GL03461

UNIVERSITY OF UTAH
RESEARCH INSTITUTE
EARTH SCIENCE LAB.

VOL. 78, NO. 35 JOURNAL OF GEOPHYSICAL RESEARCH DECEMBER 10, 1973

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Heat Flow at Spor Mountain, Jordan Valley, Bingham, and La Sal, Utah

JOHN K. COSTAIN

Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

P. M. WRIGHT

Kennecott Exploration Inc., Salt Lake City, Utah 84104

Geothermal gradients were obtained in drill holes in Utah at Spor Mountain, Enterprise, La Sal, Monticello, Bingham, and Jordan Valley. A heat flow of 3.0 ± 0.3 μcal/cm^2 sec was found at Spor Mountain (39°43'N, 113°13'W). The flux at Jordan Valley (40°47.0'N, 112°04.3'W) is estimated to be 1.8 ± 0.6 μcal/cm^2 sec. The revised heat flow at La Sal (38°14.3'N, 109°16.3'W) on the Colorado Plateau is 1.5 ± 0.2 μcal/cm^2 sec. The heat flow at Bingham (40°32'N, 112°09'W) is 2.3 ± 0.3 μcal/cm^2 sec. On the basis of much of the heat flow data now available for the Colorado Plateau, including our revised values at La Sal, there appears to be less justification for defining the Colorado Plateau as a separate heat flow province with abnormally low heat flow.

Temperatures were measured in drill holes at Spor Mountain, La Sal, Bingham, and Jordan Valley, Utah. Five drill holes were logged for temperature in the Enterprise area, and one hole near Monticello, San Juan County. In the Enterprise and Monticello areas the temperature gradients were disturbed by shallow groundwater circulation, and no further interpretation of the data from these holes was justified [*Wright*, 1966].

TEMPERATURE MEASUREMENTS

For the holes at Spor Mountain, Jordan Valley, and La Sal we used a platinum resistance thermometer, model 134HH, manufactured by Rosemount Engineering Company, with a nominal ice point resistance of 1000 ohms. A change in temperature of 0.01°C corresponds, for a 1000-ohm element, to a change in resistance of approximately 0.036 ohm. Any system used to measure resistance must be able to detect a change in resistance of this magnitude in order to resolve temperature changes as small as and smaller than 0.01°C. To measure temperature to an accuracy of ±0.01°C at, say, 50°C would require measuring the resistance of a probe whose nominal ice point resistance is 1000 ohms to an accuracy of 1197.38 ± 0.036 ohms, or to about 0.003%. The individual resistance bridge decades can be calibrated to this accuracy; however, because of the limited resistance range that will be encountered in the field by using a 1000-ohm platinum probe, about 390 ohms for the temperature range 0°–100°C, it is possible to compare the resistance of the probe with the constant resistance of an accurate primary standard for which the resistance is known to ±0.001%. For all of the holes except the one at Bingham we used a comparison bridge, model DBR-1, manufactured by the RdF Corporation, Hudson, New Hampshire. This bridge balances out most of the probe resistance with a primary standard resistance accurate to within ±0.001%. If the nominal resistance of the probe used was 1000, 2000, or 5000 ohms, then the resistance of the primary standard used was 1000.00 ± 0.01, 2000.00 ± 0.02, or 5000.00 ± 0.05 ohms, respectively. The standards were calibrated by the manufacturer, by a secondary standards laboratory, and by the National Bureau of Standards. The final bridge balance was achieved by using the Rubicon decade resistances in the bridge. We believe the accuracy of our temperature measurements with the 1000-ohm probe to be ±0.05°C and the precision to be ±0.01°C. The hole at Bing-

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ham was logged by using a 5000-ohm platinum resistance probe with a precision of about ±0.002°C.

A different apparatus was used at the Bingham hole, and we are now using a Honeywell 1551-E Mueller bridge in conjunction with Julie Research Laboratories and Electroscientific Industries SR-1 standard resistors, which are accurate to ±0.001%. A Honeywell 3972 dc microvolt null detector is used to balance the bridge. The Mueller bridge also provides for balancing out most of the resistance of the probe with an external primary standard resistance. As is true with the comparison bridge, final balance is achieved by using decades built into the bridge.

Most temperature measurements for terrestrial heat flow determinations are made by using thermistors, and here the suitability of platinum for temperature measurements in deep holes is discussed. We have consistently obtained excellent results using platinum. For example, periodic relogging of hole (B-1-2)28dcc-1 in Jordan Valley near Salt Lake City over a period of 2 years showed differences in absolute temperature at any given depth of no more than ±0.03°C, when probes of different nominal resistances made by different manufacturers were used. We obtained this accuracy for repeated measurements in every hole not disturbed by groundwater movement regardless of depth, using probes of nominal ice point resistances of 1000, 2000, and 5000 ohms. There are disadvantages to using platinum; bridge calibration and galvanometer sensitivity are more critical because of the lower resolution of platinum compared with that of thermistors, and, for the probes that we have been using, the time constants are longer. Repeated measurements in several holes confirm that the calibration curve for platinum may shift slightly but that it shifts parallel to itself and the shift can be determined by noting the change in the ice point resistance. The shift is apparently related to the amount and the type of mechanical shock received by the probe over the years. Over a period of 5 months the resistance of the 1000-ohm probe was found to increase by about 0.7 ohm, corresponding to an apparent temperature increase of about 0.2°C. This increase was generally small for any given field trip, and no change in ice point resistance was noted between field trips [*Wright*, 1966, pp. 130–131]. For short intervals in a drill hole the better resolution of thermistors is a definite advantage. Our original reason for using platinum was the better stability of platinum over thermistors; however, thermistor probes with excellent stability, such as the Fenwal oceanographic-type probes, are now available, and we have essentially shifted to thermistors for field measurements, making occasional checks by using a platinum probe. We have compared gradients obtained with a 5000-ohm platinum element with those obtained with a Fenwal oceanographic probe of about 11,000-ohm ice point resistance and about 4800 ohms at 20°C. The difference in the gradients over intervals of about 100 meters was less than 2%.

For the holes at Spor Mountain, Jordan Valley, and La Sal we used U.S. Steel Corporation 4-H-1 four-conductor double-armored Amergraph cable, which is a heavy cable with a resistance of about 15 ohms/1000 feet and a breaking strength of 7200 pounds. The leakage resistance of the Amergraph cable was always greater than 50 MΩ and usually greater than 100 MΩ. We have since changed to lighter more portable cables and are now using Mark Products WF-TQ-190 W/4 Penalastic-filled polyurethane cables. Four-conductor cables were used for all temperature measurements to minimize the effects of lead resistance.

DETERMINATION OF THERMAL CONDUCTIVITY

Of the several methods used to determine the thermal conductivity of rocks [*Beck*, 1965] the most common is the divided-bar apparatus described by *Birch* [1950]. The apparatus constructed by us was designed after that used in the Hoffman Laboratory at Harvard University.

Rock disks 2.22, 3.0, 3.31, and 3.62 cm in diameter were commercially prepared from rock samples. The surfaces of the disks were machined flat and parallel to ±0.0008 cm, diameters being uniform and accurate to ±1%. Copper-constantan thermocouples were inserted into copper disks to measure the temperature differences across fused quartz reference disks and across the rock specimen. Thermal resistance at the contacts between the disks was reduced by applying a thin layer of vaseline to the disk faces and by applying an axial pressure of at least 100 bars to the stack. In

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order to ensure axial heat flow and to minimize radial heat loss, the stack was insulated with a tight-fitting machined block of high-density polystyrene. A temperature differential of about 10°C was applied across the stack. Measurements of the emf across each quartz disk and across the rock specimen were made with a Leeds and Northrup K-3 potentiometer. The temperature difference across the stack was held constant by thermostatically controlled temperature baths.

Repeated measurements on the same low-porosity rock disk were almost always reproducible to within 2%. For some of the more porous disks it was found that a small amount of vaseline would soak into the rock during measurement. After the disk had been measured a few times, less vaseline would be absorbed. This caused the apparent rock conductivity to increase with successive measurements until the faces of the disks no longer absorbed vaseline. When this 'equilibrium' state was reached, the thermal conductivity rarely increased by more than 5%, and repeated measurements reproduced to within 2%. In order to prevent vaseline from being absorbed by the specimen, a thin foil of aluminum 0.00254 cm thick was bonded to the flat faces of some of the disks with epoxy cement. Curing of the epoxy was completed at room temperature under about 350 bars for at least 12 hours. This curing resulted in a good bond and a smooth mirrorlike disk face. Vaseline was used as a contact substance between these aluminum-surfaced disks and the copper disks of the stack. Measurements made in this manner were reproducible to about 0.5%. Several disks that had been measured without the aluminum foil coating were later surfaced as was described above. The thermal conductivity results were the same, within about 2%. Reproduction of measurements was also improved by cementing the copper disks to the quartz reference disks by using silver epoxy cement.

Reproducibility of measurement is not necessarily an indication that the measured value is correct. It is difficult to assign an absolute accuracy to the measurements. *Roy* [1963, p. 7] states that 'systematic and random errors in the measurement of a single disk amount to 5 percent.' It seems likely that this value would also apply to our conductivity apparatus.

If temperatures are measured in a water-filled drill hole, it is important to saturate the rock samples thoroughly before thermal conductivity determinations are made [*Birch and Clark*, 1940; *Walsh and Decker*, 1966]. This saturation was not done for the thermal conductivity measurements previously reported for La Sal, Utah [*Costain and Wright*, 1968]. Except for hole Bin-8-65, however, the temperature measurements were made in water-filled holes [*Wright*, 1966, p. 76]. The heat flow values for La Sal were therefore too low, and revised values are given herein. All rock samples, except as noted, were saturated with water while they were exposed to a vacuum of 5 μm. The samples were measured after soaking for several days.

Thermal conductivities reported herein were measured while the temperature of the sample was within 5°C of its in situ temperature. The stacks of the divided-bar apparatus were calibrated at the in situ temperature by replacing the rock samples with GE-101 fused quartz disks of the same size. The calibration thus included a correction for radial heat loss and contact resistance; i.e., the 'stack correction factor' required to make the measured conductivity equal to the known conductivity of fused quartz never exceeded 7% and was usually about 3%. The known thermal conductivity K of the fused quartz at a temperature of T°C was based on [*Ratcliffe*, 1959]

$$K = (3160 + 4.6T - 0.016T^2) \times 10^{-3} \text{ mcal/cm sec °C}$$

The thermal conductivities of several specimens were also measured by using crystalline quartz cut perpendicular to the optic axis. The results agreed with the conductivity values obtained by using fused quartz to within less than 3%.

RESULTS

Bingham, Utah. Hole D-142 at Bingham is located on the side of the Bingham Canyon copper mine (40°31'N, 112°09'W) at an elevation of 1963 meters above sea level. Temperatures were measured to a depth of 1200 meters. The temperature profile and gradient are shown in Figure 1. Table 1 summarizes straight-line least squares gradients in this hole for several intervals.

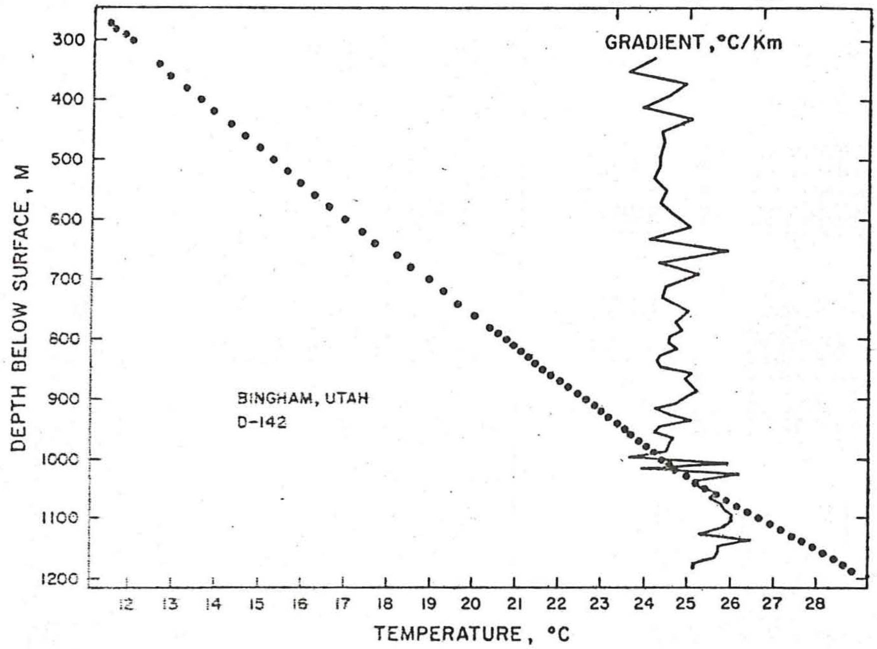

Fig. 1. Temperature profile in hole D-142, Bingham, Utah.

Since the Bingham hole is not included in *Wright* [1966], a few details concerning the terrain correction will be given here. The level of the bottom of the open-pit mine is approximately 1810 meters above sea level. The horizontal distance from the hole to the bottom of the mine is 1 km. Most of the peaks within 20 km of the hole have elevations between 2200 and 2700 meters above sea level. Nelson Peak, 2853 meters above sea level and about 9 km to the north, is the highest peak within a distance of 20 km from the hole. Terrain corrections to the geothermal gradient were calculated by using the method described by *Birch* [1950, pp. 582–600] and *Wright* [1966, pp. 149–178]. In order to examine the changes in the 'corrected' gradient for different assumptions about the physiographic history, corrections were calculated by assuming uplifts of from 0 to 4572 meters, evolution times of from 10 m.y. to infinity, and atmospheric temperature gradients of from −3°C/km to −6°C/km. Table 2 summarizes the results of the effects of different physiographic histories. The observed gradient for the depth interval 656–936 meters is 18.45° ± 0.25°C/km. The largest correction to the observed gradient is for short evolution times. For an evolution time of 10 m.y. the correction to the observed gradient, when no uplift and 4572 meters of uplift are assumed, is −9 and −15%, respectively, for an atmospheric gradient of −6°C/km. For an atmospheric gradient of −3°C/km the results are the same within about 3%. For longer evolution times the corrections are much smaller. Although the physiographic history of the region is not completely known, the effects of uplift and erosion for assumptions that probably bracket the correct physiographic history are shown in Table 2. When extreme conditions of 4572 meters of uplift and 10 m.y. of evolution time are assumed, the corrected gradient is only about 15% less than the observed gradient. For an infinite evolution time the corrected steady state gradient is 18.03° ± 0.074°C/km, or about −2% of the observed gradient. This value has been used for the corrected heat flow determinations given in Table 1.

The Bingham mine is centered on a small composite granite and granite porphyry stock that intrudes quartzites of lower Pennsylvanian age. Hole D-142 is drilled in quartzite to a depth of about 1036 meters, where it enters the stock. Associated dikes of quartz latite

TABLE 1. Summary of Gradients, Conductivities, and Heat Flow

Locality	Geographic Position	Elevation, meters	Depth Range, meters	K, mcal/cm sec °C*	Gradient, °C/km*	Uncorrected q, μcal/cm² sec	Corrected q, μcal/cm² sec
Bingham, D-142	40°32'N, 112°09'W	1963	576 to 886	13.25 ± 0.76 (15)¶	18.64 ± 0.3 (22)¶	2.47 ± 0.18	
			656 to 936	12.73 ± 0.98 (11)	18.45 ± 0.25 (23)	2.35 ± 0.21	2.30 ± 0.18
			1046 to 1156	9.08 ± 1.09 (4)†	24.77 ± 0.36 (12)	2.25 ± 0.31	

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Bingham, D-142	40°32'N, 112°09'W	1963	576 to 886	13.25 ± 0.76 (15)[¶]	18.64 ± 0.3 (22)[¶]	2.47 ± 0.18	
			656 to 936	12.73 ± 0.98 (11)	18.45 ± 0.25 (23)	2.35 ± 0.21	2.30 ± 0.18
			1046 to 1156	9.08 ± 1.09 (4)[†]	24.77 ± 0.36 (12)	2.25 ± 0.31	
			1046 to 1156	8.18 ± 0.87 (3)[§]	24.77 ± 0.36 (12)	2.03 ± 0.24	
Best value							2.3 ± 0.3
Jordan Valley, (B-1-2)28dcc-1	40°47'N, 112°04.3'W	1285	20 to 63	3.0 ± 1.0	58.72 ± 1.07 (9)	1.8 ± 0.6	1.8 ± 0.6
Spor Mountain							
103		1451	50 to 138	5.47 ± 0.14 (20)	58.48 ± 0.93 (10)	3.20 ± 0.13	
106		1451	30 to 152	5.47 ± 0.14 (20)	46.94 ± 0.51 (4)	2.57 ± 0.09	
110	39°43'N, 113°13'W	1462	30 to 131	5.26 ± 0.2 (8)	59.35 ± 0.70 (12)	3.12 ± 0.16	
110		1462	120 to 127	5.26 ± 0.2 (8)	55.0 ± 1.1 (3)	2.89 ± 0.17	
111		1448	50 to 130	5.47 ± 0.14 (20)	54.70 ± 0.56 (9)	2.99 ± 0.11	
113		1457	30 to 118	5.47 ± 0.14 (20)	57.95 ± 0.97 (10)	3.17 ± 0.3	
Best value (average of five holes)				5.47 ± 0.14 (20)	55.48 ± 0.73	3.0 ± 0.3	3.0 ± 0.3
La Sal							
HR-1-65	38°14.8'N, 109°17.4'W	2104	90 to 180	Mean Chinle conductivity = 8.61 ± 0.26 (8)	17.19 ± 0.19 (18)	1.48 ± 0.06	1.53 ± 0.07
HR-2-65	38°14.8'N, 109°17.4'W	2099	50 to 210		14.90 ± 0.96 (17)	1.28 ± 0.13	
HR-3-65	38°14.8'N, 109°17.4'W	2102	90 to 160		17.98 ± 0.23 (15)	1.55 ± 0.07	
HR-4-65	38°14.8'N, 109°17.4'W	2099	100 to 145		17.64 ± 0.33 (10)	1.52 ± 0.07	
Bin-10-65	38°16.3'N, 109°18.4'W	1981	130 to 170		21.90 ± 0.32 (5)	1.89 ± 0.15	
Bin-8-64	38°16.3'N, 109°18.4'W			11.9 ± 0.14 (4) (Wingate)	12.13 ± 0.79	1.44 ± 0.12	
Best value							1.5 ± 0.2

[*] Errors are standard errors. Gradients are straight-line least squares gradients.

[†] Samples of dike rock from depths of 676, 681, 752, and 853 meters.

[§] Samples of dike rock from depths of 676, 752, and 853 meters.

[¶] Number of temperature measurements or thermal conductivity determinations.

TABLE 2. Summary of Corrected Geothermal Gradients for Hole D-142, Bingham, for the Depth Interval 656 to 936 Meters

Evolution Time, m.y.	Amount of Uplift Assumed, meters	Corrected Gradient, °C/km
10	4572 (4572)	15.73 ± 0.066
	3048 (4572)	16.09 ± 0.066
	0 (4572)	16.80 ± 0.066
	3048 (3048)	16.73 ± 0.070
	1524 (3048)	17.10 ± 0.070
	0 (3048)	17.48 ± 0.070
100	4572 (4572)	17.25 ± 0.072
	3048 (4572)	17.37 ± 0.071
	0 (4572)	17.61 ± 0.071
	3048 (3048)	17.60 ± 0.073
	1524 (3048)	17.73 ± 0.073
	0 (3048)	17.85 ± 0.073

The collar elevation of the hole is 1963 meters, α = 6°C/km, the diffusivity is 0.02 cm^2/sec, the observed gradient is 18.45°C/km, and the steady state gradient (infinite evolution time) is 18.03 ± 0.074°C/km. Numbers in parentheses denote original elevation of uplifted surface.

porphyry and latite porphyry were emplaced last, crosscutting all other rocks [*James et al.*, 1961]. The granite has few feldspar phenocrysts and no quartz phenocrysts. Phenocrysts of feldspar make up about 50% of the granite porphyry and average 3.5 mm in length. Quartz phenocrysts are rare. The dikes of quartz latite porphyry contain feldspar phenocrysts, which make up about 35% of the rock and average 2.5 mm in length. Quartz phenocrysts, averaging 2 mm in diameter, make up 3% of the rock. The groundmass of the dikes is aphanitic. The latite porphyry contains no quartz phenocrysts and except for color is similar to the quartz latite porphyry in appearance. Since no samples of the stock below 1036 meters were available for thermal conductivity determinations, the thermal conductivity of the rock for the depth interval 1046–1156 meters was assumed to be approximately equal to that of the dikes cut by the hole above 1036 meters. The locations of the dikes in the hole were well defined by a gamma ray log run in hole D-142 to a depth of 841 meters by using a Well Reconnaissance Geo-Logger model 8036. The hole was blocked to this logging tool at 841 meters. The log was essentially featureless throughout the quartzites, but excellent response was obtained for dikes at depth intervals of 671–686 and 747–754 meters. At about 1036 meters the hole penetrated the main Bingham porphyry stock, within which the gradient is 24.77° ± 0.36°C/km. Samples of dike rock for thermal conductivity determinations were prepared from core taken from depths of 676, 681, 752, and 854 meters. The mean thermal conductivity and the standard error as determined from four saturated cylinders under a pressure of 100 bars were 9.08 ± 0.95 mcal/cm sec °C. The resulting heat flow within the stock is 2.25 μcal/cm^2 sec, there being a probable error of about 15% because of the assumption that the dike rock has approximately the same thermal conductivity as the main Bingham porphyry stock. In the depth interval 656–936 meters the mean of seven thermal conductivity determinations of the quartzite and four samples of dike rock is 12.73 ± 0.98 mcal/cm sec °C. Combined with an observed gradient of 18.45° ± 0.25°C/km in the quartzites, this value gives a heat flow of 2.35 μcal/cm^2 sec, in good agreement with the deeper interval. The mean thermal conductivity of the quartzites only was 14.77 ± 0.32 mcal/cm sec °C. The thermal conductivity determinations from hole D-142 are as follows (depths are in meters, and thermal conductivities are in millicalories per square centimeter second degree Celsius):

Depth	Thermal Conductivity
587.7	12.99
629.7	14.96
630.6	15.29
646.2	15.52
675.8	8.30*
680.6	11.79*
696.2	15.39
752.0	6.61*
767.8	15.31
790.7	14.62
799.2	15.60
825.7	14.99
844.9	12.46
853.2	9.62*
884.8	15.35

(The values with asterisks are for a porphyry dike. All disks are 2.22 cm in diameter and 2.54 cm thick.)

Our heat flow values at Bingham are somewhat higher than those determined by *Roy*

et al. [1968, p. 5219], who repo
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lower value of 1.5 μcal/cm^2 sec
determined in the main Bingha
the average thermal conductivit
7.19 ± 0.28 mcal/cm sec °C. T
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and the stock, respectively; ou
about 9 and 27% higher in the
the stock, respectively. Undoub
large differences in thermal c
tween the porphyry and the qu
tion is probably an important f
ferences observed.

We feel the best heat flow
D-142 is 2.3 ± 0.3 μcal/cm^2
three lowest conductivity valu
rock cut by hole D-142 are
assumed conductivity of the
8.18 ± 0.87 mcal/cm sec °C,
the stock would be 2.0 μcal/cm

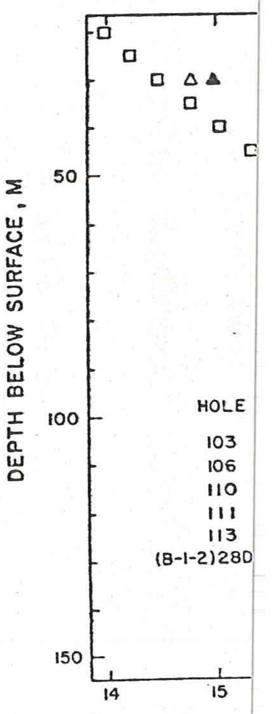

Fig. 2. Temperature pr

et al. [1968, p. 5219], who reported two values at Bingham of 1.5 and 1.9 μcal/cm² sec. The lower value of 1.5 μcal/cm² sec was apparently determined in the main Bingham stock, since the average thermal conductivity reported was 7.19 ± 0.28 mcal/cm sec °C. The value of 1.9 μcal/cm² sec was apparently determined in the quartzites, since the mean conductivity was 11.5 mcal/cm sec °C. Our mean conductivities are about 29 and 26% higher for rocks, which presumably would correspond to the quartzites and the stock, respectively; our gradients are about 9 and 27% higher in the quartzites and the stock, respectively. Undoubtedly, with the large differences in thermal conductivity between the porphyry and the quartzites, refraction is probably an important factor in the differences observed.

We feel the best heat flow value from hole D-142 is 2.3 ± 0.3 μcal/cm² sec. If only our three lowest conductivity values for the dike rock cut by hole D-142 are considered, the assumed conductivity of the stock would be 8.18 ± 0.87 mcal/cm sec °C, and the flux in the stock would be 2.0 μcal/cm² sec, still within our assumed uncertainty, and the lower conductivity value is in better agreement with that of *Roy et al.* [1968, p. 5219]. We prefer the higher value of 2.3 ± 0.3 μcal/cm² sec, since it is compatible with flux values obtained above and below the boundary of the main Bingham stock as penetrated by hole D-142.

Jordan Valley. The temperature profile in drill hole (B-1-2)28dcc-1 in Jordan Valley (40°47.0′N, 112°04.3′W) near Salt Lake City, Utah, is shown in Figure 2. This hole was drilled into interbedded sandy and muddy layers of the relatively unconsolidated Lake Bonneville deposits. Because of poor recovery of the unconsolidated deposits, no material was available for laboratory measurements of thermal conductivity. No topographic correction to the gradient was necessary.

The high gradient of 58.7°C/km (Figure 2) is believed to be due to the low thermal conductivity of the unconsolidated Lake Bonneville deposits. According to *Langseth* [1965, p. 70], published conductivity values for oceanic sediments are generally within 25% of 2.0 mcal/cm sec °C. This value could presumably be used

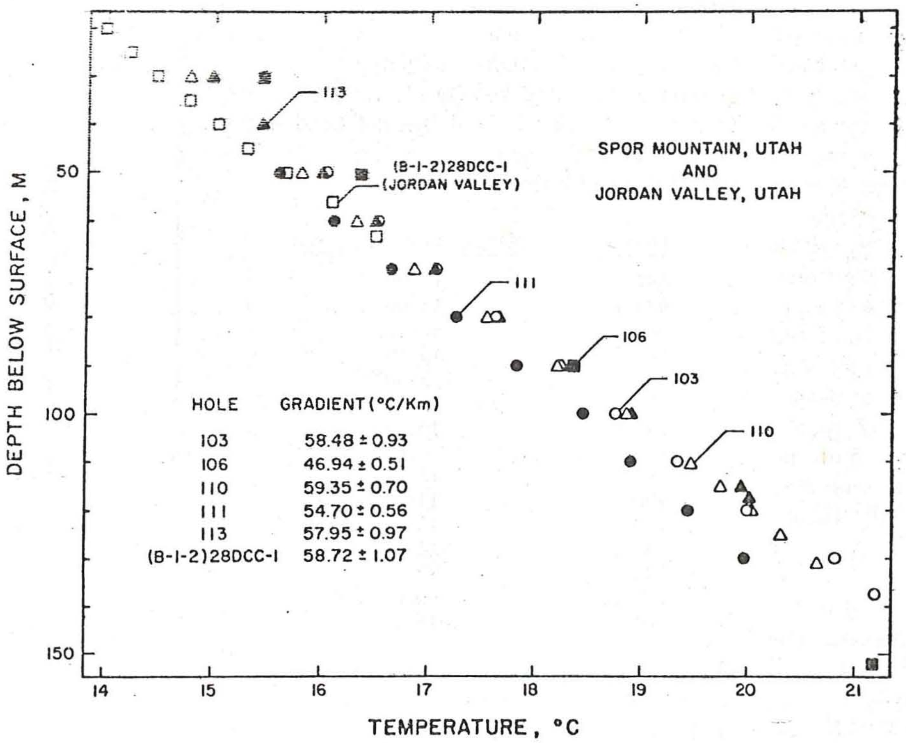

Fig. 2. Temperature profiles in drill holes at Spor Mountain and Jordan Valley, Utah.

as a lower bound for the thermal conductivity of the material in Jordan Valley. The conductivity of the Bonneville sediments is probably higher than 2.0 mcal/cm sec °C because (1) the Bonneville sediments contain more quartz (in the sandy layers) than deep oceanic sediments and (2) the porosity of a sand is generally less than the porosity of a typical oceanic lutite, which may contain 75% water; therefore a sand contains more solid material per unit volume than a lutite. Many well-consolidated shales and sandy shales have thermal conductivities of about 4.0 mcal/cm sec °C and lower [*Birch*, 1954; *Joyner*, 1960]. We may use this value as an upper limit. The sediments penetrated by the hole then probably have a thermal conductivity greater than 2.0 mcal/cm sec °C and less than 4.0 mcal/cm sec °C. If a thermal conductivity of 3.0 mcal/cm sec °C is used, the regional heat flow in Jordan Valley would be about 1.8 ± 0.6 μcal/cm² sec.

Spor Mountain. Spor Mountain is in the central part of Juab County, Utah, in the Basin and Range province. Temperatures were measured in five drill holes in the Topaz Mountain tuff. Four of these holes were within 460 meters of each other and had an average gradient of 58°C/km. The fifth hole (hole 106), located 600 meters to the north, was found to have a lower gradient of 46.9°C/km. Figure 2 shows the temperature profiles for all holes.

Table 3 lists the results of thermal conductivity determinations from the Spor Mountain area. Disks were cut from nine specimens. All of the rock specimens are representative of the Topaz Mountain rhyolite. The mean thermal conductivity and the standard error of 20 rhyolite specimens were 5.47 ± 0.14 mcal/cm sec °C. The mean geothermal gradient of all five holes was 55.5° ± 3.7°C/km. This value gives an average heat flow of 3.0 ± 0.3 μcal/cm² sec. The gradient over the depth interval 120–127 meters in hole 110 was 55.0° ± 1.0°C/km. The mean conductivity and the standard error of eight samples over this interval in hole 110 were 5.26 ± 0.2 mcal/cm sec °C. The product indi-

TABLE 3. Thermal Conductivity Measurements from the Spor Mountain Area

Disk No.	Thickness, cm	Conductivity, mcal/cm sec °C	Location
10SM66	1.27	5.51	hole 110 (123 meters)
11SM66-1	1.27	5.36	hole 110 (123 meters)
11SM66-2	1.91	5.50	
11SM66-3	2.54	5.52	
13SM66	1.91	3.78	hole 110 (125 meters)
14SM66-1	1.27	5.49	hole 110 (127 meters)
14SM66-2	1.91	5.46	
14SM66-3	2.54	5.43	
15SM66-1	1.27	6.21	hole 111 (below 130 meters)
15SM66-2	1.91	6.25	
16SM66-1	1.27	6.43	hole 111 (below 130 meters)
16SM66-2	2.54	6.63	
17SM66-1	1.27	5.46	hole 111 (below 130 meters)
17SM66-2	1.91	5.66	
18SM66-1	1.27	4.63	surface
18SM66-2	2.54	4.64	
18SM66-3	3.81	4.73	
19SM66-1	1.27	5.47	surface
19SM66-2	2.54	5.63	
19SM66-3	3.81	5.63	

All values were determined from shelf-dried specimens.

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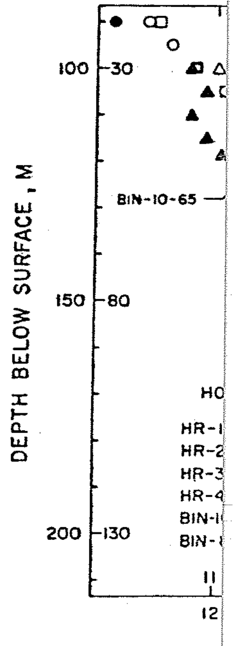

Fig. 3

cates a flux of 2.9 ± 0.2 μcal/cm² sec. No terrain corrections were necessary. The variation in the geothermal gradient between hole 106 (46.9°C/km) and the four holes to the south (average value, 57.6°C/km) might be due to near-surface groundwater circulation or more probably to lateral variation in the thermal conductivity of the rhyolite. No core was available from hole 106. All thermal conductivity values were determined on unsaturated specimens in a shelf-dried state, since the holes were all dry when they were logged.

The heat flow in the Spor Mountain area is taken to be 3.0 ± 0.3 μcal/cm² sec. The uncertainty of 10% is assigned primarily because not all of the conductivity determinations were made on core from the holes.

La Sal. Most of the gradients were determined in holes drilled into the Chinle formation, which is composed of fluvial mudstones and sandstones with irregular conglomeratic beds that probably represent ancient stream channels. One hole (Bin-8-64) was drilled entirely in the Wingate sandstone, which overlies the Chinle. Temperatures were measured in four holes (HR series) within 150 meters of each other and in two holes (Bin series) about 3 km northwest of the HR group in the Big Indian mining district [*Wright*, 1966]. The temperature profiles are shown in Figure 3. The average straight-line least squares gradient in the HR holes is 17.7° ± 0.26°C/km. The gradient typically passes several times through maximum and minimum values of about 22° and 14°C/km [*Wright*, 1966, pp. 79–86]. The 14°C/km gradient is measured in the more sandy layers of the Chinle, whereas the 22°C/km is representative of the shaly beds. By means of data from below 120 meters in hole Bin-10-65, the straight-line least squares gradient is 21.9° ± 0.32°C/km.

The holes at La Sal were surrounded by rather rugged topography, and a correction for topographic evolution was determined. The atmospheric temperature gradient assumed for the correction was −5.7°C/km. According to *Eardley* [1962, p. 424] the central part of the Colorado Plateau was uplifted 1829–2438 meters, probably beginning in Pliocene time. For an uplift of 1829 meters, 335 meters of erosion, and an evolution time of 15 m.y. (conditions that Eardley considers most representative) the corrected gradient in HR-1-65 is 17.79° ± 0.20°C/km, or 3.5% greater than the observed

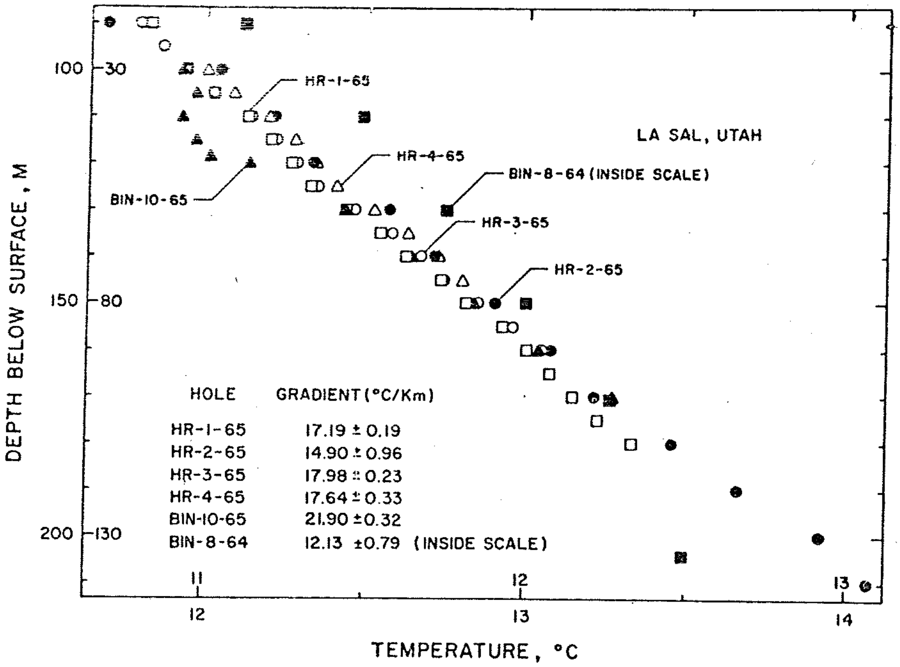

Fig. 3. Temperature profiles in drill holes at La Sal, Utah.

gradient. For an infinite evolution time the corrected gradient is 18.38° ± 0.20°C/km, or about 7% greater than the observed gradient in HR-1-65. For Eardley's assumptions about the physiographic history the correction to the gradient is small.

No core was available for the La Sal holes, and thermal conductivity was determined from samples prepared from bulk rock specimens. All specimens were collected within 2 km of the HR holes and within less than 6 km of the Bin holes. The lithology typical of the Chinle formation is about 50% sandstone and about 50% mudstone [*Wright*, 1966, pp. 92–94]. We previously reported heat flow values at La Sal based on measurements of samples in a shelf-dried condition. Nine of the Chinle samples have since been remeasured after being vacuum-saturated with distilled water. The difference between the dry and the saturated conductivities is shown in Table 4.

The mean value and the standard error of the thermal conductivity of eight saturated specimens of the Chinle formation are 8.61 ±

TABLE 4. Thermal Conductivity Measurements from La Sal, Utah

		Thermal Conductivity, mcal/cm sec °C		
Sample No.	Thickness, cm	Dry	Saturated	Remarks, Location
4H66-1	1.27	6.88		From lower 75 feet of Chinle formation, Alice-inclined shaft; sandy mudstone, ±20% quartz.
4H66-2	2.54	7.16	8.75	
6H66-1	1.27	7.40		From lower 75 feet of Chinle formation, Alice-inclined shaft; muddy sandstone, ±50% quartz.
6H66-2	2.54	7.68	9.14	
6H66-3	1.27	7.28		
6H66-4	2.54	7.08		
8H66	2.54	8.37	9.24	From lower 75 feet of Chinle formation, Alice-inclined shaft; sandstone, ±80% quartz.
9H66	2.54	5.45		From lower 75 feet of Chinle formation, Alice-inclined shaft; mudstone, 10% quartz.
1L66-1	1.27	7.05		Samples 1L66 to 9L66 are Chinle from surface exposures on the Wingate-Chinle cliff and talus slope just east of La Sal triangulation station (38°14'16.9"N, 109°16'20.7"W); muddy sandstone, ±80% quartz.
1L66-2	2.54	7.50	9.32	
2L66	2.54	7.98		Chinle; sandstone, ±80% quartz.
5L66	2.54	6.09	7.08	Chinle; muddy sandstone, ±70% quartz.
6L66	2.54	7.98	9.08	Chinle; muddy sandstone, ±70% quartz.
7L66	2.54	6.42	7.86	Chinle; muddy sandstone, ±70% quartz.
9L66-1	1.27	5.42		Chinle; sandy mudstone, ±40% quartz.
9L66-2	2.54	6.00	8.38	
11L66-1	1.27	11.50		Wingate; from Wingate-Chinle cliff; see 1L66; ±95% quartz.
11L66-2	2.54	12.19	13.94	
1SJ66-1	1.27	11.67		Wingate; from Wingate-Chinle cliff; see 1L66; ±95% quartz.
1SJ66-2	2.54	12.10		

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0.26 mcal/cm sec °C. This value represents an increase of about 20% over the corresponding unsaturated mean value of 7.15 ± 0.29. One sample of the Wingate was remeasured after saturation; unsaturated conductivity values were used for the Wingate, since hole Bin-8-64, which was entirely in the Wingate, was logged dry [*Wright*, 1966, p. 77].

The average geothermal gradient in the Chinle formation in the HR-65 holes was 17.7° ± 0.2°C/km. The mean thermal conductivity of the saturated samples of Chinle was 8.61 mcal/cm sec °C. The product indicates a flux of 1.5 μcal/cm^2 sec. Hole Bin-8-64 was dry when it was logged. The temperature gradient in the Wingate sandstone in this hole was 12.1° ± 0.8°C/km, and the mean unsaturated Wingate conductivity of four samples was 11.9 ± 0.14 mcal/cm sec °C, giving a heat flow of 1.44 ± 0.11 μcal/cm^2 sec.

Previously reported [*Costain and Wright*, 1968] values for La Sal were given as 1.2 ± 0.2 μcal/cm^2 sec. based entirely on thermal conductivity measurements of unsaturated rocks. The revised value for La Sal, based on conductivity measurements on saturated Chinle rocks as well as on unsaturated Wingate sandstone, is 1.5 ± 0.2 μcal/cm^2 sec. The uncertainty placed on the revised value is primarily a result of the uncertainty of the conductivity of the Wingate and Chinle rocks, since measurements were not made on core samples from holes in which the gradients were determined.

DISCUSSION

Decker [1969] presented nine new heat flow values in Colorado and New Mexico. Only one of these values, 1.22 μcal/cm^2 sec at Cerrillos, New Mexico, near the southern border of the southern Rocky Mountains, fell below 1.6 μcal/cm^2 sec. *Sass et al.* [1971] presented a large number of additional values for the Rocky Mountain and Colorado Plateau provinces. All of their 'category 1' values for the Colorado Plateau were 1.5 μcal/cm^2 sec or above. North of the Colorado Plateau province, at Green River, they obtained a value of 1.6 μcal/cm^2 sec. In the Basin and Range province, *Sass et al.* [1971] gave a number of new values south and west of the Colorado Plateau. Only five values are less than 1.5 μcal/cm^2 sec, and these sites are close to other sites (<20 km) where the heat flow is greater than 1.5 μcal/cm^2 sec. It would appear that the low heat flow values in Arizona southwest and south of the Colorado Plateau (5 out of 25 determinations) may not be representative of the regional heat flux and could be the result of either refraction or shallow groundwater circulation.

The revised value given in this paper for La Sal, Utah, on the Colorado Plateau is 1.5 μcal/cm^2 sec. This value is in close agreement with values found for the northern part of the Colorado Plateau by *Sass et al.* [1971], although it is considerably higher than *Spicer*'s [1964] value of 1.2 μcal/cm^2 sec. On the basis of much of the heat flow now available, there appears to be less evidence to delineate the Colorado Plateau as a separate heat flow province with abnormally low heat flow.

The extensive recent tectonic activity in the Basin and Range province is reflected by the high surface heat flow. Depending on the upward penetration of fault zones, heat flow anomalies might be expected to (1) follow superimposed trends associated with block faulting and (2) fall off rapidly away from the fault zone if the source is shallow. No linear trends in heat flow are apparent from the data available to date; however, the density of heat flow determinations is not sufficient to rule out the possibility of linear heat flow patterns associated with major trends in block faulting. Figure 4 shows all of the published heat flow values in Utah to date. A higher density of heat flow determinations might show the anomalies to be closely associated with linear seismic zones, such as the Wasatch line in Utah. The heat flow at Bingham, Utah, very close to the Wasatch line, is about 2.3 μcal/cm^2 sec. Heat flow profiles and microseismicity studies near active fault zones could establish such a correlation.

The Cordilleran thermal anomaly zone (CTAZ) of *Blackwell* [1969] may include the Colorado Plateau province. *Decker* [1969] and *Sass et al.* [1971] obtained high heat flow values (>2.0 μcal/cm^2 sec) near the eastern boundary of the plateau. The apparent overall higher heat flow in the Basin and Range province, about 2.0 μcal/cm^2 sec, suggests a higher density of fracture zones with deeper penetration into the mantle than that to the east in the Colorado Plateau province.

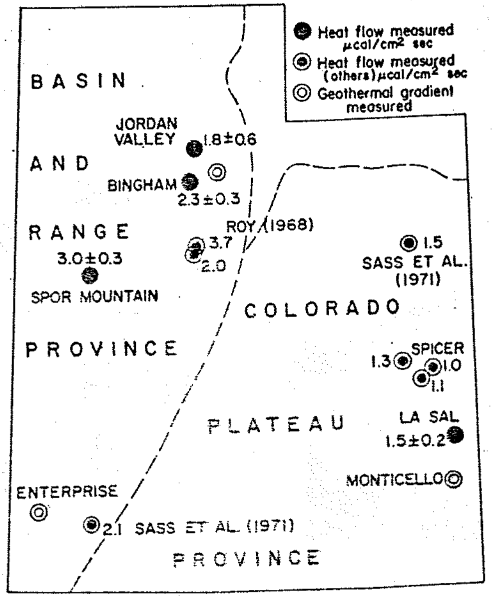

Fig. 4. Heat flow measurements to date in Utah.

Acknowledgments. This work was supported by National Science Foundation grants GP-2625, GA-608, and GA-1384. The University of Utah Research Committee sponsored some of the preliminary work in temperature measurement when the authors were at the University of Utah.

Dr. Robert F. Roy made many helpful suggestions in regard to temperature measurement and the design of the thermal conductivity apparatus. Walter Rohloff did the machine work for the thermal conductivity apparatus at the University of Utah and made many original and significant contributions to the design of the hoisting equipment.

The Atlas Minerals Corporation, the Brush Beryllium Company, the Hogle Investment Company, and the Kennecott Copper Corporation gave permission to log boreholes on their property, and their cooperation is gratefully acknowledged.

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(Received August 16, 1972;
revised August 1, 1973.)

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