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TEMPERATURES, THERMAL CONDUCTIVITY, AND HEAT FLOW FROM A WELL IN PIERRE SHALE NEAR HAYES, SOUTH DAKOTA

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

INTRODUCTION

A recent abstract (Blackwell and others, 1981) drew attention to some discrepancies between component heat flows calculated from alternating shale-carbonate layers of the Paleozoic rocks in Kansas. Blackwell and others suggested that thermal conductivities of shales as measured in the laboratory were too high by as much as 50 to 60 percent and that some values of heat flow within the mid-continent region were correspondingly high. They further suggested that all high values (>60 mWm^{-2}) in the mid continent should be revised downwards.

In 1978, the U.S. Geological Survey drilled a well in the upper Cretaceous Pierre Shale near Hayes, South Dakota (longitude 101° 01.0' W, latitude 44° 22.2' N, elevation 617 m). A core was obtained and preserved with nearly in-situ moisture content. Upon completion of drilling in August 1978, 32 mm i.d. steel casing was grouted in to total depth of 183 m This allowed us to examine the hypothesis of Blackwell and others (1981) in an extensive shale terrain.

In October 1981, we obtained a near-equilibrium temperature profile from the well (Figure 1) and 12 determinations of thermal conductivity from the core (Table 1). From these, we have made an estimate of heat flow.

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TEMPERATURE MEASUREMENTS

Temperatures were measured at intervals of 1.5 meters (5 feet). A very smooth temperature profile was obtained (Figure 1) with temperature gradients increasing systematically to a depth of 40 meters then oscillating between 60 and 70 °C km^{-1}. The least-squares gradient in the lowermost 100 meters is 67.7 ± 0.5 °C km^{-1}. In the absence of any indications of vertical water movement, this suggests that thermal conductivities in these essentially horizontally stratified sediments vary by no more than ±7 or 8 percent from the mean over the length of the borehole.

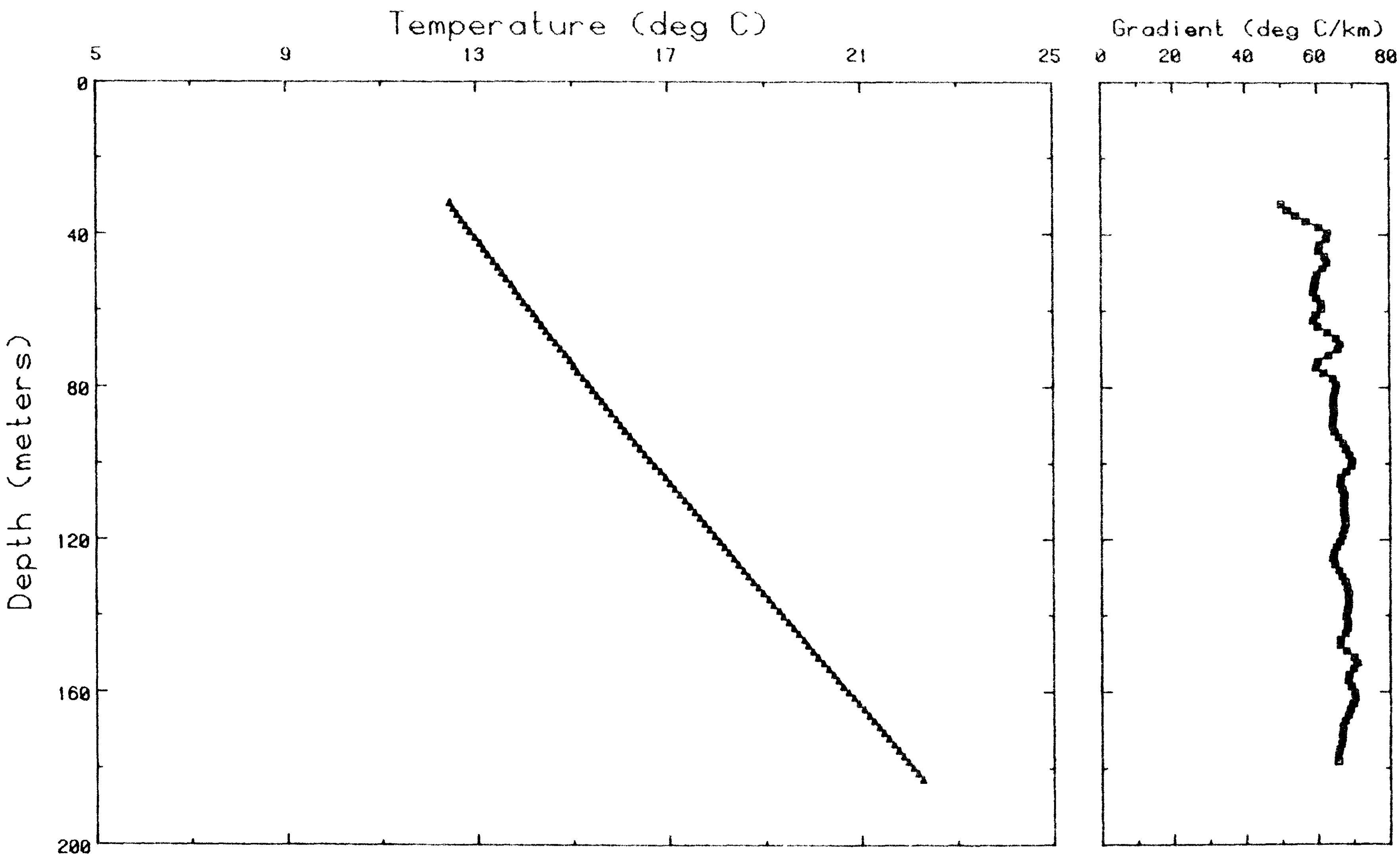

Figure 1. Temperatures at 1.5 m intervals and thermal gradients at overlapping 4.5 m intervals for borehole #3 near Hayes, South Dakota.

THERMAL CONDUCTIVITY

A five foot (1.5 m) long core was obtained between the depths of 51.8 and 53.3 m. Coring was done with a specialized sediment core barrel and the core was preserved in a steel liner capped at both ends to prevent moisture loss. At six roughly equal intervals along the core, needle probe determinations were made with the line source oriented both radially and axially (Table 1).

To calculate heat flow, we require the vertical component of thermal conductivity which cannot be measured directly by a line-source technique on anisotropic rocks. Examination of Table 1 shows that, in every instance, the "axial" thermal conductivity is higher than the "radial." Assuming horizontal symmetry and horizontal stratification, the axial conductivity (K_A) is simply K_h, the horizontal conductivity, whereas the radial conductivity (K_R) may be represented most simply as the geometric mean of the vertical and horizontal components, i.e.,

$$K_R = \sqrt{K_h \cdot K_v}$$

The quantity we desire (K_v) may then be obtained as

$$K_v = K_R^2 / K_A$$

From Table 1, the mean K_A is 1.38 ± 0.04, and the mean K_R, 1.28 ± 0.02 resulting in an average value of 1.19 ± 0.05 $Wm^{-1}\ K^{-1}$ for the vertical component K_v. The average anisotropy (K_h/K_v) is 1.16.

TABLE 1. Thermal conductivity measurements on a core from USGS Hayes #3

Depth*	Thermal conductivity† $Wm^{-1}K^{-1}$	
	"Axial" = K_h	"Radial" = $\sqrt{K_h \cdot K_v}$
51.8		
	1.28	1.22
	1.25	1.24
	1.47	1.31
	1.34	1.31
	1.43	1.30
	1.49	1.30
53.3		

*Measurements were made at roughly equally-spaced intervals (~0.3 m) along the core.

†"Axial" = K_h = horizontal conductivity: Needle probe is inserted along the axis of the core.

"Radial" ≅ $\sqrt{K_h \cdot K_v}$ = geometric mean of horizontal and vertical conductivities: Needle probe is inserted along a radius.

HEAT FLOW

If we simply multiply the least-squares gradient in the lowermost 100 m (67.7 ± 0.5) by the mean K_v (1.19 ± 0.05), we obtain a heat flow of 81 ± 4 mWm^{-2}. The question arises as to how representative of the lower 100 meters is a thermal conductivity from higher up the hole. The temperatures at 51.82 and 53.34 meters are 13.631 and 13.736 resulting in an interval gradient of 68.9°C km^{-1} and an interval heat flux of 82 mWm^{-2}. It thus appears that (in the absence of systematic errors of opposite sign) the thermal conductivity is reasonably representative of the bottom portion of the well. We adopt the value of 81 ± 4 mWm^{-2} as our "best value" at this site.

DISCUSSION

The site (Figure 2) is located in a region where the contours of Lachenbruch and Sass (1977) (see also Sass and others, 1981) predict heat flow between 1.5 and 2.5 HFU (63 and 105 mWm^{-2}). The thermal conductivity value of 1.19 $Wm^{-1} K^{-1}$ is in the range of those inferred by Blackwell and others (1981) for Paleozoic shale units in Kansas (1.05 to 1.25 $Wm^{-1} K^{-1}$). The temperature gradient is, however, sufficiently high that the resulting heat flow of 81 mWm^{-2} does not violate the previous contour and no adjustment need be made at this latitude (Figure 2). On the other hand, the site at Lyons, Kansas, (Sass and others, 1971) provides an example of a higher vertical shale conductivity (1.58 $Wm^{-1} K^{-1}$), but a sufficiently low thermal gradient so that the heat flow is moderately low (63 mWm^{-2}).

Both instances cited above serve as counter examples to the generalizations of Blackwell and others (1981) (regarding the upper limit for heat flow in the first instance and the allowable range for thermal conductivity of shales in the second). We do agree, however, that there is a significant number of mid-continental heat-flow values in the literature, particularly those based on uncorrected grain conductivities of shales using "chip" methods, that require substantial downward revision.

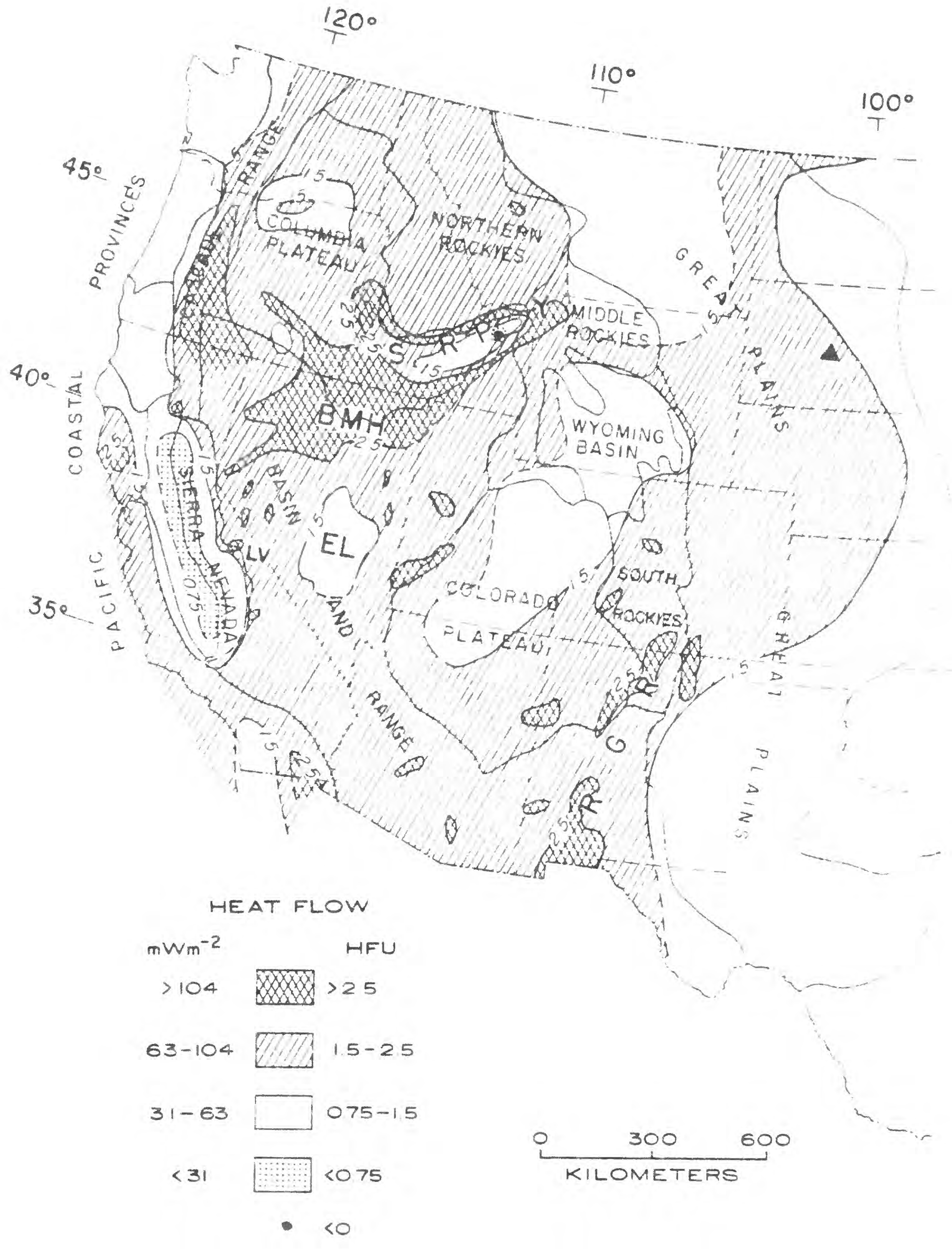

Figure 2. Heat-flow contours for the western U.S. (after Sass and others, 1981). Solid triangle indicates Hayes site.

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