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GEOTHERMAL GRADIENT MAP OF THE UNITED STATES
(Exclusive of Alaska and Hawaii)

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ABSTRACT
This paper describes an update of the Geothermal Gradient Map of the Conterminous United States (Kron and Heiken 1980) and compares the changes made since the first map. The second map presents a compilation of over 1700 wells that have been measured for temperature below 50 m and whose 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 at an enlarged scale of 1:2,500,000 and in a new format which shows the location, depth, and gradient of each well in a single color-coded symbol. This edition contains over two times the amount of data shown on the first map and is accompanied by a table, listing for each well its location, depth, gradient, heat flow (where available), thermal conductivity (where available), and a reference. Over 200 references have been consulted and are presented with the data.

BACKGROUND
Investigators in the late 1800's to early 1900's took advantage of deep oil wells (Hallock 1892) and mine shafts (Agassiz 1895; Spurr 1905) to observe the earth's temperatures and make estimates on the nature and thickness of the crust (Agassiz 1895). During the 1930's temperature measurements in the deep copper mines of Michigan were used to estimate the timing and extent of the last glacial epoch (Fisher et al. 1932; Hotchkiss and Ingersoll, 1934). Attempts to correlate temperatures with geologic structures during the 1920's to 1930's resulted in numerous observations in deep wells throughout the oil fields of Texas, Oklahoma, Kansas, New Mexico, Wyoming, and California (Van Orstrand 1926; Van Orstrand 1934). Spicer (1964) continued to measure temperatures in deep oil wells and compiled measurements made from 1910 to 1945.

Interest in determining heat flow throughout the United States began in the 1940's with investigators often utilizing the deep well measurements of Van Orstrand (Benfield 1947; Birch 1947). Since the 1950's calculation of temperature gradients in wells, tunnels, and mine shafts has primarily been for determination of heat flow for understanding crustal dynamics (Roy et al. 1968; Sass and Munroe 1974).

The quest for geothermal energy during the 1970's and 1980's promoted extensive temperature surveys across the U.S. 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 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 deepest depth as the second point. A more accurate method (and the one used for this map) for determining the geothermal gradient is to measure the temperature at regular depth intervals in a well that has attained thermal equilibrium, and calculate the slope of a least-squares line passing through a plot of the data points. A temperature log provides information that enables an interpretation of the conductive vs convective component of heat transfer in the underlying rocks.

Guffanti and Nathenson (1980) published a temperature gradient map of the U.S. containing data from over 200 wells that have been measured for temperature below 600 m. Their objective was to determine regional temperature gradients that can be expected to exist in a conductive thermal regime to a depth of two kilometers. This type of data is very useful for regional analyses but does not include information on local thermal anomalies which may also be of interest to the exploration community. The Kron and Stix (1982) map provides this additional information, however, each measurement represents conditions existing only within a particular well and cannot be considered a regional value or to extend beneath the depth of the well.

MAP FORMAT
The first map (Kron and Heiken 1980) was published at a scale of 1:5,000,000; each data point was labeled with a number representing its geothermal gradient. Data were contoured in five 15°C/km intervals and each area falling within a specific contour interval was color-coded. The
shortcomings of this display are that data from wells of various depths and different geologic settings are weighted the same, and areas with no data are given values associated with their nearest neighbors. Due to the inherent variability of the data, and subsequent inability to correlate such data meaningfully, an improved method of displaying the information was developed.

The second map (Kron and Stix 1982) shows over 1700 data points, each representing a well or group of wells for which a least-squares gradient has been determined. The points are represented by a symbol, which reflects the depth of the deepest temperature measurement in the well, and by a color which represents a gradient interval. 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. The data are not contoured and areas with no data are left blank. General trends can be noted by changes in the color of the symbols. Qualifying information such as well depth is readily distinguished.

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, and data which can 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 author is provided. 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 affects.
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 has 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 (see for e.g. Jam L. et al. 1969) a least-squares line through the data points approximates the average temperature gradient in that region. In Washington, Biggane (1981) found that a least-squares line through BHT's provided the best representation of the average gradient in the Yakima region. The location of such a measurement on the map is the approximate center point of the group of wells considered.

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, its gradient was chosen over the others.

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