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Heat Flow in Southwestern Virginia

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Eight holes in southwestern Virginia provided a heat flow value at Cripple Creek (36°49′N, 81°06′W) of 1.03 ± 0.15 μcal/cm^2 sec and a value of 1.7 ± 0.34 μcal/cm^2 sec near Grundy (37°20′N, 82°W). The value of 1.03 μcal/cm^2 sec agrees with low values to the northeast reported by Diment. The possibility of low heat flow due to nonequilibrium gradients resulting from late Paleozoic overthrusting was investigated. It was concluded that any reasonable model would be close to equilibrium in less than 80 m.y. The low heat flow value at Cripple Creek is probably the result of erosion of the upper crust before deposition of late Precambrian and Paleozoic sediments. Heat production studies of surface rocks near Alberta, Virginia, support the high heat flow of 1.4 μcal/cm^2 sec obtained there by Diment and Werre (1964).

Temperatures were measured in five holes in the Valley and Ridge province in southwestern Virginia near the town of Cripple Creek (36°49′N, 81°06′W). The holes, drilled by the American Zinc Company into dolomite of Cambrian age, have depths from 335 to 384 meters. These holes provide the first heat flow values in the Valley and Ridge province in Virginia. The only other heat flow determination in the Valley and Ridge province in the southeastern United States is in Tennessee [*Diment and Robertson,* 1963].

Three holes near Grundy, Virginia, in the Appalachian Plateau province in southwestern Virginia also provided a reliable heat flow determination. The holes were drilled by the Island Creek Coal Company into sediments of Lower Pennsylvanian age to maximum depths of 533 meters.

Measurement of Temperature

Temperature measurements were made by platinum resistance thermometers manufactured by Rosemount Engineering Company and Genesco, Inc. Several probes having nominal resistances at 0°C of 1000, 2000, and 5000 ohms were eventually used. The probe housings were vulcanized onto a Vector R3CWL-4-250 four-lead cable. At regular intervals the entire measuring system was calibrated at the ice point by a Rosemount model 911 ice bath. The ice point was usually reproducible to ±0.005°C. Two different probes used to measure the deepest hole (900 meters) showed an increase of about 0.02°C at the ice point, probably as a result of accumulated mechanical shock. Two holes were remeasured with different probes down parts of their depths, and, except for zones where water was circulating in the hole, absolute temperatures were reproducible to within ±0.04°C. Absolute temperatures reported here are considered accurate to within ±0.05°C. Temperature differences over intervals of 40 meters were reproducible to within ±0.01°C. Gradients were reproducible to within 2% for depth intervals over which groundwater disturbances were not noticeable.

The probe resistance was measured with a Honeywell Mueller bridge, model 1551-E, and a Honeywell electronic null detector, model 3972. Resistance was balanced out by Electroscientific model SR1 standard resistors, accurate to ±0.001%, and Rubicon decades in the resistance bridge.

Measurement of Thermal Conductivity

All thermal conductivity values were determined from core samples. Disks 2.96 or 3.62 cm in diameter and 1.27 or 2.54 cm thick were machined from core samples from the Cripple Creek holes. Disks 2.54 cm thick and 4.76 cm in diameter were machined from core samples from holes in the Grundy area. The disks were commercially prepared to a surface smoothness of ±0.0008 cm and a thickness tolerance of ±0.0025 cm. All samples were saturated with distilled water before measurement. The Cripple Creek samples were saturated by soaking in water for several days or weeks before measurement. Samples from the Grundy holes were saturated under a vacuum of 5 μ and then soaked for a period of 3–14 days. Several representative samples saturated by soaking were later evacuated in the vacuum chamber before being saturated with water and then allowed to soak for several days. The thermal conductivity results were the same to within 3% [*Reiter*, 1969]. The sandstone samples from the Grundy holes were also placed in a pressure cell after vacuum saturation and saturated with distilled water overnight under a pressure of 35 bars. When repeat measurements of thermal conductivity were made on the pressure-saturated samples, all thermal conductivity values with the exception of one agreed with the vacuum-saturated values to within −3%; the exception was 1.6% higher.

Thermal conductivity was determined from measurements made in a four-stack divided bar apparatus [*Birch*, 1950]. A temperature differential of approximately 10°C was maintained across the specimen and the fused quartz GE-101 reference disks by a Colora model NB circulating bath. The system was later improved for the Grundy holes by using two Lauda K2/R refrigerating circulating baths, which facilitated maintaining the temperature of the rock sample to within 5°C of its in situ temperature. The stacks were calibrated by substituting for the rock sample a fused quartz disk the same size as the rock sample. Because some of the core from the Grundy holes consisted of a well-indurated arenite with a high thermal conductivity, disks 4.76 cm in diameter and 2.54 cm thick of natural quartz cut perpendicular to the optic axis were obtained from the Valpey Corporation. These disks were th same size as the rock specimens prepared fro core from the Grundy holes. The thermal conductivity determined for the natural quartz b using fused quartz reference disks was 15. mcal/cm sec °C at 17°C, in good agreemen with the value of *Birch and Clark* [1940, p 557, Figure 8]. The thermal conductivity o five of the samples from two of the Crippl Creek holes was determined by *Reiter an Hartman* [1971], who used a different stead state method. These authors reported goo agreement between values obtained on thei apparatus and those obtained on the divide bar apparatus at Virginia Polytechnic Institute and State University. Copper disks were inserted between the rock sample and the quartz reference disks. Temperature differences across the reference disks and the rock samples were determined from thermocouples inserted into the copper disks, and measurements of potential drops across the rock disk and the reference disks were made with a Leeds and Northrup K-3 potentiometer. All measurements were made while the rock specimen was under an axial pressure of 100 bars. Tight-fitting machined high-density styrofoam approximately 4 cm thick was clamped around the stack to minimize radial heat loss. Conductivity was measured in the direction of the axis of the core sample from the hole.

Reproducibility of the thermal conductivity apparatus was generally better than 2%. Thermal conductivity measurements made on a few samples with temperature gradients of 5° and 10°C across the stack but with about the same rock temperature agreed to within 2%.

Cripple Creek, Virginia. The Cripple Creek holes are within 8 km of the town of Cripple Creek, Virginia, at 36°49′N, 81°06′W and are drilled into the Shady dolomite of Cambrian age. Figure 1 shows the temperature profiles for five holes. Low geothermal gradients in the upper parts of the holes are believed to be caused by circulating groundwater, an interpretation supported by monitoring temperatures at several depths and observing temperature fluctuations. Water moving up or down the hole can lower the geothermal gradient by tending to equalize temperatures over the interval in which water is moving. Sudden discontinuities in the temperature profiles (Figure 1) are partially ex-

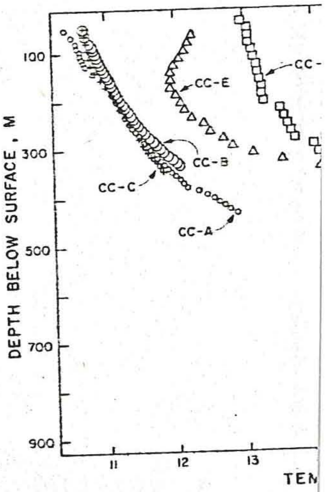

Fig. 1. Temperature-depth profiles of hole
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C-E coincides with a zone of cavitation a
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Hole CC-E is the deepest hole of the Crip
reek group. The hole was logged on three se
e occasions to check the calibration of
easuring system. The results of the gradi
erminations are given in Table 1. The ne
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er, no such disturbance could be justified,
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some unknown flow regime in the carbo
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oler water at depths of about 100–200 me
this hole. These intervals were not used
at flow determinations.

Heat flow values for the holes at Cri
reek were determined by multiplying ave
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rbances cause apparent low conductive
w over much of the depth range of
ripple Creek holes, as is shown in Tabl

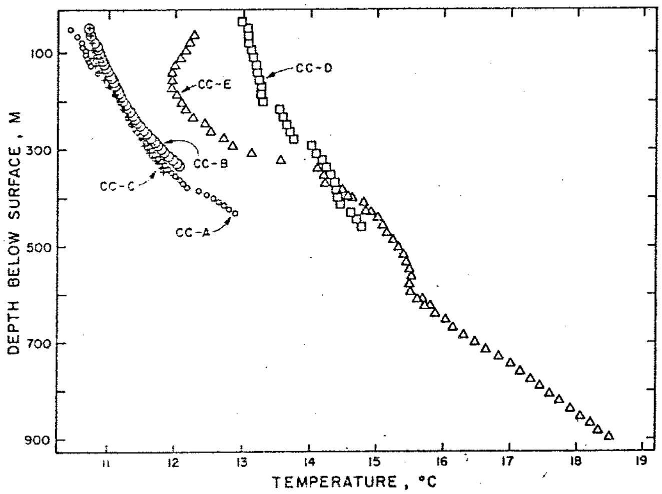

Fig. 1. Temperature-depth profiles of holes in the Cripple Creek, Virginia, area (Valley and Ridge province).

plained by the presence of large cavernous water-filled zones, which cause a sudden increase in temperature due to the low thermal conductivity of water. Such zones are common in carbonate rocks and in the Cripple Creek area were confirmed by the driller's log. The discontinuity at a depth of about 200 meters in CC-E coincides with a zone of cavitation and weathering on the lithologic log for this hole.

Hole CC-E is the deepest hole of the Cripple Creek group. The hole was logged on three separate occasions to check the calibration of the measuring system. The results of the gradient determinations are given in Table 1. The negative gradient in the upper part of CC-E suggests a recent surface disturbance, such as a building, affecting the upper 200 meters; however, no such disturbance could be justified, and the most likely cause of the negative gradient is some unknown flow regime in the carbonate section that is permitting lateral circulation of cooler water at depths of about 100–200 meters in this hole. These intervals were not used for heat flow determinations.

Heat flow values for the holes at Cripple Creek were determined by multiplying average thermal conductivities over a depth interval by a least squares straight-line temperature gradient over the same interval. Groundwater disturbances cause apparent low conductive heat flow over much of the depth range of the Cripple Creek holes, as is shown in Table 1; however, the deepest intervals of several of these holes give similar results. If the estimated heat flow values for the two bottom zones of CC-A and the bottom zone of CC-B are averaged, the resulting heat flow is 0.92 ± 0.20 μcal/cm^2 sec. If the lower two intervals in CC-E, the lower two intervals in CC-A, and the lowest interval in CC-B are averaged, the resulting heat flow is 0.97 ± 0.21 μcal/cm^2 sec.

The gradient in CC-E does not appear to be influenced by groundwater movement below a depth of about 610 meters. The gradient in CC-E was determined for three different lithologic intervals. If the gradient for each interval is multiplied by the mean conductivity for that interval, the intervals give similar heat flow values as shown in Table 1 for the depth intervals 609–670, 685–746, and 746–898 meters. Hole CC-E from 685 to 746 meters penetrated limestone; the rest of the hole for the depth intervals shown in Table 1 was in dolomite. The most reliable heat flow value for the Cripple Creek area is 1.03 ± 0.15 μsec/cm^2 sec on the basis of the data from CC-E.

Grundy, Virginia. Three holes in southwestern Virginia near Grundy, all located within about 15 km of 37°20′N, 82°W, were found to be suitable for a heat flow determination. The holes were drilled on the Island Creek Coal Company leases to the depth of the Pocohontas 3 coal seam. Pertinent data for the holes are listed in Table 1.

TABLE 1. Heat Flow Data

Locality	Location	Elevation, meters	Depth Interval, meters	No. of Temperatures	Gradient and Standard Deviation,[a] °C/km	Thermal Conductivity K,[b] mcal/cm sec °C	Heat Flow,[c] μcal/cm^2 sec
Cripple Creek, Va.	36°49'N, 81°06'W						
CC-A		713	81 to 126	4	3.17 ± 0.13 (Feb. 4, 1969)	12.9 ± 1.3 (8)	0.41
			81 to 126	4	3.36 ± 0.07 (Feb. 11, 1969)	12.9 ± 1.3 (8)	0.43
			248 to 309	5	5.79 ± 0.07 (Feb. 4, 1969)	11.2 ± 0.8 (10)	0.65
			248 to 309	5	5.72 ± 0.07 (Feb. 11, 1969)	11.2 ± 0.8 (10)	0.65
			247 to 309	5	5.74 ± 0.04 (May 11, 1969)	11.2 ± 0.8 (10)	0.64
			309 to 378	10	7.11 ± 0.06 (Feb. 11, 1969)	10.8 ± 0.5 (9)	0.77
			324 to 377	8	7.25 ± 0.13 (May 11, 1969)	10.7 ± 0.5 (7)	0.78
CC-B		725	80 to 194	16	3.36 ± 0.02 (Apr. 10, 1969)	14.6 ± 0.1 (4)	0.49
			201 to 262	9	5.10 ± 0.06 (Apr. 10, 1969)	12.5 ± 2.1 (9)	0.64
			262 to 315	8	7.02 ± 0.07 (Apr. 10, 1969)	12.1 ± 1.0 (7)	0.85
CC-C		732	140 to 187	4	5.13 ± 0.04 (Mar. 28, 1969)	14.0 ± 0.7 (7)	0.72
			187 to 285	8	4.15 ± 0.03 (Mar. 28, 1969)	12.9 ± 1.3 (11)	0.54
			285 to 346	9	5.42 ± 0.04 (Mar. 28, 1969)	11.8 ± 0.7 (9)	0.64
CC-D		640	217 to 278	5	3.25 ± 0.07 (Mar. 21, 1969)	13.5 ± 0.7 (3)	0.44
			293 to 339	4	5.27 ± 0.16 (Mar. 21, 1969)	10.5 ± 1.9 (3)	0.55
			354 to 415	5	2.40 ± 0.05 (Mar. 21, 1969)	11.6 ± 2.2 (4)	0.28
CC-E		701	609 to 670	5	8.86 ± 0.04 (May 1, 1969)	13.2 ± 1.0 (4)	1.17
			609 to 670	5	8.06 ± 0.13 (May 21, 1969)	13.2 ± 1.0 (4)	1.06
			685 to 746	5	11.8 ± 0.2 (May 1, 1969)	8.45 ± 0.85 (4)	1.00
			685 to 746	5	12.1 ± 0.3 (May 21, 1969)	8.45 ± 0.85 (4)	1.02

TABLE 1. (continued)

TABLE 1. (continued)

Locality	Location	Elevation, meters	Depth Interval, meters	No. of Temperatures	Gradient and Standard Deviation,[a] °C/km	Thermal Conductivity K,[b] mcal/cm sec °C	Heat Flow,[c] μcal/cm^2 sec
			746 to 898	11	9.74 ± 0.05 (May 1, 1969)	10.7 ± 1.4 (10)	1.04
Grundy, Va.	37°20'N, 82°00'W						
190		463.3	152 to 175	3	30.03 ± 0.08	6.42 (1)	1.93
			175 to 206	5	16.84 ± 0.52	10.79 ± 0.22 (8)[d]	1.82
			183 to 213	5	17.87 ± 0.93	10.79 ± 0.22 (8)	1.93
			206 to 244	6	24.47 ± 0.54	6.25 ± 1.26 (2)	1.53
			229 to 274	7	23.18 ± 0.46	7.06 ± 0.31 (10)[e]	1.64
			366 to 396	3	21.59 ± 0.99	7.06 ± 0.31 (10)	1.52
			427 to 465	4	7.75 ± 0.086	16.12 ± 0.63 (10)[f]	1.25
			503 to 533	3	6.07 ± 0.62	16.12 ± 0.63 (10)	0.98
VPF-1		482.5	197 to 227	3	27.07 ± 2.33	7.06 ± 0.31 (10)	1.69
			242 to 288	4	16.73 ± 1.63	10.79 ± 0.22 (10)	1.81
			273 to 394	8	26.03 ± 0.48	7.06 ± 0.31 (10)	1.84
			395 to 440	5	8.00 ± 0.12	16.12 ± 0.63 (10)	1.29

[a] Date of measurement in parentheses.
[b] Number of samples in parentheses.
[c] See text for best heat flow value.
[d] Sandstone interval. See Table 2 for average thermal conductivity used.
[e] Shale interval. See Table 2 for average thermal conductivity used.
[f] White sandstone interval. See Table 2 for average thermal conductivity used.

The holes are in horizontal rocks of Lower Pennsylvanian age. Lithologic units from a few centimeters to a few meters thick alternate between gray arenite and shale. There are no carbonates in the section. The Pocahontas 3 coal seam, about 1.5 meters thick in this area, is in the Pocahontas formation, which is truncated at a very low angle by the lowest member of the Lee formation (T. Gathright, personal communication, 1971). The base of the type Lee formation is a distinctive, well-silicified white arenite with a quartz pebble conglomerate. This unit overlies the Pocahontas formation in the Grundy area. The base of the Pennsylvanian system in this area is taken to be the redbeds at the base of the Pocahontas formation below the Pocahontas 3 coal seam.

Figure 2 shows temperature profiles for holes 188 and 190 and for Virginia Pocahontas Federal 1 (VPF-1). The temperatures are plotted as a function of depth below the surface. If the temperatures are plotted against elevation above sea level, all three curves approximately coincide with each other, and essentially flat isotherms are indicated.

The most reliable interpretation for a heat flow value is obtained by using the data from hole 190 and VPF-1. Hole 188 was blocked at a depth of about 330 meters. No core was available from VPF-1, but a γ ray density log run by Birdwell was made available by the U.S. Bureau of Mines. The log was useful in establishing predominantly sandstone or shale intervals. A similar log was not available for hole 190; however, core was available from this hole, and all thermal conductivity determinations were made on core from this hole. Hole 190 therefore provided representative sandstone, shale, and white silicified sandstone core for correlation with the gradients in the other holes. Although hole 190 was logged for temperature, the lithologic variations between sandstone and shale were so frequent that representative sampling of sandstone and shale was difficult. Several of the black shale samples broke up when they were saturated with water prior to the determination of thermal conductivity. All the thermal conductivity values reported herein are for shale samples that did not disintegrate. The values reported for the black shale may therefore be too high; however, the gray sandstone intervals were well sampled, and these intervals also gave a similar high value for the heat flow, as is shown in Table 1.

Least squares straight-line gradients for lithologic intervals in the three Grundy holes are compared in Table 1. The average gradients for the shale, gray arenite, and silicified white arenite intervals are 25.7°, 17.1°, and 7.2°C/km, respectively. Average thermal conductivities of the shale, sandstone, and white silicified sandstone determined from representative samples

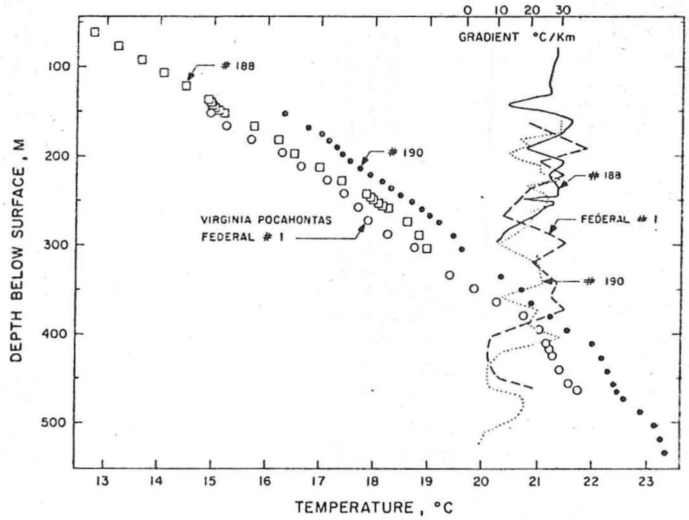

Fig. 2. Temperature-depth profiles of holes in the Grundy, Virginia, area (Appalachian Plateau province).

TABLE 2. Representativ

Depth of Core Sample, meters
179
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TABLE 2. Representative Thermal Conductivities of Gray Arenite, Black Shale, and White Arenite

Depth of Core Sample, meters	Lithology	Thermal Conductivity, mcal/cm sec °C	Average Thermal Conductivity, mcal/cm sec °C
179	Lithic quartz arenite, gray; 80 to 90% quartz; 2 to 5% rock fragments of chert, schist, slate; minor muscovite, feldspar; cementing material is quartz.	10.92	10.79 ± 0.22
194		10.35	
202		11.21	
221		10.84	
234		10.37	
316		11.71	
324		10.19	
369		10.72	
171	Black shale	6.42	7.06 ± 0.31
209	Black shale	4.99	
225	Black shale	7.51	
301	Black shale	6.51	
308	Black shale	7.76	
347	Black shale	8.40	
377	Black shale	8.20	
385	Black shale	6.42	
400	Black shale	6.83	
537	Black shale	7.53	
438	Lithic quartz arenite, white; 85 to 95% quartz; 1 to 2% rock fragments; quartz cement; very well indurated.	15.74	16.12 ± 0.63
446		17.20	
452		15.52	
453		17.69	
461		16.82	
476		15.82	
508		15.38	
514		15.16	
522		16.03	
529		15.87	

listed in Table 2 are 7.1, 10.8, and 16.1 mcal/cm sec °C, respectively. Heat flow values obtained by multiplying the average thermal conductivities by the average gradients in the shale, gray sandstone, and white sandstone intervals are 1.82, 1.85, and 1.23 μcal/cm^2 sec, respectively. The low value of 1.23 for the white arenite interval is not in agreement with the average heat flow values computed for the shale and gray arenite intervals; however, a temperature log run by Allegheny Nuclear Surveys, Inc., was made available for an unidentified hole nearby in the same sedimentary section. At several horizons this log showed abrupt decreases in temperature that coincided with changes in the caliper log indicating increases in the diameter of the hole of up to almost 4 cm. These intervals are probably thin seams of coal, and the abrupt changes in temperature and near zero to negative temperature gradients near these horizons are suggestive of groundwater circulation. The γ ray log in this hole correlates well with the γ ray log of VPF-1, particularly over the thick arenite interval. This interval is about 33 meters thick on the unidentified log, 42 meters thick in hole 188, and 34 meters thick in VPF-1, as is determined from the γ ray log of that hole. The temperature log of the unidentified hole shows a zero to negative gradient directly beneath the white sandstone. Such clear indications of groundwater circulation here in the same sedimentary section suggest that the gradients in the white arenite in VPF-1 and IC-190 may be abnormally low due to groundwater circulation near this horizon and that the heat flow value of 1.23 μcal/cm^2 sec obtained for this interval is not regionally representative.

Bullard [1939] suggested a method for determining heat flow in holes where the thermal conductivity is a rapidly changing function of depth. The heat flow q is the slope of the straight line in the equation

$$T_z = T_0 + q \sum_i (D_i/K_i) \qquad (1)$$

where T_z is the temperature at depth z, $z = \sum_i D_i$, K_i, is the thermal conductivity of the ith lithologic unit of thickness D_i, and T_0 is the temperature at the top of the lithologic section, which is composed of i lithologic units. The method is most reliable where core recovery is continuous and continuous temperature profiles are obtained. Although the sampling of core from hole 190 and the temperature log do not meet these conditions, the method was used to estimate a heat flow value from hole 190. Table 3 lists the temperatures and thermal conductivities used in the Bullard approximation. Figure 3 is plot of (1). The slope of this line is the heat flow. The least squares heat flow with standard deviation is 1.99 ± 0.02 μcal/cm^2 sec. This result may be biased toward sandstone intervals, however, since core samples of sandstone were more available. The value is probably too high. If only the data from the depth interval 175–213 meters, a predominantly sandstone interval, are used, the heat flow obtained by the Bullard approximation is 1.57 ± 0.07 μcal/cm^2 sec. The best estimate of the heat flow in the Grundy area is 1.70 ± 0.34 μcal/cm^2 sec based on averaging Bullard approximations and products of average gradient and thermal conductivities listed in Table 1.

TABLE 3. Temperatures and Thermal Conductivities Used to Determine Heat Flow in Hole 190 by the Bullard Approximation

Depth, meters	Temperature, °C	Thermal Conductivity, mcal/cm sec °C
167.64	16.787	
171.30		6.42
175.26	17.014	
178.90		10.92
182.88	17.143	
186.50		9.15
190.50	17.295	
194.20		10.35
198.12	17.400	
201.80		11.21
205.74	17.527	
209.40		5.00
213.36	17.708	
221.30		9.18
228.60	18.117	
233.80		10.37
243.84	18.453	
264.30		9.66
274.32	19.152	
285.60		13.90
289.56	19.417	
293.00		10.89
304.80	19.581	
323.00		9.82
335.28	20.293	
346.60		8.40
350.52	20.669	
358.00		12.52
365.76	20.845	
373.00		9.46
381.00	21.200	
399.9		6.63
411.48	21.964	

Elevations on the Grundy, Virginia, 7½-minute quadrangle sheet vary from 365 to 710 meters above sea level. Local relief is of the order of 100 meters. Steady state corrections to the gradient were made by following the method described by *Birch* [1950] for topography within a square grid 32 km on a side centered over the hole. In all cases the corrections were <2%.

Discussion

The first heat flow determinations in southwestern Virginia show significant differences between the folded Valley and Ridge province and the Appalachian Plateau province. Figure 4 shows the heat flow measurements published to date in Virginia. Our values are in agreement with those (corrected for Pleistocene climatic variations) that *Diment et al.* [1972, Figure 5] have predicted for southwestern Virginia; however, we feel that heat flow determinations made in carbonate rocks within which the groundwater flow regime is unknown may be subject to some uncertainty. More determinations are needed to substantiate the low heat flow anomaly in the southeastern part of the United States shown by the data thus far.

The Appalachian tectonic province shows a pattern of negative isostatic anomalies flanked by positive anomalies. A similar anomaly pattern in the Alps is associated with change in crustal composition and mean values of crustal velocity [*Woollard,* 1972]; however, the crust is thickest beneath the Valley and Ridge province and the southern part of the Blue Ridge province [*James et al.,* 1968] where the heat flow and the gravity are both low [*Diment et al.,* 1972]. Several explanations can be suggested

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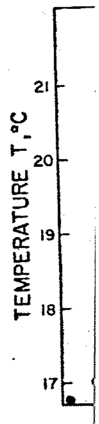

Fig. 3. Temperature

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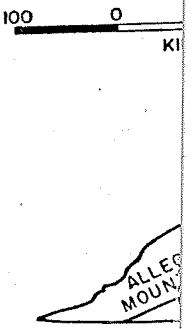

Fig. 4. Heat flow
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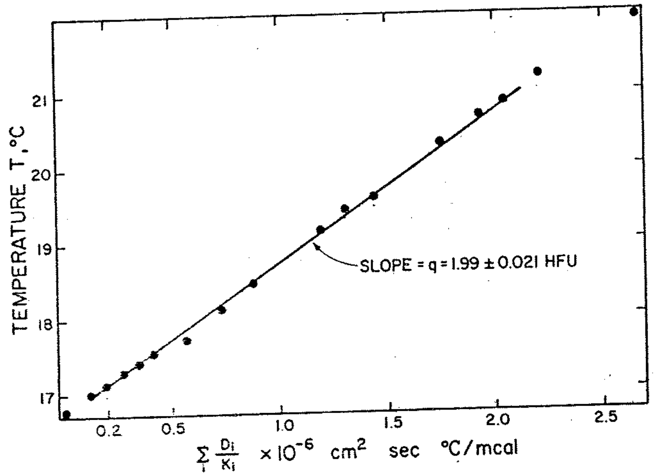

Fig. 3. Temperature versus $\Sigma D_i/K_i$ for hole 190, Grundy, Virginia. The slope of this line is the heat flow.

for this anomaly. *Birch et al.* [1968] found anomalously low heat flow values associated with Precambrian anorthosites. As was suggested by *Diment et al.* [1972], if the low values in the folded southern Appalachians are also the result of anorthosite in the buried Precambrian, low heat flow would probably not be continuous over large regions; however, heat flow data are sparse in the eastern United States, with the exception of New England, and further study might well show a series of isolated lows of limited extent. *Diment et al.* [1972] also suggest a steady state model requiring a thin eroded Precambrian crust in the vicinity of the heat flow low where gravity and seismic data indicate that the crust is thickest. There are at least 10 km of Paleozoic sediments where the crust is thickest. Diment et al. suggest that a radioactive part of the Precambrian crust has been eroded and replaced by less radioactive carbonate sediments. The dolomite in this carbonate section is of high density, and such an interpretation in this area might preclude the observed large negative gravity anomalies over the southern Appalachians.

We investigated a third possibility that the large-scale late Paleozoic thrusting found in the southern Appalachians might have decreased the regional geothermal gradient and resulted in nonequilibrium heat flow values. Large-scale thrusting in the southern Appalachians is well accepted [*King*, 1964; *Bryant and Reed*, 1962]. Only the magnitude of the displacement is in dispute. Various estimates of the displacement

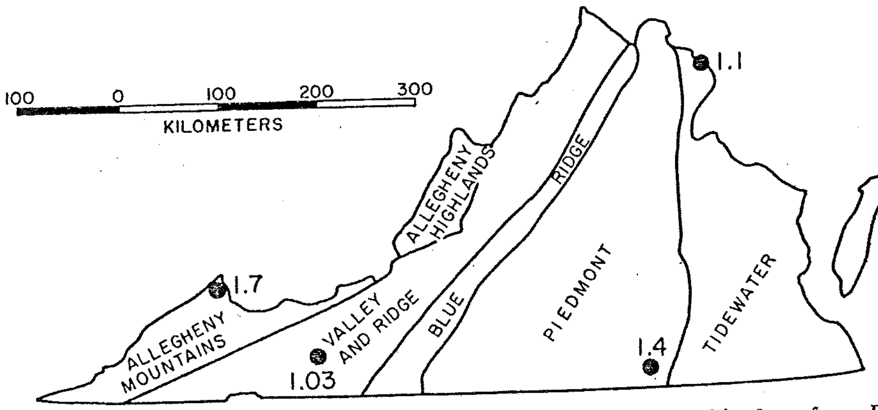

Fig. 4. Heat flow measurements in Virginia. Values of 1.4 and 1.1 μcal/cm² sec from *Diment et al.* [1965*a*] and *Diment and Werre* [1964], respectively.

range from 30 [*Rankin,* 1970] to 130 km [*Griscom,* 1962]. If the low heat flow were associated with overthrusting, then, south of Roanoke, Virginia, where the southern Appalachians begin, the low heat flow anomaly should be continuous over large areas. If the low heat flow is associated with anorthosite intrusions in a buried Precambrian basement, one would expect a series of isolated lows. We examined several one-dimensional models of a repeated gradient as a first approximation to an overthrust block. Constant diffusivities from 0.005 to 0.02 cm²/sec, initial gradients from 25° to 40°C/km, and constant thermal conductivities from 4 to 6 mcal/cm sec °C were used in a finite-difference model of a 17-km plate thrust over another 17-km plate. At time zero the initial gradient in the upper plate was repeated in the lower one. The boundary condition imposed at the base of the lower plate was that of constant heat flow equal to the initial heat flow before thrusting. In all cases essentially equilibrium gradients were reached before 100 m.y. after the thrusting. For a diffusivity of 0.005 cm²/sec, a thermal conductivity of 4 mcal/cm sec °C, and an equilibrium gradient of 40°C/km the gradient in the upper part of the overthrust plate was about 39°C/km after 80 m.y. It does not appear possible to attribute the observed low heat flow to nonequilibrium conditions associated with overthrusting; however, this explanation may be valid in other areas of more recent tectonic activity. Longer times to equilibrium might be obtained by using a more realistic model with a diffusivity that varies with time. The rate of diagenesis of sediments might be decreased if a former subduction zone with attendant lower geothermal gradients were present. It is unlikely that any model would be as much as 20% from its equilibrium value after about 250 m.y. Large-scale refraction effects might be important in this part of the Appalachians and might partially explain both the low value of 1.03 and the high value of 1.7 μcal/cm² sec. Seismic studies now in progress will help to define a model to evaluate these effects.

Further heat flow determinations in the southern Appalachians are needed to explain the magnitude and distribution of the low heat flow anomaly. On the basis of the data now available we prefer the interpretation that the low heat flow at Cripple Creek is the result of erosion of the upper crust and the removal of heat-producing elements before deposition of late Precambrian and Early Cambrian sediments.

Near Alberta, Virginia, *Diment et al.* [1965*a*] determined a heat flow value of 1.4 μcal/cm² sec uncorrected for Pleistocene climatic variations and a value of 1.6 μcal/cm² sec corrected for climatic variations [*Diment et al.,* 1972]. We have no further heat flow values from this part of Virginia; however, facilities for determining the amount of uranium, thorium, and potassium in rocks using γ ray spectroscopy have recently been completed at Virginia Polytechnic Institute and State University. From a quarry at Dolphin, 9 km from Alberta, the heat production from granitic (Petersburg granite) rocks is 11.2×10^{-13} cal/cm³ sec. The relationship between surface heat flow q and surface heat generation A in the eastern United States has been given as [*Roy et al.,* 1968] $q = 0.79 + 7.5A$. A surface heat generation of 11.2×10^{-13} cal/cm³ sec would therefore predict a heat flow of 1.6 μcal/cm² sec. The heat generation from granite collected from quarries near Trego, Virginia, 15 km from Alberta, predicts a surface heat flow of 1.4 μcal/cm² sec. The results from analyses of heat generation in rocks therefore substantiate the higher value of 1.4 μcal/cm² sec [*Diment et al.,* 1965*a*] for this part of the Piedmont. Additional results of the surface heat generation are in preparation for publication.

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