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INTRODUCTION

As part of a study of the geology and geophysics of the Charleston, South Carolina, area, thermal conductivity, thermal gradient, and heat flow were determined in a 742 meter, continuously cored, test hole. The hole is located 41 km west-northwest of Charleston near Clubhouse Corners, Figure 1, directly over a gravity and magnetic high and the possible hypocenter of the 1889 Charleston earthquake. Drilling began January 13, 1975, and the hole penetrated 750 meters of Cenozoic and Upper Cretaceous sedimentary rocks finally bottoming in 42 meters of amygdaloidal basalts. Core recovery was 70% in sedimentary formations and 100% in the basalts. Detailed systematic studies of the core and the area surrounding the borehole were presented at the Symposium: Geology and Geophysics of Charleston, South Carolina, Area, held at the annual meeting of the Northeastern and Southeastern sections of the Geological Society of America during the week of March 25-27, 1976. Results from the thermal study are summarized in this report.

THERMAL GRADIENT

Temperatures were determined by methods described by Sass and others (1971). Figure 2 is a plot of temperature versus depth for the Clubhouse Corners hole with temperatures obtained at 3-meter intervals. The temperature profile is not a straight line, an indication of thermal-conductivity stratification or departures from one-dimensional steady-state heat flow.

A formal least-squares fit to all of the temperature-depth data below the zone of annual variation (∿ 20 m) yielded a gradient of 27.2 °C/km. This was sufficient for a crude estimate of heat flux, but the obvious structure indicated by the frequent changes in slope (Figure 2) prompted us to refine our estimate by determining gradients over discrete quasi-linear depth intervals (Figure 2). From Table 2, gradients within 8 intervals range from 42.2 °C/km to 18.4 °C/km. Another method used a smoothing technique involving the calculation of gradient over a 15-meter interval, plotting this value in the center of the interval then incrementing the center of the interval by 3 meters. This "moving average" gradient was then plotted versus depth (Figure 3) and three uniform gradient intervals (A, B, C) were identified. These gradients ranges from 22.8 °C/km to 19.6 °C/km, Table 3.

THERMAL CONDUCTIVITIES

Thermal conductivities were determined by the methods described by Sass and others (1971). Of the 90 conductivity measurements, 66 were determined using the needle-probe techniques first described by Von Herzen and Maxwell (1959). The needle probe was emplaced perpendicular to the axis of the core except for conductivities measured along the axis at depths of 135.6 meters and 164.6 meters (ax, Table 1) which showed no evidence of anisotropy. Steady-state measurements were performed on the remaining 24 samples using cylindrical samples ∿3.8 cm diameter by 1.27 cm thick, and a modified Birch-type (1950) divided-bar apparatus. Table 1 lists the conductivities along with estimates of porosity and density for the steady-state measurements. Ratcliffe's (1959) conductivity values for silica glass were used as a standard. All measurements were made on water-saturated samples at a temperature of about 20°C. The steady-state samples were measured at an axial pressure of 70 bars.

The steady-state divided-bar method and the needle-probe method have about the same accuracy and reproducibility (±2-3%). However, the needle-probe method is extremely sensitive to the degree of grain size sorting. Homogeneous clays provide easily repeatable values and coarse sands with pebbles produce varied results. The latter effect is due to 1) the location of the needle probe in the sample with respect to the large pebbles, and 2) the difference in thermal conductivities among pebbles, sands and clays.

Values of thermal conductivity ranged from 11.20 HCU for a quartz-rich sandstone to 2.38 HCU (1 HCU = 1 heat conductivity unit = 1 mcal/cm sec °C) for sandy shale; the harmonic mean conductivity of all samples <K> was 4.26 ± 0.14 HCU, Figure 4, Table 1. The steady-state values were higher in general (4.85 ± 0.39 HCU) and more variable than the needle-probe values (4.07 ± 0.14 HCU).

Harmonic mean conductivities <K> were calculated for the eight depth intervals within which temperature gradients were uniform (Figures 2 and 4). These values are listed on Tables 2 and 3, respectively. Intervals I, II, and IV contain predominately clayey, silty sands and sandstones with <K> of 5.99, 6.38 and 5.28 HCU, respectively. Intervals III, V, and VII comprise predominately sandy, silty, shales and mudstones with lower harmonic mean conductivities, of 3.39, 3.76, and 3.43 HCU, respectively. Data from interval VIII (Figure 4) illustrate the agreement between needle probe and steady-state measurements on solid, homogeneous rock (basalt) with a mean of 4.23 ± 0.13 HCU. Intervals A, B, and C (Figure 3), roughly correspond to intervals I, IV, and VI, (Figure 4), but the gradients within them are more uniform, i.e., ±1.0 °C/km. Intervals A and B are in sandy limestone which have higher conductivity (6.21 and 5.26 HCU, respectively) than interval C which is in the sandy shales (3.68 HCU).

HEAT FLOW

Because of the complicated thermal-conductivity structure and the consequent difficulty in characterizing <K> for some intervals, we have calculated heat flow using different methods in an attempt to identify disturbances to the thermal regime. Ideally, the thermal conductivity downhole should change in inverse proportion with the temperature gradient assuming a constant heat flux. Deviation from constant heat flow can be explained in a number of ways; usually it is the result of temperature fluctuations caused by the convective movement of water within the hole or the formation, or of problems in specifying the thermal conductivity.

In the first method we applied a linear least-squares fit to the entire profile and multiplied the gradient so obtained by the harmonic mean of all conductivity values, i.e., $\Gamma_{LS} \langle K \rangle_{HM} = 1.16 \pm 0.24$ HFU (1 HFU = 1 heat-flow unit = 1 $\mu cal/cm^2 sec$). This method yields the appropriate heat-flow value assuming random variation in conductivity. Next we combined harmonic mean conductivity <K> and gradient Γ over eight uniform gradient intervals (Table 2) and calculated a heat flow over each interval, Figure 5. One thick section (VI, Figure 5) has a conspicuously lower heat flow than the others. The section is completely within the Tuscaloosa formation (Brenda Higgins, unpublished core descriptions) which contains intervals of coarse sand and pebbles. We concluded that convective movement of ground water probably is transferring heat in this region and the heat flow was omitted from the average. The seven remaining heat flows were then combined giving a weighted mean of 1.30 $\pm$ 0.12 HFU. We also calculated heat flows for intervals A and B (Table 3) and the weighted mean is 1.28 $\pm$ 0.39 °C/km (we omitted segment C because of the presumed water flow mentioned above). Another method (after Bullard 1939) involved calculating the integrated thermal resistance $\xi_i = \sum_i R_i \Delta z_i$ for each interval Δz_i, plotting temperature (θ) versus ξ_i and determining the heat flow q from the relation $\theta = \theta_o + q\xi_i$, Figure 6. Using a linear least squares fit of the entire section, the heat flow is 1.16 $\pm$ 0.02 HFU. The lack of uniformity in the slope of ξ_i versus θ suggests a heat sink in the lower third of the hole. The least-squares fit to the upper part of the hole where the θ versus ξ line is quite linear yields a heat flow of 1.32 $\pm$ 0.01 HFU.

Finally, we used the solid rock (basalt) found in the lowermost 42 meters of the hole as a "flux plate." The presumption here is that we have characterized thermal conductivities in this homogeneous section with greater confidence than those in the more heterogeneous unconsolidated sedimentary sections above. The heat flow over this interval is 1.28 HFU (Interval VIII, Table 2).

SUMMARY

The apparently low heat flow in the Tuscaloosa formation (Interval VI, Figures 2, 4, and 5) lends some uncertainty to any estimate of heat flow from this well; however, if we assume that the low heat flow is caused by departure from one-dimensional conductive heat flux or to a problem in adequately sampling for thermal conductivity, we can exclude this interval from our calculations. Above and below the low heat-flow interval, component heat flows are consistent with a mean of about 1.3 HFU, and we adopt the value of 1.3 $\pm$ 0.2 HFU as our best estimate. This value is within the range of values commonly found in the Coastal Plains region and adjoining parts of the Appalachian physiographic province (Figure 1; Diment and others, 1965; Diment and Robertson, 1963; Roy and others, 1968; King and Simmons, 1972).

Acknowledgments

We thank Brenda Higgins and Gregory Gohn for their help in arranging access to the hole and supplying core samples. Tom Moses arranged for casing the hole and made the temperature measurements. Gene Smith made the needle-probe determinations of thermal conductivity. We are indebted to Peter Popenoe for his cooperation in preserving the hole and for supplying copies of geophysical logs. Arthur Lachenbruch coordinated the activities of various people and was active in the initial stages of the interpretation.

References

Birch, F., Flow of heat in the Front Range, Colorado: Geol. Soc. America Bull., v. 61, p. 567-630, 1950.

Bullard, E. C., Heat flow in South Africa: Royal Soc. London Proc., A, v. 137, p. 474-502, 1939.

Diment, W. H., Marine, I. W., Neiheisel, J., and Siple, G. E., Subsurface temperature, thermal conductivity, and heat flow near Aiken, South Carolina: Jour. Geophys. Research, v. 70, no. 22, 1965.

Diment, W. H., and Robertson, E. C., Temperature, thermal conductivity, and heat flow in a drilled hole near Oak Ridge, Tennessee: Jour. Geophys. Research, v. 68, p. 5035-5047, 1963.

King, W., and Simmons, G., Heat flow near Orlando, Florida, and Uvalde, Texas, determined from well cuttings: Geothermics, v. 1, no. 4, p. 133-139, 1972.

Ratcliffe, E. H., Thermal conductivities of fused and crystalline quartz: British Jour. Appl. Physics, v. 10, p. 22-28, 1959.

Roy, R. F., Blackwell, D. D., Decker, E. R., and Birch, F., Heat flow in the United States: Jour. Geophys. Research, v. 73, p. 5207-5221, 1968.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., Jr., Heat flow in the western United States: Jour. Geophys. Research, v. 76, p. 6376-6413, 1971.

Von Herzen, R. P., and Maxwell, A. E., The measurement of thermal conductivity of deep-sea sediments by a needle probe method: Jour. Geophys. Research, v. 64, p. 1557-1563, 1959.

TABLE 1. Thermal conductivity and density of water-saturated core and apparent porosity (100 x (wet weight-dry weight)/wet weight), Clubhouse Corners, South Carolina

Depth (m)	Thermal conductivity mcal/cm sec °C	Density g/cm^3	Apparent porosity %
15.7	3.94	--	
30.9	3.90	--	
47.1	3.52	--	
62.8	3.11	--	
70.4	4.19	--	
91.7	3.49	--	
106.2	2.94	--	
122.2	3.57	--	
135.6	6.53(ax)	2.67	5.8
	6.96	2.21	7.1
153.3	3.87	--	
164.6	10.89(ax)	2.65	0.4
	10.38	2.62	1.6
185.9	3.69	--	
198.3	--	--	--
217.6	3.28	--	
231.3	2.86	--	
	2.72	1.79	49.1
243.8	7.85	2.56	5.8
258.0	4.34	--	
272.2	3.74	--	
296.1	5.54	--	
302.7	7.81	2.50	8.5
305.1	5.50	--	
321.6	5.53	--	
332.8	5.90	--	
343.5	8.14	2.59	4.1

TABLE 1. Thermal conductivity and density of water-saturated core and apparent porosity (100 x (wet weight-dry weight)/wet weight), Clubhouse Corners, South Carolina (continued)

Depth (m)	Thermal conductivity mcal/cm sec °C	Density g/cm³	Apparent porosity %
350.8	5.95	--	
367.6	7.20	--	
374.0	5.60	--	
383.1	5.64	--	
397.8	4.77	--	
415.4	11.20	2.63	1.2
418.8	5.11	--	
426.7	7.69	2.41	8.3
428.9	5.33	--	
435.3	5.52	--	
442.9	3.83	--	
452.3	3.49	--	
458.4	3.55	--	
462.7	3.30	--	
469.1	2.90	--	
	5.48	2.20	28.6
473.4	3.54	--	
476.4	6.43	--	
480.1	5.55(ax)	--	
	5.69	--	
483.1	5.37	--	
487.1	6.82	--	
504.1	5.37	--	
518.3	3.92	--	
524.6	--	--	--
533.4	3.18	--	
533.6	9.07	2.61	3.6

TABLE 1. Thermal conductivity and density of water-saturated core and apparent porosity (100 x (wet weight-dry weight)/wet weight), Clubhouse Corners, South Carolina (continued)

Depth (m)	Thermal conductivity mcal/cm sec °C	Density g/cm³	Apparent porosity %
541.2	--	--	--
543.3	2.60	--	
567.5	2.97	--	
581.9	3.05	--	
585.1	4.45	--	
594.4	6.20	--	
602.0	5.69	--	
606.9	3.29	--	
608.1	5.06	--	
610.5	3.19	--	
616.6	--	--	--
627.3	2.38	--	
632.5	--	--	--
637.2	4.51	--	
655.2	5.84	--	
673.2	2.71	--	
675.4	5.30	--	
675.7	5.59	--	
683.1	3.68	--	
702.0	4.04	--	
716.1	3.44	--	
722.7	3.19	--	
729.1	3.71	--	
732.1	3.42	--	
748.6	8.14	--	
754.1	--	--	--
757.4	3.16	2.26	7.3

TABLE 1. Thermal conductivity and density of water-saturated core and apparent porosity (100 x (wet weight-dry weight)/wet weight), Clubhouse Corners, South Carolina (continued)

Depth (m)	Thermal conductivity mcal/cm sec °C	Density g/cm^3	Apparent porosity %
760.5	4.21	--	
760.5	4.26	--	
760.5	4.30	2.71	0.7
763.5	4.18	2.80	0.8
766.3	4.27	2.82	0.5
769.6	4.58	2.88	0.4
772.7	4.47	2.89	0.7
774.5	4.63	--	
774.5	4.59	--	
774.5	4.62	2.89	0.2
776.0	4.51	2.87	0.9
778.8	4.63	2.89	0.8
781.8	4.73	2.91	0.4
785.2	3.33	2.41	5.1
787.9	4.11	2.70	1.0

TABLE 2. Temperature gradient (Γ), harmonic mean thermal conductivity (<K>), and heat flow (q) for quasi-linear segments of the temperature profile (Figure 2)

Interval	Depth (m) From	To	Γ °C/km	N	<K> HCU	S.E.	q (HFU)
I.	274.32	399.29	21.0	11	5.99	±.29	1.26
II.	405.38	441.96	23.04	5	6.38	±.83	1.47
III.	441.96	469.39	40.1	5	3.39	±.16	1.36
IV.	469.39	515.11	25.3	6	5.28	±.55	1.34
V.	509.02	554.74	30.1	4	3.76	±.82	1.13
VI.	554.74	697.99	18.4	15	3.88	±.32	.71
VII.	713.23	737.62	42.2	5	3.43	±.11	1.45
VIII.	754.38	789.43	30.35	16	4.23	±.13	1.28

TABLE 3. Temperature gradient (Γ), harmonic mean conductivity (<K>), and heat flow q over three, smoothed constant-gradient intervals

Linear segment designation	Depth (m) From	To	Γ °C/km	N	<K> HCU	S.E.	q (HFU)
A	285.0	380.0	21.00	9	6.21	.31	1.30
B	472.0	492.0	22.77	5	5.26	.66	1.20
C	606.0	670.0	19.59	6	3.69	.51	.72

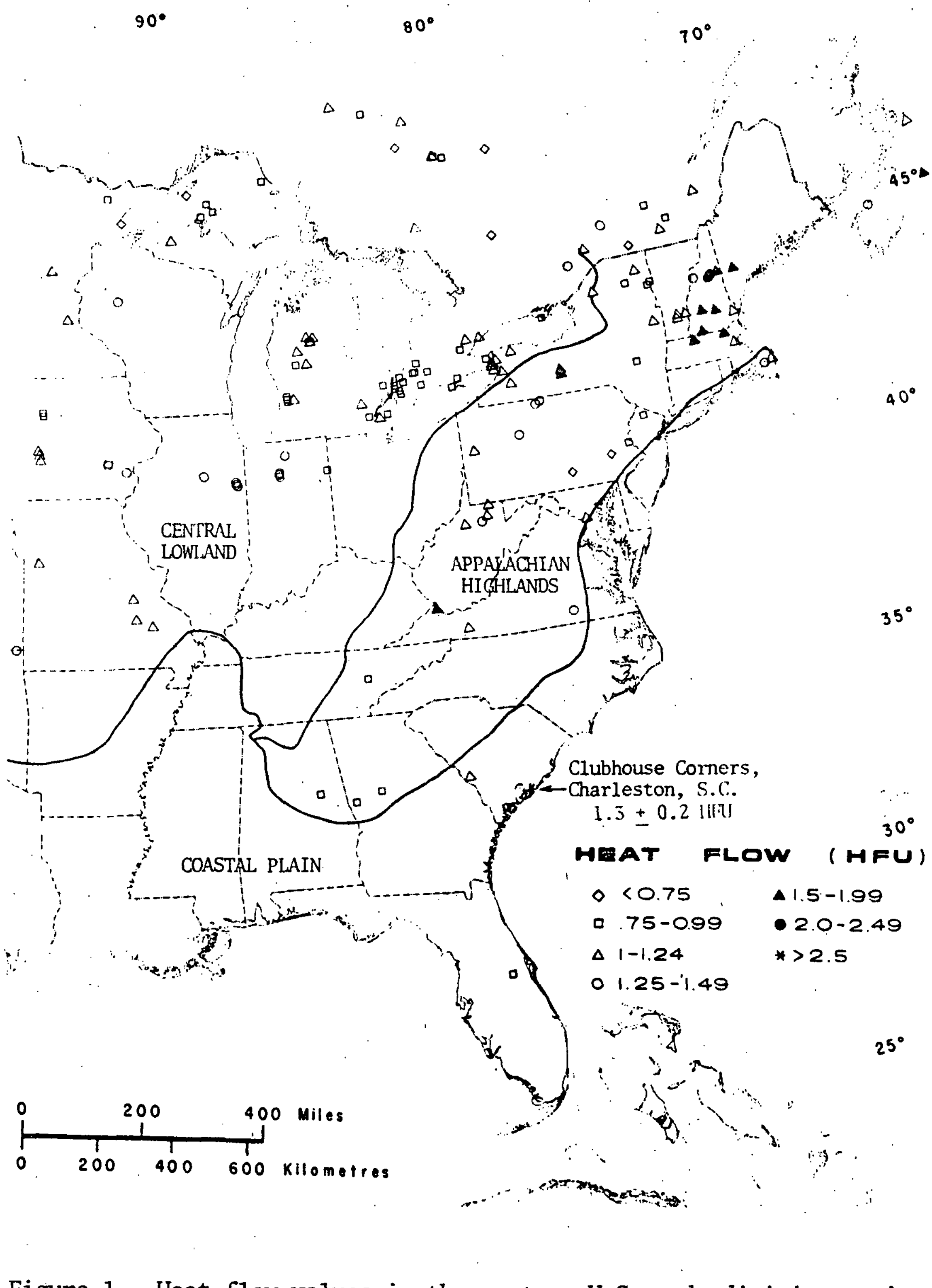

Figure 1. Heat-flow values in the eastern U.S. and adjoining regions of southern Canada

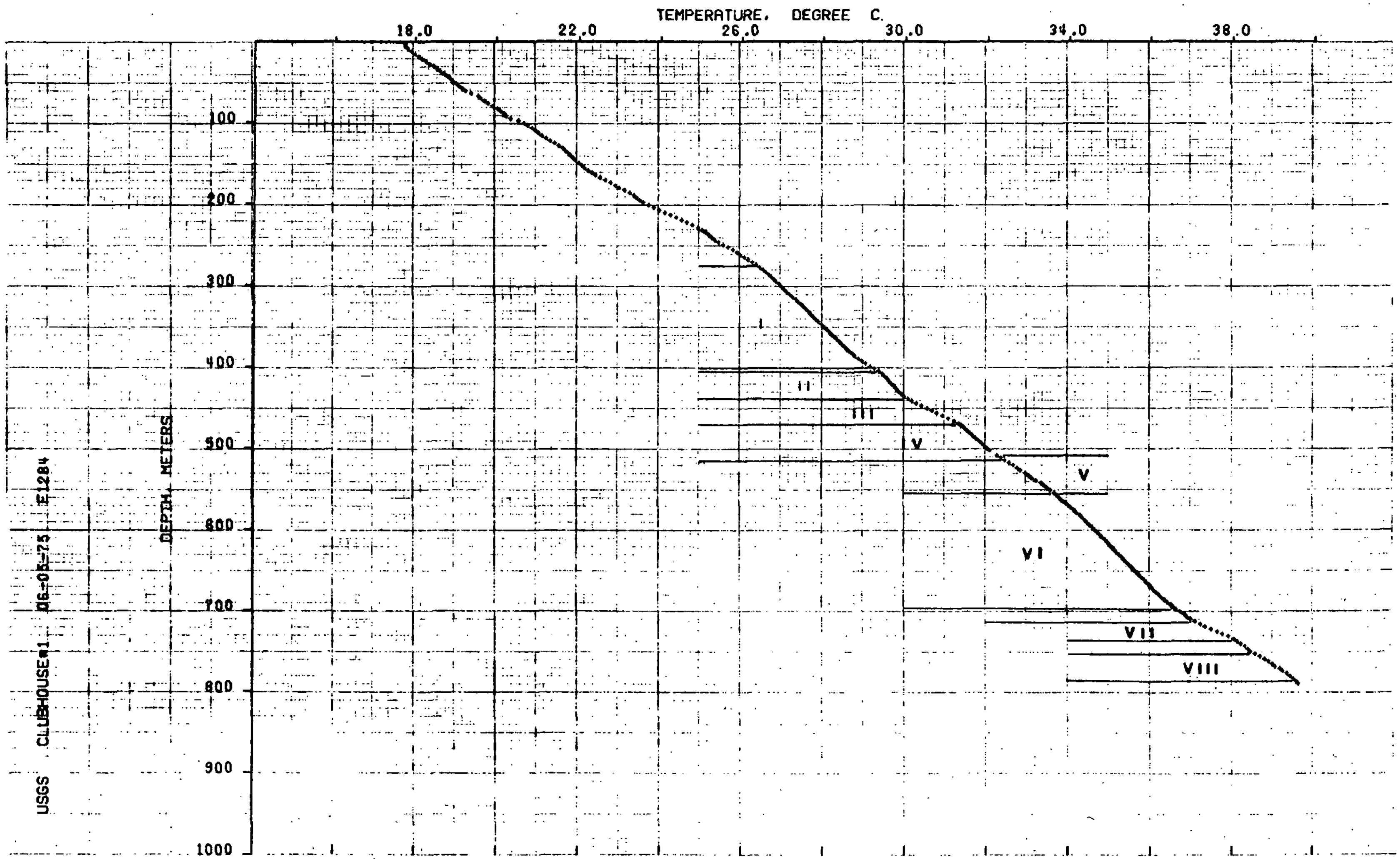

Figure 2. Temperature versus depth - Clubhouse Corners, South Carolina

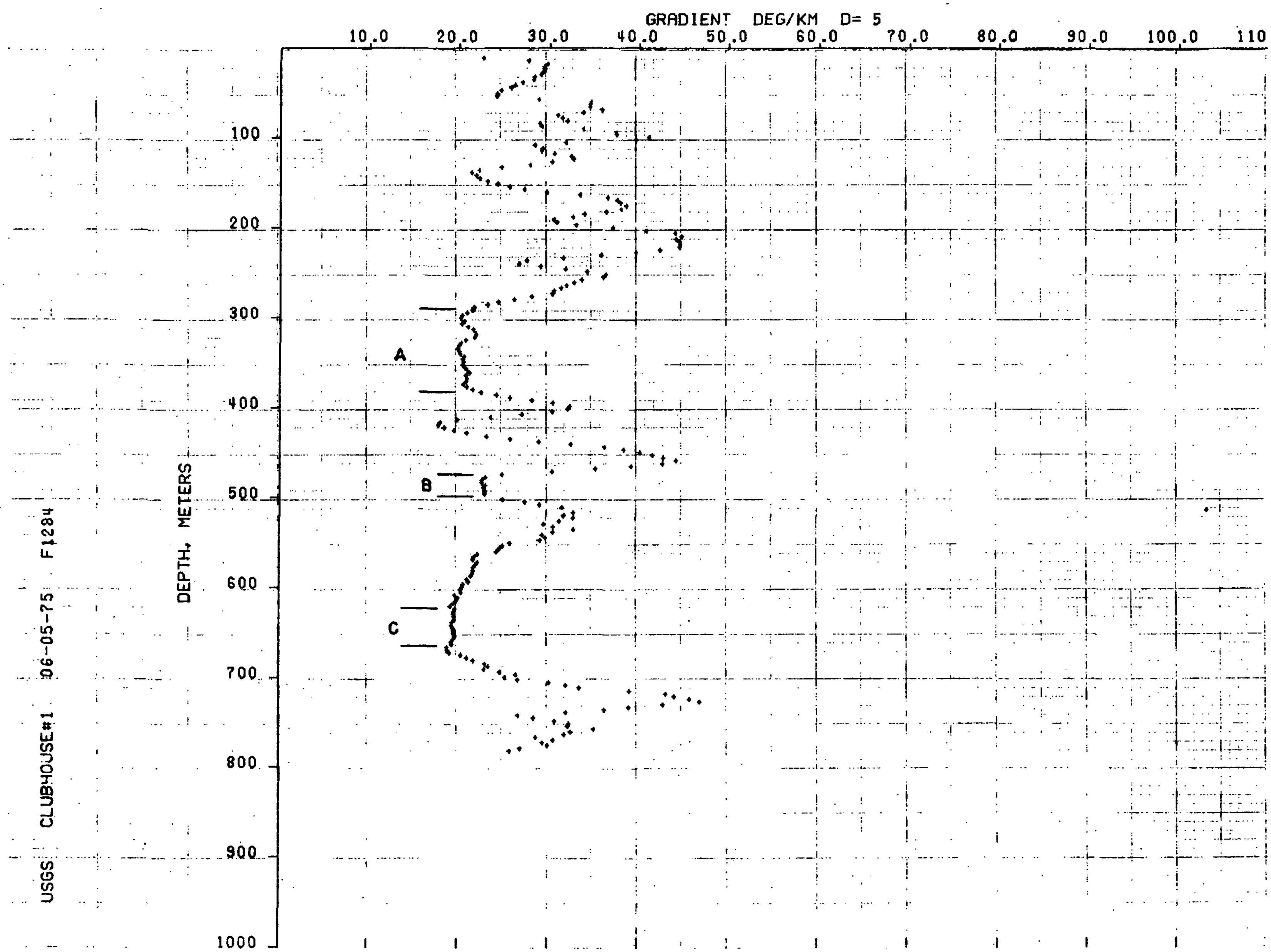

Figure 3. Smoothed gradient versus depth - Clubhouse Corners, South Carolina

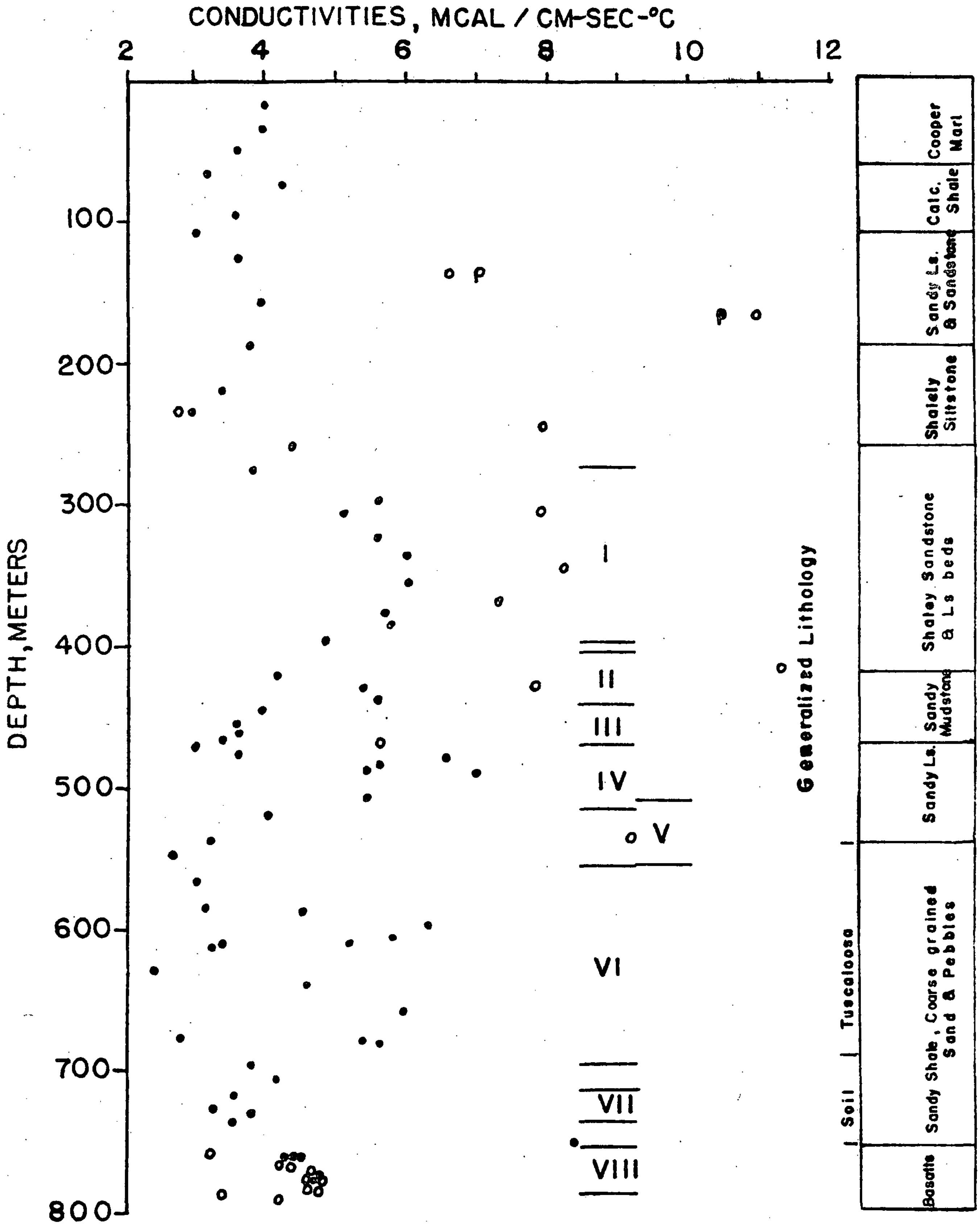

Figure 4. Conductivity versus depth with generalized lithology - Clubhouse Corners Charleston, South Carolina.
Open circles are divided-bar measurements; dots, needleprobe determinations.

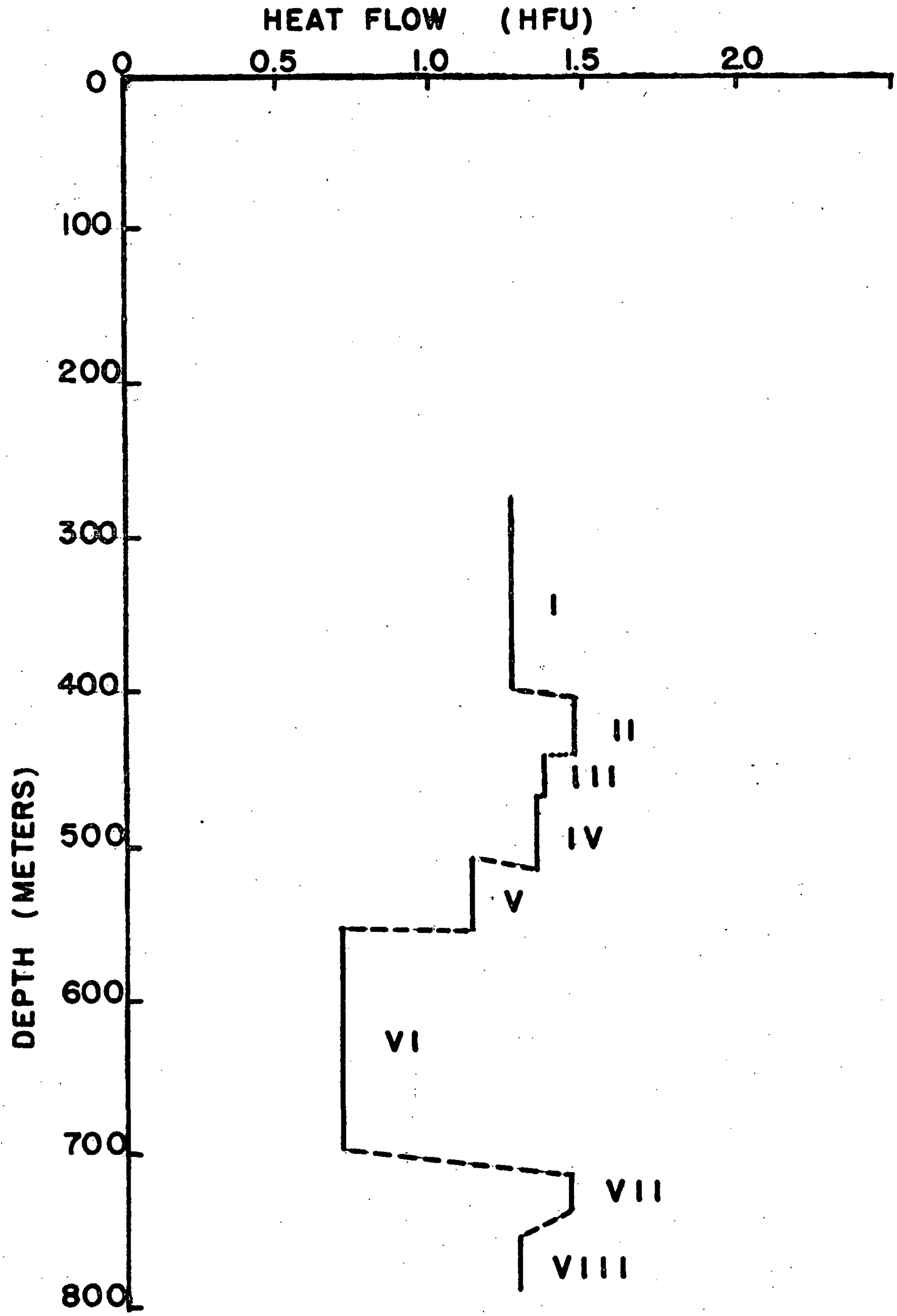

Figure 5. Heat flow versus depth over intervals of uniform gradient, Clubhouse Corners, South Carolina.

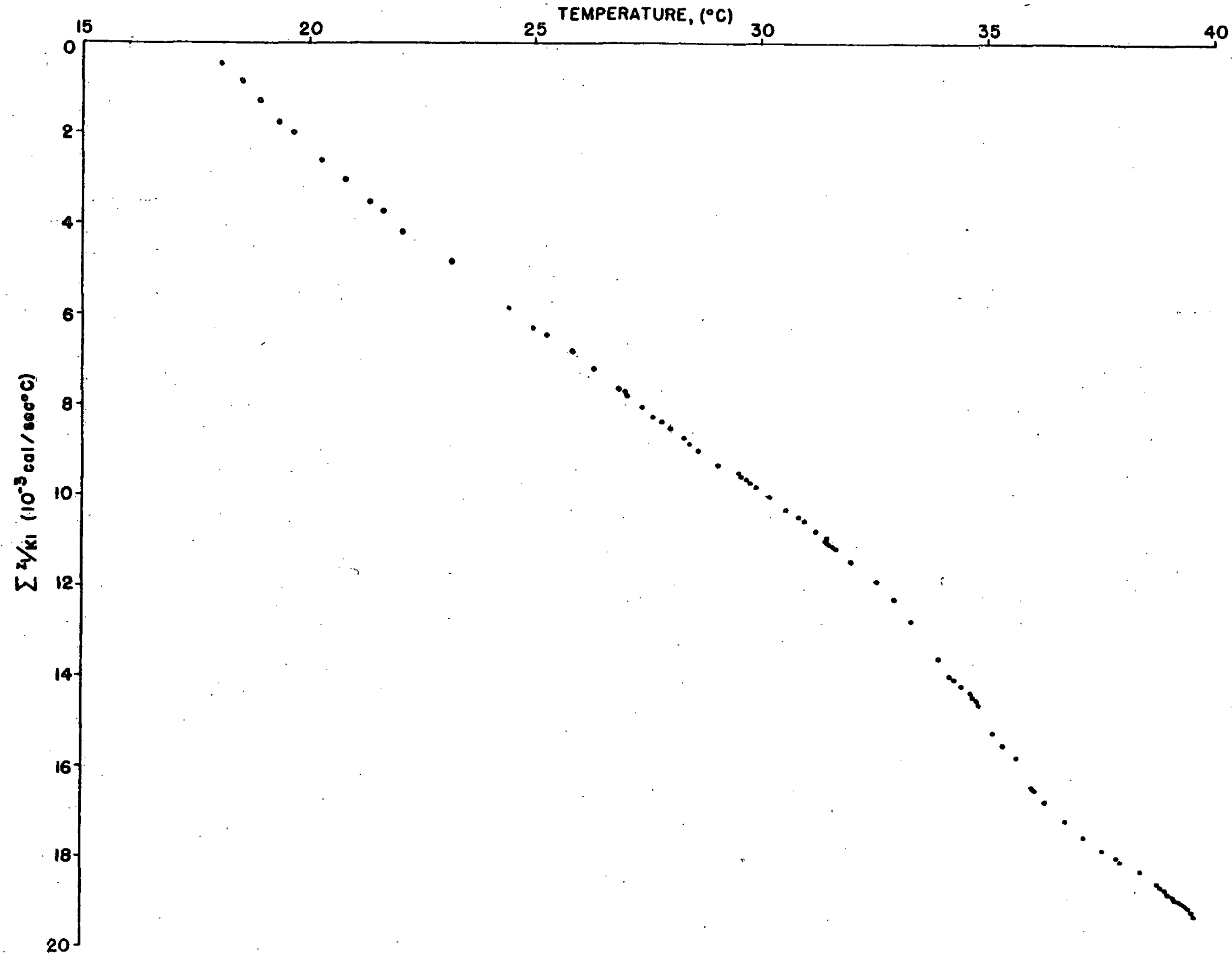

Figure 6. $\sum_i 1/k_i$ versus temperature (after Bullard), Clubhouse Corners, South Carolina.