GEOTHERMAL REGIME IN THE CENTRAL AND EASTERN UNITED STATES EAST OF THE ROCKY MOUNTAINS

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ABSTRACT

The thermal regime in the United States in the area of 25° to 49" latitude and 75° to 115" latitude and east of the Rocky Mountains has been investigated and characterized by developing and integrating several digital data bases. Data sets for heat flow, surface temperature, sedimentary rock thickness, mean thermal conductivity of the sedimentary section, and mean geothermal gradient of the sedimentary section have been developed at a resolution of 5′ of latitude and longitude (about 4 to 5 km). The advantages of the data bases are in the flexibility and adaptability to use in study of a variety of scenarios of geothermal resource evaluation and development. The design temperatures and depths for exploitation of a HDR resource, for example, *can* be varied, and potential calculated for a variety of different assumptions. As an example of the use of these data sets a temperature map for a depth of 4 km is illustrated. At the scale of study temperatures range from less than 60°C to over 150°C at 4 km. The temperature is between 70 and 110°C for about 82% of the area. There are significant areas with temperatures **of** 130°C and above. The results demonstrate the application of the data bases to geothermal resource evaluation, as well as the existence of high temperature areas at depth in the central and eastern United States that are worthy of further individual study.

INTRODUCTION

We initiated a multiyear project to evaluate the geothermal conditions at depths of several km in the United States east of the Rocky Mountains in 1991. The objective of this project is to develop the data that are essential for regional geothermal resource assessments in a easily usable set of data bases. An up-to-date data set of heat flow, geothermal gradient, and thermal conductivity will provide for improved accuracy in subsequent geothermal resource assessments. Preliminary results have been presented by Blackwell et al. (1993, 1994). Specific results described in this paper include, first, a series of maps based on digital data bases for the central and eastern United States (the region of 25° to 50" N Latitude by 75" to 115° W Longitude) and east of the **Rocky** Mountains designed to be used to estimate temperature in the depth range 3+ 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 as an example of the use of these data sets. These results have special application to hot dry rock (HDR, heat mining) resource evaluation and the evaluation of moderate and high temperature geothermal fluid potential from the deep part of sedimentary basins.

One important geothermal resource base in the eastern United States is represented by regions of hot, but relatively impermeable, basement rocks at depth. The exploitation 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 most of the presently exploited hydrothermal resources in the western United States where the high temperatures are local in geographic extent, the HDR resource is more regional in character. Thus the methods of evaluation differ. One objective of this project, to develop a rationale, and a realization of that rationale, of an resource exploration and evaluation technique for HDR in the eastern and central United States, is demonstrated in this paper.

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). The project was initiated from the platform of 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 Stele, 1992).

The first important part of this study was development of a heat flow data set in contour and gridded form (at a resolution of 5′) for the conterminous United States (Blackwell et al., 1989). This data set is detailed enough to serve as a regional specific data set for the estimation of geothermal characteristics. This information can, in turn, serve as basic input for more specific geothermal evaluation programs (e.g. Tester and Herzog, 1990,1991; Tester, 1992). This digital heat flow data set has now been updated to reflect recently published data (see below).

The second part of the project is to improve the accuracy of the prediction of temperatures in the 3+ km depth range in the central and eastern conterminous United States. 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. The emphasis in this paper is the illustration of the results of using these data bases for the calculation of a map of temperature in the eastern and central United States at 4 km, and in the statistical evaluation of that temperature distribution.

HEAT FLOW DATA BASE

A data base of all available heat flow measurements 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 Stele, 1992, see also Blackwell et al., 1991, 1992).

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 from the authors. 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. The revised contour map is shown in Figure 1. As a result of the addition of these new data the contours of the DNAG map needed to be modified in only minor ways .

In addition to the compilation of the basic data, a 5′ interval digitized version of the revised heat flow map (Figure 1) 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 can be used for quantitative analysis of the heat flow on a geographically weighted basis as opposed to a geographically biased analysis based on data sites alone. The origins of the distribution of heat flow have been discussed in detail in the references mentioned above.

THERMAL PROPERTIES DATABASES

To allow calculation of the temperatures at 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 first data set that is needed is surface temperature. The distribution used is based on temperature in shallow water wells and is of itself, useful from the point of view of shallow groundwater heat pump resource estimates (Gass, 1982). Thermal conductivity as a function of depth and position is also needed. Obtaining the thermal conductivity distribution is a

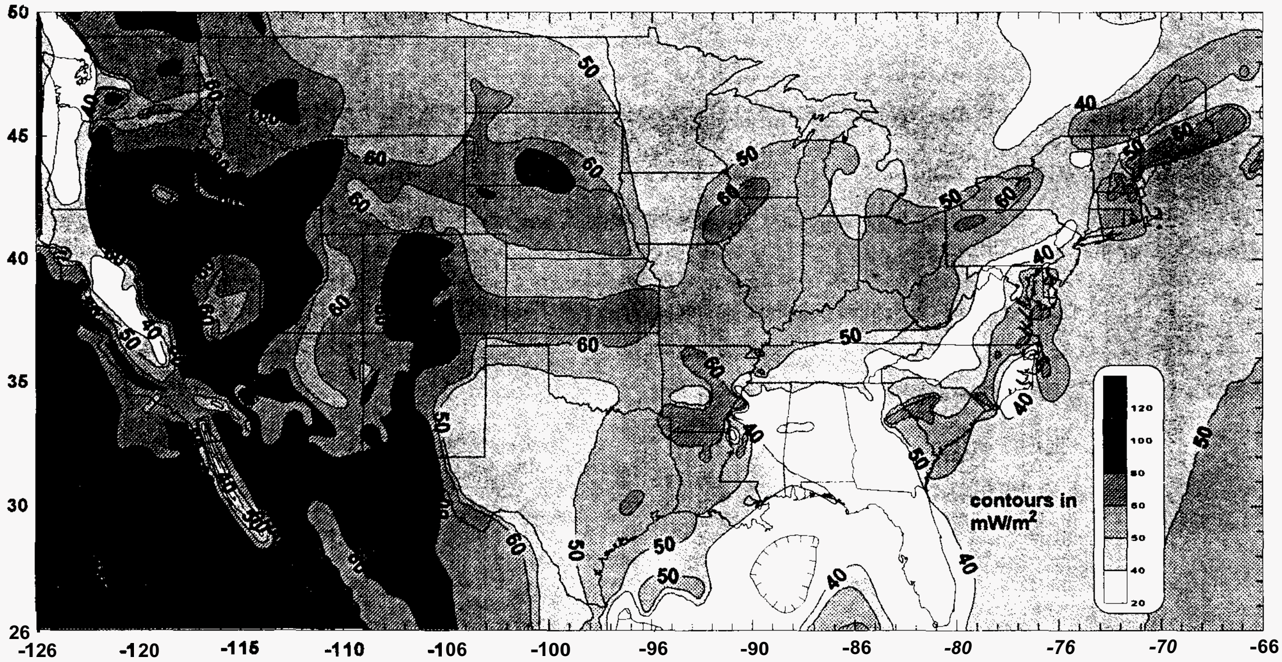

Figure 1. Heat flow map of the United States. The contours are updated from Blackwell et al. (1989) and the DNAG map with heat flow data to 1993.

difficult task 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 and their lithologic distribution as a function of space. Since the HDR resource target is in relatively impermeable basement rocks, areas with sedimentary thickness greater than a particular design depth can be excluded, although this data set is not limited by this assumption.

Thermal Conductivity Regional values of thermal conductivity are estimated based on generalized lithologies. The thermal conductivity is assumed constant in the sedimentary section so the detailed vertical thermal conductivity distribution in the sedimentary section is not considered. The geographic variation of the lithology of the sedimentary section was estimated from a set of stratigraphic 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 sites of the sections used are shown on Figure 2.

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 thermal conductivity measurements in the midcontinent region (Blackwell and Steele, 1989; Gallardo, 1989; and Carter, 1993). The thermal conductivity in the Atlantic and Gulf Coastal Plains was approximated by a constant value of 2.0 W/m/K. The section in the Gulf Coast is so variable, both vertically and horizontally, the technique of thermal conductivity determination used above is not valid. Since much of the Gulf Coast region has a sediment thickness of greater than 3 to 4 km, the HDR concept has limited applicability there.

The results of this part of the study are shown in Figure 2. There are variations in the mean thermal conductivity of the sedimentary section of almost 100%. The highest thermal conductivity values (>3.4 W/m/K on a regional basis) are associated with the areas where Paleozoic carbonates dominate the section such as in the Michigan, Illinois, and Delaware basin regions. The lowest thermal conductivity values (<2.6 W/m/K on a regional basis) are in areas where a significant part of the section is shale such as in the Great Plains (Williston Basin, Cretaceous shales, Anadarko Basin, Paleozoic shales) and in the northern Allegheny area (Paleozoic shales). The thermal gradient is inversely proportional to the thermal conductivity so for the same heat flow there can be at least a 50% variation in temperature at depth due to thermal properties alone. For example the mean thermal conductivity of the sedimentary section in the Williston Basin is only about 2.6 W/m/K while it is over 3.4 W/m/K in the Michigan and Delaware Basins.

Sediment Thickness The third 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 digital topography data set. The resulting map is illustrated in Figure 3. This map is more complicated than the thermal conductivity map illustrated in Figure 2. This map indicates local areas that might be of interest for hydrothermal development (areas with sediment at a particular depth) and areas of interest for HDR (the areas with basement deeper than a particular depth). For illustration purposes in this paper the map in Figure 3 is truncated at a depth of 4 km. With the exception of the Anadarko basin, the Gulf Coast, and the east edge of the Allegheny basin, sedimentary thickness does not exceed 4 km except in very localized regions in the area east of the Rocky Mountains.

Geothermal Gradients 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 4. The variation in the gradient is from less than 15 to over 35 °C/km on a regional basis. Within an individual well the geothermal gradient can vary by up to 500% depending on the lithology in a particular depth interval. However, the whole sedimentary section is averaged in this approach. So unlike some previous compilations of individual well gradients (Kron and Stix, 1982; Nathenson and Guffanti, 1988), this map (Figure 4) is not biased by the part of the sedimentary section in which the measurements were made. Similarly, the use of Bottom Hole Temperature (BHT) measurements is subject to bias depending on the part of the sedimentary section represented by the wells. Thus the geothermal gradient distribution shown in Figure 4 is smoother and more regionally characteristic of the geothermal gradient than existing compilations.

Figure 4 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.

TEMPERATURE AT 4 KM DEPTH

Synthesis of these databases permits rapid estimation of temperature at any depth. For example calculated temperatures at 4 km are illustrated in Figure 5. In Figure 5 the data sets for 1) mean thermal conductivity of the sedimentary section (Figure 2), 2) thickness of sedimentary rock (Figure 3), 3) geothermal

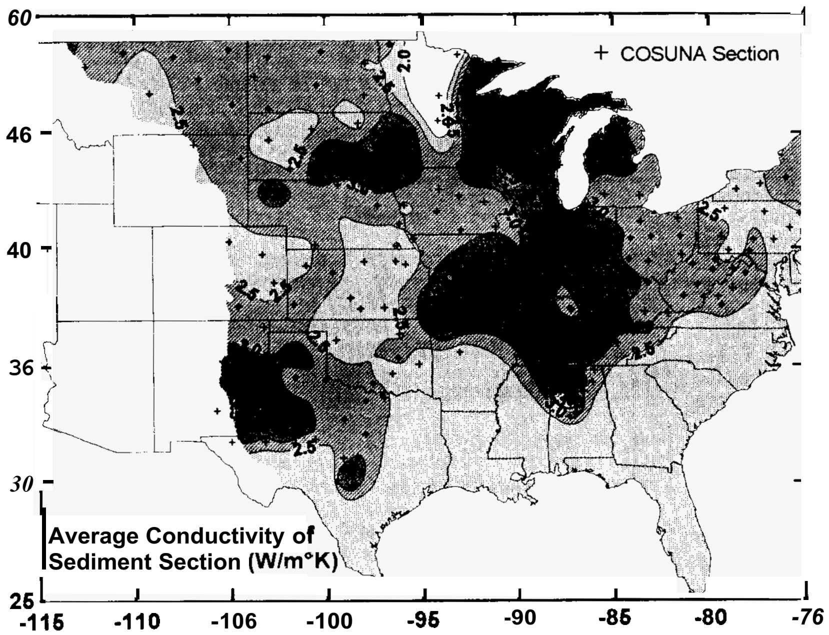

Figure 2. Mean thermal conductivity of the sedimentary section in the central and eastern United States east of the Rocky Mountains. Sites of COSUNA sections used as sample points are shown.

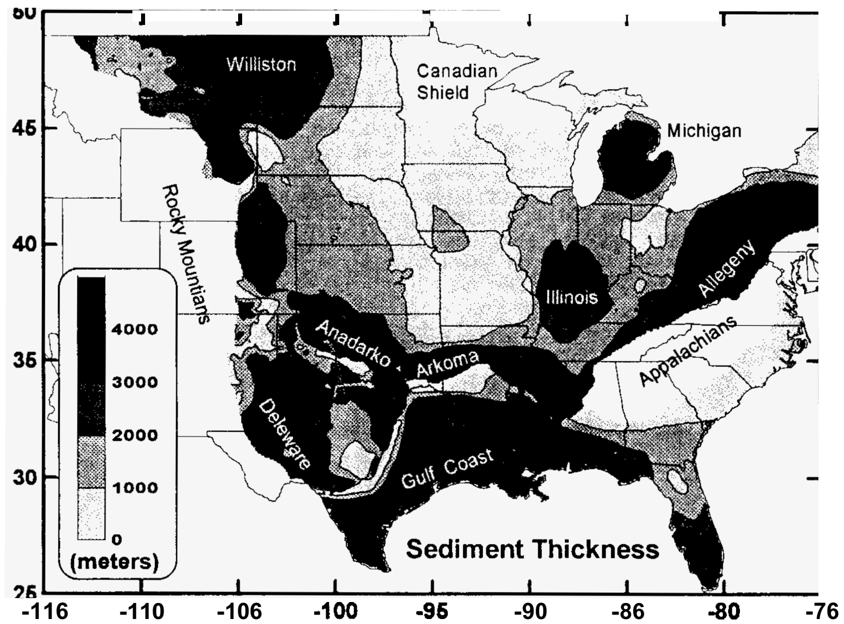

Figure 3. Thickness of sedimentary rocks in the central and eastern United States east of the Rocky Mountains.

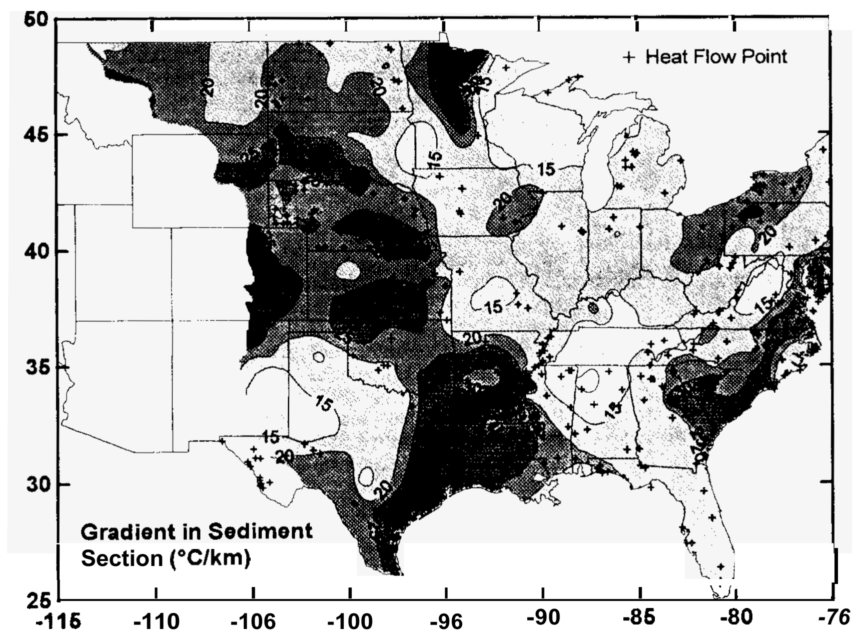

Figure 4. Gradient in the sedimentary section/basement in the central and eastern US east of the Rocky Mountains. Sites of heat flow measurements are shown.

gradient (Figure 4, from heat flow and thermal conductivity), and surface temperature (not illustrated), have been combined to calculate temperature at the example depth of 4 km. 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 major regional variations in temperature at a depth of 4 km thus showing that there are regional variations in the geothermal resource potential in the central and eastern US. At a depth of 4 km temperatures on a regional basis range from less than 70 to over 150 °C. Thus, as is the case for hydrothermal resources in the western US, some exploration is necessary to maximize success. There are large regions of relatively high temperature in the central plains states, and an area that includes southern Arkansas, northern Louisiana, and the Texas Gulf Coast. Because of the lack of heat flow data and the approximation of the thermal conductivity, the temperatures calculated in the southern part of the Gulf Coast sedimentary basin are not as reliable as those in the rest of the map. Nonetheless, the high temperatures in Northern Louisiana are not affected by this assumption as discused below.

Elsewhere the regions of highest temperature are smaller in size; in eastern Iowa, in western New York/northwestern Pennsylvania, and in the southeast. In contrast there are large areas of quite low temperatures predicted for the Appalachians, west Texas, southeastern New Mexico, and the Superior Shield region in Wisconsin and Minnesota.

The distribution of temperature is a function of the several factors discussed above, one of the primary of these factors is the heat flow. The heat flow distribution in turn is related to a number of factors. The main factors that affect the heat flow shown on Figure 1 are the radioactive heat production of the rocks and possible convection of heat by slow groundwater motion in regional aquifers *(see* the discussion by Morgan and Gosnold, 1989). On Figure 5 the areas of high and low heat flow are generally related to the mean crustal radioactivity. However, the high heat flow in Nebraska and South Dakota may relate to fluid motion in the Cretaceous Dakota sandstone and the Mississippian Madison carbonate aquifers. In this case the temperature calculation below the aquifer is problematical, *so* the high temperatures shown there at 4 km might be somewhat overestimated.

Figure *5* demonstrates how relevant data can be synthesized 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).

DISCUSSION

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 were described by Blackwell et al. (1993). The temperature-depth data from these wells are consistent with the predictions of temperature shown in Figure *5*. For example, the Mosley well in northeastern Louisiana, with a measured temperature of 130 at 3.0 km and a projected temperature at 4 km of 150+ °C, demonstrates the existence of high temperatures given the right conjunction of low thermal conductivity and high heat flow. This well also demonstrates the validity, at least at one point, of the high temperatures shown in Figure *5* for that area.

The temperatures illustrated in the map in Figure *5* are generalized. But they can be used for regional evaluation and in a statistical sense. The distribution of temperature at 4 km as illustrated on the map in Figure *5* is shown in Table 1. The distribution is log normal with about 82 % of the area having temperatures between 70 and 110°C at 4 km and 14.9% having temperatures above 110°C. In addition part of the area may have temperatures above 140°C at 4 km. 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 5). 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.

This discussion 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 analysis, combined with economic parameters, can be used in a number of different ways to obtain realistic evaluations of the potential value of the geothermal resource in the eastern and central United States.

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Table 1. Percent of area for the United States east of the Rocky Mountains with a given temperature at 4 km. The contoured area in Figure *5* is included in the calculation.

Temperature ("C)	% Area
< 70	3.2
70-80	19.9
80-90	28.5
90-100	20.2
100-110	13.3
110-120	5.6
120-130	4.4
130-140	3.5
> 140	1.4

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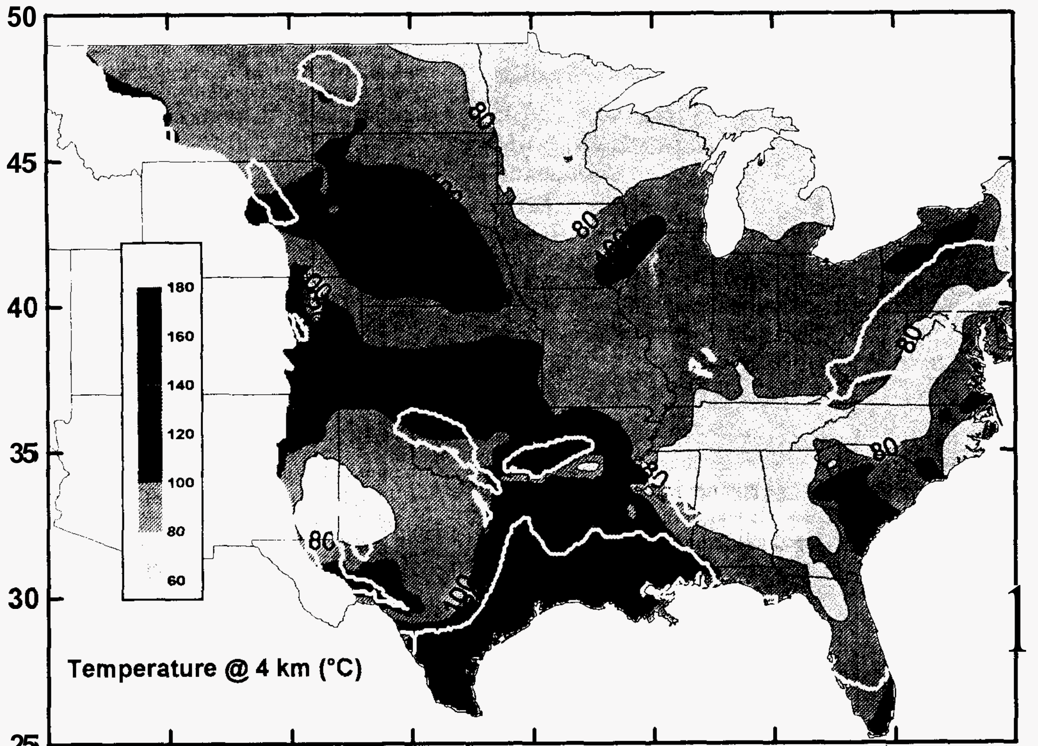

Figure 5. Temperature at a depth of 4 km in the central and eastern US east of the Rocky Mountains. areas of sediment thickness greater than 4 km are outlined in white.