# NEW HEAT FLOW VALUES FROM VIRGINIA

by

Lawrence Dunnington Perry

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APPROVED:

J.K. Costain
J.K. Costain, Chairman

E.S. Robinson
E.S. Robinson

Lynn Glover, III
Lynn Glover III

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Blacksburg, Virginia

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# INTRODUCTION

Heat flow values have been determined from three geologic provinces in western Virginia: the Alleghany Plateau, the Valley and Ridge, and the Blue Ridge, as shown in Figure 1. The Alleghany Plateau is deeply eroded and is characterized by nearly horizontal strata of Pennsylvanian age. It is bounded on the southeast by the northeast trending Valley and Ridge Province, composed of folded and faulted Paleozoic sediments. The Blue Ridge Province bordering the southeast edge of the Valley and Ridge is composed of Precambrian rocks which in places have been thrust over the Paleozoic rocks of the Valley and Ridge province.

The heat flux near Vansant, Virginia (37°12'N, 82°06'W) in the Plateau Province was obtained from a hole drilled into sandstones and shales of Pennsylvanian age. This value is near the previous value obtained by Reiter and Costain (1973).

A heat flow value was determined in Bath County at Hot Springs, Virginia (38°00'N, 79°50'W) in the Valley and Ridge Province from limestones of Middle and Late Ordovician age. The hole was near several warm springs with temperatures which range from 35°C to 40°C (Reeves, 1932) and from which the town of Hot Springs derives its name. A second heat flow value in Bath County was determined from four holes (38°14'N, 79°49'W) 26 kilometers north of Hot Springs and near the Virginia-West Virginia line. The holes were drilled into shales and sandstones of the Chemung Formation of Devonian age.

A heat flow value was obtained at Poor Mountain, Virginia (37°02'N

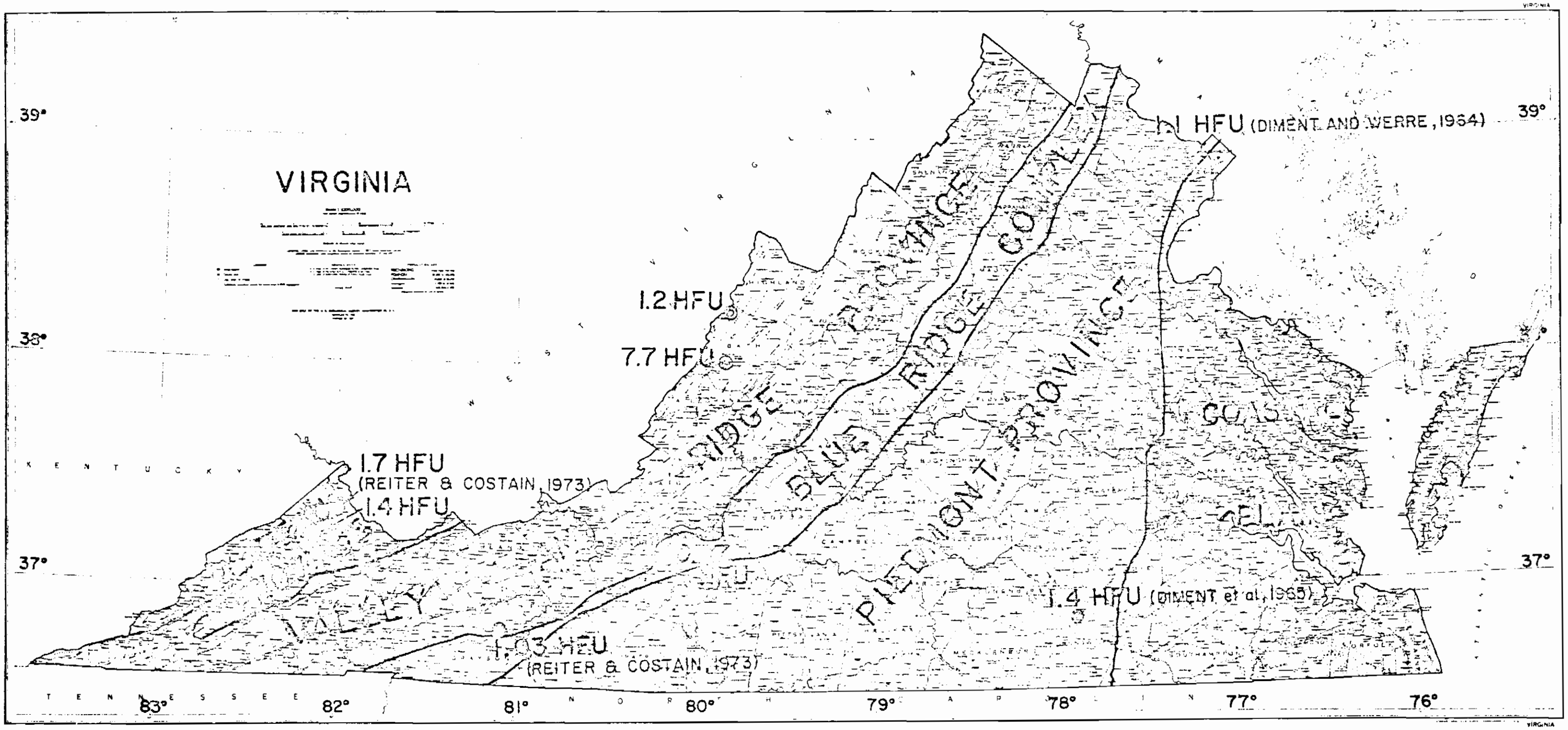

Figure 1. Geologic provinces and heat flow values in Virginia.

80°12'W) in the Blue Ridge Province from three holes drilled into the Precambrian granite gneiss of the Virginia Blue Ridge Complex.

## Previous Work in Virginia

Four values have been published to date for the heat flux in Virginia. Reiter and Costain (1973) reported values of 1.7 and 1.03 $\mu cal/cm^2$-sec for the Plateau Province at Grundy, Virginia, and the Valley and Ridge Province at Cripple Creek, Virginia, respectively. Diment et al. (1965) reported a value of 1.4 $\mu cal/cm^2$-sec (1.6 $\mu cal/cm^2$-sec when corrected for Pleistocene climatic variations (Diment et al. 1972)) for the Piedmont Province near Alberta, Virginia and Reiter and Costain (1973) found a heat generation of 11.2 x $10^{-13}$ $cal/cm^3$-sec near the location of this heat flow value. These values of heat flow and heat production are compatible with the linear relationship between heat flow and heat production, $q = 0.79 + 7.5 A$, proposed by Roy et al., (1968) for the eastern United States. Diment and Werre (1964) give a value of 1.1 $\mu cal/cm^2$-sec for the heat flux near Washington, D.C.

## MEASUREMENT OF TEMPERATURE

Temperature measurements were made with a Fenwal Oceanographic thermistor probe. A Honeywell Mueller bridge, Model 1551-E and Honeywell D.C. microvolt null detector, Model 3972 were used to measure the resistance of the probe which was balanced by Electro Scientific Model SR1 standard resistors, accurate to ±0.001%.

During the two years of the study the probe and bridge were checked at the ice point of distilled water in a Rosemont Model 911 ice bath. The probe resistance deviated from the nominal value of 11,400 ohms by only 10 ohms, equivalent to a temperature deviation of 0.02 °C.

The accuracy of the temperature measurements is approximately ±0.05 °C. The precision is considerably better and is approximately ±0.005 °C.

## MEASUREMENT OF THERMAL CONDUCTIVITY

Core was available from all of the holes except HSVA-1 at Hot Springs, Virginia, where surface samples were collected. Each sample was machined to a right circular cylinder with a diameter of approximately 4.76 cm and a thickness of 2.540 cm ±0.008 cm. All porous samples were saturated with distilled water by flooding the sample while in a vacuum of 0.001 bar or less and then placing it in a pressure cell in distilled water under pressure in excess of 25 bars. Several non-porous samples of carbonates were exempted from this procedure.

A divided bar apparatus was used to determine the thermal conductivity. The average temperature of the sample was the same temperature as the average temperature in the hole. A 10°C temperature gradient was imposed across the stack by two Lauda K2/R refrigerating circulating baths. The actual temperature gradient measured across the fused quartz standards and the sample combined was between 9°C and 10°C depending on the ambient room temperature. Axial pressures in excess of 70 bars and either silicone heat sink compound or vaseline petroleum jelly were used to reduce contact resistance in the stack. No significant difference was observed between the jelly and the heat sink compound.

A Leeds and Northrup Type K-3 potentiometer was used to measure the voltage difference across the copper-constantan thermocouples in the stack to ±0.5 μV, corresponding to a temperature difference of approximately 0.013 °C.

## Vansant, Virginia

Hole IC-225 near Vansant, Virginia, in Buchanan County is located at approximately 37°12'N and 82°06'W and was logged for temperature to a depth of 409 m. The temperature-depth profile is shown in Figure 2 and other pertinent information in Table 1. The hole was drilled into horizontal strata of Early Pennsylvanian age consisting of alternating shales and sandstones with a few thin coal seams. This alternating lithology is clearly reflected in the changes in the slope of the temperature-depth profile in Figure 2.

Three intervals, two shale and one sandstone, were judged suitable for the determination of the heat flux. The temperature gradient over each interval was determined by the least-squares fit of a straight line. The upper shale interval from 190 m to 230 m depth has a gradient and standard deviation of 24.49 ± 0.87 °C/km based on five points. A lower shale interval from 330 m to 360 m has a gradient of 26.89 ± 0.80 °C/km based on four points. Other shale intervals in the hole appear to have approximately the same gradient but are not defined by a sufficient number of points to warrant a gradient determination. The gradient determined for the intermediate sandstone interval (250 m to 280 m) is 9.11 ± 0.50 °C/km and is based on four points.

Thermal conductivities were determined from twenty-one core samples. Eleven shale samples have an average conductivity and standard deviation of 5.25 ± 0.65 mcal/cm-sec-°C. One sample of shale containing a large proportion of coal had a conductivity of 1.74 mcal/cm-sec-°C and was excluded from the above average since it repre-

Table 1. Summary of heat flow data.

| Locality | Location | meters | Elevation, meters | Gradient$^{\varepsilon}$ and standard deviation °C/km | Thermal Conductivity$^{\varepsilon}$,K, and standard deviation, mcal/cm-sec-°C | Heat Flow$^{\delta}$, µcal/cm$^{2}$-sec |
|---|---|---|---|---|---|---|
| Vansant | | | | | | |
| IC-225 | 37°12'N<br>82°06'W | 498 | 190 to 230 | 24.49 ± 0.87(5) | 5.86 ± 0.46(2) | 1.4 ± 0.2 |
| | | | 190 to 230 | 24.49 ± 0.87(5) | 5.25 ± 0.65(11)$^{\alpha}$ | 1.3 ± 0.2 |
| | | | 250 to 280 | 9.11 ± 0.50(4) | 15.88(1) | 1.4 ± 0.1 |
| | | | 250 to 280 | 9.11 ± 0.50(4) | 14.29 ± 1.28(4)$^{\beta}$ | 1.3 ± 0.2 |
| | | | 330 to 360 | 26.89 ± 0.80(4) | 6.93 ± 2.00(2) | 1.9 ± 0.6 |
| | | | 330 to 360 | 26.89 ± 0.80(4) | 5.25 ± 0.65(11)$^{\alpha}$ | 1.4 ± 0.2 |
| | Best value for Vansant | | | | | 1.4 ± 0.1 |
| Back Creek | | | | | | |
| HU-19 | 38°14'N,<br>79°49'W | 1127 | 220 to 315 | 8.47 ± 0.08(24)$^{\zeta}$ | 9.40 ± 1.76(24) | 0.8 ± 0.2 |
| | | | 320 to 480 | 12.92 ± 0.07(32) | 9.75 ± 1.47(27) | 1.3 ± 0.2 |
| | | 1031 | 250 to 375 | 13.79 ± 0.12(26) | 8.94 ± 1.95(4) | 1.2 ± 0.3 |
| | | | 395 to 460 | 13.55 ± 0.13(14)$^{\zeta}$ | 6.89 ± 0.92(8) | 0.9 ± 0.10 |
| | | | 250 to 460 | 14.14 ± 0.06(43) | 7.63 ± 1.75(15) | 1.1 ± 0.3 |
| HU-25 | | 954 | 135 to 305 | 17.67 ± 0.07(35) | 9.06 ± 2.40(11) | 1.6 ± 0.4 |
| | | | 330 to 395 | 15.09 ± 0.06(14) | 7.26 ± 0.76(2) | 1.1 ± 0.02 |
| | | | 135 to 395 | 17.34 ± 0.07(53) | 8.78 ± 2.32(13) | 1.5 ± 0.4 |

## Table 1. Continued.

| Locality | Location | Elevation, meters | Depth Interval, meters | Gradient[ε] and standard deviation °C/km | Thermal Conductivity[ε], K, and standard deviation, mcal/cm-sec-°C | Heat Flow,δ μcal/cm$^2$-sec |
|---|---|---|---|---|---|---|
| Back Creek (cont.) | | | | | | |
| B-115 | 38°14'N<br>79°49'W | 1064 | 160 to 315 | 7.13 ± 0.09(32)ζ | 7.89 ± 2.56(25) | 0.6 ± 0.2 |
| | | | 340 to 450 | 16.52 ± 0.01(15)ζ | 9.69 ± 0.80(4) | 1.6 ± 0.1 |
| | | | 480 to 545 | 14.41 ± 0.15(10) | 8.48 ± 1.27(12) | 1.2 ± 0.2 |
| | Best value for Back Creek | | | | | 1.2 ± 0.1 |
| Hot Springs | | | | | | |
| HSVA-1 | 38°00'N<br>79°50'W | 762 | 120 to 145 | 94.05 ± 0.86(11) | 7.55 ± 0.42(8) | 7.2 ± 0.4 |
| | | | 148 to 185 | 107.54 ± 0.49(16) | 7.55 ± 0.42(8) | 8.2 ± 0.5 |
| Poor Mountain | | | | | | |
| V-105 | 37°02'N<br>80°12'W | 183 | 96 to 181 | 10.31 ± 0.07(10) | 7.89 ± 0.42(8) | 0.81 ± 0.05 |
| V-106 | | 366 | 216 to 266 | 10.51 ± 0.10(6) | 9.11 ± 0.62(12) | 0.96 ± 0.07 |
| | | | 326 to 356 | 10.30 ± 0.17(4) | 8.48 ± 1.21(3) | 0.87 ± 0.14 |
| V-107 | | 178 | 56 to 96 | 10.00 ± 0.0001(4) | 8.53 ± 0.70(4) | 0.85 ± 0.07 |
| | Best value for Poor Mountain | | | | | 0.87 ± 0.07 |

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α average thermal conductivity of all the shale samples in the hole

β average thermal conductivity of the more nearly pure quartz sandstone samples

ζ gradient disturbed by groundwater flow into the hole

δ see text for values corrected for topographic evolution

ε parentheses contain the number of points from which the value is determined

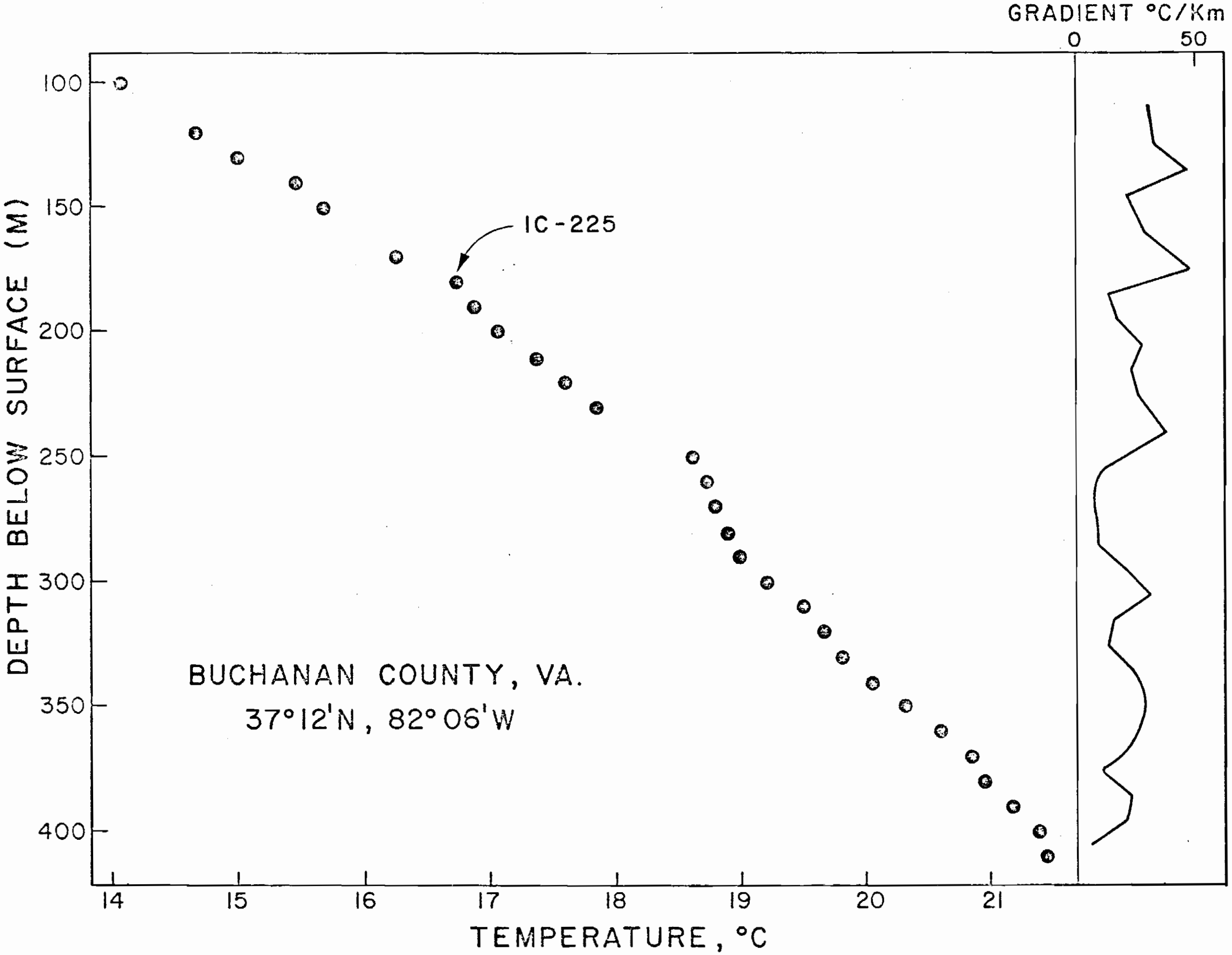

Figure 2. Temperature versus depth profile and geothermal gradient curve for hole IC-225 near Vansant, Virginia.

Table 2. Thermal conductivity values from hole IC-225,Vansant,Virginia

| Depth, m | K, $\frac{\text{mcal}}{\text{cm-sec-°C}}$ | Lithology |
|---|---|---|
| 65.0 | 10.48 | micaceous lithic sandstone |
| 107.0 | 4.42 | carbonaceous shale |
| 126.5 | 1.74 | very carbonaceous shale |
| 137.5 | 10.18 | micaceous lithic sandstone |
| 141.0 | 5.69 | interbedded mudstone with sandstone |
| 153.3 | 5.66 | interbedded mudstone with sandstone |
| 159.0 | 4.30 | carbonaceous shale |
| 170.0 | 9.75 | micaceous lithic sandstone |
| 178.0 | 11.28 | micaceous lithic sandstone |
| 191.0 | 6.18 | interbedded mudstone with sandstone |
| 203.0 | 5.53 | carbonaceous shale |
| 239.0 | 14.13 | quartz sandstone |
| 262.0 | 15.88 | quartz sandstone |
| 299.0 | 5.14 | interbedded mudstone with sandstone |
| 300.0 | 4.48 | carbonaceous shale |
| 308.0 | 14.37 | quartz sandstone |
| 311.0 | 5.35 | interbedded mudstone with sandstone |
| 330.0 | 4.93 | carbonaceous shale |
| 338.0 | 8.93 | micaceous lithic sandstone |
| 367.0 | 12.76 | quartz sandstone |
| 377.0 | 6.05 | carbonaceous shale |

sents only a small fraction of the section logged and broke when removed from the divided bar. The nine remaining sandstone samples were of a lithic quartz arenite with an average conductivity of 11.94 ± 2.44 mcal/cm-sec-°C. The sandstone samples may be divided into two groups on the basis of their lithology. One group of four samples having an average conductivity of 14.29 ± 1.28 mcal/cm-sec-°C consists of light grey to white, fine-grained, well-sorted quartz sandstone with little other material. The second group of five samples has an average conductivity of 10.07 ± 0.91 mcal/cm-sec-°C and is distinguished by a darker, medium grey color, larger grain size (up to 1 mm) and a larger percentage of material other than quartz which accounts for the lower conductivity.

Heat flux values for each interval were obtained by multiplying the gradient observed over the interval by the thermal conductivity representative of the interval. For the upper shale interval (190 m to 230 m) two samples have an average conductivity of 5.86 ± 0.46 mcal/cm-sec-°C which gives a heat flux of 1.4 ± 0.2 HFU (1 HFU = 1 heat flow unit = $10^{-6}$ μcal/$cm^2$-sec). Other determinations are listed in Table 1. The method suggested by Bullard (1939) was employed over the interval from 120 m to 230 m and gave a value of 1.5 ± 0.76 HFU. This interval includes the upper shale. For an interval including both the sandstone and lower shale (250 m to 400 m) the Bullard heat flow approximation is 1.3 ± 0.04 HFU. It is felt that the best value for this hole is 1.4 ± 0.1 HFU since the average of three intervals involving two distinct lithologies gives that value.

Steady state corrections to the gradient to account for the evolution of topography made by Reiter and Costain (1973) in the same general area and following the method described by Birch (1950) amounted to less than 2%.

Reiter and Costain (1973) obtained a value of 1.7 ± 0.3 HFU for this area; however, their value is probably too high as a result of inadequate sampling of shale. The new value of 1.4 ± 0.1 HFU is considered to be regionally representative of the area.

## Bath County, Virginia

*Back Creek*. Four holes, HU-19, HU-21, HU-25, and B-115, near Back Creek in Bath County, Virginia, located at approximately 38°14'N latitude and 79°49'W longitude were logged for temperature to depths of 560 m, 505 m, 410 m, and 545 m, respectively. All were drilled into shales and sandstones of the Brallier Formation of Devonian age. The holes are on the western limb of an anticline which is nearly overturned to the west. Temperature and gradient profiles are shown in Figure 3 and other information is given in Table 1.

In Hole HU-19 a temperature gradient of 12.92 ± 0.07 °C/km was obtained from thirty-two points over the depth interval from 320 m to 480 m. Twenty-seven samples of core from the same interval have a mean thermal conductivity of 9.75 ± 1.47 mcal/cm-sec-°C which gives a heat flux of 1.3 ± 0.2 HFU. The changes in the gradient in other parts of the hole, for example at 480 m, are attributed to water passing across the hole along permeable fracture zones. The smaller changes occurring throughout the hole are caused by the differences in the thermal conductivities of the shales and sandstones.

In Hole HU-21 the depth interval from 250 m to 375 m has a gradient of 13.79 ± 0.12 °C/km determined from twenty-six points, and an average thermal conductivity of 8.94 ± 1.95 mcal/cm-sec-°C from four samples taken from core over the same interval. The heat flux is 1.2 ± 0.3 mcal/cm-sec-°C. The average thermal conductivity may be overly influenced by the inclusion of a sandstone sample with a thermal con-

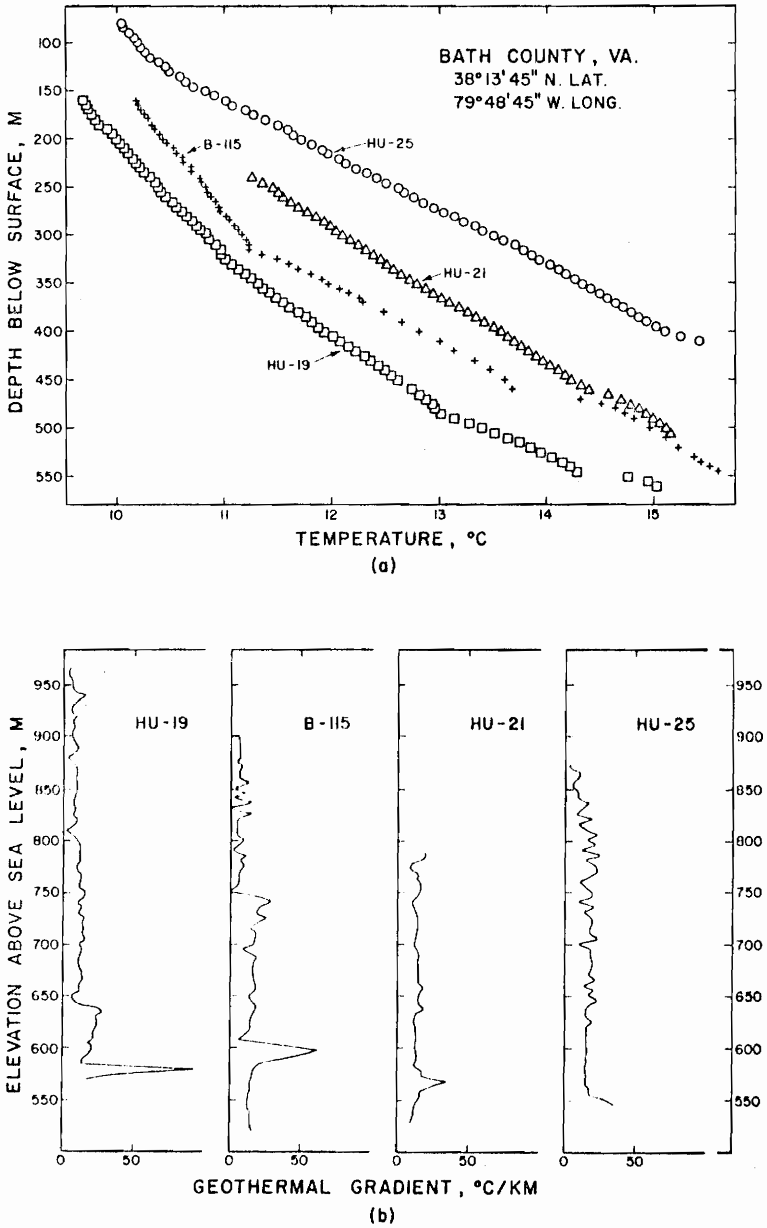

Figure 3. Temperature and depth profiles (a) and geothermal gradient curves (b) for holes HU-19, HU-21, HU-25, and B-115 in the Back Creek area of Virginia.

Table 3. Thermal conductivity values from Back Creek, Virginia

HU-19

| Depth, m | K, mcal/cm-sec-°C | Lithology |
|---|---|---|
| 200.6 | 8.66 | siltstone |
| 201.6 | 10.92 | mudstone |
| 204.4 | 7.02 | mudstone |
| 206.5 | 8.37 | mudstone |
| 208.2 | 8.65 | siltstone |
| 212.9 | 10.62 | siltstone |
| 219.8 | 8.38 | mudstone |
| 221.3 | 7.36 | mudstone |
| 224.9 | 7.99 | mudstone |
| 227.5 | 8.60 | mudstone |
| 237.4 | 10.52 | mudstone |
| 244.4 | 8.25 | mudstone |
| 247.2 | 12.26 | mudstone |
| 252.4 | 8.85 | mudstone |
| 256.0 | 9.90 | mudstone |
| 258.2 | 8.82 | siltstone |
| 260.6 | 12.17 | mudstone |
| 262.1 | 10.68 | siltstone |
| 289.9 | 7.71 | siltstone |
| 290.0 | 6.96 | mudstone |
| 295.0 | 8.63 | mudstone |
| 301.6 | 7.66 | mudstone |
| 306.5 | 10.30 | siltstone |

Table 3. Cont. HU-19

| Depth, m | K, mcal/cm-sec-°C | Lithology |
|---|---|---|
| 307.2 | 12.39 | sandstone |
| 308.2 | 12.80 | sandstone |
| 315.5 | 13.44 | sandstone |
| 316.4 | 11.08 | sandstone |
| 320.2 | 11.58 | sandstone |
| 334.4 | 10.15 | siltstone |
| 341.4 | 7.60 | mudstone |
| 343.4 | 9.90 | siltstone |
| 355.7 | 7.83 | mudstone |
| 363.8 | 9.54 | mudstone |
| 367.3 | 7.10 | mudstone |
| 369.1 | 11.28 | siltstone |
| 382.2 | 7.26 | mudstone |
| 388.2 | 9.27 | siltstone |
| 394.7 | 10.80 | mudstone |
| 405.1 | 11.92 | mudstone |
| 408.1 | 9.66 | mudstone |
| 411.5 | 10.47 | mudstone |
| 419.7 | 9.07 | mudstone |
| 422.1 | 11.65 | siltstone |
| 423.4 | 11.97 | mudstone |
| 429.2 | 8.41 | fossiliferous mudstone (A) |
|  | 9.42 | mudstone (B) |
| 430.7 | 7.98 | mudstone |
| 449.7 | 9.48 | mudstone |
| 452.3 | 9.69 | mudstone |

Table 3. Cont.

HU-19

| Depth, m | K, cal/cm-sec-°C | Lithology |
|---|---|---|
| 459.9 | 10.89 | mudstone |
| 463.0 | 8.18 | mudstone |
| 467.3 | 10.32 | siltstone |
| 470.3 | 10.24 | mudstone |
| 474.9 | 11.68 | mudstone |
| 483.4 | 8.50 | mudstone |
| 484.9 | 11.68 | mudstone |
| 489.5 | 7.61 | mudstone |
| 493.5 | 8.60 | mudstone |

Table 3. Cont.

HU-21

| Depth, m | K, mcal/cm-sec-°C | Lithology |
|---|---|---|
| 297.5 | 6.25 | mudstone |
| 319.1 | 12.02 | mudstone |
| 322.5 | 7.13 | mudstone |
| 347.5 | 8.90 | mudstone |
| 377.4 | 7.41 | mudstone |
| 387.4 | 6.98 | mudstone |
| 392.6 | 10.60 | siltstone |
| 402.6 | 7.72 | mudstone |
| 417.6 | 7.11 | mudstone |
| 422.5 | 5.90 | mudstone |
| 432.5 | 5.59 | mudstone |
| 437.7 | 6.72 | mudstone |
| 442.9 | 7.15 | mudstone |
| 452.6 | 8.41 | mudstone |
| 457.5 | 6.49 | mudstone |
| 472.4 | 7.00 | mudstone |
| 483.4 | 5.89 | mudstone |
| 487.4 | 8.81 | mudstone |
| 493.2 | 5.76 | mudstone |
| 493.2 | 10.81 | mudstone |
| 497.4 | 7.11 | mudstone |
| 502.6 | 5.85 | mudstone |

Table 3. Cont. HU-25

| Depth, m | K, mcal/cm-sec-°C | Lithology |
|---|---|---|
| 200.3 | 10.19 | siltstone |
| 207.9 | 11.27 | siltstone |
| 223.1 | 8.24 | mudstone |
| 227.1 | 11.62 | mudstone |
| 250.0 | 6.63 | mudstone |
| 257.9 | 8.14 | mudstone |
| 261.2 | 5.09 | mudstone |
| 270.4 | 6.90 | mudstone |
| 280.0 | 12.18 | mudstone |
| 285.6 | 7.82 | mudstone |
| 288.6 | 11.50 | siltstone |
| 346.6 | 6.51 | mudstone |
| 410.9 | 8.02 | mudstone |

Table 3. Cont. B-115

| Depth, m | K, mcal/cm-sec-°C | Lithology |
|---|---|---|
| 162.2 | 5.71 | mudstone |
| 167.6 | 5.03 | mudstone |
| 171.9 | 6.42 | mudstone |
| 177.7 | 8.74 | siltstone |
| 178.3 | 5.69 | mudstone(red) |
| 181.1 | 12.08 | mudstone |
| 187.1 | 9.23 | mudstone(red) |
| 191.7 | 6.52 | mudstone(red) |
| 197.2 | 10.29 | siltstone |
| 207.0 | 7.49 | siltstone |
| 212.1 | 5.68 | mudstone(red) |
| 222.2 | 4.26 | mudstone |
| 226.8 | 12.82 | sandstone |
| 232.3 | 6.68 | siltstone |
| 238.0 | 10.14 | fine sandstone |
| 252.4 | 7.28 | siltstone |
| 257.3 | 8.00 | siltstone |
| 267.0 | 8.12 | mudstone |
| 272.2 | 9.59 | siltstone |
| 277.1 | 4.50 | mudstone |
| 287.7 | 11.26 | siltstone |
| 292.3 | 6.15 | mudstone |
| 297.2 | 6.16 | mudstone |
| 301.5 | 12.83 | siltstone |
| 302.1 | 6.98 | mudstone |
| 366.1 | 9.63 | siltstone |

Table 3. Cont.

B-115

| | | |
|---|---|---|
| 396.2 | 9.95 | siltstone |
| 426.7 | 8.65 | siltstone |
| 459.6 | 10.55 | siltstone |
| 487.7 | 7.09 | mudstone |
| 487.7 | 8.32 | mudstone |
| 487.7 | 9.54 | mudstone |
| 492.9 | 9.02 | mudstone |
| 496.5 | 6.32 | mudstone |
| 506.6 | 6.19 | mudstone |
| 513.3 | 9.55 | mudstone |
| 516.6 | 8.48 | mudstone |
| 523.0 | 9.73 | siltstone |
| 532.2 | 8.70 | mudstone |
| 537.4 | 9.55 | mudstone |
| 542.2 | 7.46 | mudstone |
| 542.2 | 9.62 | mudstone |

ductivity of 12.02 mcal/cm-sec-°C. The average thermal conductivity excluding that sample is 7.42 ± 1.11 mcal/cm-sec-°C and gives a heat flux of 1.0 ± 0.3 HFU. The interval from 395 m to 460 m has a gradient of 13.55 ± 0.13 °C/km based on fourteen points and an average thermal conductivity of 6.89 ± 0.92 mcal/cm-sec-°C from eight samples which gives a heat flux of 0.9 ± 0.1 HFU. The gradient in this interval may be too low due to water moving through the hole near the bottom of the interval. The interval from 250 m to 460 m including both the previous intervals has a gradient of 14.14 ± 0.06 °C/km and an average thermal conductivity of 7.63 ± 1.75 mcal/cm-sec-°C determined from forty-three temperature-depth points and fifteen core samples. The heat flux is 1.1 ± 0.3 HFU. A heat flux of 1.1 ± 0.02 HFU was obtained from the depth interval from 375 m to 505 m using the Bullard heat flow approximation. Hole HU-21 was judged to be relatively free of circulating water except at a depth of 460 m.

Hole HU-25 is located near the floor of Little Back Creek valley whereas holes HU-19, HU-21 and B-115 are located on the adjacent ridge of Little Mountain. This topographic position affects the gradient since isotherms are compressed under valleys. The gradient for Hole HU-25 in the depth interval from 135 m to 305 m is 17.67 ± 0.07 °C/km determined from thirty-five points. The average thermal conductivity from eleven core samples is 9.06 ± 2.40 mcal/cm-sec-°C, giving a heat flux of 1.6 ± 0.4 HFU. In the bottom of the hole between 330 m and 395 m a gradient of 15.09 ± 0.06 °C/km is obtained from fourteen points which combined with an average thermal conductivity of 7.26 ±

Table 4. Topographic evolution corrections to the geothermal gradients of the Back Creek holes.

| Hole | Interval | Observed gradient, °C/km | Steady state gradient, °C/km | Case I w/uplift | Case I w/o uplift | Case II w/uplift | Case II w/o uplift |
|---|---|---|---|---|---|---|---|
| B-115 | 480-545 | 14.41 ± 0.06 | 14.82 ± 0.15 | 14.65 ± 0.15 | 14.59 ± 0.14 | 14.40 ± 0.15 | 14.26 ± 0.14 |
| HU-19 | 320-480 | 12.92 ± 0.07 | 13.42 ± 0.08 | 13.25 ± 0.07 | 13.22 ± 0.07 | 13.00 ± 0.07 | 12.94 ± 0.07 |
| HU-21 | 240-460 | 14.14 ± 0.06 | 14.71 ± 0.07 | 14.54 ± 0.07 | 14.47 ± 0.07 | 14.28 ± 0.07 | 14.14 ± 0.07 |
| HU-25 | 320-395 | 15.09 ± 0.06 | 15.27 ± 0.08 | 15.10 ± 0.08 | 15.03 ± 0.07 | 14.85 ± 0.08 | 14.69 ± 0.07 |
| HU-25 | 140-305 | 17.69 ± 0.07 | 17.13 ± 0.07 | 16.95 ± 0.07 | 16.85 ± 0.07 | 16.71 ± 0.07 | 16.46 ± 0.06 |

Errors are standard errors

0.76 mcal/cm-sec-°C from two samples gives 1.1 ± 0.02 HFU for the heat flux.

The profile of Hole B-115 suggests water moving across the hole at depths of 315 m (750 m above sea level) and 460 m (600 m above sea level). The only interval judged suitable for a reliable gradient is between 480 m and 545 m. The gradient obtained from ten points is 14.41 ± 0.06 °C/km and the average thermal conductivity is 8.48 ± 1.27 mcal/cm-sec-°C based on twelve samples. The heat flux is 1.2 ± 0.2 HFU.

Corrections for the evolution of topography were applied to each of the holes according to the method described by Birch (1950). Three cases were considered. The steady state case assumes no erosion in $10^5$ million years (m.y.). Case I assumes 2.5 km of erosion in 150 m.y. and Case II assumes 3 km of erosion in 50 m.y. All cases assume no uplift, a thermal diffusivity of 0.020 $cm^2$/sec and an atmospheric temperature gradient of 6 °C/km.

Case II is justified on the basis of recent work at VPI & SU by Hall (1975) who argues that igneous intrusions in Highland County adjacent to the area of the holes in this study and intruded into rocks of Devonian age were emplaced at a depth of approximately 3 km. The intrusions have been dated as approximately 47 m.y. old.

Case I evolves from a discussion with Dr. C.E. Sears who believes deposition in the area ended with the lower Pennsylvanian and amounted to no more than 2.5 km above the exposed Devonian formations. Results of the corrections are shown in Table 4. The negative corrections for HU-25 lend support to the idea that as a result of the lower topographic position of the hole the heat flux in the upper interval is too high and that the best value is obtained from the lower interval.

Excluding the value from the upper interval of HU-25 the average heat flux for the area is 1.2 ± 0.10 HFU, which is not changed significantly by a steady state topographic correction.

*Hot Springs, Virginia.* Hole HSVA-1 was drilled as a water well at Hot Springs, Virginia, and was logged to a depth of 225 m. No core was taken from the hole and cuttings were not available; however, the entire hole was drilled in limestone and dolomite ( personal communication, R.S. Rogers, Chief Engineer, Virginia Hot Springs, Inc.) of Early and Middle Ordovician age. The lack of core from the hole for thermal conductivity determinations precluded the determination of a reliable heat flux value, but the location of the hole near four unusual geological and geophysical phenomena was thought to be sufficient reason to proceed with conductivity values from surface samples. The well is less than 1 km from thermal springs which flow at the surface at a maximum temperature of 41 °C. The hole is also within the region known as the Schooley erosion surface, within 25 km of a local simple Bouguer anomaly of -80 mgals, and less than 50 km from the site of intrusives of Eocene age in Highland county ( Dennison and Johnson, 1971 )

The temperature and gradient profiles of the hole, Figure 4, show that the adjacent thermal springs are having some effect on the gradient since the temperatures in the bottom of the hole are approaching those of the thermal springs and the gradient is increasing.

Two temperature gradients were determined from the hole. The upper portion of the hole to a depth of 145 m has a gradient of 94.05 °C ± 0.86 °C/km and the intermediate interval between 147.5 m and 185 m has a gradient of 107.58 ± 0.49 °C/km. Below 200 m the gradient increases rapidly to 200 °C/km near the bottom of the hole.

Five bulk specimens of limestone were collected in the vicinity

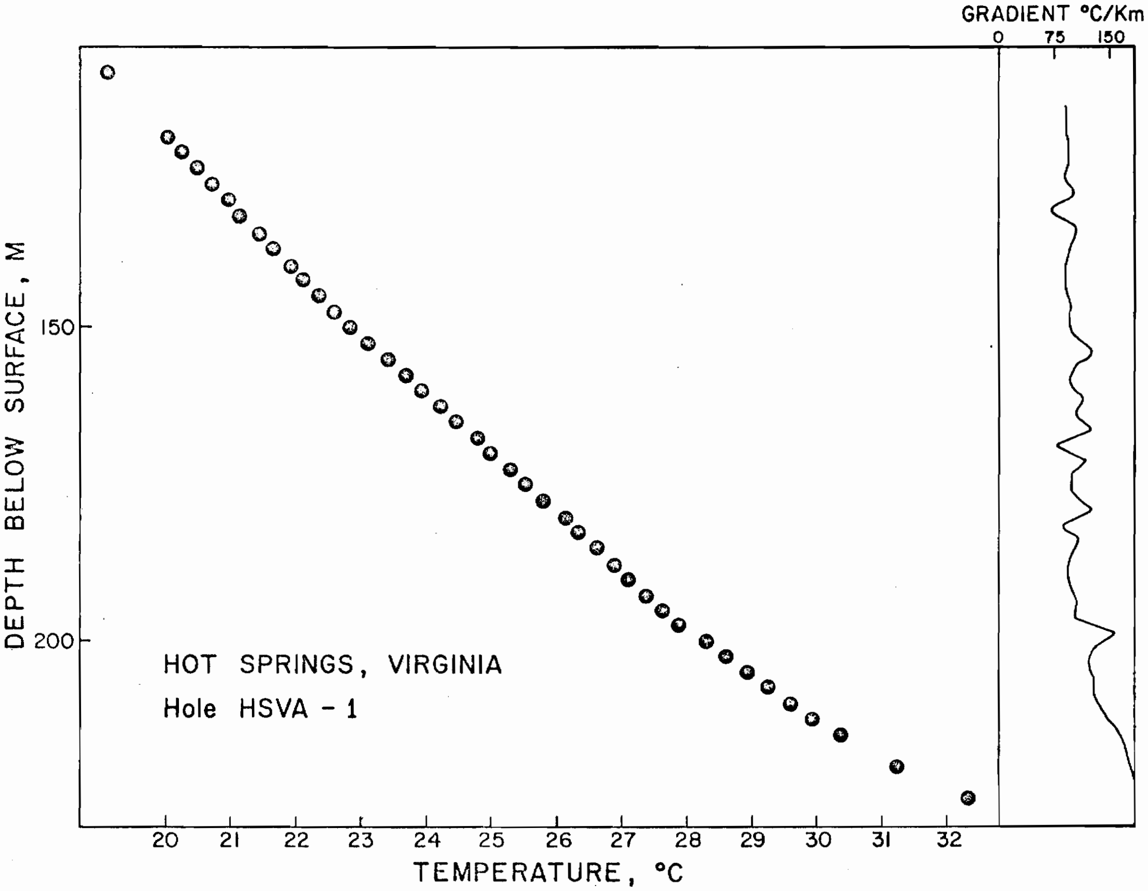

Figure 4. Temperature versus depth profile and geothermal gradient curve for hole HSVA-1 in Hot Springs, Virginia.

Table 5. Thermal conductivity values from Hot Springs, Virginia

HSVA-1

| Sample Number | K,mcal/cm-sec-°C | Lithology |
|---|---|---|
| HS-1 | 7.54 | limestone |
| HS-2A | 7.62 | limestone |
| HS-2B | 7.08 | limestone |
| HS-3 | 6.83 | limestone |
| HS-4A | 7.85 | limestone |
| HS-4B | 7.58 | limestone |
| HS-6A | 8.05 | limestone |
| HS-6B | 7.96 | limestone |

of the well and eight samples were prepared from them. Their mean thermal conductivity value is 7.55 ± 0.42 mcal/cm-sec-°C with extreme values of 6.8 mcal/cm-sec-°C and 8.0 mcal/cm-sec-°C.

The heat flux using the above gradients and mean thermal conductivity value is 7.2 ± 0.4 HFU for the upper part of the hole and 8.2 ± 0.5 HFU for the lower part without additional heat flow values. The average for the hole, 7.7 HFU, should not be regarded as an acceptable regional heat flow value due to the anomalous nature of the site.

Reeves (1932) suggested the temperature of the warm springs in the area was a result of meteoric water circulating to depths sufficient to raise its temperature in the presence of the normal geothermal gradient and then rising rapidly to the surface. Sufficient heat might be brought to the surface to account for the temperature observed.

The average geothermal gradient 26 km to the north at Back Creek is approximately 14 °C/km. Thus, water would have to circulate to a depth of only approximately 2.5 km to be heated to a temperature in excess of the temperature observed at the surface. Since the sedimentary section in the area is greater than 4 km thick, deep circulation completely within the sedimentary section is possible. Studies are in progress at V.P.I. & S.U. to evaluate a model of deep meteoric circulation as a possible explanation of the warm spring waters.

The temperature of water flowing along a fracture as a function of position, the temperature of injection, mass flow rate, time, and thermal diffusivity is given by Bodvarsson (1969) as

$$T = T_o \operatorname{erfc}((\alpha x+y)/2(\kappa t)^{1/2})$$

where $t$ = the time since the beginning of flow in the fracture

$x$ = the distance along the fracture in the direction of flow

$y$ = the distance perpendicular to the fracture

$T$ = the temperature of the fluid at the point $(x,y)$ after time, $t$

$T_o$ = the temperature of the fluid entering the fracture

$\kappa$ = the thermal diffusivity of the rock

$\alpha$ = $2k/sq$, where

$k$ = thermal conductivity of the rock

$s$ = specific heat of the fluid

$q$ = mass flow rate of the fluid per unit length of the fracture

For values of $y = 0$, $k = 9.0$ mcal/cm-sec-°C, $\kappa = 0.01$ cm$^2$/sec, $S = 1.0$ cal/gm-°C and $q = 0.189$ gm/cm-sec and for the values of $x$ and $t$ shown in Table 6, one may compute the ratios, $T/T_o$, shown in Table 6. The value of $q$ is obtained by assuming that the springs at Hot Springs which produce 300 gallons per minute (Reeves, 1932) are fed from a northwest-trending cross fault one kilometer long which crosses the northwest vertical limb of the northeast-trending doubly-plunging Warm Springs anticline. The majority of warm springs in the valley are grouped near fractures of this type. The fractures are simple cross faults (DeSitter, 1956, p. 207) which arise from tensional stress within a steeply dipping plate of extremely resistant Tuscarrora Quartzite in the northwest limb of the doubly-plunging anticline. The limited data available preclude realistic estimates of the vertical extent of the fractures; however, the proximity of each group of warm springs to a cross fault suggests that the faults play an important role in the occurrence of the springs.

Table 6. Values of $T/T_0$ for different values of time, t, in fractures with different dips.

| | x and dip angles for different fracture planes | | | |
|---|---|---|---|---|
| Time, m.y. | 2.5 km, 90° | 3.54 km, 45° | 5.0 km, 30° | 9.66 km, 15° |
| 100 | 0.99 | 0.99 | 0.99 | 0.99 |
| 10 | 0.99 | 0.99 | 0.98 | 0.97 |
| 0.1 | 0.92 | 0.89 | 0.85 | 0.71 |

The four values of x correspond to a fracture dipping at 90°, 45°, 30° and 15° and extending to a depth of 2.5 km. The significance of the high values of $T/T_o$ for all cases considered is that for any reasonable assumption regarding the length of time that circulation has been in effect, the water retains a significant proportion of its original heat. On the basis of the values in Table 6, a model envolving deep circulation does not seem unreasonable.

The model is improved by the additional consideration of a cooling radioactive pluton which would raise the temperature at depth. Jaeger (1965) gives the temperature in a buried cooling spherical pluton as:

$$\begin{aligned} T(r,t) = \frac{T_o}{2}[&\mathrm{erf}((r/a+1)/2(\kappa t/a^2)^{1/2}) \\ &- \mathrm{erf}((r/a-1)/2(\kappa t/a^2)^{1/2}) \\ &- \exp(-(r/a+1)^2/4(\kappa t/a^2)))] \end{aligned}$$

where r = the distance from the center of the pluton

a = the radius of the pluton

$\kappa$ = the thermal diffusivity of the intruded rock

t = the time since intrusion

$T_o$ = the original temperature of intrusion

Calculations for values of $T_o$ = 1200°C, t = 47 m.y., $\kappa$ = 0.01 $cm^2/sec$, and a = 5.0 km indicate that there is essentially no influence remaining from the original temperature of the intrusion. However, the contribution of the heat generation within the pluton due to U and Th is significant and is given by Schlicter (1941) as:

$$\begin{aligned} T(r,t) = \frac{2H_o a^3}{kr\pi^4} \sum_{n=1}^{\infty} \frac{-1^{n+1}}{n^4} &\{\sin(n\pi\frac{h}{a}) + n\pi(1-\frac{h}{a}) \\ &\cos(n\pi\frac{h}{a})\}\sin(n\pi\frac{r}{a})(1 - \exp(-\frac{n^2\pi^2\kappa t}{a^2})) \end{aligned}$$

where

$h = d - a$

$d$ = the depth to the center of the pluton

$H_o$ = the heat generation within the pluton, and all other symbols are defined as before.

Results of the above equations indicate that for the same values of $k$ and $\kappa$ used previously, a time of 47 m.y., a pluton with a radius of 15 km with its top at a depth of 4.8 km and with heat production of 10 to 30 HGU, the temperature at depth can be raised significantly, thus requiring shallower circulation. For example, for 10 HGU the temperature at a depth of 3 km is raised approximately 11°C, and for 20 HGU it is raised approximately 23°C. Other values for a smaller pluton are given in Table 7.

Although the geometry for which the above equation applies is not precisely that for which it has been used, the results shown in Table 7 are not unreasonable.

Table 7. Temperature increases from radiogenic heat production

| Radius of Pluton, km | Depth to top of pluton, km | Heat generation, HGU | Temperature, $^{o}$C, increase at depth of 2 km | Temperature, $^{o}$C, increase at depth of 3 km |
|---|---|---|---|---|
| 5 | 4.8 | 10 | 1 | 2 |
| 5 | 4.8 | 20 | 2 | 4 |
| 5 | 4.8 | 30 | 4 | 6 |
| 15 | 4.8 | 10 | 7 | 11 |
| 15 | 4.8 | 20 | 14 | 23 |
| 15 | 4.8 | 30 | 21 | 34 |

## Poor Mountain, Virginia

Three holes were logged at Poor Mountain in Montgomery County, Virginia, (37°02'N, 80°12'N). Holes, V-105, V-106, and V-107 were drilled to depths of 181 m, 356 m and 176 m, respectively, into the Virginia Blue Ridge complex of Precambrian age. The Virginia Blue Ridge complex is made up of the Lovingston Formation (biotite granite, biotite gneiss and biotite-quartz monzonite), the Marshall Formation (biotite-quartz-feldspar granite, gneiss and quartz monzonite) and the Moneta gneiss (biotite-hornblende gneiss)(Millici et al, 1963) 95 km northeast of Poor Mountain. It has been thrust over the Chilhowee Group, Shady Dolomite and Rome Formation, all of Cambrian age. The magnitude of northwestward horizontal displacement may be as much as 150 km (Personal communication, L. Glover, III). Temperature profiles and gradients are shown in Figure 6; other pertinent information is listed in Table 1. Thermal conductivity of core samples is given in Table 11.

In Hole V-105 a temperature gradient of 10.31 ± 0.07 °C/km was obtained from 10 points over the depth interval from 96 m to 181 m. Eight samples of core from the same interval gave a mean thermal conductivity of 7.89 ± 0.42 mcal/cm-sec-°C resulting in a heat flux of 0.81 ± 0.05 HFU. The Bullard heat flow approximation for the same interval is 0.8 ± 0.004 HFU.

In Hole V-106, the depth interval from 216 m to 266 m has a gradient of 10.51 ± 0.10 °C/km based on six points, and an average thermal conductivity of 9.11 ± 0.62 mcal/cm-sec-°C from twelve samples

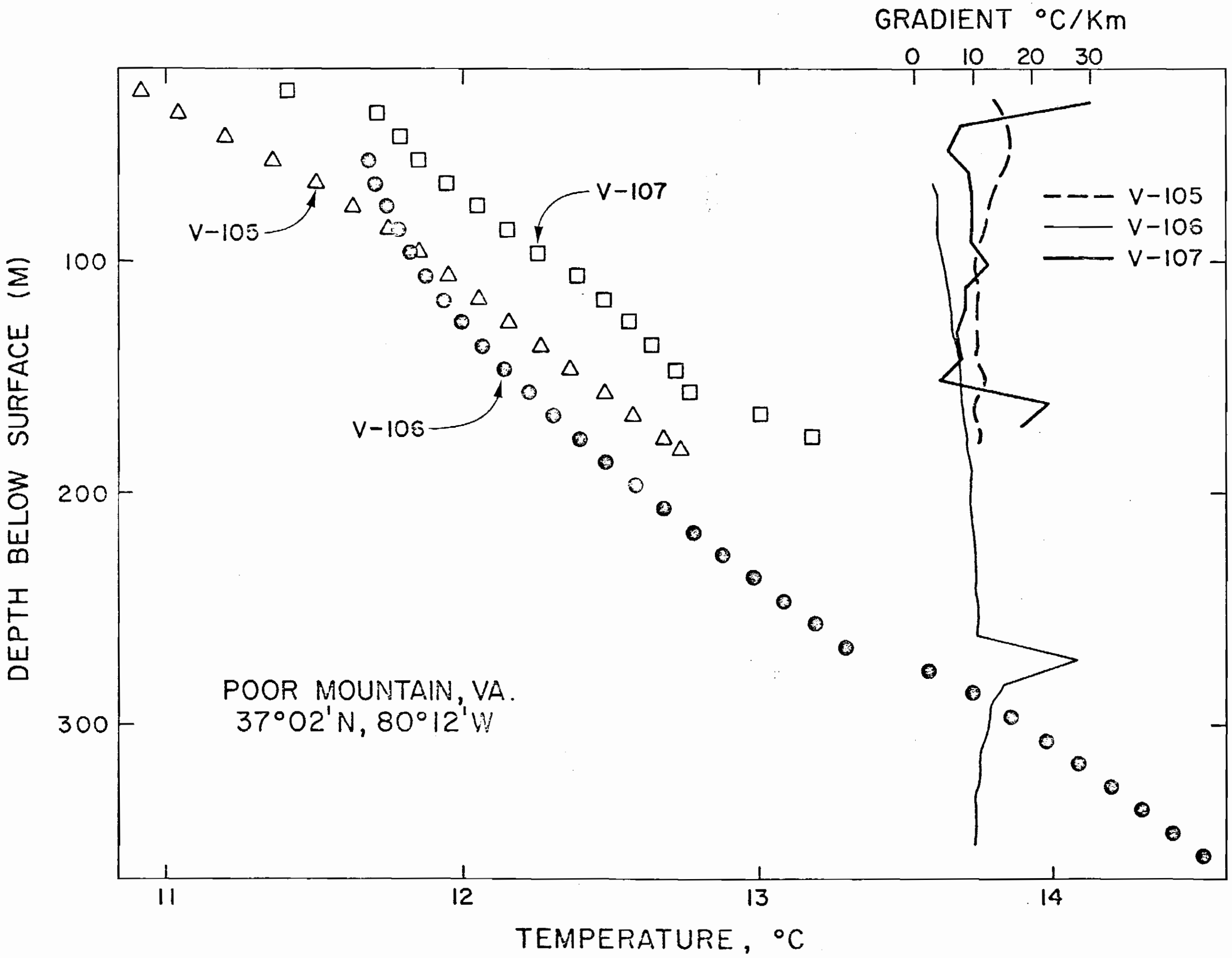

Figure 5. Temperature versus depth profiles and geothermal gradient curves for holes V-105, V-106, and V-107 at Poor Mountain, Virginia.

Table 8. Thermal conductivity values from Poor Mountain, Virginia.

V-105

| Depth, m | K, cm-sec-°C |
|---|---|
| 51.8 | 8.25 |
| 56.4 | 8.40 |
| 117.0 | 8.26 |
| 122.6 | 8.08 |
| 131.1 | 7.75 |
| 137.2 | 7.99 |
| 143.0 | 6.98 |
| 162.2 | 8.34 |
| 174.0 | 7.80 |
| 180.1 | 7.93 |

Table 8. Cont.

V-106

| Depth, m | K, cm-sec-°C |
|---|---|
| 116.1 | 8.47 |
| 118.9 | 10.28 |
| 122.8 | 9.94 |
| 216.4 | 7.40 |
| 221.0 | 8.80 |
| 225.2 | 9.72 |
| 226.8 | 9.05 |
| 230.7 | 9.77 |
| 234.7 | 10.04 |
| 237.4 | 8.27 |
| 240.2 | 9.06 |
| 250.5 | 9.64 |
| 253.3 | 9.90 |
| 255.7 | 9.79 |
| 267.0 | 7.91 |
| 328.9 | 9.87 |
| 338.0 | 8.72 |
| 341.4 | 7.55 |
| 344.4 | 8.17 |
| 347.5 | 7.58 |
| 350.2 | 7.37 |

Table 8. Cont.

V-107

| Depth, m | K, cm-sec-°C |
|---|---|
| 61.0 | 8.44 |
| 68.0 | 8.37 |
| 79.9 | 9.49 |
| 88.1 | 7.80 |

taken from each 10-meter interval between 216 m and 256 m and two Bullard heat flow approximations obtained by using first the lower value of all the intervals and then the higher. The values obtained are 0.92 ± 0.02 HFU and 1.00 ± 0.02 HFU respectively. A second depth interval in V-106 from 326 m to 356 m was found to have an average thermal conductivity of 8.48 ± 1.21 mcal/cm-sec-°C based on three samples and a temperature gradient based on four points of 10.30 ± 0.17 °C/km which gives a value of 0.87 ± 0.14 HFU for the heat flux.

Hole V-107 was samples over the interval from 56 m to 96 m depth. The four samples have an average thermal conductivity of 8.53 ± 0.70 mcal/cm-sec-°C, which in conjunction with a measured gradient of 10.0 ± 0.0001 °C/km gives a heat flux value of 0.85 ± 0.07 HFU. The average of the four values obtained from the three holes is 0.87 ± 0.07 HFU and is considered the best regional value.

Steady state corrections for the evolution of topography surrounding the Poor Mountain holes were -1.6% for Hole V-105, -1.2% for both intervals in Hole V-106 and -0.9% for Hole V-107.

No heat generation values are available for rocks from the Blue Ridge. Since the holes are drilled into an overthrust crystalline basement complex, meaningful correlation of heat flow with heat production at this site for the purpose of supporting a linear relationship is not possible. The observed value of 0.87 mcal/cm$^2$-sec is very close to the value of 0.79 mcal/cm$^2$-sec given by Roy et al (1968) for q* which implies that for some reason most of the heat producing elements normally found in the crust are missing. Lachenbruch (1970) suggests that the major proportions of heat producing elements are concentrated in a thickness of crust equal to 3D. Then for D equal to 7.5 km (Roy et al, 1968) the erosion of the autocthanous Precambrian basement may be as much as 20 km.

## Discussion

The value of 1.4 HFU reported for the Plateau Province of Virginia is felt to be a reliable regional value.

In the Back Creek area of Bath County the value of 1.2 HFU is also considered a good regional value. The value is appropriate for its location on the west side of the heat flow trough proposed by Diment, et al (1972). The value of 7.7 HFU at Hot Springs, Virginia is not acceptable by itself as a regional value without further verification by additional holes. A model of deep circulation of meteoric water appears to adequately explain the high temperatures observed. Such a model is enhanced by the consideration of a cooling radioactive pluton which raises temperatures at depth, primarily by the presence of U and Th rather than the residual temperature of intrusion, thus requiring shallower circulation than would otherwise be required.

The low value of 0.87 HFU obtained at Poor Mountain in the Blue Ridge certainly supports the heat flow low described by Diment, et al (1972). Whether the low value represents extensive erosion on the Precambrian crust, (Reiter and Costain, 1973) impoverishment of U and Th during metamorphism to granulite facies, (Lambert and Hieir, 1967) the presence of concealed anorthosites (Diment et al, 1972) such as the Roseland anorthosite 125 km to the northeast, or some other unknown effect must await more dense distribution of heat flow values.

# References

Birch, F., The Effects of Pleistocene Climatic Variations on Geothermal Gradients, Amer. J. Sci., 246, 729, 1948.

Birch, F., Flow of Heat in the Front Range, Colorado, Geol. Soc. Amer. Bull., 61, 567, 1950.

Bodvarsson, G., On the Temperature of Water Flowing Through Fractures, J. Geophys. Res., 74, 1987, 1969.

Bullard, E.C., Heat Flow in South Africa, Proc. Roy. Soc. London, A, 173, 474, 1939.

Dennison, J.J. and R.W. Johnson, Jr., Tertiary Intrusions and Associated Phenomena near the Thirty-Eigth Parallel Fracture Zone in Virginia and West Virginia, Geol. Soc. Amer. Bull., 82, 501, 1971.

Diment, W.H. and R.W. Werre, Terrestrial Heat Flow near Washington, D.C., J. Geophys. Res., 69, 2143, 1964.

Diment, W.H., R. Raspet, M.A. Mayhew, and R.W. Werre, Terrestrial Heat Flow near Alberta, Virginia, J. Geophys. Res., 70, 923, 1965.

Diment, W.H., T.C. Urban, and F.A. Revetta, Some Geophysical Anomalies in the Eastern United States, in the Nature of the Solid Earth, edited by E.C. Robertson, p. 544, McGraw-Hill, New York, 1972.

De Sitter, L.U., Structural Geology, p. 207, McGraw-Hill, New York, 1956.

Hall, S.T.,Mineralogy, Chemistry, and Petrogenesis of some Hypabyssal Intrusions, Highland County, Virginia, M.S. Thesis, Virginia Polytechnic Institute and State University, 1975.

Jaeger, J.C., Thermal Effects of Intrusions, Rev. of Geop., 2, 443, 1964.

Lachenbruch, A.H., Preliminary geothermal model of the Sierra Nevada, J. Geophys. Res., 73, 6977, 1968.

Lachenbruch, A.H., Crustal Temperature and Heat Production: Implications of the Linear Heat-Flow Relationship, J. Geophys. Res., 75, 3291. 1970.

Lambert, I.B. and K.S. Hieir, The Vertical Distribution of Uranium, Thorium and Potassium in the Continental Crust, Geochemica at Cosmochimica Acta, 31, 377, 1967.

Millici, R.C., C.T. Spiker, and J.M. Wilson, Geologic Map of Virginia, edited by J.L. Calver and C.R.B. Hobbs, Virginia Division of Mineral Resources, 1963.

Morgan, B.A., Metamorphic Map of the Appalachians, U.S. Geological Survey, Miscellaneous Geologic Investigations, Map I-724, 1972.

Rankin, D.W., Stratigraphy and Structure of Precambrain Rocks in North Western North Carolina, in Studies of Appalachian Geology: Central and Southern, edited by G.W. Fisher, F.J. Pettijohn, J.C. Reed, Jr. and K.N. Weaver, p. 227, Interscience, New York, 1970.

Reeves, F., Thermal Springs of Virginia, Va. Geol. Sur. Bull., 36, 1932.

Reiter, M.A. and J.K. Costain, Heat Flow in Southwestern Virginia, J. Geophys. Res., 78, 1323, 1973.

Roy, R.F., D.D. Blackwell, and F. Birch, Heat Generation of Plutonic Rocks and Continental Heat Flow Provinces, Earth and Planetary Science Letters, 5, 1, 1968.

Schlicter, L.B., Cooling of the Earth, Geol. Soc. Amer. Bull., 52, 561, 1941.

# VITA

| | |
|---|---|
| Name | Lawrence Dunnington Perry |
| Birthdate | 27 December, 1947 |
| Elementary School | Oak Grove Elementary School<br>Oak Grove, Virginia |
| High School | Washington and Lee High School<br>Montross, Virginia |
| University | Virginia Polytechnic Institute and State University<br>Blacksburg, Virginia<br>1966 - 1968, 1970 - 1975 |
| Degree | B.S., Geophysics<br>Virginia Polytechnic Institute and State University<br>Blacksburg, Virginia, 1973 |
| Scholarships | Economic Opportunity Grant, 1966-1968<br>Graduate Teaching Assistantship, 1973-1975<br>Graduate Research Assistantship, 1975 |

Lawrence D Perry

# New Heat Flow Values From Virginia

by

Lawrence Dunnington Perry

## Abstract

Nine holes in the Blue Ridge, Valley and Ridge, and Alleghaney Plateau Provinces of Virginia provide heat flow values of 0.87 ± 0.07 mcal/cm$^2$-sec, 7.7 ± 0.5 mcal/cm$^2$-sec, 1.2 ± 0.1 mcal/cm$^2$-sec and 1.4 ± 0.1 mcal/cm$^2$-sec at Poor Mountain (37°02'N, 80°12'W), Hot Springs (38°00'N, 79°50'W), Back Creek (38°14'N, 79°49'W) and Vansant (37°12'N, 82°06'W) respectively. The value of 0.87 mcal/cm$^2$-sec agrees with Diment's Central Region for the eastern United States. Limited data support a model of moderately deep circulation of meteoric water possibly coupled with the heat generation of buried plutonic rocks to explain the origin of the hot springs in Hot Springs, Virginia.