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GEOTHERMAL RESOURCES IN THE WILLISTON BASIN: NORTH DAKOTA

William D. Gosnold, Jr.

North Dakota Mining and Mineral Resources Research Institute

ABSTRACT

Temperatures in four geothermal aquifers in the Williston Basin are in the range for low and moderate temperature geothermal resources within an area of about128,000 km^2 in North Dakota. The accessible resource base is 13,500 x 10^{18} J., which, assuming a recovery factor of 0.001, may represent a greater quantity of recoverable energy than is present in the basin in the form of petroleum. A synthesis of heat flow, thermal conductivity, and stratigraphic data was found to be significantly more accurate in determining formation temperatures than is the use of linear temperature gradients derived from bottom hole temperature data. The thermal structure of the Williston Basin is determined by the thermal conductivities of four principal lithologies: Tertiary silts and sands (1.6 W/m/K), Mesozoic shales (1.2 W/m/K), Paleozoic limestones (3.0 W/m/K), and Paleozoic dolomites (4.0 W/m/K). The stratigraphic placement of these lithologies leads to a complex, multi-component geothermal gradient which precludes use of any single-component gradient for accurate determination of subsurface temperatures.

INTRODUCTION

Geothermal resources in the Williston Basin in North Dakota occur as thermal waters in at least four regional aquifers, i.e., the Inyan Kara (Cretaceous), Madison (Mississippian), Duperow (Devonian), and Red River (Ordovician). These resources are classified as either moderate temperature resources (150° > T > 90°) or low temperature resources (T < 90°) (Muffler, 1979). Any assessment of these resources must establish the temperature, areal extent, thickness, chemical properties, and hydrologic properties of the aquifers. Previous work by Harris et. al., (1980, 1981, 1983) provides information on areal extent, thickness, and water chemistry as well as temperature data recorded in shallow wells, a few heat flow holes, and a large amount of data recorded as bottom hole temperatures (BHT) in oil and gas exploration wells. The temperature data of Harris et. al., (1983) that are relevant to the thermal aquifers are given as linear temperature gradients calculated from the BHT and mean annual surface temperatures. Those data were used in an analysis of low-temperature geothermal resources in the United States by the U.S. Geological Survey (Sorey et. al., 1983a); and geothermal resources in North Dakota were estimated for two aquifers, the Madison and the Inyan Kara as 7.5 x 10^{18} J. and 2.3 x 10^{18} J., respectively.

Sorey et al.'s (1983a) estimate of geothermal resources suggests a major new energy resource for North Dakota. However, the BHT data used in the resource estimates gave incorrect predictions of subsurface temperatures and the resource was underestimated by about 50 percent. A fundamental problem was that a two-point temperature gradient calculation is inappropriate for the Williston Basin because there are large differences in thermal conductivity among the four principal rock types in the sedimentary section. These rock types and their estimated average conductivities in S.I. units (W/m/K) are: Tertiary clays, silts, and sands, K = 1.6; Cretaceous shales, K = 1.2; Upper Paleozoic limestones, K = 3.2; and Lower Paleozoic dolomites, K = 4.0. Consequently, a typical temperature-depth curve for the Williston Basin is a multi-component curve with slopes differing by as much as a factor of four. Each of the four rock types has a thickness on the order of a kilometer in parts of the basin. A linear temperature gradient based on accurate BHT data from any unit within the basin will give an inaccurate prediction of temperature in any other unit (Figure 1).

Because the thermal structure of the Williston Basin is complex and cannot be represented by linear temperature gradient calculations, the first goal of this project has been to determine accurately the temperatures of the thermal aquifers in the basin. The ultimate goal of this project has been to reassess the resource in the Inyan Kara and Madison aquifers and to extend the resource analysis to include the Duperow and Red River aquifers.

SUBSURFACE TEMPERATURES

Accurate determination of subsurface temperatures should be the first objective in assessing geothermal resources in sedimentary basins. The methods for determining those temperatures have

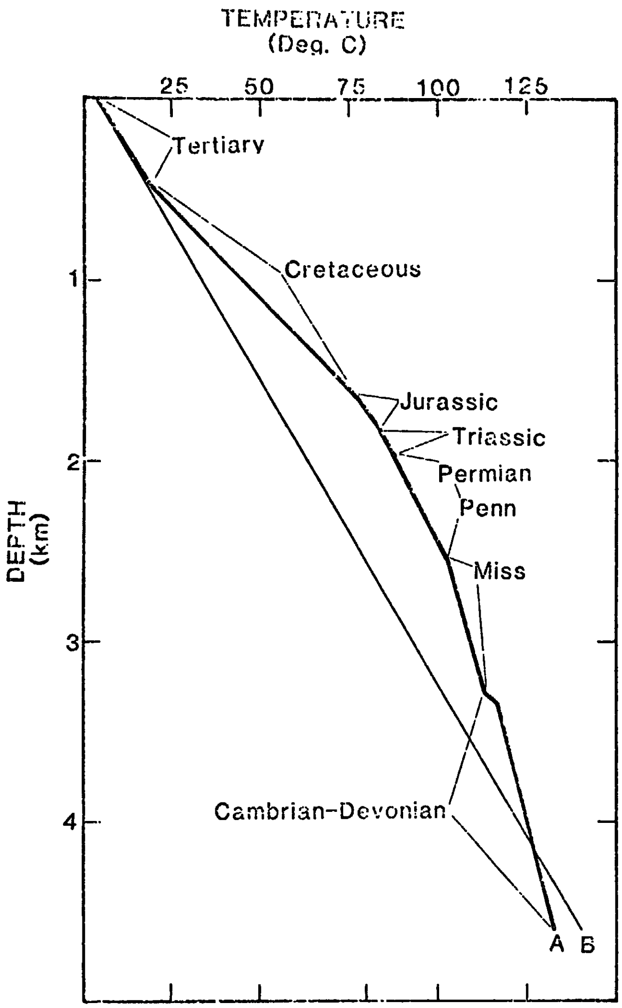

FIGURE 1 - Hypothetical temperature-depth curves for the Williston Basin in western North Dakota. Curve A was computed from heat flow and stratigraphic data. Curve B was taken from bottom hole temperature data.

differed among the various DOE State-Coupled Geothermal Resource Assessment Programs, and the most commonly used method has been to compile and analyze the bottom hole temperature data from oil and gas wells. Other methods that have been used are direct measurement in deep wells and prediction of temperatures from heat flow data. Because the basic quantity sought in exploration for geothermal resources is heat, establishing the most accurate method for determining subsurface temperatures is crucial for geothermal research.

The accuracy of bottom hole temperatures as predictors of subsurface temperatures was questioned in the introduction. In that discussion it was assumed that BHT data accurately represent the temperatures of the formations in which they were recorded. Tests of that assumption are available from studies where other methods as well as analysis of BHT data were used to determine subsurface temperatures. For example, Gosnold (1982) compared data derived from the geothermal gradient map of North America (A.A.P.G., 1976) and equilibrium temperature data in Nebraska. The temperature gradients differ on the order of 10°C/km to 40°C/km and the temperatures differ by about 20°C over the study area. In this case the equilibrium temperatures are categorically higher than the temperatures extrapolated from the BHT data.

The differences between the temperature data sets are due to the data and to the correlation applied to the data. The quality of the data in the oil fields in Nebraska is not good. Analysis of bottom hole temperatures recorded in nine different sections in western Nebraska shows that, in some cases, about 20 percent of the temperatures have the same value regardless of depth or time interval between cessation of mud circulation and logging (Gosnold, Eversoll, and Carlson, 1982). In these cases, it is suspected that the BHT is a guess by the logger rather than an actual record. The time of logging is also suspect in most of the data. In a total of 14,000 records, there are fewer than 100 instances in which recorded logging times are not exactly 1 or 2 hours after circulation ceased. The problem with the correction to the BHT data is that it was based on equilibrium temperatures recorded in wells in the Texas Gulf Coast region. The gross lithologies and the thermal properties of the sediments there are not the same as those in the Cretaceous rocks underlying Nebraska. Consequently, the constants in the correction equation (see Wallace et. al., 1979) do not apply to the rocks in Nebraska.

Uncorrected bottom hole temperatures are, as expected, less close to the equilibrium temperature data than the corrected data. This condition also was demonstrated in the Nebraska project where one of the tasks was to produce a contour map of temperature gradients calculated from uncorrected bottom hole temperature data. That map (Gosnold, 1982) is based on about 14,000 data and vaguely resembles the A.A.P.G. temperature gradient map, but it shows little agreement with the equilibrium temperature gradient map.

The Denver Basin in Nebraska has a multi-component geothermal gradient curve similar to that in the Williston Basin. The geothermal gradient in the shale-rich Cretaceous section is about 50 K/km due to the low thermal conductivity of the shales, i.e. about 1.2 W/m/K (Sass et. al., 1982; Blackwell et. al., 1981). The gradient in the Paleozoic carbonate section ranges from one-third to one-half of that in the

Mesozoic rocks due to the high conductivity of the limestones and dolomites, i.e., about 3.0 W/m/K to 4.5 W/m/K (see Sass et. al., 1981). However, for much of the Denver Basin the BHT data are based on temperatures recorded in the Dakota Group and only one component of the temperature gradient curve influences the data. This observation is most significant. In this case, a two-point temperature gradient curve should apply, yet large differences between equilibrium temperatures and BHT data exist. Therefore, BHT data may not accurately represent formation temperatures even for the case of one-component geothermal gradient areas, and use of BHT data in cases where multi-component gradients do influence the data seems wholly inadvisable.

An alternate method for determining subsurface temperatures is to use a synthesis of heat flow, thermal conductivity, and stratigraphic data. This method is a direct approach to determining subsurface temperatures because it addresses the fundamental variables in the thermal structure of the crust, i.e., heat flow and thermal conductivity. This method was used in the geothermal resource assessment of Nebraska (Gosnold and Eversoll, 1981; 1982) and its accuracy proved to be excellent. Subsequent measurement of temperatures in nine wells at depths ranging from 1.2 km to 1.8 km in the Denver Basin have found actual temperatures to be within 2 degrees of the predicted temperatures.

WILLISTON BASIN

At least four geothermal aquifers lie within the Williston Basin. Accurate determination of their temperatures was the first objective in assessing the total geothermal resource. Because of its better accuracy, the heat flow-stratigraphy synthesis method for determining subsurface temperatures was used in this analysis of the Williston Basin. Consequently, one of the significant results of this study is that it provides another comparison between the BHT and heat flow synthesis methods for assessing geothermal resources.

The data for the Williston Basin include heat flow data from previous studies (Blackwell, 1969; Combs and Simmons, 1973; Scattolini, 1978) and stratigraphic data summarized in the previous geothermal studies in North Dakota (Harris et. al., 1982). Thermal conductivities of rocks at heat flow sites were used as a basis for estimating regional conductivities for gross lithologies. Although thermal conductivity of a specific unit may differ from site to site, the range of variation for one rock type is small compared to the difference in conductivities for different rock types characteristic of the Williston Basin. For example, the range in conductivity for the Paleozoic shales in Kansas is about 0.3 W/m/K (Blackwell et al., 1982), the difference in conductivity between the Pierre shale and the Madison limestone is about 2.5 W/m/K. A constraint on the range of thermal conductivities used is obtained by comparing the predicted temperature-depth plot with the actual temperature logs taken at nearby sites (Figure 2).

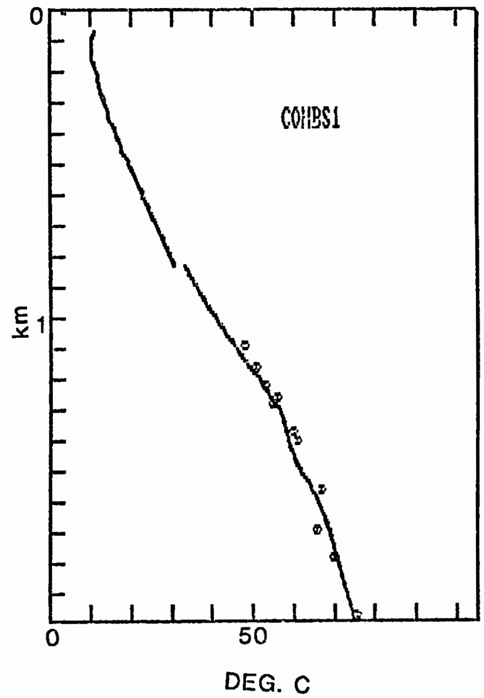

FIGURE 2 - Comparison of an equilibrium temperature-depth log (small dots) with hypothetical temperatures calculated from heat flow (large dots).

In the application of this method in the Nebraska study, stratigraphic data were taken from electric logs for a number of sites within the resource area. However, in this study the data were taken from a series of structure contour maps of the principal rock formations in the Williston Basin (Harris et. al. 1982). These maps permitted establishment of a regularly spaced grid of points for subsurface temperature computations.

Selection of the grid spacing was determined from the spacing of available heat flow data, which is the quantity most likely to vary from site to site. The nature of the temperature field arising from a radioactive basement source is essentially the same as that of a gravitational field arising from different density distributions in the basement (Simmons, 1967). The simple half-width rules and depth rules that apply to gravity data also apply to temperature data, and it is reasonable to assume that lateral variation in heat flow due to differences in basement radioactivity should have its shortest wave lengths on the order of the thickness of the sedimentary cover. For the Williston Basin the ideal spacing of heat flow data would be on the order of 4 kilometers. The actual spacing of data from previous studies (see Scattolini, 1977) ranges from 10 to greater than 100 km and is commonly about 40 kilometers. To form a grid for temperature projections, speculative interpolation of the data is necessary. However, extrapolation of these widely spaced data to a dense grid of 4 kilometers is unjustified; and the least speculative extrapolation seems to be a grid spacing of about 40 kilometers. For the purpose of portrayal on available maps, a spacing corresponding to 4 townships, i.e., 24 miles (38.6 km) was adopted.

RESOURCE ESTIMATES

Temperatures on top of each of the aquifers were projected for each point in the 9x10 grid using the simple equation for one dimensional heat flow

$$Q = K(dT/dZ) \qquad \text{(Eq. 1)}$$

where Q is heat flow, K is thermal conductivity, dT is the incremental change in temperature for an incremental change in depth of dZ. The temperature at any point Z can be calculated by

$$T = To + Zi(Q/Ki) \qquad \text{(Eq. 2)}$$

where To is surface temperature, Zi and Ki are the thicknesses and thermal conductivities of the n overlying layers.

Estimates of the mean accessible resource base were obtained using the method of Sorey et. al. (1983b), i.e.,

$$qR = p\ c\ a\ d\ (t - tr) \qquad \text{(Eq. 3)}$$

where qR is the accessible resource base, pc is the volumetric specific heat of the rock plus water, a is the reservoir area, d is the reservoir thickness, t is the reservoir temperature, and tr is 15°C. This method gives an optomistic estimate for the resource base because of the large temperature drop that is used. However, each use of geothermal waters may require different amounts of heat extraction, and heat exchanger characteristics vary widely among different types and in different applications. Therefore, it may be better to specify a specific reference temperature for purpose of resource estimation and let the potential user make additional estimates based on the data and his particular needs.

The recoverable resource can be calculated from the accessible resource base by considering the hydrologic properties of the aquifers. The general approach of Sorey et. al. (1983b) could be applied to the different aquifers in the basin using available data on their respective hydrologic properties. However, the general conclusion reached by Sorey et. al. (1983b), i.e., that the recovery factor for large sedimentary basis approaches 0.001, serves as a convenient method for making the resource estimate. In fact, applying this recovery factor to the Williston Basin data gives lower estimates for the resource than were obtained by Sorey et. al. (1983a). (See Table 7, pg. 59).

Applying this recovery factor to the data obtained in this study gives estimates for the resource that exceed the estimate of Sorey et. al. (1983a) by about 107 percent for the Inyan Kara and 25 percent for the Madison. The difference for the Madison is due only to the temperature differences used in the calculations. The difference for the Inyan Kara is due to temperature differences and to the size of the area included in the estimate. The extent of the resource area can be calculated by applying the criterion of Reed (1983), i.e., that a resource must have a temperature exceeding Tr; where

$$Tr = T10 + Z(25) \qquad \text{(Eq. 4)}$$

T10 is mean annual surface temperature plus 10°C and Z is depth to resource. The Inyan Kara underlies Cretaceous shales that have a thermal conductivity on the order of 1.2 W/m/K, assuming that the mean heat flow in the basin is 55 mW/m^2 the minimum depth at which the Inyan Kara becomes a resource can be calculated by setting Equation 2 equal to Equation 4 and solving for Z. For the conditions given above, this depth is 720 meters.

CONCLUSIONS

Methodology

The method of estimating subsurface temperatures used in this study is significantly more accurate than is the use of BHT data. Application of the heat flow synthesis method in this study relied on the assumption that thermal conductivities do not vary over the study area. This assumption is not entirely correct. Formation conductivities do vary throughout the basin, but the variation is significantly less than the differences in conductivities between formations. Consequently, errors in calculated subsurface temperature due to variation in formation conductivities are significantly less than errors that result from applying linear gradients extrapolated from BHT data.

The heat flow synthesis method would be best applied where actual conductivities are measured at each grid point. In most sedimentary basins this condition can be met. Most state geological surveys maintain drill core repositories or libraries and numerous samples are available for thermal conductivity analyses. It is suggested that a cooperative effort between the state geological surveys and the geothermal laboratories at several universities and the U.S.G.S. could lead to accurate temperature analyses of most sedimentary basins. It is recommended that this type of project be a major component of any future national geothermal program.

Resources

This assessment of geothermal resources in the Inyan Kara, Madison, Duperow, and Red River aquifers places the accessible resource base in North Dakota at 13,500 x 10^{18} J (Table 1).

TABLE 1

	Mean Temperature	Maximum Temp. °C	Minimum Temp. °C	Reservoir Area (Km^2)	Reservoir Thickness (Km)	Mean Accessible Resource Base (10^{18} J.)
Inyan Kara	51	84	25	128,000	0.091	1,100
Madison	69	117	31	128,000	0.366	6,600
Duperow	81	127	34	128,000	0.100	2,200
Red River	87	138	35	128,000	0.150	3,600

Assuming an estimated recovery factor of 0.001 for geothermal waters and that a barrel of petroleum contains 6.07 x 10^9 J., the recoverable geothermal resource contained within four aquifers in North Dakota is equivalent to the energy contained in 2.22 x 10^9 barrels of petroleum. A surprising result of this study is that the quantity of geothermal energy in the Williston Basin may exceed the energy that is present in the form of oil. The potential impact of this energy resource on the industrial climate of North Dakota should be explored, [in depth]

Technology for utilization of the geothermal resource directly as a heat source and for electric power generation with binary systems has developed to an economical stage. When exploited using both production and re-injection wells, this large energy resource is almost non-depletable and is non-polluting. Some possible uses for the resource are: electric power supply, direct heating supply, lignite drying, grain drying, electric rail systems, vegetable crops in geothermally heated green houses, and fish farming.

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REFERENCES

Blackwell, D.D., 1969, Heat-flow determinations in the Northwestern United States, Jour. Geophys. Res., v.4, p. 992-1007.

Blackwell, D.D., Steele, J.L., and Steeples, D.W. 1981a. Heat flow determinations in Kansas and their implications for midcontinent heat flow patterns (abstract), EOS, v. 62, p. 392.

Blackwell, D.D., and Steele, J.L., 1981b. Heat flow and geothermal potential of Kansas, Final report for Kansas State Agency Contract 949, 69 pp.

Combs, J. and Simmons, G., 1973. Terrestrial heat-flow determinations in the North-Central United States, Jour. Geophys. Res. v. 78, p. 441-461.

Gosnold, W.D., Jr. and Eversoll, D.A., 1981. Usefulness of heat flow data in regional assessment of low-temperature geothermal resources with special reference to Nebraska, Geothermal Resources Council Transactions, v. 5, p. 79-82.

Gosnold, W.D., Jr., Eversoll, D.A., and Carlson, M.P., 1982. Three years of geothermal research in Nebraska, in Geothermal Direct Heat Program Roundup Technical Conference Proceedings, v. 1, C.A. Ruscetta, Editor, ESL, University of Utah, Salt Lake City, Utah, p. 147-157.

Gosnold, W.D., Jr., and Eversoll, D.A., 1982. Geothermal resources of Nebraska, 1:500,000 scale map, National Geophysical and Solar Terrestrial Data Center, National Oceanic and Atmospheric Administration, Boulder, CO.

Gosnold, W.D., Jr., 1982. Geothermal resource maps and bottom hole temperatures, Geothermal Resources Council Transactions, v. 6, p. 45-48.

Harris, K.L., Winczewski, L.M., Umphrey, B.L., and Anderson, S.B., 1980. An evaluation of hydrothermal resources of North Dakota. Phase 1 Final Technical Report, E.E.S. Bull. No. 80-03-EES-02, Grand Forks, ND, 176, pp.

Harris, K.L., Howell, F.L., Winczewski, L.M., Wartman, B.L., Umphrey, B.L., and Anderson, S.B., 1981. An evaluation of hydrothermal resources of North Dakota. Phase II Final Technical Report, E.E.S. Bull. No. 81-05-EES-02, Grand Forks, ND, 296 pp.

Harris, K.L., Howell, F.L., Wartman, B.L., and Anderson, S.B., 1981. An evaluation of hydrothermal resources of North Dakota. Phase III Final Technical Report, E.E.S. Bull. No. 82-08-EES-01, Grand Forks, ND, 210 pp.

Muffler, L.J.P., and Guffanti, M., 1979, Assessment of Geothermal Resources of the United States--1978, in Assessment of Geothermal Resources of the United States--1978, L.P.J. Muffler, editor, U.S.G.S. Circular 790, 163 pp.

Reed, M.J., 1983. Introduction to Assessment of low temperature geothermal resources of the United States--1982. U.S. Geological Survey Circular 892, p. 1-8.

Sass, J.H., and Galanis, S.P., Jr., 1983. Temperatures, thermal conductivity, and heat flow from a well in Pierre shale near Hayes, South Dakota. U.S. Geol. Survey Open File report 83-25.

Sass, J.H., Blackwell, D.D., Chapman, D.S., Costain, J.K., Kecker, E.R., Lawver, L.A., and Swanberg, C.A., 1981. Heat flow from the crust of the United States, in Touloukian, Y.S., Judd, W.R., and Roy, R.F., ed., Physical Properties of Rocks and Minerals, v. II-2. McGraw-Hill Book Company, pp. 503-548.

Scattolini, R., 1977. Heat flow and heat production studies in North Dakota, Ph.D. Dissertation. University of North Dakota, Grand Forks, pp. 257.

Simmons, G., 1967. Interpretation of Heat Flow Anomalies. 1. Contrasts in Heat Production. Rev. Geophys., v. 5, pp. 43-52.

Sorey, M.L., M.J. Reed, D. Foley, and J. Renner, 1983a. Low temperature geothermal resources in the central and eastern United States. In Assessment of Low Temperature Geothermal Resources of the United States - 1982, M.J. Reed, Editor, U.S. Geological Survey Circular 892, pp. 51-66.

Sorey, M.L., M. Nathenson, and C. Smith, 1983b. Methods for assessing low temperature geothermal resources. In Assessment of Low Temperature Geothermal Resources of the United States - 1982, M.J. Reed, Editor, U.S. Geological Survey Circular 892, pp. 17-30.

Wallace, R.H., Jr., T.F. Kraemer, R.E. Taylor, and J.B. Wesselman, 1979. Assessment of Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin, in Assessment of Geothermal Resources of the United States - 1979, L.J.P. Muffler, Editor, U.S. Geological Survey Circular 790, pp. 132-155.