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Thermal data from well GD-1, Gibson Dome, Paradox Valley, Utah

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.

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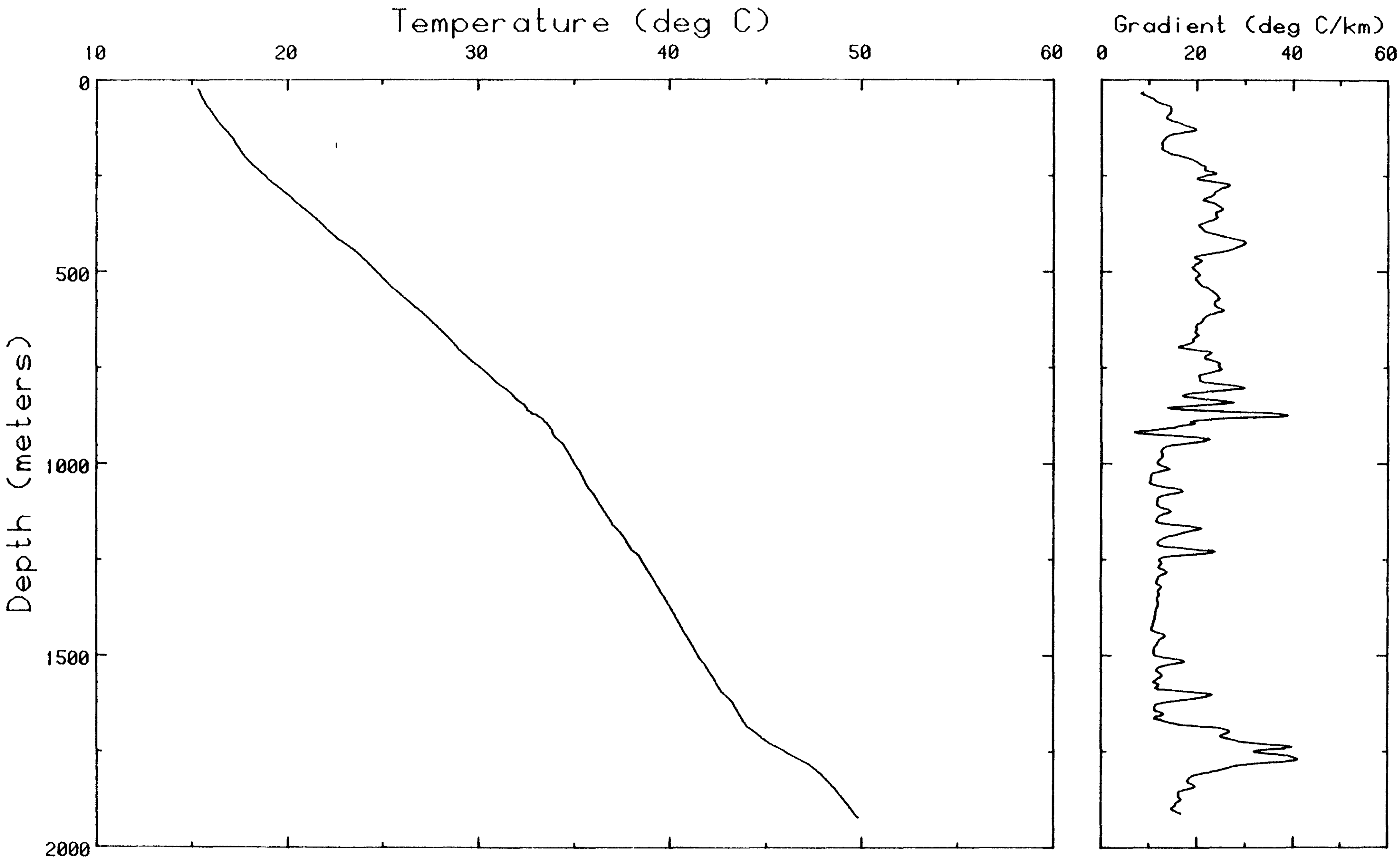
INTRODUCTION

Temperature data were obtained to a depth of ~1900 m (6300 ft) in well GD-1, W. longitude 109° 36.9', N. latitude 38° 09.8', elevation 1503 m at Gibson Dome in the Paradox Basin, southeastern Utah. Thermal conductivities were measured on 15 specimens representative of the major formations. With the possible exception of some minor perturbations within the Molas and Leadville Limestone formations near the bottom of the well, no evidence exists for vertical water movement with seepage velocities exceeding a few mm y^{-1} within the well or formation.

TEMPERATURE MEASUREMENTS

Continuous temperature logs (with temperatures recorded digitally at 0.6 m intervals) were obtained on March 25, 1981, and January 16, 1982. The last log (shown in Figure 1) is identical to the first indicating that the well is in thermal equilibrium. Excursions in the gradient profile (Figure 1) correlate very well with changes in lithology. This is particularly apparent in the high gradient "spikes" within the Paradox Formation (~900-1600 m). These correspond well to shale and siltstone interbeds within this section composed primarily of evaporites.



Gibson Dome GD-1:USGS Log of 16 January 1982.

Figure 1. Latest temperature profile from GD-1.

THERMAL CONDUCTIVITY

All measurements of thermal conductivity were performed with the needle probe (Von Herzen and Maxwell, 1959). As compared with the divided-bar apparatus (Birch, 1950) this technique has the advantage that extensive machining of these friable sedimentary rocks need not be carried out (the required 1 mm diameter × 35 mm hole can be drilled with relative ease using a high-speed twist drill). This is particularly true of the evaporites which, in general, are thermally isotropic and are easily dissolved if water is used in machining.

The disadvantage of the needle probe is that for anistropic rocks like shales, conductivity must be measured in more than one sample orientation and an interpretive procedure must be followed to extract a value of conductivity in a given direction.

For all 15 samples, thermal conductivities were measured at room temperature (∿25°C, Table 1). The column labeled "Orientation" (Table 1) refers to the direction(s) of heat flow during the determination with the axis taken as vertical. Thus if the probe is inserted along the axis of the core, heat flow is in the horizontal or xy directions. Assuming horizontal stratification and thermal isotropy in the xy directions, if the probe is inserted along a radius, the xyz orientation implies elliptical isotherms with eccentricity determined by the anisotropy. Thus to determine the conductivity in the z-direction (the relevant parameter for the determination of heat flow) an interpretive step is required. The simplest scheme involves the geometric mean between horizontal and vertical conductivities. Once again, assuming horizontal isotropy ($K_{xy} = K_x = K_y$)

$$K_{xyz} = K_{xy}^{1/2} \cdot K_z^{1/2} \tag{1a}$$

or

$$K_z = K_{xyz}^2 / K_{xy} \tag{1b}$$

Apart from the evaporites, most rocks have a higher K_{xy} than K_{xyz} (Table 1). For horizontally stratified anisotropic rocks, this is what we would expect; however, superimposed on the effects of anisotropy are random variations of the same order (3-5%) resulting from the usual errors of measurement. Thus, the estimates of K_z, (in parentheses, Table 1) which are generally lower than either measured conductivity, also have a greater uncertainty because of the magnification inherent in equation 1.

Our apparatus is designed primarily to measure thermal conductivity at or near room temperature, but in view of the fact that moderately high temperatures are reached <u>in situ</u> (Figure 1) and, because of certain engineering requirements of nuclear waste isolation, we determined conductivity to 80°C on one sample each of salt and anhydrite (Table 2). The high-temperature measurements were made in an electrically heated thermally lagged enclosure. To monitor heat losses, a set of control measurements was made on fused silica. Adjustments to raw conductivities (of

TABLE 1. Room temperature thermal conductivities, Gibson Dome

Depth m	Formation	Orientation*	K $Wm^{-1}K^{-1}$	Rock
187.6	Cutler	xy	3.28	Sandstone
		xyz	3.12	
		z	(2.97)	
244.1	Elephant Canyon	xy	2.64	Silty ss
		xyz	2.48	
		z	(2.33)	
396.3	Honaker Trail	xy	2.79	Limestone
		xyz	2.58	
		z	(2.39)	
441.0	Honaker Trail	xy	2.44	Calcareous shale
		xyz	2.48	
		z	(2.52)	
511.5	Honaker Trail	xy	3.31	Limestone
		xyz	3.12	
		z	(2.94)	
671.3	Honaker Trail	xy	3.08	Limestone
		xyz	2.94	
		z	(2.81)	
806.5	Honaker Trail	xy	2.76	Calcareous silstone
		xyz	2.36	
		z	(2.02)	
906.8	Paradox	xy	6.26	Salt 5
		xyz	5.71	
1065.8	Paradox	xy	5.97	Salt 8
		xyz	6.08	
1180.0	Paradox	xy	5.86	Anhydrite
		xyz	5.99	
1310.2	Paradox	xy†	5.86	Salt 16
		xy	6.13	
		xyz	5.92	
1516.5	Paradox	xy	2.86	Calcareous silstone
		xyz	2.73	
		z	(2.61)	
1695.3	Pinkerton Trail	xy	2.90	Siltstone
		xyz	3.27	
		z	(3.68)	
1800.6	Leadville	xy	3.23	Limestone
		xyz	3.03	
		z	(2.84)	
1919.9	Leadville	xy	3.59	Limestone
		xyz	3.54	
		z	(3.49)	

* xy represents needle probe vertical (heat flowing horizontally);
xyz represents needle probe inserted along a radius (heat flowing both horizontally and vertically);
z is conductivity in a vertical direction, calculated from $K_z = K^2_{xyz}/K_{xy}$ (see text).

† dark matter surrounding needle probe for this run.

TABLE 2. Thermal conductivity versus temperature for Paradox Formation evaporites

Sample GD-1-92 (Salt 5)		Sample GD-1-94 (Anhydrite with salt)	
Temperature °C	K $Wm^{-1} K^{-1}$	Temperature °C	K $Wm^{-1} K^{-1}$
24	6.26	24	5.87
37	5.87	36	5.46
45	5.24	39	5.51
51	5.58	46	5.23
55	5.15	50	5.26
65	5.00	57	4.67
70	4.97	60	4.72
76	4.63	72	5.03
80	5.09	77	4.93

evaporites) of up to -4.5% were made based on departures from Ratcliffe's (1959) curve for conductivity of fused silica versus temperature. The uncertainty in an individual measurement varies from ~±3 to 5% at room temperature to about ±10% at 80°C. The scatter in the data (Table 2 and Figure 2) is consistent with uncertainties of this magnitude. Regression curves of the form $K = K_o/(T/T_o)^B$ where K is conductivity at temperature T (°C), and K_o is conductivity at a reference temperature T_o taken to be 30°C were fitted to the data (Figure 2, Table 3). These curves yield reasonably good correlation coefficients and a temperature variation consistent with published values (Birch and Clark, 1940; Clark, 1966; McCarthy and Ballard, 1960). We emphasize here that the relations shown in Table 3 are for convenience in establishing the variation of conductivity within the measured temperature range. Extrapolation generally will not yield realistic values of conductivity.

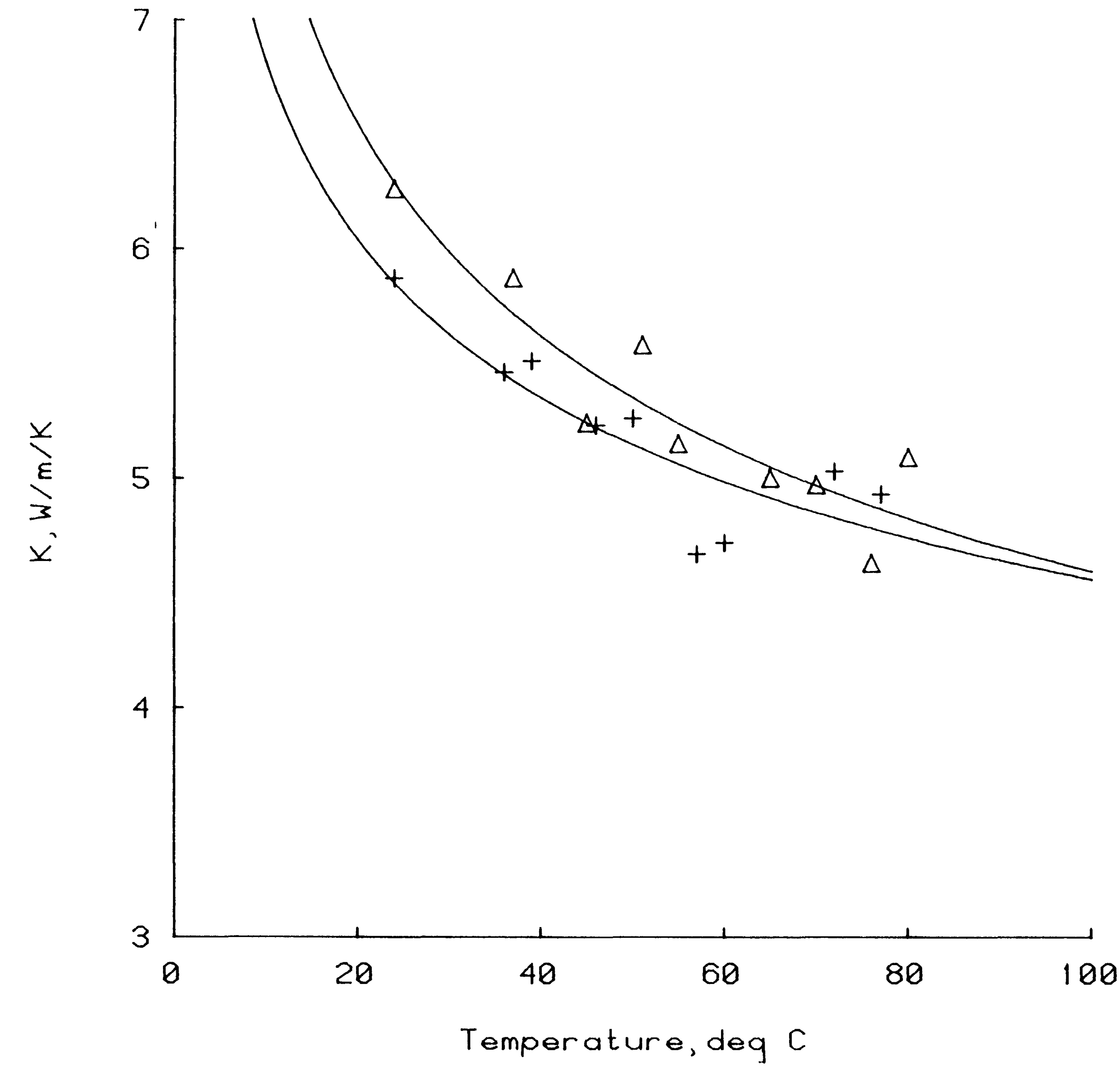


Figure 2. Variation of thermal conductivity with temperature for Salt 5 (triangles and upper curve) and anhydrite (plus signs and lower curve).

TABLE 3. Parameters of least-squares regression curve $K = K_o(\frac{T}{30})^B$ for conductivity-temperature data of Table 2 and Figure 2

Material	R*	K_o	B
Salt 5 (GD-1-92)	0.93	5.99	-0.22
Anhydrite (GD-1-94)	0.87	5.63	-0.17

*Coefficient of correlation.

HEAT FLOW

Inasmuch as major changes in gradient (Figure 1) correlate reasonably well with formation tops, heat-flow estimates were made over linear temperature-depth intervals within individual formations.

We first obtained average conductivities for individual rock types (Table 4). This was done according to 2 extreme assumptions. In the first instance (Column A, Table 4) we assumed no anisotropy and simply averaged conductivities in the xy and xyz directions. The second assumption was that all of the difference was due to anisotropy, and we calculated K_z according to equation 1. This was clearly not the case for shale, for example, and we probably should expect in this instance that the true K_z will be lower than either option in Table 4. For isotropic rocks, we did not consider option B.

The next step was to calculate a representative conductivity for each gradient interval (column 1, Table 5). This was done by using the graphic lithologic log to estimate the proportions of each rock in the intervals then calculating a weighted harmonic mean conductivity based on the averages of Table 4 with appropriate corrections for temperature variation.

We have only one sample from the Pinkerton Trail formation (Table 2) and none from the Molas (1680-1800 m), predominantly a shale formation for which there is a very high gradient (Figure 1). The temperature profile within the Leadville Limestone (1800-1900 m) is curved (Figure 1), and we have only two conductivities making this a rather uncertain heat-flow estimate. Apart from the Leadville (Table 5), heat-flow estimates are reasonably consistent among the major formations, particularly for conductivity assumption "A". The mean heat flow, weighted according to the length of the depth interval sampled, is 67 ± 2 mWm^{-2} for assumption "A" and 65 ± 3 for assumption "B" (Table 5).

We do not expect the effect of refraction to be nearly so large as that for the Salt Valley Anticline (Sass and others, 1983) where an uncorrected heat flow of 84 mWm^{-2} was lowered to 59 mWm^{-2} using a crude two-dimensional correction. Detailed examination of the conductivity-structure in the vicinity of Gibson Dome might result in comparable corrected values at the two sites.

TABLE 4. Mean thermal conductivities (at ~25°C) for individual rock types in GD-1 (see Table 1)

Rock	N*	Conductivity† $W\ m^{-1}\ K^{-1}$	
		A	B
Sandstone	1	3.20	2.97
Silty sandstone	1	2.56	2.33
Limestone	5	3.12 ± 0.32**	2.89 ± 0.39
Calcareous shale	1	2.46	2.52
Calcareous siltstone	2	2.68 ± 0.17	2.32 ± 0.30
Salt	3	5.99 ± 0.03	---
Anhydrite	1	5.92	---
Siltstone	1	3.08	3.68

*Number of cores tested.

†A, average of xy and xyz directions, 0 anisotropy assumed; B, K_z see text and footnote to Table 1.

**Standard deviation.

TABLE 5. Heat-flow determinations for GD-1

Depth interval m	Formation	Gradient °C/km	K W m^{-1} K^{-1} A	K W m^{-1} K^{-1} B	q mWm^{-2} A	q mWm^{-2} B
183-381	Elephant Canyon	23.49	3.01	3.04	71	71
427-869	Honaker Trail	21.77	3.04	2.84	66	62
945-1600	Paradox	13.04	5.31	5.19	69	68
1798-1922	Leadville	17.15	3.33	3.13	57	54
	Weighted mean				67 ±2	65 ±3

DISCUSSION

We have established that the mean observed heat flow from the Gibson Dome well is 66 ± 3 mWm^{-2}. Detailed consideration of regional thermal conductivity structure may well reduce this value by 10% or so.

Based on the internal consistency of interval heat-flow measurements above and within the Paradox Formation, that is, to a depth of nearly 1700 m we can rule out vertical water movement of more than a few mm y^{-1} based on our interpretation of equilibrium temperatures. Curvature in the temperature profile within the Pinkerton, Molas and Leadville formations is consistent with vertical water movement either in the hole or formation (or with conductive decay of a drilling disturbance, perhaps resulting from loss of drilling fluid) centered at about 1780 m ($\sim$5850 ft).

Both room-temperature determinations of thermal conductivity and estimates of temperature variation of samples from the Paradox Formation are consistent with published values for these evaporites.

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