RESULTS OF GEOTHERMAL RESOURCE EVALUATION FOR THE EASTERN UNITED STATES

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INTRODUCTION

The object of this project as described by Blackwell et al. (1993) is to increase the precision and accuracy of geothermal resource estimates and assessments by making available for the process the most up to date heat flow, geothermal gradient, and thermal conductivity information for the central and eastern United States in useful formats. The specific results described in this paper are, first, a series of maps based on digital data bases for the central and eastern United States (the region of 30° to 50° N Latitude by 75° to 110° W Longitude) designed to be used to estimate temperature in the depth range 3 to 5 km at a resolution of 5' in latitude and longitude (about 4 to 5 km), and second, statistics on the distribution of temperature at a depth of 4 km. These results have special application to the hot dry rock (heat mining) resource evaluation and the evaluation of the low temperature geothermal potential. Distribution of the results in digital form is part of the project effort.

Background This project extends the published evaluations of Sass and Lachenbruch (1979, as contained in Muffler, 1979), and Reed (1985), the preliminary analysis of Blackwell and Steele (1990), and the brief discussion of Blackwell et al. (1993). The project was initially based on the detailed geothermal data base developed for the Geological Society of America Decade of North American Geology (DNAG) *Geothermal Map of North America* (Blackwell and Steele, 1992).

One important result of the study previously described is a heat flow data set in contour and gridded form for the conterminous United States at a resolution of 5' that can serve as a site specific data set for the estimation of geothermal characteristics. This information in turn can serve as a basic input for more specific geothermal evaluation programs and objectives both by this project and in other DOE (e.g. Tester and Herzog, 1990,1991; Tester, 1992) and non-DOE geothermal resource evaluation projects. The result of this effort was described by Blackwell et al. (1993).

The second part of the project is to improve the accuracy of the prediction of temperatures in the 4± km depth range in the central and eastern conterminous United States and is described in this report. In addition to heat flow, the major additional information that this temperature estimation requires is quantification of the thermal conductivity distribution on a geographic basis in the section above the depth of interest. In general this requires information on both the sedimentary section and the basement.

HEAT FLOW DATA BASE

A data base of all available heat flow data in the United States was prepared and published by Blackwell et al. (1989) as part of the Geophysics of North America CD-ROM published by NOAA in Boulder, Colorado (Hittleman et al., 1989). The heat flow data base was used in the preparation of the (DNAG) 1:5,000,000 *Geothermal Map of North America* (Blackwell and Steele, 1992, see also Blackwell et al., 1991, 1992).

As part of this project that heat flow data base has been updated with the addition of about 100 new heat flow sites that have become available since compilation of the 1989 data list. The updated heat flow data base is available in computer compatible form (Blackwell et al., 1993). The new data fill in some gaps in the existing heat flow data distribution. For example, there are new data in the southwestern United States (Sass et al., 1994) and in the Anadarko Basin (Carter, 1993). However, large gaps in heat flow measurements remain in some areas such as the Gulf Coast, the southern Great Plains, and the Ohio Valley region. As a result of the addition of the new data the contours of the DNAG map needed to be modified in only minor ways.

As a second part of this first task, a 5' interval digitized version of the heat flow contours has been prepared and is also available from the authors in addition to the listing of the actual measurements. The digital form of the heat flow map allows quantitative analysis of the heat flow on a geographically weighted basis as opposed to the somewhat biased data sites alone. The major result described in this paper of this aspect of the study is use of this data base in the calculation of temperature in the eastern and central United States as a function of depth. Availability of information on the specific temperature distribution then allows geographic and statistical evaluation of the HDR geothermal potential based on the various economic analyses of Tester and Herzog (1992).

TEMPERATURE AT 4 KM DEPTH

One important geothermal resource base in the eastern United States is composed regions of hot, but relatively impermeable, basement rocks. The exploitation (heat mining) of this hot dry rock (HDR) energy may be economic at the present time if suitable resource temperatures can be found at depths of 3 to 4 km (Tester and Herzog, 1990,1991). Unlike the presently exploited hydrothermal resources in the western United States where the high temperatures are limited in geographic extent, except in an area such as The Geysers, the HDR resource is more regional in character. Thus the methods of evaluation differ. One objective of this project, to develop a rational, and a realization of that rational, of an resource exploration and evaluation technique for HDR in the eastern United States, is demonstrated in this paper.

To allow calculation of the temperatures at some depth a number of types of information are needed. These must be available at the same scale as in the heat flow data, in this case at a data spacing of 5' of latitude and longitude. The primary data sets that are needed are surface temperature and thermal conductivity as a function of depth and position. Obtaining the thermal conductivity is difficult and additional data bases have been constructed to accomplish the goal of predicting the geographic variation of thermal conductivity. These data sets include the thickness of sedimentary rocks (Figure 1) and their lithologic distribution. Since the target is assumed to be in relatively impermeable basement rocks, areas with sedimentary thickness greater than a particular design depth can be excluded, although the data set is not limited by this assumption and the 4 km depth is used here partly for demonstration purposes.

Thermal Conductivity Map The detailed breakdown of the thermal conductivity distribution in the sedimentary section need not be considered and the thermal conductivity can be assumed constant in the sedimentary section. The geographic variation of the lithology of the sedimentary section was estimated from a set of correlation sections published by the American Association of Petroleum Geologists (the Correlation of Stratigraphic Units of North America, COSUNA series). For the central and eastern United States 12 correlation maps and 178 correlation sections were used in the determination of the geographic variation of lithology.

The information on the geographic variation of the lithology percentages was turned into mean thermal conductivity values for the sedimentary section using typical thermal conductivity values for the different lithologies based on measurements in the midcontinent region (Blackwell and Steele, 1989; Gallardo, 1989; and Carter, 1993). The results of this part of the study are shown in Figure 2. There are significant variations in the mean thermal conductivity of the sedimentary section of almost 100%. The thermal gradient is inversely proportional to the thermal conductivity so for the same heat flow there can be at least a factor of two variation in temperature at depth due to thermal properties alone. For example the mean thermal conductivity in the Williston Basin is about 2.6 W/m/K while it is over 3.4 W/m/K in the Michigan and Delaware Basins

Basement Thickness Map The second data base developed was the thickness of sedimentary cover in the eastern United States. This data set was prepared by digitizing the elevation of basement map published by the AAPG (1970). The elevation of basement was turned into thickness by subtracting its value from the topography. The resulting map is illustrated in Figure 1. The areas with basement deeper than 4 km are the darkest shade and would not be of interest if the target was basement at about 4 km.

Geothermal Gradient Map The thermal conductivity values can be divided into the heat flow to calculate the mean thermal gradient in the sedimentary section. The resulting information is shown in map form in Figure 3. The variation in the gradient is from less than 15 to over 35 °C/km on a regional basis.

Temperature at 4 km Map Results for one major object of the study are illustrated in Figure 4. In Figure 4 the data sets discussed above for 1) thickness of sedimentary rock (Figure 1), 2) mean thermal conductivity of the sedimentary section (Figure 2), 3) geothermal gradient (Figure 3, from heat flow and thermal conductivity), and surface temperature (not illustrated), have been combined to calculate temperature at a depth of 4 km (Figure 4). To calculate this map the gradient in basement between the base of the sediment and 4 km (where the sediments are less than 4 km deep) was calculated from the heat flow assuming a constant thermal conductivity for the basement of 2.8 W/m/K.

This map shows that in terms of the temperature at a depth of 4 km there are major regional variations in the potential HDR geothermal resources in the central and eastern US. Thus, as is the case for hydrothermal resources in the western US, exploration is necessary to maximize success. At a depth of 4 km temperatures on a regional basis range from less than 70 to over 150 °C. There are regions of relatively high temperature in the northern Midwest, in Arkansas (and northern Louisiana), in eastern Iowa, and in the western New York/northwestern Pennsylvania areas. This result illustrates how the data bases can be used to develop ratings for various areas as to their suitability for various types of geothermal use.

This type of map can be used to direct possible exploitation plans to appropriate areas and to evaluate the sizes of areas that might be exploited assuming different conditions and parameters. For example it is assumed that the most favorable situation is an area with a high heat flow, low thermal conductivity, and sediment section just less that 4 km in depth (to minimize drilling costs).

CONCLUSIONS

Detailed equilibrium temperature-depth data in deep wells are rare in the eastern US. However, there are several such sites in the central part of the United States that Blackwell et al. (1993) used to illustrate the results in a three dimensional sense. The Mosley well in Louisiana demonstrates the existence of high temperatures given the right conjunction of low thermal conductivity and high heat flow. This well has a temperature of 130 °C at 3 km and a projected temperature at 4 km of 150+ °C.

Figure 3 illustrates one problem with the present stage of the analysis: there are large gaps in the heat flow data. For example Kentucky has no heat flow data at all and there are large gaps in several other areas. Areas of the Appalachian basin may have low thermal conductivity and high heat flow as is the case in northwestern Pennsylvania, but there are no data in this important area.

Table 1. Percent of area with a given temperature at 4 km. Contoured area in Figure 1 is included in the calculation.

Temperature(°C)	% Area
<70	1.6
70	10.6
80	32.0
90	23.0
100	16.8
110	6.9
120	4.0
130	3.3
>140	1.7

The temperatures illustrated in the map in Figure 4 are generalized. But they can be used in a statistical sense. The distribution of temperature at 4 km based on this map is shown in Table 1. These results demonstrate that a significant area in the central and eastern United States in underlain by temperatures of over 130 °C at 4 km (about 5 % of the area contoured in Figure 1). Smaller areas of course may have even higher temperatures, so to optimize sites, detailed exploration in the areas of identified high potential, such as the northern Louisiana/ southern Arkansas, north central Nebraska/ southcentral South Dakota, northeastern Pennsylvania, eastern Virginia, etc is still needed.

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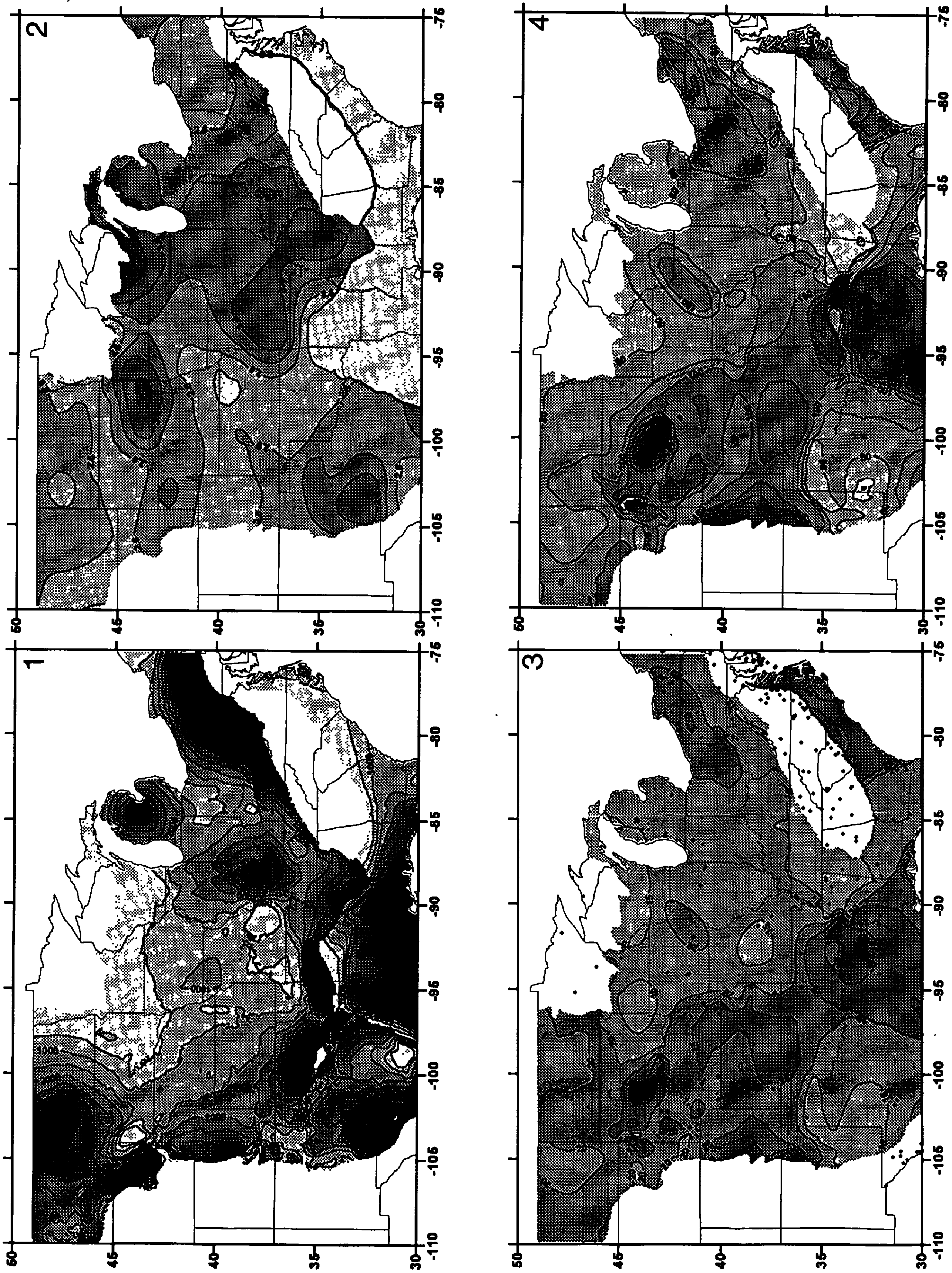
Figure 1. Thickness of sedimentary rocks in part of the central and eastern United States.

Figure 2. Thermal Conductivity of the sedimentary section in part of the central and eastern United States.

Figure 3. Gradients in the sedimentary section/basement in the Eastern United States. Sites of heat flow data are shown as asterisks.

Figure 4. Temperature at a depth of 4 km in the central and eastern US (75 to 110°W and 30-50°N). Contours of 100, 100, 125, and 150 °C are shown.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