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GEOTHERMAL MAP, UPPER PART OF MADISON GROUP, MONTANA

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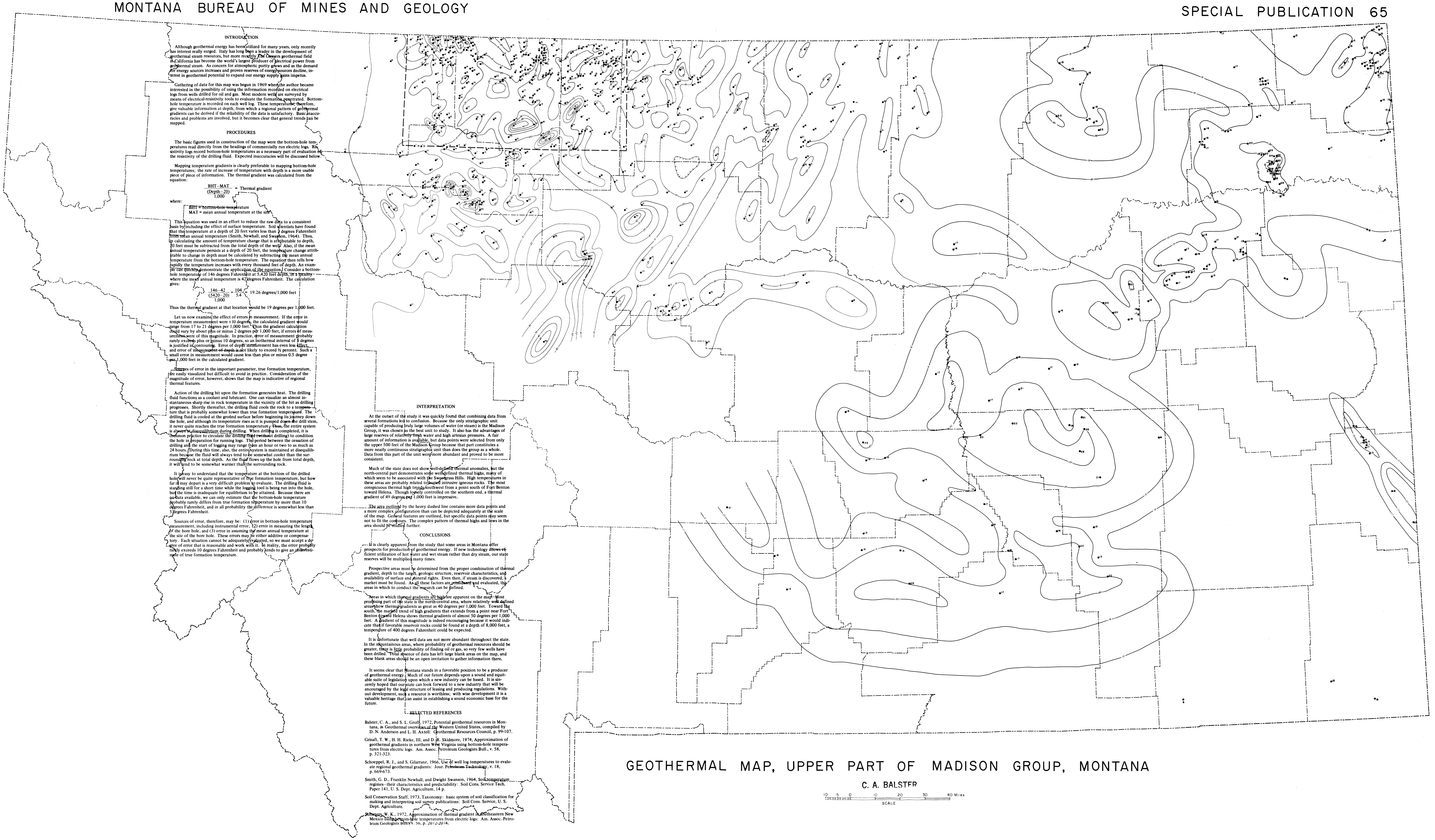

INTRODUCTION

Although geothermal energy has been utilized for many years, only recently has interest really surged. Italy has long been a leader in the development of geothermal steam resources, but more recently The Geysers geothermal field in California has become the world's largest producer of electrical power from geothermal steam. As concern for atmospheric purity grows and as the demand for energy sources increases and proven reserves of energy sources decline, interest in geothermal potential to expand our energy supply gains impetus.

Gathering of data for this map was begun in 1969 when the author became interested in the possibility of using the information recorded on electrical logs from wells drilled for oil and gas. Most modern wells are surveyed by means of electrical-resistivity tools to evaluate the formation penetrated. Bottom-hole temperature is recorded on each well log. These temperatures, therefore, give valuable information at depth, from which a regional pattern of geothermal gradients can be derived if the reliability of the data is satisfactory. Basic inaccuracies and problems are involved, but it becomes clear that general trends can be mapped.

PROCEDURES

The basic figures used in construction of the map were the bottom-hole temperatures read directly from the headings of commercially run electric logs. Resistivity logs record bottom-hole temperatures as a necessary part of evaluation of the resistivity of the drilling fluid. Expected inaccuracies will be discussed below.

Mapping temperature gradients is clearly preferable to mapping bottom-hole temperatures; the rate of increase of temperature with depth is a more usable piece of piece of information. The thermal gradient was calculated from the equation:

$$\frac{\text{BHT}-\text{MAT}}{\frac{(\text{Depth}-20)}{1{,}000}} = \text{Thermal gradient}$$

where:

BHT = bottom-hole temperature
MAT = mean annual temperature at the site

This equation was used in an effort to reduce the raw data to a consistent basis by including the effect of surface temperature. Soil scientists have found that the temperature at a depth of 20 feet varies less than 2 degrees Fahrenheit from mean annual temperature (Smith, Newhall, and Swanson, 1964). Thus, in calculating the amount of temperature change that is attributable to depth, 20 feet must be subtracted from the total depth of the well. Also, if the mean annual temperature persists at a depth of 20 feet, the temperature change attributable to change in depth must be calculated by subtracting the mean annual temperature from the bottom-hole temperature. The equation then tells how rapidly the temperature increases with every thousand feet of depth. An example can quickly demonstrate the application of the equation. Consider a bottom-hole temperature of 146 degrees Fahrenheit at 5,420 feet depth, in a locality where the mean annual temperature is 42 degrees Fahrenheit. The calculation gives:

$$\frac{146-42}{\frac{(5420-20)}{1{,}000}} = \frac{104}{5.4} = 19.26 \text{ degrees/1,000 feet}$$

Thus the thermal gradient at that location would be 19 degrees per 1,000 feet.

Let us now examine the effect of errors in measurement. If the error in temperature measurement were ± 10 degrees, the calculated gradient would range from 17 to 21 degrees per 1,000 feet. Thus the gradient calculation could vary by about plus or minus 2 degrees per 1,000 feet, if errors of measurement were of this magnitude. In practice, error of measurement probably rarely exceeds plus or minus 10 degrees, so an isothermal interval of 5 degrees is justified in contouring. Error of depth measurement has even less effect, and error of measurement of depth is not likely to exceed ½ percent. Such a small error in measurement would cause less than plus or minus 0.5 degree per 1,000 feet in the calculated gradient.

Sources of error in the important parameter, true formation temperature, are easily visualized but difficult to avoid in practice. Consideration of the magnitude of error, however, shows that the map is indicative of regional thermal features.

Action of the drilling bit upon the formation generates heat. The drilling fluid functions as a coolant and lubricant. One can visualize an almost instantaneous sharp rise in rock temperature in the vicinity of the bit as drilling progresses. Shortly thereafter, the drilling fluid cools the rock to a temperature that is probably somewhat lower than true formation temperature. The drilling fluid is cooled at the ground surface before beginning its journey down the hole, and although its temperature rises as it is pumped down the drill stem, it never quite reaches the true formation temperature. Thus, the entire system is always at disequilibrium during drilling. When drilling is completed, it is common practice to circulate the drilling fluid (without drilling) to condition the hole in preparation for running logs. The period between the cessation of drilling and the start of logging may range from an hour or two to as much as 24 hours. During this time, also, the entire system is maintained at disequilibrium because the fluid will always tend to be somewhat cooler than the surrounding rock at total depth. As the fluid flows up the hole from total depth, it will tend to be somewhat warmer than the surrounding rock.

It is easy to understand that the temperature at the bottom of the drilled hole will never be quite representative of true formation temperature, but how far it may depart is a very difficult problem to evaluate. The drilling fluid is standing still for a short time while the logging tool is being run into the hole, but the time is inadequate for equilibrium to be attained. Because there are no data available, we can only estimate that the bottom-hole temperature probably rarely differs from true formation temperature by more than 10 degrees Fahrenheit, and in all probability the difference is somewhat less than 5 degrees Fahrenheit.

Sources of error, therefore, may be: (1) error in bottom-hole temperature measurement, including instrumental error; (2) error in measuring the length of the bore hole; and (3) error in assuming the mean annual temperature at the site of the bore hole. These errors may be either additive or compensatory. Each situation cannot be adequately evaluated, so we must accept a degree of error that is reasonable and work with it. In reality, the error probably rarely exceeds 10 degrees Fahrenheit and probably tends to give an underestimate of true formation temperature.

INTERPRETATION

At the outset of the study it was quickly found that combining data from several formations led to confusion. Because the only stratigraphic unit capable of producing truly large volumes of water (or steam) is the Madison Group, it was chosen as the best unit to study. It also has the advantages of large reserves of relatively fresh water and high artesian pressures. A fair amount of information is available, but data points were selected from only the upper 500 feet of the Madison Group because that part constitutes a more nearly continuous stratigraphic unit than does the group as a whole. Data from this part of the unit were more abundant and proved to be more consistent.

Much of the state does not show well-defined thermal anomalies, but the north-central part demonstrates some well-defined thermal highs, many of which seem to be associated with the Sweetgrass Hills. High temperatures in these areas are probably related to buried intrusive igneous rocks. The most conspicuous thermal high trends southwest from a point south of Fort Benton toward Helena. Though loosely controlled on the southern end, a thermal gradient of 49 degrees per 1,000 feet is impressive.

The area outlined by the heavy dashed line contains more data points and a more complex configuration than can be depicted adequately at the scale of the map. General features are outlined, but specific data points may seem not to fit the contours. The complex pattern of thermal highs and lows in the area should be studied further.

CONCLUSIONS

It is clearly apparent from the study that some areas in Montana offer prospects for production of geothermal energy. If new technology allows efficient utilization of hot water and wet steam rather than dry steam, our state reserves will be multiplied many times.

Prospective areas must be determined from the proper combination of thermal gradient, depth to the target, geologic structure, reservoir characteristics, and availability of surface and mineral rights. Even then, if steam is discovered, a market must be found. As all these factors are considered and evaluated, the areas in which to conduct the research can be defined.

Areas in which thermal gradients are high are apparent on the map. Most promising part of the state is the north-central area, where relatively well defined areas show thermal gradients as great as 40 degrees per 1,000 feet. Toward the south, the marked trend of high gradients that extends from a point near Fort Benton toward Helena shows thermal gradients of almost 50 degrees per 1,000 feet. A gradient of this magnitude is indeed encouraging because it would indicate that if favorable reservoir rocks could be found at a depth of 8,000 feet, a temperature of 400 degrees Fahrenheit could be expected.

It is unfortunate that well data are not more abundant throughout the state. In the mountainous areas, where probability of geothermal resources should be greater, there is little probability of finding oil or gas, so very few wells have been drilled. Total absence of data has left large blank areas on the map, and these blank areas should be an open invitation to gather information there.

It seems clear that Montana stands in a favorable position to be a producer of geothermal energy. Much of our future depends upon a sound and equitable suite of legislation upon which a new industry can be based. It is sincerely hoped that our state can look forward to a new industry that will be encouraged by the legal structure of leasing and producing regulations. Without development, such a resource is worthless; with wise development it is a valuable heritage that can assist in establishing a sound economic base for the future.

SELECTED REFERENCES

Balster, C. A., and S. L. Groff, 1972, Potential geothermal resources in Montana, *in* Geothermal overviews of the Western United States, compiled by D. N. Anderson and L. H. Axtell: Geothermal Resources Council, p. 99-107.

Grisafi, T. W., H. H. Rieke, III, and D. R. Skidmore, 1974, Approximation of geothermal gradients in northern West Virginia using bottom-hole temperatures from electric logs: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 321-323.

Schoeppel, R. J., and S. Gilarranz, 1966, Use of well log temperatures to evaluate regional geothermal gradients: Jour. Petroleum Technology, v. 18, p. 669-673.

Smith, G. D., Franklin Newhall, and Dwight Swanson, 1964, Soil temperature regimes—their characteristics and predictability: Soil Cons. Service Tech. Paper 141, U. S. Dept. Agriculture, 14 p.

Soil Conservation Staff, 1973, Taxonomy: basic system of soil classification for making and interpreting soil survey publications: Soil Cons. Service, U. S. Dept. Agriculture.

Summers, W. K., 1972, Approximation of thermal gradient in southeastern New Mexico using bottom-hole temperatures from electric logs: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 2072-2074.