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Geothermal Measurements at Mount Isa, Queensland

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Abstract. A detailed geothermal study has been made in the region of Mount Isa in the Precambrian shield of northeastern Australia, involving 14 vertical or steeply dipping diamond-drilled holes in the Mount Isa Mine, 11 surface holes in the surrounding area, and 3 holes 50 km to the east of Mount Isa. The measured temperatures have been combined with 188 thermal conductivity determinations to give heat fluxes varying from 1.49 to 2.57 μcal/cm^2 sec, with a weighted mean for the Mount Isa region of 1.96 ± 0.03. The errors introduced by conductivity determinations, the method of computation of the heat flux, structural features, surface water, ventilation, and leaching and oxidation are discussed. The need for geothermal studies involving more than one borehole and detailed geological information, if a reliable value for the geothermal heat flux is to be obtained, is emphasized, particularly in areas with large conductivity contrasts and steeply dipping structures.

Introduction

Heat-flow measurements have now been published for some 24 locations in Australia [cf. *Howard and Sass,* 1964; *Sass,* 1964]. In view of the need for detailed and systematic studies to determine the extent of the area represented by and the reliability of a single heat-flow measurement, a detailed study was made of the Broken Hill region of New South Wales [*Sass and Le Marne,* 1963]. The only remaining place in Australia where a large number of boreholes is available in a small area is the Mount Isa region, which is the subject of the present study.

Mount Isa is in northeastern Queensland, 400 km south of the Gulf of Carpentaria, at 20°47′S, 139°29′E, with a surface elevation of 400 m. Geologically it lies centrally in the small Queensland Precambrian shield of some 100,000 km^2 [*Jones,* 1953; *Carter and Brooks,* 1965]. The general structure of the Precambrian rocks is that of a huge north-south anticline with its axis about 40 km east of Mount Isa. A number of smaller anticlinal and synclinal structures are associated with each limb. Strong shearing and faulting is evident, particularly around Mount Isa. In this area the strata consist of thick alternating sequences of dolomitic, siliceous, and carbonaceous shales and siltstones dipping at 60 to 80°. To the west of the Mount Isa Mine lies a metamorphic complex of amphibolites and schists. These are bounded on the west about 300 m from the mine by the Mount Isa fault or shear zone [*Carter,* 1953, 1958; *Knight,* 1953; *Murray,* 1961; *Bennett,* 1965].

The relative positions of the measured boreholes at Mount Isa are given in Figure 1. All but one of the underground holes were collared on the 13 level of the Mount Isa Mine at a depth of 700 m below the surface. The remaining hole (L 60) was collared on the 15 level, 70 m deeper. These holes generally penetrated 300 to 400 m for a maximum depth below the surface of 1200 m, and occupied a north-south line extending for 1500 m. The surface holes extend for a distance of 10 km to the north and south of the mine.

Three holes were measured at the Blockade Mine, 50 km to the east of Mount Isa at 20°35′S, 140°00′E. They lie in a broad zone of metamorphics, consisting of altered feldspar porphyrys and chlorite schists, intersected by numerous amphibolite dikes.

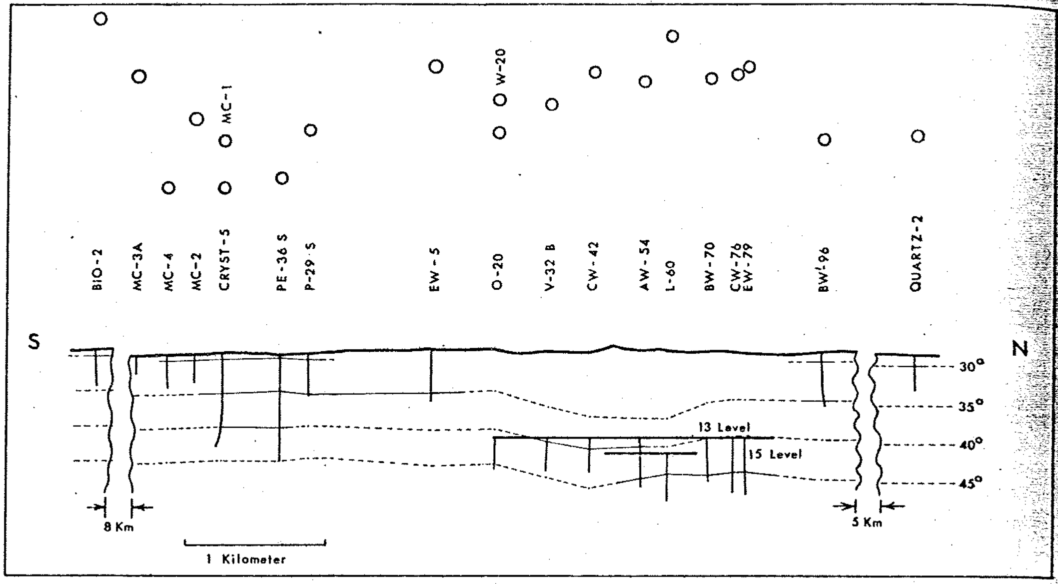

Fig. 1. Relative positions of boreholes and isothermals at Mount Isa. The isothermals given by broken lines were obtained from the extrapolation of least-square temperature gradients.

Temperature Measurements

Temperature measurements were made with thermistor probes and a Wheatstone bridge with a transistorized current amplifier as described by *Howard and Sass* [1964]. This instrumentation provided a precision of ±0.02°C for temperature differences, with absolute temperatures to better than ±0.1°C.

In the majority of holes collared on the surface, temperatures were measured at 15-m intervals, starting below the water table. Temperatures in holes that started underground were measured at 30-m intervals, except for those holes with nonuniform temperature gradients where the intervals were reduced to 15 or 8 m. The top 50 to 100 m of the underground holes were measured in detail to outline the nature and extent of the cooling resulting from mine ventilation. The upper 100 m of one surface hole (BW′ 96) subject to the cooling effect of a large tailings pond was also measured in detail. In all inclined holes, vertical depths were determined from the measured length and the inclinations measured after drilling. A profile of isothermals is given in Figure 1.

The least-squares gradient determined for each hole is given in Tables 4 and 5. The part of underground holes affected by ventilation and the top 50 to 100 m of surface holes, where temperatures may be affected by variations in surface temperatures and by the flow of groundwater, have been omitted in determining the gradients. In one hole (PE 36 S), in which the drilling had ceased only 44 hours before the measurements, temperatures from the bottom 15 m were also omitted [cf. *Jaeger*, 1961]. The mean gradient of the underground holes, weighted according to the length of the holes, was 19.9 ± 0.5°C/km; the mean for all the holes in the Mount Isa region was 19.8 ± 0.4.

The mean temperature gradient for the three holes measured in the Blockade Mine area was 19.3 ± 0.8.

Because the maximum relief of both the Mount Isa and Blockade areas is only about 40 m, no topographic correction to the gradient is necessary.

Thermal Conductivity Measurements

Thermal conductivity measurements were made with the divided bar apparatus described by *Beck* [1957] and with a two-boiling-liquids apparatus designed by *Schröder* [1963]. Both instruments were calibrated with the values for quartz given by *Ratcliffe* [1959]. The divided bar operated at a mean specimen temperature

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Pyritic shale
Carbonaceous s
Silica dolomite
Greenstone*

* These rocks are gene

of 25°C. This is somewhat lower than the rock temperatures in the measured boreholes; hence the measured conductivities will generally be slightly higher than their in situ values. The maximum error should be for quartz-rich specimens; it is less than 3% for the highest in situ temperatures. The Schröder instrument was operated at a mean specimen temperature of 35°C. Both instruments used 6-mm-thick specimens. A direct comparison of the Beck and Schröder instruments was made by overdrilling sixteen 35-mm divided bar disks to 18-mm diameter for the Schröder instrument (Table 2). A systematic difference of about 4% was noted, part of which may be accounted for by the different specimen temperature. The Beck divided bar gives reproducible measurements to ±2%, whereas the Schröder instrument appears to give values reproducible to about ±4%. The divided bar was thus used wherever the drilled core or sample was large enough to make 35-mm disks and the two-boiling-liquids instrument was used for smaller sizes.

An anisotropy of from 5 to 30% has been observed in the conductivity parallel and perpendicular to the bedding of foliated shales and siltstones (Table 1). Since the dip of the foliation in the mine is fairly uniform, the effective vertical conductivity could be obtained by combining the conductivities perpendicular ($K_\perp$) and parallel ($K_\parallel$) to the foliation according to

$$K_v = (K_\perp^{-2} \cos^2 \theta + K_\parallel^{-2} \sin^2 \theta)^{-1/2} \qquad (1)$$

In near-vertical holes or vertical parts of holes, the conductivity specimens were simply cut across the axis of the core to obtain the vertical conductivity.

With the exception of the mineralized zones, all the rock types encountered were relatively fine grained, so that the grain sizes were never an appreciable fraction of the thickness of the sample conductivity disks. The difficulty of the short-circuiting effect of high-conductivity grains [cf. *Birch and Clark*, 1940; *Beck and Beck*, 1958] thus does not arise.

In computing the mean conductivity for each rock unit in which it is assumed there is no systematic variation in conductivity from a number of conductivity samples, there is some question as to what mean should be used. The choice is of secondary importance, however, in comparison with sampling errors. In our choice we have been guided by the geometry of the field situation. For the near-vertical holes from the surface we have the largest amount of information for the vertical column of rocks penetrated by the drill. In this case, because it seemed best to combine the measured conductivities in series, we used the harmonic mean. We listed both the harmonic and arithmetic mean conductivities in Table 4 for the whole length of each surface borehole, and the difference between the two means is only a few per cent in all cases. In the mine area, the conductivity samples were collected from one horizontal level over as large an area as possible, and we used the arithmetic mean or parallel mean conductivity in estimating the effective conductivity of each rock unit.

THE CALCULATION OF HEAT FLOW

All computations of heat flow result from the integration of the heat-flow equation

$$H_z = -K\,\partial V/\partial Z \qquad (2)$$

TABLE 1. Mean Conductivities and Anisotropies for Mount Isa Rocks
Anisotropy is given as the ratio of the conductivity with heat flow parallel to the foliation to that perpendicular to the foliation.

Rock	No. of Specimens	Conductivity (arithmetic mean)	No. of Anistropies Measured	Mean $K_\parallel/K_\perp$
Dolomitic shale	36	9.7	3	1.17
Pyritic shale	6	15.7	6	1.06
Carbonaceous shale	10	8.1	6	1.38
Silica dolomite*	12	9.9		
Greenstone*	16	15.5		

* These rocks are generally isotropic.

where H_z is the component of heat flux in the z direction and K and $\partial V/\partial Z$ are the thermal conductivity and temperature gradient. The simplest form for the integration results from independently summing the temperatures and thermal resistances (per unit area) for the length of the hole being considered. Sums rather than integrals have been used because temperatures and conductivities are usually measured at discrete intervals. This can be expressed as

$$H_z = \sum_i \Delta V_i / (\sum_i R_i \, \Delta Z_i) \qquad (3)$$

where ΔZ_i is the length of borehole penetrating rock of conductivity $K_i = 1/R_i$. $\sum_i V_i$ depends only on the top and bottom temperatures measured in the hole. Temperature data from intermediate depths are not used in the reduction.

If there is no apparent systematic variation of temperature gradient with depth (i. e., temperature varying linearly with depth), it is preferable to combine the least-squares temperature gradient (which allows a statistical measure of the scatter in temperature values) and the mean resistivity according to

$$H_z = (\partial V/\partial Z)_{1.sq.} / (\sum_i R_i \, \Delta Z_i / \sum_i \Delta Z_i) \quad (4)$$

If, on the other hand, there is an indication of systematic changes in gradient with depth, *Gough's* [1963] method, in which individual heat flows are calculated at regular intervals (say 30 to 100 m) along the length of the hole, is appropriate. This can be stated as

$$H_z = (1/N) \sum_i (\Delta V_i K_i)/(\Delta Z_i) \qquad (5)$$

If the heat flux is then plotted as a function of depth, any systematic variation is readily seen. This technique is particularly useful in determining whether changing surface temperatures in the geological past have produced any significant effects.

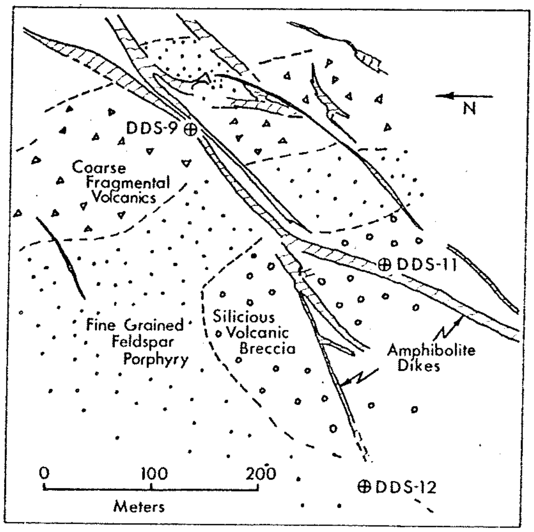

Fig. 2. Relative positions of boreholes and the surface geology at the Blockade.

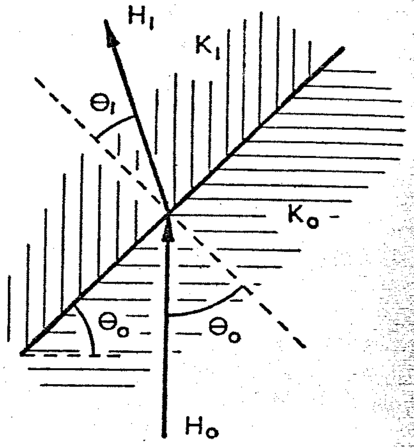

Fig. 3. Geometric refraction.

Where there are layers of rocks having different conductivities, a better method is obtained by integrating equation 1 [*Bullard*, 1939] to give

$$V_z = V_0 + H_z \sum_i \Delta Z_i R_i \qquad (6)$$

H_z can then be obtained from a least-squares determination of the slope of a plot of $\xi(z) = \sum_i \Delta Z_i R_i$ versus the temperature V_z.

All the above methods are designed to determine the best mean value for the flux flowing vertically through the rock immediately adjacent to the borehole. If the lithology is nearly horizontal, this value should approximate that to be expected if the structure were homogeneous. However, if the structure or layering has an appreciable dip angle from the horizontal, refraction of the lines of flow at the boundaries must be taken into account. More heat will flow through the high-conductivity rocks than through those of lower conductivity.

Approximate relations for parallel dipping beds, giving the true geothermal flux that would be expected if the structure were homogeneous,

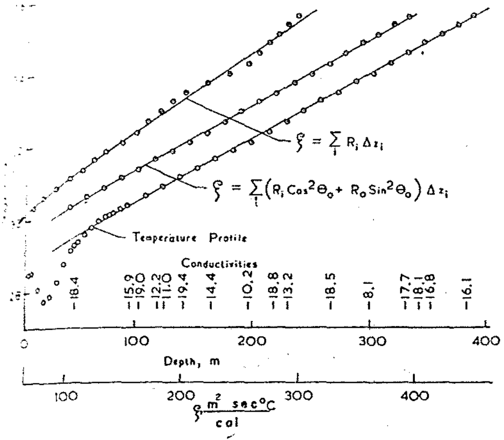

Fig. 4. Temperature-depth profile, the Bullard reduction, and the inclined bed reduction for borehole BW′ 96. The conductivity values are shown next to the depths from which the core samples were taken.

can be obtained by assuming geometrical refraction at the boundaries [cf. *Roy*, 1963]. This implies that the heat flux in each layer is not appreciably influenced by other than adjacent layers. The major difficulty encountered is that of reconciling the requirements that the flux vector become vertical both at the surface (if the surface is horizontal) and at a depth where horizontal layering or homogeneous material is encountered. In most situations both of these restrictions cannot be satisfied by geometrical refraction alone. Ideally, the effect of these two boundary conditions would be added to that of the geometrical refractions. In many cases, however, the measured temperatures will be appreciably closer to either the surface or the underlying region where the flux may be assumed to be vertical, so that consideration of one of these restrictions is sufficient.

From the boundary conditions at the contacts (continuity of normal components of heat flux and tangential components of temperature gradient) (see Figure 3),

$$\tan \theta_0/\tan \theta_1 = K_0/K_1 \qquad (7)$$

$$\cos \theta_0/\cos \theta_1 = H_1/H_0 \qquad (8)$$

where θ_0 and θ_1 are the angles with the normal of the incident and refracted heat flux vectors, K_0 and K_1 are the conductivities, and H_0 and H_1 are the magnitudes of the heat flux in the two mediums. From these two relations the heat flux H_0 (assumed vertical) can be expressed in terms of $(H_1)_v$, the vertical component of H_1 (i.e., that part measured in a vertical borehole),

$$H_0 = \frac{(H_1)_v}{\cos^2 \theta_0 + (K_1/K_0) \sin^2 \theta_0} \qquad (9)$$

where θ_0 is the dip angle of the contact.

This relation will still hold after n refractions, so that H_0, obtained in terms of $(H_n)_v$, is independent of the conductivity of the intervening layers. The effective conductivity then becomes

$$K_{ef} = \frac{\sum_i \Delta Z_i}{\sum_i (R_i \cos^2 \theta_0 + R_0 \sin^2 \theta_0)\Delta Z_i} \qquad (10)$$

where $R_i = 1/K_i$ and $R_0 = 1/K_0$. The heat flux vector is assumed to be vertical in a layer with resistivity R_0. This expression clearly illustrates the magnitudes of the errors that can arise in computing the heat flux when the effect of dipping beds of different conductivities is not considered.

For beds or a conductivity structure with an appreciable dip angle, *Bullard*'s, [1939] method may be similarly generalized. The relation obtained is

TABLE 2. Conductivities from Borehole BW′ 96

Hole Length, m	Conductivities, mcal/cm sec °C Beck Instrument (A)	Schröder Instrument Disks Overdrilled from (A)	Adjacent Disks
48	18.4	17.9	15.7
96	15.9	16.2	16.9
103	19.0	18.1	18.4
119	12.2	10.9	8.5
125	11.0	11.2	10.8
142	19.4	18.6	18.2
165	14.4	14.0	15.8
196	10.2	9.9	9.2
218	18.8	17.2	18.3
228	13.2	13.2	14.4
268	18.5	16.7	17.2
300	8.1	6.9	7.7
332	17.7	17.6	17.8
342	18.1	16.8	16.7
352	16.8	15.8	15.3
382	16.1	15.5	15.9

$$V_z = V_0 + H_0 \cdot \sum_i (R_i \cos^2 \theta_0 + R_0 \sin^2 \theta_0) \Delta Z_i \qquad (11)$$

where H_0 is the flux magnitude in a region where the flux vector is vertical.

Equation 11 is clearly an oversimplification because of the assumptions mentioned above. However, it should be a considerable improvement over the other methods because it takes refraction into account. Equation 11 has been applied to borehole BW′ 96 as a check on the validity of this type of reduction. The flux has been assumed vertical in the underlying shales and siltstones. A plot of the results is given in Figure 4. The dip angle is approximately 70°, and K_0 has been taken as 9.9, the mean value for the shales and siltstones underlying the greenstones (Figure 7). The temperatures and conductivities measured are given in Tables 2 and 3. It is readily seen that (11) approximates a straight line much more closely than (6). In (6) too large a dependence of the measured temperatures on the measured conductivities is assumed. It might be assumed that this implies that the measured conductivities are not representative of any appreciable length of the hole, but this is not borne out by measurements on adjacent samples. Samples that are 2 to 10 cm apart (Table 2) show very close correlation. The fact that the heat flow as calculated from (11) agrees with those measured in other holes in the area (cf. Table 4) also suggests the satisfactory nature of this reduction.

In the present study at Mount Isa, the majority of holes penetrated single rock units with little systematic variation in conductivity. Accordingly, the mean conductivity (harmonic for surface hole core samples and arithmetic for underground hand specimens, as indicated above) of the rock unit penetrated by the hole has been combined with the least-squares temperature gradient, and the heat flux in each hole has been measured.

The evaluation of the heat flux using Bullard's method (equation 6) has very little validity in the steeply dipping Mount Isa structure and has not been applied. The use of (11) for a dipping structure should give a better value for the heat flux, but this unfortunately requires additional information. It has been applied to two surface holes, BW′ 96 and Quartzite 2. Examination of this formula and (10) will also give an indication of the magnitudes of the errors that are possible for the other holes.

The Gough method (equation 5) on 30-m intervals has been applied in most cases to investigate any change in flux with depth. It should be noted, however, that any such variation may be the result of diffraction of heat flow lines in inclined structures of different conductivities rather than the result of climatic variations in surface temperature.

In the Blockade Mine area, with the excep-

TABLE 3. Temperatures Measured in Borehole BW′ 96

Hole Length, m	Depth, m	Temperature, °C
3.0	3.0	28.50
6.1	6.1	28.53
12.2	12.2	28.08
18.3	18.3	27.74
24.4	24.4	27.88
30.5	30.5	28.28
36.6	36.6	28.76
42.7	42.7	29.12
45.7	45.7	29.28
48.8	48.8	29.37
54.9	54.9	29.59
61.0	61.0	29.76
67.0	67.0	29.91
73.1	73.1	30.03
76.2	76.2	30.09
79.2	79.2	30.14
85.4	85.4	30.25
91.5	91.5	30.36
106.7	106.7	30.61
121.9	121.7	30.87
137.2	136.7	31.11
152.3	151.3	31.36
167.6	166.3	31.61
182.8	181.2	31.84
198.0	196.2	32.09
213.3	211.1	32.37
228.2	226.1	32.64
243.9	240.6	32.94
259.1	255.9	33.21
274.1	270.6	33.46
289.7	285.9	33.73
304.8	300.1	33.99
320.0	314.9	34.26
335.2	329.8	34.54
350.3	343.9	34.81
365.8	358.0	35.05
380.9	372.0	35.32
396.1	385.9	35.58

TABLE 4. Temperature Gradients, Thermal Conductivity, and Heat Flow for Holes Drilled from the Surface

Borehole	Hole Depth, m	Temperature Gradient, °C/km	No. of Conductivity Specimens	Conductivity, mcal/cm sec °C			Heat Flux µcal/cm² sec
				Harmonic Mean	Arithmetic Mean	Estimated	
				Mount Isa			
MC 1	670	21.0 ± 0.1	27	8.6 ± 0.3	8.8		1.81 ± 0.08*
							1.93 ± 0.06†
							1.93 ± 0.14‡
MC 2	210	22.4 ± 0.2				9.7	2.10
MC 3A	160	25.8 ± 0.2				9.7	2.50
MC 4	240	20.6 ± 0.1	5	10.0 ± 0.7	10.3		2.06 ± 0.14*
							2.06 ± 0.10‡
PE 36S	750	20.2 ± 0.1	19	9.2 ± 0.6	9.9		1.86 ± 0.13*
							1.94 ± 0.07‡
EW 5	410	18.9 ± 0.1	12	9.3 ± 0.3	9.4		1.76 ± 0.06*
Cryst 5	120	18.2 ± 0.9				9.7	1.76
P 29 S	310	21.4 ± 0.1				9.7	2.08
BW' 96	400	17.7 ± 0.1	16	14.5 ± 0.9	15.5		2.57 ± 0.17*
							2.70 ± 0.12‡
							1.81
Bio 2	280	20.2 ± 0.2	11	9.5 ± 0.3	9.6		1.92 ± 0.03*
							1.90 ± 0.07‡
Quartz 2	280	19.3 ± 0.1	9	7.7 ± 0.2	7.8		1.49 ± 0.05*
							1.49 ± 0.09‡
							1.73
					Weighted mean‖		1.96
				The Blockade			
DDS 9	100	16.7 ± 0.3	3	9.7	9.7		1.62*
DDS 11	350	19.1 ± 0.3	9	9.2 ± 0.5	9.4		1.76 ± 0.12*
							1.81 ± 0.08‡
DDS 12	350	20.2 ± 0.1	7	8.1 ± 0.8	8.5		1.84 ± 0.16*
							1.88 ± 0.08§
					Weighted mean‖		1.78

* Flux calculated from the least-squares temperature gradient and harmonic mean conductivity.

† Flux calculated independently over each of the major geological units penetrated by the borehole.

‡ *Gough*'s [1963] interval method at 30-m intervals, equation 7; equation 11, for steeply dipping structures.

§ *Bullard*'s [1939] method, equation 6.

‖ Mean, weighted according to the length of hole, of flux obtained from the least-squares temperature gradient and harmonic mean conductivity.

tion of numerous nearly vertical amphibolite dikes, there is no evidence for a steeply dipping structure. There is also relatively little scatter in the conductivities. Thus the harmonic mean conductivity is taken as giving the best heat flux value. Bullard's method should be valid in this situation and has been applied in one hole. In all cases, the error limits quoted correspond to the standard error.

SURFACE BOREHOLES

Mining Corporation No. 1. This hole was logged to a depth of 670 m. The top portion penetrates dark gray dolomitic siltstone with occasional brecciation and grades into thinly bedded dark gray dolomitic shale with dolomite stringers at about 380 m. Below 530 m there is extensive (5%) generally fine-grained pyrite. The over-all least-squares temperature gradient is 21.0 ± 0.1°C/km. Conductivities were measured on 27 samples at approximately 30-m intervals. The harmonic mean of these was 8.6 ± 0.3 mcal/cm °C, giving a heat flux of 1.81 ± 0.08 µcal/cm² sec. Since there was some significant difference in the conductivities among the three zones, but not within each zone, the heat flux was also computed by taking the mean of the heat fluxes computed individually for each section. The temperature gradients were, from the top, 21.5 ± 0.1, 19.8 ± 0.4, and 21.4 ± 1.4; the harmonic mean conductivities were 8.2 ± 0.3, 8.5 ± 0.4, and 10.8 ± 0.5, and the heat flux was 1.92 ± 0.14 μcal/cm^2 sec. Applying the Gough method at 30-m intervals gave a flux of 1.93 ± 0.06. The difference among the three methods of computation is thus barely significant. It is of interest to note that, although the mean conductivities in the bottom section are some 30 to 40% higher than in the other sections, the temperature gradients are not significantly different. The probable horizontal extent of the high-conductivity pyrite zone is therefore limited, the temperature gradients being strongly affected by adjacent lower-conductivity rock.

Mining Corporation No. 2. This hole, along with Mining Corporation No. 3A and EW 5, has been measured previously [*Howard,* 1963; *Howard and Sass,* 1964]. No conductivity samples were available, so a mean value of 9.7 has been taken for dolomitic siltstone from adjacent holes. When this is multiplied by a temperature gradient over 210 m of 22.4 ± 0.2, a flux of 2.17 is obtained.

Mining Corporation No. 3A. A gradient of 25.8 ± 0.2 over 160 m has been combined with a mean dolomitic siltstone conductivity of 9.7 taken from adjacent holes to give a heat flux of 2.50.

Mining Corporation No. 4. To the depth measured (240 m), this hole penetrates uniform, thinly bedded, light gray dolomitic shale. The least-squares temperature gradient was 20.6 ± 0.1, and the harmonic mean conductivity for five samples was 10.0 ± 0.7, which gives a heat flux of 2.06 ± 0.14. The Gough interval method gives a flux of 2.06 ± 0.10.

PE 36. The top 610 m of the hole penetrates dolomitic shales which gradually grade into dolomitic siltstones. Between 610 and 660 m, a wide zone of almost pure quartz is encountered. Below 660 m, to the depth measured (750 m), the hole penetrates carbonaceous shale, extensively sheared in places. Because temperatures were measured after a 44-hour break in drilling, the top and bottom 15 m of the hole were omitted in obtaining the temperature gradient. The gradient of 20.2 ± 0.1 and harmonic mean conductivity of 9.2 ± 0.6 for 19 samples give a heat flux of 1.86 ± 0.13. Computing the flux at 30-m intervals gives a flux of 1.94 ± 0.07.

EW 5. To a depth of 430 m, borehole EW 5 penetrates a uniform shale formation. The harmonic mean for 12 samples of the shale is 9.3 ± 0.3 and the least-squares temperature gradient 18.9 ± 0.1 for a heat flux of 1.76 ± 0.06.

Crystalina No. 5. The top 10 to 15 m lies in siltstones, below which the hole penetrates dolomitic siltstones. Measurement to a depth of 120 m gave a temperature gradient of 18.2 ± 0.2. No core was obtained for conductivity measurements, but a mean dolomitic siltstone conductivity of 9.7 from adjacent holes gave a heat flux of 1.76.

P 29 S. Temperatures were measured in this hole to a depth of 310 m. No core samples were available. The hole penetrates a uniform siltstone formation, however. A mean siltstone conductivity of 9.7 from adjacent holes and the gradient of 21.4 ± 0.1 gives a flux of 2.08.

BW' 96. Temperatures and conductivities were measured to a depth of 400 m through a complex metamorphic structure of schists containing varying amounts of chlorite, hornblende, tremolite, actinolite, serecite, and quartz. Several large zones of amphibolite were also encountered. The over-all temperature gradient was 17.7 ± 0.1 and the over-all harmonic mean conductivity for 16 samples was 14.5 ± 0.9, for a heat flux of 2.57 ± 0.17. Applying the interval method in turn gave a flux of 2.70 ± 0.12.

A number of explanations can be suggested for this high value of heat flux. The fact that the conductivities are higher than those in adjacent holes along the near-vertical structure suggests that appreciable refraction of heat into this region has taken place. As indicated by (10), the effective conductivity will be dependent on the adjacent rocks. The geological data (Figure 7) suggest that these should be dolomitic shales. Dolomitic shales encountered in adjacent holes have a mean conductivity of about 9.9. Applying this value to equation 10 and assuming that the contact follows the general 70° dip of the Mount Isa structure yields an effective conductivity of 10.3. This gives a flux of 1.82. Using the same data in equation 11 (Figure 4) results in a heat flux of 1.81. The cooling effect of a large tailings pond may contribute to the high computed flux; this is discussed below.

Biotite No. 2. Biotite No. 2 hole, which lies 10 km south of the mine area, was measured along with Quartzite No. 2, to check the uniformity of the heat flux over a fairly large distance. It penetrates a fairly uniform dolomitic siltstone with zones containing small amounts of pyrite and other sulfides. A gradient of 20.2 ± 0.2 over a depth of 280 m, combined with a harmonic mean conductivity for 11 samples of 9.5 ± 0.3, gives a flux of 1.92 ± 0.08. A value of 1.90 ± 0.07 was obtained by the interval method.

Quartzite No. 2. This hole, located 5 km north of the mine area, penetrates a uniform, relatively homogeneous shale formation. The gradient determined from temperatures to a depth of 280 m was 1.93 ± 0.1. The harmonic mean conductivity of 9 samples was 7.7 ± 0.2, giving a heat flux of 1.49 ± 0.05. The interval method in turn gave 1.49 ± 0.09. A number of superficial explanations for this anomalously low flux may be suggested.

Because the temperature-depth curve for this hole (Figure 5) reaches a constant slope only below a depth of 150 m, the gradient was computed from the temperatures below 150 m (the majority of surface holes have a constant slope within 75 m of the surface). A number of holes showing temperature profiles of this type have been cited by *Diment* [1965]. Movement of groundwater is a possible explanation. There is also always a chance of adjacent or underlying zones of high conductivity in the steeply dipping Mount Isa structure. The fact that the conductivities are anomalously low as compared with other Mount Isa holes, rather than the gradient, adds weight to this hypothesis. Computing (11) with $\theta_0 = 70°$ and $K_0 = 9.7$, the mean shale value for Mount Isa, gives a flux of 1.73. The fact that the hole was found blocked and was cleared by the repeated dropping of drill rods into it some 12 hours before measurement is a third possible cause of the nonlinear temperature variation. Although no water was circulated, some temperature disturbance may have resulted.

Blockade Holes DDS 9, 11, and 12. The three Blockade holes lie about 100 km to the east of Mount Isa in a region of altered feldspar porphyries, intersected by numerous amphibolite dikes (Figure 2). DDS 9, measured to a depth of 100 m, penetrates a 20-m zone of coarse-grained amphibolite, a zone of platy chlorite schist to 35 m, and then siliceous feldspar porphyry. A temperature gradient of 16.7 ± 0.3 was combined with the harmonic mean conductivity for three samples of 9.7 to obtain a heat flux of 1.62.

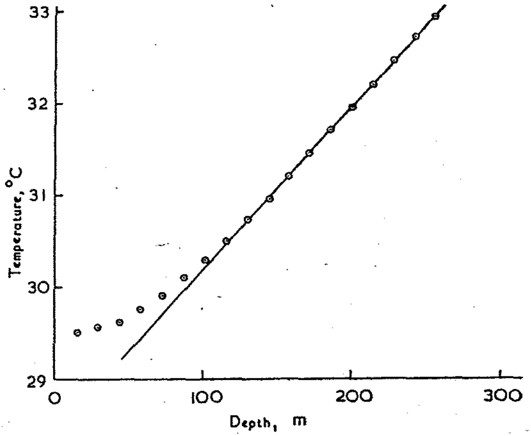

Fig. 5. Temperature-depth profile for borehole Quartz 2.

DDS 11 and DDS 12 intersect a complex structure of feldspar porphyry, scapolitized, sheared, and brecciated in places, with occasional zones of chlorite schists. A least-squares temperature gradient to 350 m in DDS 11 of 19.1 ± 0.3 was combined with a harmonic mean conductivity from 9 samples of 9.2 ± 0.5 to give a heat flux of 1.76 ± 0.12. The method of averaging the flux from 30-m intervals resulted in a value of 1.81 ± 0.08.

In DDS 12, a gradient to 350 m of 20.2 ± 0.1 and a harmonic mean conductivity for 7 samples of 9.1 ± 0.8 gives a heat flux of 1.84 ± 0.16. As there was a fairly large systematic variation in conductivity in DDS 12, the Bullard method was applied. The heat flux so obtained was 1.88 ± 0.04.

Only two of the surface holes penetrated to sufficient depth to give any indication of changes in heat flux with depth. These are MC 1 and PE 368. Borehole MC 1 shows a slight increase in flux with depth, and PE 368 shows a slight decrease. Neither is considered significant, and they may readily be explained by the thermal conductivity structure; MC 1 penetrates a high-conductivity pyrite zone near the bottom, and PE 36S encounters a low-conductivity zone of carbonaceous shales.

The mean extrapolated surface temperature for the 11 holes in the Mount Isa region was 28.66°C. No records are available for the mean annual temperature at Mount Isa, but at Camooweal, 70 km to the west, it is 24.9, and at Cloncurry, 45 km to the east, it is 25.5 [*Bureau of Meteorology*, 1956]. The difference between mean annual air temperature (25.2° assumed for Mount Isa) and extrapolated surface temperature is 3.5°. At the Blockade the mean extrapolated surface temperature is 28.11, for a difference of 2.9°. These differences are quite consistent with the average of 3.0 ± 0.3°C for Australia found by *Howard and Sass*, [1964].

UNDERGROUND BOREHOLES

Fourteen vertical or steeply dipping holes were measured underground in Mount Isa. No core samples were available for conductivity determinations because all the available core had been broken up for assay and analysis. Conductivities, measured on hand specimens from the 13 level, were chosen to represent each rock type encountered in the holes and to be fairly well distributed over the regions of the measured boreholes.

The drilled holes generally penetrate formations of dolomitic, carbonaceous, or pyritic shale, siltstone, and silica dolomite. In a few places extensive copper or lead-zinc mineralization is encountered. The arithmetic mean conductivities have been combined with the least-squares temperature gradient to determine the heat flux. A summary of the results is given in Table 5.

One set of boreholes (V 32, Vertical, East decline 1, and East decline 2) is of particular interest because the three holes, drilled at different angles from the same collar, give sufficient information to permit us to estimate the inclination of the flux vector from the vertical. The dip angles of the boreholes (down to the east) and the components of the flux measured parallel to the holes are: V, 88°, 1.83; ED 1, 72°, 1.80; ED 2, 50°, 1.72. The bottom 30-m part of V, which penetrates a high-conductivity zone, was omitted in determining the flux for that hole. These values give a flux vector inclined at an angle of 15° from the vertical (up to the west). The probable error of this value is unfortunately rather high—about ±7°.

Two holes were omitted in determining the over-all heat flux for the underground holes. In hole L 60, the presence of extensive pyrite made it difficult to estimate the effective conductivity accurately without core samples from the hole. In AW 54, ED 1, leaching was evident in the

TABLE 5. Summary of Underground Holes

Borehole	Hole Depth, m	Temperature, Gradient, °C/km	Conductivity, mcal/cm sec °C	Heat Flux, μcal/km² sec
O-20	211	18.2	9.7	1.77
W-20	192	18.2	9.9	1.80
V-32, Vertical	183	18.5	11.0	2.03
V-32, ED 1	223	20.0	9.9	1.98
V-32, ED 2	171	22.5	9.9	2.22
CW-42	236	18.4	10.6	1.95
AW-54, ED 1	267	25.5	9.9	2.60*
AW-54, ED 2	292	21.1	9.7	2.05
BW-70, ED 1	305	18.5	9.7	1.79
BW-70, ED 2	189	20.9	9.7	2.04
CW-76, WD 1	382	18.9	11.0	2.08
CW-76, WD 2	307	19.1	10.0	1.91
EW-79, Vertical	394	19.1	9.9	1.89
L-60, (15 level)	395	23.7	13.3	3.15*
		Weighted mean	1.96 ± 0.04	

* Not included in the mean.

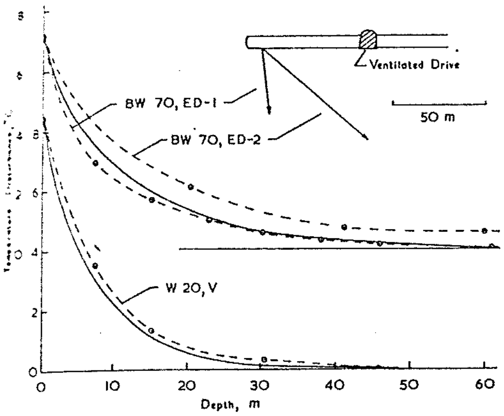

Fig. 6. Computed and observed cooling curves for the penertation of mine ventilation, for boreholes BW 70, ED-1; BW 70, ED-2; and W 20, V.

core, which suggests the movement of underground water in the region of the hole.

The isotherm profile of Figure 1 (along the strike of the geological structure) shows a definite dip of the isotherms toward the center of the mine area. This could be the result of higher conductivities in the mine area. The conductivities for pyritic shales and silica dolomites which are characteristic of the orebody regions are much higher than those of the dolomitic and carbonaceous shales which are found in the same structure but distant from the ore zones (Table 1). Another possible cause is the movement of underground water. This is discussed in the section on leaching and oxidation.

Ventilation. An important source of error in determining undisturbed temperatures in boreholes in mines is the cooling effect of mine ventilation. In shallow holes this cooling must be accounted for by comparison with theoretical cooling curves [cf. *Sass and Le Marne,* 1963]. A correction can then be applied to the measured temperatures. The Mount Isa holes, however, were sufficiently deep so that it was only necessary to determine the distance in the hole beyond which the cooling was negligible. The determination of theoretical cooling curves was complicated by the fact that all but two of the holes (O 20 and W 20) were from near the ends of dead-end crosscuts. Air had been circulated during the drilling operations, but since that time the nearest direct air circulation had been in drives 15 to 100 m distant.

An approximate calculation has been made of the theoretical cooling for holes BW 70, ED 1, and ED 2 using the theory for a cylindrical opening in an infinite medium [*Jaeger,* 1956; *Jaeger and Le Marne,* 1963]. The present measured surface temperature was assumed to have remained constant since the opening of the crosscut. The computed and observed cooling curves are given in Figure 6. As a comparison, the theoretical and observed curves are given for hole W 20, which was drilled from a drive with continuous air circulation. The data used for the holes are shown in Table 6.

A difference between the observed curves for BW 70, ED 1 and ED 2, is evident. The greater depth of cooling in ED 2 is the result of the hole passing fairly closely (within 30 m) beneath a ventilated drive.

The computed disturbances in the BW 70 holes are less than 0.1°C at a depth of 60 m. The remaining holes were drilled after the BW 70's and should have a smaller cooling penetration. No holes other than BW 70, ED 2, pass close enough to a ventilated opening for the temperatures to be appreciably affected.

Leaching and oxidation. A frequently suggested source of temperature disturbance in boreholes in the region of sulfide ore deposits is the heating effect of oxidation. This oxidation may exist naturally [cf. *Lovering and Goode,* 1963] or may be initiated by the development of mine openings. In particular, movement of

TABLE 6. Ventilation from Underground Holes

Borehole	BW-70, ED 1 and 2		W-20
Time since start of ventilation, days	1770		510
Duration of direst ventilation, days	120		510
Mean ventilation air temperature, °C	27.5		26.5
Present temperature at collar, °C	33.0		25.9
Borehole extrapolated surface temperature, °C*	40.2 (ED 1)	39.9 (ED 2)	41.2

* Diffusivity of 0.02 cm²/sec and radius of opening of 3 m assumed.

underground water may cause leaching out of water-soluble minerals such as carbonates. Thus, immediately around mine openings and where the presence of the mine has caused a lowering of the water table, air circulation may be initiated, exposing any sulfides present to oxidation.

Over the whole of the Mount Isa Mine area, the silica dolomite rocks have been leached out down to the depth of the water table (about 60 m), and the sulfides have been oxidized and carried downward. In particular, the Black Rock secondary copper orebody now being opencut mined is the result of the decomposition of chalcopyrite, down to the water table, which has then been transported in groundwater to nearby calcarious shales, where it has been deposited as carbonates and silicates [*Carter*, 1958]. A renewal of this oxidation process might be expected with the lowering of the water table resulting from the opening of the mine. All the deep surface boreholes measured were some distance from the secondary copper orebodies now being mined, so the bottom temperatures were measured in four shallow holes, RM 1, 3, 4, and 5 (80 to 110 m), immediately adjacent to the opencut (Figure 7) to determine any increase in temperature from these processes. *Carter* [1958] estimates the base of complete oxidation to be at 30 to 50 m and the limit of any oxidation to be at 65 to 100 m below the surface in this area. The temperatures agree to within 0.4° of the temperatures obtained at that depth from the least-squares fit in the deeper surface holes. It appears that there is no significant temperature effect in the area of these holes.

In one newly opened underground region of the Mount Isa Mine, temperatures exceeding 100° have been observed (P. J. Solomon, personal communication). These have been ascribed to oxidation processes caused by the exposure of sulfides to ventilation. Such processes might thus be considered as important sources of temperature disturbance in the underground boreholes. However, most of the underground holes were water filled to the collar, and in any case measurements were made only below the water level. Unless there has been significant fluctuations in water levels, or unless the underground water contains enough dissolved oxygen to support appreciable oxidation, any heating should be limited to the tops of the holes. The penetration of such heating would be similar to that of the ventilation cooling. No abnormally high temperatures were observed in the measured holes.

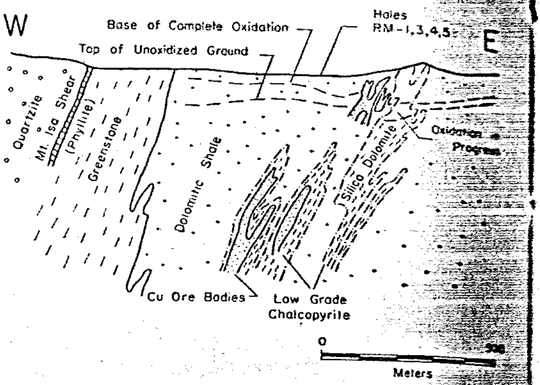

Fig. 7. Geologic cross section at 5000 ft north through the Mount Isa Mine [after *Carter*, 1958].

A more important source of temperature disturbance in the underground holes at Mount Isa is probably the movement of water facilitated by the leaching out of the silica dolomites and dolomitic shales and siltstones. The isotherm profile of Figure 1 shows a dip of the isotherms toward the center of the mine area which may be interpreted as the result of the general downward movement of water through the mine as the lower levels are pumped out. Water percolating through leached rocks would also be cooled whenever it came into contact with regions subject to mine ventilation cooling. In hole AW 54, ED 1, minor leaching was observed over most of the length of the core. A fairly straight line temperature-depth relation was obtained, but the gradient was some 25% higher than the average. A general downward percolation of water through the leached rocks penetrated by this hole is thus suggested.

Surface water. Hole BW′ 96 is collared 15 m from the edge of a tailings pond filled in late 1947. The pond is approximately 1 km long and 500 m across and is quite shallow, the mean depth being less than 10 m. At the time of the measurements (early winter) the temperature of the water in the pond was more than 10° cooler than that at the water table in the hole, 3 m below the collar. It is suggested that the water temperature is kept below the mean surface temperature through evaporation and the inflow of cool runoff water.

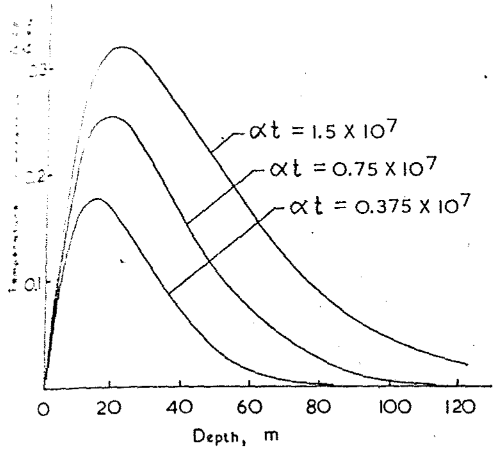

Fig. 8. Computed temperature disturbance on borehole BW′ 96 from the presence of the tailings pond.

The extent to which the pond has affected the equilibrium temperature at a given depth may be determined to a close approximation knowing (1) the mean annual temperature difference between the lake and the surrounding land, (2) the age of the pond, (3) the thermal diffusivity of the rock, and (4) the solid angle subtended by the pond at the depth under consideration. For a shallow pond the solid angle of the pond surface may be used. The surface of the tailings pond has been approximated by a series of circular sectors centered on the collar of the hole and temperature disturbance calculated according to the theory given by *Lachenbruch* [1957].

The diffusivity of the rock has been estimated from the conductivity measurements as $\alpha = 0.028$ cm^2/sec. For a duration of $t = 17$ years this gives a product $\alpha t = 1.50 \times 10^7$ cm^2. As indicated below, this appears to be too large, so the correction has also been computed for $\alpha t = 0.75 \times 10^7$ and 0.375×10^7. The relative corrections $\Delta V_z/\Delta V_0$ (where ΔV_z is the disturbance at depth z and ΔV_0 is the surface disturbance) are given in Figure 8. Using these values, we obtained approximate fits to the observed temperatures by choosing appropriate values for ΔV_0 (Figure 9). The remaining disturbance is largely explained by the penetration of seasonal variations in surface temperatures. The value of $\alpha t = 0.375$ apparently gives the best fit to the observed temperatures. For a pond age of 17 years this implies a diffusivity of 0.007 cm^2/sec, which is unreasonably low for the high-conductivity metamorphic rocks found in this hole. The effective age of the pond is thus likely in error. A possible explanation of the discrepancy is the fact that during the first few years after the pond's formation, warm water from undergound in the mine was pumped into it. This is also suggested by the small positive disturbance from the extrapolated temperatures at depths from 60 to 150 m (Figure 9).

It is seen from the above calculations that there should be a negligible disturbance below a depth of 150 m. Thus, if temperatures below 200 m are used, the heat flow will not be affected by the presence of the pond.

DISCUSSION

A rather large range of heat-flux values has been obtained in the Mount Isa region (1.49 to 2.57). This is in contrast to the study at Broken Hill [*Sass and Le Marne,* 1963], where the flux over 200 mi^2 ranged only from 1.81 to 2.07. The major cause of the large scatter is thought to be structural, the steeply dipping structure of varied conductivity causing a refraction of heat flux. As shown in equations 10 and 11, in order to estimate the true geothermal flux it is necessary to consider the conductivity structure over a large region. The study thus emphasizes the need for measurements in a number of boreholes, along with detailed geo-

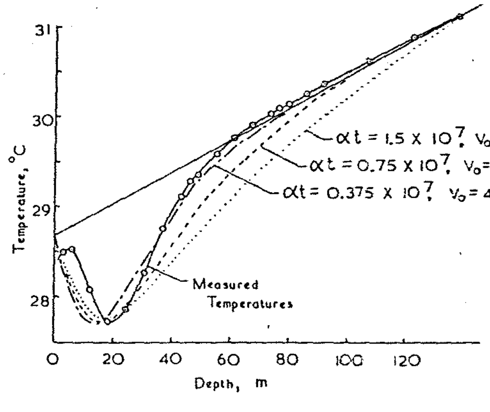

Fig. 9. Computed temperature profiles for borehole BW′ 96. The profiles have been determined for various values of the product of the rock diffusivity and the time of duration of the pond, taking V_0, the surface disturbance, so as to give the best fit.

logical information, if a reliable value for the heat flux of an area is to be obtained. Errors will be particularly large where there is a steeply dipping lithology with beds of appreciably different conductivity.

Ventilation and surface water cooling should not be important sources of error if their effect is carefully computed. Leaching and subsequent oxidation may be important in regions of sulfide ores, but no temperature disturbance has been detected in the holes measured at Mount Isa. A more important source of error appears to be the movement of underground water, particularly where facilitated by leaching processes. Such movement is suggested in one borehole at Mount Isa and may be the cause of a general dip of the isotherms in the mine area.

The differences found in the holes measured at Mount Isa do not indicate any systematic variations in heat flux. However, because of the large potential error in a single measurement, only a fairly large variation could have been detected.

There is a significant difference in heat flow between the Mount Isa and Blockade regions, 50 km apart, but more holes would be necessary in the Blockade area to show this conclusively. There are no obvious differences between the known geological parameters of the two areas with which the difference in heat flows could be associated.

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