GEOTHERMAL DATA

DATA ANNOUNCEMENT 82-TGB-16

GEOTHERMAL GRADIENT DATA AND MAP FOR THE UNITED STATES

The National Geophysical Data Center (NGDC) has produced a new multicolor Geothermal Gradient Map of the United States (exclusive of Alaska and Hawaii). This map, a joint publication of NGDC and Los Alamos National Laboratory (LANL), replaces the 1980 version of the map published by LANL. The new map presents a compilation of over 1,700 wells that have been measured for temperature at depths greater than 50 m. Temperature/depth profiles are linear, or composed of linear segments which reflect changes in the thermal conductivity of the rocks, rather than hydrology. The data are displayed on two sheets (Eastern and Western U.S.) at a scale of 1:2,500,000 in a format which shows the location, depth, and gradient of each well in a single color-coded symbol (see Figure 1). Each well is numbered and keyed to a table showing latitude, longitude, well depth, gradient, heat flow (where available), thermal conductivity (where available), and a reference (see Figure 1). Over 200 references have been consulted and are presented with the data.

In areas where wells are clustered, an average gradient for the area was determined. If the gradients in an area are similar for similar depth intervals, the gradients from several boreholes were averaged. In areas where gradients differ greatly, an average was calculated from a representative sampling of the various anomalous gradients. The location listed in the table is a center point for all the boreholes averaged in a region; the depth represents the deepest well. If a well is significantly deeper than nearby wells, the gradient for the deepest well was chosen.

The quest for geothermal energy during the 1970's and 1980's promoted extensive temperature surveys across the United States. Measuring temperatures in wells has always been the preliminary exploration tool in searching for both hydrothermal and hot dry rock geothermal systems. In 1976 the American Association of Petroleum Geologists and the U.S. Geological Survey (USGS) published a geothermal gradient map of North America using predominantly bottom-hole temperatures from oil and gas wells. The gradients were calculated using the average annual surface temperature as one point and a corrected temperature at the greatest depth as the second point.

The new map presents gradients from wells that were logged specifically for temperature; that is, the temperature was measured at regular depth intervals in a well that had attained thermal equilibrium, and the slope was calculated for the least-squares line passing through a plot of the data points. This temperature log provided information that enabled an interpretation of the conductive vs. convective component of heat transfer in the underlying rocks.

National Geophysical Data Center

CHOOSING, CALCULATING, AND AVERAGING GRADIENTS

The purpose of this map is to present gradients from wells that are in thermal equilibrium and appear to reflect a conductive regime. Only the linearity of the temperature/depth profile is used to determine if the gradient reflects a dominantly conductive regime. Other information concerning the hydrologic nature of the system is not considered. This method presents a consistent approach to evaluating data of highly variable quality, which can also be very inconsistent over small distances due to local changes in hydrology and geology. Where temperature/depth profiles are not available, a quality rating by the original author is considered. It is important to emphasize that gradients shown on this map reflect only the local conditions within a well and cannot be assumed to represent a regional value or to extend below the depth of actual measurement.

The following list specifies criteria used for selecting gradients for the map:

1. Wells must be deeper than 50 m.

2. Temperature/depth profiles should reflect minimum hydrologic disturbances (i.e., they should approximate a straight line, or consist of straight-line segments that reflect changes in the thermal conductivity of the rocks).

3. Gradients must be positive below the temperature inversion due to seasonal effects.

4. Only gradients given a high-quality rating by authors are used (generally, a least-squares line with a correlation coefficient of 10%).

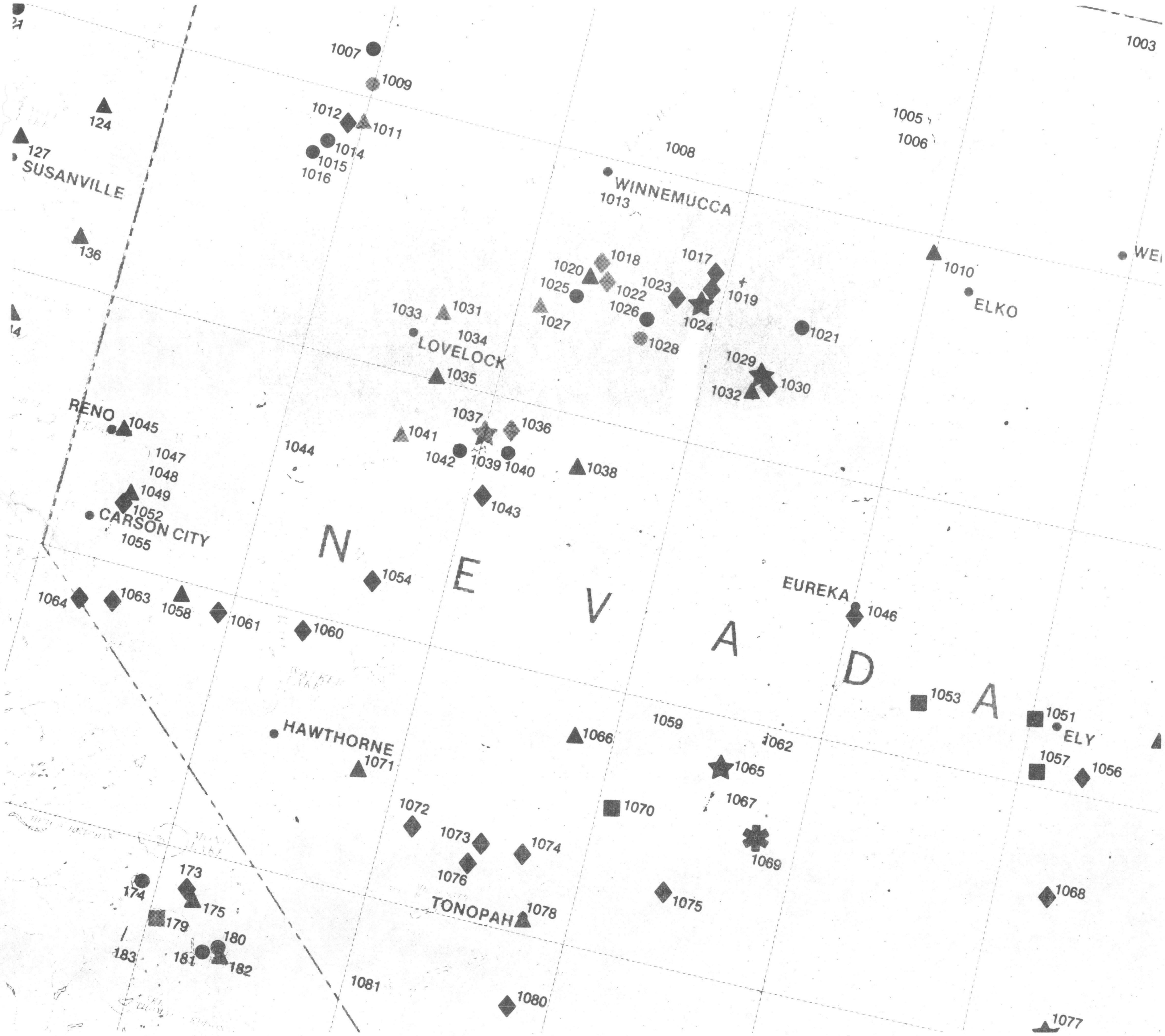
Once a gradient met the above criteria, the following methods were used to calculate a representative measurement for the well:

1. Gradients were calculated from measurements taken beneath the temperature inversion caused by changes in seasons.

2. A least-squares fit was calculated for straight-line segments of a temperature vs. depth plot and a weighted average was determined from these segments.

3. In some cases, a straight line was visually drawn to approximate a least-squares fit, and the slope of the line (or straight-line segments) was calculated.

4. In Louisiana abundant deep, bottom-hole temperature (BHT) data are available from oil and gas wells. When BHT is plotted against depth for many wells in a region, a least-squares line through the data points approximates the average temperature gradient in that region. The location of such a measurement on the map is the approximate center point of the group of wells considered.



No.	St.	Lat.	Long.	Depth	Grad.	H.F.	T.C.	Ref.
1002	NV	41 54.5	119 20.9	424	111.6			77
1003	NV	41 53.	115 05.	366	43.4	3.3		172
1004	NV	41 47.9	119 27.8	513	139.1			77
1005	NV	41 28.74	116 9.06	1600	40.			6
1006	NV	41 23.60	116 08.19	91	56.73	2.32		5 2W
1007	NV	41 12.3	119 03.8	68	88.0	2.56	2.92	134
1008	NV	41 05.34	117 31.07	122	41.01			207 2W
1009	NV	41 04.5	119 01.1	90	70.92	2.27	3.20	134
1010	NV	40 57.	116 01.	152	22.2	1.7	6.68	172
1011	NV	40 55.6	119 00.8	204	77.	1.9	2.50	147 179

Figure 1. Sample portion of Geothermal Gradient Map. Each well is represented by a symbol which reflects the depth of the deepest temperature measurement, and by a color which represents a gradient interval. The numbers are keyed to a table (see sample at bottom of figure) showing latitude, longitude, well depth, gradient, heat flow, thermal conductivity, and a reference.

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HOW TO ORDER

The cost of the map is $10 folded or $12 flat per set (Eastern and Western U.S.). Digital data used in making the map are also available in the same format as the list shown on the map. Output may be obtained on magnetic tape for $200. Please make check or money order payable to COMMERCE/NOAA/NGDC. Orders may also be charged to an American Express card by including card account number, expiration date, and signature. All inquiries should be directed to:

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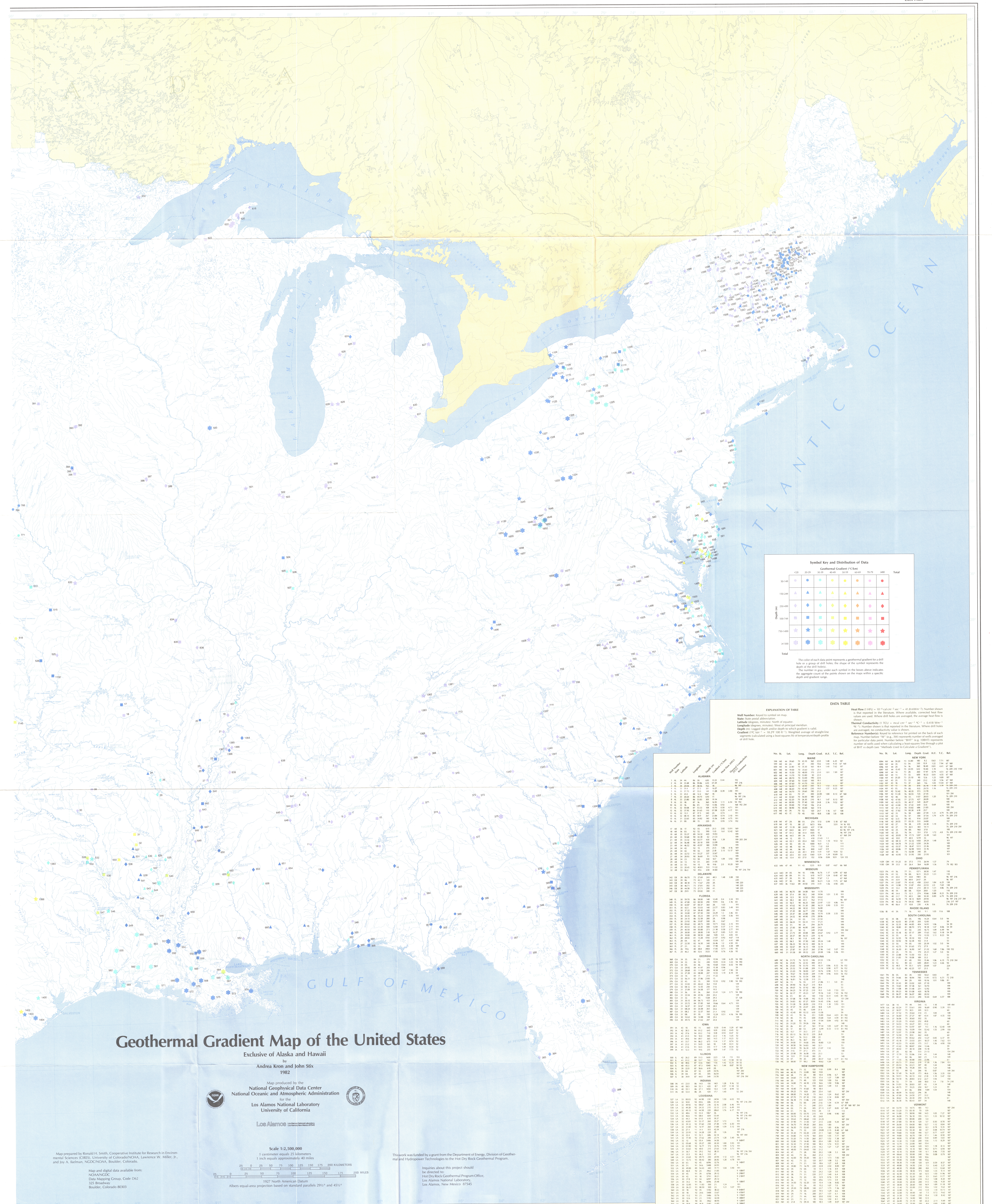

Symbol Key and Distribution of Data

Geothermal Gradient (°C/km): <20, 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, ≥80, Total

Depth (m): 50-149, 150-249, 250-499, 500-749, 750-1499, ≥1500, Total

The color of each data point represents a geothermal gradient for a drill hole or a group of drill holes; the shape of the symbol represents the depth of the drill hole(s).

The number in gray under each symbol in the boxes above indicates the aggregate count of the points shown on the maps within a specific depth and gradient range.

Geothermal Gradient Map of the United States

Exclusive of Alaska and Hawaii

by
Andrea Kron and John Stix

1982

Map produced by the
National Geophysical Data Center
National Oceanic and Atmospheric Administration
for the
Los Alamos National Laboratory
University of California

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Map prepared by Ronald H. Smith, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado/NOAA, Lawrence W. Miller, Jr., and Joy A. Ikelman, NGDC/NOAA, Boulder, Colorado.

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Data Mapping Group, Code D62
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Scale 1:2,500,000
1 centimeter equals 25 kilometers
1 inch equals approximately 40 miles

25 0 25 50 75 100 125 150 175 200 KILOMETERS

25 0 25 50 75 100 125 150 175 200 MILES

1927 North American Datum
Albers equal-area projection based on standard parallels 29½° and 45½°

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INTRODUCTION

This map presents gradients from wells logged deeper than 50 m that have attained thermal equilibrium and have nearly linear temperature vs depth profiles. It is an update of Kron and Heiken (1980a; see also Kron and Heiken 1980b).

A geothermal gradient is the rate at which temperatures in the earth change with depth. The average gradient to a certain depth can be *estimated* by calculating the slope of a line connecting the bottom-hole temperature (BHT) in a drill hole and the mean annual surface temperature (e.g., American Association of Petroleum Geologists and U.S. Geological Survey, 1976). A more accurate method for determining a gradient is to fit a line through a series of temperature measurements plotted against depth (e.g., Kron and Heiken, 1980a, b; Guffanti and Nathenson, 1980; and this map). A plot of temperature vs depth provides information on the mode of heat transfer in the vicinity of a drill hole. A linear profile often indicates conductive heat transfer. Using temperature measurements from drill holes logged deeper than 600 m, Guffanti and Nathenson (1980) mapped the regional distribution of geothermal gradients across the U.S. that can be expected to exist in a conductive thermal regime to a depth of two kilometers. Without knowledge of the thermal conductivity of the rocks nor an understanding of the regional hydrology in the vicinity of each drill hole, these gradients should not be extrapolated below the depth of actual measurement nor assumed to represent a regional value.

Sources for the data presented on this map include journal publications, open file reports, and limited unpublished information. Temperature data for wells in these reports are presented in a variety of formats: single gradient values listed in a table, plots of temperature vs depth, lists of temperatures at specific depths, and/or continuous temperature logs. The following sections describe the methods used to evaluate the various data sets and derive the gradients shown on this map.

MAP FORMAT

This map displays 1698 data points, each representing a well or group of wells. The data are coded by symbol, which reflects the depth of the measurement, and by color, which reflects the gradient. Each well is numbered and keyed to a table showing latitude, longitude, well depth, gradient, heat flow (where available), thermal conductivity (where available), and a reference. Data for states in the western U.S. are printed on the western map; similarly, data for the eastern U.S. are found on the eastern sheet. A complete list of references is printed on the reverse side of each map.

CRITERIA USED FOR SELECTING GRADIENTS

1. Drill holes must be logged deeper than 50 m.
2. Temperature/depth profiles should reflect minimum hydrologic disturbances; i.e., they should approximate a straight line or consist of straight-line segments which reflect changes in the thermal conductivity of the rocks.
3. Gradients must be positive below the temperature inversion caused by seasonal effects.
4. In cases where temperature/depth profiles or actual measurements were not listed in a publication, the original investigator usually provided a quality rating or confidence level for the data. The gradients listed for heat flow measurements were used if the error for these values was less than 20%.

METHODS USED TO CALCULATE A GRADIENT

1. Gradients were calculated from measurements taken below the shallow temperature inversion.
2. When temperature vs depth measurements were available for a well, the data were plotted using a computer program that calculated a least-squares fit for a line passing through the data points. If abrupt changes in slope occurred, a least-squares fit for each straight-line segment was calculated. The final gradient for the well is a weighted average of the straight-line segments.
3. In some publications, only temperature/depth profiles were presented for drill holes. In order to determine a gradient using this type of data, a straight line (or straight-line segments) was visually drawn through the plot and the slope of the line(s) was calculated.
4. In Louisiana abundant deep, BHT data are available from oil and gas wells. When BHT's and depths for many wells in a region are plotted on the same graph, a least-squares line through the data points approximates the average temperature gradient in the area (Bebout 1981, personal communication). In Washington, Biggane (1981) found that a least-squares line passing through BHT's provides the best representation of the average gradient in the Yakima region. Except for a locality in Texas, these are the only gradients that have been determined using this method. The location of such a measurement on the map is the approximate center of the group of wells (for Louisiana, the data are grouped by parish).

AVERAGING GRADIENTS

Several wells may be logged for temperature in a limited area for one of two reasons. The area may be favorable for geothermal exploration due to indications of abnormal heat in the subsurface. Alternatively, exploration for oil and gas led investigators to measure the temperature of wells in an oil field in an attempt to correlate temperature gradient with geologic structure (See Spicer, 1964).

Temperature gradients from geothermal areas often exhibit a wide range of values, representing areas of recharge and discharge of geothermal fluids. When highly contrasting values occurred over a closely spaced area, the various anomalous gradients were averaged. In the oil fields, gradients from nearby wells usually did not vary significantly. In this case some (but not necessarily all) of the gradients in a field were averaged. Usually, the deeper wells with the straightest temperature/depth profiles were chosen. If a well in any region was significantly deeper than others nearby, the gradient from the deep well was listed rather than an average of the others.

The location presented in the table for wells averaged in a region is the center point of that region. The depth shown is that of the deepest well. The number of wells averaged is listed after the reference number (e.g. "5W" means five wells were averaged for a particular data point).

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DATA TABLE

EXPLANATION OF TABLE

Well Number: Keyed to symbol on map.
State: State postal abbreviation.
Latitude (degrees, minutes): North of equator.
Longitude (degrees, minutes): West of principal meridian.
Depth (m): Logged depth and/or depth to which gradient is valid.
Gradient ($1^{\circ}C\ km^{-1} = 18.2^{\circ}F\ 100\ ft^{-1}$): Weighted average of straight-line segments (calculated using a least-squares fit) of temperature/depth profile of drill hole.
Heat Flow ($1\ HFU = 10^{-6}\ cal\ cm^{-2}\ sec^{-1} = 41.8\ mWm^{-2}$): Number shown is that reported in the literature. Where available, corrected heat flow values are used. Where drill holes are averaged, the average heat flow is shown.
Thermal Conductivity ($1\ TCU = mcal\ cm^{-1}\ sec^{-1}\ {}^{\circ}C^{-1} = 0.418\ Wm^{-1}\ {}^{\circ}K^{-1}$): Number shown is that reported in the literature. Where drill holes are averaged, no conductivity value is shown.
Reference Number(s): Keyed to reference list printed on the back of each map. Number before "W" (e.g., 3W) represents number of wells averaged for particular data point. Number before "BHT" (e.g. 10BHT) represents number of wells used when calculating a least-squares line through a plot of BHT vs depth (see "Methods Used to Calculate a Gradient").

No.	St.	Lat.		Long.		Depth	Grad.	H.F.	T.C.	Ref.

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Geothermal Gradient Map of the United States

Exclusive of Alaska and Hawaii

1982

West Half

DATA TABLE

ARIZONA

Well Number	State	Latitude		Longitude		Depth (m)	Gradient (°C/km)	Heat Flow (HFU)	Thermal Conductivity (TCU)	Reference
33	AZ	36	58.	109	09.	1402	25.4	1.55		160
34	AZ	36	36.	110	09.	460	19.	1.7		162
35	AZ	36	02.	110	31.	420	19.	1.8		162
36	AZ	35	43.	114	22.	245	40.77	2.82	7.14	67 168
37	AZ	35	30.	110	24.	230	23.	1.5	6.6	162
38	AZ	35	22.1	114	08.1	800	24.7	1.76	7.13	186
39	AZ	35	08.	113	49.	260	28.6	2.14	8.06	67 168
40	AZ	35	07.	109	21.	320	57.	3.8	6.6	162
41	AZ	35	06.	109	26.	370	52.	2.6		162
42	AZ	34	59.	109	09.	1878	29.4	2.19	8.22	160
43	AZ	34	55.9	111	49.4	370	12.04	1.07		186
44	AZ	34	45.1	112	04.9	510	17.55	1.58		186
45	AZ	34	38.5	113	58.6	1574	41.61	2.19		180
46	AZ	34	38.5	113	41.0	800	28.79	1.90		186
47	AZ	34	35.5	113	11.5	460	21.	1.64		67 168 2W
48	AZ	34	26.3	112	29.9	740	28.4	2.01		186
49	AZ	34	17.0	113	56.6	625	34.43	1.68		180
50	AZ	34	09.9	112	48.1	200	34.84	2.82		186
51	AZ	34	09.4	113	10.6	1646	36.46	1.62		180
52	AZ	34	07.8	112	51.5	905	32.19	1.68		180
53	AZ	34	02.5	112	21.1	500	51.6	2.11	4.09	186
54	AZ	34	01.	109	13.	345	43.9	2.09	4.76	204
55	AZ	34	00.3	113	13.1	1317	34.05	1.90		180
56	AZ	33	59.	109	23.	120	35.9	1.37		204
57	AZ	33	55.	109	27.	107	25.3	0.10	3.99	204
58	AZ	33	55.	109	20.	85	35.4	1.22	3.44	204
59	AZ	33	54.	109	09.	355	71.6	2.76	3.85	204
60	AZ	33	45.06	112	49.89	250	55.20			203 8W
61	AZ	33	38.	114	20.	410	33.51	2.4		67 168 5W
62	AZ	33	25.0	110	57.5	300	25.55	2.13		186
63	AZ	33	25.	112	01.	175	29.6	1.1	3.7	172
64	AZ	33	23.9	110	51.9	580	28.84	2.80	10.05	186
65	AZ	33	19.	111	43.	280	45.7	1.7	3.79	172

Symbol Key and Distribution of Data

Geothermal Gradient (°C/km)