, Manuel Nathenson, Frank W. Olmsted, Reid T. Stone, Frank W. Trainer, Alfred H. Truesdell, and Donald E. White.

Finally, we acknowledge the continuing support and encouragement of Robert L. Christiansen (Coordinator, USGS Geothermal Research Program), John H. Salisbury (DOE Division of Geothermal Energy), and Clayton R. Nichols (DOE Division of Geothermal Energy).

Table 2.--*Conversion factors*

Mass:	1 kilogram (kg) = 2.205 pound (lb)
Length:	1 meter (m) = 3.281 foot (ft) 1 kilometer (km) = 0.6214 mile (mi)
Area:	1 km^2 = 0.3861 mi^2
Volume:	1 liter (L) = 0.2642 gallon (gal) 1 km^3 = 0.2399 mi^3
Temperature:	Degrees Celsius (^oC) = 5/9(degrees Fahrenheit-32) 0^oC = 273.15 kelvin (K)
Temperature gradient:	$1^oC/m$ = $0.55^oF/ft$
Pressure (absolute)	10^5 Pascal (Pa) = 1 bar = 0.9869 atmosphere (atm) = 14.50 lb/in^2 (psia)
Energy:	1 joule (J) = 0.239 calorie (cal) = 9.480 x 10^{-4} British thermal unit (Btu) 10^{18} J ≃ 10^{15} Btu = 1 quad
Energy equivalent of methane:	≃ 1000 Btu per standard cubic foot of methane ≃ 3.73 x 10^7 J per standard cubic meter of methane
Power:	1 watt (W) = 1 J/s = 0.239 cal/s
Heat flow:	1 milliwatt per m^2 = 10^{-7} $J/cm^2/s$ = 2.39 x 10^{-8} $cal/cm^2/s$ = 2.39 x 10^{-2} heat flow units (HFU)

REFERENCES CITED

Diment, W. H., Urban, T. C., Sass, J. H., Marshall, B. V., Munroe, R. J., and Lachenbruch, A. H., 1975, Temperatures and heat contents based on conductive transport of heat, in White, D. E., and Williams, D. L., (eds.), Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 84-103.

Haas, J. L., Jr., An empirical equation with tables of smoothed solubilities of methane in water and aqueous sodium-chloride solutions up to 25 weight percent, 360°C, and 138 MPa: U. S. Geological Survey Open-File Report 78-1004, 41 p.

Mariner, R. H., Brook, C. A., Swanson, J. R., and Mabey, D. R., 1978, Selected data for hydrothermal convection systems in the United States with estimated temperatures ≥90°C: U. S. Geological Survey Open-File Report 78-858.

Muffler, L. J. P., and Cataldi, R., 1978, Methods for regional assessment of geothermal resources: Geothermics, v. 7, no. 2-4. (in press)

Muffler, L. J. P., and Christiansen, R. L., 1978, Geothermal resource assessment of the United States: Pure and Applied Geophysics, v. 117, p. 160-171.

Nathenson, Manuel, 1975, Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas: U. S. Geological Survey Open-File Report 75-525, 35 p.

_____, 1978, Methodology of determining the uncertainty in the accessible resource base of identified hydrothermal convection systems: U. S. Geological Survey Open-File Report 78-1003, 50 p.

Nathenson, Manuel, and Muffler, L. J. P., 1975, Geothermal resources in hydrothermal convection systems and conduction-dominated areas, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 104-121.

Page, C. H, and Vigoureux, Paul, 1972, The international system of units (SI): U. S. National Bureau of Standards Special Publication 330, 42 p.

Papadopulos, S. S., Wallace, R. H., Jr., Wesselman, J. B., and Taylor, R. E., 1975, Assessment of geopressured-geothermal resources in the northern Gulf of Mexico basin, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 125-146.

Peck, D. L., 1975, Recoverability of geothermal energy directly from molten igneous systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 122-124.

Renner, J. L., White, D. E., and Williams, D. L., 1975, Hydrothermal convection systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 5-57.

Renner, J. L., and others, 1976, Selected geothermal resources data: hydrothermal convection systems in the states of Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming: National Technical Information Service CRPU-76-16, 358 p.

Schanz, J. J., Jr., 1975, Resource terminology: an examination of concepts and terms and recommendations for improvement: Palo Alto, Calif., Electric Power Research Institute, Research Project 336, August 1975, 116 p.

Schurr, S. H., and Netschert, B. C., 1960, Energy in the American economy, 1850-1975: Baltimore, Johns Hopkins Press, 774 p.

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 58-83.

Smith, R. L., Shaw, H. R., Luedke, R. G., and Russell, S. L., 1978, Comprehensive tables giving physical data and energy estimates for young igneous systems of the United States: U. S. Geological Survey Open-File Report 78-925.

U. S. Geological Survey, 1976, Principles of the mineral resource classification system of the U. S. Bureau of Mines and U. S. Geological Survey: U. S. Geological Survey Bulletin 1450-A, 5 p.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, 155 p.

Wright, P. M., Foley, Duncan, Nichols, C. R., and Grim, P. J., 1978, Western States cooperative direct heat geothermal program of DOE: Geothermal Resources Council Transactions, vol. 2, p. 739-742.

Heat Flow and Conduction-Dominated Thermal Regimes

By John H. Sass and Arthur H. Lachenbruch

ABSTRACT

Refined regional heat-flow data do not change the conclusion of Diment and others (1975) in USGS Circular 726 that $33 \pm 4 \times 10^{24}$ J of thermal energy is stored at temperatures above mean annual surface temperature in the outer 10 km of the Earth beneath the United States. Updated heat-flow information is depicted on maps 1 and 2.

INTRODUCTION

At most of the localities under consideration for the exploitation of geothermal energy, heat is being transported to (or almost to) the ground surface primarily by the vertical motion of water and(or) steam. However, even in the thermally active Western United States, such localities are anomalous, and they occupy a very small fraction of the Earth's surface. Beneath the vast majority of the land area of the United States, the vertical transport of heat in the upper crust is believed to be primarily by thermal conduction. Under this condition, the temperature to depths of several kilometers can be estimated with some confidence from measurements of the rate of conductive heat flow in wells drilled to depths of only a few hundred meters or less. Consequently, a knowledge of the regional distribution of heat flow permits an estimate of the regional distribution of heat stored in the upper crust. An estimate of this quantity, based on heat-flow data available in 1975, was developed in some detail by Diment and others (1975). They concluded that the heat stored at temperatures above the mean annual surface temperature in the outer 10 km of the Earth beneath the United States was about $8 \pm 1 \times 10^{24}$ calories ($33 \pm 4 \times 10^{24}$ joules). This is the amount of heat that would have to be extracted if the entire 10-km layer were to be cooled to the temperature characteristic of the Earth's surface. Inasmuch as the energy that can be extracted is only a fraction of what is theoretically available, interest in this quantity of heat lies mainly in its order of magnitude, which would not be changed if the 1975 calculations were repeated using the more refined information on regional heat flow presently available. However, estimates of the heat storage and of the ambient thermal regime beneath particular regions and the design of exploration programs, both regional and local, do depend upon refinements in the regional heat-flow distribution. For this reason, updated heat-flow information is presented on maps of the Western United States and Alaska (maps 1 and 2).

HEAT-FLOW CONTOURS

Heat-flow contours shown on map 1 of the western conterminous United States represent an additional contribution to a series of contour maps beginning with the preliminary version by Sass and others (1976). Lachenbruch and Sass (1977) showed the heat-flow contours in relation to hot springs, seismicity, and Cenozoic volcanism, and a refined version for the Western United States was published as figure 1 of Lachenbruch and Sass (1978). The contours on the map accompanying this volume are generalized from the preceeding figure 1 with additional control from Oregon (Hull and others, 1977) and Colorado and New Mexico (Edwards and others, 1977). A list of the published sources of heat-flow data is given at the end of this report.

Although no heat-flow data are available for large regions of the Western United States, many individual areas have coverage much too dense to be represented as individual data points at the scale of this map. It was therefore necessary to generalize in many areas. In areas where heat flow was fairly uniform, the control was generalized simply by deleting some data points and leaving sufficient control to characterize the local heat flow. In other areas where heat flow varies greatly over short distances, an average heat flow was plotted for the mean coordinates. The most extreme example of this procedure was Grass Valley, Nevada, where data from 82 sites within a 200-km^2 area (Sass and others, 1977) were combined and shown as a single point on the map. Thus the reader interested in the detailed local coverage of a given area is urged to consult the source publications listed below.

REFERENCES CITED

Diment, W. H., Urban, T. C., Sass, J. H., Marshall, B. V., Munroe, R. J., and Lachenbruch, A. H., 1975, Temperatures and heat contents based on conductive transport of heat, in White, D.E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 84-103.

Edwards, C. L., Reiter, Marshall, Shearer, Charles, and Young, Wesley, 1977, Terrestrial heat flow and crustal radioactivity in northeastern New Mexico and southeastern Colorado: Geological Society of America Bulletin, v. 89, no. 9, p. 1341-1350.

Hull, D. A., Blackwell, D. D., Bowen, R. G., and Peterson, N. V., 1977, Heat flow study of the Brothers fault zone, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report 0-77-3, 43 p.

Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, in Heacock, J. G., ed., The Earth's crust--its nature and physical properties: American Geophysical Union Geophysical Monograph 20, p. 626-675.

_____, 1978, Models of an extending lithosphere and heat flow in the Basin and Range Province, in Smith, R. B., and Eaton, G. P., Cenozoic tectonics and regional geophysics of the Western Cordillera: Geological Society of America Memoir 152. (in press)

Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Monroe, R. J., Moses, T. H., Jr., and Urban, T. C., 1976, A heat-flow contour map of the conterminous United States: U. S. Geological Survey Open-File Report 76-756, 24 p.

Sass, J. H., Ziagos, J. P., Wollenberg, H. A., Munroe, R. J., di Somma, D. E., and Lachenbruch, A. H., 1977, Application of heat-flow techniques to geothermal energy exploration, Leach Hot Springs area, Grass Valley, Nevada: U. S. Geological Survey Open-File Report 77-762, 125 p.

PUBLISHED SOURCES FOR HEAT-FLOW MAP

1. Benfield, A. E., 1947, A heat flow value for a well in California: American Journal of Science, v. 245, p. 1-18.

2. Birch, Francis, 1950, Flow of heat in the Front Range, Colorado: Geological Society of America Bulletin, v. 61, p. 567-630.

3. Birch, Francis, and Clark, Harry, 1945, An estimate of the surface flow of heat in the west Texas Permian Basin: American Journal of Science v. 243-A, p. 69-74.

4. Blackwell, D. D., 1967, Terrestrial heat flow determinations in the northwestern United States: Cambridge, Massachusetts, Harvard University, Ph.D. thesis, 147 p.

5. _____, 1969, Heat flow determinations in the northwestern United States: Journal of Geophysical Research, v. 74, p. 992-1007.

6. _____, 1974, Terrestrial heat flow and its implications on the location of geothermal reservoirs in Washington: Washington Division of Mines and Geology Information Circular no. 50, p. 21-33.

7. Blackwell, D. D., and Baag, D., 1973, Heat flow in a blind geothermal area near Marysville, Montana: Geophysics, v. 38, p. 941-956.

8. Blackwell, D. D., and Robertson, E. C., 1973, Thermal studies of the Boulder batholith and vicinity, Montana: Society of Economic Geologists Guidebook, Butte Field Meeting, Aug. 18-21, p. D-1, D-8.

9. Bowen, R. G., 1973, Geothermal activity in 1972: Ore Bin, v. 35, no. 1, p. 4-7.

10. Brott, C. A., Blackwell, D. D., and Mitchell, J. C., 1976, Heat flow study of the Snake River Plain region, Idaho: Geothermal investigations in Idaho, Water Information Bulletin 30, part 8, Idaho Department of Water Resources, 195 p.

11. Clark, S. P., Jr., 1957, Heat flow at Grass Valley, California: Transactions, American Geophysical Union, v. 38, p. 239-244.

12. Combs, J. B., 1970, Terrestrial heat flow in North Central United States: Cambridge, Massachusetts, Massachusetts Institute of Technology, Ph.D. thesis, 317 p.

13. _____, 1971, Heat flow and geothermal resource estimates for the Imperial Valley, in Cooperative geological-geophysical-geochemical investigations of geothermal resources in the Imperial Valley area of California: University of California, Riverside, Education Research Service, p. 5-27.

14. _____, 1975, Heat flow and microearthquake studies, Coso geothermal area, China Lake, California: Final Report, Order Number 2800, contract NO0123-74-C-2099, Advanced Research Projects Agency, Washington, D.C., p. 65.

15. Combs, J. B., and Simmons, G., 1973, Terrestrial heat flow in the north central United States: Journal of Geophysical Research, v. 78, p. 441-461.

16. Costain, J. K., and Wright, P. M., 1973, Heat flow at Spor Mountain, Jordan Valley, Bingham, and La Sal, Utah: Journal of Geophysical Research, v. 78, no. 35, p. 8687-8698.

17. Decker, E. R., and Birch, Francis, 1974, Basic heat flow data from Colorado, Minnesota, New Mexico, and Texas: U. S. Geological Survey Open-File Report 74-9, p. 5-1 - 5-59.

18. Decker, E. R., and Smithson, S. B., 1973, Geophysical studies in the southern Rio Grande Rift: EOS (American Geophysical Union Transactions), v. 54, p. 463.

19. _____, 1975, Heat flow and gravity interpretation across the Rio Grande Rift in southern New Mexico and west Texas: Journal of Geophysical Research, v. 80, p. 2542-2552.

20. Edwards, C. L., Reiter, Marshall, Shearer, Charles, and Young, Wesley, 1977, Terrestrial heat flow and crustal radioactivity in northeastern New Mexico and southern Colorado: Geological Society of America Bulletin, v. 89, no. 9, p. 1341-1350.

21. Henyey, T. L., 1968, Heat flow near major strike-slip faults in central and southern California: Pasadena, California, California Institute of Technology, Ph.D. thesis, 414 p.

22. Henyey, T. L., and Wasserburg, G. J., 1971, Heat flow near major strike-slip faults in California: Journal of Geophysical Research, v. 76, no. 32, p. 7924-7946.

23. Henyey, T. L., and Lee, T. C., 1976, Heat flow in Lake Tahoe, California-Nevada, and the Sierra Nevada - Basin and Range transition: Geological Society of America Bulletin, v. 87, no. 8, p. 1179-1187.

24. Herrin, E. T., and Clark, S. P., 1956, Heat flow in west Texas and eastern New Mexico: Geophysics, v. 21, p. 1087-1099.

25. Hull, D. A., Blackwell, D. D., Bowen, R. G., and Peterson, N. V., 1977, Heat flow study of the Brothers fault zone, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report 0-77-3, 43 p.

26. Lachenbruch, A. H., Sass, J. H., Munroe, R. J., and Moses, T. H., Jr., 1976, Geothermal setting and simple heat conduction models for the Long Valley caldera: Journal of Geophysical Research, v. 81, p. 769-784.

27. Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, in Heacock, J. G., ed., The Earth's crust--its nature and physical properties: American Geophysical Union Geophysical Monograph 20, p. 626-675.

28. Lachenbruch, A. H., and Sass, J. H., 1978, Models of an extending lithosphere and heat flow in the Basin and Range Province, in Smith, R. B., and Eaton, G. P., Cenozoic tectonics and regional geophysics of the Western Cordillera: Geological Society of America Memoir 152. (in press)

29. Lovering, T. S., 1949, Geothermal gradients, recent climatic changes, and rate of sulfide oxidation in the San Manuel district, Arizona: Economic Geology, v. 43, p. 1-20.

30. Morgan, Paul, Blackwell, D. D., Spafford, R. E., and Smith, R. B., 1977, Heat flow measurements in Yellowstone Lake and thermal structure of the Yellowstone caldera: Journal of Geophysical Research, v. 82, no. 26, p. 3719-3732.

31. Potter, R. M., 1973, Heat flow of the Jemez Plateau (abs.): EOS (American Geophysical Union Transactions), v. 54, no. 11, p. 1214.

32. Reiter, M. A., and Costain, J. K., 1973, Heat flow in southwestern Virginia: Journal of Geophysical Research, v. 78, p. 1323-1333.

33. Reiter, M., Edwards, C. L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande Rift, New Mexico and southern Colorado: Geological Society of America Bulletin, v. 86, p. 811-818.

34. Roy, R. F., 1963, Heat flow measurements in the United States: Cambridge, Massachusetts, Harvard University, Ph.D. thesis, 76 p.

35. Roy, R. F., Blackwell, D. D., and Birch, F., 1968, Heat generation of plutonic rocks and continental heat flow provinces: Earth and Planetary Science Letters, v. 5, no. 1, p. 1-12.

36. Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, F., 1968, Heat flow in the United States: Journal of Geophysical Research, v. 73, p. 5207-5221.

37. Roy, R. F., Blackwell, D. D., and Decker, E. R., 1972, Continental heat flow, in Robertson, E. C., ed., The nature of the solid Earth: New York, McGraw-Hill, p. 506-543.

38. Sass, J. H., Munroe, R. J., and Lachenbruch, A. H., 1968, Measurement of geothermal flux through poorly consolidated sediments: Earth and Planetary Science Letters, v. 4, p. 293-298.

39. Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., Jr., 1971, Heat flow in the western United States: Journal of Geophysical Research, v. 76, p. 6376-6413.

40. Sass, J. H., Olmsted, F. H., Sorey, M. L., Wollenberg, H. A., Lachenbruch, A. H., Munroe, R. J., Galanis, S. P., Jr., 1976, Geothermal data from test wells drilled in Grass Valley and Buffalo Valley, Nevada: U. S. Geological Survey Open-File Report 76-85, 43 p.

41. Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Munroe, R. J., Moses, T. H., Jr., and Urban, T. C., 1976, A heat-flow contour map of the conterminous United States: U. S. Geological Survey Open-File Report 76-756, 24 p.

42. Sass, J. H., Galanis, S. P., Jr., Munroe, R. J., and Urban, T. C., 1976, Heat-flow data from southeastern Oregon: U. S. Geological Survey Open-File Report 76-217, 52 p.

43. Sass, J. H., and Sammel, E. A., 1976, Heat flow data and their relation to observed geothermal phenomena near Klamath Falls, Oregon: Journal of Geophysical Research, v. 81, p. 4863-4868.

44. Sass, J. H., Galanis, S. P., Jr., Marshall, B. V., Lachenbruch, A. H., Munroe, R. J., Moses, T. H., Jr., 1977, Conductive heat flow in the Randsburg area, California: U. S. Geological Survey Open-File Report 78-756, 45 p.

45. Sass, J. H., Ziagos, J. P., Wollenberg, H. A., Munroe, R. J., di Somma, D. E., and Lachenbruch, A. H., 1977, Application of heat-flow techniques to geothermal energy exploration, Leach Hot Springs area, Grass Valley, Nevada: U. S. Geological Survey Open-File Report 77-762, 125 p.

46. Spicer, H. C., 1964, Geothermal gradients and heat flow in the Salt Valley anticline, Utah: Bolletino di Geofisica Teorica ed Applicata, v. 6, no. 23, p. 263-282.

47. Urban, T. C., and Diment, W. H., 1975, Heat flow on the south flank of the Snake River Rift (abs.): Geological Society of America Abstracts with Programs, v. 7, p. 648.

48. Warren, R. E., Sclater, J. G., Vacquier, Victor, and Roy, R. F., 1969, A comparison of terrestrial heat flow and transient geomagnetic fluctuations in the southwestern United States: Geophysics, v. 34, p. 463-478.

49. Wright, P. M., 1966, Geothermal gradient and regional heat flow in Utah: Salt Lake City, Utah, University of Utah, Ph.D. thesis, 181 p.

Igneous-Related Geothermal Systems

By R. L. Smith and H. R Shaw

ABSTRACT

Calculations based on conductive cooling of magma indicate that 101,000 x 10^{18} J still remains in evaluated young igneous-related systems of the United States to a depth of 10 km. The total energy in both evaluated and unevaluated young igneous-related systems is estimated to be an order of magnitude greater. Recent studies of the effects of hydrothermal processes on the cooling of a pluton do not change the conclusions of Smith and Shaw (1975) in USGS Circular 726 that the effects of hydrothermal cooling are balanced by the effects of magmatic preheating and additions of magma after the presumed time of emplacement.

INTRODUCTION

In USGS Circular 726 we developed a rationale for identification and evaluation of geothermal systems associated with young igneous rocks. We also presented relevant data, available in 1975, on known young systems and devised a simplified general scheme to provide a numerical basis for evaluation of the resource base.

Since 1975 an abundance of new data has been generated and several in-depth studies have been made; others are in progress. This continuing research is directed toward creating a framework within which much more systematic and quantitative evaluations will be possible. Currently, however, the new information does not indicate a need for any major conceptual revisions of the models considered in 1975 for systems of fixed volumes dominated by conductive cooling in the roof rocks; in fact the new data appear to strengthen the concepts and estimates made in Circular 726 for that restricted class of igneous systems. This report only updates and refines the data base and graphical interpretation of Circular 726, which provides more detailed background.

ESTIMATES OF THERMAL ENERGY

The principal basis for estimating thermal energy in igneous-related geothermal systems is the evidence for the existence of high-level silicic magma chambers, their volumes, and the ages of the latest eruptions from them. These data are given in table 1 of USGS Open-File Report 78-925 (Smith and others, 1978), which furnishes details of calculations leading to estimates of thermal energy still remaining in the ground. These calculations are based on the assumption that a fixed volume of magma cooled from an initial temperature of 850°C to its present temperature purely by conduction in surrounding rocks, starting from a fixed time. We emphasize that this assumption is an oversimplification of the complex processes taking place as magma solidifies and cools in the Earth's crust. Notwithstanding, the assumption is justified as a simple and logical model to make quantitative estimates of thermal energy. Estimates made on this basis are conservative (see Smith and Shaw, 1975, p. 74-76 for a discussion of factors that influence the estimate).

The existence of hydrothermal activity does not change our general conclusions even though it affects the cooling times for chambers of fixed volumes, as discussed later in this report. Our conclusions are based on the fact that each of the silicic chambers for which volume estimates were made has a long prehistory of magmatic activity that represents additional thermal energy in the surrounding crustal rocks that is not accounted for in the estimates for single chambers.

Table 3 is abstracted from the comprehensive table of Open-File Report 78-925, which has been updated from table 7 of Smith and Shaw (1975). Table 3 gives an estimate of the amount of the thermal energy that still remains in the ground (in magma, solidified pluton, and roof rocks) for conduction models referred to dry rock. Table 3 includes only those systems that can be inferred to have high-level magma chambers, generally silicic, and for which age and size data are adequate to make a thermal estimate. These systems are located on maps 1 and 2, the number of triangles around the dot symbolizing the range of thermal energy still remaining in the ground. The same systems are also plotted on figure 3 in order to indicate the present solidification state.

UNEVALUATED AND UNDISCOVERED IGNEOUS SYSTEMS

Our 1975 report indicated that the total igneous-related energy was at least 2 and possibly up to 10 times greater than our estimate for identified systems ($\sim$25,000 calories = $\sim$105,000 joules). We were not more explicit because of the large uncertainties in estimating volcanic lifetimes prior to the youngest eruption. Table 26 of the summary article (White and Williams, 1975) of Circular 726, however, did give an estimate of $\sim$75,000 calories ($\sim$310,000 joules) for the undiscovered thermal energy in hot igneous systems to a depth of 10 km. Because this estimate has been cited in subsequent reports (for example, Milora and Tester, 1976; Muffler and Christiansen, 1978), an updated comment is in order.

Table 3.--*Thermal energy still remaining in igneous systems of the United States*

(Abstracted from column 11 of table 1 of Smith and others, 1978)

Name and number	Name of area	Thermal energy remaining in system (10^{18} joules)
ALASKA		
AK 4	Davidof	29
AK 5	Little Sitkin	180
AK 6	Semisopochnoi (Cerberus)	360
AK 9	Tanaga	960
AK 10	Takawangha	54
AK 12	Kanaga	180
AK 14	Adagdak	50
AK 15	Great Sitkin	>13
AK 22	Seguam	480
AK 25	Yunaska	96
AK 34	Okmok	603
AK 37	Makushin	25
AK 39	Akutan	25
AK 43	Fisher	1440
AK 51	Emmons	1440
AK 58	Veniaminof	481
AK 59	Black (Purple)	50
AK 60	Aniakchak	540
AK 63	Peulik (Ugashik caldera)	71
AK 66	Novarupta	120
AK 69	Katmai	50
AK 75	Kaguyak	38
AK 84	Drum	~840
AK 86	Wrangell	120
AK 87	White River	190
AK 88	Edgecumbe	603
ARIZONA		
AZ 1	San Francisco Mountains	3010
AZ 2	Kendrick Peak	150
AZ 3	Sitgreaves Peak	46
AZ 4	Bill Williams Mountain	4
CALIFORNIA		
CA 1	Lassen Peak	960
CA 2	Clear Lake	3610
CA 3	Long Valley	5780
CA 4	Salton Sea	480
CA 5	Coso Mountains	1570
CALIFORNIA--Continued		
CA 6	Mono Domes	1570
CA 7	Medicine Lake	724
CA 8	Shasta	724
CA 9	Sutter Buttes	<42
CA 14	Big Pine	<85
CA 19	Templeton Domes	603
HAWAII		
H 1	Kilauea	96
IDAHO		
ID 1	Island Park system	16,850
ID 3	Blackfoot Domes	240
ID 4	Big Southern Butte	<240
ID 6	Rexburg Caldera	8400
NEW MEXICO		
NM 1	Valles Caldera	8425
OREGON*		
OR 1	Crater Lake	>770
OR 2	Newberry	240
OR 3	South Sister	240
OR 14	Glass Buttes	<40?
OR 19	Wart Peak Caldera	8
OR 20	Frederick Butte area	4
UTAH		
UT 1	Mineral Mountains	710
UT 2	Cove Creek Domes	84
UT 4	Thomas Range	42
WASHINGTON		
WA 2	Glacier Peak	35?
WA 4	Mount St. Helens	>35
WYOMING		
WY 1	Yellowstone Caldera system	36,100
TOTAL OF BOTH COLUMNS		101,000

*Preliminary thermal energy calculations have been made for three additional systems in Oregon: OR 7, Melvin-Three Creeks Buttes (76×10^{18} J); OR 8, Cappy-Burn Butte (26×10^{18} J); OR 18, Bearwallow Buttes (41×10^{18} J). These estimates are not shown on map 1 as triangles because of an oversight. However, these systems are plotted on figure 3 of this report and are listed on table 1 of Open-File Report 78-925.

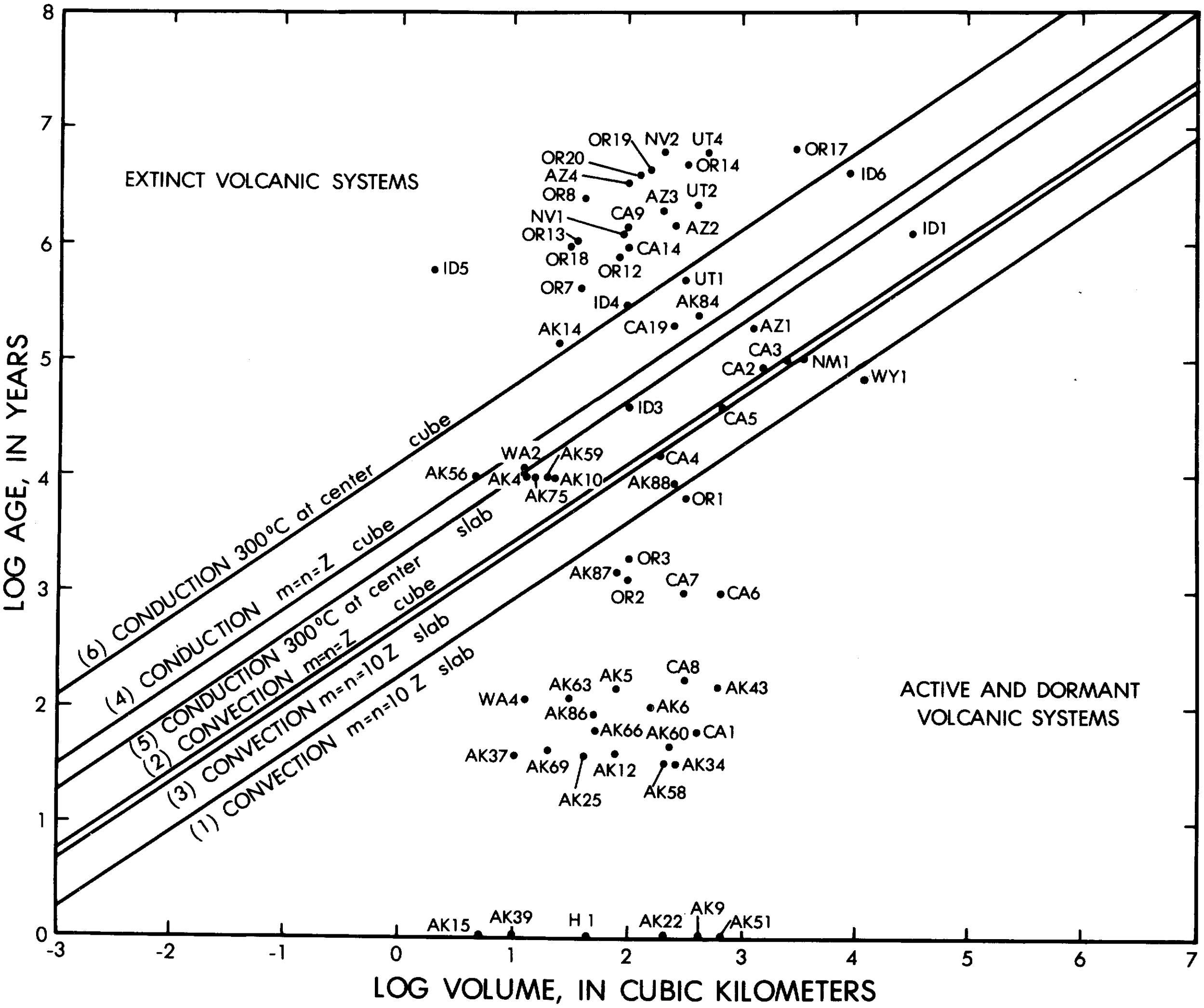

Figure 3--Relation of theoretical cooling models (straight lines) to ages and sizes of young igneous systems of the Western United States. Lines 1-4 are models for cooling from 850° to 650°C; lines 5 and 6 represent the total time required for the center of the magma chamber to cool to 300°C. Lines 1 and 2 assume that cooling is by conduction in the country rock but is accompanied by convection within the magma chamber. Lines 3 and 4 assume that cooling is by conduction only, both inside and outside the magma chamber. Lines 1, 3, and 5 are for a slab model with horizontal dimensions (m and n) 10 times the vertical dimension (z). Lines 2, 4, and 6 are for a cubic model. Points representing young igneous systems of the United States are plotted at the age of the youngest known (or dated) associated extrusion. Assuming that the entire plotted volume of the magma chamber was instantaneously emplaced and cooled from this time, the figure gives an estimate of the likely solidification state and temperature today. For example, a system that plots below lines 1 and 2 probably still has a magma chamber with a large molten fraction, whereas a system that plots above lines 5 and 6 is now approaching ambient temperatures at the depth of emplacement. Those systems for which thermal energies are calculated from the age and volume data of Smith and others (1978) are named in table 3. Ten additional systems plotted on this figure have age and volume data deemed too tentative for reliable estimation of thermal energies: AK 56 (Dana), ID 5 (East Butte), NV 1 (Steamboat Springs), NV 2 (Silver Peak), OR 7 (Melvin-Three Creeks Buttes), OR 8 (Cappy-Burn Butte area), OR 12 (China Hat and East Butte), OR 13 (Quartz Mountain), OR 17 (Harney-Malheur), and OR 18 (Bearwallow Buttes).

We now feel that the total igneous-related energy is at least an order of magnitude greater than our updated fixed-volume estimate of ~101,000 joules (table 3), and thus substantially greater than the 1975 estimate of White and Williams. Very young systems with relatively small single-chamber volumes are likely to have subchamber support systems much greater in extent and longevity than are inferred from the age and extent of surface volcanic products (table 1 of Open-File Report 78-925).

It is not possible at present to give a more quantitative estimate of this undiscovered and unevaluated igneous thermal energy, primarily because the number of age determinations of volcanic rocks up to 20 million years old is still inadequate. New geochronologic studies since 1975 (for example, Duffield and others, 1979) demonstrate the age data needed for all of the identified systems, including the older systems and the older parts of young systems. Evaluation of the overall thermal budget requires that greatly increased attention be given to developing additional systematic and extensive suites of age determinations. We are confident that a tenfold increase in the number of determinations for carefully selected rocks erupted during the last 20 million years will allow us to make a numerical estimate of the total thermal energy remaining today in all hot igneous systems. Furthermore, we should be able to give rough breakdowns according to depth and to evaluate hydrothermal redistribution of thermal energy along the lines discussed below.

EFFECT OF HYDROTHERMAL CIRCULATION ON COOLING MODELS

The role of hydrothermal systems in magmatic cooling was stated in necessarily vague terms in 1975. Unpublished calculations made at that time representing a variety of limiting hydrothermal effects indicated that the time scales and proportions of heat loss by circulating ground waters probably would not shorten the cooling time portrayed in figure 4 (Circ. 726) by more than a factor of about two. This factor could not be stated with confidence, however, and the question was left open.

Recently, several studies (Norton and Knight, 1977; Peck and others, 1977; Shaw and others, 1977) representing widely different approaches to the effects of hydrothermal cooling in and around magma bodies indicate that it may be timely to begin outlining a concept of hydrothermal cooling efficiencies for magmatic systems. At present, the application of this concept to actual igneous systems is largely subjective. Therefore, we mention only a few types of systems that may represent limiting cases of efficiencies; "high efficiency" refers to situations in which large volumes of groundwater circulating in the vicinities of magma bodies greatly increase local cooling rates relative to pure conduction of heat through dry rock.

In order to give some quantitative perspective to the scale of efficiencies, we mention three types of reference conditions representing "calibration points." The zero efficiency reference condition is given by the conduction models discussed in Circular 726. Another reference condition is chosen from the set of hydrothermal convection models of Norton and Knight (1977); the third condition is based on precise monitoring and numerical modeling of contrasting cooling histories, in conduction and water-quenched modes, of a ponded body of lava with sheetlike geometry (Shaw and others, 1977; Peck and others, 1977).

None of these reference conditions represents an exact cooling model because of uncertainties in thermal properties. For any system, the 50 percent probable error cited by Smith and Shaw (1975, p. 75) still represents a rule-of-thumb estimate of uncertainty in thermal properties and boundary conditions for closed systems. The hydrothermal effects are superimposed on these sets of conditions in a manner analogous to, but of opposite sign from, the effects of continuing supplies of magma at depth below high-level chambers.

One conclusion illustrated by either of the hydrothermal cooling models (Norton and Knight, 1977; Shaw and others, 1977) is that calculated times for solidification of magma by either conduction or magma convection models (see fig. 4, Circ. 726) are affected negligibly by the presence and amount of water in the surroundings. Water cannot transfer heat or penetrate the solidifying outer shells of an initially continuous magma body fast enough by any of the mechanisms investigated to date to greatly influence the interior cooling regimes that govern the overall duration of magmatic crystallization. However, water can profoundly influence the later stages of subsolidus cooling and hence significantly shorten the overall time required for cooling from the emplacement temperature to ambient temperature.

The main difference between the two types of hydrothermal cooling models relates to the boundary conditions controlling the access of water to the magma surface. Cooling of plutons by hydrothermal convection of groundwater (Norton and Knight, 1977) depends primarily on porosity and permeability of the surrounding rocks in relation to the surface area of the igneous contacts; the amount of cooling depends on the heat carried by the convecting fluid and lost elsewhere by combined convective-conductive processes. Cooling of a lava sheet subjected to rainfall, on the other hand, involves these processes but is dominated by virtually instantaneous contact of the water, via a complex of contraction joints and cracks, with rock at temperatures exceeding the vaporization temperature of water (Shaw and others, 1977). In this type of cooling model, the recharge source of water (rainfall on the actual lava surface) is at the immediate igneous contact, and each volume increment of water lost by vaporization carries with it an amount of heat exceeding the latent heat of vaporization. In other words, the potential heat sink for hydrothermal cooling is much greater by this model than by convection of groundwater without extensive vaporization, or even with vaporization if recondensation occurs within the hydrothermal convection system; recondensation is likely in the roof rocks above most intrusive igneous systems and in the upper parts of extrusive bodies thicker than a few tens of meters (the extrusive sheet studied by Shaw and others, 1977, was about 15 meters thick). The rate-limiting relation of the vaporization model is a balance between the heat conducted to the vaporization interface (approximately the 100°C isotherm) and the amount of rainfall supplying the recharge of water. Thus, this model probably represents the most efficient realizable mechanism of hydrothermal quenching of initially continuous bodies of magma in environments of significant rainfall; we specifically exclude consideration of subaqueous and composite lava flows. In both sorts of hydrothermal models, the area of the upper igneous contact is of primary importance in determining rates of cooling. The effects of lateral margins and the lower contacts are of secondary significance for slablike bodies, but adjoining hydrothermal cells may contribute significantly to the cooling of bodies that are taller than they are wide (see Norton and Knight, 1977)

Comparison of the vaporization model with conduction models (Shaw and others, 1977, p. 401) and with hydrothermal convection models (Norton and Knight, 1977) places some approximate numerical limits on the range of possible hydrothermal cooling rates. The vaporization model for a lava sheet subjected to 250 cm of rainfall per year indicated that the time to reach a maximum of 100°C at the center of the sheet is one-fifth the time to reach that temperature by conduction. This result agrees well with an actual record of temperatures of Alae lava lake, Hawaii (Peck and others, 1977). Judged from the array of hydrothermal convection models by Norton and Knight (1977), the analogous lifetime of subsolidus cooling by hydrothermal convection could be about half the conduction time; that is, hydrothermal convection models are much less effective than the vaporization models. These proportions suggest the possibility of creating a numerical scale of efficiencies for the purpose of comparisons and eventual classification of coupled igneous-hydrothermal systems.

The envisaged scale of hydrothermal cooling efficiencies is a factor scale ranging from zero to 100 percent. The zero refers simply to the limit of conductive models for total durations of cooling in hot dry rock. The 100 percent limit corresponds to quenched systems penetrated by water over all cooling surfaces at rates equivalent to the model of Shaw and others (1977). On this scale the model of the lava sheet quenched by rainfall penetrating the porous and permeable upper surface represents roughly 50 percent efficiency. Most hydrothermal systems above high-level silicic chambers would be considerably less efficient than the model of quenched lava; efficiencies probably range from zero to 20 percent. For example, Yellowstone probably represents a system near 20 percent efficiency. All systems resembling water-quenched lava bodies would be grouped with efficiencies near 30 percent, depending on the recharge rate for vaporized water; efficiencies above 30 percent would be anticipated only in very wet climates such as Hawaii.

It will be useful in making future thermal energy estimates to classify all systems of table 3 with respect to relative position on such an efficiency scale (deemphasizing the precise numerical values). Eventually it will be necessary to relate the efficiency scale to quantitative scales of thermal energy values as adjustments to table 3 and to table 1 of Smith and others (1978). At present, that attempt is premature without additional exploration of quantitative numerical models of hydrothermal convection.

The relation of the efficiency scale to cooling times requires additional modeling. Post-solidification cooling times are shortened by factors ranging from unity at zero percent efficiency to about one-fifth at 50 percent efficiency relative to the conduction models of figure 3. Because cooling times and efficiencies are not linearly proportional, the relation requires more quantitative evaluation in specific cases. Systems with efficiencies of around 20 percent will have post-solidification cooling times about half those of the conduction models. This adjustment of times also will affect the estimate of total heat transferred to roof rocks and heat lost from the system (columns 11 and 12, table 1 of Smith and others, 1978). One of the significant effects would be to decrease the estimate of time required for initiation of heat loss to the surface. For example, systems of about 20 percent efficiency might have significant losses at times roughly half that of the conduction estimate. The respective cutoff for ages of such systems that may have lost significant amounts of heat to the atmosphere would be reduced from 360,000 years to 180,000 years. Many systems would require reductions of thermal energy values in column 11 and increases of heat losses from the system in column 12, depending on evidence of sufficiently long-lived hydrothermal activity to be consistent with the assumed efficiency.

MAGMATIC LONGEVITY VERSUS HYDROTHERMAL COOLING

In multiple systems and systems of complex history, the effects of longevity of the magmatic system mask the effects of hydrothermal heat losses. In such cases the overall effects of hydrothermal cooling, like the effects of supply rates of magma to the root system beneath the chamber, must be integrated over the lifetime of the system. The hydrothermal efficiency as used in the preceding discussions applies only to post-solidification histories following the time when magma supply effectively ended. Up to that time, the supply of magmatic heat may balance hydrothermal heat transfer within the roof rocks. Systems that have inadequate recharge rates to maintain significant hydrothermal efficiencies may progressively lose pore fluids with time and evolve toward hot dry rock systems. In such cases the conduction models apply when the magma supply is terminated.

Figure 3 is the revised version of figure 4 in Circular 726. This revision does not affect the theoretical basis or the positions of the time-volume lines for magmatic cooling. The effects of either subchamber heating or hydrothermal cooling are not accounted for. Subchamber heating and hydrothermal cooling work in opposition so far as cooling times are concerned. However, subchamber heating sufficient to sustain a high-level chamber automatically dominates the hydrothermal cooling effects. Therefore, times indicated by the cooling curves in figure 3 should be increased almost in direct proportion to the longevity of subchamber heating as indicated by the history of associated volcanism (basaltic "shadows," intermediate volcanic dome sequences, previous caldera cycles, and so on). The hydrothermal longevity is similarly prolonged if the recharge rate is high enough; otherwise the system will evolve toward the hot dry rock type or show evidence of intermittent hydrothermal activity.

A given igneous anomaly can potentially give rise to a variety of geothermal "reservoirs" (such as hot dry rock, magma, hot water, and vapor-dominated). The energy values of table 3 refer to the entire system without regard to types of hydrothermal activity. Quantitative modeling of the hydrothermal effects discussed above may significantly modify some of these estimates. For example, the estimate of 360,000 years as a measure of the characteristic time when heat losses at the Earth's surface become significant may be too large if hydrothermal cooling is highly efficient. If so, the smaller igneous systems may have lost significant fractions of their heat by then. Clearly, table 3 does not represent an estimate of the hot dry rock resource of the United States. Estimates of the thermal energy in hot dry rock require geologic evaluation of the evidence for hydrothermal and volcanic longevity of specific igneous systems.

REFERENCES CITED

Duffield, W. A., Bacon, C. R., and Dalrymple, G. B., 1979, Late Cenozoic volcanism, geochronology, and structure of the Coso Range, Inyo County, California: Journal of Geophysical Research. (in press)

Milora, S. L., and Tester, J. W., 1976, Geothermal energy as a source of electric power: Cambridge, Mass., The MIT Press, 186 p.

Muffler, L. J. P., and Christiansen, R. L., 1978, Geothermal resource assessment of the United States: Pure and Applied Geophysics, v. 117, p. 160-171.

Norton, D., and Knight, J., 1977, Transport phenomena in hydrothermal systems: cooling plutons: American Journal of Science, v. 277, p. 937-981.

Peck, D. L., Hamilton, M. S., and Shaw, H. R., 1977, Numerical analysis of lava lake cooling models; Part II, Application to Alae lava lake, Hawaii: American Journal of Science, v. 277, p. 415-437.

Shaw, H. R., Hamilton, M. S., and Peck, D. L., 1977, Numerical analysis of lava lake cooling models; Part I, Description of the method: American Journal of Science, v. 277, p. 384-414.

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 58-83.

Smith, R. L., Shaw, H. R., Luedke, R. G., and Russell, S. L., 1978, Comprehensive tables giving physical data and energy estimates for young igneous systems of the United States: U. S. Geological Survey Open-File Report 78-925.

White, D. E., and Williams, D. L., 1975, Summary and conclusions, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 147-155.

Hydrothermal Convection Systems With Reservoir Temperatures ≥ 90°C

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ABSTRACT

Evaluation of volume and temperature data available in June 1978 indicates that 1650 ± 140 x 10^{18} J are present in reservoirs of 215 identified hydrothermal convection systems ≥90°C in the United States to a depth of 3 km (excluding energy in National Parks). Thermal energy recoverable at the surface from these reservoirs is estimated to be 400 ± 60 x 10^{18} J. Electrical energy producible from identified high-temperature (>150°C) systems is estimated to be 23,000 ± 3400 megawatts for 30 years, and beneficial heat producible from identified intermediate-temperature (90°-150°C) systems is estimated to be 42 ± 13 x 10^{18} J. Undiscovered thermal energy is evaluated by geologic provinces; the total undiscovered component is estimated to be 8000 x 10^{18} J, of which 2000 x 10^{18} J might be recoverable. The total identified and undiscovered thermal energy in reservoirs of hydrothermal convection systems to a depth of 3 km (excluding energy in National Parks) is estimated to be 9600 x 10^{18} J. Total recoverable energy of 2400 x 10^{18} J could contribute 95,000-150,000 megawatts of electricity for 30 years and 230-350 x 10^{18} J of beneficial heat, with the higher number for electricity going with the lower number for beneficial heat, and conversely.

INTRODUCTION

This report deals with hydrothermal convection systems in the United States with mean reservoir temperatures greater than or equal to 90°C and depths less than 3 km. Our goal is to determine (1) the accessible resource base, (2) the resource, and (3) the amount of electricity or beneficial heat that might be produced from these systems. We divide the thermal energy in hydrothermal convection systems into that which is identified and that which is undiscovered. The identified systems are listed in tables 4, 5, and 6, along with estimates of their reservoir properties, thermal energy content, recoverable energy, and electricity or beneficial heat production. Undiscovered thermal energy is estimated by geomorphic province and is listed in table 8.

The accessible resource base is the stored thermal energy for individual hydrothermal convection systems and for the sum of all the systems. The accessible resource base for an individual system is defined for this assessment as the amount of geothermal energy within a specified volume of rock and at a specified temperature referenced to 15°C. The accessible resource base corresponds to the "resource base" of White and Williams (1975) and Renner, White, and Williams (1975) in the Assessment of Geothermal Resources of the United States--1975 (U.S. Geological Survey Circular 726). It differs slightly from the "accessible resource base" defined by Muffler and Cataldi (1978) in that we refer to energy in the Earth between two specified depths, rather than from the surface to a specified depth. The depth limit of economic production drilling for geothermal resources varies with drilling costs and economics and currently is about 3 km. As in the 1975 assessment, we therefore do not consider any system or part of a system deeper than 3 km.

The recoverable energy is that fraction of the accessible resource base that can be produced at the wellhead under reasonable assumptions of future technology and economics and is defined as the resource (Muffler and Cataldi, 1978).

Essential components of a hydrothermal convection system are a heat source, a fluid (usually water but in a few rare instances steam), and adequate vertical permeability to allow the hot, low-density fluids to rise and, in most systems, be replaced by cooler fluids. Most of the thermal energy in the Earth is stored in rocks. Convective circulation of hot fluids is the primary mechanism whereby the energy is transported to reservoirs near enough to the Earth's surface so that it can be economically extracted.

Geologic settings of hydrothermal convection systems in the United States are diverse. They are most likely to develop in areas where there is residual heat related to relatively young volcanic activity and in areas where regional heat flow is high. Fault zones appear to be the most common conduits for movement of fluids in convecting systems; locations of many systems seem to be controlled by intersecting structures. Reservoirs from which the hot fluids are produced can be either porous or fractured rock; fracture reservoirs are more important in high-temperature systems.

Hydrothermal convection systems can be classified into two main types--vapor-dominated and hot-water, depending on whether steam or liquid water, respectively, is the continuous, pressure-controlling phase in the reservoir. The characteristics of each type of system have been described by White, Muffler, and Truesdell (1971), Truesdell and White (1973), and White (1970, 1973).

Vapor-dominated systems are rare. Their surface activity is characterized by fumaroles, acid-sulfate springs, and acid-leached ground, with no neutral chloride-bearing springs. When drilled, these systems produce saturated to slightly superheated steam with little or no liquid water. Reservoir fluid pressures show little change with depth, a characteristic indicating that steam is the pressure-controlling phase. Steam and liquid water coexist in the reservoir, although steam dominates the largest fractures. Liquid water is relatively immobilized in small pores and fractures, but is the major phase by mass (Truesdell and White, 1973).

Hot-water systems are more common and are characterized by circulating liquid water which controls subsurface pressures and transfers heat from depth into the geothermal reservoir. Most of the known hot-water systems are identified by the presence of springs discharging neutral to alkaline chloride-bearing thermal water at the surface. However, some hot-water systems boil at depth, and the escaping steam gives rise to fumaroles and acid-sulfate springs, similar to the surficial features of vapor-dominated systems. In addition to the temperature and volume of water that can be produced from a hot-water reservoir, the amount and chemical character of dissolved solids in the water are important factors in determining what use can be made of the hot water.

Each estimate of accessible resource base made below is based on the amount of thermal energy contained at present in a specified volume of rock and water (the reservoir) and does not consider possible resupply of heat from below or from the sides. Accordingly, from this point of view, all our estimates are minima. For vapor-dominated reservoirs and for hot-water reservoirs of low natural fluid discharge, however, resupply of heat is likely to be only a small fraction of energy producible from storage alone (Ramey, 1970; Isherwood, 1977; Nathenson 1975; Muffler and Cataldi, 1978). For hot-water systems of high natural fluid discharge, resupply of heat could well be significant (Nathenson, 1975) and could increase some of the estimates reported below. Owing to the paucity of meaningful flow data for most systems and the difficulty of evaluating discharge of thermal waters into near-surface aquifers, we make no attempt to quantify possible augmentation of thermal estimates by heat resupply.

USE OF TABLES

Individual hydrothermal convection systems are listed in tables 4, 5, and 6 at the end of this report. The systems are categorized in the same fashion as in the 1975 assessment (Renner and others, 1975): vapor-dominated systems (table 4), high-temperature hot-water convection systems (with estimated mean reservoir temperatures greater than 150°C; table 5), and intermediate-temperature hot-water convection systems (with estimated mean reservoir temperatures from 90° to 150°C; table 6). Each system has been given a number that appears at its location on the accompanying map of the geothermal resources of the Western United States (map 1). Convection systems in each state are numbered in sequential order from north to south and west to east with the states arranged alphabetically. The numbers are merely for convenience in identifying and locating hydrothermal convection systems between the tables and the map; no other significance is intended.

Because of the importance that temperature plays in determining the use of a geothermal fluid and in order to present the raw data from which energy calculations are made, reservoir temperatures are reported in two columns of the tables. The minimum, maximum, and most likely temperatures for the respective reservoirs are given in column 4, and the means and standard deviations derived from those values are given in column 5. The mean value is used to assign a hydrothermal convection system to a temperature category, >150°C, 90°-150°C, or <90°C (for a discussion of the last, see Sammel, this volume).

A geothermal reservoir is a complex, heterogeneous volume of rock and water, and temperature undoubtedly varies from place to place within the volume. To estimate the total accessible resource base, however, we must assume that each reservoir has a single characteristic temperature. Accordingly, the minimum and maximum values listed in tables 4, 5, and 6 (end of report) do not represent the extreme temperatures expected in each system but rather are the values estimated for the reservoir under the generalized assumption that the reservoir is isothermal. There may, therefore, be measured values within the reservoir that either exceed the maximum or fail to reach the minimum.

Reservoir volumes (column 6) are calculated from estimates of area and thickness, given in Mariner, Brook, Swanson, and Mabey (1978). The mean reservoir thermal energy (column 7), which is the accessible resource base, is calculated from the mean reservoir temperature and volume by equation 1 given below. The wellhead thermal energy (or resource), wellhead available work, and electrical energy or beneficial heat are calculated in turn from the reservoir thermal energy.

Basic data on identified hydrothermal convection systems are stored in the U.S. Geological Survey's GEOTHERM computer file (Swanson, 1977a, b). Pertinent data for the systems listed in tables 4, 5, and 6 are published in U. S. Geological Survey Open-File Report 78-858 (Mariner and others, 1978).

DETERMINATION OF ACCESSIBLE RESOURCE BASE

The methodology used in determining the accessible geothermal resource base for each hydrothermal convection system is essentially the same as in Circular 726. Reservoir temperatures, subsurface areas, and thicknesses are estimated for each system and are the variables in the equation used to calculate reservoir thermal energy:

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

where:

- q_R = reservoir thermal energy in joules (J)
- ρc = volumetric specific heat of rock plus water (2.7 J/cm^3/^{o}C)
- a = reservoir area
- d = reservoir thickness
- t = reservoir temperature
- t_{ref} = reference temperature (15^{o}C).

The volumetric specific heat, ρc, is calculated assuming the rock volumetric specific heat to be 2.5 J/cm^3/^{o}C and the reservoir porosity to be 15 percent. The reference temperature, t_{ref}, is the mean annual surface temperature and for simplicity is assumed to be constant for the entire United States.

One significant modification to the procedure used in Circular 726 is the incorporation of statistical methods into the calculations of thermal energies. This allows us to quantify the uncertainty in the estimates of accessible resource base, resource, electricity, and beneficial heat. The uncertainty is expressed in two forms: (1) as the standard deviation about a mean reservoir thermal energy, both for individual systems and for the total of all systems, and (2) as confidence limits for the total energy values. Details of the methodology for determining these quantities are given in U. S. Geological Survey Open-File Report 78-1003 (Nathenson, 1978).

The uncertainty in the identified accessible resource base (and hence resource, electricity, and beneficial heat) results from the uncertainties in the values estimated for temperature t, thickness d, and area a of each reservoir. These values result from human judgement based on geology, geothermometry, geophysics, and downhole measurements. To determine the uncertainties in the estimates, we assume for each variable a triangular probability density (fig. 4) that most nearly corresponds to our subjective judgement of the true density. A triangular form is easy to understand and estimate, and it can have either positive or negative skewness.

Using temperature t as an example, the parameters t_1, t_2, and t_3 of the triangular density are defined as:

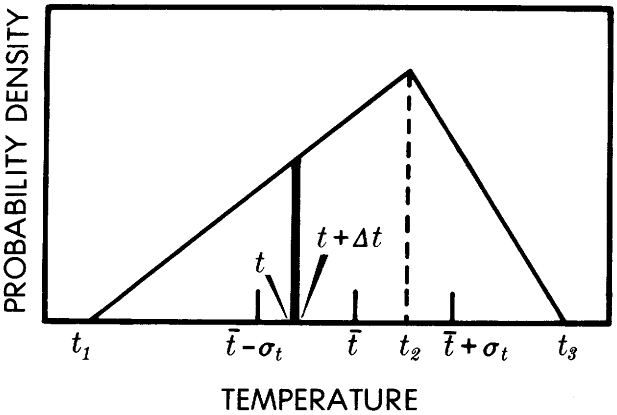

Figure 4.--Example of a triangular probability density. The parameters t_1, t_2 and t_3 are the minimum, most likely, and maximum characteristic reservoir temperatures, respectively. The mean, $\bar{t}$, and the mean plus or minus one standard deviation, $\bar{t} \pm \sigma_t$, are also shown. The area of the solid vertical band gives the probability that the characteristic reservoir temperature is between the values t and $t + \Delta t$ where Δt is a small number. The total area of the triangle is the probability of all events and equals one.

- t_1 = minimum reservoir temperature -- the characteristic reservoir temperature is certain to be at least this value (that is, the probability equals zero that the temperature is less than t_1).
- t_3 = maximum reservoir temperature -- the probability equals zero that the characteristic temperature is greater than t_3.
- t_2 = most likely reservoir temperature -- the characteristic temperature that has the greatest likelihood of occurring.

Two important statistical measures are the mean and standard deviation. The mean, $\bar{t}$, is calculated by taking the arithmetic average of the three parameters t_1, t_2, and t_3. It can be, but is not necessarily, equal to the most likely value. If the mean is not equal to the most likely value, then the density exhibits skewness (see fig. 4). The standard deviation σ_t measures the dispersion, or spread, of the density about the mean.

For each system, means and standard deviations for t, d, and a were calculated from the respective minimum, maximum, and most likely values. The mean reservoir thermal energy was then calculated for each system using mean values in equation 1:

$$\bar{q}_R = \rho c \cdot \bar{v} \cdot (\bar{t} - \bar{t}_{ref}), \quad (1a)$$

where: $$\bar{v} = \bar{a} \cdot \bar{d}. \quad (1b)$$

This kind of multiplication generally cannot be done with most likely values but, under certain conditions, can be done with mean values. Multiplying mean values to get a resultant mean value requires that the variables *t*, *d*, and *a* be statistically independent random variables within a geothermal reservoir, which we assume to be the case. Formulas to calculate the standard deviation of reservoir thermal energy and reservoir volume for each system are given in Nathenson (1978, appendix I).

The total mean reservoir thermal energy $\overline{Q}_R$ for all systems (that is, the total mean identified accessible resource base) is simply the sum of the mean thermal energies of the individual systems. The overall standard deviation σ_{Q_R} is the square root of the sum of the squares of the individual standard deviations.

We are fully aware that some systems may be better known by others than by us and that our thermal energy estimates for individual systems may therefore differ from those of others. Hence, the thermal energy of individual systems is not emphasized. Rather, it is the total energy of all the systems that is of importance in a national resource assessment.

TEMPERATURE ESTIMATES

Chemical geothermometers are used to estimate reservoir temperatures for most of the systems. The geothermometers are based on temperature-dependent, water-rock reactions which control the chemical and isotopic composition of the thermal water. This method is applicable only to hot-water systems because the common chemical constituents of thermal water (SiO_2, Na, K, Ca, Mg, Cl, HCO_3, and CO_3) are soluble in liquid water but lack significant solubility in steam (White, 1973).

The silica, Na-K-Ca, and sulfate-isotope geothermometers that are used to estimate most of the temperatures are valid only when certain assumptions are met. These assumptions, discussed in detail by Fournier, White, and Truesdell (1974), are listed below:

1. Temperature-dependent reactions at depth control the concentration of the constituents used in the geothermometer.
2. The reservoir contains an adequate supply of the reactants.
3. Water-rock equilibrium is established in the reservoir.
4. The constituents used in the geothermometer do not reequilibrate with the confining rock as the water flows to the surface.
5. Mixing of thermal and nonthermal groundwater does not occur.

Problems arise in using the geothermometers when one or more of these assumptions are violated. The common violations of the assumptions and the attempts that we have made to correct the various geothermometers for these violations are discussed below.

The concentration of silica in a thermal water depends principally on the temperature-dependent solubility of quartz, chalcedony, alpha cristobalite, or amorphous silica (Fournier, 1973; Fournier and Rowe, 1966). We may make the following generalizations: (1) the solubility of quartz controls silica concentrations in all high-temperature reservoirs (>180°C), and quartz may be the controlling mineral in granitic rocks down to temperatures as low as 90°C (R. O. Fournier, oral commun., 1978); (2) chalcedony commonly controls silica concentrations in lower temperature reservoirs and may be the limiting mineral in basaltic rocks up to 180°C (Arnórsson, 1975); and (3) in some low-temperature environments the rapid decomposition of silicates, such as plagioclase and serpentine, allows solutions to become supersaturated with respect to quartz and chalcedony. In many systems, the rate at which silicates dissolve is controlled, in part, by the concentration of dissolved CO_2. At higher concentrations, the silicates dissolve faster (Wildman and others, 1968). Many cold CO_2-charged waters have silica concentrations that approach saturation with respect to amorphous silica, apparently because of slow rates of precipitation of quartz and chalcedony and the continued addition of CO_2 from depth. The cold CO_2-charged waters with high silica concentrations that were included in the previous assessment (Renner and others, 1975) are not included in tables 5 and 6 (end of report) because the silica concentrations are a function of the high CO_2 concentrations, not high subsurface temperatures.

Silica geothermometers give accurate results in thermal systems that are associated with springs of neutral to slightly acid pH. However, several thermal systems listed in table 6 discharge dilute waters with pH's of 8 to 9.3 and with anomalously large silica concentrations. These dilute thermal waters contain virtually no free CO_2 and typically occur in granitic terranes. Consequently, the alkaline pH's cannot be due to loss of CO_2 in the spring or reaction with magnesium silicates. Instead, they may be due to the hydrolysis of feldspar in the absence of appreciable dissolved CO_2. These hydrolysis reactions lead to the formation of clay and more alkaline water while feldspar is consumed:

$$\text{Na-feldspar} + H^+ + \text{Water} \rightarrow Na^+ + \text{Clay}, \quad (2)$$

which could also be written

$$\text{Na-feldspar} + \text{Water} \rightarrow Na^+ + OH^- + \text{Clay}. \quad (3)$$

Dissolved silica (SiO_2) reported in chemical analyses is actually present as H_4SiO_4 (silicic acid) and various dissociated species, particularly $H_3SiO_4^-$; SiO_2 does not exist as a distinct dissolved species in nature. The temperature-dependent reaction

Quartz or chalcedony		Water		Silicic acid	
SiO_2	+	$2H_2O$	=	H_4SiO_4	(4)

forms the basis for the silica geothermometer. In alkaline waters, however, hydroxide reacts with the silicic acid to reduce the proportion of silicic acid to total dissolved silica:

Silicic acid		Hydroxide		Dissociated silicic acid		Water	
H_4SiO_4	+	OH^-	=	$H_3SiO_4^-$	+	H_2O.	(5)

The total concentration of dissolved silica measured in the laboratory (H_4SiO_4 and $H_3SiO_4^-$) must therefore be reduced by the concentration of $H_3SiO_4^-$ to obtain an accurate estimate of the temperature of the thermal reservoir. For example, at a temperature of 80°C and pH of 9, approximately 44 percent of the dissolved silica is in the dissociated form ($H_3SiO_4^-$), whereas at a pH of 7, less than 1 percent of the dissolved silica is in the dissociated form. If total dissolved silica was 100 mg/L and chalcedony was the controlling silica mineral, then temperature estimates should be reduced from 110°C (pH 7) to 78°C (pH 9).

To correct for the dissociation of silica in these alkaline waters, we have used a very simple correction which requires that the pH in the thermal spring is the same as in the associated thermal reservoir. The concentration of silicic acid (H_4SiO_4) is calculated at the spring temperature and pH. This concentration, recast as SiO_2, is used in the appropriate geothermometer. Corrections for the dissociation of silicic acid are not made unless the correction is 10°C or more.

Many reservoirs containing fluids of neutral pH and high CO_2 can be associated with wells and springs of alkaline pH's owing to the loss of CO_2 to a steam phase or to the atmosphere. However, since the silica geothermometers are based on reservoir conditions, the analyses of these waters should not be corrected for the dissociation of silicic acid.

Mixing of thermal (high-silica) and nonthermal (low-silica) waters can sharply reduce the temperatures estimated from the silica geothermometers. However, it is possible to calculate the temperature of the thermal component if sufficient chemical and isotopic data are available for both the thermal and cold waters, if chemical equilibration has not taken place at or below the mixing temperature, and if there has been negligible conductive heat loss (Fournier and Truesdell, 1974). The problem with any unexplored system is proving that the water issuing at the surface is mixed. The simplest proof would be a linear trend between measured spring temperatures and chloride concentration. Normal groundwater usually has low chloride concentrations, whereas thermal waters from high-temperature systems usually contain at least several hundred milligrams per liter chloride. A linear trend between the isotopic composition of the water (deuterium or oxygen-18) and dissolved chloride is another definitive proof of mixing (for example, Mariner and Willey, 1976). In this assessment, mixing models were used where deuterium-chloride or temperature-chloride relations demonstrated mixing. However, very few areas have sufficient springs of different chemical and isotopic composition to prove mixing by these rigorous criteria.

The Na-K-Ca geothermometer (Fournier and Truesdell, 1973) is based on an empirical relation between the proportions of potassium to sodium, square root of calcium to sodium, and measured reservoir temperatures. Although relatively insensitive to dilution, temperatures estimated from the Na-K-Ca geothermometer can be sharply increased by precipitation of $CaCO_3$ owing to loss of CO_2 after the thermal water has left the reservoir. Sensitivity of the geothermometer to this loss of calcium can be tested in a specific water by doubling the measured calcium concentration and recalculating the estimated reservoir temperature. A change of only a few degrees indicates that the loss of calcium does not appreciably alter the estimated reservoir temperature.

A major modification of the Na-K-Ca geothermometer used in this assessment is the addition of a magnesium correction. A high magnesium concentration or large magnesium to calcium ratio had long been considered a qualitative indicator of low reservoir temperature (Ellis, 1970; White, 1970). In the intervening years since the previous assessment, it became apparent that the concentration of magnesium in some waters was interfering with the Na-K-Ca geothermometer (Fournier and Potter, 1978). The magnesium correction produces better agreement between the silica and cation geothermometers, particularly in the 90° to 150°C range. Magnesium corrections were determined on a preliminary graph provided by R. O. Fournier, and the corrections we determined may differ slightly from those given by the subsequently developed equation (Fournier and Potter, 1978).

The sulfate-water isotope geothermometer (McKenzie and Truesdell, 1977), a geothermometer for which data were not previously available, was extensively used for higher temperature systems. It is based on the temperature-dependent equilibration of the isotopes of oxygen ($^{16}O/^{18}O$) between water and dissolved sulfate. Isotopic reequilibration during ascent of the thermal fluid from the reservoir to the surface apparently occurs at a slower rate than the reequilibration of chemical constituents used in the other geothermometers.

McKenzie and Truesdell (1977) describe three end-member models for calculating reservoir temperatures with the sulfate-water isotope geothermometer: 1) conductive heat loss (that is, no steam loss), 2) one-step steam loss, and 3) continuous steam loss. Isolated springs with low flows and (or) no steam loss and condensed total flow samples from wells are assumed to have cooled conductively without any change in isotopic composition. One-step steam loss occurs in geysers and steam wells with two-phase discharge where only the water is sampled. Continuous steam loss may occur in springs issuing in areas having fumaroles and steaming ground. In most cases, we used the continuous steam loss model for boiling springs and the conductive steam loss model for all other samples. Erroneous temperature estimates will be produced by addition of any sulfate not equilibrated in the thermal regime, such as that derived from solution of gypsum, oxidation of sulfide to sulfate, or mixing with sulfate-bearing brines.

Temperatures listed for the various systems (tables 4, 5, and 6) are important in determining the energy content of the system. Higher temperatures could be estimated for many of the systems if dilution were assumed. However, speculation about possible high temperatures in some of the systems does not seem warranted with the data presently available. Furthermore, future changes in volume estimates of individual systems will probably change the estimated energy contents more than changes in estimated temperatures.

VOLUME ESTIMATES

Subsurface Area

The largest uncertainty in estimating the thermal energy in a reservoir is the area of the reservoir. In only a very few geothermal systems has the approximate area of the reservoir been determined by drilling. Indirect evidence must therefore be used to estimate the area for nearly every system. All available geologic, geophysical, and geochemical data have been used in making our estimates. Where the only evidence for the existence of a reservoir of hot water is a single spring or well or group of springs in a small area, a mimimum area of 1 km^2 and a maximum of 3 km^2 with a most likely area of 2 km^2 are assumed. These standard estimates are believed to be representative of the smaller systems and are comparable to the areas determined for many such systems where geophysical or geologic evidence formed the basis for our estimates. Where two or more springs or wells in an area have similar water chemistry and the surface geology suggests that they might reflect a common reservoir, the inferred boundary of the reservoir is assumed to encompass the wells and springs. The extent of alteration at the surface sometimes indicates the size of an underlying reservoir. If the heat flow or thermal gradient anomaly associated with a system has been defined, this information is often a good indicator of the area of the reservoir. Low resistivity anomalies are related to many hydrothermal systems, and the extent of the anomaly can sometimes be used to estimate the area of the system. Gravity, passive and active seismic, and magnetic surveys also provide data useful in estimating the area of a reservoir.

Thickness

In estimating the reservoir thickness to be used in calculating the volume, a uniform thickness over the area of the reservoir has been assumed. Although the geometry of most reservoirs is much more complex, the data for most systems do not justify refinement beyond this simple model. Because the estimates in this assessment involve thermal energy only to a depth of 3 km below the surface, the bottom of a reservoir is normally assumed to be at 3 km unless there is evidence to suggest a shallower value. If data from drilling or geophysical surveys provide any indication of the top of the reservoir, these data were used as guides in estimating the thickness. Temperature-gradient profiles in particular were commonly used to determine the tops, and in some cases the bottoms, of geothermal reservoirs. Otherwise, a minimum depth of 0.5 km, a maximum of 2.0 km, and a most likely depth of 1.5 km to the top of the reservoir are assumed. Depths to the tops of reservoirs of most of the drilled geothermal systems fall within this range. Our standard thickness estimates are thus a mimimum of 1 km, a maximum of 2.5 km, and a most likely of 1.5 km, assuming that the reservoir extends to 3 km depth. For most reservoirs, the uncertainties in the thickness are small compared to those for the area.

Because a hydrothermal convection system is composed of both rock and fluid and because most of the thermal energy is contained in the rock, we consider a reservoir to be a volume of rock and water regardless of porosity and permeability. Therefore, in making our estimates of area and thickness, no attempt is made to distinguish those parts of a reservoir that are porous and permeable from those that are not.

Recovery of Thermal Energy from Hydrothermal Convection Systems

The methodology used to estimate the energy obtainable from a hydrothermal convection system consists of two major steps:

1) Estimation of the fraction of thermal energy (referenced to 15°C) recoverable at the surface, under reasonable assumptions of future technology and economics. This quantity is defined as the resource.
2) Estimation of the efficiency with which the resource can be converted into electrical energy or beneficial heat.

RESOURCE DETERMINATION

Estimating hot-water geothermal resources involves defining a geothermal recovery factor, Rg, such that Rg is the ratio of geothermal energy recovered at the wellhead, q_{WH}, to the geothermal energy originally in the reservoir, q_R:

$$Rg = q_{WH}/q_R \quad (6)$$

Rg reflects the physical and technological constraints that prevent all the geothermal energy (>15°C) in the reservoir from being extracted. The resource of each system is determined by multiplying the mean reservoir thermal energy by a value for *Rg*.

The derivation of Rg for hot-water systems is based on a model of heat extraction called intergranular flow, or the sweep process as discussed by Nathenson (1975) and Bodvarsson (1974). The model assumes that liquid water stored in pores and fractures is heated by conduction from reservoir rocks. As the hot, lower density water rises and is discharged, new cold water sweeps into the reservoir, either by injection or by natural recharge, and is also heated by conduction. Because discharge is balanced by recharge, reservoir pressures do not drop enough to allow boiling of pore water to steam. The fluid leaving the reservoir is assumed to be in the liquid phase, although it may flash to a steam-water mixture in a wellbore.

Nathenson (1975) estimates that 50 percent of the thermal energy in an ideal reservoir may be recovered in a sweep process, assuming that total porosity, ϕ_t, = effective porosity, ϕ_e, = 20 percent. However, for real reservoirs a correction factor must be applied to this value of *Rg* to account for nonideal behavior, related primarily to the fact that much of a reservoir volume may not be porous and permeable. On the average, nonideal behavior is assumed to reduce the recovery factor by one-half (Nathenson and Muffler, 1975). Thus, as a first approximation we shall assume that *Rg* equals 25 percent for all hot-water reservoirs. This value of *Rg* is assumed to include the relatively small energy and friction losses (~2 to 5 percent of q_{WH}) that occur in the wellbore as the reservoir fluid rises to the surface. This assumption is based on the consideration that subtracting such small losses from q_{WH} would be unjustifiably precise in light of the larger uncertainties in the value of *Rg* for hot-water systems.

Resource calculations are made for only one vapor-dominated system, The Geysers, because the other identified vapor-dominated systems, Lassen and Mud Volcano, are in National Parks and thus not available for exploitation of geothermal energy. Accordingly, for The Geysers we do not use a general recovery factor, but instead calculate recoverable thermal energy from measurements of wellhead enthalpy and an estimate of the mass of steam recoverable. We use the equation:

$$q_{WH} = m_{WH} \cdot (h_{WH} - h_{\text{ref}}), \qquad (7)$$

where:
- m_{WH} = mass of steam produced at the wellhead
- h_{WH} = enthalpy (or heat content) per unit mass of steam at the wellhead
- h_{ref} = enthalpy per unit mass of saturated water at the reference temperature of 15°C.

The measured average flowing wellhead enthalpy, h_{WH}, for superheated steam produced from a deep (>2 km) reservoir at The Geysers is equal to 1208 Btu/lb = 2810 J/g (Ramey, 1970; Stephen Lipman, oral. commun., 1978.).

The mass of steam produced is based on the vapor-dominated model of White, Muffler, and Truesdell (1971) and Truesdell and White (1973) and is given by:

$$m_{WH} = (v) \cdot (0.5) \cdot (\phi_e) \cdot (x) \cdot (\rho) \qquad (8)$$

where:
- v = reservoir volume
- 0.5 = fraction of reservoir volume which is porous and permeable (Nathenson and Muffler, 1975)
- ϕ_e = effective porosity
- x = fraction of pores filled with liquid water
- ρ = density of liquid in g/cm^3, assuming pure water.

(ϕ_e) (x) equals the percent of the total reservoir volume filled with liquid water. For The Geysers, this is estimated to be 5 percent (Nathenson and Muffler, 1975). Use of equation 8 assumes that all the liquid mass originally in the reservoir is vaporized, that the mass of steam originally in the reservoir is negligible, and that no recharge occurs. For The Geysers q_{WH} is 9.3 x 10^{18} J and q_R is 99.8 x 10^{18} J; these quantities allow us to calculate from equation 6 an apparent recovery factor of 9.3 percent. Note that if all of the reservoir were porous and permeable, the recovery factor would be 18.6 percent.

Available Work

Electricity is produced from geothermal resources by converting part of the thermal energy into mechanical energy (work) and then using this work to generate electrical energy. In the conversion of thermal energy to mechanical work, some heat is always rejected to the surroundings as waste heat, even under ideal conditions. Thermodynamic reasoning demonstrates that there is a maximum amount of work that can be obtained from a given amount of thermal energy. This is called available work (W_A); it is an ideal, or theoretical, amount which does not represent the actual amount of electrical energy (E) obtainable from a real energy conversion cycle (see for example, Jones and Hawkins, 1960). To determine E, available work is reduced by applying a utilization factor (η_u).

Available work is calculated only for systems >150°C. Below 150°C, we assume that thermal energy is used directly, without involving a mechanical cycle (for example, for space heating).

Available work is given by:

$$W_A = \Delta H - T\Delta S \qquad (9)$$

where: H = enthalpy
S = entropy
T = temperature (kelvin) of the surroundings to which heat is rejected.

Enthalpy change (ΔH) is the amount of energy liberated or absorbed when a fluid changes from some initial state (characterized by T_1 and P_1) to some final state (at T_o and P_o). ΔS is the entropy change of a fluid; $T\Delta S$ can be considered a measure of the waste heat generated by the conversion of energy to work under ideal conditions.

For a geothermal reservoir >150°C, available work is calculated by assuming that a mass of fluid, produced at the wellhead, changes from initial wellhead conditions to a final state, converting thermal energy into work in the process. Expanding equation 9 we have:

$$W_A = m_{WH} \left[h_{WH} - h_o - t_o \left(s_{WH} - s_o\right)\right], \qquad (10)$$

where:

m_{WH} = mass of fluid produced at the wellhead
h_{WH} = enthalpy per unit mass of fluid at the wellhead
h_o = enthalpy per unit mass of fluid at the final state
T_o = rejection temperature (kelvin)
s_{WH} = entropy per unit mass of fluid at the wellhead
s_o = entropy per unit mass of fluid at the final state.

The assumptions made for the initial and final fluid states influence the value of W_A. For all hot-water systems, we assume the initial wellhead condition to be saturated liquid, mainly because a fluid that is all liquid has a smaller entropy (s_{WH}) value than a two-phase fluid with the same enthalpy. Thus, the W_A value assuming liquid water is greater than any two-phase mixture of the same enthalpy and is an appropriate reference condition. The assumption of saturated liquid is not intended to represent the true state of the wellhead fluid, which would generally be a steam-liquid mixture as a result of flashing in the wellbore. For the vapor-dominated system at The Geysers, the initial wellhead state is superheated steam.

For the final state both of hot-water systems and of The Geysers, the choice of the rejection temperature (T_o in equation 10) is important because of the large effect it has on the $T\Delta S$ term and hence on W_A. Two likely choices are T_o equal to atmospheric (15°C; 288 K) or to condenser temperature (say, 40°C; 313 K). Condenser temperature, although a better representation of the actual temperature of the surroundings to which heat is rejected, gives a smaller (by ~20 percent) W_A value than atmospheric temperature. We prefer to use 15°C in order to keep W_A a maximum value and thus the most appropriate reference value. Also, the necessity of specifying a condenser temperature, which varies from plant to plant, is avoided. We assume the final fluid to be saturated liquid. The values of h_o and s_o in equation 10 of saturated liquid water at 15°C are found in steam tables.

The enthalpy of liquid water at the wellhead (h_{WH} in equation 10) can be estimated by subtracting the energy loss due to raising the water against gravity from the enthalpy of the water in the reservoir, h_R:

$$h_{WH} = h_R - (Z_R \cdot g) \qquad (11)$$

where: Z_R = depth to middle of reservoir in m
= depth of reservoir bottom minus one-half the reservoir thickness
g = acceleration of gravity
= 0.098 m/s^2.

This estimation of h_{WH} assumes isenthalpic flow; that is, no heat is lost by conduction as the water comes to the surface. The value of h_R is obtained from steam tables using reservoir temperature, assuming a saturated liquid.

The entropy of water at the wellhead (s_{WH} in equation 10) is obtained from steam tables by using the corresponding value for h_{WH} (previously calculated). Wellhead temperature is never explicitly needed to determine h_{WH} or s_{WH}. The mass of water produced at the wellhead is given by:

$$m_{WH} = \frac{q_{WH}}{(h_{WH} - h_{ref})} \qquad (12)$$

where h_{ref} = enthalpy per unit mass of water at 15°C, the reference temperature. The value of q_{WH} for hot-water systems need not be adjusted for energy loss due to raising the water against gravity because Rg is assumed to include such loss.

Figure 5 summarizes these calculations for hot-water systems in a convenient form. The ratio of available work to reservoir thermal energy, W_A/q_R, is plotted on the vertical axis against reservoir temperature on the horizontal axis, for two values of the depth to the middle of the reservoir, Z_R. This graph can be used to find W_A for any system with known temperature, thermal energy, and depth to the middle of the reservoir.

For The Geysers, available work was calculated also using equation 10. The values for h_{WH} and m_{WH} are the same as those used in the resource calculation (equations 7 and 8). The measured average flowing wellhead pressure (p_{WH}) for superheated steam from a deep reservoir at The Geysers is equal to 153 psia = 10.5 bar abs (Stephen Lipman, oral. commun., 1978). Using these values for h_{WH} and p_{WH}, s_{WH} is found in the vapor section of steam tables. T_o, s_o, and h_o in equation 10 are the same values as for hot-water systems, because the final state is the same in both cases.

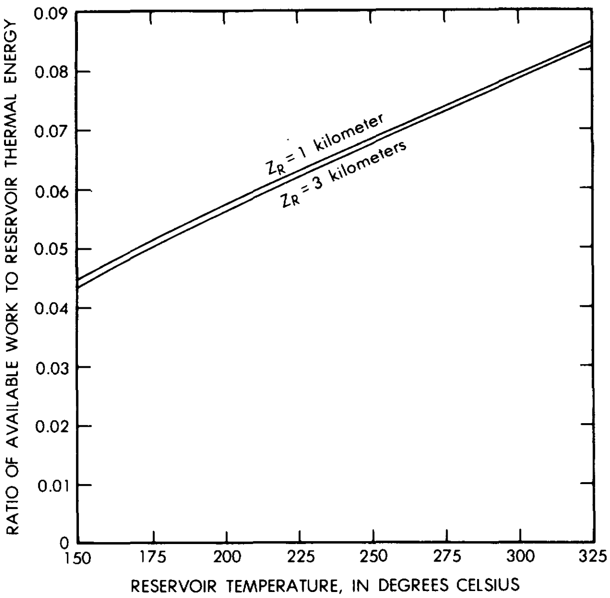

Figure 5.--Ratio of available work to reservoir thermal energy, W_A/q_R, for hot-water systems plotted against reservoir temperature for two values of depth to middle of reservoir, Z_R. A recovery factor of 25 percent was used in calculating W_A.

Electricity

The electrical energy E obtainable from a geothermal reservoir is given by the equation:

$$E = W_A \cdot \eta_u \quad (13)$$

in which η_u is a utilization factor less than one to account for mechanical and other losses that occur in a real power cycle. For a specific fluid temperature and power cycle (for example, saturated steam, optimized single flash, dual flash, binary, total flow), the value of η_u was determined by calculating the actual work (= electrical energy) (Nathenson, 1975, equation 11, 14, 15, 19 and 23) and dividing by the available work. η_u was calculated for several cycles over a range of reservoir temperatures (fig. 6), and for hot-water systems a representative value of 0.4 was chosen. This value is used in equation 13 to calculate E for each hot-water system >150°C. For all cycles, T_o is chosen as 15°C in the calculation of W_A and 40°C in the calculation of actual work. The value 0.4 is applicable only when these reference conditions are used. Factors such as the effect of noncondensable gases are ignored.

For The Geysers, η_u = 0.5 was calculated from the published data for Units 5 and 6 (Finney, 1973), using a gross power output of 55 MWe, and a steam flow of 968,000 lb/hr.

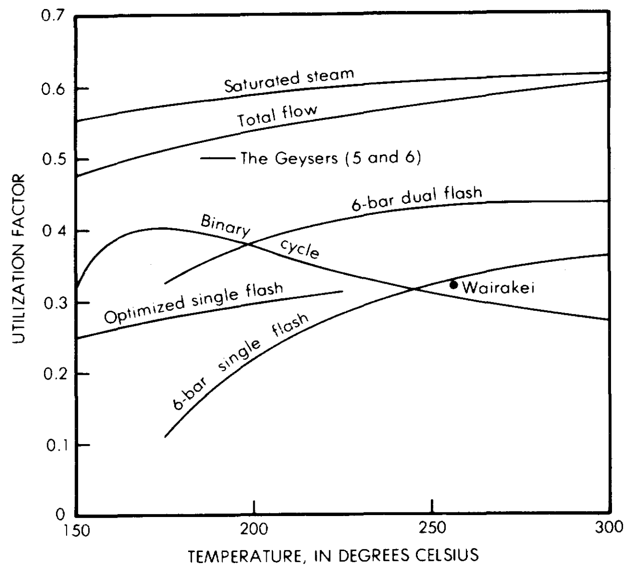

Figure 6.--Utilization factors, η_u, for electric power generation (equation 9) calculated for several conversion technologies as a function of temperature (based on Nathenson, 1975). For saturated steam, temperature is wellhead temperature. For hot-water systems, temperature corresponds to wellhead enthalpy treating the fluid as liquid water. All the cycles assume 40°C condensing temperature. Single- and dual-flash cycles assume 6 bars for the first separation, so are not appropriate at temperatures lower than approximately 200°C. Optimized single flash is calculated by iterating wellhead separation pressure to obtain maximum work. Many cycles involving various optimization schemes are available in the literature; the various cycles shown here illustrate the general behavior.

Beneficial Heat

Following the methodology of Nathenson and Muffler (1975), the amount of the resource that could be directly applied to nonelectric uses is calculated for systems of 90° to 150°C. This amount of thermal energy is called beneficial heat and is calculated from:

$$\text{Beneficial heat} = Q_{WH} \cdot u_B \quad (14)$$

where u_B is defined as the beneficial heat utilization factor. The value of u_B is the fraction of thermal energy obtained when 150°C water undergoes a 32°C drop or 100°C water undergoes a 20°C drop and is equal to 0.24.

PROBABILITY DISTRIBUTIONS OF ACCESSIBLE RESOURCE BASE, RESOURCE, ELECTRICITY, AND BENEFICIAL HEAT

In an earlier section, estimates of minimum, most likely, and maximum values for temperature, area, and thickness were made for each identified hydrothermal convection system. Assuming triangular probability densities, these values were used to calculate the mean and the standard deviation for each variable and for the thermal energy in each hydrothermal convection system (tables 4, 5 and 6). These values can also be used to calculate probability distributions for the total thermal energy in identified hydrothermal convection systems. A probability distribution is defined here as the probability that the variable *X* is greater than or equal to a value *x*. A probability distribution is the integral of a probability density and is useful in that it allows ready estimation and depiction of confidence limits. The probability distribution for the sum of reservoir thermal energy in many systems, Q_R, was calculated from the input values using a Monte Carlo computer program written by Harold Javitz of SRI International (Appendix III of Nathenson, 1978).

Figure 7 shows the distributions for the sum of reservoir thermal energy in high-temperature systems, intermediate-temperature systems, and all systems ≥90°C (in each case excluding National Parks). We see, for example, that the probability is 0.5 that the reservoir thermal energy in all identified hydrothermal convection systems ≥90°C is greater than 1650 x 10^{18} joules. Similarly, the probability is 0.9 that the reservoir thermal energy in all identified systems is between 1440 x 10^{18} joules and 1880 x 10^{18} joules.

Probability distributions are also useful for estimating the confidence limits for the recoverable thermal energy, electricity (from high-temperature systems), and beneficial heat (from intermediate-temperature systems). In the earlier discussion of recoverability, the recovery factor, *Rg*, was treated as a single number, 25 percent for hot-water systems and 9.3 percent for The Geysers. However, these quantities can be treated statistically as random variables. We can analyze *Rg* by separating it into a recovery factor for an ideal reservoir, Rg_i, and a correction factor, *k*, for imperfect recovery caused by permeability variations, blocks of reservoir that cannot be tapped, and so on. The recovery factor for an ideal hot-water reservoir is 50 percent; for an ideal vapor-dominated reservoir of 5 percent water content and 240°C, the recovery factor is 18.6 percent (see p. 24 and Nathenson, 1975). The nonideal correction factor, *k*, lies between 0 and 1, but the empirical basis for estimating its value in individual systems is very limited. For a very few geothermal systems, it is possible to say that one could recover a higher percentage of energy from one system than from another, but the leap from such a statement to estimating minimum, maximum, and most likely values of *k* for individual systems is very great. Accordingly, for this resource assessment we assume that the same probability density of *k* can be applied to each hydrothermal system. We believe that the probability that *k* is in the interval 0.45 to 0.55 is greater than the probability that it is in

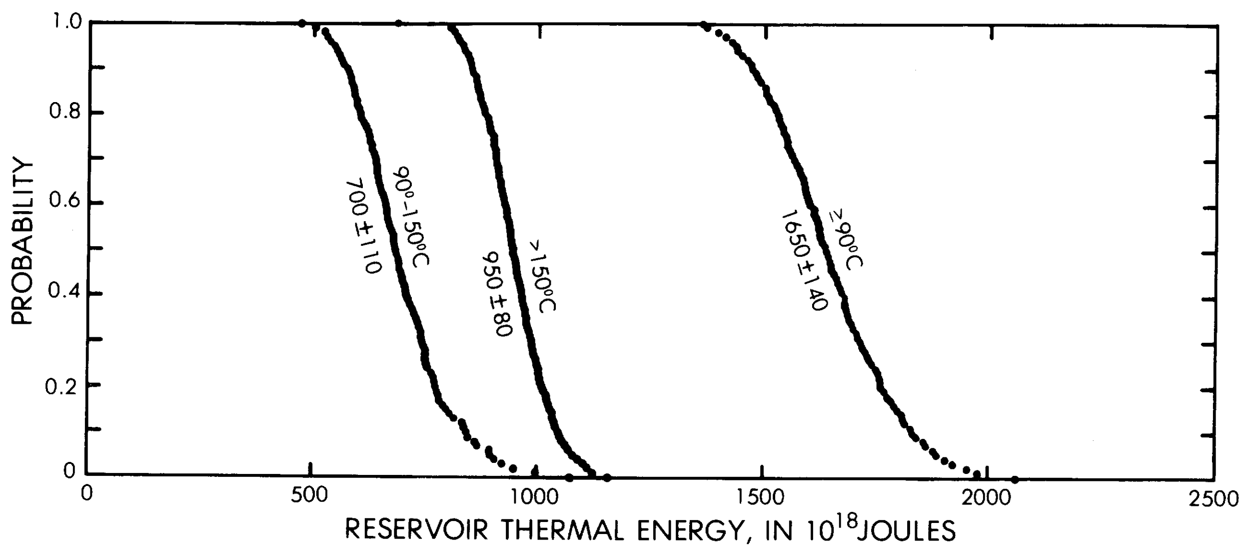

Figure 7.--Monte Carlo sample distributions for the thermal energy in identified hydrothermal convection systems with reservoir temperatures 90°-150°C, >150°C, and ≥90°C. Systems in National Parks excluded. Vertical axis gives the probability that reservoir thermal energy is greater than or equal to a value indicated on the horizontal axis. Monte Carlo sample size, 400. Mean and standard deviation shown for each curve in units of 10^{18} joules.

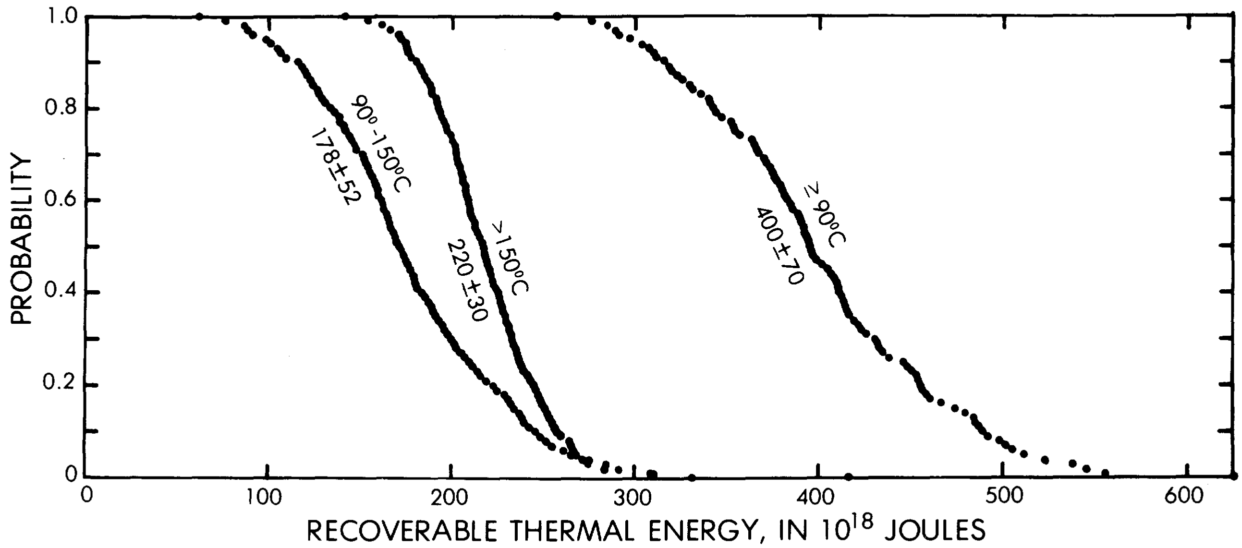

Figure 8.--Monte Carlo sample distributions for the recoverable thermal energy from identified hydrothermal convection systems with reservoir temperatures 90°-150°C, >150°C, and ≥90°C. Systems in National Parks excluded. Vertical axis gives the probability that recoverable thermal energy is greater than or equal to a value indicated on the horizontal axis. Monte Carlo sample size, 400. Mean and standard deviation shown for each curve in units of 10^{18} joules.

the intervals 0 to 0.1 or 0.9 to 1. Also, the probability that k is either very high (0.9 to 1) or very low (0 to 0.1) should not be zero and should be roughly equal. And, finally, the mean value should be 0.5. A triangular probability density with a minimum of 0, a most likely value of 0.5, and a maximum of 1 satisfies these constraints. Different densities may suggest themselves to others, but only extensive field histories will give us the background to choose the best representation.

Using the assumed triangular density for k, we have used a Monte Carlo program to obtain the sample distributions for recoverable thermal energy shown in figure 8. The recoverable energy is much less than the reservoir thermal energy, so the scale of figure 8 is quite different than that of figure 7. Comparison of the two figures shows that the statistical spread in the recovery factor adds additional uncertainty to estimates of recoverable energy compared to energy in the reservoirs. The probability is 0.9 that the recoverable thermal energy in all identified systems is between 300 x 10^{18} joules and 510 x 10^{18} joules.

To calculate the electricity producible from high-temperature systems, we use equations 1, 6, 10, 11, 12, and 13 for hot-water systems and equations 8, 10, and 13 for vapor-dominated systems in a Monte Carlo program. The result (fig. 9) gives a mean of 23,000 MWe for 30 years, with a probability of 0.9 that the electricity producible will be between 17,400 and 28,000 MWe for 30 years.

Following Nathenson and Muffler (1975), the beneficial heat is calculated as 24 percent of the recoverable thermal energy from intermediate-temperature systems. The resultant mean value of beneficial heat is 42 x 10^{18} J. The probability distribution is the same as shown in figure 8, but with the energy scale reduced to 24 percent of the values shown.

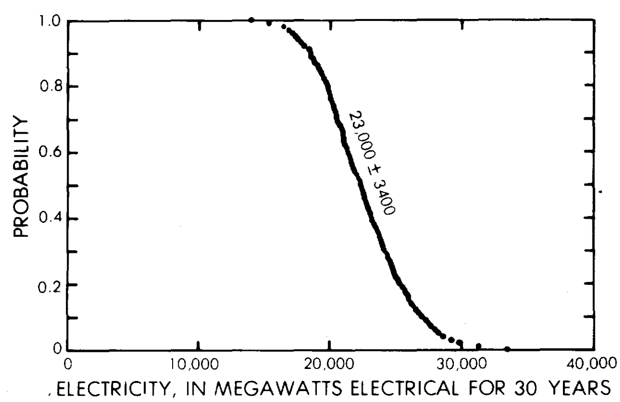

Figure 9.--Monte Carlo sample distribution for the electrical energy from identified hydrothermal convection systems with reservoir temperatures >150°C. Systems in National Parks excluded. Vertical axis gives the probability that electrical energy is greater than or equal to a value indicated on the horizontal axis. Monte Carlo sample size, 400. Mean and standard deviation shown in units of megawatts electrical for 30 years.

THERMAL ENERGY COMPARED WITH CIRCULAR 726

Although the fundamental methodology used by us to evaluate identified hydrothermal convection systems is similar to that used by Renner, White, and Williams (1975) in the previous assessment (Circular 726), significant differences should be noted. One of the major differences is our use of statistics in the calculation of thermal energies. We estimate minimum, maximum, and most likely values of reservoir temperature, thickness, and area and use them to derive the corresponding mean values needed for calculation of thermal energies and their associated uncertainties. On the other hand, in Circular 726 single best estimates of each variable (t, d, and a) were used to calculate thermal energy in each system; these best estimates were not based on an explicit statistical methodology and do not necessarily correspond to either most likely or mean values. Similarly, the ranges reported in Renner and others (1976) are not necessarily consonant with the definitions of minimum and maximum presented in this 1978 assessment. A comparison of 1975 and 1978 thermal energies for selected hydrothermal convection systems is given in table 7.

Perhaps the greatest difference between the two assessments lies in the refinement of the temperature estimates. In Circular 726, both the SiO_2 and Na-K-Ca geothermometers were used to estimate the reservoir temperatures. However, the SiO_2 temperatures were based only on equilibrium with quartz (quartz conductive and quartz adiabatic geothermometers) rather than chalcedony or other forms of SiO_2. As we pointed out in the discussion of geothermometry, we have considered not only the Na-K-Ca, quartz conductive, and quartz adiabatic geothermometers, but also the chalcedony, cristobalite, amorphous silica, and sulfate-water isotope geothermometers. The geothermometers were evaluated by taking into account the surrounding rock types, flow rates, and, commonly, other chemical constituents of the thermal waters. In addition to this, we have made pH corrections on the SiO_2 geothermometers and Mg corrections on the Na-K-Ca geothermometers where applicable. Mixing temperatures are used in the few instances for which the data suggest a reasonable certainty of mixing. As a result of this reinterpretation, estimates of the reservoir temperatures of several systems have been reduced, and calculation of mean reservoir temperatures has eliminated many systems from the ≥90°C category altogether. Although a few new systems have been identified from information made available through research and industry exploration programs since 1975, overall 24 percent fewer hydrothermal convection systems are reported in this assessment than in Circular 726.

A histogram of numbers of identified hydrothermal convection systems in 20°C temperature intervals is presented in figure 10A. Also shown (fig. 10B) is a similar histogram constructed from the 1975 data (Renner and others, 1975). The pronounced difference between the two histograms at temperatures less than 150°C is a direct result of the temperature refinements made in 1978.

The 1978 data plotted as cumulative frequency versus temperature in figure 11 show that the number of identified hydrothermal convection systems increases exponentially with decreasing temperature in a remarkably regular manner. The equation for the straight line that best fits the data can be used to generate the synthetic histogram shown in figure 10A. If the straight line of figure 11 indeed represents the actual

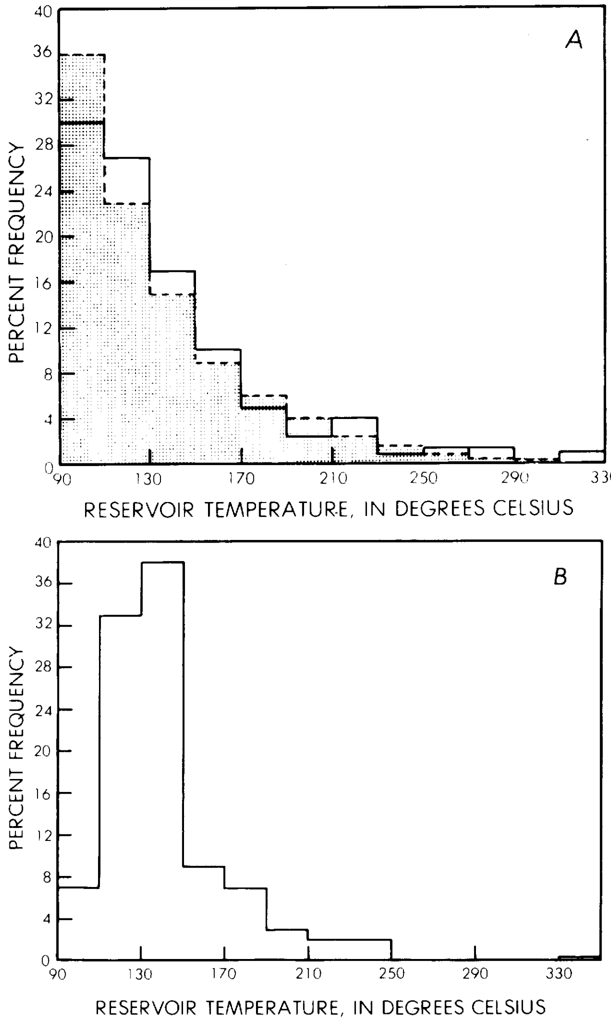

Figure 10.--Percent frequency of identified hydrothermal convection systems by reservoir temperature (20°C classes). A, 1978 data. B, 1975 data (from Renner and others, 1975). Also shown in A is a synthetic frequency histogram (shaded) constructed from the equation of the line that best fits the plot of cumulative frequency vs. reservoir temperature of the 1978 data (fig. 11).

Table 7.--*Comparison of 1975 and 1978 estimates of thermal energies for selected hydrothermal convection systems ≥90°C*

(Thermal energies in units of 10^{18} J.)

System	1975[1]	1978	Primary cause(s) of change from 1975 to 1978.
Surprise Valley--------	100	79	Decrease in reservoir temperature from 175°C to 152°C; small decrease in thickness.
Lassen-----------------	26	42	Increase in reservoir thickness from 1.0 to 1.7 km.
The Geysers------------	79	100	Increase in reservoir area from 70 to 100 km^2.
Long Valley caldera----	230	78	Decrease in reservoir area from 225 to 82 km^2.
Coso-------------------	172	25	Decrease in reservoir area from 168 to 27 km^2.
Salton Sea-------------	88	97	Increase in reservoir area from 54 to 60 km^2 overcompensates for temperature decrease from 340° to 323°C.
Brawley----------------	12.6	22	Increase in reservoir temperature from 200°C to 253°C; increase in reservoir area from 18 to 27 km^2.
Westmoreland-----------	--	67	System not identified in 1975.
East Mesa -------------	23	16.3	Decrease in reservoir thickness from 2 to 1.1 km.
Heber------------------	46	31	Decrease in reservoir temperature from 190° to 175°C; decrease in reservoir area from 50 to 42 km^2.
Weiser-----------------	26	1.38	Decrease in reservoir temperature from 160° to 130°C; decrease in reservoir area from 35 to 2.7 km^2.
Crane Creek-Cove Creek-	25	16.4	Decrease in reservoir area from 30 to 23 km^2; slight decrease in reservoir temperature from 180° to 171°C.
Bruneau-Grand View-----	1100	450	Decrease in reservoir area from 2250 to 1483 km^2; decrease in reservoir temperature from 145° to 107°C.
Newdale area-----------	0.84	20	Increase in reservoir area from 1.5 to 53 km^2.
Raft River-------------	9.6	7.4	Decrease in reservoir area from 20 to 16.7 km^2; also decrease in reservoir thickness from 1.5 to 1.2 km.
Steamboat Springs------	8.0	14.4	Increase in reservoir area from 6 to 11.7 km^2.
Stillwater area--------	9.2	23	Increase in reservoir area from 10 to 35 km^2.
Desert Peak------------	--	29	System not identified in 1975.
Valles caldera---------	75	87	Increase in reservoir temperature from 240° to 273°C.
Vale Hot Springs-------	36	45	Increase in reservoir area from 50 to 70 km^2.
Klamath Falls----------	126	30	Decrease in reservoir area from 240 to 69 km^2.
Cove Fort-Sulphurdale--	20	16.0	Increase in reservoir area from 15 to 24 km^2; also decrease in reservoir temperature from 200°C to 167°C.
Roosevelt--------------	4.2	32	Increase in reservoir area from 4 to 24 km^2; also increase in reservoir temperature from 230° to 265°C.
Yellowstone caldera----	560	1240	Increase in reservoir area from 375 to 1092 km^2.

[1]Converted from values in calories (Renner and others, 1975).

frequency distribution of identified systems in nature, figure 10A suggests that the geothermal systems between 90°C and 100°C are still under-represented in the 1978 data set, but not nearly so much as in 1975.

Area estimates for a few systems have been refined as a result of geophysical and drill hole data made available since 1975. This refinement usually involves the larger systems that are being actively explored. In particular, the areas for the Coso (California), Long Valley (California), and Klamath Falls (Oregon) systems have been markedly decreased, whereas the areas at the Stillwater (Nevada), Newdale (Idaho), and Roosevelt (Utah) systems have been substantially increased. As shown in table 7, the corresponding changes in thermal energy contents are commonly very large.

The Bruneau-Grand View system in southwestern Idaho merits special attention because of its large area and because our new area and temperature estimates are considerably less than in Circular 726. Existing wells at Bruneau-Grand View define a very large area that is underlain by thermal water. Thermal water occurs in wells tens of kilometers to the east and southeast and could be part of a reservoir that is continuous with that at Bruneau-Grand View. However, in estimating the areas of reservoirs in this region, the identified systems are not considered to extend great distances beyond known occurrences of thermal water. Thus, the decrease in the area for Bruneau-Grand View does not reflect new evidence that the reservoir is smaller than previously assumed but rather a different approach to making the estimates.

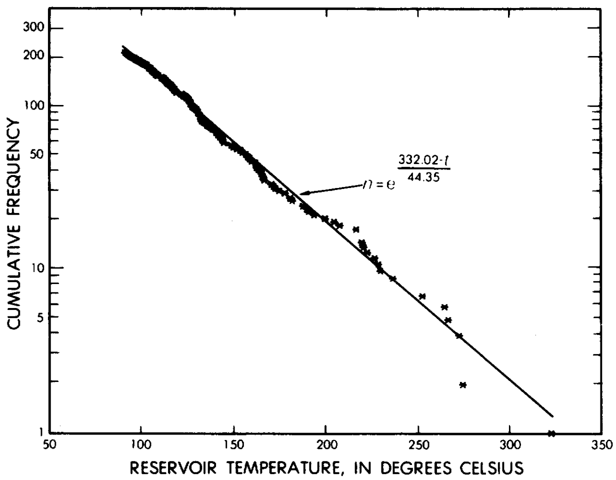

Figure 11.--Cumulative frequency as a function of reservoir temperature for hydrothermal convection systems identified in 1978. The equation describes the straight line that is the least-squares best fit to the data.

UNDISCOVERED ACCESSIBLE RESOURCE BASE

In addition to the accessible resource base calculated for identified systems, a substantial undiscovered component of the accessible resource base undoubtedly exists. As discussed in Circular 726 (Renner and others, 1975), this undiscovered part consists of (1) additional thermal energy due to upward revisions of the volumes of identified systems, (2) additional thermal energy due to upward revisions of temperature estimates, and (3) thermal energy in systems that have not yet been identified. Note that in this assessment both the identified and undiscovered components of the accessible resource base are restricted to depths less than 3 km. Any future change of this depth limit that might be brought about by improved technology or more favorable economics would increase the accessible resource base proportionally.

Most of the hot-water systems listed in tables 5 and 6 (end of report) were originally identified because springs were discharging hot water at the surface. Some systems were discovered accidentally in the drilling of wells for other purposes, and others were discovered through exploration programs designed to locate geothermal resources. However, some thermal springs have not been thoroughly investigated, and future studies of these may lead to the identification of additional geothermal reservoirs with temperatures ≥90°C. More systems will likely be discovered by the drilling of water wells, oil and gas tests, mineral exploration holes, and by exploration programs specifically designed to search for geothermal systems. Exploration tools are being developed and improved that should increase the effectiveness of exploration programs, and as the knowledge of geothermal systems increases so will the ability to find them.

A net increase in the identified accessible resource base can be anticipated as a result of additional investigations of identified hydrothermal convection systems. Some identified systems are likely to be larger than indicated by existing evidence. Experience shows that for a majority of the systems where exploration programs have been carried out, the volume of the reservoir fixed by systematic exploration is larger than estimates based on surface indications. Furthermore, analysis of water samples collected from newly-drilled wells, measurements of actual reservoir temperatures, or application of mixing models may result in the reclassification of known low-temperature systems into systems ≥90°C.

The distribution of geothermal systems bears some obvious but not always well understood relation to geologic provinces. Therefore, undiscovered geothermal resources will be estimated by provinces that are basically the physical divisions defined by Fenneman (1946) but modified locally to be more consistent with the dis-

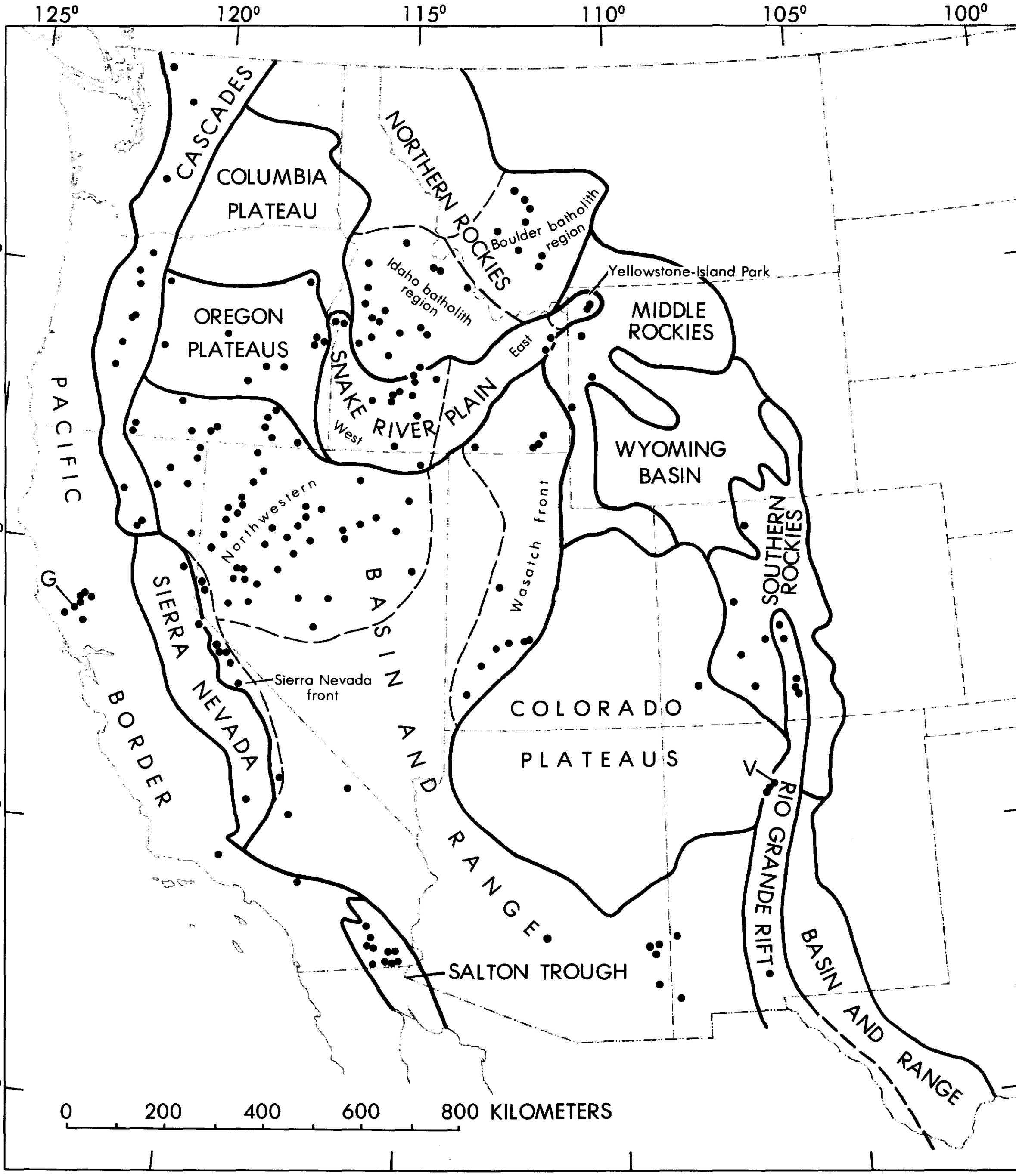

Figure 12.--Map showing geologic provinces of the Western United States (modified from the physiographic provinces of Fenneman, 1946). Dots indicate locations of identified hydrothermal convection systems with reservoir temperatures ≥90°C. G = The Geysers; V = Valles Caldera.

tribution of identified geothermal systems. The provinces and subprovinces are shown in figure 12, and the identified and undiscovered components of the accessible resource base for each province are given in table 8.

In the preparation of the estimates summarized in table 8, the undiscovered component usually is estimated to be 1, 2, 5, 10 or 20 times the identified accessible resource base for each geologic province considered. In provinces where substantial information is available on the hydrothermal convection systems, the estimate is based primarily on the size of the area that appears favorable for the occurrence

Table 8.--*Summary of the identified and undiscovered accessible resource base for geologic provinces of the Western United States*
(Province boundaries are shown in figure 12. Identified component includes energy in National Parks.)

Province	Accessible resource base ($\times 10^{18}$ J) Identified	Undiscovered
Pacific Border		
The Geysers-Clear Lake area	150	150
Other	3	15
Cascades Mountains	57	1,140
Sierra Nevada Mountains	5	5
Columbia Plateau	0	0
Oregon Plateaus	80	400
Snake River Plain		
Western		
Central and southwest	470	940
Camas Prairie and northern margin	21	100
Eastern	21	1,520
Yellowstone-Island Park	1240	170
Basin and Range		
Northwestern	280	1,400
Sierra Nevada front	120	40
Wasatch Front and northeastern margin	67	170
Other	12	60
Salton Trough	240	480
Rio Grande rift		
Valles caldera area	87	87
Other	6	60
Colorado Plateaus	1	50
Rocky Mountains		
Idaho batholith	14	70
Boulder batholith	11	55
Middle Rocky Mountains and Wyoming Basin	2	10
Southern Rocky Mountains	5	25
Alaska		
Alaska Peninsula and Aleutian Islands	10	580
Central Alaska	11	220
Southeast Alaska	10	100
Other	0	100
Hawaii	9	45
TOTAL	2900	8000

of systems similar to the identified systems. Where little information is available on the hydrothermal convection systems, the estimate of the undiscovered component is based on thermal models inferred from geologic, geophysical, and hydrological data. However, because the geologic settings of hydrothermal convection systems are so diverse, subjectivity necessarily plays an important role in making our estimates.

Pacific Border -- Most of the geothermal systems in the Pacific Border Province are in The Geysers-Clear Lake area of the Coast Ranges. This area appears to be unique, and no similar systems are likely to be found in the remainder of the province. Although considerable exploration has been carried out in The Geysers-Clear Lake area, the total accessible resource base has not been completely defined, and the undiscovered component is estimated to equal the identified component.

In the Pacific Border Province outside of The Geysers-Clear Lake area, a few relatively small geothermal systems have been identified. In the Coast Ranges south of San Francisco Bay, the heat flow is about average for the Western United States; elsewhere in the province it is below average. The undiscovered accessible resource base outside of The Geysers-Clear Lake area is not likely to be large and is estimated to be five times the identified for this same area.

Cascade Mountains -- Although no large hydrothermal convection systems have been identified in the Cascade Mountains, the abundance of young volcanic rocks and the isolated occurrences of hot water along the range suggest that a large resource may exist. Much more work must be done before the identified systems can be evaluated and the undiscovered accessible resource base estimated. The Cascade Mountains probably lie over a subduction zone, and magma moving into or through the upper crust has transported large amounts of heat into the upper crust under the range, as is indicated by the numerous volcanoes. Precipitation is high over much of the area, and the resulting abundance of shallow cold water is likely to be masking underlying convection systems. Primarily because of the favorable geologic setting, we estimate the undiscovered accessible resource base in the Cascade Mountains to be twenty times the identified and recognize that it may be even greater.

Sierra Nevada -- The identified accessible resource base (5.6×10^{18} J) in the Sierra Nevada is not large. The Sierra Nevada is a region of unusually low heat flow, and there is no reason to expect a large geothermal resource there. Hydrothermal reservoirs in the batholithic terrane are probably of limited extent and confined to narrow conduits within fault zones. The undiscovered component is estimated to be equal to the identified accessible resource base.

Columbia Plateau -- The Columbia Plateau Province is underlain primarily by the Miocene Columbia River Basalt Group. No identified geothermal systems with reservoir temperatures ≥90°C occur here, and there is no evidence indicating that a large geothermal resource will be discovered.

Oregon Plateaus -- Several identified hydrothermal convection systems occur in the Cenozoic volcanic rocks of the Oregon Plateaus and in older rocks of the Blue Mountains. The Newberry caldera and Vale systems are large. The geology of central and southeast Oregon appears favorable for the occurrence of other large systems and the identified systems may be substantially larger than currently estimated. We estimate additional exploration in this part of Oregon may discover geothermal energy equal to five times the identified accessible resource base.

Snake River Plain -- The Snake River Plain is an area of extensive late Tertiary (Neogene) and Quaternary volcanic activity. On the basis of the distribution of known hydrothermal convection systems and corresponding changes in the geologic character of the plain, the province is divided into a western part, an eastern part, and the Yellowstone-Island Park area. Although the Yellowstone-Island Park area was considered by Fenneman (1946) as part of the Middle Rocky Mountains Province, it is included here because of its genetic relation to the Snake River Plain (Christiansen and McKee, 1978).

Thermal waters occur in numerous wells on the western Snake River Plain and in several springs on or near the edges of the plain. In many of these occurrences, measured or computed reservoir temperatures exceed 90°C. An estimate of the accessible resource base of the region will depend in very large part on the assumption made concerning the continuity of the reservoirs underlying the known occurrences of thermal waters. Numerous wells in the Bruneau-Grand View area have defined a very large geothermal system (table 6); five occurrences of hot water to the east are treated as separate systems. The boundaries of of these systems have not been determined, and a large continuous system may underlie the region. Because hot water is likely to underlie a much larger area than has been established by existing drill holes, the undiscovered accessible resource base in the central part of the western Snake River Plain and in the area of silicic volcanic rocks lying southwest of the plain is estimated to be twice the identified component. The northern margin of the plain and Camas Prairie seem particularly favorable for the occurrence of geothermal systems. Large areas along this margin of the plain have not been tested, and the undiscovered component in this zone is estimated to be five times the identified.

The eastern part of the Snake River Plain is a region of abundant young volcanic rocks, a fact which suggests that it is a region of high heat flow. However, because of the lack of deep drill holes, the regional heat flow below the thick, cold water aquifer that underlies most of the region has not been determined. Only two occurrences of hot water with indicated reservoir temperatures in excess of 90°C have been identified, and these are both near the edge of the plain. The geology underlying the surface volcanic rocks of the eastern Snake River Plain is largely unknown, but available data suggest that high thermal gradients, abundant water, and structures favorable to the development of reservoirs underlie the plain. Thus, the existence of significant geothermal systems appears probable, and the geothermal resource may be huge. Studies currently underway are designed to provide the information needed to evaluate the geothermal energy of the region. Until these studies are completed, a major uncertainty will exist as to the size of the accessible resource base. The tentative estimate of the undiscovered component on the eastern Snake River Plain is 1520×10^{18} J, which is equal to the total identified and undiscovered accessible resource base for the western Snake River Plain.

In the Yellowstone-Island Park area, the identified hydrothermal convection systems (both hot-water and vapor-dominated) ≥90°C are mostly restricted to the Yellowstone caldera in Yellowstone National Park. The hot-water system alone contains the highest thermal energy content (more than 1200×10^{18} J) of any system in the United States, and it is highly unlikely that another similar system occurs.

The volcanic area west and south of the Yellowstone caldera includes the Island Park igneous-related system (Smith and Shaw, this volume) of Pleistocene age. This area of calderas appears favorable for the development of hydrothermal convection systems, but none is known to occur with reservoir temperatures ≥90°C. Accordingly, the general methodology used to estimate the undiscovered component of the accessible resource base in other areas cannot be applied here. Instead, we estimate the percentage of the igneous-related thermal energy that might be contained in hidden hydrothermal systems by comparison with the percentage of igneous-related thermal energy in identified hydrothermal systems known to be associated with other young calderas. This comparison is given in table 9. For the very active Yellowstone caldera system, about 3.5 percent of the igneous-related thermal energy is contained in the hydrothermal convection system. However, for the two less active systems (Long Valley and Valles), the thermal energy contained in the hydrothermal component is only about 1 to 1.5 percent. Smith and Shaw (this volume) estimate about $16{,}850 \times 10^{18}$ J for the Island Park igneous-related system. On the basis of the similarity between this and the Long Valley and Valles systems, we estimate that perhaps 1 percent of the thermal energy in the Island Park igneous system may be contained in undiscovered hydrothermal systems. Thus, the undiscovered accessible resource base for the Yellowstone-Island Park area, excluding Yellowstone National Park, is estimated at 170×10^{18}J.

Basin and Range -- The Basin and Range Province used here is basically that defined by Fenneman (1946). It is extended a few kilometers to the east in southeastern Idaho and Utah, however, to include a number of geothermal systems in an area of basin-and-range structure that Fenneman included in the Middle Rocky Mountains and Colorado Plateau Provinces. The Salton Trough and Rio Grande rift will be considered as provinces separate from the Basin and

Table 9.--*Thermal energy contents of silicic, igneous-related systems with large calderas compared to thermal energy contents of associated hot-water hydrothermal convection systems ≥90°C*
(Energy values in units of 10^{18} J.)

System	Thermal energy in igneous-related system[1]	Thermal energy in associated hydrothermal system[2]	Percentage in hydrothermal system
Long Valley (CA 3)------------------	5780	80	1.4
Valles caldera (NM 1)--------------	8425	81	1.0
Yellowstone caldera system (WY 1)--	36,100	1240	3.4

[1]Smith and Shaw (this volume).
[2]This report.

Range. Identified hydrothermal convection systems in the province are concentrated in the northwest part, near the Sierra Nevada front, near the Wasatch front in Utah, and in the Clifton-Silver City area of Arizona and New Mexico.

Regional heat flow throughout most of the Basin and Range Province is high and in some areas is very high. The thermal blanket effect of the thick layer of sedimentary rocks in many of the valleys results in local increases in the already high thermal gradients. The complex pattern of faulting provides conduits for deep circulation of waters. These factors combine to make a setting favorable for the development of hot-water convection systems. In addition to these favorable regional conditions, young volcanic activity in several areas throughout the province has produced local hot spots.

The concentration of geothermal systems in the northwestern part of the Basin and Range Province appears to result from heat flow higher than normal for the province (the Battle Mountain heat flow high covers a large part of the area) and complex structure resulting from crustal extension that began in Miocene time. Although many systems are known in this area, probably only about one-fifth of the total accessible resource base has been identified. Much of the undiscovered component represents postulated extensions of identified systems.

The high-temperature systems near the Sierra Nevada front, such as Coso and Long Valley, are related to large, young volcanic features, and data are available to estimate the volume of the reservoirs in these systems. However, no additional hydrothermal convection systems associated with large, young volcanic features are likely to exist. Other systems are apparently the result of deep circulation in areas of extensively fractured rock, and their reservoirs are not as well defined. Although these latter systems may be larger than estimated here, we do not foresee the occurrence of any major unidentified systems in this area and therefore estimate the undiscovered accessible resource base to be twice the identified component excluding the Coso and Long Valley systems.

Like the western margin of the province, some geothermal systems along the Wasatch front and northeastern margins are related to young volcanic features (for example, Roosevelt) and some are not. Several identified systems have not been well defined. Two young volcanic areas, Black Rock (Utah) and the Blackfoot lava field (Idaho), have not been tested but appear promising for undiscovered systems. The undiscovered accessible resource base for this area is estimated to be five times the identified excluding the Roosevelt system, with about half of this being extension of identified systems and half as yet unidentified systems.

Except for a grouping in southwestern New Mexico and southeastern Arizona, the identified systems in the remainder of the Basin and Range Province are widely scattered, and the total estimated reservoir volume is small. Much of the area has not been explored, and many unidentified systems may exist. The undiscovered accessible resource base is here estimated to be five times the identified but may be much larger.

Salton Trough -- The Salton Trough is a structural depression extending landward from the Gulf of California. The Gulf of California is characterized by active crustal spreading and high heat flow, and these features are believed to continue beneath the trough. Quaternary volcanism has occurred at the Salton Sea geothermal field on the north and at the Cerro Prieto, Mexico, geothermal field on the south.

Although surface hydrothermal manifestations are rare, the Salton Trough has been intensively explored for geothermal systems, and the identified accessible resource base ($\sim 240 \times 10^{18}$ J) is large. Five major fields (Salton Sea, Westmorland, Brawley, East Mesa, and Heber) are currently under development or approaching development; one of the fields (Westmorland) was discovered since the last assessment. Four more fields may be defined by temperature gradient anomalies. Artesian wells in a broad area of about 550 km^2 between Brawley, East Mesa, and Heber produce warm waters from depths less than 425 m (Reed, 1975). Although the chemical geothermometers for these waters do not indicate reservoir temperatures ≥90°C, the waters may be from the upper reservoirs in a stacked geothermal system, and hotter reservoirs may occur at depth. The Salton Trough is probably not underlain by a single, large hydrothermal convection system but rather by many individual systems. The undiscovered component for the Salton Trough is likely to be twice the identified.

Rio Grande rift -- The Rio Grande rift, as used here, extends from the southern border of New Mexico into central Colorado and includes the San Luis and upper Arkansas Valleys. The geothermal resources of the rift are dominated by the Valles caldera system located on the western border of the rift in northern New Mexico. High heat flow has been measured over part of the rift (Reiter and others, 1975) and geothermal features are common throughout; however, excluding Valles caldera, the identified accessible resource base is small. Three wells in the San Luis Valley have encountered hot water. Map 1 and table 6 show them as separate small systems, but they may be parts of larger systems. Geophysical evidence suggests that buried magma bodies exist near Socorro, New Mexico (Sanford and others, 1977; Chapin and others, 1977), and heat flows in excess of 250 mW/m^2 have been determined at San Diego Mountain and Mirage in southern New Mexico (Reiter and others, 1978). Additional exploration may discover hydrothermal convection systems in these areas.

The hydrothermal convection system at Valles caldera has been explored, and the identified accessible resource base (87×10^{18}J) is large. There are no other systems in the Rio Grande rift comparable to Valles caldera, and the undiscovered accessible resource base in the general area of the caldera is considered to be equal to the identified. Because of the favorable geologic setting and widely distributed occurrences of hot water, the undiscovered accessible resource base for the remainder of the Rio Grande rift is estimated to be ten times the identified.

Colorado Plateaus -- Only one hydrothermal convection system with reservoir temperature ≥90°C is identified in the Colorado Plateaus Province. Although the heat flow over this region is low, young volcanic features in northern Arizona and New Mexico are promising areas for additional exploration. If hydrothermal convection systems are associated with these volcanic features, the accessible resource base could be large. Furthermore, the deeply incised canyons of the Colorado Plateaus have lowered the water table to considerable depths in some areas. Thus, hydrothermal convection systems could discharge completely in the subsurface without any surface manifestations. Although the Colorado Plateaus Province may be devoid of any major hydrothermal convection systems, we estimate the undiscovered accessible resource base for the province as 50×10^{18} J.

Rocky Mountains -- In the Northern Rocky Mountains, identified hydrothermal convection systems ≥90°C occur in a zone that includes the Idaho and Boulder batholiths in central Idaho and southwestern Montana, respectively.

Hydrothermal convection systems are numerous in the region of the Idaho batholith. However, none of these systems has been studied in detail, and estimates of the accessible resource base in this region are highly speculative. The regional heat flow appears to be high. The region may have a very large resource of hot water, or the hot springs may represent small systems with insignificant reservoirs. Although a large uncertainty is recognized, the undiscovered component for the Idaho batholith region is estimated at five times the identified accessible resource base.

Hydrothermal convection systems in the Boulder batholith region of Montana appear to be isolated and small; only Marysville has been studied in detail. Other systems are likely to be similar, and the undiscovered accessible resource base in this area of Montana is estimated to be five times the identified.

Few hydrothermal convection systems ≥90°C are identified in the Middle Rocky Mountains and Wyoming Basin. Lower temperature systems are scattered throughout the province, and temperatures in excess of 90°C may be discovered related to these systems. We estimate that the undiscovered accessible resource base for the Middle Rocky Mountains and Wyoming Basin province is five times the identified.

Scattered geothermal systems occur throughout the Colorado part of the Southern Rocky Mountains. These systems appear to be small, and the undiscovered component of the accessible resource base for this area is estimated to be five times the identified component.

Alaska -- Little geothermal exploration has been done in Alaska, and the geothermal systems that have been identified have not been studied in detail. Known systems occur on the Alaska Peninsula and the Aleutian Islands, in a band across central Alaska south of the Arctic Circle, and in southeast Alaska (map 2).

The Alaska Peninsula and Aleutian Islands overlie an active subduction zone with associated volcanism. Although volcanoes are numerous in the area, only six hydrothermal convection systems with reservoir temperatures ≥90°C are identified; the total thermal energy in these systems is about 10×10^{18} J. The geologic setting is favorable for the development of hydrothermal systems, and several may exist that discharge in the subsurface and (or) are masked by overlying cold water. To estimate the undiscovered component here, we use a similar approach as for the Island Park area. Smith and Shaw (this volume) estimate that the thermal energy remaining in 22 known high-level (<10 km) igneous-related systems along the Alaska Peninsula and Aleutian Islands is 7300×10^{18} J. These systems constitute only about one-fourth of all the systems listed by Smith, Shaw, Luedke, and Russell (1978) for this area, so it is conceivable that as much as $29{,}000 \times 10^{18}$ J may be contained in all of the igneous systems in the area. In Circular 726, White and Williams (1975, p. 148) also estimate that the thermal energy content in the combined identified and undiscovered components of the accessible resource base for all igneous-related systems is about four times that in the identified systems alone. We estimate that 1 to 2 percent of this energy may be contained in undiscovered hydrothermal systems. The undiscovered hydrothermal component for the area therefore is about 290 to 580 x 10^{18}J and is likely to be nearer the higher value.

The many thermal springs across central Alaska all have estimated reservoir temperatures less than 150°C and are probably the result of deep circulation. The identified accessible resource base calculated for the region is about 11 x 10^{18} J. Because of the large area involved, it is reasonable to assume that the undiscovered component may be at least twenty times this amount. Thermal springs in southeast Alaska are also thought to result from deep circulation. The identified accessible resource base here is about 10 x 10^{18} J, and the undiscovered component may be on the order of ten times this amount.

Outside of the three regions discussed above, large areas of Alaska remain to be explored, and the likelihood of finding new hydrothermal convection systems is great. We estimate the undiscovered accessible resource base for these remaining areas to be on the order of 100 x 10^{18} J. The total undiscovered accessible resource base for Alaska, therefore, is about 1000 x 10^{18} J and may be much larger.

Hawaii -- Very large temperature anomalies are apparent on the summit and rifts of Kilauea and Mauna Loa Volcanoes. A hot-water reservoir has been drilled near Kapoho on the east rift zone of Kilauea, and two other hydrothermal convection systems have been identified. Many uncertainties exist concerning the subsurface geology as it relates to the development of geothermal reservoirs on these volcanoes, but undiscovered reservoirs are likely to exist. Also hydrothermal systems may be associated with the older volcanoes on Hawaii and with Haleakala on Maui and perhaps even older volcanoes on the other Hawaiian Islands. The undiscovered accessible resource base in the State of Hawaii is estimated to be five times the identified.

Central and Eastern United States -- Thermal waters are known to occur in three main areas of the Central and Eastern United States: (1) in the Madison Group of North and South Dakota, Montana, and Wyoming, (2) the Hot Springs area, Arkansas, and (3) the Appalachian Mountains. However, no reservoirs with temperatures ≥90°C have been found in these areas (see also Sammel, this volume). Although the region encompasses a diversity of geologic environments, the relatively stable tectonic setting, normal heat flow, and absence of young volcanic activity seem to preclude the likely occurrence of intermediate- and high-temperature hydrothermal convection systems typical of the Western United States. Therefore, we cannot quantitatively judge the amount of undiscovered accessible resource base for the region.

DISTRIBUTION OF UNDISCOVERED THERMAL ENERGY BETWEEN HIGH- AND INTERMEDIATE-TEMPERATURE CATEGORIES

As shown in table 8, the total undiscovered component of the accessible resource base for hydrothermal convection systems is 8000 x 10^{18} J. In order to estimate electricity and beneficial heat that might be produced from this geothermal energy, we must make some assumption about its division between the two temperature categories, >150°C and 90° to 150°C. One possible assumption is that this division for the undiscovered component is the same as for the identified component. This assumption, however, is extremely sensitive to the way in which we treat the two giant systems (Yellowstone and Bruneau-Grand View) that dominate the data. If we include both, the ratio of thermal energy of high-temperature systems to the thermal energy of all identified systems is 76 percent. If we omit both, the ratio is 79 percent. But if we omit Yellowstone (there is essentially no chance of finding another one!) but include Bruneau-Grand View (we just might find another), the percentage of thermal energy in high-temperature systems drops to 58. Furthermore, all these calculations fail to take into consideration that exploration and evaluation to date have been primarily for the high-temperature systems. Because more data are available for the high-temperature systems, 77 percent of them have calculated reservoir volumes (tables 4 and 5) other than the standard volume estimate (3.33 km^3), compared to only 23 percent of the identified systems in the intermediate-temperature category (table 6).

Instead of assuming that the actual energy distribution of identified systems applies to the undiscovered component, we can base our analysis on two other assumptions: a) the relation between reservoir volume and temperature in identified systems for which volume data exist also applies to the undiscovered component; and b) the synthetic frequency histogram (number versus temperature) of identified systems (fig. 10A) applies to new systems. Our procedure can be outlined as follows:

1. Determine two limiting cases for the relation of volume and temperature of identified systems,
2. Use these cases to estimate the additional geothermal energy contributed by volume increases in identified systems for which only standard volumes (3.33 km^3) are now calculated,
3. Transform the synthetic frequency histogram of identified systems (fig. 10A) to histograms of energy versus tempera-

ture under the two limiting cases of volume-temperature relations, and

4. Use these energy histograms to estimate the division of undiscovered energy between the 90°-150°C and >150°C components of new systems and of identified systems that increase in temperature and volume (over and above the volume increase in standard-volume systems calculated in step 2).

Figure 13 plots volume versus temperature for all identified reservoirs for which data are adequate to calculate other than a standard volume. From this plot, there is some suggestion that volume generally increases with temperature, as expressed by the straight line fit by least-squares regression to the data. This suggestion is compatible with the geologic observations that high-temperature hydrothermal systems commonly are associated with young igneous systems whereas many intermediate-temperature systems are related merely to deep circulation of water along faults. An alternative interpretation of the data, however, is that the increase of volume with temperature is spurious and results from our far greater knowledge of high-temperature systems than intermediate-temperature systems. This interpretation is perhaps strengthened when we remember that only 23 percent of the identified intermediate-temperature reservoirs have other than standard volumes (and are thus plotted on fig. 13) compared to 77 percent of the high-temperature reservoirs. If the volume data set were complete, we might find the average volume of intermediate-temperature reservoirs to be the same as the average volume of high-temperature reservoirs.

Given these uncertanties in interpreting figure 13, we use two limiting cases in the following analysis: a) volume tends to increase with temperature along the straight line shown on figure 13; and b) the average volume for high-temperature systems and intermediate-temperature systems is the same. Excluding the 139 systems for which only standard volumes are available and also excluding the two giant systems (Yellowstone and Bruneau-Grand View), the average volume of identified hydrothermal convection systems is 29.6 km^3.

Treating the constant-volume case first, we use equation 1 to calculate how much thermal energy would be in each standard-volume system if that system had a volume of 29.6 km^3. We then subtract the energy previously tabulated in tables 4, 5, or 6 (end of report) from each newly calculated value. The sum of the resultant values is the increase in thermal energy expected if each of these standard-volume systems had a volume of 29.6 km^3. For this constant-volume limiting case, the increase in energy of intermediate-temperature systems is 900 x 10^{18} J, and the increase in energy of high-temperature systems is 151 x 10^{18} J.

For the increasing-volume case, we use equation 1 to calculate how much thermal energy

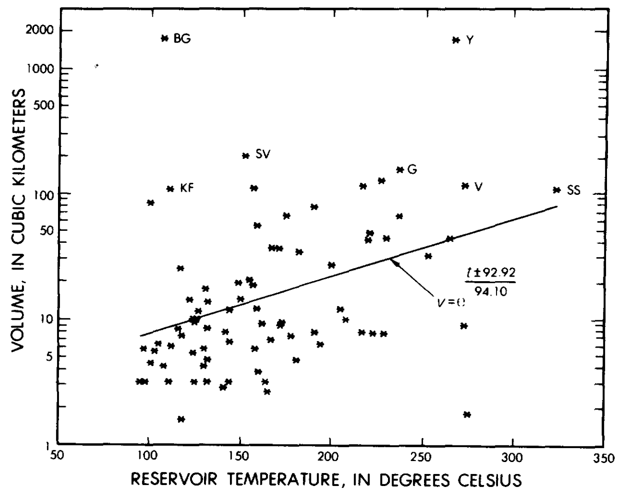

Figure 13.--Mean reservoir volume in relation to mean reservoir temperature for hydrothermal convection systems identified in 1978, excluding those systems for which data are not adequate to calculate other than a standard volume of 3.3 km^3. BG = Bruneau-Grand View; Y = Yellowstone; KF = Klamath Falls; SV = Surprise Valley; G = The Geysers; V = Valles caldera; SS = Salton Sea. The equation describes the straight line that is the least-squares best fit to the data.

would be in each standard-volume system if that system had the volume indicated by the straight line on figure 13 for the respective reservoir temperature. We then subtract the energy previously tabulated in tables 4, 5, or 6 from the newly calculated value. The sum of the resultant values is the increase in thermal energy expected if each of these standard-volume systems had a volume corresponding to the line on figure 13. For this increasing-volume limiting case, the increase in energy of intermediate-temperature systems is 210 x 10^{18} J, and the increase in energy of high-temperature systems is 76 x 10^{18} J.

We now turn to the energy likely to be in new reservoirs yet to be discovered. First, we assume that the form of the frequency histogram of new systems will be identical to the form of the synthetic frequency histogram of identified systems (fig. 10A). We then transform the synthetic frequency histogram into energy histograms by using n_{20}/n_{total} in a modification of equation (1):

$$q_{20} = \rho c \cdot v \cdot n_{total} \cdot (t - 15^{\circ}C) \cdot \frac{n_{20}}{n_{total}} \quad (1c)$$

where q_{20} is the thermal energy in each 20°C class, t is the median temperature of each temperature class, n_{20} is the number of systems in each 20°C class, and n_{total} is the total number of new systems. The value of n_{20}/n_{total} is derived from the ordinate of figure 10A. Assuming that the average volume in each temperature class is the same, the form of the resultant energy histogram (in percent) is given by the solid line on figure 14. Since neither the number of systems (n_{20}) nor the average volume is specified, the histogram does not give absolute values of energy. The figure does indicate, however, that, under the constant-volume case, 38 percent of the energy in new reservoirs is at temperatures greater than 150°C and 62 percent at temperatures of 90° to 150°C.

The comparable energy histogram for the increasing-volume case is constructed by assuming that the variation of reservoir volume with temperature is given by the line on figure 13. This energy histogram (the dashed line on figure 14) shows that, under the increasing-volume limiting case, 62 percent of the energy in new reservoirs is at temperatures greater than 150°C, and 38 percent at temperatures of 90° to 150°C.

Finally, we must consider the increase in energy caused by any increases in temperature or volume of already identified reservoirs (over and above the volume increase in standard-volume systems). The factors that affect the division of this energy into high- and intermediate-temperature categories are the same as those that affect the division of energy in systems yet to be discovered (that is, the synthetic frequency histogram of figure 10A and the volume-temperature relations of figure 13). Consequently, as a first approximation, the energy histograms of figure 14 can also be applied to the extensions of already identified systems. Accordingly, the percentages cited above apply not only to new systems but also to the entire undiscovered component over-and-above the energy previously calculated for the increase in volume of standard-volume systems.

The results of this analysis are summarized in table 10. We subtract the total energy in increases of standard-volume systems (290 x 10^{18} J under the increasing volume case; 1050 x 10^{18} J under the constant-volume case) from the total undiscovered component (8000 x 10^{18} J). The resultant values (7700 x 10^{18} J and 7000 x 10^{18} J) are then apportioned into energy >150°C and energy at 90°-150°C according to the percentages derived above.

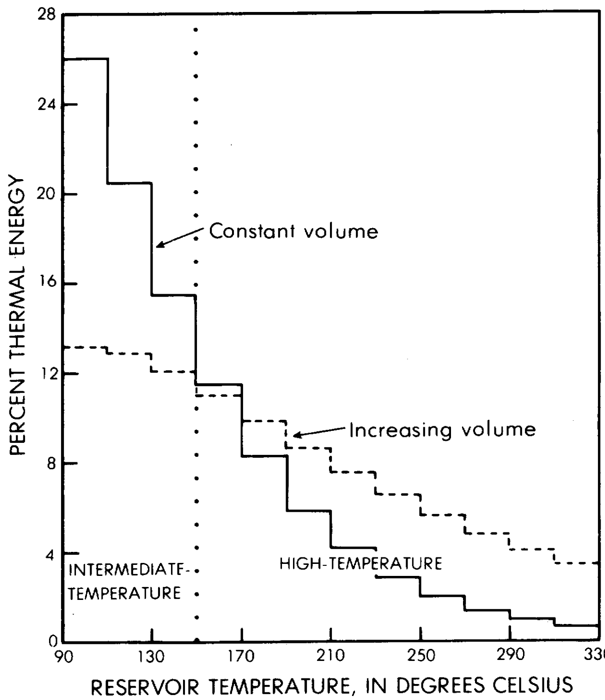

Figure 14.--Histogram of thermal energy in undiscovered hydrothermal convection systems by reservoir temperature (20°C classes, 90°-330°C). Constructed from the synthetic frequency histogram of figure 10a under the assumption that its form represents the form of the frequency histogram of undiscovered hydrothermal convection systems. The energy histogram shown by the solid line assumes that the average volume of new systems in each 20°C class is the same. The energy histogram shown by the dashed line assumes that the average volume of new systems in each 20°C class increases with temperature following the equation given on figure 13. Both histograms represent the same total amount of energy. Neither this total nor the total number of new systems is specified; thus, the figure gives only relative energy by percent in temperature classes.

SUMMARY

Total values for the various categories of identified accessible resource base determined in this assessment are compared with those from Circular 726 in the upper part of table 11. National Parks are estimated to have considerably more thermal energy in this assessment than in Circular 726. This large increase is due primarily to the substantial increase in the area estimated for the Yellowstone hot-water system. The estimate of thermal energy for The Geysers, the only vapor-dominated system known outside of National Parks, has also increased slightly over the 1975 assessment, again owing to the increase in estimated area. However, the totals of both high-temperature and intermediate-temperature hot-water systems have decreased considerably from 1975. As we explained above, these decreases are the result of fewer identified systems ≥90°C, lower estimated reservoir temperatures for many systems, and smaller estimated areas for many systems. The changes in area estimates were particularly important for several of the large systems (for example, Bruneau-Grand View, Klamath Falls, Coso, Long Valley) and have strongly influenced the totals.

A significant difference between this assessment and Circular 726 is the method of estimating the undiscovered component of the accessible resource base. Renner, White, and Williams (1975) estimated the undiscovered component for the United States as a whole to be five times the identified component for high-temperature hot-water systems (excluding National Parks), and three times for intermediate-

Table 10.--*Undiscovered accessible resource base in hydrothermal convection systems ≥90°C*
(Numbers are rounded off to two significant figures or to three significant figures when the first digit is 1.)

Assumption 1 - volume increases with temperature

	90°-150°C	>150°C
Extensions of identified systems of standard volume	210×10^{18} J	76×10^{18} J
Remaining undiscovered component	2900×10^{18} J	4800×10^{18} J
TOTAL	3100×10^{18} J	4900×10^{18} J

Assumption 2 - constant volume

	90°-150°C	>150°C
Extensions of identified systems of standard volume	900×10^{18} J	151×10^{18} J
Remaining undiscovered component	4300×10^{18} J	2600×10^{18} J
TOTAL	5200×10^{18} J	2800×10^{18} J

temperature hot-water systems. We estimate the undiscovered accessible resource base by geologic provinces and then divide it into temperature categories. In Circular 726, the ratio of the undiscovered component to the identified component (excluding National Parks) was 4, whereas in Circular 790 it is approximately 5.

The bottom line of table 11 gives the sums of the identified and undiscovered components for this assessment of hydrothermal convection systems, along with the corresponding sums from Circular 726. The decrease of 21 percent in accessible resource base and resource from 1975 is due primarily to two factors: (1) the decrease in estimates of volume of some of the largest identified systems, and (2) the fact that the undiscovered component is usually estimated as a multiple of the identified component and is thus affected by any change in size of the identified component. Under the assumption that volume increases with temperature following the line of figure 13, the total amount of electrical energy is estimated to be essentially the same as in 1975. Under the constant-volume assumption, however, the total amount of electrical energy is only 62 percent of that estimated in 1975. In a complementary manner, the total beneficial heat estimated in 1978 under the constant-volume assumption is the same as that estimated in 1975, but under the increasing-volume assumption is only 66 percent of the 1975 estimate. We emphasize that the estimates of electrical energy and beneficial heat by the two limiting assumptions are complementary. Consequently, it is not possible for the higher value of electricity to exist simultaneously with the higher value of beneficial heat.

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Table 11.--*Summary of energies of hydrothermal convection systems ≥90°C compared with corresponding energies from Circular 726*

(The values of 1978 means and standard deviations for accessible resource base, resource, and beneficial heat are calculated analytically. Means and standard deviations for electrical energy are obtained from Monte Carlo calculations rather than analytically because of the nonlinear dependence of available work (and thus electrical energy) on reservoir temperature. Not included in this table is the accessible resource base in National Parks, estimated in Circular 726 to be 590 x 10^{18} J and in Circular 790 as 1290 x 10^{18} J. Numbers are rounded off to two significant figures or to three significant figures when the first digit is 1.)

	Number of systems		Accessible resource base (10^{18} J)		Resource (10^{18} J)		Electrical energy (MW_e for 30 yr)		Beneficial heat (10^{18} J)	
	1975	1978	1975	1978	1975	1978	1975	1978	1975	1978
IDENTIFIED (excluding National Parks)										
Vapor-dominated (The Geysers)---------------	1	1	79	100 ± 24	8	9.3 ± 4.5	1620	[a]1630 ± 770	-	-
Hot-water >150°C--------	61	51	1000	850 ± 80	250	210 ± 30	25,000	[a]21000 ± 3300	-	-
Hot-water 90°-150°C-----	221	163	1440	700 ± 110	360	176 ± 55	-	-	87	42 ± 13
Total identified--------	283	215	2500	1650 ± 140	620	400 ± 60	27,000	23,000 ± 3400	87	42 ± 13
UNDISCOVERED										
Vapor-dominated and hot-water >150°C-------	-	-	5300	[c]2800-[b]4900	1300	[c]700-[b]1230	127,000	[c]72,000-[b]127,000	-	-
Hot-water 90°-150°C-----	-	-	4400	[c]5200-[b]3100	1100	[c]1300- [b]770	-	-	260	[b]184-[c]310
Total undiscovered------	-	-	9700	8000	2400	2000	127,000	[c]72,000-[b]127,000	260	[b]184-[c]310
TOTAL identified (excluding National Parks) and undiscovered------------	-	-	12,200	9600	3000	2400	153,000	[c]95,000-[b]150,000	350	[b]230-[c]350

[a]These values of electrical energy differ from the sums shown in tables 4 and 5 because of slightly different methods of calculation (Monte Carlo in this table and analytical in tables 4 and 5).
[b]Increasing-volume assumption for undiscovered component (see text and fig. 13).
[c]Constant-volume assumption for undiscovered component (see text and fig. 13).

REFERENCES CITED

Arnórsson, Stefân, 1975, Application of the silica geothermometer in low temperature hydrothermal areas in Iceland: American Journal of Science, v. 275, p. 763-784.

Bodvarsson, G., 1974, Geothermal resource energetics: Geothermics, v. 3, p. 83-92.

Chapin, C. E., Chamberlin, R. M., Osburn, G. R., White, D. W., and Sanford, A. R., 1977, Exploration framework of the Socorro geothermal area, New Mexico: New Mexico Geological Society Special Pub. 7, p. 115-130.

Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane region, in Smith, R. B., and Eaton, G. P., Cenozoic tectonics and regional geophysics of the Western Cordillera: Geological Society of America Memoir 152. (in press)

Ellis, A. J., 1970, Quantitative interpretation of chemical characteristics of hydrothermal systems, in United Nations symposium on development and utilization of geothermal resources, Pisa 1970, v. 2, pt. 1: Geothermics, Special Issue 2, p. 516-528.

Fenneman, N. M., 1946, Physical divisions of the United States: U. S. Geological Survey, scale 1:7,000,000.

Finney, J. P., 1973, Design and operation of The Geysers power plant, in Kruger, Paul and Otte, Carel, eds., Geothermal energy--resources, production, stimulation: Stanford, Calif., Stanford University Press, p. 145-161.

Fournier, R. O., 1973, Silica in thermal waters: Laboratory and field investigations, in Proceedings of international symposium on hydrogeochemistry and biogeochemistry, Japan, 1970, Volume 1, Hydrochemistry: Washington, D. C., J. W. Clark, p. 122-139.

Fournier, R. O., and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-stream wells: American Journal of Science, v. 264, p. 685-697.

Fournier, R. O., and Potter, R. W., 1978, A magnesium correction for the Na-K-Ca chemical geothermometer: U. S. Geological Survey Open-File Report 78-486, 24 p.

Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochimica et Cosmochimica Acta, v. 37, p. 1255-1275.

_____, 1974, Geochemical indicators of subsurface temperature - part 2, estimation of temperature and fraction of hot water mixed with cold water: U. S. Geological Survey Journal of Research, v. 2, no. 3, p. 263-270.

Fournier, R. O., White, D. E., and Truesdell, A. H., 1974, Geochemical indicators of subsurface temperature - part 1, basic assumptions: U. S. Geological Survey Journal of Research, v. 2, no. 3, p. 259-262.

Isherwood, W. F., 1977, Reservoir depletion at The Geysers, California, in Geothermal--State of the art: Geothermal Resources Council Transactions, v. 1, p. 149.

Jones, G. B. and Hawkins, G. A., 1960, Availability and irreversibility, chapter 11 in Engineering Thermodynamics: New York, John Wiley, p. 363-388.

Mariner, R. H., Brook, C. A., Swanson, J. R., and Mabey, D. R., 1978, Selected data for hydrothermal convection systems in the United States with estimated temperatures ≥90°C: U. S. Geological Survey Open-File Report 78-858.

Mariner, R. H., and Willey, L. M., 1976, Geochemistry of thermal waters in Long Valley, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 792-800.

McKenzie, W. F., and Truesdell, A. H., 1977, Geothermal reservoir temperatures estimated from the oxygen isotope compositions of dissolved sulfate and water from hot springs and shallow drillholes: Geothermics, v. 5, p. 51-61.

Muffler, L. J. P., and Cataldi, R., 1978, Methods for regional assessment of geothermal resources: Geothermics, v. 7, nos. 2-4. (in press)

Nathenson, Manuel, 1975, Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas: U. S. Geological Survey Open-File Report 75-525, 35 p.

_____,1978, Methodology of determining the uncertainty in the accessible resource base of identified hydrothermal convection systems: U. S. Geological Survey Open-File Report 78-1003, 50 p.

Nathenson, Manuel, and Muffler, L. J. P., 1975, Geothermal resources in hydrothermal convection systems and conduction-dominated areas, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the

United States - 1975: U. S. Geological Survey Circular 726, p. 104-121.

Ramey, H. J., Jr., 1970, a reservoir engineering study of The Geysers geothermal field: Document submitted as evidence, Reich and Reich, Petitioners v. Commissioner of Internal Revenue, 1969 Tax Court of the United States, 52, T. C. No. 74, 28 p., 19 exhibits.

Reed, M. J., 1975, Chemistry of thermal water in selected geothermal areas of California: California Division of Oil and Gas Report No. TR15, 31 p.

Reiter, M., Edwards, C. L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geological Society of America Bulletin, v. 86, p. 811-818.

Reiter, M., Shearer, C., and Edwards, C. L., 1978, Geothermal anomalies along the Rio Grande rift in New Mexico: Geology, v. 6, p. 85-88.

Renner, J. L., and others, 1976, Selected geogeothermal resources data: hydrothermal convection systems in the states of Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Wahshington, and Wyoming: National Technical Information Service CRPU-76-16, 358 p.

Renner, J. L., White, D. E., and Williams, D. L., 1975, Hydrothermal convection systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States-1975: U. S. Geological Survey Circular 726, p. 5-57.

Sanford, A. R., Mott, R. P., Jr., Shuleski, P. J., Rinehart, E. J., Caravella, F. J., Ward, R. M., and Wallace, T. C., 1977, Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico: American Geophysical Union Monograph 20, p. 385-403.

Smith, R. L., Shaw, H. R., Luedke, R. G., and Russell, S. L., 1978, Comprehensive tables giving physical data and thermal energy estimates for young igneous systems of the United States: U. S. Geological Survey Open-File Report 78-925.

Swanson, J. R., 1977a, GEOTHERM data file, in Geothermal--State of the art: Geothermal Resources Council Transactions, v. 1, p. 285-286.

_____, 1977b, GEOTHERM users guide: U. S. Geological Survey Open-File Report 77-504, 53 p.

Truesdell, A. H., and White, D. E., 1973, Production of superheated steam from vapor-dominated geothermal reservoirs: Geothermics, v. 2, p. 154-173.

White, D. E., 1970, Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources, in United Nations symposium on development and utilization of geothermal resources, Pisa 1970, v. 1, pt. 2: Geothermics, Special Issue 2, p. 58-80.

_____, 1973, Characteristics of geothermal resources, in Kruger, P., and Otte, C., eds., Geothermal energy: Stanford, Calif., Stanford University Press, p. 69-94.

White, D. E., Muffler, L. J. P., and Truesdell, A. H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Economic Geology, v. 66, no. 1, p. 75-97.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States - 1975: U. S. Geological Survey Circular 726, 155 p.

Wildman, W. E., Jackson, M. L., and Whittig, L. D., 1968, Serpentinite rock dissolution as a function of carbon dioxide pressure in aqueous solution: American Mineralogist, v. 53, p. 1252-1263.

Table 4.--*Locations, temperatures, volumes, and*

(For reservoir temperature estimates, first number is most likely value, subscript is maximum value, and followed by standard deviations. Temperatures given to three significant figures; in most cases volumes figures are given in order to approximate more closely uniform percentage accuracy.)

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
					C A	L I F
040	Lassen	40 26.0 121 26.0	215 240 255	237 ± 8	71 ± 25	42 ± 15
048	The Geysers	38 48.0 122 48.0	215 240 255	237 ± 8	1167 ± 39	100 ± 24
					W	Y O M
215A	Mud Volcano area	44 37.5 110 26.0	200 230 240	223 ± 8	8.2 ± 1.7	4.6 ± 1.0
	TOTALS--					147 ± 28 -

*Totals of wellhead thermal energy, available work, and electrical energy exclude National Parks.

energies of identified vapor-dominated systems

superscript is minimum value. Mean values of temperature, volume, and reservoir thermal energy are and energies are given to two significant figures. However, if the first digit is 1, three significant

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
O R N I A			
Low-chloride and acid-sulfate character of thermal waters and presence of fumaroles suggest a vapor-dominated system, but this has not been confirmed by drilling. Temperatures are assumed to be similar to The Geysers. Area may range from 10 to 70 km^2. Withdrawn from commercial exploration or development because of National Park status.	-	-	--
Area may range from 60 to 120 km^2. Boundaries of the reservoir have not been exactly delimited, although unsuccessful step-out wells have been drilled at the northwest and southeast edges of the presently developed field. Reservoir probably extends deeper than 3 km. More than 200 wells have been drilled. Generating capacity in early 1979 will be 663 MW_e; facilities to generate an additional 320 MW_e are under construction and planned to be operational by mid 1980.	9.3	3.1	1610
I N G			
A vapor-dominated system of limited extent which has apparently developed from the hot-water system of Yellowstone caldera. Resistivity data suggest that the vapor-dominated reservoir is underlain by hot water at about 1.5 km depth. Withdrawn from commercial exploration or development because of National Park status.	-	-	--
---	9.3*	3.1*	1610*

Table 5.--*Locations, temperatures, volumes, and energies of*

(For reservoir temperature estimates, first number is most likely value, subscript is maximum value, and

A. Quartz conductive
B. Quartz conductive, pH-corrected.
C. Quartz adiabatic
D. Chalcedony
E. Chalcedony, pH-corrected
F. Cristobalite

No letter indicates a subjective estimate. Mean values of temperature, volume, and reservoir thermal volumes and energies are given to two significant figures. However, if the first digit is 1, three

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						A L A
017	Hot Springs Cove	53 14 168 21	143 (A) 148 (I) 200 (N)	164 ± 13	3.3 ± 0.9	1.34 ± 0.39
018	Geyser Bight	53 13 168 28	177 (I) 182 (C) 264 (K)	208 ± 20	10.6 ± 3.0	5.5 ± 1.7
027	Bailey Bay Hot Springs	55 59.0 131 39.5	155 (I) 165 (A) 165 (A)	162 ± 2	3.3 ± 0.9	1.32 ± 0.37
						A R I
029	Power Ranches Inc., Wells	33 17.1 111 41.2	150 165 180	165 ± 6	2.8 ± 0.9	1.12 ± 0.36
					C A	L I F
035	Surprise Valley area	41 40 120 12	129 (I) 143 (A) 185	152 ± 12	210 ± 90	79 ± 32
041	Morgan Springs-Growler Springs	40 23 121 31	176 (C) 230 (I) 245 (K)	217 ± 15	8.3 ± 2.6	4.5 ± 1.5
046	Sulphur Bank mine (Hot Bolata)	39 01 122 39	186 (M) 186 (M) 210	194 ± 6	6.7 ± 1.9	3.2 ± 0.9
047	Clear Lake volcanic field area	38 55 122 43	165 (A) 195 (N) 210 (N)	190 ± 9	83 ± 35	39 ± 17

identified hot-water hydrothermal convection systems >150°C

superscript is minimum value. Letters indicate method used to estimate temperature as follows:

G. Amorphous silica
H. Na-K
I. Na-K-Ca
J. Na-K-Ca, Mg-corrected
K. Sulfate-water isotope
L. Surface
M. Reported well
N. Mixing
O. Renner, 1976

energy are followed by standard deviations. Temperatures given to 3 significant figures; in most cases significant figures are given in order to approximate more closely uniform percentage accuracy.)

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
S K A			
Springs with temperatures to 89°C occur in two groups about 1 km apart; located about 20 km southwest of Okmok caldera, which last erupted in 1945.	0.33	0.064	27
Three thermal areas consisting of hot springs, geysers, fumaroles, and sinter deposits in a zone 2 km long. Temperatures measured to 102°C. Located about 5 km southwest of Hot Springs Cove.	1.37	0.32	136
Springs to 88°C discharging 314 L/min.	0.33	0.062	26
Z O N A			
Two wells drilled to about 3 km depth and located about 1 km apart; bottom hole temperatures of 163° and 184°C; discharge estimated at 19,000 L/min from below 2 km. No surface manifestations. No chemical or isotopic data available.	0.28	0.053	23
O R N I A			
Four main groups of thermal springs and eight wells in zone about 20 km long; violent mud eruption in 1951. Deepest well drilled to over 2 km; maximum reported well temperature 160°C at 1.1 km.	19.8	3.5	1490
Several springs in two groups about 1.2 km apart; abundant sinter deposits. System may be larger and is probably related to the adjacent vapor-dominated system at Lassen. Surface temperatures to 95°C; discharge 350 L/min.	1.13	0.28	116
Hot springs, fumaroles, and associated mercury and sulfur deposits. Four wells, deepest about 1.2 km; maximum reported temperature 186°C at about 0.4 km.	0.80	0.178	75
Several warm springs and local occurrences of sulfur deposition and gas seeps scattered throughout Quaternary volcanic field adjacent to The Geysers steam field. Few deep wells with unconfirmed temperatures as high as 270°C at 3 km depth. There is no evidence to indicate that the volcanic field is completely underlain by a hydrothermal convection system.	9.8	2.1	900

Table 5.--*Locations, temperatures, volumes, and energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km³)	Mean reservoir thermal energy (10^{18} J)
					C A	L I F
056	Long Valley caldera	37 40 118 52	200 230 250	227 ± 10	136 ± 36	78 ± 21
057	Coso area	36 03 117 47	190 230 240	220 ± 11	46 ± 12	25 ± 7
058	Randsburg area	35 23 117 32	115 (M) 150 250	172 ± 29	9.4 ± 2.3	4.0 ± 1.2
064	Salton Sea area	33 12 115 36	300 330 340	323 ± 8	116 ± 34	97 ± 28
064A	Westmorland	33 05 115 39	200 215 235	217 ± 7	123 ± 35	67 ± 19
065	Brawley	33 03 115 32	230 250 280	253 ± 10	34 ± 8	22 ± 5
068	East Mesa	32 47 115 15	165 180 200	182 ± 7	36 ± 7	16.3 ± 3.0
070	Border	32 44 115 07	150 (O) 160 (O) 170 (O)	160 ± 4	4.0 ± 0.6	1.57 ± 0.25
071	Heber	32 43.0 115 31.7	160 180 185	175 ± 5	71 ± 14	31 ± 6
					C	O L O
078	Paradise Hot Spring	37 45.2 108 07.9	130 161 (A) 170 (J)	154 ± 9	3.3 ± 0.9	1.25 ± 0.36

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
O R N I A			
` deep (2.1 km) geothermal test well in the eastern part of the caldera encountered temperatures of only 72°C. The high-temperature system is probably confined to the western part of the caldera west of the Hilton Creek fault. Enthalpy-chloride relations indicate possible maximum temperature of 282°C.	19.4	4.9	2100
Surface activity consists of acid-sulfate springs and weak fumaroles. A geothermal test well 1,477-m deep encountered a chloride water at 1,064 m; maximum recorded temperature was 189°C at 628 m. Enthalpy-chloride relations indicate possible temperatures of 240° to 275°C.	6.3	1.55	650
One well 235 m deep; maximum recorded temperature 115°C. Hot water apparently flashes in borehole.	1.00	0.199	84
More than 20 wells drilled to depths of 0.7 to 2.4 km; maximum reported temperature 360°C at 2.1 km. Produced fluids are hypersaline brines. A geothermal loop experimental facility is currently being tested.	24	8.1	3400
No surface discharge. Six geothermal test wells, maximum depth about 2.6 km. Temperatures at 1.9 km average between 190°C and 250°C. May be extension of the Salton Sea system.	16.7	4.0	1710
No surface discharge. About 6 wells, deepest about 4 km; maximum reported temperature 262°C at 2.4 km in brine. May consist of two separate systems.	5.5	1.51	640
No surface discharge. Twenty or more wells between about 0.9 and 2.8 km deep; maximum reported temperature 204°C at 2.3 km in brine. A 10 MW_e binary cycle plant designed for a working temperature of about 180°C is under construction; additional facilities to produce 48 MW_e are planned.	4.1	0.85	360
No surface discharge. Area identified by temperature gradient anomaly. Estimated reservoir temperatures may be too high.	0.39	0.073	31
No surface discharge. Eleven wells between 0.9 and 3.3 km deep. Average bottom hole temperature is 180°C; maximum field temperature is about 190°C. Plans to develop a 50 MW_e plant have been announced.	7.7	1.55	650
R A D O			
Hot springs discharging 114 L/min with surface temperatures of 40° to 46°C. Saline water; chemical geothermometers may be unreliable and probably indicate higher temperatures than actually present.	0.31	0.056	24

Table 5.--*Locations, temperatures, volumes, and energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						H A W
083	Steaming Flats (Sulphur Bank)	19 26.5 155 16.0	100 (O) 150 (O) 240 (O)	163 ± 29	3.3 ± 0.9	1.33 ± 0.46
084	Kamaili Homesteads (1955 eruption)	19 26.5 154 57.0	240 290 290	273 ± 12	9.5 ± 4.3	6.7 ± 3.1
085	Kapoho Reservoir (Puulena area)	19 28.5 154 53.8	244 (I) 290 (M) 290 (M)	275 ± 11	1.87 ± 0.73	1.31 ± 0.52
						I D
093	Crane Creek-Cove Creek area	44 18.3 116 44.7	151 (D) 163 (I) 200	171 ± 10	39 ± 18	16.4 ± 7.6
105	Big Creek Hot Springs	45 18.8 114 19.2	149 (C) 157 (A) 179 (I)	162 ± 6	3.3 ± 0.9	1.32 ± 0.37
						N E V
130	Baltazor Hot Springs	41 55.3 118 42.6	152 (I) 158 (K) 165 (A)	158 ± 3	6.1 ± 2.1	2.4 ± 0.8
132	Pinto Hot Springs	41 21 118 47	153 (C) 176 (I) 190	173 ± 8	10.0 ± 3.1	4.3 ± 1.4
137	Great Boiling Springs (Gerlach)	40 39.7 119 21.7	158 (C) 170 205 (I)	178 ± 10	3.3 ± 0.9	1.46 ± 0.42
138	San Emedio Desert area	40 24 119 25	125 185 (A) 189 (I)	166 ± 15	3.3 ± 0.9	1.36 ± 0.40
141	Steamboat Springs	39 23 119 45	186 (M) 207 (I) 207 (K)	200 ± 5	29 ± 12	14.4 ± 5.9

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
A I I			
Fumarole area on rim of Kilauea Crater. System may be hotter and larger than estimated. Located within Hawaii Volcanoes National Park.	-	-	--
Located in East Rift near site of 1955 lava flows. No surface activity; area identified by geophysical anomaly. Three wells, deepest 211 m; maximum temperature 113°C at 211 m. May be a self-sealing system. ("1955 eruption area" of Circular 726.)	1.66	0.48	210
One well 1967 m deep located in a geophysical anomaly in the East Rift; maximum temperature 358°C measured at bottom hole in a zone of conductive heat flow. Reservoir at 290°C is considered to be in an isothermal zone (convective heat flow) between 1220 m and 1769 m depth. Installation of 5 MW_e well-head generator is proposed. ("Puulena area" of Circular 726.)	0.33	0.096	41
A H O			
Two groups of springs about 11 km apart with surface temperatures to 92°C and similar water chemistries occurring in a zone of mercury mineralization and sinter deposits. Two wells 550 and 610 m deep. Sulfate-water isotope geothermometer indicates temperatures as high as 249°C and may reflect a very deep source for the water. May be two separate systems.	4.1	0.81	340
Several springs with temperatures to 93°C discharging at 280 L/min. Sulfate-water isotope geothermometer gives 105°C and may indicate oxidation of sulfide to sulfate prior to sample collection.	0.33	0.062	26
A D A			
A shallow well discharges 25 L/min at 90°C; nearby spring discharges 100 L/min at 80°C. Sinter and travertine deposits.	0.59	0.109	46
One shallow well and several springs to 93°C depositing travertine and sinter.	1.07	0.21	90
Several springs in two major groups discharging 1,000 L/min; surface temperatures to 90°C. One well 150 m deep; maximum temperature 110°C.	0.36	0.075	32
Hot seeps in three groups with surface temperatures to 95°C. Negligible flow rates make quantitative interpretation of geothermometers impossible. Sinter and travertine deposits.	.34	0.066	28
Several springs discharging 250 L/min from extensive sinter apron. Six exploration wells 218 to 558 m deep; maximum temperature 186°C at 221 m; several other wells used for spa supply; calculated total discharge 4,300 L/min.	3.6	0.82	350

Table 5.--*Locations, temperatures, volumes, and energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J) N E V
143	Lee Hot Springs	39 12.6 118 43.4	162 (C, I) 162 (C, I) 173 (A)	166 ± 3	3.3 ± 0.9	1.36 ± 0.38
144	Soda Lake area	39 34 118 51	144 (M) 161 (I) 165 (A)	157 ± 5	19.6 ± 11.3	7.5 ± 4.3
145	Stillwater area	39 31 118 33.1	140 (I) 159 (C) 177 (K)	159 ± 8	59 ± 22	23 ± 9
146	Fernley area	39 35.9 119 06.4	161 (A) 166 (I) 220 (K)	182 ± 13	3.3 ± 0.9	1.51 ± 0.44
147	Brady Hot Springs	39 47.2 119 00.0	140 155 170	155 ± 6	22 ± 11	8.2 ± 4.2
148	Desert Peak area	39 45 118 57	208 (M) 225 (I) 229 (K)	221 ± 5	52 ± 18	29 ± 10
151	Humboldt House	40 32.1 118 16.1	172 (K) 230 (J) 249 (I)	217 ± 16	3.3 ± 0.9	1.82 ± 0.53
152	Kyle Hot Springs	40 24.4 117 52.9	154 (K) 161 (A) 161 (A)	159 ± 2	12.8 ± 5.6	5.0 ± 2.2
154	Leach Hot Springs	40 36.2 117 38.7	155 (A) 160 (J) 170 (K)	162 ± 3	9.7 ± 2.7	3.9 ± 1.1
162	Beowawe Hot Springs	40 34.2 116 34.8	211 (M) 226 (C) 251 (K)	229 ± 8	8.2 ± 1.9	4.7 ± 1.1
164	Hot Sulphur Springs (Tuscarora)	41 28.2 116 09.0	144 (D) 167 (A) 184 (I)	165 ± 8	3.3 ± 0.9	1.35 ± 0.39

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
A D A			
Several springs with temperatures to 88°C discharging 130 L/min. Sulfate-water isotope geothermometer indicates temperatures to 282°C. Travertine deposits suggest reservoir temperatures may be lower.	0.34	0.066	28
No surface discharge; small area altered by gases. Two wells 152 and 1313 m deep; maximum reported temperature of 144°C at bottom of shallower well.	1.88	0.35	146
No surface discharge. A 1.3-km-deep exploration well encountered a maximum temperature of 156°C at 0.4 km.	5.7	1.06	450
Three shallow wells to 229 m with maximum reported temperature of 132°C. One additional well of unknown depth drilled in 1974.	0.38	0.079	33
More than 13 wells ranging in depths from 73 to 2219 m; maximum reported temperature 214°C. Springs became inactive after drilling of first wells in the early 1960s. Na-K-Ca geothermometer gives 246°C and may indicate a deep source for the water. Geothermal fluid with a working temperature of 154°C is used commercially to dehydrate vegetables.	2.0	0.37	157
No surface manifestations. Three wells, deepest 2.3 km, sited by geophysical techniques; recorded temperatures over 200°C; two wells capable of total mass flow of more than 200,000 kg/hr. Geothermal fluids are chemically different from nearby Brady area, indicating a separate system.	7.2	1.78	750
Two deep and one shallow geothermal test wells near Rye Patch KGRA.	0.45	0.110	47
Several springs with temperatures to 77°C. Low flow rates (20 L/min) may have permitted extensive near-surface water-rock reactions which in turn may have adverse effects on the Na-K-Ca geothermometer.	1.24	0.23	97
Several springs with temperatures to 95°C discharging 690 L/min; sinter.	0.96	0.182	77
Twelve wells ranging in depth from 72 to 2917 m; maximum temperature 211°C at 2917 m; similar temperatures reported in shallower wells.	1.18	0.30	127
Springs to 90°C with abundant sulfur.	0.34	0.065	27

Table 5.--*Locations, temperatures, volumes, and energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km³)	Mean reservoir thermal energy (10^{18} J)
						N E V
169	Sulphur Hot Springs (Hot Sulphur Springs)	40 35.2 115 17.1	171 (C) 181 (I) 183 (A)	178 ± 3	7.8 ± 2.8	3.4 ± 1.2
					N E	W M
171	Valles caldera	35 54 106 32	250 278 (M) 290	273 ± 8	125 ± 56	87 ± 39
						O R E
184	Newberry caldera	43 43 121 14	180 230 280	230 ± 20	47 ± 16	27 ± 10
190	Crump's Hot Springs	42 13.8 119 53.0	144 (I) 173 (A) 185	167 ± 9	7.2 ± 2.8	3.0 ± 1.2
196	Mickey Hot Springs	42 40.5 118 20.7	180 (A) 207 (I) 227 (K)	205 ± 10	12.8 ± 6.7	6.5 ± 3.5
197	Alvord Hot Spring	42 32.6 118 31.6	148 (A) 164 (J) 231 (K)	181 ± 18	5.0 ± 2.1	2.2 ± 1.0
198	Hot (Borax) Lake area	42 20 118 36	165 (C) 176 (I) 231 (K)	191 ± 14	8.3 ± 3.5	4.0 ± 1.7
199	Trout Creek area	42 11 118 23	140 (A) 143 (I) 180	154 ± 9	3.3 ± 0.9	1.25 ± 0.36
203	Neal Hot Springs	44 01.4 117 27.6	173 (A) 181 (I) 210 (K)	188 ± 8	3.3 ± 0.9	1.56 ± 0.44
204	Vale Hot Springs	43 59.4 117 14.0	152 (A) 157 (I) 161 (K)	157 ± 2	117 ± 54	45 ± 21

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
A D A			
Several springs with temperatures to 95°C discharging 500 L/min; sinter deposits.	0.86	0.176	74
E X I C O			
One group of acid-sulfate springs, extensive hydrothermal alteration and associated gas seeps, and 17 wells in southwest quadrant of Pleistocene caldera. Typical wells are 1525 to 2745 m deep; maximum measured temperature is about 330°C. A vapor-dominated reservoir locally overlies the hot-water reservoir. A 50 MW_e generating plant is planned.	22	6.4	2700
G O N			
Reported hot springs appear to be drowned fumaroles which issue along the shores of East Lake and Paulina Lake in Pleistocene caldera. Reservoir temperatures are inferred and based on temperatures estimated for other Quaternary volcanoes.	6.9	1.74	740
Several hot springs and seeps and one geysering well; maximum well temperature 121°C at 201 m depth; sinter deposits.	0.74	0.144	61
Hot springs to 73°C discharging 100 L/min; mud pots; extensive sinter.	1.63	0.38	160
Several hot springs to 76°C discharging 500 L/min in area about 0.5 km^2.	0.56	0.117	49
Several springs to 96°C and one large pool (lake); total discharge 3500 L/min; sinter.	0.99	0.22	91
Hot springs and seeps to 52°C discharging 200 L/min. Sulfate-water isotope geothermometer gives 235°C and may indicate leakage from the systems in the Alvord Desert (Hot Lake, Alvord and Mickey Hot Springs).	0.31	0.056	24
Hot springs to 87°C discharging 100 L/min; sinter.	0.39	0.084	36
Large area suggested by audio-magnetotelluric survey and heat flow anomaly. Hot springs in two groups to 97°C, but low flow rates. Another sulfate-water isotope determination gives 200°C.	11.2	2.0	870

Table 5.--*Locations, temperatures, volumes, and energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						U T
208	Cove Fort-Sulphurdale	38 36 112 33	150 170 180	167 ± 6	39 ± 10	16.0 ± 4.1
209	Roosevelt Hot Spring (McKeans)	38 30.0 112 50.9	243 (M) 269 (M) 284 (I)	265 ± 8	47 ± 20	32 ± 13
					W A	S H I
213	Gamma Hot Springs	48 10.0 121 02.0	140 161 (A) 195 (J)	165 ± 11	3.3 ± 0.9	1.35 ± 0.39
						W Y O M
215	Yellowstone caldera area	44 28 110 50	230 270 300	267 ± 14	1820 ± 590	1240 ± 410
	TOTALS---					2100 ± 400 --

*Total of wellhead thermal energy, available work, and electrical energy exclude National Parks.

Comments	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (MW_e for 30 yr)
A H			
Area of H_2S gas seeps, sulfur and sinter deposits, but no springs. Three wells 582 to 2226 m deep; maximum temperature 179°C at 2226 m. Reservoir temperatures are measurements from one well and could be higher at other locations.	4.0	0.78	330
Seven wells in a 6-km^2 area and ranging in depth from 382 to 2234 m are capable of producing over 4.5 x 10^5 kg/hr total mass flow at 260°C. A 55 MW_e plant is planned. Minimum and most likely temperatures are recorded temperatures at about 380 and 1870 m, respectively. Springs are inactive; extensive sinter deposits along a 4.8-km trend.	8.0	2.3	970
N G T O N			
Hot springs to 60°C discharging 13 L/min located on the flank of dormant Glacier Peak volcano within the Glacier Peak Wilderness Area.	0.34	0.065	27
I N G			
Numerous thermal phenomena, mostly within the Pleistocene Yellowstone caldera. Thirteen research holes; maximum measured temperature 237°C at 332 m. Mixing models indicate possible temperatures of 360°C in an assumed deep, laterally extensive reservoir at 2-4 km depth. At least one vapor-dominated system (Mud Volcano) of limited extent has developed over the hot-water system. Area withdrawn from commercial exploration or development because of National Park status.	-	-	--
---	210*	51*	21000*

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

(For reservoir temperature estimates, first number is most likely value, subscript is maximum value, and

A. Quartz conductive
B. Quartz conductive, pH-corrected.
C. Quartz adiabatic
D. Chalcedony
E. Chalcedony, pH-corrected
F. Cristobalite

No letter indicates a subjective estimate. Mean values of temperature, volume, and reservoir thermal volumes and energies are given to two significant figures. However, if the first digit is 1, three

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						A L A
001	Okpilak Springs	69 18 144 02	78 (D) 90 (I) 107 (A)	92 ± 6	3.3 ± 0.9	0.69 ± 0.20
002	Serpentine (Arctic) Springs	65 51 164 42	104 (D) 131 (A) 161 (I)	132 ± 12	3.3 ± 0.9	1.05 ± 0.31
003	Pilgrim (Kruzgamepa) Hot Springs	65 06 164 55	110 (D) 137 (A) 146 (I)	131 ± 8	3.3 ± 0.9	1.04 ± 0.30
004	Lava Creek	65 13 162 54	90 (E,I) 90 (E,I) 128 (A)	103 ± 9	3.3 ± 0.9	0.79 ± 0.24
005	Clear Creek	64 51 162 18	82 (I) 99 (D) 127 (A)	103 ± 9	3.3 ± 0.9	0.79 ± 0.24
006	South	66 09 157 07	72 (I) 86 (D) 114 (A)	91 ± 9	3.3 ± 0.9	0.68 ± 0.21
007	Dulbi	65 16 155 16	99 (D) 126 (A) 159 (I)	128 ± 12	3.3 ± 0.9	1.02 ± 0.31
008	Melozi (Melozitna) Hot Springs	65 08 154 40	92 (D) 124 (A) 124 (A)	113 ± 8	3.3 ± 0.9	0.88 ± 0.26
009	Little Melozitna	65 28 153 20	97 (D) 125 (A) 125 (A)	116 ± 7	3.3 ± 0.9	0.91 ± 0.26
010	Reed River Hot Spring	67 17 154 55	99 (D) 126 (A) 126 (A)	117 ± 6	3.3 ± 0.9	0.92 ± 0.26
011	Kanuti	66 20 150 48	85 (H) 120 (J) 120 (J)	108 ± 8	3.3 ± 0.9	0.84 ± 0.25

identified hot-water hydrothermal convection systems 90-150°C

superscript is minimum value. Letters indicate method used to estimate temperature, as follows:

G. Amorphous silica	J. Na-K-Ca, Mg-corrected	M. Reported well
H. Na-K	K. Sulfate-water isotope	N. Mixing
I. Na-K-Ca	L. Surface	O. Renner, 1976

energy are followed by standard deviations. Temperatures given to three significant figures; in most cases significant figures are given in order approximate to more closely uniform percentage accuracy.)

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
S K A		
Spring(s) to 48°C.	0.173	0.041
Two groups of springs 0.8 km apart to 77°C discharging 133 L/min; sinter and travertine deposits.	0.26	0.063
Several springs to 88°C discharging less than 50 L/min.	0.26	0.062
Spring(s) to 65°C.	0.20	0.047
Springs to 67°C discharging 1000 L/min. High flow rate suggests that reservoir temperatures may be nearer to the minimum estimate.	0.20	0.047
Several springs to 50°C.	0.170	0.041
Several springs to 52°C; may be a mixed water.	0.25	0.061
One main spring at 56°C discharging about 500 L/min; H_2S odor.	0.22	0.053
Springs to 38°C; H_2S odor; geothermometer temperatures may be unreliable.	0.23	0.055
Spring(s) to 50°C.	0.23	0.055
Several springs to 66°C; strong H_2S odor.	0.21	0.050

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						A L A
012	Tolvana	65 16 148 50	93 (D) 122 (A) 162 (I)	126 ± 14	3.3 ± 0.9	1.00 ± 0.31
013	Manley (Baker)	65 00 150 38	83 (J) 86 (D) 114 (A)	94 ± 7	3.3 ± 0.9	0.71 ± 0.21
014	Chena	65 03 146 03	67 (E) 97 (B) 137 (I)	100 ± 14	3.3 ± 0.9	0.77 ± 0.25
015	Circle	65 29 144 39	107 (D) 134 (A) 143 (I)	128 ± 8	3.3 ± 0.9	1.02 ± 0.29
016	Great Sitkin Island	52 04 176 05	100 (O) 125 (O) 200 (O)	142 ± 21	3.3 ± 0.9	1.14 ± 0.38
019	Hot Spring on Umnak Island	53 14 168 18	78 (I) 106 (D) 133 (A)	106 ± 11	3.3 ± 0.9	0.82 ± 0.25
020	Hot Springs Bay (Akutan Island)	54 10 165 50	126 (D) 136 (J) 151 (A)	138 ± 5	3.3 ± 0.9	1.10 ± 0.31
021	East of Cold Bay	55 13 162 29	88 (D) 117 (A) 144 (I)	116 ± 11	3.3 ± 0.9	0.91 ± 0.28
022	North end of Tenakee Inlet	58 02 136 01	120 (I) 122 (D) 147 (A)	130 ± 6	3.3 ± 0.9	1.03 ± 0.29
023	Hooniah Hot Springs (White Sulphur Springs)	57 48 136 20	109 (D) 136 (A) 136 (A)	127 ± 6	3.3 ± 0.9	1.01 ± 0.29
024	Near Fish Bay	57 22 135 23	70 143 (A) 143 (A)	119 ± 17	3.3 ± 0.9	0.93 ± 0.31
025	Goddard Hot Springs (Sitka)	56 50 135 22	122 (D) 148 (A,I) 148 (A,I)	139 ± 6	3.3 ± 0.9	1.12 ± 0.32
026	Shakes Springs (Chief Shakes)	56 43 132 02	115 (D) 142 (A) 175 (I)	144 ± 12	3.3 ± 0.9	1.16 ± 0.34

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
S K A		
Several springs to 60°C, low discharge; geothermometer temperatures may be unreliable.	0.25	0.060
Three springs to 59°C discharging about 550 L/min.	0.178	0.043
Several springs to 67°C (?) discharging more than 800 L/min; sulfur deposits.	0.193	0.046
Several springs to 57°C discharging about 500 L/min; sinter, travertine, sulfur, and alum deposits reported.	0.25	0.061
Several springs and fumaroles to 99°C in area of Holocene volcanism.	0.28	0.068
A single spring (65°C) located about 2.5 km southeast of the Hot Springs Cove thermal area.	0.20	0.049
Springs to 84°C and fumaroles located near active Akutan Volcano.	0.27	0.066
Springs to 54°C in area of Holocene volcanism.	0.23	0.055
Several springs to 82°C discharging about 40 L/min; travertine deposits.	0.26	0.062
Three springs to 44°C discharging about 115 L/min; travertine deposits. The water is suspected of having a high pH; reservoir temperatures may therefore be considerably lower.	0.25	0.061
Several springs to 47°C discharging about 95 L/min. Incomplete chemical analysis. Geothermometer temperatures are not reliable.	0.23	0.056
Three springs to 65°C discharging 50 L/min (?).	0.28	0.067
Several springs to 52°C discharging about 380 L/min. Geothermometer temperatures may be unreliable.	0.29	0.070

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						A L A
028	Bell Island Hot Springs	55 56 131 34	93 (E) 135 (I) 150 (A)	126 ± 12	3.3 ± 0.9	1.00 ± 0.30
						A R I
030	Eagle Creek	33 02.8 109 26.4	85 (D) 85 (D) 114 (A)	95 ± 7	3.3 ± 0.9	0.72 ± 0.21
031	North of Clifton	33 04.7 109 18.2	107 (D) 164 (N,J) 164 (N,J)	145 ± 13	3.3 ± 0.9	1.17 ± 0.35
032	Gillard Hot Springs	32 58.5 109 21.0	107 (D) 134 (A) 169 (K)	137 ± 13	3.3 ± 0.9	1.09 ± 0.33
033	San Simon Well	32 24 109 18	125 134 (M) 145	135 ± 4	2.3 ± 0.5	0.75 ± 0.17
					C A	L I F
034	Fort Bidwell area	41 51.8 120 09.6	99 (D) 126 (A) 179 (I)	135 ± 17	3.3 ± 0.9	1.08 ± 0.34
036	West Valley Reservoir Hot Spring	41 11.5 120 23.1	138 (I) 138 (I) 152 (A)	143 ± 3	3.3 ± 0.9	1.15 ± 0.32
037	Bassett Hot Spring	41 08.7 121 06.6	88 (D) 88 (D) 117 (A)	98 ± 7	3.3 ± 0.9	0.74 ± 0.22
038	Kelly Hot Spring	41 27.5 120 50.0	95 (I) 116 (D,M) 143 (A)	118 ± 10	3.3 ± 0.9	0.93 ± 0.27
039	Big Bend Hot Springs	41 01.3 121 55.1	92 (D) 120 (A) 137 (I)	116 ± 9	3.3 ± 0.9	0.91 ± 0.27
042	Wendel-Amadee area	40 18 120 11	107 (M) 128 (I) 143 (C)	126 ± 7	10.6 ± 3.0	3.2 ± 0.9

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
S K A		
Five springs to 72°C discharging about 40 L/min.	0.25	0.060
Z O N A		
Two springs to 36°C discharging less than 10 L/min. Geothermometer temperatures may be unreliable due to very low flow rate. Water is supersaturated with calcite and may be in equilibrium with amorphous silica at surface temperature. Reservoir temperatures may be lower than estimated here.	0.180	0.043
Two springs to 59°C; very low flow rate. Probably a mixed water. Warm springs (39°C) issuing at Clifton 3 km to the south may be part of this system.	0.29	0.070
Five springs to 82°C.	0.27	0.065
One well; maximum reported temperature 134°C; depth unknown.	0.188	0.045
O R N I A		
Five springs to 45°C discharging 400 L/min. Geothermometer temperatures may be unreliable: low surface temperature and high flow rate suggest that reservoir temperatures may be nearer the minimum estimate, or the waters may be mixed.	0.27	0.065
Spring(s) discharging 12 L/min at 77°C. Sulfate-water isotope geothermometer indicates temperatures above 200°C.	0.29	0.069
Spring(s) discharging 200 L/min at 79°C.	0.185	0.044
One spring discharging 1250 L/min at 91°C. Two wells 978 and 1035 m deep; maximum reported temperature 116°C at 1035 m. Sulfate-water isotope geothermometer indicates temperatures near 200°C.	0.23	0.056
Six springs to 82°C discharging about 340 L/min.	0.23	0.055
Several springs to 96°C discharging about 3600 L/min. Six wells (including two deep tests) 58 to 1538 m deep; maximum reported temperature 107°C at 338 m; temperatures not available for the two deep wells. Water from Wendel Hot Springs used in greenhouse operation.	0.79	0.190

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
					C A	L I F
043	Sierra Valley area	39 42.7 120 19.3	109 (D) 131 (I) 136 (A)	125 ± 6	10.0 ± 3.2	3.0 ± 1.0
044	Wilbur Springs area	39 02.2 122 25.2	141 (M) 141 (M) 150	144 ± 2	12.5 ± 4.0	4.4 ± 1.4
045	Chalk Mountain area	39 04.8 122 35.0	105 (D) 105 (D) 128 (C)	113 ± 5	3.3 ± 0.9	0.88 ± 0.25
049	Skaggs Hot Springs	38 41.5 123 01.5	95 (J) 95 (J) 150 (A)	113 ± 13	3.3 ± 0.9	0.88 ± 0.28
050	Calistoga Hot Springs	38 34.9 122 34.4	137 (M,D) 141 (I) 153 (C)	144 ± 3	6.9 ± 1.9	2.4 ± 0.7
051	Grovers Hot Springs	38 41.9 119 51.6	110 (D) 130 (J) 137 (A)	126 ± 6	3.3 ± 0.9	1.00 ± 0.28
052	Fales Hot Springs	38 20.0 119 24.0	84 (J) 119 (D) 145 (A)	116 ± 12	3.3 ± 0.9	0.91 ± 0.28
053	Buckeye Hot Spring	38 14.3 119 19.6	87 (J) 122(A) 122 (A)	101 ± 8	3.3 ± 0.9	0.77 ± 0.23
054	Travertine Hot Springs area	38 14.8 119 12.1	87 (J) 110 (D) 137 (A)	111 ± 10	3.3 ± 0.9	0.87 ± 0.26
055	North Shore Mono Lake (Black Rock Point Hot Spring)	38 02.4 119 04.8	85 (J) 94 (D) 122 (A)	100 ± 8	3.3 ± 0.9	0.77 ± 0.23
059	Tecopa Hot Springs	35 53.2 116 14.2	97 (E) 137 (A) 145 (I)	126 ± 10	3.3 ± 0.9	1.00 ± 0.30
060	Scovern Hot Spring	35 37.1 118 28.4	85 (D) 114 (A) 119 (I)	106 ± 7	3.3 ± 0.9	0.82 ± 0.24

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
O R N I A		
No natural surface activity. One geothermal test well 680 m deep; seven shallower artesian wells used for stock watering; surface temperatures range from 39° to 94°C; total discharge exceeds 240 L/min.	0.74	0.179
Several springs in four groups with temperatures to 67°C and aggregate flow of less than 100 L/min. Two wells; maximum temperature 141°C at 1132 m.	1.09	0.26
Area of sulfur fuming and hydrothermally altered rock; warm springs with temperatures to 24°C discharging 11 L/min. Geothermometer temperatures are probably not reliable because of low flow rate, high Mg and HCO_3 concentrations, and likelihood of near-surface reactions.	0.22	0.053
Three springs to 57°C discharging 57 L/min. Geothermometer temperatures are in doubt owing to low flow rate.	0.22	0.053
Several springs and wells, including one geysering well; maximum well temperature 137°C at 610 m (?); silica deposits in well pipes.	0.60	0.145
Two main springs to 64°C discharging 400 L/min.	0.25	0.060
Several springs to 61°C discharging more than 1000 L/min. One well 126 m deep. Geothermometer temperatures may be inaccurate owing to CO_2-rich water and calcite precipitation. Sulfate-water isotope geothermometer gives about 130°C. Extensive travertine deposits.	0.23	0.055
Spring(s) to 64°C discharging 400 L/min; fossil travertine deposits.	0.193	0.046
Several springs in two groups about 2.5 km apart; temperatures to 69°C; total discharge 135 L/min. One well 300 m deep. Extensive travertine deposits.	0.22	0.052
Spring(s) to 66°C discharging 150 L/min; travertine deposits. One well about 3 km to the south had maximum temperature of 57°C at 743 m (TD).	0.193	0.046
Springs to 48°C discharging 15 L/min. Geothermometer temperatures may be unreliable due to likelihood of reaction of water with tuffaceous lacustrine rocks.	0.25	0.060
Spring discharging 435 L/min at 53°C.	0.20	0.049

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km³)	Mean reservoir thermal energy (10^{18} J)
					C A	L I F
061	Sespe Hot Springs	34 35.7 118 59.9	109 (D) 136 (A) 148 (I)	131 ± 8	3.3 ± 0.9	1.04 ± 0.30
062	Arrowhead Hot Springs	32 11.2 117 15.9	110 (D) 137 (A) 150 (I)	132 ± 8	3.3 ± 0.9	1.06 ± 0.31
063	Pilger Estates Hot Springs	33 26.0 115 41.1	96 (D,J) 96 (D,J) 124 (A)	105 ± 7	3.3 ± 0.9	0.81 ± 0.24
066	Glamis (East Brawley)	32 58.0 115 11.0	105 120 170	132 ± 14	3.3 ± 0.9	1.05 ± 0.32
067	Glamis East	33 00.0 115 02.1	105 120 170	132 ± 14	5.0 ± 1.7	1.57 ± 0.56
069	Dunes	32 48.2 115 00.8	105 120 170	132 ± 14	8.9 ± 2.4	2.8 ± 0.8
					C	O L O
072	Routt Hot Springs	40 33.6 106 51.0	103 (D) 131 (A) 157 (I)	130 ± 11	3.3 ± 0.9	1.04 ± 0.31
073	Penny (Avalanche) Hot Springs	39 13.6 107 13.5	90 (I) 98 (D) 126 (A)	105 ± 8	3.3 ± 0.9	0.81 ± 0.24
074	Mt. Princeton Hot Springs area	38 43.9 106 10.2	93 (I) 103 (D) 140 (K)	112 ± 10	6.4 ± 1.7	1.68 ± 0.48
075	Poncha Hot Springs	38 29.8 106 04.6	98 (D) 101 (I) 127 (A)	109 ± 7	3.3 ± 0.9	0.84 ± 0.24
076	Waunita Hot Springs	38 30.8 106 30.5	116 (D) 143 (A) 165 (I)	141 ± 10	3.3 ± 0.9	1.14 ± 0.33
077	Cebolla (Powderhorn) Hot Springs	38 16.4 107 05.9	47 (J) 105 (D) 133 (A)	95 ± 19	3.3 ± 0.9	0.72 ± 0.26

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
O R N I A		
Four springs to 90°C discharging 470 L/min. Sulfate-water isotope geothermometer gives 110°C.	0.26	0.062
Several springs in two groups; temperatures to 86°C; discharge about 200 L/min.	0.26	0.064
Hot-water well 92 m deep discharges more than 3000 L/min at 79° to 82°C.	0.20	0.049
No surface activity; area identified by temperature gradient anomaly; temperatures assumed to be similar to those estimated for the Dunes system.	0.26	0.063
No surface activity; area identified by temperature gradient anomaly; temperatures assumed to be similar to those estimated for the Dunes system.	0.39	0.094
No surface activity; area identified by temperature gradient anomaly. One well 612 m deep; maximum recorded temperature 103°C at about 280 m.	0.70	0.168
R A D O		
Five springs to 64°C discharging 200-300 L/min.	0.26	0.062
Several springs scattered for 0.8 km along river; temperatures to 56°C; total discharge 750 L/min.	0.20	0.049
Several springs to 85°C; total discharge 675 L/min. Five wells to 55 m. Extensive zeolitic alteration.	0.42	0.101
Five springs to 71°C discharging about 900 L/min; travertine deposits.	0.21	0.050
Several springs in two groups; temperatures to 80°C; total discharge more than 600 L/min.	0.28	0.068
Three springs to 41°C discharging more than 11 L/min. CO_2-rich water; geothermometry may be unreliable. Fossil travertine and sinter deposits; appears to be an old system.	0.180	0.043

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
					C O	L O
079	Wagon Wheel Gap	37 41.1 106 49.8	86 (J) 100 (D) 128 (A)	105 ± 9	3.3 ± 0.9	0.81 ± 0.24
080	Sand Dunes Swimming Pool Well	37 46.7 105 51.3	122 (D) 148 (A) 152 (J)	141 ± 7	3.0 ± 0.7	1.02 ± 0.26
081	Mapco State Well 1-32	37 40.2 105 40.0	90 128 (M) 135	118 ± 10	1.67 ± 0.42	0.46 ± 0.12
082	Splashland Hot Water Well	37 29.3 105 51.4	116 (D) 143 (A) 165 (J)	141 ± 10	3.3 ± 0.9	1.14 ± 0.33
						I D
086	Red River Hot Springs	45 47.2 115 11.9	80 (I) 83 (E) 112 (B)	92 ± 7	3.3 ± 0.9	0.69 ± 0.20
087	Riggins Hot Springs	45 25.0 116 10.2	91 (D) 95 (I) 120 (A)	102 ± 6	3.3 ± 0.9	0.78 ± 0.23
088	Krigbaum Hot Springs	44 58.1 116 11.4	92 (D) 96 (I) 120 (A)	103 ± 6	3.3 ± 0.9	0.79 ± 0.23
089	White Licks Hot Springs	44 40.9 116 13.8	114 (D) 140 (A) 162 (K)	139 ± 10	3.3 ± 0.9	1.11 ± 0.32
090	Vulcan Hot Springs	44 34.0 115 41.5	87 (E,L) 138 (I) 140 (A)	122 ± 12	3.3 ± 0.9	0.96 ± 0.29
091	Cabarton Hot Springs	44 25.0 116 01.7	96 (D) 99 (I) 124 (A)	106 ± 6	3.3 ± 0.9	0.82 ± 0.24
092	Boiling Springs	44 21.9 115 51.4	86 (L,K) 100 (I) 112 (B)	99 ± 5	3.3 ± 0.9	0.76 ± 0.22
094	Weiser area	44 17.9 117 02.9	90 (E) 142 (I) 157 (A)	130 ± 14	4.4 ± 1.7	1.38 ± 0.55

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
R A D O		
Two springs to 57°C discharging about 250 L/min; fossil travertine and sinter deposits. Geothermometry may be unreliable because of of CO_2-rich water.	0.20	0.049
No surface activity; one well 1342 m deep. Geothermometers may give excessively high temperatures because of dilute, high-pH water. Area may be larger.	0.25	0.061
No surface activity; one well with measured temperature of 128°C at 2890 m. Area may be larger.	0.115	0.028
No surface activity; one well 610 m deep. Geothermometers may give excessively high temperatures because of dilute, high-pH water. Area may be larger.	0.28	0.068
A H O		
Several springs to 55°C. A very dilute, high-pH water.	0.173	0.041
Springs to 42°C discharging over 190 L/min; travertine deposits. A very dilute, high-pH water.	0.195	0.047
Two springs to 43°C discharging more than 150 L/min. A very dilute, high-pH water.	0.20	0.047
Several springs to 67°C discharging 115 L/min.	0.28	0.067
Several springs to 87°C discharging 1900 L/min; sinter apron. A dilute, high-pH water; pH-corrected chalcedony geothermometer indicates surface temperatures; pH-corrected quartz conductive geothermometer indicates 114°C; temperature estimates may therefore be too high.	0.24	0.058
Several springs to 70°C discharging 265 L/min. A very dilute water.	0.20	0.049
Several springs in three main groups; temperatures to 86°C; total discharge about 625 L/min; sinter deposits with minor carbonate. A very dilute, high-pH water.	0.190	0.046
Several springs to 77°C discharging 20 L/min. Six shallow wells 28 to 183 m deep; maximum reported temperature 77°C at 31 m. Sulfate-water isotope geothermometer indicates 219° to 235°C; possibly a stacked system or very deep source for some of the hot water.	0.34	0.083

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						I D
095	Roystone Hot Springs	43 57.2 116 21.2	122 (D) 135 (J) 148 (A)	135 ± 5	3.3 ± 0.9	1.08 ± 0.31
096	Bonneville Hot Springs	44 09.5 115 18.4	87 (B) 91 (K) 136 (A,I)	105 ± 11	3.3 ± 0.9	0.81 ± 0.25
097	Payette River area near Banks	44 05.1 116 03.0	111 (D) 138 (A) 143 (I)	131 ± 7	3.3 ± 0.9	1.04 ± 0.30
098	Neinmeyer Hot Springs	43 45.5 115 34.7	90 (I) 93 (K) 100	94 ± 2	3.3 ± 0.9	0.71 ± 0.20
099	Latty Hot Springs	43 07.0 115 18.3	110 (D) 125 137 (A,I)	124 ± 6	3.3 ± 0.9	0.98 ± 0.28
100	Radio Towers area	43 02.2 115 27.4	101 (D) 124 (I) 150	125 ± 10	3.3 ± 0.9	0.99 ± 0.29
101	Gravel Pits area	42 56.3 115 29.6	79 (D) 109 (A) 120 (J)	103 ± 9	3.3 ± 0.9	0.79 ± 0.23
102	Bruneau-Grand View area	42 56.0 115 56.0	90 (I,E) 110 120	107 ± 6	1830 ± 420	450 ± 110
103	Murphy Hot Springs	42 01.8 115 22.0	51 (L) 99 (D) 160 (I)	103 ± 22	3.3 ± 0.9	0.79 ± 0.30
104	Owl Creek Hot Springs	45 20.5 114 27.0	103 (D) 131 (A) 144 (I)	126 ± 9	3.3 ± 0.9	1.00 ± 0.29
106	Sharkey Hot Springs	45 00.8 113 36.3	102 (K) 107 (D) 134 (A)	114 ± 7	3.3 ± 0.9	0.89 ± 0.26
107	Sunbeam Hot Springs	44 16.1 114 44.9	81 (E) 124 (I) 130 (A)	112 ± 11	3.3 ± 0.9	0.87 ± 0.26

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
A H O		
Five springs to 55°C discharging about 75 L/min.	0.27	0.065
Several springs to 85°C discharging 1370 L/min; minor sinter and travertine. A dilute, high-pH water.	0.20	0.049
One spring at 78°C discharging 76 L/min; a dilute, high-pH water.	0.26	0.062
Several springs to 76°C discharging over 1300 L/min; sinter. A dilute, high-pH water; pH-corrected quartz conductive geothermometer gives 85°C; mean reservoir temperature is probably nearer 90°C.	0.178	0.043
Spring at 55°C; extremely dilute, high-pH water for which chemical geothermometry may not be applicable.	0.24	0.059
No surface activity. One well 580 m deep discharging 30 L/min at 38°C. A deep geothermal test well about 0.5 km to the north had a maximum temperature of about 185°C at 2.7 km; may be a stacked system.	0.25	0.059
No surface activity. One well 403 m deep discharging less than 8 L/min at 34°C. Geothermometers may not be reliable because of low flow rate.	0.20	0.047
Several water wells between 0.3 and 1 km deep used for irrigation; maximum well-head temperature 83°C; two deep geothermal test wells to 3 km (abandoned, no information). May be a stacked system; sulfate-water isotope geothermometer gives 95° to 130°C. Volume is considerably less than estimated in Circular 726 owing to smaller area estimates (see text).	113	27
Springs to 51°C flowing about 265 L/min; a very dilute water; geothermometers may be unreliable.	0.20	0.047
Springs to 50°C. A dilute, high-pH water; geothermometers may be unreliable.	0.25	0.060
Spring discharging 30 L/min at 63°C; depositing travertine.	0.22	0.053
Several springs to 76°C; total discharge more than 1675 L/min; travertine and sinter. A dilute, high-pH water.	0.22	0.052

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
			I D			
108	Slate Creek Hot Springs	44 10.1 114 37.4	90 (I) 101 (D) 129 (A)	107 ± 8	3.3 ± 0.9	0.82 ± 0.24
109	Magic Reservoir area	43 19.7 114 23.9	114 (D) 140 (A) 192 (K)	149 ± 16	3.3 ± 0.9	1.20 ± 0.37
110	Worswick (Wasewick) Hot Spring	43 33.5 114 47.2	81 (L) 93 (I) 107 (D)	94 ± 5	3.3 ± 0.9	0.71 ± 0.20
111	Wardrop Hot Springs	43 23.0 114 55.9	67 (L) 89 (B) 136 (I)	97 ± 14	3.3 ± 0.9	0.74 ± 0.25
112	Barron's Hot Springs	43 17.5 114 54.4	90 (I) 95 (D) 123 (A)	103 ± 7	3.3 ± 0.9	0.79 ± 0.23
113	White Arrow Hot Springs	43 02.9 114 57.2	100 (I) 100 (I) 109 (D)	103 ± 2	5.8 ± 1.4	1.39 ± 0.34
114	Banbury area	42 41.4 114 50.0	108 (I,D) 108 (I,D) 136 (A)	117 ± 7	27 ± 8	7.4 ± 2.3
115	Raft River area	42 06.1 113 22.8	135 (K) 147 (M) 164 (A)	149 ± 6	21 ± 7	7.4 ± 2.5
116	Ashton Warm Springs	44 05.7 111 27.5	41 (L) 91 (I) 143 (A)	92 ± 21	3.3 ± 0.9	0.69 ± 0.27
117	Newdale area	43 53.2 111 35.4	84 (I) 93 (D) 122 (A)	100 ± 8	89 ± 35	20 ± 8
118	Maple Grove Hot Springs	42 18.2 111 42.2	77 (D,L) 95 (J) 106 (A)	93 ± 6	3.3 ± 0.9	0.70 ± 0.20
119	Riverdale area (Ben Meek Well)	42 09.9 111 50.4	75 (J) 97 (D) 125 (A)	99 ± 10	3.3 ± 0.9	0.76 ± 0.23
120	Wayland (Battle Creek) Hot Springs	42 08.0 111 55.6	82 (L) 116 (D) 142 (A)	113 ± 12	3.3 ± 0.9	0.88 ± 0.27

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
A H O		
Several springs to 50°C discharging 700 L/min; travertine. A dilute, high-pH water; geothermometers may be unreliable.	0.20	0.049
Flowing well 79 m deep discharging 20 L/min at 72°C. Mg-corrected Na-K-Ca geothermometer gives 145°C.	0.30	0.072
Several springs to 81°C discharging over 1760 L/min; sinter and travertine. A dilute water; geothermometers may be unreliable.	0.178	0.043
Several springs to 67°C discharging 730 L/min. A very dilute, high-pH water; Na-K-Ca geothermometer (maximum temperature) may be unreliable and mean reservoir temperature may be less than 90°C.	0.185	0.044
Several springs to 73°C discharging about 115 L/min.	0.20	0.047
Four springs to 65°C discharging over 3100 L/min; travertine. Area includes 49-m deep well at Chalk mine about 2 km to the east.	0.35	0.083
Several springs to 59°C discharging 1550 L/min; travertine. A dilute, high-pH water; geothermometers may be unreliable.	1.84	0.44
Four deep geothermal test wells 866 to 1996 m deep; producing zones occur between 1.1 and 1.8 km; stabilized reservoir temperature is about 147°C.	1.85	0.44
Spring(s) to 41°C; dilute water and very low flow rate (8 L/min); geothermometers probably unreliable.	0.173	0.041
No surface activity; several wells to 36°C.	5.1	1.22
Several springs to 76°C discharging more than 1300 L/min; travertine. High flow rate suggests that reservoir temperatures are probably near surface temperature.	0.175	0.042
No surface activity. One well 12 m deep with temperature of 44°C. Geothermometers may be unreliable.	0.190	0.046
Four springs to 84°C discharging more than 2200 L/min; travertine. A saline water; geothermometry may be unreliable.	0.22	0.053

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (^{o}N) Longitude (^{o}W)	Estimates of reservoir temperature (^{o}C)	Mean reservoir temperature (^{o}C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						I D
121	Squaw Hot Springs area	42 07.1 111 55.7	84 (L) 124 (D) 150 (A)	119 ± 14	3.3 ± 0.9	0.94 ± 0.29
					M	O N T
122	Marysville Test Well	46 45.2 112 22.6	103 (M) 117 (A) 145 (J)	122 ± 9	15.0 ± 4.7	4.3 ± 1.4
123	Broadwater (Helena) Hot Spring	46 35.7 112 06.7	97 (E) 120 (J) 136 (A)	118 ± 8	3.3 ± 0.9	0.92 ± 0.27
124	Alhambra Hot Springs	46 26.8 111 59.0	86 (D,J) 86 (D,J) 115 (A)	96 ± 7	3.3 ± 0.9	0.73 ± 0.21
125	Boulder Hot Springs	46 12.0 112 05.6	130 (K) 136 (I) 142 (A)	136 ± 2	3.3 ± 0.9	1.09 ± 0.31
126	Gregson (Fairmont) Hot Springs	46 02.6 112 48.6	101 (D) 124 (I) 128 (A)	118 ± 6	3.3 ± 0.9	0.92 ± 0.26
127	Norris (Hapgood, Beartrap) Hot Springs	45 34.5 111 41.0	87 (J) 103 (D) 130 (A)	107 ± 9	3.3 ± 0.9	0.82 ± 0.25
128	Silver Star (Barkel's) Hot Springs	45 41.5 112 17.2	116 (D) 135 (K,I) 143 (A)	131 ± 6	3.3 ± 0.9	1.05 ± 0.30
129	Ennis (Thexton) Hot Springs	45 22.0 111 44.8	108 (D) 135 (A) 145 (J)	129 ± 8	3.3 ± 0.9	1.03 ± 0.30
						N E V
131	Dyke Hot Springs	41 34.0 118 33.7	76 (E) 106 (B) 137 (I)	106 ± 12	3.3 ± 0.9	0.82 ± 0.26
133	Double Hot Springs area	41 02.9 119 01.7	114 (D) 127 (I) 140 (A)	127 ± 5	12.2 ± 4.2	3.7 ± 1.3
134	Black Rock Point area	40 57.0 119 00.2	116 (I) 122 (D) 148 (A)	129 ± 7	3.3 ± 0.9	1.02 ± 0.29

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
A H O		
Four springs to 73°C discharging 590 L/min; travertine. One shallow well (7 m) discharging 115 L/min at 84°C. Saline water; geothermometers may be unreliable.	0.23	0.056
A N A		
No surface activity; area identified by heat flow anomaly. One geothermal test well 2071 m deep; maximum temperature 103°C at 915 m.	1.08	0.26
Two springs to 66°C discharging 110 L/min. Four wells to 73 m; maximum temperature 68°C at 37 m. A dilute, high-pH water; geothermometers may be unreliable.	0.23	0.055
Four main springs to 59°C discharging 385 L/min. Seven wells to 95 m; maximum temperature 55°C at 25 m. Ancient travertine deposit.	0.18	0.044
Several springs to 76°C; large flow rate. A dilute, high-pH water.	0.27	0.065
Several springs to 73°C discharging 1150 L/min.	0.23	0.055
Several springs to 52°C discharging 425 L/min.	0.20	0.049
Four springs to 73°C discharging 150-200 L/min.	0.26	0.063
Spring discharging 115 L/min at 83°C. Two wells 100 m deep; maximum temperature 89°C at 30 m. Sulfate-water isotope geothermometer gives 92°C.	0.26	0.062
A D A		
Spring(s) to 66°C discharging 100 L/min. Dilute, high-pH water.	0.20	0.049
Several springs to 80°C and high ground temperatures along linear trend.	0.92	0.22
Springs to 90°C.	0.25	0.061

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J) N E V
135	Butte Springs (Trego)	40 46.0 119 07.0	96 (D) 124 (A,I) 124 (A,I)	115 ± 7	3.3 ± 0.9	0.90 ± 0.26
136	Fly Ranch (Wards) Hot Springs	40 52.0 119 20.9	99 (D) 100 (J) 126 (A)	108 ± 6	4.4 ± 1.3	1.12 ± 0.35
139	The Needles (Needle Rocks, Pyramid Lake)	40 08.8 119 40.5	115 (D) 116 (M) 137 (C)	123 ± 5	3.3 ± 0.9	0.97 ± 0.27
140	Moana area	39 29.7 119 48.9	96 (M) 96 (M) 155 (A)	116 ± 14	8.8 ± 1.8	2.4 ± 0.6
142	Wabuska Hot Springs	39 09.7 119 11.0	106 (M) 140 (K) 146 (I)	131 ± 9	18.3 ± 11.9	5.7 ± 3.8
149	Dixie Hot Springs	39 47.9 118 04.0	127 (K) 145 (A) 145 (A)	139 ± 4	3.3 ± 0.9	1.12 ± 0.31
150	Colado area	40 14.9 118 24.7	61 (M) 101 (D) 128 (A)	97 ± 14	3.3 ± 0.9	0.73 ± 0.24
153	Sou (Gilbert's) Hot Springs	40 05.4 117 43.4	79 (J) 86 (D) 114 (A)	93 ± 8	3.3 ± 0.9	0.70 ± 0.21
155	Golconda Hot Springs	40 57.7 117 29.6	86 (D,I) 86 (D,I) 115 (A)	96 ± 7	3.3 ± 0.9	0.73 ± 0.21
156	Hot Pot (Blossom Hot Springs)	40 55.3 117 06.5	97 (D) 114 (J) 125 (A)	112 ± 6	3.3 ± 0.9	0.87 ± 0.25
157	Hot Springs Ranch	40 45.7 117 29.5	125 (D) 150 (A) 160 (J)	145 ± 7	3.3 ± 0.9	1.17 ± 0.33
158	Buffalo Valley Hot Springs	40 22.1 117 19.5	97 (D) 135 (J) 140 (K)	124 ± 10	5.7 ± 2.0	1.67 ± 0.60

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
A D A		
Several springs to 84°C.	0.22	0.054
Two artesian wells 244 and 305 m deep discharging 500 L/min at 80°C; maximum well temperature 108°C; extensive travertine.	0.28	0.067
Several springs and three wells, deepest 1795 m, maximum temperature 116°C.	0.24	0.058
Springs inactive. More than 20 wells to 307 m; maximum temperature 96°C at 94 m. High silica content may result from dissolution of diatomite and adversely affect the silica geothermometer; maximum temperature may therefore be too high. Thermal water used for space heating.	0.60	0.143
Several springs to 97°C; travertine. At least three wells 149 to 678 m deep; maximum temperature 106°C.	1.43	0.34
Springs and seeps to 72°C discharging several hundred L/min.	0.28	0.067
No surface activity. Two wells; well head temperature 60°C.	0.183	0.044
Several springs to 73°C; travertine.	0.175	0.042
Several springs to 74°C discharging 750 L/min.	0.183	0.044
Spring discharging 265 L/min at 58°C.	0.22	0.052
Springs to 85°C; minor travertine. One well 937 m deep; no information.	0.29	0.070
Several springs to 79°C discharging 36 L/min; travertine; geothermometers may be unreliable owing to low flow rate.	0.42	0.100

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						N E V
159	Smith Creek Valley area	39 18.7 117 32.5	116 (D) 143 (A,K) 156 (I)	138 ± 8	3.3 ± 0.9	1.11 ± 0.32
160	Spencer Hot Springs	39 19.5 116 51.5	88 (J) 95 (D) 123 (A)	102 ± 8	3.3 ± 0.9	0.78 ± 0.23
161	Darrough Hot Springs	38 49.3 117 10.8	129 (M) 132 (C) 136 (A)	132 ± 1	14.4 ± 7.9	4.6 ± 2.5
163	Hot Springs Point	40 24.2 116 31.0	74 (M) 87 (D) 116 (A)	92 ± 9	3.3 ± 0.9	0.70 ± 0.21
165	Carlin area	40 42.0 116 08.0	81 (I) 90 (D) 118 (A)	96 ± 8	3.3 ± 0.9	0.73 ± 0.22
166	Hot Hole (Elko Hot Springs)	40 49.1 115 46.5	80 (J) 86 (D) 114 (A)	93 ± 7	3.3 ± 0.9	0.70 ± 0.21
167	Mineral (San Jacinto Hot Springs)	41 47.3 114 43.3	100 (D,I) 100 (D,I) 128 (A,I)	109 ± 7	3.3 ± 0.9	0.85 ± 0.25
168	Hot Sulphur Springs (Sulphur Springs)	41 09.4 114 59.1	85 (J) 102 (D) 129 (A)	105 ± 9	6.7 ± 1.9	1.63 ± 0.48
170	Cherry Creek area	39 51.0 114 54.3	90 (I) 114 (D) 140 (A)	115 ± 10	3.3 ± 0.9	0.90 ± 0.27
					N E	W M
172	Jemez Springs (Ojos Calientes)	35 46.3 106 41.4	96 (D) 96 (D) 124 (A)	105 ± 7	3.3 ± 0.9	0.81 ± 0.24
173	Spence Spring	35 51.0 106 37.8	63 (I) 110 (D) 137 (A)	103 ± 15	3.3 ± 0.9	0.79 ± 0.26
174	San Francisco (Lower Frisco) Hot Springs	33 14.7 108 52.8	99 (D,J) 99 (D,J) 128 (A)	109 ± 7	3.3 ± 0.9	0.84 ± 0.24

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
A D A		
Several springs to 86°C discharging 75 L/min; minor travertine.	0.28	0.067
Springs and artesian wells to 72°C discharging 50 L/min.	0.195	0.047
Several springs to 95°C discharging several hundred L/min; minor travertine. One well 278 m deep; maximum temperature 129°C at TD; discharge 4300 L/min.	1.14	0.28
Several springs to 54°C discharging 125 L/min. Two wells less than 1 km deep; maximum temperature 74°C.	0.175	0.042
Spring(s) to 79°C.	0.183	0.044
Springs to 56°C; extensive travertine.	0.175	0.042
Several springs and shallow wells to 60°C discharging more than 4500 L/min.	0.21	0.051
Several springs to 55°C; travertine.	0.41	0.098
Several springs to 61°C.	0.22	0.054
E X I C O		
Several springs to 76°C discharging more than 750 L/min; water may be derived in part from high-temperature reservoir beneath Valles caldera.	0.20	0.049
Spring discharging 167 L/min at 41°C; water may represent leakage from the high-temperature reservoir beneath Valles caldera.	0.20	0.047
Several springs and seeps to 37°C discharging less than 50 L/min and scattered for 2 km along river.	0.21	0.050

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
					N E	W M
175	Radium Hot Springs	32 30.0 106 55.5	74 (M) 96 (D) 124 (A)	98 ± 10	3.3 ± 0.9	0.75 ± 0.23
176	Lightning Dock area	32 08.9 108 49.9	107 (M) 158 (A) 168 (I)	144 ± 13	3.3 ± 0.9	1.16 ± 0.35
						O R E
177	Mount Hood area	45 22.5 121 42.5	90 (O) 125 (O) 150 (O)	122 ± 12	3.3 ± 0.9	0.96 ± 0.29
178	Carey (Austin) Hot Springs	45 01.2 122 00.6	87 (I) 98 (D) 126 (A)	104 ± 8	3.3 ± 0.9	0.80 ± 0.24
179	Breitenbush Hot Springs	44 46.9 121 58.5	99 (D) 127 (A) 149 (I)	125 ± 10	3.3 ± 0.9	0.99 ± 0.29
180	Kahneetah Hot Springs	44 51.9 121 12.9	102 (I) 113 (D) 113 (D)	109 ± 3	3.3 ± 0.9	0.85 ± 0.24
181	Belknap Hot Springs	44 11.6 122 03.2	82 (I) 108 (D) 148 (K)	113 ± 14	3.3 ± 0.9	0.88 ± 0.28
182	Foley Hot Springs	44 09.8 122 05.9	81 (D) 106 (I) 111 (A)	99 ± 7	3.3 ± 0.9	0.76 ± 0.22
183	McCredie (Winino) Hot Springs	43 42.6 122 17.3	81 (I) 96 (D) 96 (D)	91 ± 4	3.3 ± 0.9	0.68 ± 0.19
185	Umpqua Hot Springs	43 17.5 122 22.0	100 (J) 104 (D) 131 (A)	112 ± 7	3.3 ± 0.9	0.87 ± 0.25
186	Klamath Hills area	42 03.0 121 44.5	104 (D) 131 (A) 138 (K)	124 ± 7	10.6 ± 3.8	3.1 ± 1.1
187	Klamath Falls area	42 14 121 46	99 (M) 104 (D) 131 (A)	111 ± 7	114 ± 55	30 ± 15

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
E X I C O		
Original springs with reported temperatures to 85°C are now dry. One pumped well has surface temperature of 52°C.	0.188	0.045
No surface activity. Four shallow irrigation wells; maximum temperature 107°C at 90 (?) m. Oil test well 3 km north of area recorded 122°C at 2.2 km.	0.29	0.070
G O N		
Fumaroles and acid-sulfate springs to 90°C; reservoir temperatures are speculative; may be a small vapor-dominated system.	0.24	0.058
Several springs to 91°C discharging 950 L/min. Sulfate-water isotope geothermometer gives 181°C.	0.20	0.048
Several springs to 92°C discharging 3400 L/min. Sulfate-water isotope geothermometer gives 195°C.	0.25	0.059
Several springs to 52°C dicharging 200 L/min.	0.21	0.051
Three springs to 71°C discharging 300 L/min; may be part of a larger system that includes Foley Hot Springs.	0.22	0.053
Four springs to 79°C; system may be larger and include Belknap Hot Springs 6 km to the northeast.	0.190	0.046
Several springs to 73°C discharging about 75 L/min.	0.170	0.041
Two springs to 46°C discharging less than 20 L/min; travertine. CO_2-rich water; geothermometers may be unreliable.	0.22	0.052
Several wells to 127 m; maximum temperature 93°C at 127 (?) m; 9 km^2 area of silicified rocks. Thermal water used in greenhouse operation.	0.78	0.187
Several wells ranging in depth from 40 to 550 m used for space heating; downhole temperatures as high as 113°C are reported. Area includes 74°C springs at Olene Gap 13 km to the southeast. Sulfate-water isotope geothermometer gives about 190°C.	7.4	1.79

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km^3)	Mean reservoir thermal energy (10^{18} J)
						O R E
188	Summer Lake Hot Springs	42 43.5 120 38.7	107 (D) 112 (I) 134 (A)	118 ± 6	7.8 ± 2.8	2.2 ± 0.8
189	Lakeview area (Hunters and Barry Ranch Hot Springs)	42 12.0 120 21.6	143 (I) 149 (C) 158 (K)	150 ± 3	15.3 ± 5.6	5.6 ± 2.0
191	Fisher Hot Spring	42 17.9 119 46.5	95 (D) 123 (A,J) 123 (A,J)	114 ± 7	3.3 ± 0.9	0.89 ± 0.26
192	Weberg Hot Springs	44 00.0 119 38.8	99 (D) 100 (J) 126 (A)	108 ± 6	3.3 ± 0.9	0.84 ± 0.24
193	Harney Lake area	43 10.9 119 03.2	105 (D,J) 105 (D,J) 133 (A)	114 ± 7	3.3 ± 0.9	0.89 ± 0.26
194	Crane Hot Springs	43 26.4 118 38.4	99 (D) 124 (I) 127 (A)	117 ± 6	3.3 ± 0.9	0.91 ± 0.26
195	Riverside area	43 28.0 118 11.3	96 (I) 116 (D) 143 (A)	118 ± 10	3.3 ± 0.9	0.93 ± 0.28
200	McDermitt area	42 04.7 117 45.6	84 (E) 90 (I) 120 (A)	98 ± 8	3.3 ± 0.9	0.75 ± 0.22
201	Medical Hot Springs	45 01.1 117 37.5	66 (I) 97 (D) 125 (A)	96 ± 12	3.3 ± 0.9	0.73 ± 0.23
202	Little Valley area	43 53.5 117 30.0	118 (D,I) 118 (D,I) 145 (A)	127 ± 6	3.3 ± 0.9	1.01 ± 0.29
						U T
205	Abraham (Baker, Crater) Hot Springs	39 36.8 112 43.9	86 (J) 89 (D) 117 (A)	97 ± 7	6.1 ± 2.1	1.36 ± 0.48
206	Monroe-Red Hill Hot Springs	38 38.2 112 06.2	79 (D) 109 (A) 114 (J)	101 ± 8	4.7 ± 1.6	1.09 ± 0.38

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
G O N		
Three springs to 43°C discharging 75 L/min. Sulfate-water isotope geothermometer gives about 190°C.	0.54	0.130
Several springs to 96°C discharging 2500 L/min; travertine and sinter. Two geothermal exploration wells 189 and 1658 m deep; several shallow wells used for space heating.	1.39	0.33
Spring discharging 75 L/min at 68°C.	0.22	0.053
Spring discharging 40 L/min at 46°C. CO_2-rich water; geothermometers may be unreliable.	0.21	0.050
Several springs to 68°C discharging 550 L/min. Reservoir may be larger than estimated.	0.22	0.053
Two springs to 78°C discharging 550 L/min.	0.23	0.055
Several springs to 63°C discharging 200 L/min.	0.23	0.056
Several springs to 52°C discharging 750 L/min.	0.188	0.045
Several springs to 60°C in two groups discharging 200 L/min.	0.183	0.044
Several springs to 70°C discharging 550 L/min. Sulfate-water isotope geothermometer gives 215°C.	0.25	0.061
A H		
Springs to 84°C discharging more than 1000 L/min; extensive travertine.	0.34	0.082
Three main springs to 76°C discharging more than 1200 L/min; extensive travertine.	0.27	0.065

Table 6.--*Locations, temperatures, volumes, and thermal energies of*

No.	Name of area	Latitude (°N) Longitude (°W)	Estimates of reservoir temperature (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (km³)	Mean reservoir thermal energy (10^{18} J)
						U T
207	Joseph Hot Springs	38 36.7 112 11.2	87 (J) 104 (D) 131 (A)	107 ± 9	3.3 ± 0.9	0.83 ± 0.25
210	Thermo Hot Springs	38 11.0 113 12.2	130 (J) 144 (A) 151 (K)	142 ± 4	8.3 ± 3.5	2.8 ± 1.2
211	Newcastle area	37 39.7 113 33.7	100 (I) 143 (A) 148 (I)	130 ± 11	6.1 ± 2.9	1.90 ± 0.91
					W A	S H I
212	Baker Hot Spring	48 45.9 121 40.2	102 (E) 139 (A) 162 (I)	134 ± 12	3.3 ± 0.9	1.07 ± 0.32
214	Ohanapecosh Hot Springs	46 44.2 121 33.6	108 (K) 135 (J) 137 (A)	127 ± 7	3.3 ± 0.9	1.00 ± 0.29
						W Y O M
216	Huckleberry Hot Springs	44 07.0 110 41.0	124 (D,J) 124 (D,J) 150 (A)	133 ± 6	3.3 ± 0.9	1.06 ± 0.30
217	Granite Hot Springs	43 22 110 27	83 (D,J) 83 (D,J) 112 (A)	93 ± 7	3.3 ± 0.9	0.70 ± 0.21
218	Auburn Hot Springs	42 49.5 111 00.0	72 (D) 96 (J) 102 (A)	90 ± 6	3.3 ± 0.9	0.67 ± 0.20
	TOTALS--					700 ± 110 --

*Totals for wellhead thermal energy and beneficial heat exclude National Parks.

identified hot-water hydrothermal convection systems 90-150°C--Continued

Comments	Wellhead thermal energy (10^{18} J)	Beneficial heat (10^{18} J)
A H		
Several springs to 64°C discharging 114 L/min; travertine.	0.21	0.050
Several springs to 89°C discharging about 500 L/min; travertine. One deep test well.	0.71	0.171
No surface activity. One deep (152 m) and several shallow irrigation wells contain thermal water; maximum temperature 108°C at 85 m.	0.47	0.114
N G T O N		
Spring(s) to 44°C discharging 26 L/min; may be a mixed water.	0.27	0.064
Five springs to 49°C discharging 225 L/min; travertine. Withdrawn from commercial development or exploration because of National Park (Mount Ranier) status.	-	-
I N G		
Springs to 71°C in two small groups discharging 380 L/min.	0.26	0.064
Two springs discharging 1200 L/min at 44°C.	0.175	0.042
Several springs to 59°C discharging 150 L/min; travertine mounds.	0.168	0.040
----------	176*	42*

Occurrence of Low-Temperature Geothermal Waters in the United States

By E. A. Sammel

ABSTRACT

This report tabulates information on low-temperature (<90°C) geothermal waters at depths less than 1 km and presents maps that depict areas in the United States favorable for discovery and development. It is not yet possible to quantify the amount of the thermal energy in the ground or the amount of energy that might be recovered. However, low-temperature geothermal waters at depths less than 1 km appear to be widely available throughout much of the United States and to have the potential for significant utilization in space heating and agriculture on a local basis.

INTRODUCTION

Thermal springs occur at many places on the Earth's surface, and man has undoubtedly enjoyed the use of this free geothermal energy for cooking, comfort, and healing since his early beginnings. Only in recent years, however, has it been generally recognized that thermal springs are merely the surface manifestation of a widely available subsurface energy resource that may be used to satisfy a variety of energy needs. A significant part of this resource consists of high- or intermediate-temperature waters (see Brook and others, this volume). A much larger part, by volume, consists of widely distributed waters having temperatures only a few degrees or a few tens of degrees above normal ground-water temperatures. Despite the relatively low temperatures of these waters, they constitute a large source of energy, potentially useful at many places for direct applications in space heating, agriculture, and industry. Much of the usefulness of these waters is directly related to their widespread occurrence and accessibility at shallow depths.

Low-temperature geothermal waters identified in this report occur at depths shallow enough (<1 km) to be tapped in the foreseeable future and hence are part of the accessible geothermal resource base (Muffler and Cataldi, 1978). It is likely that in most of the areas described below, a fraction of the accessible resource base can be extracted legally and economically today or at some future time; this fraction thus constitutes either a geothermal reserve or a geothermal resource (Muffler and Cataldi, 1978).

Current knowledge does not allow quantifying the recoverable energy for low-temperature waters, as was done for hydrothermal convection systems ≥90°C (Brook and others, this volume). However, there is a growing need for information on the nature and distribution of low-temperature waters. Therefore, this compilation of data on low-temperature geothermal waters in the United States has been made in order to summarize current knowledge of the resource as an aid in further exploration and development.

The investigations that will eventually quantify and evaluate sources of low-temperature energy have barely begun in most of the promising areas of the country, and data currently available from these studies do not afford a basis for quantitative evaluation. This assessment is, therefore, largely descriptive. Because it relies almost entirely on recent compilations of data by numerous individuals and agencies, the assessment is not necessarily consistent in its approach. It is most certainly not complete. Perhaps its most useful result will be to signal the gaps and deficiencies that must be remedied if the low-temperature geothermal resources of the nation are to fill their potential role in supplying energy for the future.

ACKNOWLEDGMENTS

Investigations of low-temperature geothermal waters are now being carried on by state agencies and institutions in 13 western states, funded under the Western States Cooperative Direct-Heat Geothermal Program of the Department of Energy (DOE). In addition, the U. S. Geological Survey (USGS) is engaged in both direct and cooperative studies of geothermal geohydrology, geochemistry, and geophysics in most of these western states and has granted funds to several state agencies for similar studies. Selection and depiction of favorable geothermal areas for this report were accomplished in consultation with the principal DOE-supported and USGS investigators in each state.

Information on resources in Central and Eastern United States was provided by investigators at Los Alamos Scientific Laboratory, the Bureau of Economic Geology at the University of Texas at Austin, Virginia Polytechnic Institute and State University, the Applied Physics Laboratory of The Johns Hopkins University, and the USGS. Locations and information on the thermal springs of the Appalachian Mountains are taken from Hobba, Fisher, Pearson, and Chemerys (1977).

The author is indebted to many people who contributed information for this report. Space limitations preclude listing all, although references in the accompanying tables cite the principal contributions. Special thanks are due, however, to Duncan Foley, University of Utah Research Institute, who provided liaison between the author and the DOE Western States

Cooperative Direct-Heat Geothermal Program, and whose aid and collaboration were invaluable in assembling information for this assessment. James A. Swanson provided data on geothermal wells and springs and graphical analyses of these data from the computer file GEOTHERM. Tables and illustrations were compiled with the help of Robert W. Craig. The assistance of these colleagues is gratefully acknowledged.

OCCURRENCE OF LOW-TEMPERATURE GEOTHERMAL WATERS

Western United States

Low-temperature geothermal waters are widely available in the Western United States, as shown by the symbols for thermal wells and springs (maps 1 and 2) and by patterns for extensive favorable areas (map 1).

Thermal springs are defined for this report as those having surface temperatures at least 10°C above mean annual air temperatures. Thus, springs may have minimum temperatures ranging from 10°C in Alaska to 30°C in southern Arizona. Thermal wells are also defined on the basis of minimum temperatures 10°C above mean annual air temperatures but, in addition, are required to have thermal gradients exceeding the 30°C/km average for continental crustal rocks. Thus, a shallow thermal well in Alaska might have a temperature as low as 10°C, and a well in the same area producing water from a depth of 1 km would have a temperature of at least 30°C. On the other hand, thermal wells in southern Arizona might have minimum temperatures of 30°C at very shallow depth and 50°C at a depth of 1 km. Wells included in this report are generally limited for economic reasons to those having depths less than 1 km.

The thermal springs and wells scattered on maps 1 and 2 are so numerous as to preclude individual description in this report. Most of these springs and wells derive their thermal waters from aquifers whose nature and extent are currently unknown. It is evident, therefore, that these sources of energy cannot be evaluated at this time, although they represent a significant fraction of the total low-temperature energy in the region.

The numbered patterns on map 1 represent areas generally greater than 20 km^2 in which low-temperature geothermal waters are believed to occur in extensive aquifers within 1 km of land surface. Data from wells, test holes, and springs in these areas are given in table 12 (end of report).

Criteria used in selecting and defining the favorable areas include the temperature and thermal-gradient minima described above for thermal wells and springs. In addition, regional conductive heat-flow measurements were given considerable weight, especially in a few areas for which hydrologic data suggested only marginal favorability but for which regional heat flows were high. Heat flow is generally greater than 60 mW/m^2 in most areas. One index of water quality, concentration of dissolved solids, is reported for areas where it is known, but this index was not used as a basis for selection of favorable areas.

Geothermal gradients used in evaluating the favorable areas were, with few exceptions, calculated by subtracting mean annual air temperatures from maximum reported fluid temperatures in wells and test holes and dividing by the total depths of the wells. The resulting linear gradients do not necessarily reflect actual depths of occurrence of thermal water. The gradients may also be unreliable because of convective flow in the wells or in surrounding formations. Because of these factors, the gradients obtained at most places do not represent conductive thermal gradients in the Earth's crust.

The limiting of depths of occurrence to about 1 km is the only specific economic criterion used in the selection of favorable areas. Under current or near-future economic conditions, low-temperature waters more than 1 km deep are probably not attractive targets for exploration or development at most places except where useable deep wells have already been drilled for other purposes. No attempt has been made to consider other economic factors such as proximity to potential users or specific utilization of the thermal waters. Similarly omitted were considerations of legal ownership, jurisdiction, and environmental constraints.

It is apparent from table 12 (end of report) that much of the information needed to satisfy basic criteria is not available for many areas. Reliable geothermal gradients are lacking at most places, as well as local heat-flow data. In most instances, only a generalized knowledge of the geohydrology was available to guide the location of areal boundaries. The selection of favorable areas is most solidly based, therefore, on high regional heat flows and the presence of thermal springs and wells. This information does not permit the inference that thermal water may be found everywhere within the depicted areas, and users of this report are cautioned that additional exploration will be required prior to development at almost any site in the areas.

Additional facts that should be obtained prior to development of thermal ground water but that generally were not available for this assessment include: values of transmissivity and storage coefficient for geothermal aquifers; data on availability of ground-water recharge adequate to sustain withdrawals; effects of ground-water withdrawals on flow of existing wells and springs, and on aquifer fabrics (subsidence); and quality considerations, such as concentrations of dissolved-solids, corrosion potential, or boron concentrations (important for agricultural uses).

In the selection of favorable areas, it was not possible to apply established criteria uniformly throughout the western states. Inconsistencies exist from state to state as the result of the differing quality and quantity of available data, differing geologic terranes, and differing views on the significance of the data. In Montana, for example, where fractured crystalline and sedimentary rocks underlie much of the land surface, the boundaries of many areas are drawn conservatively because of uncertainty as to the exact nature and extent of aquifers in fractured rocks. In contrast, areas depicted in young sedimentary basins of the Basin and Range Province and the Rio Grande rift are generally larger than those shown elsewhere on the assumption that aquifers in these basins are almost certainly extensive and that thermal waters are also likely to be extensive. In each of these differing terranes, however, detailed investigations of geologic structure and permeability distributions will be required in order to determine the precise locations and extent of the thermal waters.

The diversity of terranes favorable for the occurrence of low-temperature waters is apparent from the descriptions in table 12. In Alaska, for example, thermal waters occur in faults and fractures at the margins of granitic plutons as well as in young volcanic rocks derived from recently active volcanoes. In Montana and Colorado, thermal springs issue from Mississippian limestone, Cretaceous sandstone and granite, Tertiary volcanic rocks, and alluvium. In Washington, Oregon, and Idaho, thermal waters commonly circulate in layered Cenozoic basalt, and, in the Basin and Range Province, in deep faults. In Idaho, most of the thermal waters occurring outside the Snake River Plain circulate in faults and fractures in Cretaceous granitic rocks of the Idaho batholith. At The Geysers in California, thermal waters and steam occur in rocks ranging from upper Mesozoic eugeosynclinal rocks to upper Pleistocene volcanic rocks. Three elements common to these and most other geothermal occurrences are the presence of high heat flow, deep crustal fracture zones, and convectively circulating thermal water.

Thermal ground water is present nearly everywhere in the upper few kilometers of the crust, warmed by normal crustal heat flow. The appearance of this water at the land surface depends, however, on the less common occurrence of vertically connected zones of high permeability (for example, fault planes) that intersect the land surface. It may be logically inferred, therefore, that in regions of generally high heat flow and faulting at depth in the crust, thermal waters may rise to shallow depths at many places, but without reaching the land surface. This inference is supported by a significant number of areas in which no springs occur but which are regarded as resource areas solely on the basis of evidence from shallow wells.

As shown in map 1, a notable concentration of low-temperature geothermal areas occurs in the Basin and Range Province of Arizona, New Mexico, northeastern and southern California, Nevada, Utah, and adjacent areas of southeastern Oregon and Idaho. Much of this region is a tectonically active area of crustal extension characterized by generally high but variable regional heat flow, intense thermal discharge at volcanic centers, magmatic manifestations, and possible laterally extensive silicic partial melts in the thin crust (Lachenbruch and Sass, 1977; Lachenbruch, 1977). Deep, fault-bounded structural basins in the region typically are sites of rapid vertical transport of thermal water.

Low-temperature geothermal waters are present in nearly all large sediment-filled valleys of the Basin and Range Province. Areas favorable for exploration may surround many isolated springs and wells, and future exploration in the region may lead to the discovery of many low-temperature resources for which there is presently no evidence.

East of the Basin and Range Province, a great crustal rift zone, referred to in New Mexico and Colorado as the Rio Grande rift, is the locus of major intermediate- and high-temperature geothermal systems. This zone of crustal fracturing probably extends southward into Texas and may extend northward into southeastern Wyoming (David Blackwell, oral commun., 1978). The region is characterized by deep, fault-bounded basins (for example, San Luis Valley, Colorado), deeply circulating thermal waters, and higher than normal heat flow. The areal extent of most thermal waters in the Rio Grande rift is unknown, but much of the region has been depicted as generally favorable for exploration and potential development.

Hydrologic characteristics of the deep sedimentary basins in the Rio Grande rift are similar to those of the Basin and Range Province, and the occurrence of most thermal waters in both regions is believed to be caused by deep circulation along range-bounding fault systems. In both regions, withdrawal of geothermal water is likely to be limited by the generally low permeability of sediments that occupy the structural basins and by the small amounts of recharge that penetrate to the aquifers.

The magnitude of the low-temperature geothermal accessible resource base in the western states is undoubtedly very large, but the energy per unit volume of thermal water is low and in general the fluids cannot be transported economically over large distances. Effective use of the resource will require greatly increased knowledge of several kinds, including the hydrology of faulted structural basins in arid regions, the relations of hydrothermal convection systems to active volcanic centers and shallow magma chambers, and the geohydrology of basaltic terranes. Equally essential are the technological ingenuity and economic motivation required to stimulate utilization of low-temperature energy in regions of generally low population density and energy demand. Despite these and other problems, use of low-temperature geothermal energy for space heating, agriculture, and some industrial needs is increasing rapidly in most of the western states. Current uses, generally well documented elsewhere, are not described in this report, but they demonstrate that at many places in the Western United States low-temperature geothermal water can be an economical and environmentally safe energy resource.

Central and Eastern United States

The geothermal waters of the Central and Eastern United States have been regarded, until recently, as little more than local curiosities. Consisting almost entirely of scattered thermal springs and a few thermal wells, these occurrences engendered little or no interest as possible sources of energy. Increasing awareness of possible energy shortages in the Eastern United States, however, has resulted in new interest in the geothermal potential of the entire region, and investigations are now underway at many places. Preliminary data from most of the current studies, as well as published data from older literature, are summarized in tables 13 and 14 (end of report), and areas of presumed geothermal potential are shown in figures 15 and 16.

The occurrence of a linear belt of warm springs in the eastern Appalachian Mountains between Georgia and Massachusetts (fig. 15) is related to buried thrust faults that resulted from the collision of the Euro-Asian and North American crustal plates in late Paleozoic time. At places, such as the Warm Springs area of Virginia, the thermal waters appear to issue through permeable zones at the conjunction of buried cross faults and "kink-band" folds in fractured rocks (Geiser, 1976) after having circulated to depths of 1 to 1½ km in a region of normal crustal heat flow.

Hot Springs, Ark., is a single large spring system located in the Ouachita Mountains, in a tectonic setting similar to that of the Appalachians. In a region that extends over about 50,000 km^2 of southwestern Arkansas and southeastern Oklahoma, zones of thrust faulting in folded Paleozoic rocks permit thermal waters to rise from depths of at least 1800 m (table 13).

Current knowledge of the structural control on the occurrence of thermal springs in both the Appalachians and the Ouachita Mountains leads to the expectation that as yet undiscovered thermal waters exist at shallow depths in these two environments. Temperatures of rock-water equilibration estimated by geothermometers are not high (maximum 64°C at Hot Springs, Ark.), and it is probable that temperatures of undiscovered thermal waters are within the range of present spring temperatures, about 20° to 64°C.

Southwest of the Ouachita Mountains, the Ouachita structural belt extends across the high plains of Texas in a series of subparallel thrust faults along the margin of the Gulf geosyncline (fig. 16). Wells in this area produce thermal waters with temperatures as high as 70°C from depths less than 1400 meters. Thermal waters are already being used at places in this area, and exploration for additional resources is underway (Woodruff, 1978). Increased knowledge of the structural and hydrologic controls on the occurrence of the thermal waters will be required in order to expand their use in this area.

Underlying sedimentary rocks in the Atlantic Coast Piedmont and Coastal Plain Provinces are a number of plutons. Radioactive decay of uranium and thorium in the more silicic plutonic rocks produces heat in sufficient quantities to increase crustal heat flow and thermal gradients above the plutons. Known areas of higher than normal gradients on the Atlantic Coast are listed in table 13 and are shown as areas of inferred geothermal potential in figure 15. The relation of the anomalous gradients to the presence of buried plutons and presumed anomalous heat flows remains to be determined by current and future investigations (Costain and others, 1976). At present, the magnitude of the resource is almost entirely unknown.

Identified geothermal resources of the Gulf Coast range from low-temperature artesian springs in Florida to deeply buried high-temperature geopressured zones in Mississippi, Louisiana, and Texas. The geopressured resource, evaluated elsewhere in this Circular, is one of the major geothermal resources of the United States. Overlying the geopressured zones, however, are widespread low-temperature waters that have been found in thousands of oil, gas, and water wells.

Data thus far compiled from these wells suggest that waters overlying geopressured zones at depths less than 1 km may have temperatures greater than 50°C at many places along the Gulf between Florida and south Texas (R. H. Wallace, oral commun., 1978). Many of these waters are moderately to highly saline, and permeabilities in the shallow coastal deposits are likely to be generally low. Data for low-temperature thermal waters on the Gulf Coast have not been tabulated for this report. However, known characteristics of the thermal waters place them in the category of geothermal resources at many places and suggest that further studies are warranted in order to evaluate these apparently vast reservoirs of low-temperature energy.

In the Central United States, geothermal areas of major significance occur in the Northern Great Plains Province. In South Dakota, thermal springs issue from the Permian Minnekahta Limestone south of the Black Hills. These low-temperature waters probably arise from deep circulation in the underlying Minnelusa and Pahasapa Limestones (Davis and others, 1961) (see table 13).

The Pahasapa Limestone is the local equivalent of the Madison Group, a regional aquifer

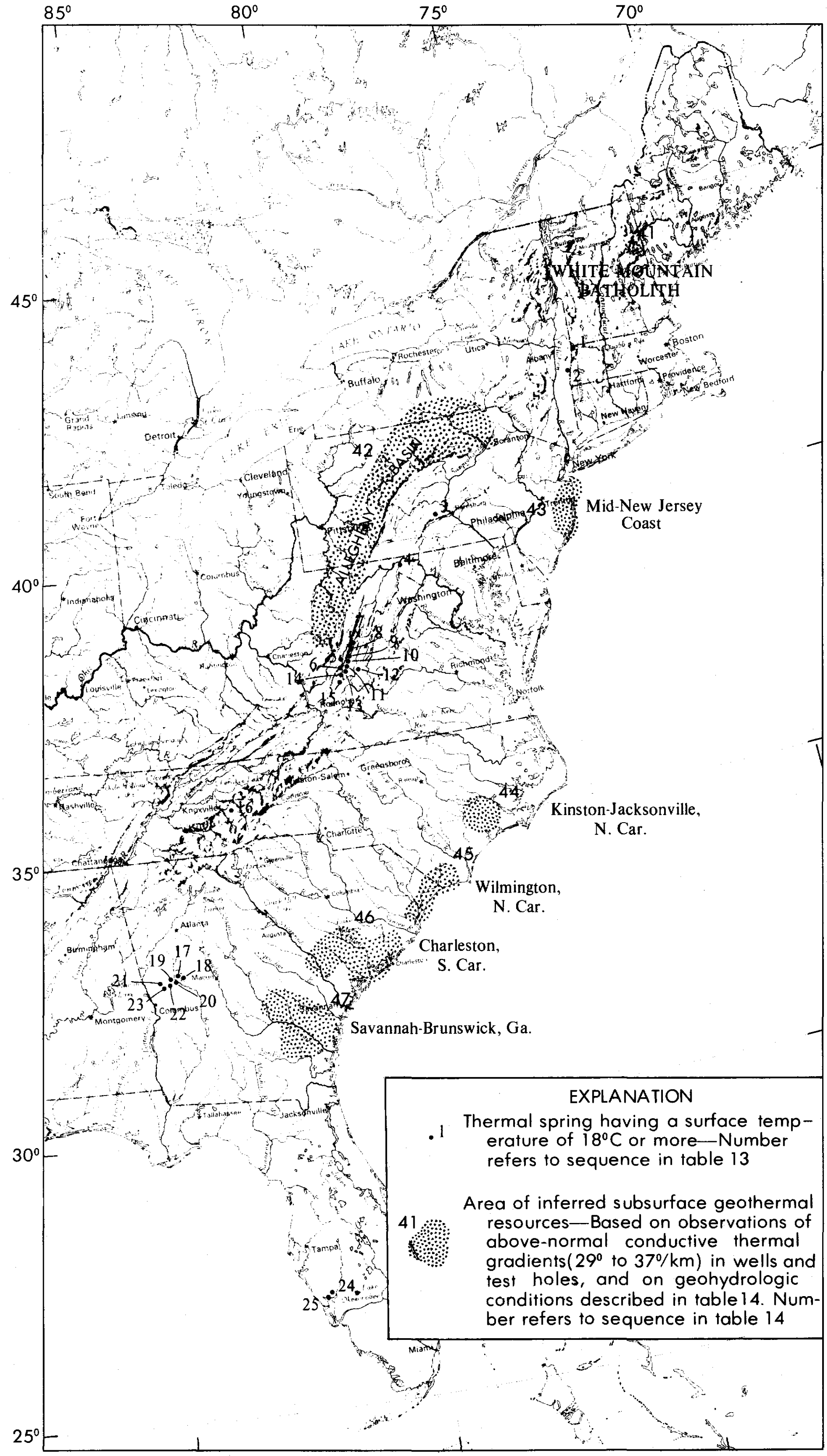

Figure 15.--Locations of known and inferred low-temperature geothermal waters in states of the Atlantic Coast.

that thickens to the north and east of the Black Hills in the Williston Basin. At places in central South Dakota and the Williston Basin of North Dakota, thermal waters from the Madison Group and older formations apparently rise toward the surface through permeable zones in overlying formations. Major areas in which wells less than 1 km deep are known to tap these waters are shown in figure 16. Contours on the surface of the Madison Group (fig. 16) suggest that the great depths to thermal aquifers in much of the Williston Basin generally preclude economic withdrawal of low-temperature water except for the places where unusually permeable zones occur.

In south-central and southeastern South Dakota where the Madison Group is absent, anomalous thermal gradients (30° to 70°C/km) and moderate temperatures (15° to 35°C) are measured in some shallow wells penetrating the Dakota Sandstone. The source of heat for these thermal waters is not known with certainty but is believed to be high-temperature recharge from underlying or adjacent formations (Adolphson and LeRoux, 1968).

A number of areas having inferred geothermal potential remain to be explored in Central and Eastern United States. One such area is the Allegheny Basin (fig. 15), where Paleozoic sedimentary rocks occupy a deep structural trough. Thermal gradients of 30°C/km are reported in oil and gas wells in this area, but hydrologic data have not yet been evaluated (James Maxwell, written commun., 1978). Although the occurrence of nonsaline thermal waters in fairly shallow permeable formations has not yet been demonstrated in this or other sedimentary basins of the North-central United States, preliminary indications suggest that these basins may have significant geothermal potential.

CONCLUSIONS AND PROBLEMS

Previous assessments of geothermal resources have supported the belief that most of the readily recoverable geothermal energy in the nation occurs in the Western United States and the Gulf Coast. Information on low-temperature waters, compiled for this report, confirms this belief but also suggests that a perhaps unexpected resource exists in parts of the Central and Eastern United States. On the basis of this assessment, low-temperature thermal waters appear to constitute one of the most widely available energy sources in the nation.

The magnitude and recoverability of this energy cannot be reliably estimated at this time because such estimates depend on innumerable details of local geologic structure and geohydrology as well as on rapidly changing economic factors. This assessment is not quantitative in terms of energy, but rather describes and tabulates the known facts concerning low-temperature thermal waters.

Ground-water flow in low-temperature geothermal systems is complex in detail but susceptible to analysis and evaluation by proven methods of hydrologic study. Future estimation of recoverable low-temperature energy, however, will depend on satisfactory resolution of several important problems. For example, application of chemical geothermometers to low-temperature waters is clearly unreliable in many instances because of possible mixing of thermal and nonthermal waters and because of nonequilibrium chemical relations. Current reliance on silica geothermometers in low-temperature waters is particularly questionable unless the total chemistry of the waters and the host rocks is carefully evaluated. Furthermore, available exploration tools, such as surface geophysical methods, are unable at present to reliably determine hydrologic boundaries and aquifer properties of geothermal systems in complex environments.

Estimates of the magnitude and availability of low-temperature geothermal resources in the Western United States hinge on the crucial question of whether extensive aquifers containing thermal waters occur in the regions surrounding the numerous thermal springs and wells. In contrast, the low-temperature geothermal waters of Central and Eastern United States are known or inferred to be areally extensive, and their utilization hinges on locating points at which conditions are favorable for recovery. Solutions to research problems such as those mentioned in the preceding paragraph will go far toward minimizing exploration costs and making low-temperature geothermal waters economically attractive as sources of energy over large areas of the nation.

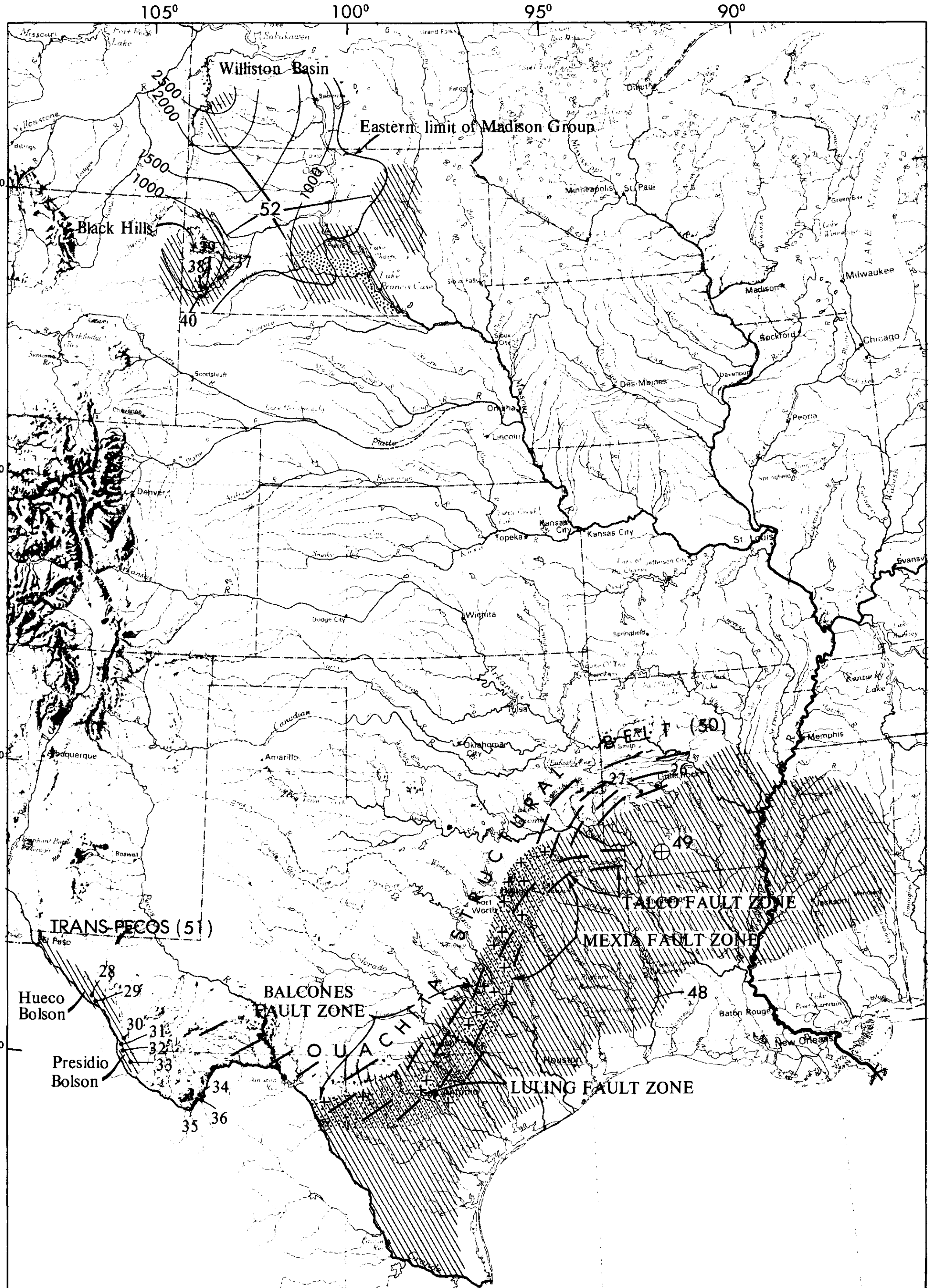

Figure 16.--Locations of known and inferred low-temperature geothermal waters in the Central United States.

EXPLANATION

Area most favorable for the discovery and development of local sources of low-temperature (<90°C) thermal water—Based on above-normal thermal gradients and heat flows measured in wells and test holes, and the known or inferred presence of extensive thermal aquifers at depths less than 1 km. See table 14 for description of these areas

48 Area where thermal gradients measured in wells and test holes are generally above normal and where some wells may produce thermal water from depths less than 1 km—In contrast to the "most favorable" areas, these areas have lower permeabilities in most aquifers, greater depth of occurrence or more limited areal extent of thermal waters, or inadequate information. See table 14 for descriptions of areas

Ouachita structural belt

—1000— Structure contour—Drawn on top of Madison Group, North and South Dakota. Depths in meters below land surface. Contour interval 500 m

26. Thermal spring having a surface temperature of 30°C or more (18°C or more in South Dakota)—Number refers to sequence in table 13

⊕49 Area of thermal brine wells in southwest Arkansas—Number refers to sequence in table 14

+ Location of well in the Ouachita structural belt of Texas known to have above-normal thermal gradient and water temperature at depth less than 1 km

REFERENCES CITED

Numbers preceding references are keyed to tables 1-3. Reference list includes sources of unpublished data.

1. Adolphson, D. G., and LeRoux, E. F., 1968, Temperature variations of deep flowing wells in South Dakota: U. S. Geological Survey Professional Paper 600-D, p. D60-D62.

2. American Association of Petroleum Geologists, 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U. S. Geological Survey, Geologic Maps of North America Series, scale 1:5,000,000 (2 sheets).

3. Barrett, J. K., and Pearl, R. H., 1978, An appraisal of Colorado's geothermal resources: Colorado Geological Survey Bulletin 39, 224 p.

4. Bedinger, M. S., Pearson, F. J., Jr., Reed, J. E., Sniegocki, R. T., and Stone, C. G., 1974, The waters of Hot Springs National Park, Arkansas--their origin, nature, and management: U. S. Geological Survey Open-File Report, 102 p.

5. Blackwell, D. D., 1969, Heat-flow determinations in the northwestern United States: Journal of Geophysical Research, v. 74, p. 992-1007.

6. _____, 1974, Terrestrial heat flow and its implications on the location of geothermal reservoirs in Washington, in Energy resources of Washington: Washington Department of Natural Resources, Division of Geology and Earth Science Information Circular 50, p. 25-33.

7. Breckenridge, R. M., and Hinckley, B. S., 1978, Thermal springs of Wyoming: Wyoming Geological Survey Bulletin 60, 104 p.

8. Brook, C. A., Mariner, R. H., Mabey, D. R., Swanson, J. R., Guffanti, Marianne, and Muffler, L. J. P., 1979, Hydrothermal convection systems with reservoir temperatures ≥90°C: this volume.

9. Bryan, Kirk, 1924, The hot springs of Arkansas: Journal of Geology, v. 32, no. 6, p. 449-459.

10. California Division of Mines and Geology, 1978, Sacramento, California, unpublished data.

11. Cater, F. W., and others, 1973, Mineral resources of the Idaho Primitive Area and vicinity, Idaho: U. S. Geological Survey Bulletin 1304, 431 p.

12. Center for Water Resources Research, 1973, University of Nevada, Reno, Desert Research Institute, unpublished data.

13. Chaturvedi, L. N., 1978, New Mexico State University, Department of Civil Engineering, Las Cruces, New Mexico, unpublished data.

14. Cohen, Philip, and Loeltz, O. J., 1964, Evaluation of hydrogeology and hydrogeochemistry of Truckee Meadows area, Washoe County, Nevada: U. S. Geological Survey Water-Supply Paper 1779-S, 59 p.

15. Costain, J. K., Glover, Lynn, III, and Sinha, A., 1976 and continuing, Evaluation and targeting of geothermal energy resources in the southeastern United States: Virginia Polytechnic Institute and State University, Blacksburg, Virginia, Quarterly Progress Reports to the U. S. Department of Energy, Division of Geothermal Energy.

16. Davis, R. W., Dyer, C. F., and Powell, J. E., 1961, Progress report on wells penetrating artesian aquifers in South Dakota: U. S. Geological Survey Water-Supply Paper 1534, 100 p.

17. Decker, E. R., 1978, University of Wyoming, Laramie, Wyoming, unpublished data.

18. Dellechaie, F., 1978, A geological and hydro-geochemical study of the La Grande area, Union County, Oregon, in Geothermal energy--a novelty becomes resource: Annual Meeting, Geothermal Resources Council, Hilo, Hawaii, 1978, Transactions, v. 2, p. 145-148.

19. Dutt, G. R., and McCreary, J. W., 1970, The quality of Arizona's domestic, agricultural, and industrial water: University of Arizona, Agricultural Experimental Station Report 256, 83 p.

20. Eakin, T. E., 1962, Ground water appraisal of Gabbs Valley, Mineral and Nye Counties, Nevada: Nevada Department of Conservation and Natural Resources, Ground Water Resources Reconnaisance Service Report 9, 27 p.

21. Eakin, T. E., Maxey, G. B., Robinson, T. W., Fredricks, J. C., and Loeltz, O. J., 1951, Contributions to hydrolo-

gy, eastern Nevada: Nevada Department of Conservaton and Natural Resources Water Resources Bulletin 12, 171 p.

22. Erskine, H. M., 1948, Principal springs of West Virginia, a report on the location, discharge and temperature of the principle springs of West Virginia: Conservation Commission of West Virginia, 50 p.

23. Everett, D. E. and Rush, F. E., 1967, Brief appraisal of water resources of Walker Lake area, Mineral, Lyon, and Churchill Counties, Nevada: Nevada Department of Conservation and Natural Resources Water Resources Reconnaisance Service Report 40, 44 p.

24. Ferguson, G. E., Lingham, C. W., Love, S. K., and Vernon, R. O., 1947, Springs of Florida: Florida Geological Survey Bulletin 31, 196 p.

25. Fiero, G. W., 1968, Regional ground-water flow systems of Central Nevada: University of Nevada, Reno, Desert Research Institute, Center for Water Resources Research Miscellaneous Report 5, 139 p.

26. Fitch, W. E., 1927, Mineral waters of the United States and American spas: New York, Lea and Febiger, 799 p.

27. Garside, L. J., and Schilling, J. H., 1978, Inventory of thermal waters of Nevada: Nevada Bureau of Mines and Geology Bulletin 91. (in press)

28. Geiser, P. A., 1976, Structural mapping in the Warm Springs Anticline, Northwestern Virginia, in Costain, John K., and others, Evaluation and targeting of geothermal resources in the southeastern United States, Progress Report, May 1-October 31, 1976: Virginia Polytechnic Institute and State University, Blacksburg, Virginia, p. 116-164.

29. Goode, Henry, 1978, University of Utah, Salt Lake City, Utah. (in preperation)

30. Gott, G. B., and Schnabel, R. W., 1963, Geology of the Edgemont NE quadrangle, Fall River and Custer Counties, South Dakota, in Geology and uranium deposits of the southern Black Hills: U. S. Geological Survey Bulletin 1063, p. 127-190.

31. Grose, L. T., and Keller, G. V., 1975, Colorado School of Mines Progress Report 4, Feb. 1, 1975 to Oct 31, 1975: Colorado School of Mines Report, National Science Foundation Grant GI43866, 109 p.

32. Hahman, W. R., Sr., Stone, Claudia, and Witcher, J. C., compilers, 1978, Preliminary map, geothermal energy resources of Arizona: Arizona Bureau of Geology and Mineral Technology Geological Survey Branch, University of Arizona, scale 1:1,000,000.

33. Hansen, B. P., Gay, F. B., and Toler, L. G., 1974, Hydrologic data of the Hoosic River basin, Massachusetts: Massachusetts Water Resources Commission Hydrologic-Data Report 15, 33 p.

34. Heindl, L. A., Cosner, O. J., and Kister, L. R., 1961, Hydrologic data and driller's logs, Papago Indian Reservation, Arizona: Arizona State Land Department Water Resources Report 9, 116 p.

35. Henry, C. D., 1977, Geologic setting and geochemistry of thermal water and geothermal assessment, Trans-Pecos, Texas: Bureau of Economic Geology, University of Texas at Austin, 135 p.

36. _____, 1978, Crustal structure deduced from geothermal studies, Trans-Pecos Texas: Conference on Cenozoic Geology of the Trans-Pecos Volcanic Field of Texas, Alpine, Texas, May, 1978, Proceedings, Bureau of Economic Geology, Austin, Texas.

37. Hewett, D. F., and Crickmay, G. W., 1937, The warm springs of Georgia, their geologic relations and origin: U. S. Geological Survey Water-Supply Paper 819, 40 p.

38. Hobba, W. A., Jr., Chemerys, J. C., Fisher, D. W., and Pearson, F. J., Jr., 1977, Geochemical and hydrologic data for wells and springs in thermal-spring areas of the Appalachians: U. S. Geological Survey Water-Resources Investigations Report 77-25, 36 p.

39. Hobba, W. A., Jr., Fisher, D. W., Pearson, F. J., Jr., and Chemerys, J. C., 1978, Hydrology and geochemistry of thermal springs of the Appalachians: U. S. Geological Survey Professional Paper 1044. (in press)

40. Hose, R. K., and Taylor, B. E., 1974, Geothermal systems of northern Nevada: U. S. Geological Survey Open-File Report 74-271, 27 p.

41. Idaho Bureau of Mines and Geology, 1978, Moscow, Idaho, unpublished data.

42. Johns Hopkins University Applied Physics Laboratory, 1978, Energy Programs: Quarterly Report, 46 p.

43. Jones, P. H., 1975, Geothermal and hydrocarbon regimes, northern Gulf of Mexico Basin, in Dorfman, M. H. and Deller, R. W., eds., First geopressured geothermal energy conference: Proceedings, University of Texas, Austin, p. 15-90.

44. Lachenbruch, A. H., 1978, Heat flow in the Basin and Range Province and thermal effects of tectonic extension: Pure and Applied Geophysics, v. 117. (in press)

45. Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, in Heacock, J. G., ed., The nature and physical properties of the earth's crust: American Geophysical Union, Geophysical Monograph series, v. 20, p. 626-675.

46. Lane, Gary, 1978, Battelle Pacific Northwest Laboratories, Richland, Washington, unpublished data.

47. Lawson, D. C., and Sonderegger, J. L., 1978, Geothermal data-base study; mine-water temperatures: Montana Bureau of Mines and Geology Special Publication 79, 38 p.

48. Leonard, R. B., Brosten, T. M., and Midtlyng, N. A., 1978, Selected data from thermal-spring areas, southwestern Montana: U. S. Geological Survey Open-File Report 78-438, 71 p.

49. Mariner, R. H., 1978, U. S. Geological Survey, Menlo Park, California, unpublished data.

50. Mariner, R. H., Presser, T. S., and Evans, W. C., 1976, Chemical characteristics of the major thermal springs of Montana: U. S. Geological Survey Open-File Report 76-480, 30 p.

51. Mariner, R. H., Presser, T. S., Rapp, J. B., and Willey, L. M., 1975, The minor and trace elements, gas, and isotope compositions of the principle hot springs of Nevada and Oregon: U. S. Geological Survey Open-File Report, 27 p.

52. Mariner, R. H., Rapp, J. B., Willey, L. M., and Presser, T. S., 1974, The chemical composition and estimated minimum thermal reservoir temperatures of principle hot springs of northern and central Nevada: U. S. Geological Survey Open-File Report 74-1066, 32 p.

53. Maxwell, James, 1978, Los Alamos Scientific Laboratory, New Mexico, written communication.

54. Miller, M. R., Hardman, G. and Mason, H. G., 1953, Irrigation waters in Nevada: University of Nevada, Reno, Agricultural Experimental Station Bulletin 187, 63 p.

55. Miller, T. P., compiler, 1973, Distribution and chemical analyses of thermal springs in Alaska: U. S. Geological Survey Open-File Report, scale 1:2,500,000.

56. Miller, T. P., and Barnes, Ivan, 1976, Potential for geothermal-energy development in Alaska--summary, in Circum-Pacific energy and mineral resources: American Association of Petroleum Geologists Memoir 25, p. 149-153.

57. Miller, T. P., Barnes, Ivan, and Patton, W. W., Jr., 1973, Geologic setting and chemical characteristics of hot springs in central and western Alaska: U. S. Geological Survey Open-File Report, 24 p.

58. Miser, H. D., and Purdue, A. H., 1929, Geology of De Queen and Caddo Gap Quadrangles of Arkansas: U. S. Geological Survey Bulletin 808, p. 182-189.

59. Mitchell, J. C., 1976, Geothermal investigations in Idaho, part 6, Geochemistry and geologic setting of the thermal and mineral water of the Blackfoot Reservoir Area, Caribou County, Idaho: Idaho Department of Water Administration Water Information Bulletin 30, 47 p.

60. Mitchell, J. C., and Johnson, L. L., 1978, Geothermal investigations in Idaho, part 9, Potential for direct applications of geothermal resources: Idaho Department of Water Administration Water Information Bulletin 30. (in press)

61. Moore, D. E., and Eakin, T. E., 1968, Ground-water appraisal Snake River tributaries, Elko and Humbolt Counties, Nevada: Nevada Department of Conservation and Natural Resources Ground Water Reconnaissance Report 48, 103 p.

62. Muffler, L. J. P., and Cataldi, R., 1978, Methods for regional assessment of geothermal resources: Geothermics, v. 7, no. 2-4. (in press)

63. Mundorf, J. C., 1970, Major thermal springs in Utah: Utah Geological and Mineral Survey Water Resources Bulletin 13, 60 p.

64. Nevada Bureau of Mines and Geology, 1978, Reno, Nevada, unpublished data.

65. Nevada Oil and Gas Conservation Commission, 1978, Reno, Nevada, unpublished data.

66. Olmsted, F. H., Glancy, P. A., Harrill, J. R., and Van Denburgh, A. S., 1975, Preliminary hydrogeologic appraisal of selected hydrothermal systems in northern and central Nevada: U. S. Geological Survey Open-File Report 75-56, 274 p.

67. Oregon Department of Geology and Mineral Industries, 1978, Portland, Oregon, unpublished data.

68. Parker, G. G., and Cooke, C. W., 1944, Late Cenozoic geology of southern Florida, with a discussion of the ground water: Florida Geological Survey Bulletin 27, 119 p.

69. Peale, A. C., 1886, Lists and analyses of the mineral springs of the United States: U. S. Geological Survey Bulletin 32, 235 p.

70. Post, E. V., 1967, Geology of the Cascade Springs quadrangle, Fall River County, South Dakota, in Geology and uranium deposits of the southern Black Hills: U. S. Geological Bulletin 1063, Chap. L, p. 443-504.

71. Price, P. H., McCue, J. B., and Hoskins, H. A., 1936, Springs of West Virginia: West Virginia Geological Survey Reports, v. 6, 146 p.

72. Rahn, P. H., and Gries, J. P., 1973, Large springs in the Black Hills, South Dakota and Wyoming: South Dakota Geological Survey Report of Investigations 107, 46 p.

73. Reeves, Frank, 1932, Thermal springs of Virginia: Virginia Geological Survey Bulletin 36, 56 p.

74. Rex, R. W., 1978, Republic Geothermal, Santa Fe Springs, California, unpublished data.

75. Romero, John, and Fawcett, Donald, 1978, Geothermal resources of south central Colorado and their relationship to ground and surface waters: Colorado Division of Water Resources Final Report to the U. S. Geological Survey (Grant no. 14-08-0001-6-330), 127 p.

76. Ross, P. P., 1978, Geothermal reconnaissance of Verde Valley, Arizona, unpublished data.

77. Ross, S. H., 1971, Geothermal potential of Idaho: Idaho Bureau of Mines and Geology Pamphlet 150, 72 p.

78. Rush, F. E., 1978, Reconnaissance of the hydrothermal resources of Utah, unpublished data.

79. Sammel, E. A., 1976, Hydrologic reconnaissance of the geothermal area near Klamath Falls, Oregon: U. S. Geological Survey Water Resources Investigations Open-File Report 76-127, 129 p.

80. Sanders, J. W., and Miles, M. J., 1974, Mineral content of selected geothermal waters: University of Nevada, Reno, Desert Research Institute, Center for Water Resources Research Project Report 26, 37 p.

81. Sass, J. H., Galanis, S. P., Jr., Munroe, R. J., and Urban, T. C., 1976, Heat-flow data from southeastern Oregon: U. S. Geological Survey Open-File Report 76-217, 52 p.

82. Schoon, R. A., and McGregor, D. J., 1974, Geothermal potentials in South Dakota: South Dakota Geological Survey Report of Investigations 110, 76 p.

83. Sonderegger, J. L., Bergantino, R. N., and Miller, M. R., 1977, Phase 0 study results; geothermal potential of the Madison Group at shallow depth in eastern Montana, final report: Montana Bureau of Mines and Geology Open-File Report 25, 8 p.

84. Stose, G. W., and Stose, A. J., 1947, Origin of the hot springs at Hot Springs, North Carolina: American Journal of Science, v. 245, no. 10, p. 624-644.

85. Summers, W. K., 1976, Catalog of thermal waters in New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 4, 80 p.

86. Swanberg, C. A., 1978, Geothermal resources of New Mexico: New Mexico Energy Institute, Las Cruces, New Mexico. (in press)

87. Swanberg, C. A., Morgan, Paul, Stoyer, C. H., and Witcher, J. C., 1977, An appraisal study of the geothermal resources of Arizona and adjacent areas in New Mexico and Utah and their value for desalination and other uses: New Mexico Energy Institute Report 6, Las Cruces, New Mexico, 76 p.

88. Taylor, F. B., 1915, Berlin-Graylock Folio: U. S. Geological Survey, Geologic Division, Denver, Co., unpublished folio in Field Records File.

89. Thomas, Donald, 1978, Hawaii Institute of Geophysics, Honolulu, Hawaii, unpublished data.

90. Turner, D. L., and Forbes, Robert, 1978, University of Alaska, Fairbanks, Alaska, unpublished data.

91. Tshanz, C. M., 1978, U. S. Geological Survey, Denver, Colorado, unpublished data.

92. U. S. Bureau of Reclamation, 1972, An appraisal of geothermal resources in the Mid-Pacific Region: U. S. Department of the Interior, Bureau of Reclamation Report, 67 p.

93. U. S. Geological Survey, 1978, Water Resources Division, Bismarck, North Dakota, unpublished data.

94. _____, 1978, Water Resources Division, Boise, Idaho, unpublished data.

95. _____, 1978, Water Resources Division, Helena, Montana, unpublished data.

96. _____, 1978, Water Resources Division, Las Cruces, New Mexico, unpublished data.

97. _____, 1978, Water Resources Division, Little Rock, Arkansas, unpublished data.

98. _____, 1978, Water Resources Division, Tacoma, Washington, unpublished data.

99. U. S. Navy, 1978, Hawthorn Navy Ammunition Depot, Hawthorn, Nevada, unpublished data.

100. Van Denburgh, A. A., and Rush, F. E., 1974, Water resources appraisal of Railroad and Penoyer Valleys, east-central Nevada: Nevada Department of Conservation and Natural Resources, Water Resources Reconnaissance Service Report 60, 61 p.

101. Van Ostrand, C. E., 1928, On the nature of isogeothermal surfaces: American Journal of Science, 5th series, v. 15, p. 495-519.

102. Various authors, 1976, Geothermal investigations of the U. S. Geological Survey in Long Valley, California, 1972-73: Journal of Geophysical Research, v. 81, p. 721-860 and 1527-1532.

103. Washington Department of Natural Resources, 1978, Division of Geology and Earth Science, Olympia, Washington, unpublished data.

104. White, D. E., 1955, Thermal springs and epithermal ore deposits: Economic Geology, 50th Ann. Vol., p. 100-154.

105. White, D. E., Hem, J. D., and Waring, G. A., 1963, Chemical composition of sub-surface waters: U. S. Geological Survey Professional Paper 440-F, 67 p.

106. Wollenberg, H. A., Asaro, F., Bowman, H., McEvilly, T., Morrison, F., and Witherspoon, P., 1975, Geothermal energy resource assessment: University of California, Lawrence Berkeley Laboratory Report VCID-3762, U. S. ERDA Contract No. W-7405-ENG-48, 92 p.

107. Woodruff, C. M., Jr., 1978, Regional assessment and prospective site analysis of geothermal potential along the Balcones, Luling-Mexia-Talco Systems, central Texas: Texas Bureau of Economic Geology, University of Texas, Austin, Quarterly Report to the Department of Energy, April-June, 1978, 12 p.

108. Young, H. W., 1977, Reconnaissance of ground water resources in the Mountain Home Plateau Area, Southwest Idaho: U. S. Geological Survey Water Resources Investigations Open-File Report 77-108, 40 p.

109. Young, H. W., and Mitchell, J. C., 1973, Geothermal investigations in Idaho, part I, Geochemistry and geologic setting of selected thermal waters: Idaho Department of Water Administration Water Information Bulletin 30, 43 p.

110. _____, 1978, Idaho Department of Water Resources, Boise, Idaho, unpublished data.

111. Briggs, P. C., 1969a, Ground-water conditions in McMullen Valley, Maricopa, Yuma, and Yavapai Counties, Arizona: Arizona State Land Department Water Resources Report 40, 31 p.

112. _____, 1969b, Ground-water conditions in the Ranegras Plain, Yuma County, Arizona: Arizona State Land Department Water Resources Report 41, 28 p.

113. Dondanville, R. F., 1978, Geologic characteristics of the Valles Caldera geothermal system, New Mexico: Geothermal Resources Council Transactions, v. 2, sect. 1, p. 157-159.

114. McLean, J. S., 1970, Saline ground-water resources of the Tularosa Basin, New Mexico: Office of Saline Water Research and Development Programs Report 561, 128 p.

115. Moyle, W. R., Jr., 1978, unpublished data.

116. Trainer, F. W., 1975, Mixing of thermal and non-thermal waters in the margin of the Rio Grande Rift, Jemez Mountains, New Mexico: New Mexico Geological Society Guidebook to the Las Cruces Country, New Mexico, p. 213-218.

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Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered			Thermal springs		Thermal gradients[b]	Equilibration temperature[c]
	No.	Depths (m)	Temperature (°C)	No.	Temperature (°C)	(°C/km)	(°C)
							*A L A
North Slope	*>17	---	---	2	32, 49	37-45	**90
Seward Peninsula - Interior Alaska	--	---	---	25	15-77	30-50	*84-137
Alaska Peninsula - Aleutian Islands	4	3,830-4,381	122-206	7	6-104	31-47	*106-182
Cook Inlet	12	632-3,291	32-96	1	---	38-123	---
Southeast Alaska	--	---	---	10	39-85	---	*120-165
							A R I
1. Yucca	2	112, 306	27, 34	--	---	45	*80
2. Chambers	6	280-365	32-47	--	---	66-99	---
3. Verde Valley	40	10-175	16-30	3	20-40	200	*60-141
4. McMullen Valley	9	---	30-40	--	---	23-49	*50-100
5. Ranegras	8	24-385	27-35	--	---	32-58	*50-100
6. Harquahala-Tonopah	30	63-244	30-50	--	---	80-422	*65
7. Hyder	20	56-387	30-50	--	---	60-218	*80
8. Phoenix-Chandler	60	66-458	30-75	--	---	61-305	*80-90
9. Cotton Center	4	137-156	30-36	--	---	80-105	*68-83

temperature (<90°C) geothermal water in Western United States, including Alaska and Hawaii

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
S K A	
	*Information on geothermal waters is tabulated below for regions of Alaska. No map depiction of favorable areas has been attempted on the basis of data currently available.
---	*Oil and gas wells; data available but not compiled. **Na-K-Ca geothermometer on Okpilak Spring. References: 8, 90
250-6,000	At least 40 thermal springs in a 1,000 km east-west zone of volcanic and metamorphosed crystalline terranes. Generally associated with faults and fractures at the contacts between granitic plutons. Area contains 6 identified high-temperature spring systems. Most springs assumed to represent shallow systems of limited extent. *Various geothermometers. References: 8, 57, 90
350-3,500	At least 38 thermal springs, most of them closely related to Pleistocene and Holocene volcanic centers. Area contains 19 identified high-temperature spring systems. Wells are oil and gas tests with calculated thermal gradients as shown. *Various geothermometers, high-temperature systems. References: 8, 56, 90
saline	Wells are oil and gas tests with calculated thermal gradients as shown. Spring, Hot Lake, at Crater Peak. Deep well waters are saline. Deep sedimentary basin. References: 55, 90
270-5,000	At least 23 thermal springs, many associated with fractured granitic plutons. Some late Cenozoic volcanic rocks occur, apparently unrelated to thermal springs. *Various geothermometers for 7 identified high-temperature spring systems. References: 8, 55
Z O N A	
280-420	Deep circulation. *Average of several geothermometers. References: 32, 87
3,000	Deep circulation beneath shallow sedimentary basin. Aquifers in alluvium. References: 32, 87
100-3,800	Deep circulation along faults. Dissolved solids to 90,000 mg/L in evaporite horizons. *Average of Na-K-Ca and quartz geothermometers. References: 32, 49, 76, 87
200-350	Deep circulation. Aquifers in Tertiary and Quaternary alluvium. *Na-K-Ca and silica geothermometers. References: 32, 87, 111
460-3,700	Deep circulation. Aquifers in Tertiary and Quaternary alluvium. *Na-K-Ca and silica geothermometers. References: 32, 87, 112
400-1,100	Deep circulation. Aquifers in alluvial and lacustrine deposits. Area contains W-C Maricopa State KGRA. *Na-K-Ca geothermometer, Tonopah well. References: 32, 87
270-3,000	Deep circulation. Aquifers in Tertiary and Quaternary alluvium. Area contains Agua Caliente Spring (now dry), and Gila River State KGRA. *Average, Na-K-Ca and Quartz geothermometers. References: 32, 87
500-4,000	Deep circulation. Aquifers in basin-fill sediments. Heat flow 144 mW/m^2 at places. May be heat contribution from exothermic reactions in evaporite deposits. Area contains Buckhorn-Higley State KGRA. *Na-K-Ca geothermometers; indicated temperature 200°C for some wells. References: 32, 87
1,800-3,300	Deep circulation. Aquifers in basin-fill sediments. Heat flow 100 mW/m^2. *Na-K-Ca and quartz geothermometers agree. References: 32, 87

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Depths (m)	Temperature (°C)	Thermal springs No.	Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
							A R I
10. Gila Bend	50	40-532	26-48	--	---	32-204	*53-102
11. Maricopa	9	15-184	25-40	--	---	70-230	---
12. Coolidge - Casa Grande	14	30-824	30-75	--	---	61-200	*45-99
13. Avra Valley	20	20-610	30-45	--	---	35-390	*50-150
14. Gu Oidak	8	36-214	34-36	--	---	60-450	*70-90
15. Kom Vo	3	128-218	40-50	--	---	117-208	*51-114
16. Tucson	15	49-244	30-41	--	---	36-106	*55-70
17. Clifton	--	---	---	6	30-82	---	*31-164
18. Safford - Bowie	30	10-1,149	20-75	5	33-47	36-175	*70-116
19. Willcox	7	19-235	20-37	--	---	90-550	*126
20. San Pedro Valley - Hooker Hot Spring	6	16-453	31-42	2	55	82-410	*66
						C	A L I F
1. Surprise Valley	4	60-655	40-139	10	21-86	40-80	*111-160
2. Kelly Hot Springs	8	60-977	27-110	3	27-33	120	*117
3. Susanville	2	90, 180	36, 49	--	---	High	*100-110
4. Sierra Valley	10	7-335	39-94	1	30	140-250	---

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
Z O N A	
925-2,105	Deep circulation. Aquifers in alluvium. *Quartz and Na-K-Ca geothermometers. References: 32, 87
200-15,000	Deep circulation. Aquifers in basin-fill sediments. References: 32, 87
550-3,000	Deep circulation. Aquifers in basin-fill sediments. Quartz and Na-K-Ca geothermometers. References: 32,87
200-725	Deep circulation. Aquifers in basin-fill sediments. Area contains Roskruge Mountain State KGRA. *Quartz geothermometers. References: 32, 87
200-500	Deep circulation. Aquifers in basin-fill sediments. *Quartz geothermometers. Reference: 34
325-475	Deep circulation along fault. Aquifers in basin-fill sediments. *Quartz geothermometers. Reference: 34
300-1,200	Deep circulation along faults. Aquifers in basin-fill sediments. *Average of Na-K-Ca and quartz geothermometers. References: 19, 87
380-14,550	Deep circulation along fault, with high(?) radiogenic heat production. Water from Precambrian intrusions, Paleozoic sedimentary and Tertiary volcanic rocks, and alluvium. Area contains Clifton and Gillard Hot Springs (KGRA's). *Highest equilibration temperature from spring north of Clifton Hot Springs; Quartz geothermometer, mixing model. References: 8, 87
250-8,300	Deep circulation. Aquifers in Tertiary alluvial and lacustrine deposits. *Quartz geothermometer. Possible heat contribution from exothermic reactions in evaporite deposits. Reference: 87
100-106,000	Deep circulation. Aquifers in Tertiary alluvial and lacustrine deposits. Area contains Willcox State KGRA. *Quartz geothermometer. Reference: 87
90-9,200	Deep circulation. Aquifer: fractured granite. *Chalcedony geothermometer (Hooker Hot Springs). References: 49, 87
O R N I A	
350-1,200	Deep circulation in Surprise Valley fault zone with possible magmatic source at depth. Aquifers in valley-fill deposits; thermal waters may originate in Miocene volcanic rocks of the Cedarville Series. Includes Lake City KGRA, Surprise Valley high-temperature system. *Quartz, chalcedony, and Na-K-Ca geothermometers. Reference: 10
900-1,200	Deep circulation in Likely fault and associated fault zones. Aquifers in Pliocene and Pleistocene volcanic rocks and lake sediments, and the Miocene Cedarville Series of Russell (1928). Includes Kelly Hot Spring (92°C) high-temperature system. *Na-K-Ca geothermometer (Kelly Hot Springs). References: 8, 10
200-600	Deep circulation in fault zones. System appears to be unrelated to nearby Wendell-Amedee Hot Springs. *Quartz geothermometer. Reference: 10
800-1,500	Deep circulation in Hot Springs fault. Aquifers are permeable zones in lake-bed sediments and late Tertiary volcanic rocks. Includes Beckworth KGRA. Reference: 10

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Wells considered Depths (m)	Wells considered Temperature (^{o}C)	Thermal springs No.	Thermal springs Temperature (^{o}C)	Thermal gradients[b] ($^{o}C/km$)	Equilibration temperature[c] (^{o}C)
						C A	L I F
5. Lovelady - Wilbur Hot Springs	--	---	---	7	27-67	---	*141
6. The Geysers	--	---	---	--	---	---	---
7. Bridgeport	2	281, 299	50	3	35-65	134, 143	*108
8. Mono Lake	2	245, 743	53, 58	5	33-95	34, 106	*80
9. Long Valley	--	---	---	25	34-90	---	---
10. Paso Robles	4	<300	? -47	3	35-50	90	---
11. Tecopa	1	122	48	5	27-43	230	
12. Trona	4	92-182	30-58	1	33	133, 209	---
13. Imperial - Coachella Valleys	--	---	---	--	---	---	---
14. Ocotillo Hot Spring	8	45-365	31-39	--	---	53-360	---
						C	O L O
1. Routt - Steamboat Hot Springs	--	---	---	3	20-64	---	*71, 131
2. Glenwood Canyon	--	---	---	4	32-51	---	?
3. Cement Creek - Ranger Springs	--	---	---	2	25, 27	---	*25-32

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
O R N	I A
---	Includes Lovelady Ridge KGRA, Wilbur Hot Springs high-temperature system. *Na-K-Ca geothermometer, Wilbur Hot Springs. References: 8, 10
---	The Geysers region contains many hot springs issuing from hot-water systems that are not contained within the vapor-dominated field. The area depicted on the map generally encloses these springs. Reference: 10
3,000-4,500	Deep circulation in Pliocene caldera. Aquifer: fractured volcanic rocks. *Chalcedony geothermometer. Reference: 10
1,200-26,000	Deep circulation in region of young silicic volcanism. High-salinity waters probably mixed with Mono Lake water. Includes Mono Lake KGRA. *Chalcedony geothermometer. References: 10, 49
~1,400	Long Valley KGRA. Low-temperature thermal waters at depths less than 1 km in the Long Valley geothermal system generally are mixtures of deep thermal waters and shallow meteoric waters. Consult the reference for detailed studies and data. Reference: 102
610	Deep circulation in Pliocene and (or) Pleistocene continental sediments (Paso Robles Formation). Reference: 10
---	Deep circulation along Basin and Range faults. Aquifers in valley-fill deposits. Reference: 10
Briny	Deep circulation in Basin and Range faults(?). Water from playa sediments mined for salts. Reference: 10
---	A vast low-temperature geothermal resource is believed to be present in a continuous zone extending from the north end of the Coachella Valley (Desert Hot Springs area) to the Mexican border. Within this area are the Salton Sea, Brawley, Glamis, East Mesa, Heber, and Dunes KGRA's, all containing high-temperature resources. The resource, except for that in the Coachella Valley, is described in a voluminous literature. In the Coachella Valley, 14 wells <150 m deep have temperatures ranging from 39° to 98°C. Dissolved solids range from 290 to 1,290 mg/L (Moyle, 1974). The source of heat is assumed to be deep circulation in faults lying between the San Andreas and San Jacinto fault zones, with a probable magmatic source at depth. Reference: 115
---	Deep circulation in San Jacinto fault zone. Reference: 74
R A D	O
500-6,200	Deep circulation in faults along the Park Range. Aquifers in Dakota Fm. (Cretaceous) and Browns Park Fm. (Tertiary). *Steamboat Springs (chalcedony) and Routt Hot Springs (quartz). References: 3, 8
750-21,500	Deep circulation either stratigraphically or fault controlled. Aquifers: Mississippian Leadville Ls. (Glenwood, Dotsero Springs), Cretaceous Dakota Fm. (South Canyon Hot Springs). Geothermometers unreliable; probably low equilibration temperature. Reference: 3
375-500	Deep circulation in faults and fractures in Precambrian granitic rocks (Cement Creek) and Cambrian to Mississippian limestones (Ranger). *Chalcedony geothermometer. High CO_2 contents. Reference: 3

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered			Thermal springs		Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
	No.	Depths (m)	Temperature (°C)	No.	Temperature (°C)		
						C	O L O
4. Dunton - Rico Hot Springs	--	---	---	4	28-46	---	*58
5. Pinkerton - Tripp Hot Springs	--	---	---	4	32-44	---	*35-65
6. Pagosa Springs	3	175-915	39-70	2	27, 54	120	*79
7. Rio Grande Rift	10	15-2,890	20-128	32	18-84	25-49	*40-148
8. Canyon City	2	550-	28, 35	1	40	42, 55	---
							H A W
Kauai Island	14	<280	22-28	--	---	---	---
Oahu Island	13	<300	25-30	--	---	---	---
Maui Island	11	<250	20-33	--	---	---	---
Hawaii Island	36	<400	18-93	1	33	---	---
							I D
1. Lochsa	--	---	---	4	40-48	moderate	*70
2 Salmon River, Middle Fork	--	---	---	22	35-88	moderate	*90-97
3. Stanley - Challis	--	---	---	6	38-76	25->100	*55-130

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
R A D	O
1,260-6,500	Deep circulation in faults; complex relations of late Paleozoic and Mesozoic rocks. Rico "springs" are abandoned drill holes. *Na-K-Ca geothermometer (Rico area). References: 3,8
3,200-4,000	Deep circulation in faults, probably in sediments and evaporite deposits of the Hermosa Formation (Pennsylvanian). *Geothermometers unreliable; equilibration temperatures probably in this range. Reference: 3
100-3,300	Deep circulation. At least 10 geothermal wells used in Pagosa Springs; local heat flow ~ 200 mW/m^2. Aquifers in Mancos Shale; reservoir may be in Precambrian rocks. *Chalcedony geothermometer (Pagosa Springs). References: 3, 8
96-4,070	Deep circulation in faults and fractures in Precambrian basement rocks and overlying valley fill (San Luis Valley); in Arkansas Valley, Tertiary igneous and sedimentary rocks and Precambrian granites. Includes Alamosa, Mineral Hot Springs., Poncha, and Valley View KGRA's; Mt. Princeton, Poncha, and Wagon Wheel Gap Hot Springs, and Sand Dune, Splashland, and Mapco #1-32 wells high-temperature systems. Numerous water wells in San Luis Valley <1 km deep have temperatures from 20° to 60°C. Heat flow generally 80-110 mW/m^2. Includes Ojo Caliente, Mamby's and Ponce de Leon Hot Springs areas in New Mexico. *Various geothermometers. References: 3, 8, 75
1,200-1,500	Probably deep circulation in Mississippian Leadville Limestone. Geothermometers not reliable, but probably low equilibration temperature. Reference: 3
A I I	
175-750	Wells in coastal areas, generally associated with volcanic rifts or calderas. Anomalous silica concentrations in these and other nonthermal wells nearby may indicate the presence of thermal anomalies in the Wailua and Nohili Point areas. Reference: 89
140-800	Wells in coastal areas, generally associated with volcanic rifts or calderas. Anomalous silica concentrations and temperatures suggest the presence of a thermal anomaly on the western cape of the island, in and near Waianae caldera. Reference: 89
120-2,000	Wells in coastal areas, generally associated with volcanic rifts. Anomalous silica concentrations and temperatures suggest the presence of a thermal anomaly on the western cape near Lahaina. Reference: 89
90-8,000	Wells and spring in coastal areas, associated with volcanic rifts. Anomalous temperatures and silica concentrations suggest the presence of geothermal anomalies in the Kawaihae area and the Puna area, where a high-temperature source is being developed. Anomalous silica concentrations may indicate a thermal anomaly in the Ka'u area. Reference: 89
A H O	
135-380	Deep circulation, fault controlled, in region of high heat flow in Idaho batholith. Large-scale convection system in fractured, altered Cretaceous granitic rocks. *Chalcedony geothermometer. Reference: 109
200-640	Deep circulation in Idaho batholith as described above. Includes Indian Creek Hot Springs, possible high-temperature system. *Na-K-Ca, chalcedony geothermometers. Reference: 11
120-600	Deep circulation along structural trend in Idaho batholith. Includes Sunbeam Hot Springs high-temperature system. *Various geothermometers. References: 41, 60, 109

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Wells considered Depths (m)	Wells considered Temperature (°C)	Thermal springs No.	Thermal springs Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C) I D
4. Warm Lake	--	---	---	7	55-87	moderate	*62-148
5. Payette River Springs	--	---	---	24	39-85	---	*60-148
6. Boise River, Middle Fork	--	---	---	19	37-76	---	*75, 100
7. Pine - Featherville	2	25, 90	41	4	53-56	---	*56, 99
8. Ketchum	--	---	---	2	62, 71	---	*85
9. South western Idaho	--	---	---	--	---	---	---
Council - Cambridge	>15	~300	20-65	4	25-70	---	*70-85
Boise Front	25	122-460	20-76	--	---	70-100	*79
Nampa - Caldwell	8	46-131	20-51	--	>20	70-100	*36, 70
*Mountain Home	10	53-184	20-32	--	---	40-100	**65
Hollister City	3	---	35-38	1	36	50-100	*80
Artesian City	3	100-500	20-38	--	---	50-100	*75
10. Camas Prairie	6	58-122	21-72	5	32-72	100	*90-100
11. Newdale	7	80-140	21-36	--	---	~100	*75
12. Blackfoot Reservoir	5	120-210	23-42	6	23-28	---	*50
13. Pocatello	5	22-177	20-41	1	20	---	*60

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
A H O	
200-360	Deep circulation, Idaho batholith. Includes Vulcan Hot Springs KGRA (high-temperature system). *Various geothermometers. References: 60, 91, 109
200-350	Deep circulation, Idaho batholith. Includes Bonneville, Payette River, and unnamed hot springs high-temperature systems. *Various geothermometers. References: 60, 77, 109
200-270	Deep circulation, Idaho batholith. *Na-K-Ca, chalcedony geothermometers, respectively, for 3 springs. Reference: 60
200	Deep circulation, Idaho batholith. *Na-K-Ca geothermometers. Reference: 60
200, 325	Deep circulation, structural control. Aquifers in Paleozoic sediments. *Na-K-Ca geothermometer. Reference: 110
---	Comprises most of the western Snake River Plain, parts of the Idaho batholith, and the Weiser River valley. Includes Crane Creek, Weiser, Castle Creek, Mountain Home, Bruneau, and Raft River KGRA's; Banbury Hot Springs, Raft River, Chalk Mine-White Arrow-Radio Tower, Bruneau-Grandview, Crane Creek, White Licks, and Krigbaum high-temp. systems. Subareas especially favorable for low-temperature sources are listed below. (Subareas not outlined on map of western states.)
250-670	Source of heat uncertain. Aquifers in Columbia River basalt Group, alluvial cover in the Weiser River valley. *Chalcedony, Na-K-Ca geothermometers. Reference: 110
190-800	Snake River Plain along margin of Idaho batholith, vicinity of Boise. Deep circulation, structural control. Aquifers in upper Pliocene and lower Pleistocene(?) Glenns Ferry Fm.; thermal water probably from Idaho batholith. *Na-K-Ca geothermometer. References: 94, 110
145-385	Snake River Plain, west of Boise. More than 30 thermal wells, depths <300 m. Source of heat uncertain. *Chalcedony, Na-K-Ca geothermometers. References: 60, 94
230-490	Snake River Plain, southeast of Boise. Aquifers in Tertiary to Quaternary basaltic rocks and sediments. *Area does not contain Mountain Home KGRA. **Chalcedony, Na-K-Ca geothermometers. Reference: 108
200-470	Snake River Plain south of Twin Falls. About 8 wells are anomalously warm. *Na-K-Ca geothermometer. Reference: 110
180-460	Central Snake River Plain. Declared critical ground-water area by state. Contains ~30 thermal wells. *Chalcedony, Na-K-Ca geothermometers. References: 77, 109
160-1,000**	Deep circulation, structural control. Aquifers in Quaternary valley-fill deposits overlying Cretaceous granitic rocks, margin of Idaho batholith. Includes Barrons, Wardrop Hot Springs, Magic Reservoir well, high-temperature systems. *Chalcedony geothermometer. **Dissolved solids, Magic Reservoir well. References: 8, 60
170-380	Deep circulation in fault zones. Aquifers: late Pleistocene Huckleberry Ridge Tuffo. *Chalcedony, Na-K-Ca geothermometers. References: 60, 94
880-3,500	Heat source young (<100,000 yrs.) rhyolitic intrusions. Aquifers in Paleozoic and young volcanic rocks. *Chalcedony geothermometer (ave.). References: 59, 94
660-710	Deep circulation in inferred fault. Aquifers: alluvial deposits overlying basalt(?). *Chalcedony geothermometer. Reference: 109, 110

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Wells considered Depths (m)	Wells considered Temperature (°C)	Thermal springs No.	Thermal springs Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
							M O N
1. Little Bitterroot	1	74	51	3	~45	30	*51-73
2. Little Rockies	--	---	---	9	22-32	---	---
3. Warner - Plunket's Springs	--	---	---	2	18, 23	---	---
4. Warm Springs	--	---	---	1	77	---	*77
5. Pipestone Hot Springs	--	---	---	1	57	---	*89
6. Silver Star Hot Springs	--	---	---	1	77	---	*135
7. Bozeman	1	138	48	1	~55	---	*85
8. Jackson	--	---	---	1	58	---	*72
9. Pullers	--	---	---	1	44	---	*52
10. Ennis Hot Spring	8	33-130	15-90	1	83	56-100	*135
11. Lovell-Brown	--	---	---	3	19-24	---	---
12. West Fork Madison	--	---	---	2	29, 30	---	*73, 77
13. Lower Red Rock Lake	--	---	---	2	23, 31	---	*34, 52
14. Upper Red Rock Lake	--	---	---	?	23	---	---
							N E V
1. Vya	--	---	---	7	23-28	---	---

temperature ($<90^{\circ}$C) geothermal water in Western United States, including Alaska and Hawaii--Continued

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
T A N A	
270-410	Deep circulation in valley-boundary faults. Area includes Camas Hot Springs. *Chalcedony and Na-K-Ca geothermometers. Reference: 95
1,000-1,800	Deep circulation in fault zones. Springs issue from rocks of Madison Group in three major areas. References: 47, 83
150-500	Deep circulation in fault zones. Springs issue from rocks of Madison Group. Scattered irrigation wells have above-normal water temperatures. Reference: 83
1,250	Deep circulation in fault zones. Water may have limestone source. *Chalcedony and Na-K-Ca geothermometers. References: 48, 50, 83
350	Deep circulation in fault zones. *Chalcedony and Na-K-Ca geothermometers. References: 48, 50
600	Deep circulation in fault zones. Reported thermal well east of springs; thermal springs in Jefferson River. Silver Star Hot Springs is high-temperature hydrothermal system. *Quartz and sulfate-oxygen geothermometers. References: 48, 50
425	Deep circulation in fault zones. *Chalcedony and Na-K-Ca geothermometers References: 48, 50
670	Deep circulation in fault zones. Reportedly warm well at Ranch Station; reported snow-free area may extend 25 miles to north. *Chalcedony geothermometer. References: 48, 50
1,200	Deep circulation in fault zones. *Chalcedony geothermometer. References: 48, 50
*800	Deep circulation in fault zones. Additional warm wells reported. Ennis Hot Spring is high-temperature hydrothermal system. *Based on analysis of spring water; quartz geothermometer. References: 48, 50
~500	Deep circulation in fault zones. Springs issue from aquifer in Madison Group, locally overlain by volcanic rocks and alluvium. Reference: 83
180-260	Springs issue from Tertiary volcanic rocks and alluvial deposits. *Chalcedony and Na-K-Ca geothermometers, one spring. Reference: 83
400	Deep circulation in fault zones. Seven spring orifices occur in 1½ km zone. Source of water possibly in Madison group. *Chalcedony and Na-K-Ca geothermometers, one spring. Reference: 83
---	Deep circulation in fault zones. Thermal springs in and near lake. Possible 5°C change in temperature from south to north across lake following structural trend. Reference: 83
	Note: Several of the geothermal sources in southwest Montana that are shown on map 1 only by spring symbols may represent more extensive geothermal reservoirs. For example, Boulder, New Biltmore, White Sulfur and La Duke springs, which issue from fractured crystalline or sedimentary rocks, may represent convective hot-water systems that extend into adjacent valley-fill deposits. Lack of data precludes depiction of the areal extent of these and possibly other geothermal systems on the map.
A D A	
---	Deep circulation in fault zones. Reference: 64

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Wells considered Depths (m)	Wells considered Temperature (°C)	Thermal springs No.	Thermal springs Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
							N E V
2. Bog - Baltazor Hot Springs	2	---	30, 90	4	30-90	---	*162
3. McDermitt	3	135-182	48-60	--	---	High	---
4. Jackpot	1	38	38	4	25-64	---	*100
5. Smoke Creek and Black Rock Deserts	4	<1,000	37-96	28	21-95	---	*127-185
6. Winnemucca - Golconda	--	---	---	6	28-58	---	*86
7. Wells	--	---	---	4	38-51	---	*143
8. Elko - Carlin	--	---	---	6	37-96	---	*84
9. Pyramid Lake	3	---	44-94	3	45-95	*63	**115
10. Carson Desert - Brady's Hot Spring - Hazen	3 2	<300 <1,000	88-166 168-199	2	88-90	*75	**198
11. Buffalo Valley - Dixie Valley	--	<300	20-25	10	48-95	moderate	**145
12. Cresent Valley - Beowawe	1	<300	74	7	51-98	High	*226
13. Sulfur Springs	--	---	---	5	35-79	---	*181
14. Steptoe Valley	--	---	---	5	25-89	*64	---
15. Sierran Front	42	<1,000	40-87	7	47-71	High	*207
16. Yerington - Mason Valley - Smith Valley	1	<300	47	2	61, 62	---	*139
17. Hawthorne	10	<300	24-51	--	---	---	---
18. Gabbs	5	<300	21-68	--	---	High	---

temperature (<90°C) geothermal water in Western United States, including Alaska and Hawaii--Continued

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
A D A	
200-600	Deep circulation in fault zones. Area includes Baltazor KGRA. *Quartz geothermometer, Baltazor Hot Springs. References: 51, 52, 80
Low	Wells at Cordero mercury mine. Reference: 104
<300	Deep circulation in fault zones. *Na-K-Ca and chalcedony geothermometers, Mineral Hot Spring. References: 54, 61
1,400-4,000	Deep circulation, possible magmatic source at great depth. Shallow system occurs in Lake Lahontan sediments of low permeability. Area includes 8 KGRA's: Double Hot Springs, Fly Ranch, Fly Ranch N.E., Gerlach, Gerlach N.E., Pinto Hot Springs, San Emidio Desert, and Trego. *Quartz geothermometer, high-temperature springs. References: 31, 51, 52
---	Deep circulation in fault zones. *Na-K-Ca geothermometer, Golconda Hot Spring. References: 51, 52
1,000-2,000	Deep circulation in fault zones. *Quartz geothermometer, unnamed spring near Wells. References: 51, 52
500-2,000	Deep circulation in fault zones. Area includes Elko Hot Springs KRGA. *Chalcedony geothermometer, Hot Hole (Elko Hot Spring). References: 21, 51, 52
<1,000-5,000	Deep circulation in fault zones. *Gradient from 1,220-m well. **Chalcedony geothermometer, The Needles. Reference: 66
2,000-7,500	Deep circulation, possible residual heat from Holocene basaltic intrusions. Area includes Brady-Hazen, Stillwater-Soda Lake, and Salt Wells KGRA's. *Conductive thermal gradient in Carson Sink; high convective gradients elsewhere. **Quartz geothermometer, Brady's Hot Spring. References: 40, 66
900-2,000	Deep circulation in fault zones. Includes Dixie Valley KGRA. *Na-K-Ca and Quartz geothermometers, Dixie Hot Spring. References: 51, 52
1,100-1,300	Deep circulation in fault zones. Includes Beowawe, Hot Springs Point KGRA's. *Quartz geothermometer, Beowawe Hot Spring. References: 51, 52, 106
300-450	Deep circulation in fault zones. Spring flows >375 L/s from lower Paleozoic carbonate rocks. *Na-K-Ca geothermometer, Sulfur Hot Spring. References: 51, 52
<500	Deep circulation in fault zones. Includes Monte Neva KGRA. *Gradient from 2,562-m test well. References: 40, 51, 52
150-1,100	Deep circulation in range faults, possible magmatic sources. Hot waters in Comstock District deep mines. Includes Moana Springs and Steamboat Springs KGRA's; Walleys, Lawton, and Bowers Mansion Hot Springs. *Na-K-Ca geothermometer, Steamboat Springs. References: 14, 105
300-400	Includes Wabuska and Wilson Hot Springs KGRA's. *Quartz geothermometer, Wabuska Hot Springs. References: 27, 51, 52
600-1,000	Deep circulation in fault zones. References: 23, 99
---	Deep circulation in fault zones. Reference: 20

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Depths (m)	Temperature (°C)	Thermal springs No.	Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
							N E V
19. Northern Big Smokey Valley	1	60	29	6	22-95	---	*132
20. Diana's Punch Bowl	--	---	---	4	45-59	---	*86
21. Little Fish Lake Valley	--	---	---	2	40, 42	---	---
22. Hot Creek Valley	1	---	33	12	21-72	---	*80
23. Railroad Valley	2	<1,000	21, 60	14	22-71	---	---
24. Fish Lake Valley	?	<300	23-27	--	---	~50	---
25. Sarcobatus Flats - Beatty	5	---	---	12	22-43	near normal	---
26. Yucca Flat	2	518, 571	37, 42	--	---	40-50	---
27. Amargosa Desert	>100	46-1,000	22-25	--	20-34	sl. above normal	---
28. Las Vegas Valley	40	<300	21-41	--	---	---	---
						N E	W M
1. Mancisco Mesa	11	117-2,055	27-72	--	---	*64	---
2. Jicarilla Apache Reservation	35	666-4,115	41-98	--	---	*71	---
3. Little Blue Mesa	2	304-686	32-48	--	---	70	---
4. Valles Caldera	12	780-2,125	120-240	6	32-76	very high	---
5. Crownpoint - White Mesa	8	271-904	28-56	--	---	*52-59	---
6. San Ysidro	2	167-?	46	3	25-45	---	---
7. Socorro	1	81	33	3	35	---	---
8. The Meadows - Gila Hot Springs	--	---	---	9	27-66	---	*77
9. Cliff	2	11-91	30-33	1	25	---	---

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
A D A	
350-800	Includes Darrough Hot Springs KGRA; Spencer's Hot Springs. *Quartz geothermometer, Darrough Hot Springs. References: 25, 92
400-450	Deep circulation in fault zones. *Na-K-Ca geothermometer, Diana's Punch Bowl. References: 51, 52
200-300	Deep circulation in fault zones. Reference: 25
150-850	Deep circulation in fault zones. Includes Warm Springs KGRA. *Chalcedony geothermometer, Warm Springs. References: 51, 52, 80
400-900	Deep circulation in subsurface faults. References: 25, 100
700-2,500	Reference: 65
300-600	Reference: 12
250-650	Deep circulation in fault zones. Reference: 27
---	Deep circulation in fault zones. Reference: 27
250-500	Deep circulation in fault zones. Reference: 27
E X I	C O
---	Deep circulation. Aquifers in Late Cretaceous and early Tertiary sedimentary rocks. Major oil and gas field. *From 4 wells <1 km deep. Reference: 13
---	Deep circulation. Aquifers in Tertiary sedimentary rocks. Major oil and gas field. *From 6 wells <1 km deep. Reference: 13
---	Deep circulation. Aquifers in early Tertiary sedimentary rocks. Reference: 13
5,000	Low-temperature waters in Quaternary tuffaceous and rhyolitic rocks in association with high temperature resource. KGRA. References: 86, 113
---	Deep circulation. Aquifers in Cretaceous shales and sandstones, Mesaverde Group. *Measured in 5 wells. References: 13, 85, 86
---	Deep circulation. Reference: 116
*230	Deep circulation in fault zone. Aquifers probably in Tertiary volcanic rocks. KGRA. *Water from Socorro Gallery. Reference: 85
150-450	Deep circulation in area of Tertiary and Quaternary sedimentary rocks, basaltic lavas, and rhyolitic tuffs. Area contains Gila Hot Springs KGRA. *Na-K-Ca geothermometer. References: 49, 85
500	Deep circulation. Aquifers: Gila Conglomerate, Holocene alluvium, and terrace gravels. Reference: 85

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Wells considered Depths (m)	Wells considered Temperature (°C)	Thermal springs No.	Thermal springs Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
						N E	W M
10. Rio Grande Rift	15	<320	25-71	2	34, 52	---	*96
11. North Animas Valley	4	29-147	27-35	--	---	---	---
12. Lightning Dock	2	25	99	--	---	---	*157
13. Southern Tularosa Basin	2	133-227	50-71	--	---	190-400	---
							O R E
1. Belknap - Foley Hot Springs	2	~150	14, 22	3	61-89	85, 92	*107
2. Willamette Pass	2	150	15, 21	3	41-71	80	*97
3. Craig Mountain - Cove (La Grande)	5	45-885	30-80	11	24-82	40-50 cond. 96 conv.	*89, 92
(9. IDAHO) Western Snake River Basin, Oregon	50	30-310	20-103	3	20-97	85	*157
4. Glass Buttes	3	60-220	18-48	--	---	120-190	---
5. Northern Harney Basin	7	50-300	22-72	5	21-27	150	*110, 125
6. Southern Harney Basin	20	30-160	22-25	15	20-68	75-140	*130
7. Alvord Desert	4	35-95	16-22	10	36-97	*47-300	**
8. Lakeview	~15	15-300	40-94	3	72-94	60-150	*96-140
9. Klamath Falls	~600	20-550	15-95	8	16-87	30-1,000 conv. 80 cond.	*105

temperature (<90°C) geothermal water in Western United States, including Alaska and Hawaii--Continued

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
E X I	C O
1,000-3,500	Deep circulation; possible magmatic sources at depth. Heat flow generally >100 mW/m^2; very high at places. Aquifers in sediment-filled basins. Area contains Radium Hot Springs, Kilbourne Hole KGRA's. *Chalcedony geothermometer, Radium Hot Springs well. References: 85, 86, 96
---	Deep circulation. Reference: 13
1,500	Deep circulation. Aquifers in rhyolitic welded tuff. KGRA. *Quartz geothermometer, Lightning Dock well. References: 49, 86
1,100-9,000	Deep circulation along active faults. Aquifers in basin-fill sediments. Reference: 114
G O N	
1,000-2,500	Heat source probable lateral migration from Holocene volcanic centers. Heat flow 110-140 mW/m^2. Includes Belknap Springs KGRA, Foley Springs high-temperature system, and Bigelow Hot Springs. *Chalcedony and Na-K-Ca geothermometers (Belknap and Foley Hot Springs). References: 8, 67
1,000-4,000	Heat source probable lateral migration from Holocene volcanic centers. Heat flow ~105 mW/m^2. Includes McCredie Hot Springs KGRA, Kitson and Wall Creek Hot Springs. *Chalcedony geothermometer (McCredie Hot Springs). References: 8, 67
225-525 wells 200-900 spgs.	Deep circulation in complexly faulted graben. Aquifer: Permian and Triassic greenstones. *Na-K-Ca geothermometer (Hot Lake Hot Springs), chalcedony geothermometer (Medical Hot Springs). References: 8, 18, 67
~1,000	Deep circulation in faults, Grassy Mountain Basalt and Columbia River Basalt Group. High convective gradients at places. Heat flow 105 mW/m^2 (ave.). *Max. temperature at Vale Hot Springs high-temperature system. References: 8, 67
---	Circulation in faults in rhyolitic dome; possible magmatic heat source. Heat flow 122-193 mW/m^2. Reference: 67
400-2,000	Deep circulation near rim of caldera(?). Aquifers in basin sediments, interlayered volcanic rocks. Heat flow 80-105 mW/m^2. *Quartz, Na-K-Ca geothermometers, respectively. Reference: 67
100-2,000	Deep circulation, possible magmatic source (rhyolitic intrusions). Aquifers in basin sediments, interlayered volcanic rocks. Water quality best in north (Brothers fault zone). *Quartz geothermometer in Harney Lake high-temperature system. References: 8, 67
1,300-3,200	Deep circulation in faults (?). *Four gradient holes <100 m deep in low-conductivity sediments. **Sulfate-oxygen isotope geothermometer (Alvord, Hot Lake, and Mickey Hot Springs) is 230°C. References: 8, 81
~1,000	Deep circulation; possible heat source in Warner Range to east. Aquifers in valley-fill deposits. Heat flow ~105 mW/m^2. *Na-K-Ca geothermometer, Hunters and Barry Ranch wells. References: 8, 67
250-3,000	Deep circulation in range faults, Tertiary volcanic rocks. More than 500 wells used for space heating. Hottest waters have dissolved solids <1,000 mg/L. Many aquifers in Tertiary and Pleistocene rocks. Heat flow 60 mW/m^2 in Lower Klamath Lake basin. *Chalcedony, Na-K-Ca geothermometers for principal geothermal reservoirs. References: 8, 79

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Wells considered Depths (m)	Wells considered Temperature (°C)	Thermal springs No.	Thermal springs Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
							T E
Trans-Pecos	--	---	---	--	---	---	---
							U T
1. Cache Valley	19 5	60-300 300-833	20-30 30-49	1	31	35-97	---
2. Wasatch Front	9 135	<300 <300	35-74 20-35	17 23	35-58 20-35	27-380	---
3. Tooele and Skull Valleys	14	<300	20-35	13	20-35	---	---
4. Bonneville Salt Flats	2 10	366, 499 <300	35 20-35	1	~30	75, 145	---
5. Uinta Basin	11 3	<390 <300	43-56 20-35	--	---	38	---
6. Central Sevier River - Sanpete Valleys	0	(<1 km)	---	3 5	>35 20-35	---	---
7. Abraham Hot Spring - Newcastle	6 63	<300 <300	35-67 20-35	7	20-36	Reportedly high	---
8. Beaver Valley	3	---	20-35	1	~30	---	---
						W A	S H I
1. Olympic - Sol Duc Springs	--	---	---	11	46-56	---	*90
2. Yakima	11	265-396	26-30	--	---	>40	---
3. Ephrata	4	80-300	25-30	--	---	~60	---
4. Walla Walla	2	400, 484	26, 28	--	---	35, 33	---
							W Y O
1. Thermopolis	4	152-274	51-54	8	22-56	30-35 cond. 180->300 conv.	*60

temperature (<90°C) geothermal water in Western United States, including Alaska and Hawaii--Continued

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
X A S	
---	Springs listed in table 13. Description in table 14.
A H	
---	Deep circulation in fault zones. Mostly Quaternary aquifers; some wells tap Tertiary Salt Lake Formation. Shallow thermal waters restricted to valley margins. Highest temperature (49°C) encountered in 833 m oil test well. References: 29, 63
1,000-45,000	Deep circulation in fault zones. Most wells in Lake Bonneville and older Quaternary deposits. Thermal springs have high yields of moderately saline to briny water. Reference: 29
sl. to mod. saline	Deep circulation in fault zones. Wells in Lake Bonneville and older Quaternary deposits. Favorable sites along valley margins. Reference: 29
Briny	Deep circulation in fault zones. Wells in Lake Bonneville and older Quaternary deposits. Reference: 29
Briny Fresh-sl. saline	Deep circulation in Duchesne fault zone. Includes Ashley Valley oil and gas field. Reference: 29
<2,000-5,000	Deep circulation in fault zones. Includes Monroe-Red Hill and Joseph KGRA's. Reference: 29
1,000-5,000	Deep circulation with possible cooling magma at depth. Includes Crater Springs, Newcastle Meadow-Hatton, Cove Fort, Roosevelt, Thermo, and Lund KGRA's. References: 29, 78
---	Deep circulation in fault zones. References: 29, 63
N G T O N	
250-300	Deep circulation in steeply dipping faults; springs along structural trend. *Na-K-Ca geothermometer (not reliable). References: 98, 103
*200-400	Circulation in Yakima Basalt Subgroup overlain by low-conductivity sediments. Possibly region of anomalously high heat flow from mantle. Numerous flowing irrigation wells, many with thermal waters. *Analyses of nonthermal shallow ground water. References: 6, 98, 103
170-240	Circulation in Yakima Basalt Subgroup overlain by low-conductivity sediments. Possibly region of anomalously high heat flow from mantle. Numerous irrigation wells, many with thermal waters. References: 6, 98, 103
180-375	Circulation in Yakima Basalt Subgroup overlain by low-conductivity sediments. Possibly region of anomalously high heat flow from mantle. Additional irrigation wells have thermal waters. References: 6, 98, 103
	Note: More than 200 irrigation wells with depths <600 m in southeast Washington have anomalous temperatures and thermal gradients. Many are symbolized on the map of the western states (this volume). Current information does not permit grouping of these wells in favorable areas. Reference: 46
M I N G	
800-2,400	Deep circulation in inferred fault zones. Warm waters encountered in deep oil tests north and east of area. Heat flow $\sim$60 mW/m^2. *Chalcedony geothermometer. References: 5, 7

Table 12.--*Areas favorable for discovery and development of local sources of low-*

Area number[a] and name	Wells considered No.	Depths (m)	Temperature (°C)	Thermal springs No.	Temperature (°C)	Thermal gradients[b] (°C/km)	Equilibration temperature[c] (°C)
						W	Y O
2. Gas Hills	8	100-360	15-27	--	---	40-90	---
3. Douglas	2	510	28, 29	--	---	41, 49	---

[a]Areas, numbered in a separate sequence for each western state except Alaska and Hawaii, are shown in maps 1 and 2. Geothermal occurrences in east Texas, North Dakota, and South Dakota are described in tables 13 and 14 and are shown in figures 15 and 16.

[b]Most thermal gradients reported in this table were calculated by subtracting mean annual air temperatures from maximum reported fluid temperatures in wells and test holes and dividing by the total depths of the wells. The resulting linear gradients do not reflect actual depths of occurrence of thermal waters or variations due to changes in thermal conductivity with depth, and they may be strongly influenced by convective flow in the wells and in the formations. At most places, therefore the gradients do not represent conductive thermal gradients in the earth's crust. "Cond." = probable conductive gradients, "conv." = affected by convection.

Dissolved solids (mg/L)	Remarks[d] (asterisks relate specific comments to columns at left)
M I N G	
---	Deep circulation in fault zones(?). Several warm springs in area; no measured temperatures. References: 17
*500-1,000	Deep circulation in above-normal conductive gradient. Oil test wells reportedly encounter water >30°C at depths <900 m. Water wells <200 m deep have low yields (<0.6 L/sec). *In water from shallow (<200 m) wells. References: 7, 17

[c]Temperatures of rock-water equilibration estimated by means of chemical geothermometers; mostly unreliable for low-temperature waters unless possible effects of mixing, ionic interference, high concentrations of dissolved solids, amorphous silica, and other factors are accounted for; not considered reliable for most of the lower temperature waters included in this table. In some areas where equilibration temperatures are not available for low-temperature waters, estimates from high-temperature (≥90°C) springs are given. Most of these estimates are taken from Brook and others, Hydrothermal convection systems with reservoir temperatures ≥90°C, this volume.

[d]Criteria used in selecting the described areas are given in the text of this report. Many confirmed high-temperature geothermal systems are not included in the areas listed (see map 1). Although it may be assumed that conditions favorable for the occurrence of low-temperature waters exist in the vicinity of most high-temperature systems, available data permit depiction of favorable areas only at a few such locations.

Spring number[a] and name	Latitude, longitude (deg min)	Maximum temper- ature (°C)	Dissolved solids (mg/L)	Flow (L/s)	Heat discharge (MWt)	Minimum equilibration temperature (°C)	Local geothermal gradient (°C/km)
APPALACHIAN HIGHLANDS							
Massachusetts							
1. Sand Springs	42 44.1 73 12.0	*24	110	*25.2	1.69	--	
New York							
2. Lebanon Springs	42 28.8 73 22.2	22	b150	6.6	.39	*51 ?	**27
Pennsylvania							
3. Perry County Warm Springs	40 19.7 77 14.8	18	b150	8.8	.30	*36 ?	**27
West Virginia							
4. Berkeley Springs	39 37.6 78 13.8	22	b150	107	4.94	*38 ?	**23
5. Minnehaha Springs	38 09.8 79 58.5	21	b150	25	1.06	*34 ?	**21
6. Old Sweet Spring	37 37.7 80 15.5	23	--	25	1.27	--	--
Virginia							
7. Bragg Spring	38 14.3 79 09.5	24	--	1.9	.10	--	--
8. Bolar Spring	38 13.1 79 40.4	22	b200	130	6.00	*30	**20
9. Warm Springs	38 03.3 79 46.8	35	525	63	6.34	*41	**20
10. Hot Springs	37 59.8 79 49.8	41	586	63	6.34	*41	**20
11. Healing Spring	37 57.6 79 51.6	30	596	*0.8	.07	**43	--
12. Rockbridge Bath Springs	37 53.9 79 27.7	22	--	*4.4	1.48	--	--
13. Falling Spring	37 52.2 79 56.0	25	672	250	14.47	*40	**20
14. Layton Spring	37.51.5 79 59.2	22	--	6.3	.29	--	--
15. Sweet Chalybeate Spring	37 38.7 80 15.0	24	--	*5.5	3.00	--	--

Depth of circulation (m)	Area of thermal influence[c] (km²)	Remarks (asterisks relate specific remarks to columns at left)
--	25	*Prior to recent construction at spring. References: 33, 88
1,580 ?	5.7	*Quartz geothermometer mixing model (ref. 39). (Unreliable, but possible maximum temperature.) **Reference 39. References: 38, 39, 69
590 ?	4.4	*Quartz geothermometer (ref. 39). (Unreliable, but possible maximum temperature.) **Reference 39. References: 38, 39, 69
1,175 ?	85	*Quartz geothermometer (ref. 39). (Unreliable, but possible maximum temperature.) **Reference 39. References: 38, 39, 71, 22
1,095 ?	20	*Quartz geothermometer (ref. 39). (Unreliable, but possible maximum temperature.) **Reference 39. References: 38, 39, 71, 22
--	24	Reference: 73
--	2.0	Reference: 73
950	120	*Tritium mixing model. **Reference 39. References: 38, 39, 73
1,500	125	*Based on Na-K-Ca geothermometer applied to water from Warm Springs, and on temperature observed at Hot Springs. **Reference 39. References: 38, 39, 73
1,500	125	
--	1.4	*Combined flow of three springs. **Chalcedony and Na-K-Ca geothermometers Reference: 73
--	29	*Combined flow of two springs. Reference: 73
1,450	290	*Chalcedony geothermometer and tritium mixing model. **Reference 39. References: 39,73
--	5.8	Reference: 73
--	60	*Combined flow of two springs. Reference: 73

Spring number[a] and name	Latitude, longitude (deg min)	Maximum temper-ature (°C)	Dissolved solids (mg/L)	Flow (L/s)	Heat discharge (MWt)	Minimum equilibration temperature (°C)	Local geothermal gradient (°C/km)
APPALACHIAN HIGHLANDS--Continued							
North Carolina							
16. Hot Springs	35 53.8 82 49.6	41	[b]430	.5	.09	*50	**27
Georgia							
17. Lifsey Spring	33 02.2 84 22.5	26	141	5.2	.20	--	--
18. Taylor Spring	33 01.1 84 19.6	24	105	24.3	.71	--	--
19. Thundering Spring	32 57.9 84 40.0	24	66	24.0	.70	--	--
20. Barker Spring	32 55.2 84 26.3	23	107	1.9	.05	--	--
21. Warm Springs	32 53.6 84 41.4	31	120	55.8	3.14	*34	**21.2
22. Brown's Spring	32 52.4 84 32.8	20	144	1.6	.02	--	--
23. Parkman Spring	32 51.7 84 40.0	25	114	4.7	.16	--	-
GULF COAST							
Florida							
24. Little Salt Spring	27 04.6 82 14.3	29	[b]3,100	9.5	.28	--	--
25. Big Salt Spring	27 03.6 82 15.3	30	17,812	315	10.57	*30	**24
INTERIOR HIGHLANDS							
Arkansas							
26. Hot Springs	34 30.9 93 03.2	64	189	37.9	6.34	*64	**25
27. Caddo Gap Springs	34 23.2 93 36.5	35	150	--	--	--	--
BASIN AND RANGE							
Texas (Trans-Pecos)							
28. Red Bull Spring	30 51.7 105 20.4	37	960	.8	.06	*56	**32

Depth of circulation (m)	Area of thermal influence[c] (km²)	Remarks (asterisks relate specific remarks to columns at left)
1,480	1.3	*Chalcedony geothermometer **Reference 101. Reference: 38, 39, 84, 101
--	3.8	Reference: 37
--	13	Reference: 37
--	13	Reference: 37
--	.9	Reference: 37
815	60	*Chalcedony and Na-K-Ca geothermometers and temperatures in a nearby well. A chemical mixing model applied to water from a second well provides an estimated maximum reservoir temperature of 70°C. ** Reference 39. References: 37, 38, 39
--	.4	Reference: 37
--	3.0	Reference: 37
--	6.0	References: 24, 68
330	210	*Chalcedony geothermometer. **Based on map contours, reference 2. References: 24, 68
1,840	100	*Chalcedony geothermometer. **Based on map contours, reference 2. References: 4, 9
--	--	Reference: 58
1,170	1.2	*Chalcedony geothermometer. **From reference 36. References: 35, 36

Spring number[a] and name	Latitude, longitude (deg min)	Maximum temper-ature (°C)	Dissolved solids (mg/L)	Flow (L/s)	Heat discharge (MWt)	Minimum equilibration temperature (°C)	Local geothermal gradient (°C/km)
BASIN AND RANGE--Continued							
Texas (Trans-Pecos)--Continued							
29. Indian Hot Springs	30 49.4 105 18.9	***47	***8,230	6.7	.48	*60	**32
30. Capote Warm Spring	30 12.6 104 33.7	37	329	6.7	.45	*57	**40
31. Nixon Springs	30 08.0 104 36.1	32	507	<1	--	*60	**40
32. Hot Springs Ruidosa	30 02.3 104 35.9	45	549	1.25	.13	*55	**40
33. Las Cienagas Spring	29 47.2 104 27.7	30	723	16.7	.63	*60	**40
Big Bend National Park							
34. Big Bend #2	29 10.9 102 59.5	40	879	--	--	*40	**30
35. Hot Springs	29 10.8 102 59.7	41	884	--	--	*41	**30
36. Rio Grande Village	29 10.8 102 57.2	36	842	--	--	*36	**30
NORTHERN GREAT PLAINS							
South Dakota (Black Hills)							
37. Buffalo Gap Spring	43 31.6 103 22.6	18	--	245	9.23	--	--
38. Hot Brook Creek Spring	43 26.8 103 30.5	24	--	56	3.52	--	--
39. Hot Springs	43 26.3 103 29.0	31	--	649	59.78	*44	**20
40. Cascade Springs	43 20.0 103 33.1	19	[b]1750	639	26.76	*35	-

[a]Sequence numbers identify spring locations on figures 5 and 16.

[b]Concentration of dissolved solids estimated from specific electrical conductance.

Depth of circulation (m)	Area of thermal influence[c] (km²)	Remarks (asterisks relate specific remarks to columns at left)
1,300	9.6	Ranges: Temp. 27-47, DS 2,200-8,230. *Chalcedony geothermometer. Reference 36. ***Maxima in 5 springs. References: 35, 36
1,200	7.2	*Chalcedony geothermometer. **Reference 36. References: 35, 36
1,300	--	*Chalcedony geothermometer. **Reference 36. References: 35, 36
1,135	2.6	*Chalcedony geothermometer. **Reference 36. References: 35, 36
1,300	13	*Chalcedony geothermometer. **Reference 36. References: 35, 36
630	--	*Chalcedony geothermometer. **Reference 35. References: 35
670	--	*Chalcedony geothermometer. **Reference 35. References: 35
500	--	*Chalcedony geothermometer. **Reference 35. References: 35
--	--	Reference: 72
--	--	Reference: 72
1,260	1,200	*Chalcedony geothermometer and mixing model. **Reference 72. References: 26, 30, 72
--	--	*Chalcedony geothermometer and mixing model. References: 70, 72

[c]Area of thermal influence represents a probable minimum land-surface area beneath which each spring or spring system is assumed to concentrate the heat conducted through the crust toward the land surface. The calculation is based on the following arbitrary assumptions: (1) The thermal water absorbs heat uniformly over the area at depth in the normal crustal thermal gradient; and (2) the thermal water collects the total normal heat flow over the calculated area. These assumptions result in calculated areas that are probably minima for the areas influenced by the spring flows. Crustal heat flow is calculated for each area from the nearest observed thermal gradient and from thermal conductivities estimated for rocks known to underlie the areas.

Table 14.--*Subsurface geothermal regimes, Central and Eastern United States*

NEW ENGLAND

[a]41. White Mountain batholith

Granitic plutonic complex having high radiogenic heat production (fig. 15). At places where the plutonic rocks are insulated by overlying rocks of low thermal conductivity, thermal gradients may be above normal and low-temperature geothermal energy may be available at depths less than 1 km. Information on thermal gradients and availability of thermal water is currently sparse. Possible exploration target for hot dry rock.
Reference: 53

ALLEGHENY BASIN

42. West Virginia-Pennsylvania-New York

Area in which Paleozoic sedimentary rocks overlie Precambrian basement in a deep structural basin (fig. 15). Thermal gradients greater than 30°C/km measured in oil and gas test wells suggest that low-temperature geothermal waters may be produced from depths less than 1 km in this area. Information on availability of thermal water is currently sparse.
Reference: 53

ATLANTIC COASTAL PLAIN

43. Mid-New Jersey Coast
44. Kinston-Jacksonville, N.C.
45. Wilmington, N.C.
46. Charleston, S.C.
47. Savannah-Brunswick, Ga.

Areas of anomalous geothermal gradients (fig. 15) assumed to be caused by radiogenic heat from buried granitic plutons. At places where the plutonic rocks are well insulated by overlying coastal sediments of low thermal conductivity, low-temperature geothermal energy may be present at depths less than 1 km. Conductive gradients measured over significant intervals in wells range from 18°C/km to 38°C/km and are generally greater than 29°C/km. The availability of thermal water in the areas of high gradients is largely unknown at present. A test drilling program will provide additional information on these areas by late 1978.
References: 15, 42

GULF COASTAL PLAIN

48. Alabama-Texas (Map depiction only in western Gulf Coast states)

A region of anomalously high geothermal gradients in Cenozoic geosynclinal deposits (fig. 16). At 1- to 2-km depth, gradients range from 20°C/km to more than 100°C/km and in general vary inversely with the thickness of the Cenozoic deposits. The shallow thermal waters are closely associated with deep geopressured zones at many places, and the escape of water from geopressured zones probably accounts for the anomalous temperatures and high salinities in the overlying hydropressured zones. Salinities, expressed as mg/L of NaCl, range from <6,000 to >100,000 throughout the region. The low-temperature thermal waters are best known in the western Gulf Coast States but probably extend eastward into Alabama.
Reference: 43

49. Brine wells, southwestern Arkansas

In the Hope-El Dorado area of southwestern Arkansas (fig. 16), wells producing thermal brines have anomalous gradients ranging from 33° to 40°C/km. Producing horizons are in formations of Jurassic and Cretaceous age at depths ranging from 365 to 2500 m. Maximum temperatures in the deepest wells reportedly are 140°C. The occurrence of uniform permeabilities and thermal gradients over a wide area extending south to Louisiana suggests the existence of a large thermal brine field.
References: 53, 97

Table 14.--*Subsurface geothermal regimes, Central and Eastern United States*--Continued

OUACHITA STRUCTURAL BELT

50. Southwest to northeast Texas

Zone of thrust faulting along the margin of the Gulf Coast geosyncline (fig. 16). Within the area of Texas generally bounded by the Balcones, Luling, Mexia, and Talco fault zones and extensions of these zones, measured geothermal gradients range from 25° to 45°C/km within 1 km of the surface. Temperatures of water in wells penetrating the Cretaceous and early Tertiary formations are as high as 70°C at depths <1400 m; concentrations of dissolved solids range from 600 to 3800 mg/L. The source of the above-normal thermal gradients is assumed to be deep circulation in the thrust-fault zone. The structural area of interest for geothermal exploration may extend into the Ouachita Mountains of Oklahoma and Arkansas.
Reference: 107

BASIN AND RANGE PROVINCE

51. Texas (Trans-Pecos)

Probable extension of the Rio Grande rift zone and associated basin-and-range faulting (fig. 16). The area, extending south from El Paso, Texas, along the Rio Grande, consists of a series of linear sediment-filled bolsons having depths to basement rocks as great as 2700 m. Measured heat flows and thermal gradients to depths of 1 km are typical of the Basin and Range Province (40-125 mW/m^2; 30°-70°C/km). Temperatures of thermal waters in springs and wells range from 30° to 90°C. Concentrations of dissolved solids range from 300 to 8200 mg/L. Observed temperatures and thermal gradients are greatest in the Presidio Bolson and adjacent areas of Mexico, but a scarcity of data in other areas precludes meaningful comparisons. The source of heat is deep circulation, structurally controlled. See table 13 for data on springs in this area.
Reference: 35, 36

NORTHERN GREAT PLAINS

52. North and South Dakota

Areas in and near the Williston Basin (fig. 16) where thermal waters occur as the result of deep circulation in regional aquifers. South of the Black Hills, South Dakota, thermal springs having moderate temperatures issue from Permian limestone (table 13). North and east of the Black Hills in both South and North Dakota, thermal waters occur at depths <1 km at places, apparently arising from deep aquifers such as the Madison Group and the underlying Red River Formation. In an area of south-central South Dakota west of the Missouri River, designated in figure 16 as most favorable for discovery and development of low-temperature thermal waters, wells penetrating the Dakota Sandstone have water temperatures ranging from 36° to 67°C and thermal gradients as high as 125°C/km. An average gradient for wells <600 m deep is about 40°C/km. Less favorable areas depicted in figure 16 have generally lower thermal gradients and water temperatures. Most thermal wells in the region have artesian flows that have declined in recent years, presumably as the result of large withdrawals. Contours on upper surface of the Madison Group (fig. 16), one of the youngest thermal aquifers, show that these aquifers occur at great depths in much of the region and suggest that, at most places, wells <1 km deep will obtain thermal water only where unusually permeable zones occur in overlying formations.
References: 1, 82, 93

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[a]Sequence numbers identify areas shown on figures 15 and 16.

Assessment of Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin

By R. H. Wallace, Jr., T. F. Kraemer, R. E. Taylor, and J. B. Wesselman

ABSTRACT

This report estimates the geopressured-geothermal energy contained in pore waters of sedimentary rocks to a depth of 22,500 ft (6.86 km) in the northern Gulf of Mexico basin, both onshore and offshore. The total thermal energy in waters of both sandstone and shale is estimated to be 107,000 x 10^{18} J, of which 11,000 x 10^{18} J is in sandstone and thus represents the amount from which initial production will be drawn. Assuming saturation of the water with methane, the total methane dissolved in water within sandstone and shale is 59,000 x 10^{12} standard cubic feet. Of this, 5700 x 10^{12} standard cubic feet, equivalent to 6000 x 10^{18} J of thermal energy, is contained in water within sandstone. Application of the recoverability analysis presented by Papadopulos and others (1975) in USGS Circular 726 suggests that recoverable thermal energy ranges from 270 x 10^{18} J under plan 3 (controlled development with limited pressure reduction and subsidence) to 2800 x 10^{18} J under plan 2 (depletion of reservoir pressure). The energy equivalent of recoverable methane ranges from 158 x 10^{18} J under plan 3 to 1640 x 10^{18} J under plan 2. The electricity producible from this thermal energy at a conversion efficiency of 8 percent ranges from 23,000 MWe for 30 yr under plan 3 to 240,000 MWe for 30 yr under plan 2. As in Circular 726, the dissolved methane is not considered to be used locally, and, accordingly, no electrical energy is calulated.

INTRODUCTION

Many large basins contain sedimentary rocks with pore fluids under confining pressure higher than normal (usually considered to correspond to a vertical pressure gradient of about 10.5 kPa/m or 0.465 psi/ft). These sedimentary rocks are termed "geopressured," and the energy contained in them is termed "geopressured-geothermal energy." Papadopulos, Wallace, Wesselman and Taylor (1975) used the term "fluid resource base" to refer to "the energy contained in the waters stored in the sand and shale beds of geopressured reservoirs." These waters are hot, confined under pressure higher than normal, and are presumed to be saturated with dissolved methane at formation pressure, temperature, and salinity. The fluid resource base, therefore, consists of thermal energy, mechanical energy, and the energy represented by the methane dissolved in these waters. Following Muffler and Cataldi (1978), the fluid resource base at depths shallow enough to be reached by drilling in the forseeable future is now termed the "accessible fluid resource base." That part of the accessible fluid resource base that can be extracted for use under reasonable technology and economics is termed the "geopressured-geothermal resource."

The most intensely studied basin containing geopressured-geothermal energy is the northern Gulf of Mexico basin. Because of the potential value of this energy, various attempts to estimate its magnitude and recoverability have been carried out. The U. S. Geological Survey (USGS) in 1975 published the first estimate of the accessible fluid resource base and resource in Tertiary deposits beneath the onshore part of the northern Gulf of Mexico basin (Papadopulos and others, 1975), an area of about 145,000 km^2. The occurrence of Tertiary geopressured sediments gulfward beneath the continental shelf and the occurrence of Cretaceous geopressured deposits farther inland were recognized, but the accessible fluid resource base was not evaluated. Their study estimated that the identified accessible fluid resource base consisted of 46,000 x 10^{18} joules (J) of thermal energy, 25,000 x 10^{18} J equivalent of dissolved methane, and 200 x 10^{18} J of mechanical energy in both sandstone and shale of the study area.

Jones (1976a) subsequently estimated that 49,000 x 10^{12} standard cubic feet[1] (1370 x 10^{12} standard cubic meters) of dissolved methane occurs in geopressured waters of sandstone in the northern Gulf of Mexico basin, onshore and offshore. In addition, he estimated a comparable amount dissolved in geopressured water of shale, bringing the total to approximately 100,000 x 10^{12} ft^3 (2800 x 10^{12} m^3) of dissolved methane. Jones further suggested that 1146 x 10^{12} ft^3 (32.5 x 10^{12} m^3) might be recoverable.

Hise (1976), on the other hand, using different assessment techniques for essentially the same area, concluded that only 3000 x 10^{12} ft^3 (85 x 10^{12} m^3) of dissolved methane is present in geopressured sandstone, and only about 125 x 10^{12} ft^3 (3.54 x 10^{12} m^3) could be recovered.

[1] In the petroleum industry, the custom is to express quantities of methane in standard cubic feet referenced to 1 atmosphere (10^5 Pascal) and 60°F (15.6°C). In this report, these standard cubic feet are converted to "standard cubic meters" without changing the reference temperature and pressure. When referring to gas volumes hereafter in this report, standard cubic feet is abbreviated as ft^3 and standard cubic meters is abbreviated as m^3. The energy equivalent of methane is taken to be 1000 Btu/ft^3 = 3.73 x 10^7 J/m^3 .

Hawkins (1977, p. 35-37) estimated the total recoverable geopressured-geothermal energy of southern Louisiana onshore and offshore to the gulfward limit of State-controlled waters (3 miles--4.8 km--from shoreline) to be 34 quads (1 quad equals 10^{15} British thermal units) or about 36 x 10^{18} J. This amount consists of 19.5 quads (20.6 x 10^{18} J) of thermal energy, 13.6 quads (14.3 x 10^{18} J) of methane energy and 1.2 quads (1.3 x 10^{18} J) of hydraulic energy.

Kuuskraa, Brashear, Doscher, and Elkins (1978b, p. 53) have estimated the recoverable dissolved methane resource of onshore Texas and Louisiana to be 42 x 10^{12} ft^3 (1.2 x 10^{12} m^3). They also have estimated the economically recoverable reserves (at $3 per 1000 ft^3) to be 1.1 x 10^{12} ft^3 (0.03 x 10^{12} m^3).

No wells have yet been drilled and produced for geopressured-geothermal energy. Therefore, determination of recoverability is based on assumed production models rather than actual production data. It is almost certain, however, that the amount of recoverable energy will be only a very small fraction of the accessible fluid resource base.

The assessments discussed above used different techniques, and several did not measure the same components of the accessible fluid resource base, cover the same areas, or report results in the same units, so the figures presented above are not directly comparable. In an effort to increase the reliability of the estimates of the accessible fluid resource base and to assess the entire area in the northern Gulf of Mexico basin where geopressured sedimentary rocks are known to occur, the present study refines the preliminary USGS assessment conducted in 1975. The area of investigation is expanded from 145,000 km^2 to 310,000 km^2 in order to assess the accessible fluid resource base in sedimentary rocks beneath the Gulf of Mexico continental shelf and in the inland Upper Cretaceous sandstone and shale. Results reported in this Circular show an increase in identified accessible fluid resource base of about 2½ times that of the previous onshore USGS assessment by addition of the energy contained in geopressured waters of the offshore and Upper Cretaceous deposits. It should be noted that the depth of investigation for the present assessment has been increased from 6 km in Texas and decreased from 7 km in Louisiana to a uniform depth of assessment of 6.86 km (22,500 ft) for the entire area.

In this assessment, a much larger sample of the abundant information concerning subsurface conditions has been analyzed and evaluated as compared to the 1975 assessment. Over 3500 wells have been used in this study as compared to about 250 in the 1975 study.

This assessment clearly separates the part of the accessible fluid resource base contained in sandstone from the part contained in shale, because the sandstone has aquifer properties favorable for production, whereas the shale does not. However, the undercompacted shale contains the bulk of the accessible fluid resource base and may yield significant quantities of water to the permeable sandstone when subjected to production stress. It should be kept in mind that even in sandstone the recoverable fluid is only a few percent of the fluid in place.

Sandstone volumes and physical conditions existing at depths greater than about 18,000 ft (about 5500 m) are not extensively documented because relatively few wells are drilled to these depths. As a result, estimates of the accessible fluid resource base below 18,000 ft (5500 m) are less reliable than the estimates at shallower levels. An attempt to evaluate the accessible fluid resource base at these great depths is necessary, however, in order to include the deep Tertiary and Upper Cretaceous geopressured reservoirs that occur in Louisiana.

The accuracy of an assessment of the fluid resource base is dependent not only on the techniques used, but also on the validity of certain assumptions that must be made. An important assumption is whether the geopressured-geothermal waters are actually saturated with methane. Results of the first test of geopressured-geothermal aquifers have now confirmed the presence of significant amounts of dissolved methane gas. In fact, two to four times more methane was produced from two separate aquifers in a well in Vermilion Parish, La. (Department of Energy, Edna Delcambre #1; see map 3), than would have been expected if the formation water were at saturation. If the ideas presented by Randolph (1977b) concerning the presence of a few percent of trapped immobile gas in the reservoir pore space are proved correct, gas in place in highly geopressured aquifers may be five to ten times greater than the assumption of saturation would indicate. However, many more test data and analyses will be required to satisfy the uncertainties surrounding the immobile gas hypothesis as well as the assumption of saturation.

The types, sources, and accuracy of data used and the basis on which various data in this chapter were determined are discussed in the section entitled "Supplemental information on data collection and organization" at the end of this report.

GULF COAST SEDIMENTARY MODEL

This assessment is based on a simplified sedimentary model of the northern Gulf of Mexico basin. The model envisions a deep basin filled with sandstone and shale that were deposited in fluvial, deltaic, and marine environments similar to those that exist today in the region. In reality, Gulf Coast formations rarely consist exclusively of sandstone and shale but contain mixtures of these and other sedimentary rock types, particularly siltstone. For the purpose of this assessment, however, all sedimentary rocks of the Gulf Coast are considered to be either sandstone or shale.

On the basis of sandstone percentage, three generalized depositional facies are recognizable in sedimentary beds of all ages occurring in the Gulf Coast geosyncline (Thorsen, 1964; Norwood and Holland, 1974):

(1) a massive sandstone facies in which sandstone constitutes 50 percent or more of the sedimentary volume;

(2) an alternating sandstone and shale facies in which sandstone constitutes 15 to 35 percent of the sedimentary volume; and

(3) a massive shale facies in which sandstone constitutes 15 percent or less of the sedimentary volume (Norwood and Holland, 1974, p. 175-178).

For rocks of a given age, the massive sandstone facies occurs nearest the land and the massive shale facies farthest gulfward. Because the geosynclinal deposits grew by building out into the gulf, these three depositional environments have shifted gulfward in time. As a consequence, the volume of sandstone generally decreases vertically with increasing depth and decreases horizontally toward the Gulf of Mexico (fig. 17). Salt tectonics and syndepositional (growth) faulting have increased the complexity of depositional patterns in the Gulf Coast geosyncline. The major subsurface fault patterns of the onshore Gulf Coast are shown on map 3 to illustrate the degree of structural complexity. The localized radial fault patterns indicate the presence of salt domes, whereas the patterns with a regional trend represent growth faults. Growth faults are characterized by appreciable thickening of sedimentary section on the Gulfward or down-thrown side.

Fluid pressures higher than normal are most commonly associated with the alternating sandstone and shale facies and the massive shale facies. These fluid pressures usually increase with increasing depth and shale volume from the alternating sandstone and shale facies into the massive shale facies (Norwood and Holland, 1974, p. 184-186). Fluid pressures in these facies are high because expulsion of pore fluids is restricted. In addition, thermal expansion of water and addition of water from dehydration of clay tend to increase the volume of pore water. As a result, geopressures have probably existed in these sediments since burial to depths of 2000 ft (610 m) or less (Chapman, 1972, p. 790). The fluids in geopressured zones must support a large part of the weight of the overburden.

Fluid pressures in the massive sandstone facies most commonly are normal because pore waters have been free to drain, allowing the sand to compact in response to increasing sedimentary load and thereby permitting the dissipation of pressure (Dickinson, 1953, p. 415). In some cases, however, facies boundaries, growth faults, salt tectonics, or post-depositional alteration have effectively isolated sandstone bodies and prevented compaction and fluid expulsion; thus geopressures can exist locally in the massive sandstone facies.

These relations between pressure and facies are shown diagramatically in figure 17 and are reflected on map 3 by variations in the depth of occurrence of the top of the geopressured zone. In most instances, deep occurrences of the top of the geopressured zone correlate with deep occurrences of the alternating sandstone and shale facies (overlain by thick sections of the massive sandstone facies). On the other hand, shallow occurrences of the top of the geopressured zone (see area shaded in gray on map 3) correlate with shallow occurrences of the alternating sandstone and shale facies or the massive shale facies.

The distribution of temperature, like the distribution of geopressure, is also related to facies. Comparison of figure 18 and map 3 shows that the 150°C (302°F) isothermal surface is usually deepest where the top of the geopressured zone is deepest, and conversely. Lower temperatures are associated with the normally pressured massive sandstone facies and higher temperatures with the massive shale facies.

Figures 19, 20, and 21 illustrate the general correlation of water quality, temperature, and fluid pressure with the different facies shown in figure 17. High salinity, low temperature, and normal fluid-pressure gradients (0.465 psi/ft) commonly are associated with the massive sandstone facies. Moderately high salinity, moderately high temperature, and intermediate fluid-pressure gradients (0.5 to 0.7 psi/ft) are associated with the alternating sandstone and shale facies. Low salinity, high temperature, and high fluid-pressure gradients (0.7 psi/ft) are associated with the massive shale facies. These relations, however, may be altered by geologic structure or other factors. Wallace, Taylor and Wesselman (1977, p. GI42-62), presented a detailed discussion of these relations in the lower Rio Grande embayment of Texas.

These basic relationships indicate that sandstone reservoirs having potential for development of geopressured-geothermal resources will occur most frequently within the alternating sandstone and shale facies and, to a lesser extent, within the massive shale facies. Several localities have already been identified in the study area where thick, high-pressure, high-temperature sandstone masses exist as a result of isolation by growth faults, salt movement, facies boundaries, and other factors (see map 3). Detailed reports discussing some of the localities shown have been published (Bebout, Gavenda and Gregory, 1978; Loucks, 1978; and Bebout, Loucks and Gregory, 1978a). Almost all of the areas identified on map 3 as having potential for development of geopressured-geothermal energy occur in areas where the top of the geopressured zone occurs at depths greater than 6000 ft (1829 m).

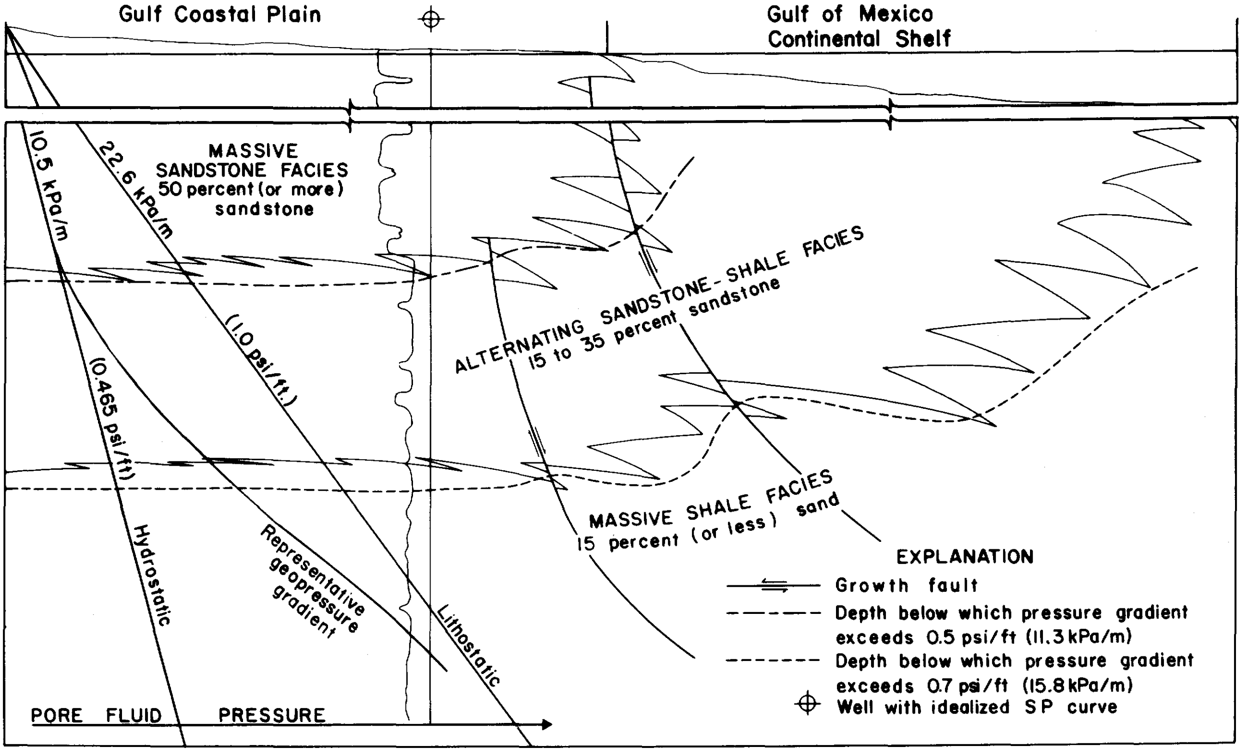

Figure 17.--Generalized sedimentary model of the northern Gulf of Mexico basin, based on percentage sandstone and showing, diagrammatically, the relation of gross lithology to fluid-pressure gradient and growth faulting (modified from Norwood and Holland, 1974).

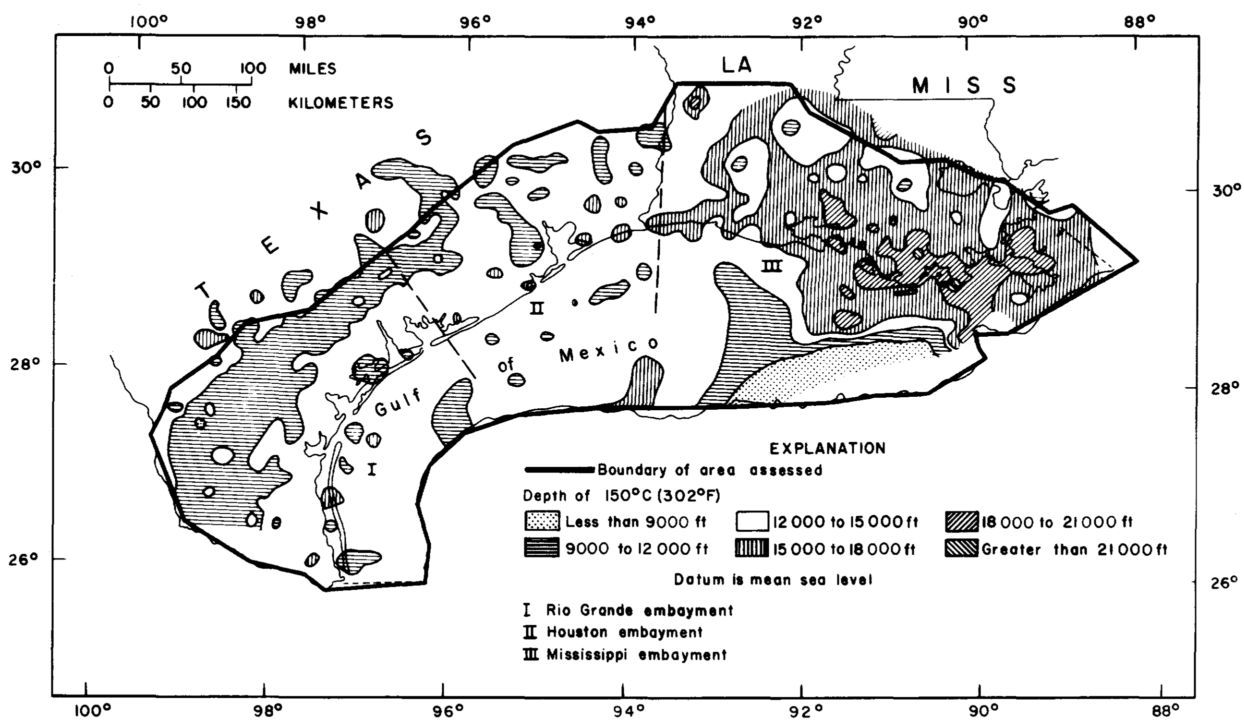

Figure 18.--Location map with assessment area boundary and showing the Rio Grande, Houston, and Mississippi embayments in relation to the depth of occurrence of the 150°C (302°F) isotherm.

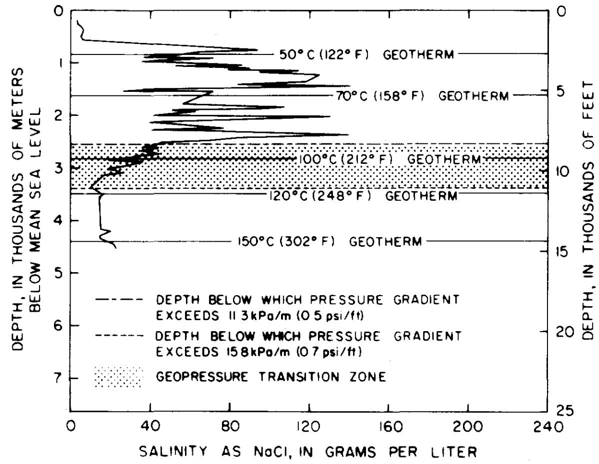

Figure 19.--Salinity profile and variations in pressure and temperature with depth in an onshore Texas well that penetrates Oligocene and younger sedimentary rocks in the lower Rio Grande embayment.

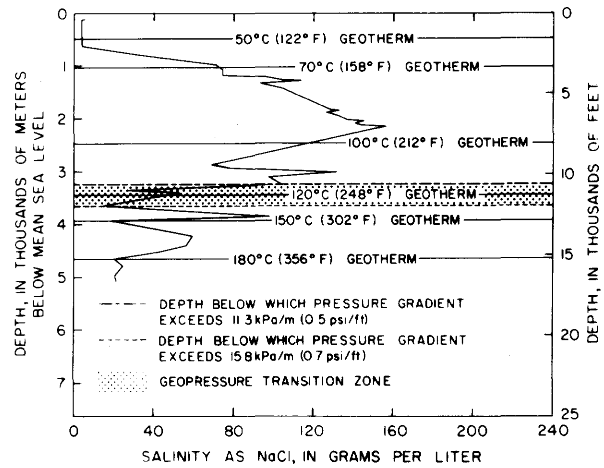

Figure 21.--Salinity profile and variations in pressure and temperature with depth in an onshore Texas well that penetrates Eocene and younger sedimentary rocks in the Houston embayment.

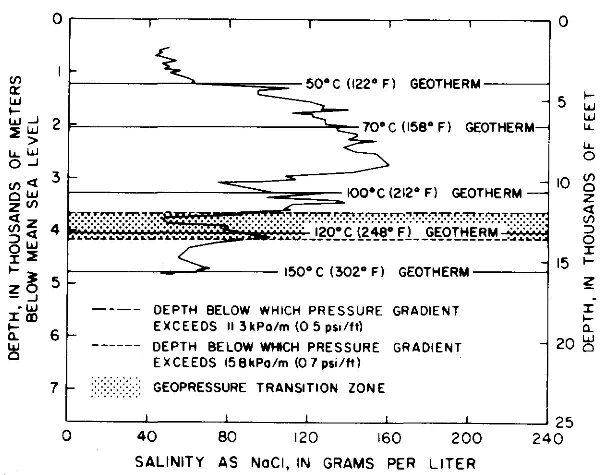

Figure 20.--Salinity profile and variations in pressure and temperature with depth in an offshore Louisiana well that penetrates Miocene and younger sedimentary rocks in the lower Mississippi embayment.

ASSESSMENT TECHNIQUES

The accessible fluid resource base, as defined earlier, represents the thermal, mechanical, and methane energy stored in the fluids of a geopressured sedimentary body. The volume of this body, its porosity, and the temperature, salinity, and pressure of its contained water must be determined in order to estimate the accessible fluid resource base. Both the amount of thermal energy and the content of dissolved methane in the pore water (assuming saturation) can then be estimated. Assessments published by Papadopulos, Wallace, Wesselman, and Taylor (1975) and by Hawkins (1977) showed that mechanical energy constituted less than 1 percent of the total accessible fluid resource base. Therefore, an assessment of mechanical energy is not included in this report.

The geopressured sedimentary body in the Gulf Coast is so large and heterogeneous that single values of porosity, temperature, pressure, and salinity cannot be used throughout. However, simplifying assumptions can be made that permit a close approximation of the actual conditions but still allow construction of a workable model.

For example, the vertical alternation of sandstone and shale would be extremely difficult to depict in detail, and calculations of temperature, pressure, and salinity within each bed would not be feasible. However, the geopressured body can be divided readily into horizontal intervals in which the cumulative thickness of sandstone and shale can be estimated and in which average values of temperature, pressure, and salinity can be assigned to the fluid.

The assessment technique was designed to consider relatively local variations in conditions using a reasonable amount of the vast quantity of available data. The study area was divided vertically into fourteen horizontal intervals each 1500 ft (457 m) thick. For each depth interval in the geopressured zone, generalized physical properties were integrated into estimates of the accessible fluid resource base. A computer program generated a trend-surface that depicted the magnitude and areal distribution of each of the four initial parameters (sandstone thickness, temperature, salinity, and pressure) for each interval. Subsequently, a fifth parameter - shale thickness - was developed as a complement of the sandstone thickness. A computer program then separately calculated the distribution of thermal and methane energy in the fluids contained in sandstone and shale of each depth interval. A simplified flow diagram of the computational procedure is shown in figure 22. The energy data presented on map 3 represent the summation and integration of the calculations for sandstones.

The assessment technique included computer processing of parameter values from nonuniformly distributed well data into a three-dimensional structure in order to organize all parameter values into a format acceptable by the computer program used to calculate energy. A grid consisting of 68 rows and 125 columns with 30,000-ft (9144-m) spacing was constructed for each interval and for each parameter (fig. 23a). Thus, the northern Gulf of Mexico basin was represented by a three-dimensional computerized structure. The divisions of this structure were arbitrarily selected large enough to be readily processed by computer but small enough to retain relatively fine detail. The technique used consisted of five basic steps:

1. From each of the four parameter data files, a computer program changed point-source information (a depth and a measured or computed parameter value) for every well into a calculated parameter value at the midpoint of each 1500-ft (457-m) interval. In the process, net sandstone thickness per 500-ft interval (as stored in the data file) was converted to net sandstone thickness per 1500-ft interval and then used to compute net shale thickness (1500 ft minus net sandstone thickness equals net shale thickness). The section entitled "Supplementary information on data collection and organization" at the end of this report explains in detail the preparation and processing of each parameter to obtain a midpoint value.

2. In the first step, each parameter value in the 14 intervals was identified with its respective well by latitude and longitude. The Lambert conformal conical projection algorithms changed the latitude-longitude location into X-Y coordinates (in feet). This change was necessary to conform to input requirements of the Surface Approximation and Contour Mapping (SACM) computer program. The SACM program is a commercially available program for analysis of irregularly spaced data.

Another conversion changed the net sandstone for each well in each interval into linear measure of water per interval based upon equations that represent the porosity-depth relation depicted in figure 24. These relations were derived from porosity measurements made on samples of sandstone taken from each of the three major embayments (fig. 18). Depending upon the location of each well, the appropriate equation was used to convert net sandstone to a linear measure of water in sandstone. Porosity calculated at the midpoint of each interval was multiplied by amount of net sandstone in that interval to give meters of water. The net thickness of shale for each well in each interval was likewise converted into meters of water, except that only one depth-porosity equation was used throughout the entire area.

3. The SACM computer program was used to convert nonuniformly distributed midpoint data values (fig. 23b) to a uniform grid point value (fig. 23c) for each interval of each parameter. The calculated parameter value at each grid point or node (juncture of a row and column) was obtained by applying a least-squares surface approximation to the closest data point in each of 8 sectors surrounding the node. Because the grid for each parameter was constructed in the same manner, a given node represented the same point in space in every grid. For example, the lower left corner nodes (fig. 23c) for the grids of water-in-sandstone, temperature, pressure, and salinity for interval 1, although processed separately, are actually at the same location and depth.

The water-in-sandstone and water-in-shale grids were then compared with a grid that represented the top of the geopressured zone in order to include in subsequent steps only water in the geopressured zone. For example, if this comparison determined that three-fourths of a particular interval at a node is within the geopressured zone, then three-fourths of the water-in-sandstone in that interval and all the water-in-sandstone in the underlying intervals are used with the energy equations in step 4.

4. A computer program that processed four grids (water-in-sandstone or water-in-shale, temperature, pressure, and salinity) by interval on a node-by-node basis was used to create energy output grids. Thus, for example, the node in the lower left corner (fig. 23c) for the water-in-sandstone, temperature, pressure, and salinity grids of interval 1 is a common input to equations to calculate the thermal or methane energy in sandstone at that same node on the output grids.

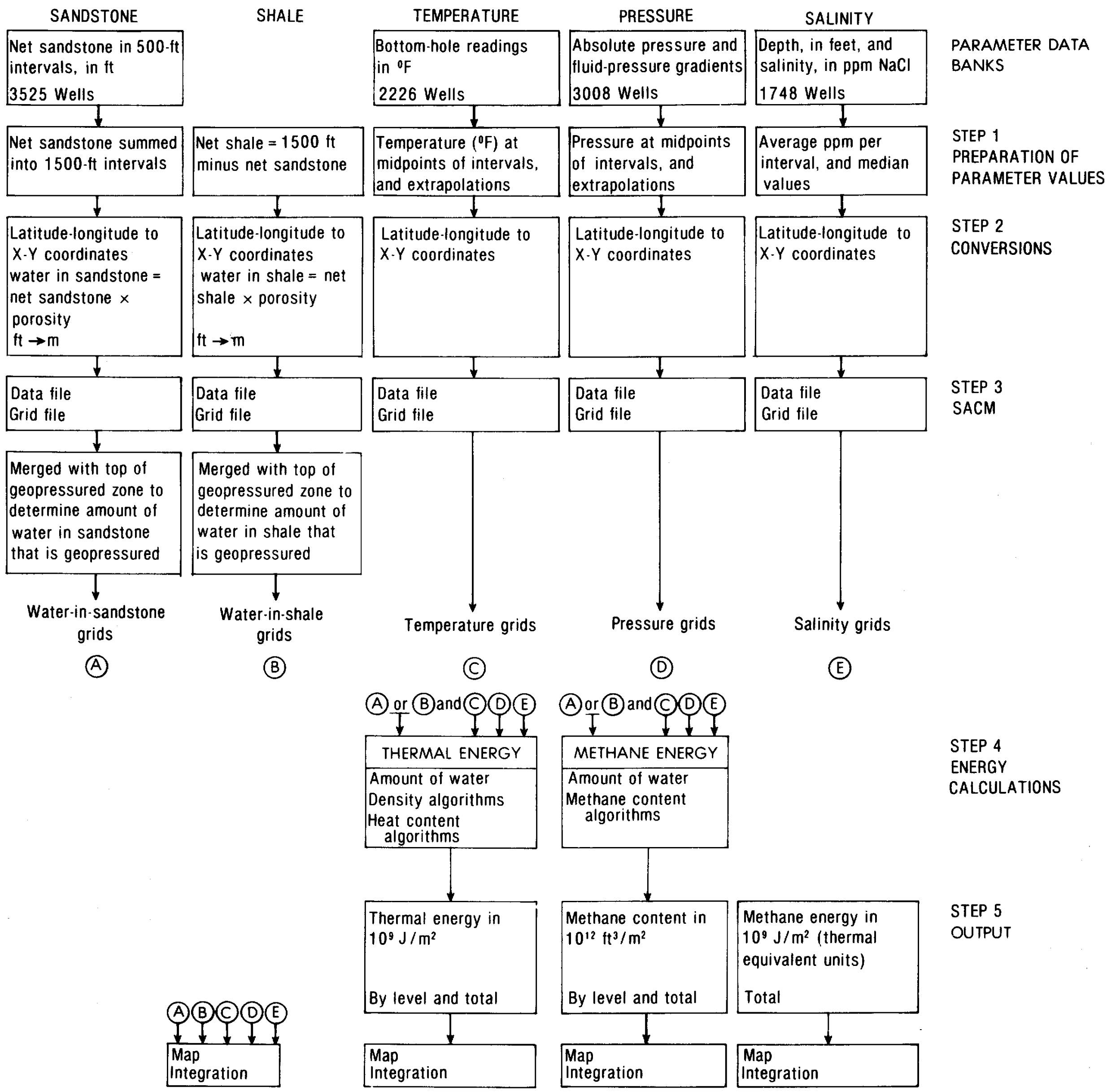

Figure 22.--Flow chart of assessment procedure.

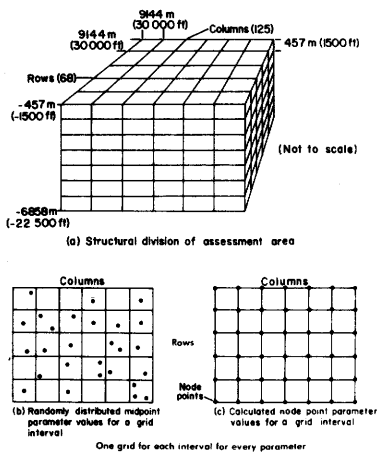

Figure 23.--Structural division of the assessment area and of the grid interval.

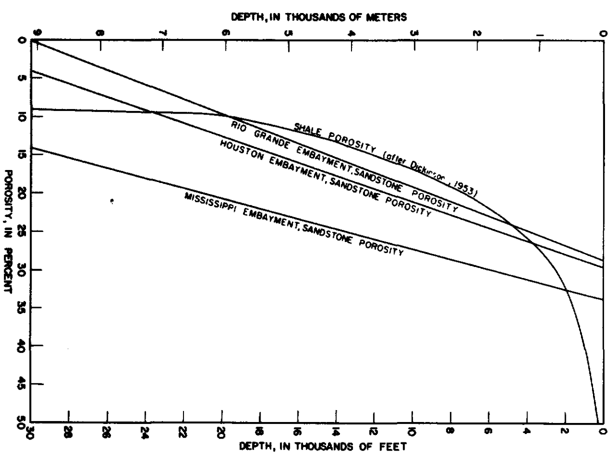

Figure 24.--Porosity change with depth for sandstone in the Rio Grand, Houston, and Mississippi embayments, and shale porosity change with depth for the northern Gulf of Mexico basin.

Thermal energy per unit area in sandstone was calculated for each node according to the following relation: (water-in-sandstone) x (density of water) x (heat content of water) = thermal energy per unit area. The density of water was calculated from the equations of Potter and Brown (1977) using input values from the temperature, pressure, and salinity grids. The heat content of water (above 15°C) was calculated similarly from equations provided by John Haas, USGS, Reston, Virginia.

Methane energy per unit area in sandstone was calculated for each node according to the following relation: (water-in-sandstone) x (methane content of water) x (heat equivalent of methane) = methane energy per unit area. The heat equivalent of methane was taken to be 3.73×10^7 J/m^3. Methane content of water was calculated from equations of Haas (1978) using input values from the temperature, pressure, and salinity grids. The effects of these parameters on methane solubility are shown in figure 25. For example, the solubility of methane at a constant temperature of 100°C (212°F) and a constant pressure of 20,000 psi (137,900 kPa) is reduced from 8.4 m^3/m^3 (47 ft^3/bbl) in fresh water to 5.5 m^3/m^3 (31 ft^3/bbl) in water having a salinity of 110,000 mg/L and to 2.3 m^3/m^3 (13 ft^3/bbl) in water having a salinity of 296,500 mg/L.

5. For each interval, the grids of thermal and methane energy were processed to obtain a total energy value for sandstone in the interval. Total energy values of shale in each interval were calculated similarly. The SACM program was then used to generate a contour map (map 3) showing areal distribution of thermal and methane energy of water in sandstone reservoirs in the study area and to compute through integration the total volume of water and the thermal energy and methane energy of water contained in both sandstone and shale.

In order for the numerical approximation to represent the natural state as closely as possible and still be workable, certain conditions were assumed or approximated for computer synthesis and processing of the data base. These conditions were classified as (1) assumptions concerning physical relations occurring in the sediments or water and (2) criteria concerning the use of these assumptions and of other physical and chemical information in the computations of energy estimates.

1. The assumptions are:
   a. The lithology of the sedimentary rocks is either sandstone or shale.
   b. All sedimentary rocks in which the fluid-pressure gradient exceeds 11.3 kPa/m (0.5 psi/ft) are assumed to be geopressured.
   c. The water is saturated with methane at the subsurface pressure, temperature, and salinity.
2. The criteria are:
   a. The horizontal extent of the assessment study area is bounded by the limits of well-control data defining the top of the geopressured zone (see fig. 18).
   b. In instances where data at depth are insufficient or unavailable, values for temperature, pressure, and salinity are selectively extrapolated downward.
   c. Sandstone content was not extrapolated downward to intervals below well control, but instead was estimated by horizontal extrapolation using trend-surface analysis from deeper neighboring wells that did penetrate the intervals.
   d. A data file was created for each parameter at the midpoint depth for each interval. Each file was then processed separately through the computations.

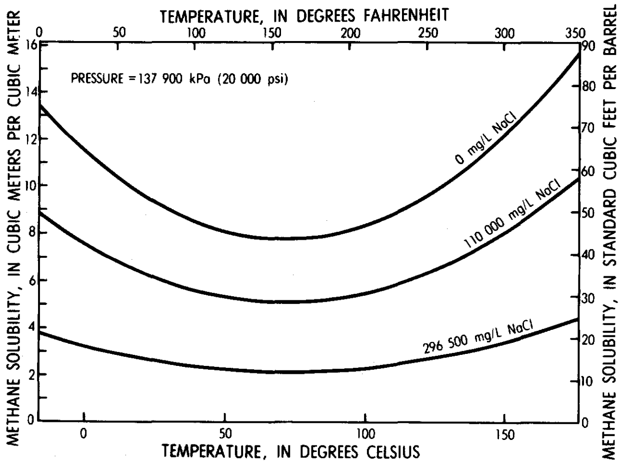

Figure 25.--The effect of salinity and temperature variations on methane solubility in aqueous solutions at a constant pressure of 137,900 kPa (20,000 psi). One barrel = 42 gallons = 5.61 ft^3.

e. Values of a parameter computed for each node during the creation of a grid file for an interval were not allowed to exceed the range of calculated values within that interval for that particular parameter.

These assumptions and criteria were imposed during various steps of the computational procedure as indicated in the simplified flow diagram (fig. 22).

ESTIMATE OF ACCESSIBLE FLUID RESOURCE BASE

The volume of water stored in the geopressured sandstone and shale beds of the northern Gulf of Mexico basin is calculated to be 196 x 10^{12} m^3 (see table 15). About 10 percent of this volume occurs in sandstone, and about 90 percent occurs in shale. The thermal energy in this volume of stored water, referenced to 15°C, is 107,000 x 10^{18} J of thermal energy; 11,000 x 10^{18} J of the thermal energy is estimated to be contained in sandstone reservoirs and 96,000 x 10^{18} J in shale.

The volume of methane calculated to be dissolved in the geopressured waters of the northern Gulf of Mexico basin at saturation conditions is estimated to be 1670 x 10^{12} m^3 or 59,000 x 10^{12} ft^3. Expressed in thermal equivalent, this methane energy equals 63,000 x 10^{18} J, assuming a heat equivalent of 3.73 x 10^7 J/m^3 of methane. The volume of methane dissolved in waters of sandstone is 160 x 10^{12} m^3 (5700 x 10^{12} ft^3), whereas waters in shale are estimated to contain 1510 x 10^{12} m^3 (54,000 x 10^{12} ft^3). These estimates represent only the amount of methane that could theoretically be held in solution at reservoir pressures, temperatures, and salinities as determined in the assessment procedure.

Total energy in the accessible fluid resource base as thermal energy and thermal-equivalent methane energy is given in table 16 by lithology and by State to the outer limit of State-controlled waters in the Gulf of Mexico and by Federal ownership within the Outer Continental Shelf (OCS) area. The total accessible fluid resource base is estimated to be 170,000 x 10^{18} J. Almost half (45 percent) occurs in Texas, 17 percent in Louisiana, and the remainder in the Federal OCS area. This refined and expanded estimate of the identified accessible fluid resource base, as thermal and methane energy in both sandstone and shale, increases the preliminary estimate reported by Papadopulos, Wallace, Wesselman, and Taylor (1975, table 24) by about 2½ times.

In the present assessment, the sandstone volume in relation to the total volume of sediment has been determined to be 36 percent less than in Papadopulos, Wallace, Wesselman and Taylor (1975). This reduction can be attributed to three facts: 1) dimensions of the study area have changed both vertically and horizontally, 2) net sandstone thicknesses in the individual wells were restricted to counted thicknesses without extrapolation below the total depth of the wells, and 3) most importantly, significantly more information was available to define the accessible fluid resource base more accurately.

Areal distribution of the thermal and methane energy contained in pore waters of sandstone in the study area is shown on map 3. In general, the areas of high and low energy contour values for both thermal and methane energy are in agreement. Agreement is also good on map 3 between areas of high thermal energy content (40 x 10^{15} J/km^2 or more) and areas identified as having high potential for the development of geopressured-geothermal resources. For example, in Texas the Hidalgo Fairway identified by Bebout, Loucks and Gregory (1978a) and the Harris Fairway identified by Bebout, Gavenda, and Gregory (1978) show thermal energy contents from about 40 to more than 80 x 10^{15} J/km^2. However, some discrepancies in location are observed. For instance, in the vicinity of the Brazoria Fairway, the 40 x 10^{15} J/km^2 contour should appear coincident with the fairway. The discrepancy is probably attributable to: 1) the selection of different wells by University of Texas and USGS investigators, 2) insufficient well control in the present study, relative to the grid spacing used, and 3) the computer routine used in contouring in the present study.

Other areas of high energy content are not necessarily hydrogeologically acceptable prospects. Detailed analysis of the geopressured-geothermal resource potential of these areas is necessary to locate additional sites for development or testing. The impression of reservoir continuity given by the contour map can be misleading because the reservoirs containing the

Table 15.--*Accessible fluid resource base of geopressured-geothermal energy in the northern Gulf of Mexico basin by depth interval*

(Volumes and energies given to two significant figures. However, if the first digit is 1, three significant figures are given in order more closely to approximate uniform percentage accuracy. Energy equivalent of methane considered to be 3.73 x 10^7 J/m^3.)

Lithology	Interval number	and depth to midpoint (ft)	(m)	Volume of water in storage ($10^{12}m^3$)	Thermal energy (10^{18} J)	METHANE ENERGY Thermal equivalent (10^{18} J)	METHANE ENERGY Volume ($10^{12}m^3$)	METHANE ENERGY Volume (10^2ft^3)	Total thermal and methane energy (10^{18} J)
Sandstone	1	2250	(686)	0.1	11	3	0.1	2.8	14
	2	3750	(1143)	.1	24	6	.2	5.9	30
	3	5250	(1600)	.3	60	20	.5	18.5	80
	4	6750	(2057)	.6	160	52	1.4	50	210
	5	8250	(2514)	1.2	380	130	3.5	124	520
	6	9750	(2972)	1.7	630	220	5.7	200	840
	7	11250	(3429)	2.1	900	320	8.6	310	1,220
	8	12750	(3886)	2.2	1,040	410	11.0	390	1,450
	9	14250	(4343)	2.2	1,130	530	14.0	500	1,660
	10	15750	(4800)	2.1	1,200	620	16.3	580	1,810
	11	17250	(5258)	1.7	80	570	15.2	540	1,550
	12	18750	(5715)	2.7	1,640	1,150	30	1,090	2,800
	13	20250	(6172)	1.3	870	550	14.7	530	1,420
	14	21750	(6629)	2.8	2,000	1,460	39	1,380	3,500
Sandstone	TOTAL---------------------			21	11,000	6,000	160	5,700	17,100
Shale	TOTAL---------------------			175	96,000	57,000	1,510	54,000	153,000
TOTALS---------------------------------				196	107,000	63,000	1,670	59,000	170,000

energy resource are, in fact, compartmented by faulting. Size of the compartment would determine, in part, the plan of development.

Table 16.--*Accessible fluid resource base of geopressured-geothermal energy in the northern Gulf of Mexico basin, by area*

(Energies given in units of 10^{18} joules rounded off to two significant figures or to three significant figures if the first digit is 1. Energy equivalent of methane considered to be 3.73×10^7 J/m^3.)

		Sandstone	Shale	Total
Texas	Thermal	3,200	44,000	47,000
	Methane	1,890	28,000	30,000
	Total---	5,100	72,000	77,000
Louisiana	Thermal	2,600	16,100	19,000
	Methane	1,330	9,000	10,000
	Total---	4,000	25,000	29,000
Federal Outer	Thermal	5,200	37,000	42,000
Continental	Methane	2,800	19,400	22,000
Shelf Area	Total---	8,000	56,000	64,000
TOTAL NORTHERN	THERMAL	11,000	96,000	107,000
GULF OF MEXICO	METHANE	6,000	57,000	63,000
BASIN	TOTAL---	17,100	153,000	170,000

RELIABILITY OF ESTIMATES OF ACCESSIBLE FLUID RESOURCE BASE

Many factors affect the reliability of the estimate of the accessible fluid resource base. The density of control points is very important in that, ideally, the entire assessment area should be sampled sufficiently to gain precise knowledge of the conditions everywhere within it. Uncertainties about the properties of the sedimentary rocks and contained fluids will also affect the reliability of the estimates of the accessible fluid resource base.

One of the major problems that arose in this study was the obtaining of adequate data coverage, particularly at depth, for the entire basin. The Federal OCS off the Texas coast contains relatively few wells, and most of these are concentrated along the 3-league (19.3-km) State-Federal jurisdictional boundary and also in the High Island area near the boundary of the neighboring Federal OCS off Louisiana. Several large areas have been only sparsely drilled. The very limited data in these areas necessarily reduce the reliability of the assessment.

Information also becomes scarce and unevenly distributed with increasing depth (see table 17 for vertical distribution of data points). Many deep wells have been or are being drilled in the hydrocarbon-producing regions of the Upper Cretaceous Tuscaloosa Formation in central Louisiana, where gas has been discovered at approximately 20,000 ft (6100 m). Similarly, in the deep Miocene hydrocarbon-producing region along coastal Louisiana, many wells are drilled to 18,000 ft (5500 m) and deeper. In these regions, reliable data can usually be collected from deep reservoirs. These reservoirs, however, constitute only a small percent of the total assessment area. As a result, most data from deeper intervals are concentrated in two small areas. Data on deep conditions over the remainder of the assessment area are provided only by a few widely separated, deep wildcat wells.

It is readily apparent, therefore, that the estimate of the accessible fluid resource base is most reliable in the shallower intervals, where most of the data occur, and becomes less reliable with increasing depth. Intervals 12, 13 and 14 have the least amount of data, and, consequently, the greatest degree of uncertainty. This deficiency helps explain the variability in calculated energies in sandstone beds in these intervals.

In the following evaluation, all of the factors that influence our calculations are considered in order to determine the maximum reasonable error due to uncertainties in the various data sets and physical-chemical properties. In order to estimate a lower bound for the accessible fluid resource base, the evaluation assumes that all errors contribute to a reduction of the estimate.

Inaccuracies in water density, heat content, and the experimentally determined solubility of methane are unlikely to cause any appreciable error in the estimates of the accessible fluid resource base. Uncertainties in temperature and pressure, especially in areas of sparse data, would probably cause a combined error of about 10 percent. Reasonable errors of 2 or 3 percent in porosity could result in an error of about 20 percent in the estimated volume of stored water (Papadopulos and others, 1975, p. 133). A systematic error in determining the depth to the top of the geopressured zone by 305 m (1000 ft) would result in a 5 percent or less reduction of the accessible fluid resource base. An error in salinity of 100 percent (actual greater than calculated) would probably result in a decrease of 25 percent in the methane solubility. Combining all the above factors would reduce the fluid resource base from $170,000 \times 10^{18}$ J to $95,000 \times 10^{18}$ J. Assuming further that the actual methane content of formation water is only 50 percent of experimentally determined saturation values at the actual water salinities, the accessible fluid resource base would be further reduced to $82,000 \times 10^{18}$ J.

Table 17.--*Number of wells or observations used in this assessment by parameter and midpoint depth of interval*

Interval number	and depth to midpoint (ft)	(m)	Sandstone data[1] Texas	Texas Off-shore	Loui-siana	Loui-siana Off-shore	TOTAL	Temperature data[1] Texas	Texas Off-shore	Loui-siana	Loui-siana Off-shore	TOTAL	Salinity data[1] Texas	Texas Off-shore	Loui-siana	Loui-siana Off-shore	TOTAL	Pressure data[2] Texas	Texas Off-shore	Loui-siana	Loui-siana Off-shore	TOTAL
1	2250	(686)	1435	276	756	680	3147	1400	256	374	196	2226	730	207	143	190	1270	19	7	1	21	48
2	3750	(1143)	1449	282	959	778	3468	1399	255	374	196	2224	769	216	237	352	1574	93	17	2	61	173
3	5250	(1600)	1449	282	973	794	3498	1395	248	374	196	2213	737	223	257	365	1582	269	15	8	90	382
4	6750	(2057)	1433	276	977	783	3469	1352	231	374	195	2152	687	204	257	354	1052	622	33	65	147	867
5	8250	(2514)	1361	251	978	754	3344	1263	202	373	188	2026	651	179	251	337	1418	643	18	324	231	1216
6	9750	(2972)	1210	215	978	686	3089	1073	150	372	179	1774	570	125	229	314	1238	315	5	595	274	1189
7	11250	(3429)	913	151	890	593	2547	732	101	339	160	1332	393	69	217	267	946	93	1	541	256	891
8	12750	(3886)	545	90	723	445	1803	409	47	279	129	864	214	33	166	206	619	42	3	451	125	621
9	14250	(4343)	307	40	540	283	1170	232	16	207	86	541	113	5	135	135	253	15	0	261	48	324
10	15750	(4800)	166	10	363	107	646	126	4	126	30	286	50	3	93	45	191	2	0	77	9	88
11	17250	(5258)	64	5	176	17	262	43	0	68	4	115	20	3	64	14	101	1	0	9	0	10
12	18750	(5715)	23	1	66	2	92	16	0	30	1	47	6	1	31	3	41	1	0	6	1	8
13	20250	(6172)	4	0	25	0	29	5	0	14	0	19	1	0	14	1	16	4	0	2	0	6
14	21750	(6629)	2	0	10	0	12	3	0	7	0	10	0	0	4	1	5	0	0	0	0	0

[1]Number of wells used, by interval.
[2]Number of observations

ASSESSMENT OF RECOVERABLE ENERGY

The recoverability of energy from geopressured reservoirs depends on the amount of water that can be produced by wells tapping these reservoirs. In turn, this production depends on the hydrogeolgic properties of the sandstone and shale that comprise the reservoirs. The most important hydrogeologic factor is transmissivity (Papadopulos and others, 1975, p. 173).

In order to provide an "order-of-magnitude" assessment of recoverability, Papadopulos, Wallace, Wesselman, and Taylor (1975) selected three development plans on the basis of hydrogeologic, economic, and environmental factors and then applied these plans to generalized "conceptual" reservoirs. Each plan specified the transmissivity, production period, well diameter, flow rate, and allowable drawdown (or wellhead pressure). In plan 1, wellhead pressure was restricted to a minimum of 14 MPa (2000 lb/in^2). In plan 2, wellhead pressure was unrestricted, and in plan 3, wellhead pressure was kept sufficiently high to limit ground subsidence to 1 m. Recoverable energy as a percentage of accessible fluid resource base was 2.1 percent for plan 1, 3.3 percent for plan 2, and 0.5 percent for plan 3. Mechanical energy was calculated for plans 1 and 3 only, and constituted only 2.6 percent and 3.8 percent, respectively, of the total energy produced.

In the present assessment, the ratio of sandstone volume to the total volume of sedimentary rock has been determined to be 36 percent less than the value determined by Papadopulos, Wallace, Wesselman and Taylor (1975). Furthermore, it is estimated that only one-half of the sandstone volume will be developed. The net result of these adjustments is that the transmissivities for this assessment are reduced by 66 percent from those assumed in the previous assessment.

Following the methodology of Papadopulos, Wallace, Wesselman and Taylor (1975, p. 140), a two-thirds reduction in transmissivity gives corresponding reductions in recoverable energy of about 20 percent in the case of plan 2 and 50 percent in the case of plan 3. This adjustment results in a range of recoverable energy of 0.25 to 2.6 percent of the accessible fluid resource base. See table 18 for estimates of recoverable energy by area and development plan.

Using these percentages, the total recoverable thermal energy and energy equivalent of methane is estimated to be between 430 x 10^{18} and 4400 x 10^{18} J. This range encompasses the range of most of the recoverability estimates of others discussed previously in this report.

These estimates assume that the geopressured-geothermal water is saturated with methane. If significant quantities of free gas are trapped in the pore space of the reservoir, recoverable energy in excess of 2.6 percent may be possible. However, if the water is undersaturated in methane, the recoverable energy will be proportionally less.

Table 18.--*Geopressured-geothermal resource (= recoverable thermal energy and energy equivalent of methane) in the northern Gulf of Mexico basin, by area*

(Energies given in units of 10^{18} joules rounded off to two significant figures or to three significant figures if the first digit is 1. Energy equivalent of methane considered to be 3.73 x 10^7 J/m^3. Development plans are those of Papadopulos, Wallace, Wesselman, and Taylor, 1975.)

		Plan 2	Plan 3
Texas	Thermal------	1220	117
	Methane------	790	76
	Total--------	2000	193
Louisiana	Thermal-------	490	47
	Methane-------	270	26
	Total---------	760	73
Federal Outer Continental Shelf Area	Thermal------	1080	104
	Methane-------	580	56
	Total--------	1660	160
TOTAL NORTHERN GULF OF MEXICO BASIN	THERMAL------	2800	270
	METHANE------	1640	158
	TOTAL--------	4400	430

Garg, Pritchett, Rice, and Riney (1977) concluded that energy recoverable from a geopressured-geothermal reservoir would be increased 5 to 10 times with reinjection into the producing reservoir. If the reservoir volume is one-half of the sandstone volume and if sandstone constitutes 10 percent of the total sedimentary volume, the upper estimate of recoverable energy would increase to approximately 5 percent of the total accessible fluid resource base.

Credible estimates of the amount of recoverable geopressured-geothermal energy, based upon reasonable production scenarios, must await the results of ongoing and future tests of aquifers designed to determine their hydraulic properties accurately. Short-term test data currently available, although encouraging, are inconclusive. Reservoir parameters, especially transmissivity and individual reservoir extent, which are the most critical factors determining ultimate resource recoverability, are no better defined now than they were in 1975.

REQUIREMENTS FOR FUTURE STUDIES

The accuracy of the accessible fluid resource base estimated in the present study is dependent largely on the one factor that, at this time, is the most uncertain - that is, whether water contained in sedimentary rocks of the geopressured zone of the northern Gulf of Mexico basin indeed is saturated with dissolved methane. A corollary to this is whether immobile gas exists in geopressured reservoirs, as suggested by Randolph (1977b). Resolution of this uncertainty is necessary prior to any further attempts to refine the accessible fluid resource base.

Recoverability of energy from the accessible fluid resource base is another largely unknown factor that requires many test data for proper evaluation. Knowledge of the behavior of a geopressured aquifer over several years of large-scale production is necessary in order to determine the most efficient and economical drilling and development plans with respect to number of wells, well spacing, flow rates, reinjection programs, water disposal methods, and other factors.

Information concerning the factors mentioned above will be gained only by a program of identifying prospective areas suitable for geopressured-geothermal development and drilling wells in these areas to test both aquifer hydraulics and methane content. Such a program is being carried out by the U.S. Department of Energy (DOE). The first geopressured-geothermal test well, the DOE (Coastal States Gas Producing Company and Preston Oil Company) Edna Delcambre #1, an abandoned gas well in Tigre Lagoon Field, Vermilion Parish, La., indicated methane present at approximately saturation values in water from two aquifers. Results of short-term tests (approximately 3 weeks for both aquifers tested) designed to examine the potential for energy recovery were encouraging.

Several additional short term (2-week to 3-month) aquifer tests are planned by the DOE in both Louisiana and Texas. In addition, drilling began in June, 1978 on the DOE (General Crude Oil Co.) Pleasant Bayou #1 well in Brazoria County, Texas. This is the first well in the United States designed and drilled specifically to test geopressured-geothermal aquifers. Testing is expected to last for about a year in order to obtain information on the long-term behavior of sandstone aquifers subjected to large-volume water production. The drilling of at least one similar long-term test well is also planned for Louisiana. These tests should yield valuable data that will permit recoverability to be estimated in the future with a greater degree of certainty.

The degree to which the data needs outlined in this section are met will determine, in large part, futher refinements of estimates presented in this report. With additional, more reliable data and adjustments of the techniques used in this report, a better approximation of the accessible fluid resource base and its recoverability can be achieved.

OTHER GEOPRESSURED BASINS OF THE UNITED STATES

In conjunction with this assessment of geopressured-geothermal energy in the northern Gulf of Mexico basin, information has been compiled on other geopressured basins of the United States (fig. 26). A general description of physical conditions in these basins is given in table 19. This information is presented primarily to call attention to those areas outside the northern Gulf of Mexico basin where hydrogeologic conditions may be similar and, therefore, where geopressured-geothermal energy might exist. The potential is greater for some of the basins listed than it is for others. For example, the dominant geopressuring mechanism of the northern Gulf of Mexico basin is vertical compression due to rapid sedimentary loading (table 19). This mechanism is very signficant in forming large volumes of geopressured sedimentary rocks, but it may not be the dominant mechanism in some of the other basins. Geopressured zones are only local occurrences in some of these basins and may occur sandwiched between shallower and deeper zones of normal pressure. Also, the sediments in some geopressured basins may not be as hot as those of other basins. Methane is likely to be dissolved in waters of geopressured basins other than the northern Gulf of Mexico basin, as is suggested by the occurrence of natural gas in tight formations in the Green River basin and elsewhere. Similarly, Berry (1973, p. 1237) considers dry gas in California's Sacramento Valley to originate by the continuing release from aqueous solution of a dominantly methane-rich gas phase that ascends from regions of high fluid pressure.

SUPPLEMENTAL INFORMATION ON DATA COLLECTION AND ORGANIZATION

Sandstone Content

The areal and vertical distribution of sandstone beds in the study area was determined from 3525 geophysical well logs. The number of wells used in each interval is given in table 17. Net sandstone thicknesses were measured and recorded in 500-ft (152-m) intervals over the entire length of the log, using sea level as reference.

For the most part, net sandstone thickness was determined using the spontaneous potential (SP) curve. Appropriate shale and sandstone base lines were drawn on the log. A third line, drawn halfway between the base lines, was used

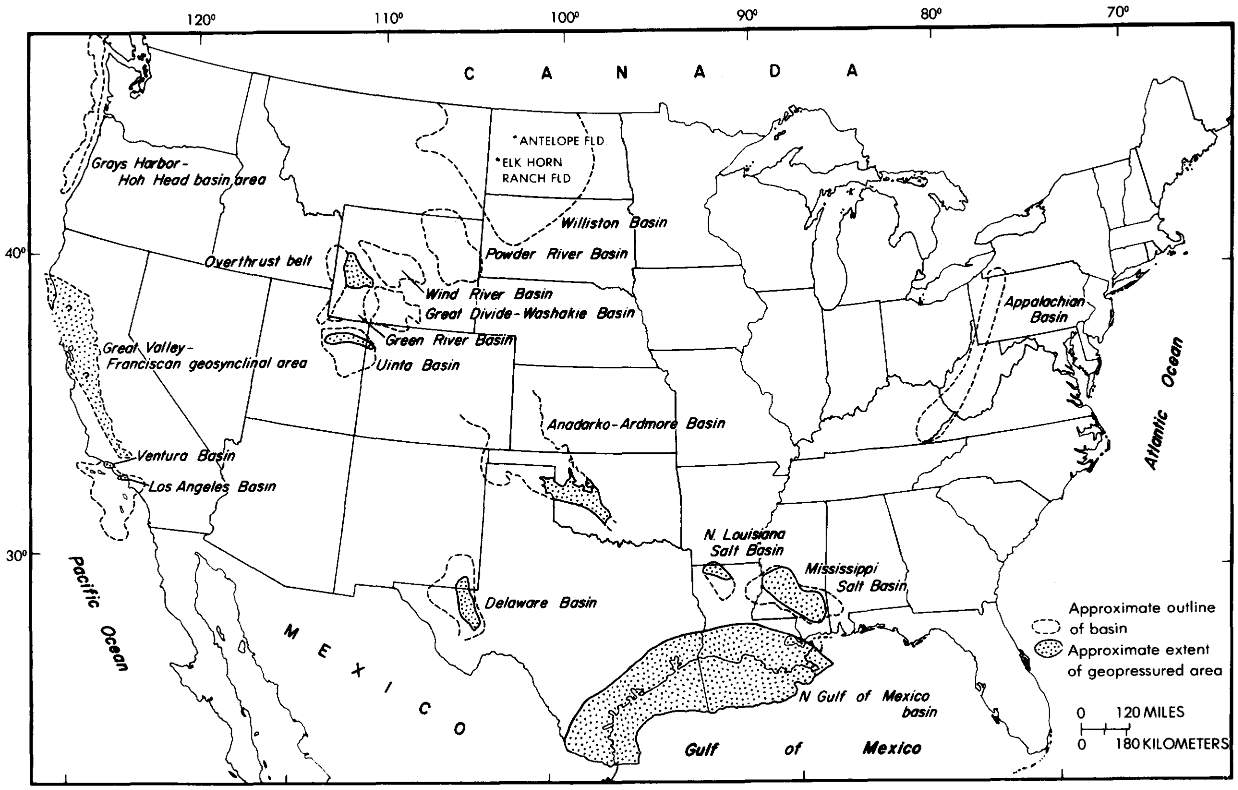

Figure 26.--Geopressured basins of the United States.

as the sandstone-shale divider. When the SP curve was deflected across the midline to the left, sandstone was recorded until it again deflected across the midline to the right, indicating shale.

This procedure worked well except when sandstone beds of low porosity or low salinity were encountered. In such cases, the SP curve becomes very subdued, disappears completely or reverses, and cannot be used to determine sandstone accurately. The resistivity curve usually was used in these instances to distinguish sandstone from shale because the sandstone exhibited higher resistivity. Sandstone thickness was then determined by accumulating the definite peaks on the resistivity log.

In some instances, especially in very deep wells and in wells penetrating Cretaceous sedimentary rocks, a gamma ray-resistivity log was run in place of the SP-resistivity log for the deeper runs. If the gamma ray log showed suitable variation in intensity, indicating clear distinction of sandstone and shale, the gamma ray curve was used to estimate sandstone content. If, as was many times the case, the gamma ray log was noisy or otherwise nondistinctive, the resistivity curves were again used to estimate sandstone content.

After the selected wells were "sand counted" and the net sandstone value per 500-ft (152-m) interval coded, the data were converted by computer into the 1500-ft (457-m) intervals for use in the assessment. Vertical extrapolations of sandstone content below the total depths of wells were not attempted. For wells not penetrating a complete 500-ft (152-m) interval, only the amount of sandstone recorded to total depth from the beginning of the last 500-ft (152-m) interval was used. No extrapolation or proportioning was carried out to estimate total sandstone in the last segment as if it were a complete 500-ft (152-m) interval. The amount of sandstone below the depths reached by these wells in the assessment model was controlled by horizontal extrapolation using trend-surface analysis based on available control within each depth interval.

Porosity

Sandstone

Decrease of porosity with depth was determined individually for each major embayment in the study area. For the Rio Grande and Houston embayments a wide range of porosity determinations from side-wall cores, conventional cores, and well test data were used. For the Mississippi embayment, porosity information from the Federal Power Commission's (FPC) (now Federal Energy Regulatory Commission) files (form 15), which contain average porosities of gas reservoirs, was used. A linear relation of porosity (ϕ in percent) with depth (D in ft) was then determined by least-squares regression analysis for the data in each embayment. The resulting relations, along with the number of data points (n) used, are:

a. Rio Grande embayment
$\phi = 28.6534 - (0.000951)\ D \qquad (n = 3519)$

b. Houston embayment
$\phi = 29.5457 - (0.000847)\ D \qquad (n = 945)$

c. Mississippi embayment
$\phi = 33.5985 - (0.000652)\ D \qquad (n = 4816)$

These relations, plotted in figure 24, show that the porosity of sandstone at any depth is highest and decreases least with depth in the Mississippi embayment, followed by the Houston embayment, and finally the Rio Grande embayment.

Owing to the scatter of data points, no systematic increase in porosity at any depth was seen. In individual wells, however, porosity has been observed to increase below the top of the geopressured zone and then to decrease at greater depth (Stuart, 1970).

Bebout, Loucks, and Gregory (1978b) identified and described various "geothermal fairways" (see map 3 for locations) in the Texas Gulf Coastal Plain. Their description included porosity estimates based on diamond core analyses. Diamond core is generally better than side-wall core for determining porosity in that diamond coring is less damaging to the sample of the formation taken. Consequently, diamond cores may reflect more accurately the porosity under in situ conditions. Porosities calculated by the equations developed in this study were compared to porosities reported in the fairways. Agreement was usually within 1-2 percent.

In comparing porosity values obtained from conventional or diamond cores with porosities calculated using the equations presented in this study, it should be pointed out that almost all of the measured porosity values in Texas were from sedimentary rocks of Oligocene age. In the Gulf Coast, however, porosity generally decreases with the increasing age of the geologic formation (see, for example, Maxwell, 1964). In the study area, all three embayments contain sedimentary rocks ranging in age from Upper Cretaceous to Holocene. Thus, although the porosity equations for the Houston and Rio Grande embayments predict actual conditions in Oligocene rocks quite well, they may predict higher than average values for Eocene rocks and, conversely, lower than average values for Miocene and younger sandstone offshore.

For the Mississippi embayment, the equation developed predicts higher porosities than for either of the two Texas embayments because most of the porosity data used in generating the equations comes from Miocene gas reservoirs. Porosity conditions in these sedimentary rocks of the Mississippi embayment are probably well represented by the equation, but porosities in the Cretaceous sandstones may be lower than predicted by the equation and porosities in the Pleistocene sand beds may be higher.

Variations in porosity may also result from the effects of deep burial and high temperature. In coastal south Texas, where subsurface temperatures are generally higher at equivalent depth than in Louisiana, the corresponding porosities are usually much lower. Pore space has apparently been reduced by diagenetic reactions occurring in the hotter but petrologically immature Oligocene sandstones of Texas.

Shale

Determination of shale porosity with depth was accomplished in essentially the same way in this study as in Papadopulos, Wallace, Wesselman, and Taylor (1975). The general plot of porosity decrease in shale with depth for the Tertiary of the Gulf Coast shown by Dickinson (1953, p. 428, fig. 15) was approximated by a polynomial equation that was used to determine the shale porosity at each interval midpoint for each well (fig. 24, this study). Dickinson based his curve on a shale density versus depth curve for the same geographic area in which he showed that newly deposited clayey sediments contain 60-90 percent water and have a density of 1.8 g/cm^3. Other shale measurements at greater depths showed progressively increasing density to a limit of approximately 2.5 g/cm^3 at which the density remained constant or increased only slightly toward the theoretical density of the constituent shale particles of 2.65 g/cm^3 ("zero porosity").

Like the porosity equations for sandstone, the slope of Dickinson's curve for shale porosity shows no change when the geopressured zone is intersected. Individual wells, particularly in southern Louisiana and offshore, do show increases in shale porosity below the top of the geopressured zone (Schmidt, 1973, p. 324). This, in fact, is a common phenomenon, as shown by the numerous well logs that show low-resistivity or low-density shale (undercompacted shale with high porosity) below the top of the geopressured zone. A method for relating this increase on a regional scale to a curve like Dickinson's does not exist at the present time.

Use of Dickinson's curve for shale may lead to errors of the same type as those discussed regarding the sandstone porosity method because for any given interval, all shale will be treated the same. Thus, the Miocene and younger sediments of southern Louisiana and the Federal OCS area will be assigned the same porosity value as the Cretaceous shales in the northern extreme of the study area. They are, in fact, quite different. At comparable depths, the young offshore sediments have not been subjected to high temperatures for as great a time period as have the Cretaceous sedimentary rocks. Rocks in these two areas also differ mineralogically.

Similarly, the higher temperature conditions in the part of the study area in Texas, as compared with the part in Louisiana, have permitted thermal diagenetic reactions in shale to proceed further in the Texas area. Thermal diagenesis

Table 19.--*General description of the geopressured*

Geologic basin(s)	Geologic ages and (or) formations	Approximate depth range
1. Northern Gulf of Mexico basin: Texas and Louisiana, onshore-offshore.	Almost all Cenozoic formations and some deep Mesozoic formations of Cretaceous and Jurassic age.	1500 ft (457 m) to maximum depth drilled 25,600 ft (7802 m)
2. Mississippi salt basin: Mississippi, southwest Alabama(?).	Mesozoic formations: Cretaceous to Jurassic age: Buckner Mbr. of Haynesville Fm., Smackover and Norphlet Fms., and Cotton Valley Group.	12,500 ft (3810 m) to maximum depth drilled 25,640 ft (7815 m)
3. Appalachian basin: New York, Pennsylvania, West Virginia, western Virginia.	Paleozoic formations: Devonian to Cambrian age: Oriskany, Onondaga, and Knox Formations.	11,225 ft (3421 m) to 20,222 ft (6163 m)
4. Anadarko - Ardmore basin: basin: northwest Texas, west-central Oklahoma.	Paleozoic formations: Pennsylvanian, Devonian, Silurian, Ordovician: Mona sand, Atoka, Deese, Sycamore, Viola, Springer, and Hunton Fms., Dornick Hills and Simpson Gps., and Morrowan and Chesterian Series.	6000 ft (1829 m) to 30,050 ft (9159 m)
5. North Louisiana salt basin: north central Louisiana and south central Arkansas(?).	Mesozoic formations: Smackover Fm. and Gray sand.	10,900 ft (3322 m) to 13,000 ft (3962 m)
6. Delaware basin: southeastern New Mexico and west Texas.	Paleozoic formations: Permian, Pennsylvanian, Mississippian, Devonian, Ordovician: Strawn, Atoka, Springer, Barnett, Woodford and Simpson Fms. and Morrowan Series.	8000 ft (2438 m) to 23,000 ft (7010 m)
7. Uinta basin: northeastern Utah and western Colorado.	Cenozoic and Mesozoic fms.: Eocene: Green River, Wasatch and older Formations.	10,000 ft (3048 m) to 19,500 ft (5943 m)
8. Greater Green River basin including over-thrust belt, Wind River, Powder River and associated basins: Wyoming, eastern Idaho, northern Utah and northern Colorado.	Cenozoic and Paleozoic formations: Eocene and Permian age: Wasatch and Green River through Phosphoria Formations.	1000 ft (305 m) to 20,000 ft (6096 m)
9. Williston basin: North Dakota.	Paleozoic formations: Devonian: Sanish zone-Antelope and Elk Horn Ranch fields.	10,000 ft (3048 m) to 10,600 ft (3231 m)
10. Great Valley miogeosyncline Franciscan eugeosyncline, Santa Barbara Channel, Los Angeles, Ventura and Tanner Banks basins: California onshore-offshore.	Cenozoic and Mesozoic formations: Pliocene to Jurassic age.	400 ft (122 m) to 17,700 ft (5395 m)
11. Grays Harbor to Hoh Head basin area: offshore Oregon and Washington, Coos Bay to Vancouver Island.	Cenozoic Formations: Pliocene to Eocene age.	3000 ft (914 m) to 12,000 ft (3657 m)

basins of the United States shown on figure 26

Approximate fluid-pressure range	Approximate temperature range	Probable geopressuring mechanisms
0.46 to 1.00 psi/ft (10.4 to 22.6 kPa/m)	<100°F to 555°F (<38°C to 291°C)	Vertical compression (static load); resistance to fluid expulsion; diagenesis; uplift.
0.50 to 1.06 psi/ft (11.3 to 23.96 kPa/m)	240°F to 456°F (116°C to 236°C)	Diagenesis; internal forces; vertical compression (static load); resistance to fluid expulsion.
0.60 to 0.94 psi/ft (13.6 to 21.24 kPa/m)	160°F to 272°F (71°C to 133°C)	Horizontal compression (dynamic loading); resistance to fluid expulsion; diagenesis.
0.52 to 0.85 psi/ft (11.8 to 19.2 kPa/m)	140°F to 425°F (60°C to 218°C)	Horizontal compression (dynamic loading); resistance to fluid expulsion; uplift.
0.55 to 0.90 psi/ft (12.4 to 20.3 kPa/m)	200°F to 300°F (93°C to 149°C)	Internal forces; vertical compression (static load); resistance to fluid expulsion.
0.65 to 0.94 psi/ft (14.7 to 21.24 kPa/m)	140°F to 340°F (60°C to 171°C)	Vertical compression (static load); resistance to fluid expulsion.
0.55 to 0.83 psi/ft (12.4 to 18.8 kPa/m)	200°F to 284°F (93°C to 140°C)	Horizontal compression (dynamic loading); resistance to fluid expulsion; uplift.
0.57 to 0.91 psi/ft (12.9 to 20.6 kPa/m)	100°F to 320°F (38°C to 160°C)	Horizontal compression (dynamic loading); resistance to fluid expulsion; uplift.
0.51 to 0.73 psi/ft (11.5 to 16.5 kPa/m)	140°F to 260°F (60°C to 127°C)	Uplift; resistance to fluid expulsion.
0.44 to 1.00 psi/ft (9.9 to 22.6 kPa/m)	<100°F to 390°F (<38°C to 199°C)	Horizontal compression (dynamic loading); internal forces; uplift; resistance to fluid expulsion.
0.62 to 0.86 psi/ft (14.0 to 19.4 kPa/m)	100°F to 205°F (38°C to 96°C)	Vertical compression (static load); uplift; resistance to expulsion.

causes dewatering of shale by freeing bound intracrystalline water at high temperature (higher than the critical 93°-110°C temperature range) (Burst, 1969). If the water is expelled from the shale, a net loss of pore space can occur.

Temperature

Collection of temperature data for this study was accomplished by essentially the same technique as for Circular 726. In fact, the original data base was updated and supplemented for this assessment. Processing of the data differed, however, because of differences in approach between the first assessment and this one.

The temperature data base was selected from well log headings of 2226 wells located throughout the study area. Temperature measurements of each log run for each well were assembled into a data file. The number of temperature measurements per well ranged from 1 to more than 15. The temperatures entered were then corrected to equilibrium conditions according to depth using an equation developed by the American Association of Petroleum Geologists' Geothermal Survey of North America Committee:

$$T_E = T_L + (7.689 \times 10^{-14} D^3 - 3.888 \times 10^{-9} D^2 + 3.619 \times 10^{-5} D + 0.270245)\ D/100$$

where T_E is the equilibrium temperature, in degrees Fahrenheit, T_L is the log temperature, in degrees Fahrenheit, and D is the depth, in feet, at which the log temperature was measured.

After correction, the temperature at interval midpoints was calculated for each well by using gradients calculated from the temperature measurements in each well and interpolating to obtain the temperature at each interval midpoint. If the first log-run temperature was deeper than an interval midpoint, a linear gradient between a near-surface reference temperature and the log-run temperature was used to calculate the midpoint temperature. Because the amount of temperature data available decreased with depth, it became necessary to extrapolate to lower interval midpoints in order to obtain a sufficient number of data points for intervals 12, 13, and 14 (table 17). For depths below interval 10, the average increase in temperature was 20°F/1500 ft. This gradient was used to extrapolate temperatures to the lower interval midpoints. Only those wells with measurements in interval 11 or deeper were used in the extrapolation.

Density

Density of water at the temperature, pressure, and salinity existing at interval midpoints was determined using the data of Potter and Brown (1977), which give the density of water under conditions to 500°C (932°F), 200 MPa (29,000 psi), and 25 weight percent NaCl. See sections on temperature, pressure and salinity for explanation of how these parameters were estimated for interval midpoints.

Heat Content

Heat content of the water at interval midpoint conditions of temperature and salinity was calculated using a computer program developed by John L. Haas, Jr. (USGS, Reston, Virginia). This program determines the average specific heat, in J/g/K, of water of specified salinity between two temperature values. The temperature values in this study were the temperature at the midpoint of an interval and 15°C (288 K). Multiplying the average specific heat term by the number of degrees in the temperature range gave a close approximation of the heat content of water referenced to 15°C (288 K).

Salinity

Salinity of formation water in sandstone of the study area was estimated exclusively from geophysical well logs. A computer program, based upon a widely used petroleum industry service company method, was developed for salinity determinations using SP measurements and log heading data. This technique has a solid basis in physical chemistry (see for example, Gondouin and others, 1957). Equations were generated that replace the charts used in this method for determination of salinity as dissolved NaCl. The program also corrects temperature values obtained from the log heading to an equilibrium temperature using the American Association of Petroleum Geologists' Geothermal Survey of North American Committee temperature correction equation (see section on temperature), before entry into the analytical part of the program, thus enabling a more precise determination of salinity.

Sandstone beds 30 ft (9 m) or greater in thickness with fully developed SP curves were selected from the logs for salinity calculation. Depth datum was sea level. After calculation of a salinity for each sandstone SP measurement selected, the resulting data base was organized into 1500-ft (457-m) intervals for determination of average salinity at interval midpoints for each of the wells selected. A total of 1748 wells was used for this part of the study.

With increasing depth, the number of salinity determinations per 1500-ft (457-m) interval decreased drastically until, for the last two intervals, only 16 and 5 values were available in the 13th (midpoint = 20,250 ft) and 14th (midpoint = 21,750 ft) intervals, respectively. For these last two intervals, the median values of the salinities in the respective interval were used as the salinity values at interval midpoints.

Salinity of water in shale was assumed to be the same as salinity of water in sandstone in the geopressured zone. For a well in Manchester Field, Louisiana, Schmidt (1973) showed that, above the top of the geopressured zone, water in sandstone was considerably more salty than water in shale. Below the top of the geopressured zone, however, the salinity of water in sandstone more closely approximated the salinity of water in shale. Since the present study deals only with the geopressured zone, this assumption seems reasonable, especially since ultimately only those salinity determinations below the top of the geopressured zone were used.

Determination of Fluid Pressure at Interval Midpoints

Measured Pressures

Pressure information was collected from several sources. The major source of data for southern Louisiana onshore and offshore was the FPC files (form 15) that list the original formation pressures of commercially produced gas reservoirs in Tertiary formations of onshore and offshore coastal Texas and Louisiana up to 1974. Other sources of data were petroleum company reports of bottom-hole shut-in pressure (BHSIP) collected from drill stem tests and production tests, and USGS Conservation Division files containing reports of BHSIP's from production tests and wireline repeat formation testers from wells in the Federal OCS area.

Since most gas production in the Gulf Coast occurs in Louisiana and its Federal OCS extension, most of the data in the FPC files come from this area. The fewest measurements available from any source were those from the Federal OCS area offshore of Texas. This is due primarily to the scarcity of commercially producing hydrocarbon reservoirs in this area. In fact, for this region, nearly all of the pressure measurements came from repeat formation-tester results of possible pay zones in wildcat wells.

The FPC files (form 15) list each gas-producing reservoir by field name and number. To obtain a geographic reference for these reservoirs, they were keyed to the American Petroleum Institute (API) unique number for the field's discovery well or an alternate. In this way, latitude, longitude, and depth (the midpoint of the top and the bottom of the reservoir) could be assigned to each measurement. For pressure measurements from individual wells, the API unique numbers for the wells were used for identification, and the latitudes and longitudes of the wells were used to determine locations. The depth of the measurement completed the necessary three-dimensional location information.

Determination of Depth to Top of Geopressured Zone

In the present study, the top of the geopressured zone was considered to be the depth at which the 0.5 psi/ft gradient was found. In the Texas onshore and offshore area, the depth to the top of the geopressured zone was determined by using concurrently 1) mud weights from well log headings converted to pressure gradients, 2) pressure information converted to gradients, and 3) analysis and inspection of corresponding well logs using techniques presented by Wesselman and Heath (1977). Basically, their techniques use shale-bed resistivity measurements to determine the most likely depth at which the sediments become geopressured. This depth could then be compared with the converted mud weights and pressure measurements, if available, to define further the top of the geopressured zone.

For the Louisiana onshore and offshore segment of the study area, a major oil company provided a file containing several hundred well locations and depths corresponding to fluid-pressure gradients of about 0.5 (the top of the geopressured zone in this study) and 0.7 psi/ft (11.3 and 15.8 kPa/m). Information in the file was determined by the oil company from measurements of the density of shale cuttings and from inspection of geophysical logs. Some revision, correction, and updating were necessary, but the file supplied a large number of determinations of the depths to the top of the geopressured zone over a wide area.

In some cases, however, determinations made using only shale density gave depths to the top of the geopressured zone that were greater than the depths determined by the other methods described at the beginning of this section. In instances where additonal data (logs) were available, the depths calculated from shale density alone were adjusted by a verification process. The remaining points, however, could not be verified, and, accordingly, some geopressured sedimentary rocks may have been excluded. Such an exclusion would cause the depth to the top of the geopressured zone in the Louisiana onshore and offshore part of map 3 to be locally somewhat too great, and the calculated accessible fluid resource base to be slightly low. However, compared to the uncertainty of about 500-1000 ft (152-305 m) in determining the depth to the top of the geopressured zone inherent in the methods used for the rest of the assessment area, the aggregate error possibly introduced by using unverified shale density measurements is considered to be within acceptable limits. This is particularly true considering the fact that many of the depths given in the oil company file required either no correction or only minor corrections of less than a few hundred feet.

Calculation of Fluid Pressures at Interval Midpoints

All measurements of fluid pressure at depths shallower than the top of the geopressured zone were deleted from the data base. For wells with two or more pressure measurements within the geopressured zone, a fluid pressure at interval midpoint was determined between readings by interpolation. Extrapolation of pressure to deeper interval midpoints (below a depth of 11,250 ft (3429 m) in Texas and 14,250 ft (4343 m) in Louisiana), where necessary to supplement the few data available, was performed by linearly extending the rate of pressure increase with depth as determined from the recorded pressure measurements. In no case was the pressure increase with depth allowed to exceed a pressure gradient of 0.9 psi/ft (20.3 kPa/m).

For wells with a single pressure measurement or no pressure measurement in the geopressured zone, the estimated depth to the top of the geopressured zone was used to estimate pressures at interval midpoints as follows:

(1) If one pressure measurement was available, it was converted to a gradient by dividing by the recorded depth. The difference between the depth to the top of the geopressured zone and the depth at which the pressure measurement was made allowed determination of the rate of increase in gradient with depth, which was then used to calculate pressures at the midpoints of intervals.

(2) If only the depth to the top of the geopressured zone was available, the increase in gradient with depth was assumed to be 0.1 psi/ft per 1500-ft. interval.

Thus, gradients (and hence pressures) were calculated for all interval midpoints. More than 3000 wells were used in determining pressure at interval midpoints and for control in contouring the depth to top of the geopressured zone shown on map 3.

Methane Solubility

Culberson and McKetta (1951) and Sultanov, Skripka, and Namiot (1972) have studied the solubility of methane in fresh water, and O'Sullivan and Smith (1970), Dodson and Standing (1944), and Duffy, Smith, and Nagy (1961) have studied the effects of water salinity on methane solubility. However, the ranges of temperature, pressure and salinity in these studies do not span the entire range of conditions expected to exist in geopressured-geothermal deposits. In order to eliminate this problem and obtain useful data for the entire range of conditions expected for this assessment, Haas (1978) examined the work of these investigators for relations that would permit extrapolation of methane solubility in water to 360°C (680°F), 138,000 kPa (20,000 psi), and 250,000 mg/L salinity. Haas' results were used in this assessment to calculate methane solubility in geopressured water.

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SELECTED REFERENCES

Bebout, D. G., Gavenda, V. J., and Gregory, A. R., 1978, Geothermal resources, Wilcox Group, Texas Gulf Coast: ORO/4891-3, U. S. Department of Energy, Division of Geothermal Energy, 82 p.; available from U. S. Department of Commerce, National Technical Information Service, Springfield, VA 22161.

Bebout, D. G., Loucks, R. G., and Gregory, A. R., 1978a, Geopressured geothermal fairway evaluation and test-well site location Frio Formation, Texas Gulf Coast: ORO/4891-4, U. S. Department of Energy, Division of Geothermal Energy, 124 p.; available from U. S. Department of Commerce, National Technical Information Service, Springfield, VA 22161.

_____, 1978b, Frio sandstone reservoirs in the deep subsurface along the Texas Gulf coast; their potential for production of geopressured-geothermal energy: Bureau of Economic Geology, University of Texas at Austin, Report of Investigations no. 91, 93 p.

Berry, F. A. F., 1973, High fluid potentials in the California Coast Ranges and their tectonic significance: American Association of Petroleum Geologists Bulletin, v. 57, no. 7, p. 1219-1249.

Buckley, S. E., Hocott, C. R., and Taggart, M. S., Jr., 1958, Distribution of dissolved hydrocarbons in subsurface waters (Gulf Coastal Plain), _in_ Habitat of oil-a symposium: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 850-882.

Burst, J. F., 1969, Diagenesis of gulf coast clayey sediments and its possible relation to petroleum migration: American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 73-93.

Chapman, R. E., 1972, Clays with abnormal interstitial fluid pressures: American Association of Petroleum Geologists Bulletin, v. 56, no. 4, p. 790-795.

Culberson, O. L., and McKetta, J. J., Jr., 1951, Phase equilibria in hydrocarbon-water systems, III--the solubility of methane in water at pressures to 10,000 psia: Petroleum Transactions, American Institute of Mining Engineers, v. 192, p. 223-226.

Dickinson, G., 1953, Geological aspects of abnormal reservoir pressures in Gulf Coast Louisiana: American Association of Petroleum Geologists Bulletin, v. 37, no. 3, p. 410-432.

Dodson, C. R., and Standing, M. B., 1944, Pressure-volume-temperature and solubility relations for natural-gas-water mixtures: American Petroleum Institute Drilling and Production Practices, p. 173-179.

Doll, H. G., 1947, the SP log: Theoretical analysis and principles of interpretation: American Institute of Mining and Metallurgical Engs., Tech. Pub. No. 2463, 40 p.

Dorfman, M. H., 1976a, The supply of natural gas from geopressured zones: engineering and costs, in The future supply of nature-made petroleum and gas, First UNITAR conference on energy and the future, and Second IIASA conference on energy resources, 5-16 July, Schloss Laxenburg, Laxenburg, Austria: New York, Pergamon Press, Technical Reports, p. 873-888.

_____, 1976b, Potential reserves of natural gas in the United States Gulf Coast geopressured zones, in Natural gas from unconventional geologic sources: The National Research Council, Board of Mineral Resources, Commission on Natural Resources, National Academy of Sciences, p. 34-40.

Doscher, T. M., Osborne, R. H., Wilson, T., and Rhee, S. W., 1978, The economics of producing methane from geopressured aquifers: Department of Petroleum Engineering, University of Southern California, 69 p.

Duffy, J. R., Smith, N. O., and Nagy, B., 1961, Solubility of natural gases in aqueous solutions. I. Liquidus surface in the system CH_4-H_2O-NaCl-$CaCl_2$ at room temperature and at pressures below 1000 psia: Geochimica et Cosmochimica Acta, v. 24, p. 23-31.

Fertl, W. H., 1976, Abnormal formation pressures; implications to exploration, drilling and production of oil and gas resources; Developments in Petroleum Science, 2: New York, Elsevier, 382 p.

Garg, S. K, Pritchett, J. W., Rice, M. H., and Riney, T. D., 1977, U. S. Gulf Coast geopressured-geothermal reservoir simulation: SSS-R-77-3147, prepared by Systems, Science and Software for the University of Texas at Austin under U. S. Energy Research and Development Administration Contract E (40-1)-5400, 112 p.

Gondouin, M., Tixier, M. P., and Simard, G. L., 1957, An experimental study on the influence of the chemical composition of electrolytes on the SP curve: Jour. Petroleum Technology, v. 9, no. 3, p. 58-72.

Haas, J. L., Jr., 1978, An empirical equation with tables of smoothed solubilities of methane in water and aqueous sodium chloride solutions up to 25 weight percent, 360°C, and 138 MPa: U. S. Geological Survey Open-File Report 78-1004, 41 p.

Hawkins, M. F., Jr., 1977, Investigations on the geopressure energy resource of southern Louisiana: Final Report, ORO-4889-14, ERDA Contract EY-76-S-05-4889, Petroleum Engineering Department, Louisiana State University, Baton Rouge, Louisiana, 181 p.

Hise, B. R., 1976, Natural gas from geopressured zone, in Natural gas from unconventional sources: The National Research Council, Board of Mineral Resources, Commission on Natural Resources, National Academy of Sciences, p. 41-63.

Isokrari, O. F., and Knapp, R. M., 1976, Natural gas production from geothermal-geopressured aquifers: Society of Petroleum Engineers, American Institute of Mining Engineers, preprint No. SPE 6037, 16 p.

Jones, P. H., 1969, Hydrology of Neogene deposits in the northern Gulf of Mexico basin: Louisiana Water Resources Research Institute Bulletin GT-2, 105 p.

_____, 1975, Geothermal and hydrocarbon regimes, northern Gulf of Mexico basin: Geopressured-geothermal energy conference, 1st, Austin, Texas, June 2-4, 1975, Center for Energy Studies, University of Texas at Austin, Proceedings, p. 15-89.

_____, 1976a, Natural gas resources of the geopressured zones in the northern Gulf of Mexico basin, in Natural gas from unconventional geologic sources: The National Research Council, Board of Mineral Resources, Commission on Natural Resources, National Academy of Sciences, p. 17-33.

_____, 1976b, Gas in geopressured zones, in The future supply of nature-made petroleum and gas, First UNITAR conference on energy and the future, and Second IIASA conference on energy resources, 5-16 July, Schloss Laxenburg, Laxenburg, Austria: New York, Pergamon Press, Technical Reports, p. 889-911.

Karkalits, O. C., and Hankins, B. E., 1978, Chemical analysis of dissolved natural gas in water from the world's first geopressured-geothermal well: Geothermal Resources Council Transactions, v. 2, sec. 1, p. 351-354.

Kuuskraa, V. A., Brashear, J. P., Doscher, T. M., and Elkins, L. E., 1978a, Enhanced recovery of unconventional gas, the program-volume II (of 3 volumes): HCP/T2705-02, U. S. Department of Energy, Office of Fossil Energy Programs, Div. of Program Control and Support, ch. 6, p. 6-1-6-64.

_____, 1978b, Vast potential held by four "unconventional" gas sources: Oil and Gas Journal, v. 77, no. 24, June 12, p. 47-54.

Loucks, R. G., 1978, Geothermal resources, Vicksburg Formation, Texas Gulf Coast: ORO/4891-2, U. S. Department of Energy, Division of Geothermal Energy, 52 p.; available from U. S. Department of Commerce, National Technical Information Service, Springfield, VA 22161.

Maxwell, J. C., 1964, Influence of depth, temperature, and geologic age on porosity of quartzose sandstone: American Association of Petroleum Geologists Bulletin, v. 48, no. 5, p. 697-709.

Muffler, L. J. P., and Cataldi, R., 1978, Methods for regional assessment of geothermal resources: Geothermics, v. 7, no. 2-4. (in press)

Murray, G. E., 1961, Geology of the Atlantic and gulf coastal province of North America: New York, Harper, 692 p.

Norwood, E. M., Jr., and Holland, D. S., 1974, Lithofacies mapping a descriptive tool for ancient delta systems of the Louisiana outer continental shelf: Gulf Coast Association Geological Societies Transactions, v. 24, p. 175-188.

O'Sullivan, T. D., and Smith, N. O., 1970, The solubility and partial molar volume of nitrogen and methane in water and in aqueous sodium chloride from 55 to 125° and 100 to 600 atm: Journal Physical Chemistry, v. 74, no. 7, p. 1460-1466.

Papadopulos, S. S., 1975, The energy potential of geopressured reservoirs: Hydrogeologic factors: Geopressured-geothermal energy conference, 1st, Austin, Texas, June 2-4, 1975, Center for Energy Studies, University of Texas at Austin, Proceedings, p. 173-192.

Papadopulos, S. S., Wallace, R. H., Jr., Wesselman, J. B., and Taylor, R. E., 1975, Assessment of onshore geopressuredgeothermal resources in the northern Gulf of Mexico basin, <u>in</u> White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 125-146.

Potter, R. W., II, and Brown, D. L., 1977, The volumetric properties of aqueous sodium chloride solutions from 0°C to 500°C at pressures up to 2,000 bars based on a regression of available data in the literature: U. S. Geological Survey Bulletin 1421-C, 36 p.

Price, L. C., 1976, Aqueous solubility of petroleum as applied to its origin and primary migration: American Association of Petroleum Geologists Bulletin, v. 60, no. 3, p. 213-244.

Randolph, P. L., 1977a, Natural gas from geopressured aquifers?: Society of Petroleum Engineers, American Institute of Mining Engineers, preprint No. SPE 6826, 12 p.

_____, 1977b, Natural gas content of geopressured aquifers: Geopressured-geothermal energy conference, 3rd, November 16-18, 1977, University of Southwestern Louisiana, Lafayette, Proceedings, v. 1, p. ES-23-46.

Ritch, H. J., and Smith, J. T., 1976, Evidence for low free gas saturation in water bearing bright spot sands: Society of Professional Well Log Analysts, Annual Logging Symposium, 17th, June 9-12, 1976, Transactions, p. 1-11.

Schmidt, G. W., 1973, Interstitial water composition and geochemistry of deep Gulf Coast shales and sandstones: American Association of Petroleum Geologists Bulletin, v. 57, no. 3, p. 321-337.

Stuart, C. A., 1970, Geopressures: Symposium on abnormal subsurface pressures, 2nd, Louisiana State University, Baton Rouge, January 30, 1970, Proceedings, 121 p.

Sultanov, R. G., Skripka, V. G., and Namiot, A. Y., 1972, Solubility of methane in water at high temperatures and pressures: Gazovaia Promyshlennost, v. 17, p. 6-7 (in Russian).

Swanson, R. K., Oetking, P., Osoba, J. S., and Hagens, R. C., 1976, Development of an assessment methodology for geopressured zones of the upper Gulf Coast based on a study of abnormally pressured gas fields in south Texas: Final report COO-2786-5, Southwest Research Institute, prepared for U. S. Energy Research and Development Administration, 75 p.

Thorsen, C. E., 1964, Miocene lithofacies in southeast Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 14, p. 193-201.

Wallace, R. H., Jr., Taylor, R. E., and Wesselman, J. B., 1977, Use of hydrogeologic mapping techniques in identifying potential geopressured-geothermal reservoirs in the lower Rio Grande embayment Texas: Geopressured-geothermal energy conference, 3rd, November 16-18, 1977, University of Southwestern Louisiana, Lafayette, Proceedings, v. 1, p. GI-1-88.

Wallace, W. E., 1962, Water production from abnormally pressured gas reservoirs in south Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 12, p. 187-193.

Wesselman, J. B., and Heath, J., 1977, Computer techniques to aid in the interpretation of subsurface fluid-pressure gradients: Bay St. Louis, Miss., U. S. Geological Survey Computer Contributions, 34 p.; available only from U. S. Department Commerce, National Technical Information Service, Springfield, VA 22161 as report PB 268-603.

White, D. E., and Williams, D. L., 1975, Summary and conclusions, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 147-155.

Wyllie, M. R. J., 1963, The fundamentals of well log interpretation (3rd ed.): New York, Academic Press, 238 p.

Summary

By L. J. P. Muffler

The petroleum crisis of 1973 caused an awakening of many countries to the need to evaluate and develop alternative energy sources. Consequently, during the past six years geothermal exploration, utilization, and research have taken a dramatic upswing, both in the United States and throughout the world. This upswing in the United States has resulted in new information, improved exploration, extraction, and utilization technologies, and a greater understanding of resource characteristics. But has this expanded activity of the past few years resulted in a significantly different assessment of the geothermal resource? To answer this question, the U. S. Geological Survey, with the support of the Department of Energy, has reevaluated the geothermal resources of the United States in the light of nonproprietary data available in June of 1978. This new geothermal resource assessment is an update of USGS Circular 726 (White and Williams, eds., 1975), to which the reader is referred for background information.

In both Circular 726 and this assessment a careful distinction is made between the geothermal energy in the ground to a specified depth (the resource base of Circular 726 and the accessible resource base of this assessment) and the thermal energy that could be extracted and used at some reasonable future time (the resource). It is the resource, not the accessible resource base, that is of real significance to man and that can be compared with other energy resources. Accordingly, any evaluation of thermal energy in the ground is incomplete without considering how much energy might be extracted and used.

CONDUCTION-DOMINATED REGIMES

In Circular 726, Diment and others (1975) concluded that the amount of thermal energy stored at temperatures above mean annual surface temperature in the outer 10 km of the United States is about 8,000,000 x 10^{18} cal (= 33,000,000 x 10^{18} J; table 20). Similarly, 3,300,000 x 10^{18} J exists at depths less than 3 km (Diment and others, 1975), and 17,200,000 x 10^{18} J at depths less than 7 km (table 20). According to Sass and Lachenbruch (this volume), these figures would not be significantly changed if the 1975 calculations were repeated using the additional heat-flow information now available.

As White and Williams (1975) pointed out, these numbers are huge because of the immense volumes of rock involved; the numbers thus provide background values or upper limits for any discussion of geothermal energy. Included in the numbers is the thermal energy in geopressured basins, in sedimentary basins at hydrostatic pressure, and in hydrothermal convection systems unrelated to young igneous intrusions. Superimposed on the regional conductive environment is geothermal energy related to young igneous intrusions, contained in either magma, solidified igneous rock, hot country rock, or associated hydrothermal convection systems.

Use of the thermal energy in regional conductive environments is subject to several major impediments:

1. At depths less than 3 km, temperatures higher than 100°C are likely to be present only in anomalous areas, such as young igneous systems, hydrothermal convection systems, or regions of much higher than average heat flow (such as the Battle Mountain High; map 1).
2. At greater depths, temperatures are indeed high, but drilling costs become prohibitive.
3. Also, at great depths, permeabilities are likely to be low, requiring stimulation or hot dry rock technologies.

Accordingly, one cannot take the results of calculations based on regional heat flow data and apply a simple recovery factor to get usable thermal energy, much less electrical energy. Instead, one must conceptually isolate those parts of the upper crust that are accessible to drilling and that have hydrologic and thermal characteristics such that thermal energy can be extracted (for example, hydrothermal convection systems or geopressured systems). None of the remaining thermal energy contained in rocks of relatively low permeability should be classified as a resource until the extraction technology is demonstrated and the utilization economics reasonably inferred.

IGNEOUS-RELATED SYSTEMS

Smith and Shaw (1975) estimated the thermal energy remaining in young igneous systems to a depth of 10 km, on the basis of a model of conductive cooling since a time represented by the age of the youngest silicic extrusion of each system. Cooling of the igneous body by hydrothermal convection was assumed to be offset by the effects of magmatic preheating and additions of magma after the assumed time of emplacement. Smith and Shaw (this volume) have reevaluated this assumption in the light of recent studies of the effects of hydrothermal cooling in and around magma bodies and conclude that it is

Table 20.--*Geothermal energy of the United States*

	Accessible resource base to 10 km (10^{18} J)	Accessible resource base to 7 km (10^{18} J)	Accessible fluid resource base to 6.86 km (10^{18} J)			Accessible resource base to 3 km (10^{18} J)			Resource (10^{18} J)	Electricity (MWe for 30 yr)	Beneficial heat (10^{18} J)
			Sandstone	Shale	Total	>150°C	90°-150°C	Total			
Conduction-dominated											
Land area	33,000,000[a]	17,000,000[b]	--	--	--	--	--	3,300,000[a]	--	--	--
Offshore Gulf Coast	370,000[c]	180,000[c]	--	--	--	--	--	36,000[c]	--	--	--
Total	33,000,000	17,200,000	--	--	--	--	--	3,300,000	--	--	--
Igneous-related											
Evaluated	101,000	--	--	--	--	--	--	--	--	--	--
Unevaluated	>900,000	--	--	--	--	--	--	--	--	--	--
Total	>1,000,000	--	--	--	--	--	--	--	--	--	--
Reservoirs of hydrothermal convection systems (≥90°C)											
Identified	--	--	--	--	--	950[d]	700	1650[d]	400	23,000	42
Undiscovered	--	--	--	--	--	2800-4900	3100-5200	8000	2000	72,000-127,000	184-310
Total	--	--	--	--	--	3800-5800	3800-5900	9600	2400	95,000-150,000	230-350
Northern Gulf of Mexico basin (onshore and offshore)											
Thermal energy	850,000[e]	410,000[e]	11,000	96,000	107,000	--	--	--	270[f]-2800[g]	--	--
Methane energy	--	--	6,000	57,000	63,000	--	--	--	158[f]-1640[g]	--	--
Total	--	--	17,000	153,000	170,000	--	--	--	430[f]-4400[g]	--	--
Other geopressured basins	--	--	--	--	46,000[h]	--	--	--	--	--	--

[a]"Best estimates" of Diment and others (1975, table 14). These values are each approximately 18 percent greater than the values determined by the "basic calculation" of Diment and others (1975, table 13).

[b]Equations on p. 85 and 91 of Diment and others (1975) (assuming an exponential decrease of heat production with depth) give $13,700,000 \times 10^{18}$ J for the "basic calculation". This value is then increased by approximately 18 percent to give a figure comparable to the "best estimates" of Diment and and others (1975, table 14).

[c]Calculated for an area of 135,000 km^2 using the "basic calculation" of Diment and others (1975) and the thermal parameters listed for the coastal plain on their table 13. The result is then increased by approximately 18 percent to give a figure comparable to their "best estimates".

[d]Does not include 1290×10^{18} J in National Parks (mainly Yellowstone).

[e]Calculated for an area of 310,000 km^2 using the "basic calculation" of Diment and others (1975) and the thermal parameters listed for the coastal plain on their table 13. The result is then increased by approximately 18 percent to give a figure comparable to their "best estimates".

[f]Plan 3 of Papadopulos, Wallace, Wesselman, and Taylor (1975).

[g]Plan 2 of Papadopulos, Wallace, Wesselman, and Taylor (1975).

[h]From White and Williams (1975, table 28); thermal energy only.

still valid. It should be emphasized that the figures reported by Smith and Shaw (1975 and this volume) do not represent an inventory of measured thermal energy, but instead are estimates based on a model.

The thermal energy estimated by Smith and Shaw (this volume) is 101,000 x 10^{18} J, little changed from the 25,000 x 10^{18} cal (= 105,000 x 10^{18} J) estimated by the same authors in 1975. For some systems (for example, Coso, Calif.) there are significant new age and volume data, but for most systems the data sets are the same as in 1975. As shown on the comprehensive tables of Smith, Shaw, Luedke, and Russell (1978), there are still many systems, particularly in Alaska, for which age and size data are still inadequate to make any thermal estimates.

In Circular 726, Smith and Shaw (1975, p. 76) suggested that their estimates of igneous-related thermal energy would be increased by two to ten times by inclusion of unevaluated and untabulated systems and by consideration of the longevity of igneous intrusion and subchamber heating in all systems. On the basis of this suggestion, White and Williams (1975, table 26) presented an estimate of 100,000 x 10^{18} cal (= 420,000 J) for the identified and undiscovered thermal energy of igneous-related systems. Smith and Shaw (this volume), however, suggest that the total igneous-related thermal energy is at least an order of magnitude greater than their updated estimate of 101,000 x 10^{18} J. If correct, the total thermal energy related to young igneous systems in the United States would be approximately 1,000,000 x 10^{18} J. Although this figure is highly speculative, it does engender optimism for the future discovery of substantial quantities of geothermal energy, both in hydrothermal convection systems and in hot rock of low permeability.

HYDROTHERMAL CONVECTION SYSTEMS WITH RESERVOIR TEMPERATURES OF 90°C OR MORE

Brook and others (this volume) present a detailed inventory of thermal energy to a depth of 3 km in identified hydrothermal convection systems with reservoir temperatures of 90°C or more. Significant changes from Circular 726 (Renner and others, 1975) include: (1) a decrease of 24 percent in the number of identified systems, (2) a greater preponderance of intermediate-temperature systems, and (3) substantial decreases in estimated size of several of the largest systems (for example, Bruneau-Grand View, Klamath Falls, Long Valley, and Coso). Changes (1) and (2) are due primarily to the use of improved chemical geothermometers, whereas change (3) is due to a combination of improved geothermometers and additional drillhole data that have become available since 1975. The net result of these changes is a reduction of 34 percent in the estimate of thermal energy in identified hydrothermal convection systems outside of National Parks.

The analysis of recoverability and the calculation of the geothermal resource by Brook and others (this volume) is essentially the same as in Circular 726 (Nathenson and Muffler, 1975); both analyses are based on Nathenson (1975). A recovery factor of 25 percent is used for all identified hot-water systems to give the resource (that is, the thermal energy producible at the wellhead). The Geysers is the only identified vapor-dominated system outside of National Parks, and the resource there is calculated to be 9.6 percent of the accessible resource base to 3 km.

For systems having reservoir temperatures of 90° to 150°C, Brook and others (this volume) estimate beneficial heat as 24 percent of the resource (following Nathenson and Muffler, 1975). For systems of reservoir temperature greater than 150°C, Brook and others (this volume) calculate available work and then electrical energy (in MWe for 30 yr). The percentage of wellhead thermal energy convertible to electrical energy under their assumptions ranges from 7 percent at 150°C to 13 percent at 325°C.

In Circular 726, Renner and others (1975) estimated that, for the whole United States, the undiscovered component of hot-water convection systems having reservoir temperatures greater than 150°C was five times the identified component (excluding Yellowstone). The undiscovered component at 90°-150°C was estimated as three times the identified. In Brook and others (this volume), the undiscovered accessible resource base for hydrothermal convection systems is again estimated as a multiple of the identified component. Instead of treating the United States as a whole, however, the undiscovered component is estimated by geologic province, thus taking into account differing geologic characters of the various provinces. The undiscovered component of Brook and others (this volume) is approximately five times the identified, compared to four times in Circular 726 (Renner and others, 1975). However, because of the lesser energy calculated for the identified component in 1978 and because in both Circulars the basic methodology involves multiplying the identified component by a factor to get the undiscovered component, the undiscovered component in 1978 is only 82 percent of the 1975 value. The lower estimate for the undiscovered component in 1978 is, of course, reflected in the different estimates of the total accessible resource base: 9600 x 10^{18} J in 1978 compared to 12,200 x 10^{18} J in 1975.

The assessment of the undiscovered accessible resource base or resource of any mineral deposit or fuel inherently has a high degree of uncertainty. Assessment of undiscovered geothermal energy has an added complication, in that one must allocate the estimate of the total undiscovered thermal energy into one part in reservoirs with temperatures of 150°C or greater and another part in reservoirs with temperatures of 90° to 150°C. Only the part in reservoirs greater than 150°C is considered amenable for electrical generation. Brook and others (this volume) use a method of allocation based on the frequency of identified hydrothermal convection systems in 20°C temperature intervals and on two limiting cases for the relation between reservoir volume and temperature. The first case assumes that the average volume of reservoirs in each 20°C class is the same; the second case assumes that reservoir volume increases linearly with temperature. The ranges given in table 20 for the undiscovered accessible resource base and resource reflect these two limiting assumptions.

The apparent agreement between the totals for electricity and beneficial heat of Circular 726 and the upper bounds of the corresponding totals of Brook and others (this volume) is illusory. The ranges cited for electricity and beneficial heat by Brook and others reflect different allocations of the estimated undiscovered geothermal energy to the temperature categories (greater than 150°C and 90°-150°C). Accordingly, the higher value of electricity cannot occur simultaneously with the higher value of beneficial heat.

Not evaluated in either Circular 726 or Brook and others (this volume) is the possible extension of hydrothermal convection systems to depths greater than 3 km. Obviously, any such extensions would increase the accessible resource base proportionally to the combined effects of increased volume and increased temperature. However, drillhole data at depths greater than 3 km in hydrothermal convection systems are almost completely lacking, and it is unlikely that commercial drilling to significantly greater depths will be feasible for many years, since drilling costs per meter increase sharply with depth. Furthermore, although rock at greater depths is likely to be hotter, it may be less permeable and thus less able to produce fluids without expensive and uncertain artificial stimulation.

LOW-TEMPERATURE GEOTHERMAL WATERS

Sammel (this volume) presents a preliminary evaluation of low-temperature (less than 90°C) geothermal waters of the United States. This evaluation is severely limited by the inadequate and often conflicting data sets; accordingly, no quantitative estimates of accessible resource base are made. However, areas favorable for discovery and development of low-temperature geothermal waters at depths less than 1 km are depicted on map 1 and in the text figures.

The low-temperature geothermal waters of the United States are a promising source of low-grade thermal energy. Although unlikely to contribute to electrical generation, they do have the potential for significant utilization for space heating and agriculture on a local basis. This potential is being evaluated by the Department of Energy in its Western States Cooperative Direct-Heat Geothermal Program (Wright and others, 1978).

GEOPRESSURED-GEOTHERMAL ENERGY

A preliminary estimate of the geopressured-geothermal energy of the northern Gulf of Mexico basin was presented by Papadopulos, Wallace, Wesselman, and Taylor (1975) in Circular 726. Using data from 250 wells, they estimated that 46,000 x 10^{18} J of thermal energy was contained in geopressured waters of the onshore Tertiary sedimentary rocks of the Gulf Coast, to depths of 6 km in Texas and 7 km in Louisiana. They also estimated that an additional 25,000 x 10^{18} J of energy was represented by methane dissolved in these geopressured waters. Undiscovered and unevaluated geopressured-geothermal energy in offshore, deeper Tertiary, and onshore Cretaceous sedimentary rocks of the Gulf Coast was estimated to be 1½ to 2½ times the identified energy. The total identified and undiscovered thermal and methane energy in geopressured fluids of the northern Gulf of Mexico basin was thus estimated to be approximately 106,000-178,000 x 10^{18} J.

Wallace, Kraemer, Taylor, and Wesselman (this volume) present an estimate of the thermal and dissolved methane energy contained in the entire northern Gulf of Mexico basin, both onshore and offshore, to depths of 22,500 feet (6.86 km). Their estimate, based on data from over 3500 wells, in general substantiates the preliminary estimate of Papadopulos, Wallace, Wesselman, and Taylor (1975). The total identified thermal energy in fluids of both sandstone and shale is estimated to be 107,000 x 10^{18} J; 11,000 x 10^{18} J is in the sandstone and thus represents the amount from which initial production will be drawn. Assuming saturation of the waters with methane, the total methane dissolved in waters of both sandstone and shale is 59,000 x 10^{12} standard cubic feet (equivalent to 63,000 x 10^{18} J); 5700 x 10^{12} standard cubic feet (6000 x 10^{18} J) is in waters of the sandstone.

The major uncertainty in both geopressured-geothermal resource assessments lies in determining the amount of fluid that can be recovered at the surface. The few production tests carried out to date have not significantly modified the recoverability analysis presented by Papadopulos, Wallace, Wesselman, and Taylor (1975). Application of this analysis to data of Wallace, Kraemer, Taylor, and Wesselman (this volume) suggests that the recoverable thermal energy from geopressured waters of the northern Gulf of Mexico basin ranges from 270 x 10^{18} J under plan 3 (controlled development with limited pressure reduction and subsidence) to 2800 x 10^{18} J under plan 2 (depletion of reservoir pressure). Recoverable methane energy ranges from 158 x 10^{18} J under plan 3 to 1640 x 10^{18} J under plan 2. If 8 percent of the recoverable thermal energy could be converted to electricity (as assumed by Papadopulos, Wallace, Wesselman, and Taylor, 1975), the electricity produced would range from 23,000 MWe for 30 yr under plan 3 to 240,000 MWe for 30 yr under plan 2.

Wallace, Kraemer, Wesselman, and Taylor (this volume) show the locations of other sedimentary basins of the United States where geopressured fluids are known or inferred to exist. Knowledge of these geopressured environments is scanty, and no thermal estimate is made. White and Williams (1975, table 28) suggested that perhaps 11,000 x 10^{18} cal (= 46,000 x 10^{18} J) of thermal energy might exist to a depth of 10 km in these other basins, with perhaps a similar amount of energy from dissolved methane.

HOT DRY ROCK

In recent years, considerable attention has been drawn to the possibility of extracting energy from rock that is hot but of low natural permeability. Specifically, extensive research has been carried out on the technology to fracture this rock and to set up a confined artificial water-circulation loop between two wells intersecting the fractures, thus allowing thermal energy to be extracted from the rock (Smith, 1978). A small-scale pilot loop has been tested, but many difficulties remain before demonstration of the technology and economics of a production loop. Consequently, it is not yet possible to give an estimate of the fraction of hot impermeable rock at depth that might someday be producible using this technology. However, it is possible to put some constraints on the amount of thermal energy in the upper 10 km of the Earth's crust that might reside in hot impermeable rock.

Hot rock that is truly dry (that is, rock that has no water in pores or intergranular space) probably exists only rarely. However, particularly in the deeper parts of the crust, there are likely to be large volumes of rock that contain some water but that have such low porosity and permeability that wells drilled into them would produce no natural fluid. With regard to extraction of heat, such situations approximate dry rock. Consequently, hot dry rock can be defined as hot rock that is sufficiently impermeable to allow extraction of heat by means of a confined, artificial circulation system, with minimal losses of water to the country rock.

Hot dry rock thus involves three concepts: low porosity (and water content), very low permeability, and high temperature. How high a temperature obviously depends on the use for which the thermal energy is intended and the economics of the situation. The economics, in turn, are strongly influenced by the depth of occurrence, the fact that drilling costs per meter go up sharply with depth, and the technological difficulty and expense of creating large volumes of fractured rock at depth.

With increasing porosity and permeability, hot dry rock as defined above grades into rock where the natural pore fluid can be used to extract heat, although not necessarily at economic rates. Such situations are candidates for "stimulation" (that is, creation of artificial permeability by hydraulic fracturing, explosives, chemical means, and so forth) but are conceptually equivalent to conventional hydrothermal reservoirs. The gradation from hot dry rock to conventional permeable reservoirs can be broken into categories as follows:

1. Hot dry rock in the strict sense defined above.
2. Rock that is too permeable to support a confined circulation loop but that is not permeable enough to produce natural fluids.
3. Rock that is sufficiently permeable to produce fluid naturally, but not at economically acceptable rates.
4. Permeable reservoirs such as found in favorable hydrothermal convection systems, geopressured-geothermal basins, or sedimentary basins with fluids under hydrostatic pressure.

Exploration for hot dry rock poses a major problem, since most of the geochemical and geophysical techniques yet developed for geothermal exploration either depend directly on the presence of fluids in the rocks (for example, chemical geothermometry and electrical resistivity) or cannot discriminate between thermal anomalies due to conduction or to hydrothermal convection (for example, shallow thermal measurements). At our present state of knowledge, extensive deep drilling is an essential step in exploration for hot dry rock. Geologic, geophysical, and geochemical techniques used alone are simply inadequate.

Hot dry rock occurs in two of the geothermal categories discussed in this Circular: (a) conduction-dominated regimes, and (b) igneous-related systems. In neither category can the amount of hot dry rock be specified with any confidence. However, the available data do allow some constraints to be imposed.

Table 20 shows that only 0.3 percent of the conduction-dominated accessible resource base to 3 km occurs in identified and undiscovered hydrothermal convection systems having reservoir temperatures of 90°C or greater. The rest of the energy is assumed to be in rock at temperatures expected from the representative conductive gradient of the particular region (see fig. 27), with a gradation from porous and permeable rocks of sedimentary basins to rock that is effectively nonporous and impermeable (dry rock). The volume of dry rock depends on many tectonic and hydrologic factors whose effects remain to be evaluated. However, even if the volume of dry rock were only 5 percent of the total volume, the energy contained in it would amount to 165,000 x 10^{18} J, or 17 times the total energy

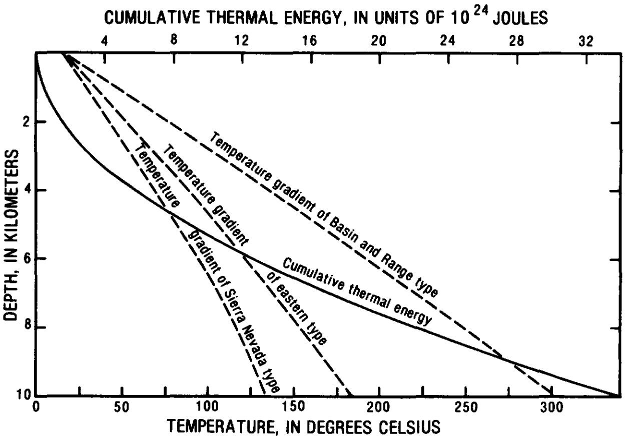

Figure 27.--Geothermal energy (cumulative with depth) and temperatures in heat-flow provinces in the United States. Cumulative thermal energy (solid line) is calculated using the equations on p. 85 and 91 of Diment and others (1975) and the parameters of their "basic calculation." The results are then increased by approximately 18 percent to give figures comparable to the "best estimates" of Diment and others (1975, table 14). Temperatures (dashed lines) are calculated from the equation for exponential decrease of radioactive heat generation with depth on p. 85 of Diment and others (1975), assuming an average surface heat production of 2.1 x 10^{-6} J/(m^3·s) and a thermal conductivity of 2.5 J/(m·s·°C).

in hydrothermal convection systems at temperatures of 90°C or greater to a depth of 3 km.

Use of this energy, however, is sharply constrained by the relatively low temperatures at depths less than 3 km outside of hydrothermal convection systems and igneous-related systems. Under the assumptions of figure 27, the temperature at 3 km in the three regional environments specified by Diment and others (1975) for the United States is only 57°C for the Sierra Nevada, 71°C for provinces of the eastern type (72 percent by area of the United States), and 107°C for provinces of the Basin and Range type. It is thus clear that the thermal energy in conductive environments at depths less than 3 km is likely to be used only for direct purposes (that is, beneficial heat), and then only when the energy can be produced by tapping natural pore water. Economic development of artificial circulation loops in impermeable rock at these low temperatures seems unlikely.

Between the depths of 3 to 7 km, however, the total accessible resource base is approximately 14,000,000 x 10^{18} J. This energy amounts to over 1400 times the energy in hydrothermal convection systems at temperatures equal or greater than 90°C to 3 km, and over 90 times the thermal energy in water of geopressured systems to a depth of 6.86 km. In contrast to the energy at 0 to 3 km, the energy at 3 to 7 km is increasingly likely to be in impermeable (dry) rock, excluding deep sedimentary basins and areas of active tectonic fracturing. If only 10 percent of the accessible resource base between 3 and 7 km were hot dry rock, it would amount to approximately 1,400,000 x 10^{18} J. Furthermore, average temperatures from 3 to 7 km under the assumptions of figure 27 would be 80°C for the Sierra Nevada, 104°C for provinces of the Eastern type, and 164°C for provinces of the Basin and Range type. Consequently, hot dry rock found at 3 to 7 km in a province of the Basin and Range type might be a candidate for electrical generation, and hot dry rock at 3 to 7 km in a province of the eastern type might be a candidate for direct use (in both cases assuming that technological problems could be solved and that the costs proved competitive with other energy sources).

The energy occurring in conduction-dominated environments at 7 to 10 km is approximately 16,000,000 x 10^{18} J. If 25 percent of this energy were in hot dry rock, it would amount to approximately 4,000,000 x 10^{18} J. Temperatures also become increasingly favorable at greater depths. The average temperature between 7 and 10 km under the assumptions of figure 27 would be 119°C for the Sierra Nevada, 160°C for a province of the eastern type, and 261°C for a province of the Basin and Range type. Thus, temperatures at depths of 7 to 10 km would be sufficiently high for generation of geothermal electricity anywhere in the United States except the Sierra Nevada. However, high temperatures by no means guarantee that the energy can be extracted economically from these great depths. It should be noted that the deepest wells drilled to date for any purpose extend to about 10 km, but that these wells were exceedingly expensive (many millions of dollars) and were designed to produce either petroleum or natural gas both of which have a much higher energy content per unit mass than does hot water. Furthermore, these deep wells were drilled in sedimentary rocks that are softer and easier to drill than rocks expected in most geothermal environments. Clearly, the difficulty and high cost of deep drilling is a very severe impediment to any use of hot dry rock (or any other form of geothermal energy) at depths of 7 to 10 km.

Superimposed on the regional conductive environments is the energy of igneous-related systems, estimated by Smith and Shaw (this volume) to be perhaps 1,000,000 x 10^{18} J to a depth of 10 km. This energy occurs as magma, as low-permeability rock (both solidified igneous rock and hot country rock), and as associated hydrothermal convection systems. Table 20 shows that the energy estimated to be in igneous-related geothermal systems to a depth of 10 km is approximately 1000 times the energy estimated to be in identified and undiscovered hydrothermal convection systems having temperatures of 90°C or greater to a depth of 3 km. Although some hydrothermal convection systems may extend to depths of at least 5 km, it is unlikely that the total energy in hydrothermal convection systems at depths greater than 3 km is more than five times the energy in hydrothermal convection systems at depths less than 3 km. Thus, the energy estimated by Smith and Shaw (this volume) for igneous-related systems must be present primarily in low-permeability rock or magma. The low-permeability rock is likely to be at temperatures substantially higher than the temperatures at equivalent depths in any of the three regional conductive environments. Consequently, the igneous-related systems shown on maps 1 and 2 provide the prime target for exploration for hot dry rock.

Direct information about these igneous systems at depth, however, is very sparse. Several of the major systems have been drilled to approximately 3 km in the search for hydrothermal convection systems, and study of exhumed older igneous bodies gives us some idea of the conditions likely to exist at depths of 7 to 10 km in young igneous systems. However, we know almost nothing about the geometry and hydrologic characteristics of hydrothermal convection systems at depths greater than 3 km, and the nature, effects and importance of hydrothermal cooling of intrusions are subjects of considerable debate. Until information can be obtained by direct sampling and measurement in drillholes at depths greater than 3 km in igneous-related geothermal systems, any attempts such as the above to categorize energy of igneous-related systems into hydrothermal convection systems or hot dry rock (or something in between) are unavoidably speculative.

In summary, it seems reasonable that a substantial fraction of the thermal energy of the upper 10 km of the Earth's crust occurs in hot, impermeable rock. However, available information on porosity, permeability, and other physical properties at depth is insufficient to allow us to quantify either the amount of hot impermeable rock or the amount of energy in it. Furthermore, the technology for large-scale fracturing of the rock and extracting heat on a production scale has not yet been demonstrated, and the economics of production are unknown. Hence, none of the energy in hot impermeable rock at any depth can today be termed a resource.

CONCLUSIONS

In general, this new geothermal resource assessment substantiates the overall conclusions of USGS Circular 726. There is little significant difference in the total energies calculated, although substantially smaller energies are estimated for some of the larger hydrothermal convection systems. Both assessments show that there are immense quantities of thermal energy in the conduction-dominated and igneous-related environments, but the technology to utilize most of this energy has not yet been demonstrated. At present, the geothermal resource is concentrated in the hydrothermal convection systems and the geopressured sedimentary basins. Both of these geothermal categories represent a significant resource of great importance to the energy economy of the United States. The immense amount of energy that exists in conduction-dominated environments and in igneous-related systems, particularly at depths greater than 3 km, provides an exciting goal for future exploration and for the development of advanced drilling and extraction technologies.

Major uncertainties still remaining include:

1. What is the amount of thermal energy likely to be recovered from hydrothermal convection systems and geopressured-geothermal systems?
2. How much undiscovered energy at what temperatures exists in hydrothermal convection systems?
3. What are the physical conditions at depths greater than 3 km in hydrothermal and igneous-related systems, and what is the division of energy between hydrothermal convection systems and hot, low-permeability rock at these depths?
4. What is the magnitude of the hot dry rock resource (that is, the thermal energy that someday might be extracted from hot dry rock and utilized under reasonable technological and economic assumptions)?

REFERENCES CITED

Diment, W. H., Urban, T. C., Sass, J. H., Marshall, B. V., Munroe, R. J., and Lachenbruch, A. H., 1975, Temperatures and heat contents based on conductive transport of heat, in White, D. E., and Williams, D. L., (eds.), Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 84-103.

Nathenson, Manuel, 1975. Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas: U. S. Geological Survey Open-File Report 75-525, 35 p.

Nathenson, Manuel, and Muffler, L. J. P., 1975, Geothermal resources in hydrothermal convection systems and conduction-dominated areas, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 104-121.

Papadopulos, S. S., Wallace, R. H., Jr., Wesselman, J. B., and Taylor, R. E., 1975, Assessment of geopressured-geothermal resources in the northern Gulf of Mexico basin, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological

Survey Circular 726, p. 125-146.

Renner, J. L., White, D. E., and Williams, D. L., 1975, Hydrothermal convection systems, in White, D. E., and Williams, D. L. , eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 5-57.

Smith, M. C., 1978, Heat extraction from hot, dry crustal rock: Pure and Applied Geophysics, v. 117. (in press)

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 58-83.

Smith, R. L., Shaw, H. R., Luedke, R. G., and Russell, S. L., 1978, Comprehensive tables giving physical data and energy estimates for young igneous systems of the United States: U. S. Geological Survey Open-File Report 78-925.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, 155 p.

White, D. E., and Williams, D. L., 1975, Summary and conclusions, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U. S. Geological Survey Circular 726, p. 147-155.

Wright, P. M., Foley, Duncan, Nichols, C. R., and Grim, P. J., 1978, Western States cooperative direct heat geothermal program of DOE: Geothermal Resources Council Transactions, vol. 2, p. 739-742.

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