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Heat Flow and Precision Temperature Measurements in Boreholes

by

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Abstract

There are both theoretical and practical considerations that make it desirable to determine the magnitude and spatial distribution of heat flowing out from the earth's surface. Thermal energy plays an important role in diastrophism and any theory of the earth's origin. Heat flow measurements in boreholes might prove to be a valuable supplementary exploration method in the future. Both the geothermal gradient and the rock thermal conductivity are necessary for a heat flow measurement. Temperature measurements are easily made in boreholes to obtain the geothermal gradient. Comparison of the resistance of a platinum resistance probe with a primary standard resistance yields resistance measurements accurate in the field to about 0.003% which for a probe whose nominal ice-point resistance is about 1,000 ohms, is equivalent to an accuracy of  $\pm 0.01^\circ\text{C}$ . However, other factors lower the absolute accuracy of temperature measurements to about  $\pm 0.05^\circ\text{C}$ . Thermal conductivity measurements on rock discs are repeatable to a precision of about one percent. The overall accuracy of heat flow measurements is probably 10% to 15%.

A capstan hoist powered by a 2-hp electric motor was used to raise a double-armored cable out of the borehole. The hoist is mounted in a panel truck which is thermally insulated with polyurethane foam and air-conditioned to control the inside temperature during field measurements. The temperature coefficient of resistance of the primary standard resistance was less than  $0.0007 \text{ ohm}/^\circ\text{C}$  over the range  $20^\circ\text{C}$  to  $30^\circ\text{C}$ .

A heat flow value of  $2.8 \mu\text{cal}/\text{cm}^2\text{-sec}$  was found at Spor Mountain, Utah ( $39^\circ 43' \text{N}$ . lat.,  $113^\circ 13' \text{W}$ . long.). This value may be subject to revision because of probable circulation of warm ground water in the area. A heat flow value of  $1.8 \mu\text{cal}/\text{cm}^2\text{-sec}$  was estimated at Jordan Valley, Utah ( $40^\circ 47' \text{N}$ . lat.,  $112^\circ 04.3' \text{W}$ . long.). The heat flow at La Sal, Utah ( $38^\circ 14.3' \text{N}$ . lat.,  $109^\circ 16.3' \text{W}$ . long.) was found to be  $1.2 \pm 0.2 \mu\text{cal}/\text{cm}^2\text{-sec}$ .

### Introduction

There are both theoretical and practical considerations that make it desirable to determine the magnitude and spatial distribution of heat flowing out from the earth's surface. Thermal energy plays an important role in diastrophism, in the evolution of geological provinces, and in the origin of the earth itself. Any theory of the earth's origin or present thermal state must be compatible with the observed pattern of heat flow. From a practical standpoint, many mining districts are known to be associated with abnormally high heat flow, for whatever the reason, and it is not inconceivable to consider heat flow as a supplementary exploration method in the future. Temperature isotherms are warped by the juxtaposition of rocks of differing thermal conductivities (Simmons, 1961; McBirney, 1963; MacKenzie and Costain, 1968). A detailed three-dimensional isothermal map showing isothermal surfaces in an area of salt dome intrusions might shed light on the mechanics and time history of the salt emplacement. In addition, there is widespread interest in geothermal energy sources.

Almost all of the heat flow measurements being made at the present time, however, are made for the purpose of adding to an understanding of the regional differences in heat flow on a continental scale, and interpreting these observations in terms of regional geology. Local anomalous areas such as many mining districts and known hydrothermal areas are not regionally representative. In spite of the relative sparseness of heat flow measurements on land as compared with those from oceanic areas, there has emerged a general recognition of regional variations in heat flow which can be correlated with geological provinces (Lee, 1965).

The average heat flow from oceanic and continental areas is 1.4 microcalories per  $\text{cm}^2$  per second (Lee, 1965 p. 53). The low heat flow values in the continental United States and Canada are found in Precambrian shield areas; the relatively high values are in areas of geologically recent tectonic activity, such as the Basin and Range province and other parts of western United States (Blackwell, 1967; Roy, Decker, Blackwell, and Birch, 1968). Regional variations of greater than 10% are considered to be real and meaningful. The reasons for the variations are not completely understood, but the distribution of radioactive elements in the upper 30 kilometers or so of the earth's crust is now known to play an important role (Roy and Decker, 1965; Roy, Blackwell, Decker and Birch, 1968; Birch, Roy and Decker, 1968).

### Fundamental Law of Heat Conduction

Heat energy flowing out through the crust of the earth does so by conduction according to Fourier's Law of Heat Conduction (Carslaw and

Jaeger, 1959, p. 7) which is

$$Q = K \frac{\Delta T}{\Delta Z}$$

Q is the heat flow in microcalories per cm<sup>2</sup> per second ( $\mu\text{cal}/\text{cm}^2\text{-sec}$ ), K is the thermal conductivity in millicalories per cm per second per degree Centigrade ( $\text{mcal}/\text{cm-sec-}^\circ\text{C}$ ), and  $\Delta T/\Delta Z$  is the geothermal gradient in degrees Centigrade per cm ( $^\circ\text{C}/\text{cm}$ ) in the direction of heat flow, usually vertical or at least assumed to be vertical if the gradient is measured in a vertical borehole. Gradients are generally reported in degrees Centigrade per kilometer ( $^\circ\text{C}/\text{km}$ ).

The measurement of temperatures at different depths in a hole yields the geothermal gradient. These measurements are straightforward and are easily made in a borehole. Measurement of the thermal conductivity is not as easy. Most measurements on land require carefully prepared rock samples either taken from or representative of the same portion of the borehole where temperatures were measured. Sample preparation is time-consuming and selection of rock samples for thermal conductivity measurements must be made with care.

For an isotropic, homogeneous material accurate heat flow measurements would not be difficult to make. The earth is not isotropic, and important factors such as diurnal and secular near-surface temperature variations, ground water movement, thermal conductivity anisotropy and experimental error will individually or collectively combine to lower the accuracy of a terrestrial heat flow measurement. Temperature changes in the hole caused by diurnal and seasonal changes of surface temperature are damped out at depths greater than about 25 meters, so measurements must be made at least as deep as this and preferably to at least 300 meters.

#### Measurement of the Geothermal Gradient

The most accurate and stable sensing element for measuring temperature is a platinum resistance element the resistance of which changes as a function of temperature. Another commonly used sensing element is the thermistor which has the advantage of a greater change in resistance per given change in temperature as compared with platinum. However, thermistors have been known to be less stable than platinum although recent developments in design and ageing seem to indicate increased reliability and stability for thermistors. We used platinum throughout this study.

The temperature gradient, not the absolute temperature, is required for a heat flow measurement. However, it is desirable to measure temperature as accurately as possible at any particular depth in a hole in order to monitor the stability of the sensor element over a period of time, and in order to be able to compare temperature measurements made by other workers in the same hole.

We used a platinum resistance thermometer, Type 134HH manufactured by Rosemount Engineering Company, with a nominal ice-point resistance of 1,000 ohms. Initial calibration of this probe by Rosemount Engineering Company at temperatures of  $0^{\circ}\text{C} \pm 0.015^{\circ}\text{C}$ ,  $50^{\circ}\text{C} \pm 0.02^{\circ}\text{C}$ , and  $100^{\circ}\text{C} \pm 0.02^{\circ}\text{C}$  gave probe resistances of 999.99 ohms, 1197.38 ohms, and 1391.89 ohms, respectively. The International Practical Temperature Scale of 1948 for platinum resistance thermometers used in the range  $0^{\circ}\text{C}$  to  $630.5^{\circ}\text{C}$  (Berry, 1962; Robertson and Walch, 1962) is based on the Callendar equation

$$T = \frac{(R_T - R_0)}{\alpha R_0} + \delta \left( \frac{T}{100} - 1 \right) \cdot \left( \frac{T}{100} \right)$$

where  $R_T$  = resistance at temperature  $T$  ( $^{\circ}\text{C}$ )

$R_0$  = resistance at  $0^{\circ}\text{C}$ , i.e., the ice-point resistance

$\alpha$  = the "fundamental" coefficient of a platinum thermometer obtained by calibration of the probe

$\delta$  = the Callendar coefficient, obtained by calibration of the probe

Typical values of  $\alpha$  and  $\delta$  are 0.0039261 and 1.495, respectively.

The Callendar equation was programmed for use on a digital computer and tables of resistance versus temperature were computed for the range  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$  in increments of  $0.01^{\circ}\text{C}$ . A change in temperature of  $0.01^{\circ}\text{C}$  corresponded, for this probe, to a change in resistance of approximately 0.036 ohm. Any instrument used to measure probe resistance must therefore be able to detect a change in resistance of this magnitude in order to resolve temperature changes as small as  $0.01^{\circ}\text{C}$ .

If it is desired to measure temperature at, say,  $50^{\circ}\text{C}$  to an accuracy of  $\pm 0.01^{\circ}\text{C}$  using a conventional Wheatstone bridge this means measuring the resistance of a probe whose nominal ice-point resistance is 1,000 ohms to an accuracy of  $1197.38 \pm 0.036$  ohms, or to about 0.003%. Such accuracy in a Wheatstone bridge is not practical for a portable field instrument. However, because of the limited resistance range that would be encountered in the field using this probe, about 390 ohms for the temperature range  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ , it is possible to use a modification of a Wheatstone bridge, a comparison bridge, which compares the resistance of the probe with the resistance of a highly accurate primary standard resistance for which the resistance is known to  $\pm 0.001\%$ . We used a comparison bridge, Model DBR-1 manufactured by the RdF Corporation, Hudson, New Hampshire. The comparison bridge compares the resistance of the probe with that of a primary standard resistor. The primary standard resistances were manufactured by Julie Research Laboratories and were accurate to  $\pm 0.001\%$ . These were calibrated by the manufacturer, by a secondary standards laboratory, and by the National Bureau of Standards. Figure 1 is a schematic wiring diagram of the bridge circuit. In this diagram  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  are resistors of the upper ratio arms. The resistances of these two arms are set equal by

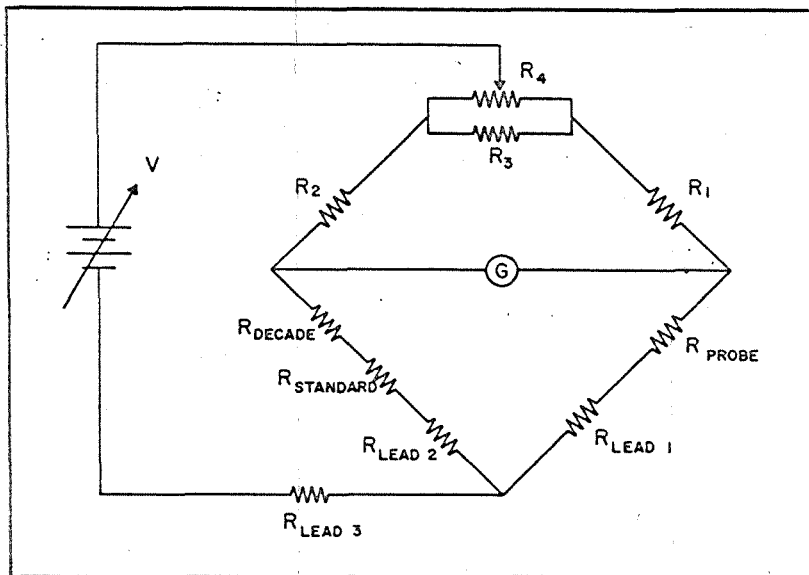


Figure 1

adjusting  $R_4$  at the beginning of the field work, and, although it was checked periodically, this initial adjustment did not have to be changed subsequently.  $R_{probe}$  is the resistance of the probe, and  $R_{standard}$  is the resistance of the primary standard.  $R_{decade}$  is a decade resistance which is variable from 0 to 99.99 ohms in steps of 0.01 ohm. This resistance can be switched into either of the lower two arms of the bridge. The resistance of  $R_{decade}$  is varied until the bridge is balanced. A null detector with a sensitivity of 0.01 microamp per scale division will detect a bridge unbalance of 0.01 ohm. Thus, if the probe resistance is 1050.23 ohms and the resistance of the primary standard is 1000.00 ohms then the bridge will be balanced when  $R_{probe} = R_{standard} + R_{decade}$ . Taking into account the accuracy of the decade ( $\pm 0.05\%$ ) and the accuracy of the primary standard ( $\pm 0.001\%$ ) this gives a probe resistance of

$$R_p = (1000.00 \pm 0.010) + (50.23 \pm 0.025)$$

$$= 1050.23 \pm 0.035$$

or 1050.23 plus or minus about 0.003%. The accuracy stated is the optimum accuracy that could be hoped for in measuring absolute values of temperatures. It is not possible to measure temperature in drill holes to an absolute accuracy of better than a few hundredths of a degree Centigrade for other reasons which will be obvious in the discussion to follow. However, relative values, which are the main objective for heat flow measurements, will be considerably more accurate. We believe our absolute temperature measurements are accurate to  $\pm 0.05^\circ\text{C}$  or better.

Terminals on the resistance bridge for connection to the three lead wires effectively place the battery of the bridge in the circuit at the

probe element, and a lead-wire resistance appears in each lower arm of the bridge as shown in Figure 1. If the resistances of the lead wires are equal then automatic compensation for lead-wire resistance would be obtained. Since measurement showed that none of the resistances of the four cable conductors was the same, a switching scheme was devised so that lead-wire resistance could be eliminated. A balance was first reached with  $R_{\text{lead 1}}$  and  $R_{\text{lead 2}}$  as shown in Figure 1, and the decade reading was noted. Then a second decade reading was taken after the leads had been interchanged. It can easily be shown that the average of these two decade readings added to, or subtracted from, the resistance of the standard gives the correct probe resistance. Switching was provided by a Leeds and Northrup rotary switch with very low contact resistance so that any two of the four lead wires could be used for these averages. Thus, four probe resistance readings resulted from using all possible combinations of lead wires. During field measurements these four probe resistance determinations always agreed to within 0.01 ohm.

Other factors enter into decreasing the accuracy of temperature measurements. One of the most important components in a temperature-measuring system is the logging cable. Either a 3-wire or a 4-wire cable is satisfactory. The cable must have a high leakage resistance, and must be strong enough so that it will stretch very little under its own weight, and preferably should have conductors of low electrical resistance. We used Type 4-H-1 double-armored Amergraph cable manufactured by U. S. Steel Corp. This cable has a resistance of about 15 ohms per thousand feet and a breaking strength of 7,200 pounds. The leakage resistance of our 1000-foot cable was always greater than 50 megohms and usually greater than 100 megohms. The cable was marked at 5-meter intervals. Tests made by Mechanical Engineering Department at the University of Utah established that the cable stretch was about 0.03 percent when the 1,000-foot cable hung fully extended under its own weight of 142 pounds per 1,000 feet. Depths at which temperatures are reported in this paper should therefore be accurate to better than 0.1 meter, the maximum expected stretch for the cable.

Figure 2b shows the capstan hoist which was used to bring the armored logging cable out of the hole. The diameter of the capstan is 16 inches and the capstan is powered by a 2-hp, 110-volt electric motor with a speed variable from zero to 90 feet per minute. The maximum direct lift capability of the hoist is about 1,800 pounds. Power is supplied by a 3,000-watt, 110-volt gasoline-driven alternator. The hoist and associated equipment which was designed especially for this work was built in the machine shop of the University of Utah, and is now at Virginia Polytechnic Institute. During the time that the research reported on in this paper was carried out, the capstan, because of the mechanical construction of the motor, was restricted to rotate only in such a direction as to raise the cable out of the hole. When lowering the cable into the hole, power was not used and the capstan was stationary. Several wraps of cable around the capstan provided enough friction to give excellent control of the lowering speed. Subsequent to the work described in this paper, solid-state control circuitry was added and the motor modified to provide for reversal of the electric motor and capstan in order to lower as well as to raise the cable under power.

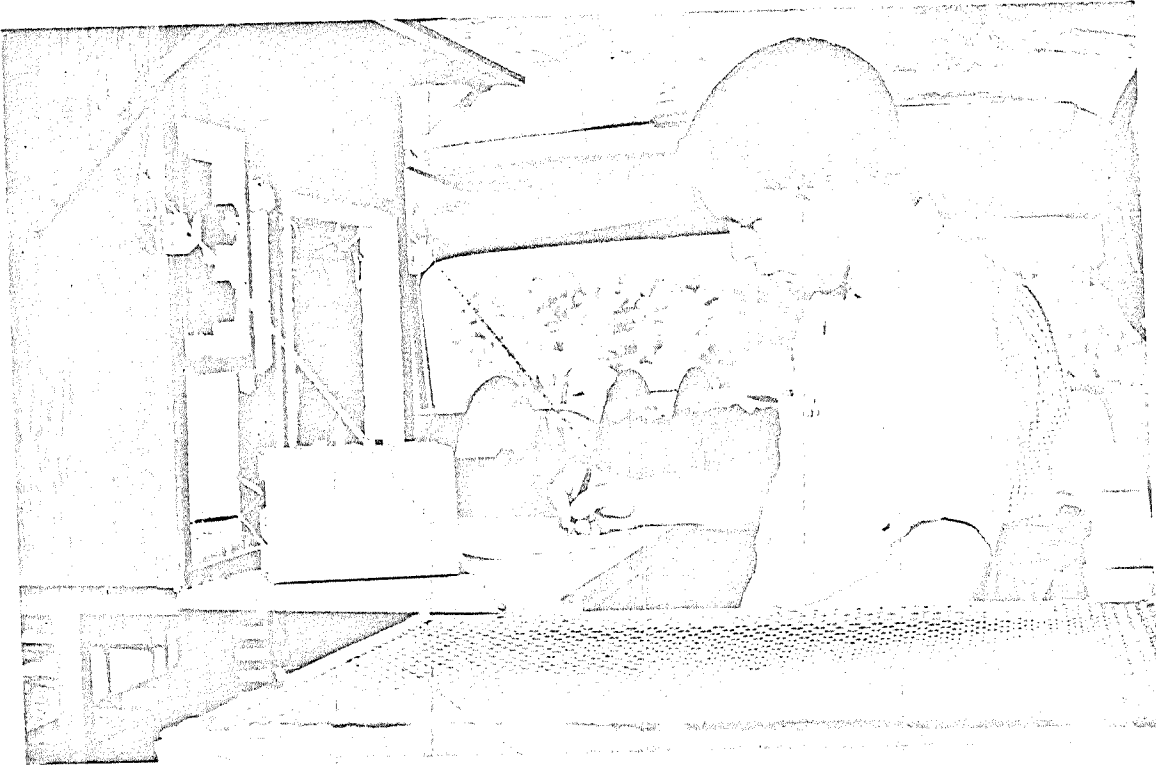


Figure 2a. Interior of vehicle. Capstan hoist in foreground.

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Figure 2b. Capstan hoist.

The cable storage, or take-up reel is shown in Figure 3a. The use of a capstan hoist permits storing the cable on the take-up reel under very little tension since most of the tensional stress that is present in the cable while it is being raised is relieved in the several wraps of cable around the capstan.

The vehicle is air-conditioned and thermally insulated inside with polyurethane. The back end is fitted with a removable polyurethane insulated door which is generally in place during logging operations. This makes it possible to control the inside temperature to within 5°F during field measurements. Temperature control minimizes changes in the resistances of the primary standards and the comparison bridge due to temperature variations inside the truck. The temperature coefficient of resistance of the primary standard resistances was extremely small, less than 0.0007 ohm/°C over the range 20°C to 30°C.

#### Measurement of Thermal Conductivity of Rocks

Rocks are poor conductors of thermal energy. Of the several methods that have been used to measure the thermal conductivity of rocks (Beck, 1965) the most reliable method uses the stacked, divided bar apparatus described by Birch (1950). Figure 3b shows the apparatus constructed for our work. This device was made in the machine shop at the University of Utah and is now at Virginia Polytechnic Institute. The apparatus is patterned almost exactly after the equipment designed and used in the Hoffman Laboratory at Harvard University.

Rock discs were commercially prepared from core samples by Technical Ceramic Processing Company, Peabody, Massachusetts. The surfaces of the discs were machined flat and parallel to  $\pm 0.0003$  inch, with diameters uniform and accurate to  $\pm 2$  percent. Figure 4 shows a typical "stack" configuration made up of a quartz disc above and below a rock disc. Copper-constantan thermocouples are inserted into the copper discs to measure the temperature differences across the quartz discs and across the rock specimen. Thermal resistance at the contacts between the discs is reduced by applying a thin layer of Vaseline to the disc faces. Thermal resistance is further reduced by applying an axial pressure of 200 bars to the stack. In order to ensure axial heat flow and minimize radial heat loss the stack is insulated with a tight-fitting cylindrical shell of high-density Polystyrene. A temperature differential of about 15°C is then applied across the entire stack. The stack will usually reach thermal equilibrium within 30 minutes and measurements of the temperature differences across each quartz disc and across the rock specimen can be made with a potentiometer such as a Leeds and Northrup Type K-3. The temperature difference across the stack is accurately maintained by thermostatically controlled temperature baths that can be seen to the right and left of the apparatus in Figure 3b.

Assuming axial heat flow and no radial heat loss then the heat flow through the upper quartz disc,  $q_1$ , will equal the heat flow through the rock disc,  $q_2$ , which equals the heat flow,  $q_3$ , through the lower quartz disc; i.e.,



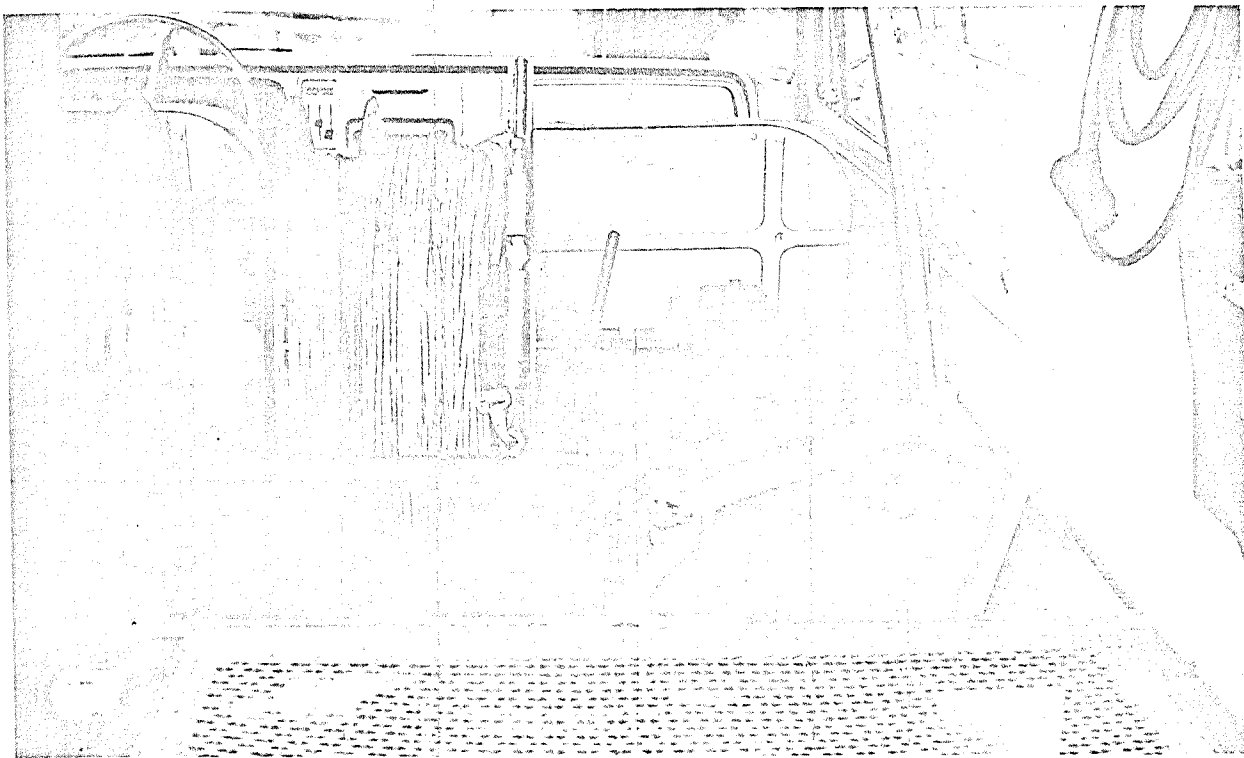


Figure 3a. Cable take-up reel.

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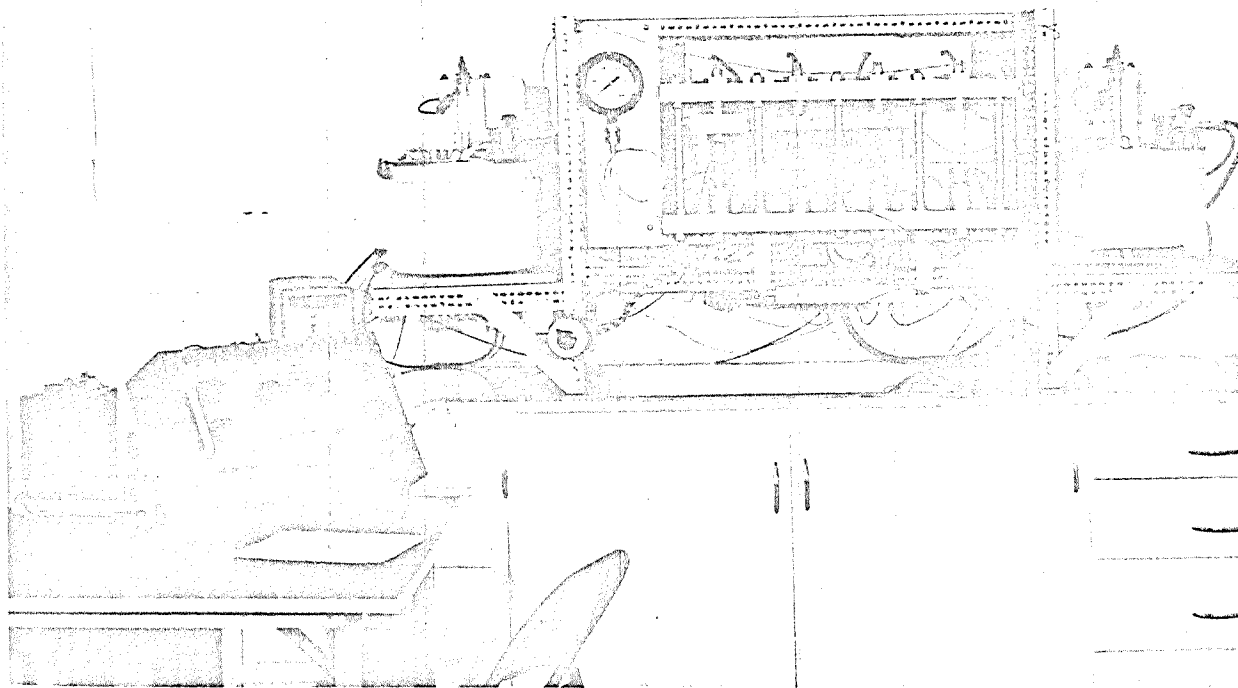


Figure 3b. Thermal conductivity measuring apparatus.

$$q_2 = q_1$$

$$q_2 = q_3$$

and, adding these relations

$$2q_2 = q_1 + q_3$$

$$q_2 = \frac{q_1 + q_3}{2}$$

or,

$$K_r \frac{\Delta T_2 A_2}{\Delta Z_2} = \frac{K_q \frac{\Delta T_1 A_1}{\Delta Z_1} + K_q \frac{\Delta T_3 A_3}{\Delta Z_3}}{2}$$

Where  $K_r$  is the thermal conductivity of the rock of cross-sectional area  $A_2$  and  $K_q$  is the thermal conductivity of the quartz of cross-sectional areas  $A_1$  and  $A_3$ . Solving for  $K_r$

$$K_r = \frac{K_q \frac{\Delta T_1 A_1}{\Delta Z_1} + K_q \frac{\Delta T_3 A_3}{\Delta Z_3}}{2 \frac{\Delta T_2 A_2}{\Delta Z_2}}$$

It is no problem to grind identical quartz discs so that  $A_1 = A_3 = A$ , and  $\Delta Z_1 = \Delta Z_3 = \Delta Z$ . This reduces the above equation to

$$K_r = K_q \left[ \frac{\Delta T_1 + \Delta T_3}{2\Delta T_2} \right] \cdot \left[ \frac{\Delta Z_2}{\Delta Z} \cdot \frac{A}{A_2} \right]$$

The temperature drops  $\Delta T_1$ ,  $\Delta T_2$  and  $\Delta T_3$  are directly proportional to the emf's generated between the thermocouples and these are measured with the potentiometer. The thermal conductivity of the rock,  $K_r$ , can then be computed with respect to the thermal conductivity of quartz. Either fused quartz or crystalline quartz can be used in the stack. The thermal conductivities of fused and crystalline quartz were determined by Ratcliffe (1959). All of our conductivity measurements are relative to the value for fused quartz,

although the thermal conductivities of several specimens were also measured using crystalline quartz and found to agree with the values obtained from fused quartz within two percent or less. Using the apparatus shown in Figure 3b, thermal conductivity measurements can be made on four specimens almost simultaneously.

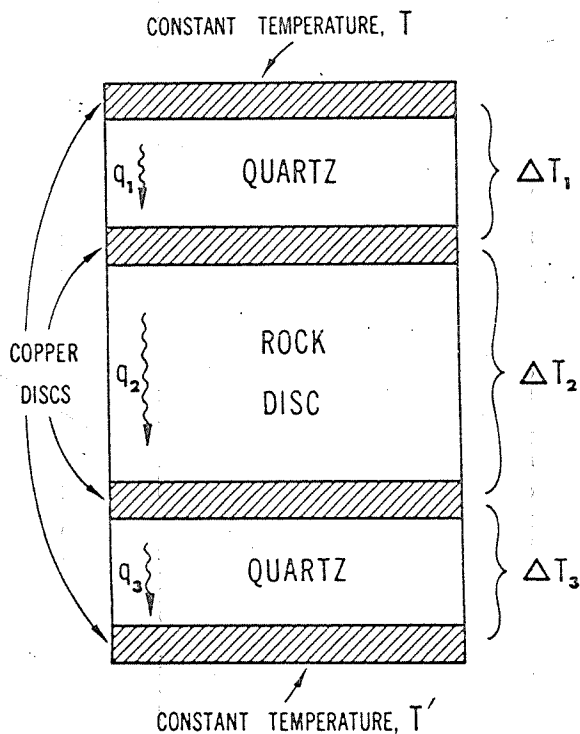


Figure 4

When assembling the stack, the surfaces must be kept free of any small particles that might rupture the quartz discs when an axial pressure of 200 bars is applied. Each time the stack is assembled to measure a new specimen or to repeat a measurement, there is no assurance that exactly the same conditions of thermal resistance, thermocouple seating, or radial heat loss can be duplicated. However, repeat measurements on the same rock disc were almost always reproducible to within two percent.

For some of the more porous rock discs, it was found that the Vaseline would soak into the rock during measurement, leaving only a small area of good contact. After the disc had been measured a few times, less Vaseline would be absorbed, and a progressively better contact would result. This had the effect of causing the apparent rock conductivity to increase with successive measurements until the faces of the discs no longer absorbed Vaseline. When this "equilibrium" state was reached, reproducibility of measurement was almost always within two percent.

In order to obtain a more uniform contact, and to prevent Vaseline from being absorbed by the specimen, a thin foil of aluminum 0.001" thick was bonded to the flat faces of some of the discs with epoxy cement. Curing

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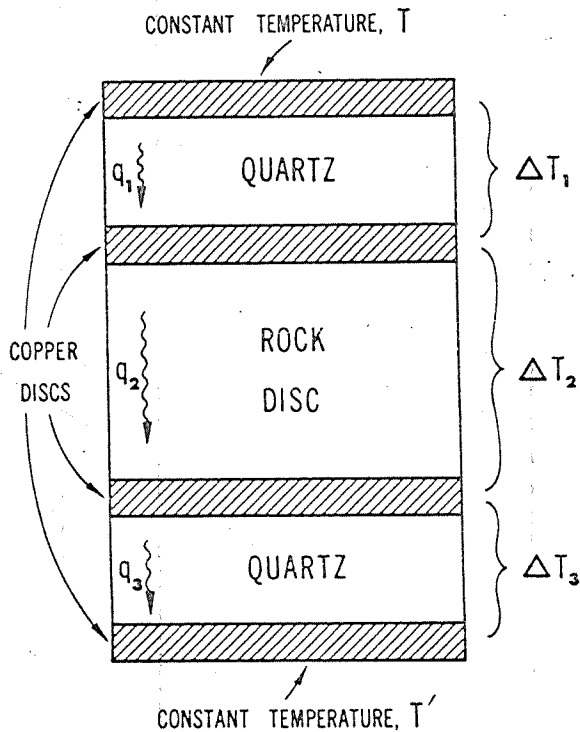


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of the epoxy was completed at room temperature under about 5,000 psi for at least 12 hours. This resulted in a good bond and a smooth, mirror-like disc face. Vaseline was used as a contact substance between these aluminum-surfaced discs and the copper discs of the stack. Measurements made in this manner were reproducible to about 0.5 percent. Several discs which had been measured without the aluminum foil coating were later surfaced as described above. The thermal conductivity results were the same, within about two percent, as those which had been obtained after the disc had stopped absorbing Vaseline.

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 disc amount to  $\pm 5$  percent." It seems likely that this figure would also apply to our conductivity measuring apparatus.

#### Accuracy of Terrestrial Heat Flow Measurements

Geothermal gradients measured in a borehole are not always suitable for heat flow determinations. A negative gradient or an essentially zero gradient can often be explained as being caused by shallow ground water disturbances, i.e., the holes were not deep enough to obtain a regionally representative geothermal gradient. Indeed, it is not always possible to be certain when the gradient is representative. Ideally, for laterally isotropic media such as layered rock sequences, if the vertical heat flow remains constant along the length of the borehole, then the product of the geothermal gradient and the thermal conductivity should be the same anywhere in the hole. If the geothermal gradient increases, then the conductivity must decrease, and vice versa. Roy, Decker, Blackwell and Birch (1968, p. 5213) give an excellent correlation between lithology, gradient and conductivity over a thickness of 120 meters of layered argillites and quartzites. Their work also points out the potential usefulness of precision temperature measurements as an aid in the correlation of stratigraphic units.

Detailed sampling of the rocks for thermal conductivity measurements is not always possible, and if only a limited number of heat flow determinations can be made from a borehole, then the samples for thermal conductivity measurements should be selected from those intervals in the hole where the gradient is uniform. Furthermore, thermal conductivity should be measured in the laboratory under conditions of temperature and water saturation similar to the environment from which the rock was taken (Birch and Clark, 1940; Walsh and Decker, 1966).

The overall accuracy of most heat flow measurements is probably 10-15%. If the rock discs on which the thermal conductivity measurement are made are known to be representative of the rock as a whole, if the geothermal gradients are stable and are not disturbed by ground water movement, if isotherms are not refracted by local geology, and if geological corrections for uplift, erosion and topography have been properly made, then heat flow measurements are probably accurate to within five percent.

Results

The locations of some heat flow and geothermal gradient measurements made in Utah are shown on Figure 6. Also shown are measurements by Spicer (1942) north of La Sal. Geothermal gradients were measured at Monticello and Enterprise but those temperatures were disturbed by shallow ground water movement.

The heat flow determinations at Spor Mountain, Jordan Valley and La Sal point out some typical problems encountered in obtaining a heat flow measurement. No core was available for thermal conductivity measurements for the holes at La Sal, Utah, and conductivity was measured from bulk rock specimens that were representative of the rock penetrated by the boreholes. The holes at Spor Mountain, Utah and La Sal, Utah were dry when drilled and when measured, and therefore the thermal conductivity measurements on rock discs from these areas were made on specimens that were in a shelfdried condition. The hole at Jordan Valley, Utah, was drilled into unconsolidated sediments for which the thermal conductivity had to be estimated. Shallow ground water disturbances might be affecting the heat flow determination at Spor Mountain. The results of all of the measurements are shown on Figure 6.

Geothermal gradients for all holes were computed by fitting a least squares straight line to points on the temperature vs. depth curve.

Spor Mountain. Spor Mountain is in the central part of Juab county, Utah, in the basin and Range province. Geothermal gradients were measured in five holes drilled by the Brush Beryllium Company in the Topaz Mountain Tuff. (Lat. 39°43'N, Long. 113°13'W). Figure 5 shows a typical temperature-depth and gradient plot.

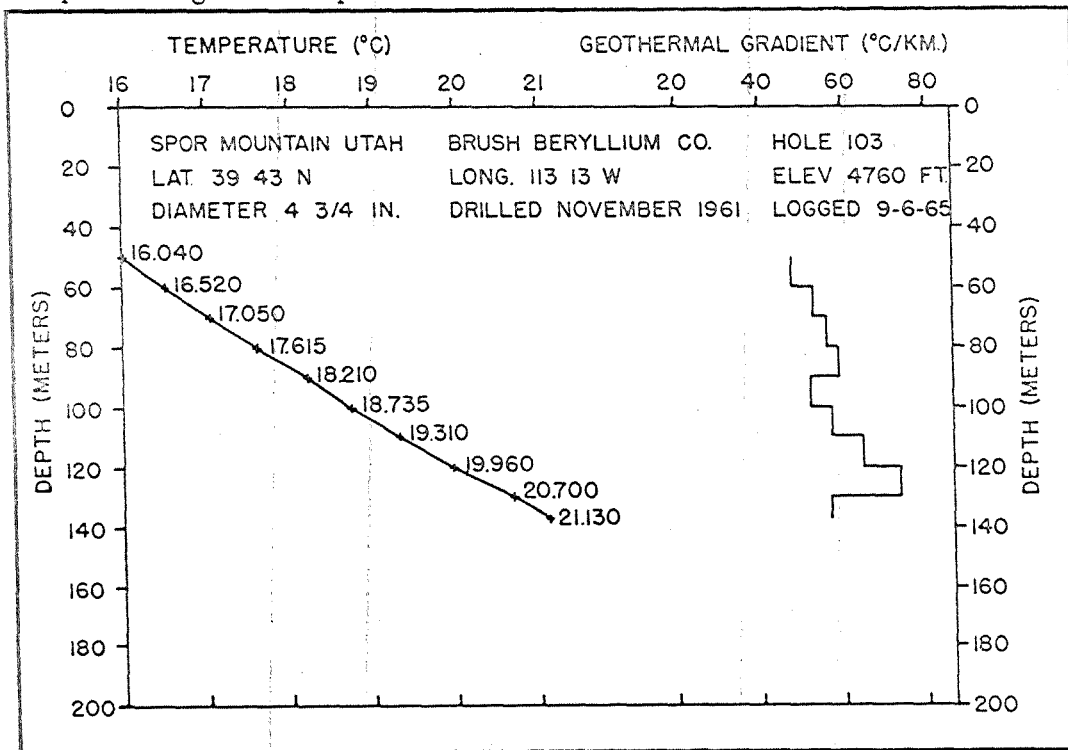


Figure 5.

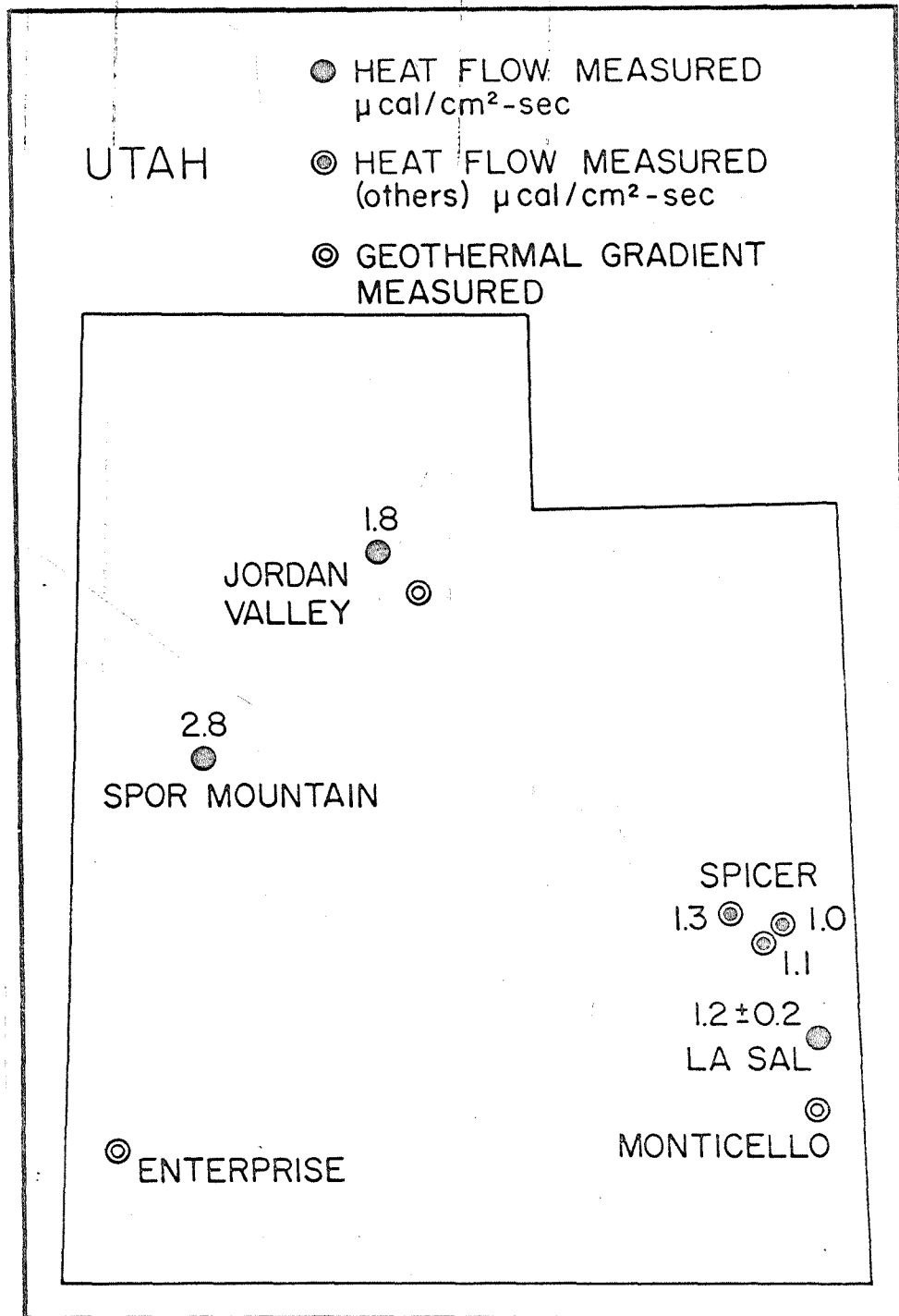


Figure 6. Heat flow measurements in Utah

Four of these holes were within 1500 feet of each other and had an average gradient of 58°C/km. The fifth hole (Hole 106) located 2000 feet to the north was found to have a lower gradient of 47°C/km. The reason for the difference between this hole and the holes to the south is not clear. Wright (1966) discusses in detail possible reasons for the difference.

Thermal conductivity values were determined for 20 rock discs from the Spor Mountain area. These discs were cut from nine rock specimens. Specimens 10SM66 through 14SM66 (Table 1) were pieces of core from hole 110, taken over the depth interval from 120 meters to 127 meters. Temperatures were measured over this interval in hole 110. Specimens 15SM66 through 17SM66 were core specimens from hole 111, but they were from a depth interval deeper than the deepest temperatures measurement in that hole. Specimens 18SM66 were blocks taken from outcrops near holes 110, 113, and 103. All of the rock specimens are representative of the volcanic Topaz Mountain Rhyolite. Table 1 also lists results of the thermal conductivity measurements on rocks from the Spor Mountain area. The average value is 5.4 mcal/cm-sec-°C.

Disc number	Thickness (inches)	Conductivity mcal/cm-sec-°C	Location	Remarks
10SM66	1/2	5.51	hole 110 (123 m)	no prominent banding
11SM66-1	1/2	5.36	hole 110 (123 m)	contorted banding
11SM66-2	3/4	5.50		
11SM66-3	1	5.52		
13SM66	3/4	3.78	hole 110 (125 m)	volcanic breccia, fragments to 1 cm.
14SM66-1	1/2	5.49	hole 110 (127 m)	no prominent banding
14SM66-2	3/4	5.46		
14SM66-3	1	5.43		
15SM66-1	1/2	6.21	hole 111	3 bands, 1/4" wide
15SM66-2	3/4	6.25	below 130 m	45° to disc
16SM66-1	1/2	6.43	hole 111	1 band, 1/2" wide
16SM66-2	1	6.63	below 130 m	70° to disc axis
17SM66-1	1/2	5.46	hole 111	
17SM66-2	3/4	5.66	below 130 m	
18SM66-1	1/2	4.63	surface	no banding
18SM66-2	1	4.64		
18SM66-3	1-1/2	4.73		
19SM66-1	1/2	5.47	surface	no banding
19SM66-2	1	5.63		
19SM66-3	1-1/2	5.63		

Table 1. Conductivity measurements from Spor Mountain area.

A geothermal gradient of 58°C/km and a rock conductivity of 5.4 mcal/cm-sec-°C give a heat flow of 3.1  $\mu\text{cal}/\text{cm}^2\text{-sec}$ . It is difficult to place error limits on this value because it is not known how closely the 58°C/km gradient represents the actual regional, undisturbed gradient. Variations in the geothermal gradient were found between Hole 106 and the four holes to the south in the Spor Mountain area and this variation might possibly be attributed to near-surface ground water disturbances.



Jordan Valley. The geothermal gradient measured in borehole (B-1-2)28dcc-1 in Jordan Valley (Lat. 40° 47.0'N, Long. 112° 04.3'W) near Salt Lake City was 58.9°C/km. This hole was drilled into the interbedded sandy and muddy layers of the relatively unconsolidated Lake Bonneville deposits. Although a core drill was used, core recovery was very poor because of the unconsolidated nature of the deposits, and no core was available for laboratory measurements of thermal conductivity.

The high gradient of 58.9°C/km 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 percent of 2.0 mcal/cm-sec-°C. This value could presumably be used as an indication of the thermal conductivity of the material in the hole in Jordan Valley. The conductivity of the Bonneville sediments is probably larger than 2.0 mcal/cm-sec-°C for two reasons: (1) the Bonneville sediments contain more quartz (in the sandy layers) than deep oceanic sediments contain, and (2) because the porosity of a sand is generally less than the porosity of a typical oceanic lutite, which may contain 75 percent water, a sand contains more solid material per unit volume than a lutite. Many well-consolidated shales and sandy shales have thermal conductivities 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, but less than 4.0 mcal/cm-sec-°C. If a value of 3.0 mcal/cm-sec-°C is used, the heat flow value would be about 1.8  $\mu$ cal/cm<sup>2</sup>-sec.

This value of heat flow is the approximate value of the regional heat flow in Jordan Valley. According to Marine and Price (1964, p. 47), Jordan Valley contains two areas of thermal springs. The hole under discussion was drilled in an area which is characterized by warm water above 60°F. Temperatures in this hole were found to be about 61°F at depths below 50 meters.

La Sal, Utah. Most of the holes logged were in the Chinle Formation which is composed of fluvial mudstones and sandstones with irregular conglomeratic beds which probably represent ancient stream channels. Temperatures were measured in four holes close together belonging to the Atlas Minerals Corporation in the Big Indian mining district. Detailed information can be found in Wright (1966). The measured temperatures give a straight-line least squares gradient of about 17.7°C/km. High coefficients of correlation indicate a nearly linear relation between temperature and depth. The gradient typically passes several times through maximum and minimum values of about 22 and 14°C/km, respectively. The plots of temperature gradient versus depth are similar for all of these holes. The shapes of the gradient curves indicate the existence of beds of different thermal conductivity. The 14°C/km-gradient is measured in the more sandy layers, (quartz has a high thermal conductivity), whereas the 22°C/km-gradient is representative of the shaly beds. Core was not available from these holes.

Since no core was available, thermal conductivity was measured from bulk rock specimens. Table 2 gives the measured thermal conductivity values along with disc thickness and a brief rock description. The four specimens labelled H66 were taken from the lower 75 feet of the Chinle Formation. Specimens 1L66 through 11L66 were taken from surface exposures on the Wingate-Chinle cliff and talus slope immediately east of the La Sal triangulation station (Lat. 38°14' 16.9"N., Long., 109°16' 20.7"W.). Specimens 1SJ66 and 11L66 are both representative of the Wingate Sandstone. The remainder of the L66 specimens are from the upper 200 feet of the Chinle Formation. All specimens were collected within 3.5 miles of the holes. Table 2 also gives an estimate based on hand specimen examination of the amount of quartz sand in the rock. In general, it can be seen that the more sandy portions of the Chinle Formation have a higher thermal conductivity than the more muddy portions. Specimen 8H66, with an approximate sand content of 80 percent, was found to have a thermal conductivity of 8.37 mcals/cm-sec-°C. Specimen 9H66, with an approximate sand content of 10 percent, had a thermal conductivity of 5.45 mcals/cm-sec-°C. The other Chinle specimens had conductivities and sand contents between these extremes.

Disc Number	Thickness (inches)	Conductivity mcals/cm-sec-°C	Location	Remarks
4H66-1	1/2	6.88	Alice incline	Chinle, 20% quartz; sandy mudstone
4H66-2	1	7.16		
6H66-1	1/2	7.40	Alice incline	Chinle, 50% quartz; muddy sandstone
6H66-2	1	7.68		
6H66-3	1/2	7.28		
6H66-4	1	7.08		
8H66	1	8.37	Alice incline	Chinle, 80% quartz; sandstone
9H66	1	5.45	Alice incline	Chinle, 10% quartz; mudstone
1L66-1	1/2	7.05	Surface	Chinle, 70% quartz; muddy sandstone
1L66-2	1	7.50		
2L66	1	7.98	Surface	Chinle, 80% quartz; sandstone
5L66	1	6.09	Surface	Chinle, 75% quartz; muddy sandstone
6L66	1	7.98	Surface	Chinle, 70% quartz; muddy sandstone
7L66	1	6.42	Surface	Chinle, 70% quartz; sandy mudstone
9L66-1	1/2	5.42	Surface	Chinle, 40% quartz; sandy mudstone
9L66-2	1	6.00		
11L66-1	1/2	11.50	Surface	Wingate, 95% quartz; sandstone
11L66-2	1	12.19		
15J66-1	1/2	11.67	Surface	Wingate, 95% quartz; sandstone
15J66-2	1	12.10		

Table 2. Thermal conductivity measurements from La Sal area.

The average value of thermal conductivity for the 10 specimens from the Chinle Formation was 6.9 mcal/cm-sec-°C. It is unlikely, however, that this value represents the average Chinle conductivity. The 166 specimens in the Chinle were collected from a slope on which outcrops projected through the talus. The beds which had survived surface weathering enough to form a resistant outcrop were the more sandy layers. Also, the more shaly layers of the Chinle were highly weathered, and were too incompetent to make discs. Therefore, specimen collecting was biased toward the sandstones, and the average thermal conductivity of the Chinle Formation is probably less than 6.9 mcal/cm-sec-°C. The Chinle has been described in many areas near the Big Indian mining district (Dane, 1935; Barber, 1933; Rodgers, 1954). These descriptions, taken as a whole, indicate that the typical Chinle is about 50 percent sandstone, and about 50 percent shale or mudstone. The average conductivity of the three mudstones (less than 50 percent quartz) in the La Sal specimens listed in Table 2 is 5.9 mcal/cm-sec-°C; the average conductivity of the sandstones (50 percent or more quartz) in these specimens is 7.3 mcal/cm-sec-°C. The mean of these values is 6.6 mcal/cm-sec-°C, the value accepted as the average thermal conductivity of the Chinle Formation.

The measured temperature gradient and thermal conductivity can be combined in several ways to obtain a heat flow value. The average geothermal gradient in the Chinle Formation was observed to be 17.7°C/km. The average thermal conductivity for the Chinle was 6.6 mcal/cm-sec-°C. The product of these two quantities indicates a heat flow value of 1.2  $\mu$ cal/cm<sup>2</sup>-sec. Also, the temperature gradient in the Wingate Sandstone was 12°C/km, and the measured thermal conductivity of the Wingate was about 12  $\mu$ cal/cm-sec-°C. The product of these two quantities gives a heat flow of 1.4  $\mu$ cal/cm<sup>2</sup>-sec.

Temperature measurements taken in the Chinle Formation in the HR-65 holes indicated the existence of beds of varying thermal conductivity. A gradient of about 14°C/km was typical in the most sandy layers. Chinle sandstone beds had an average conductivity of about 8 mcal/cm-sec-°C. A heat flow of 1.1  $\mu$ cal/cm<sup>2</sup>-sec is therefore indicated in the sandy layers of the Chinle. Also, the more muddy layers had a gradient of about 22°C/km, and a conductivity of about 5.9 mcal/cm-sec-°C. A heat flow value of 1.3  $\mu$ cal/cm<sup>2</sup>-sec is thus indicated in these beds.

Since these heat flow values all agree to within about 20 percent, a value of  $1.2 \pm 0.2$   $\mu$ cal/cm<sup>2</sup>-sec is believed to be representative for the La Sal, Utah area.

A topographic evolution correction to correct for effects of topography, uplift and erosion (Birch, 1950) was calculated for the La Sal holes. The uncertainty placed on the uncorrected heat flow value for La Sal was 20 percent. The computed topographic evolution corrections were only a few percent and so no correction was necessary. The value of  $1.2 \pm 0.2$  mcal/cm<sup>2</sup>-sec is the corrected heat flow value at La Sal, Utah.

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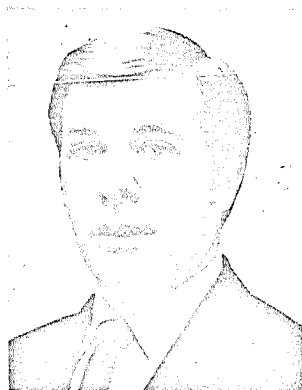
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