Heat Flow Measurements in a Low Radioactivity Area of the Western Australian Pre-Cambrian Shield

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Summary

Two measurements in basic low radioactivity rocks on the Pre-Cambrian Shield of Western Australia give heat flows of 0.69 and 0.82 μcal/cm²s. The very low heat flows suggest that the crust in these areas is very depleted in radioactive elements and that the heat flux from the mantle is probably less than 0.4 μcal/cm²s. Anomalously low temperature gradients appear in the top 50 to 200 m of the measured boreholes. This behaviour is shown to be common and is explained in terms of an increase in mean surface temperature 50 to 100 years before the measurements, caused by a clearing or burning of the bush and tree cover.

Introduction

Heat flow measurements by L. E. Howard first showed that low heat flows were characteristic of the Archaean shield of Western Australia (Jaeger & Thyer 1960, Howard & Sass 1954). A number of additional measurements by Sass (1964) confirmed Howard’s results, and measurements on other continents have shown that low heat flows are characteristic of all Archaean continental shields (Lee & Uyeda 1965).

Lambert & Heier (1967a, 1967b) pointed out that most of the shield heat flow values were in basic and ultrabasic rocks which have low surface concentrations of radioactive heat-producing elements and which make up less than 20 per cent of the shield surface area. A borehole measured by Hyndman et al. (1967) in a high radioactivity granitic area of the shield has substantiated the low shield heat flows, although the measured value of 1.2 μcal/cm²s is slightly higher than the average of previous shield heat flows. They have shown that the Australian surface heat flow and radioactivity measurements indicate that in most of the shield the radioactive elements must be concentrated in a thin surface layer. In areas of low radioactivity surface rocks where very low heat flows have been measured, this high radioactivity surface layer is largely absent. They estimated crustal radioactivity profiles for areas of high (granitic) and low (greenstone) surface radioactivity.

An important factor in estimating crustal radioactivity and temperature profiles
is the heat flow coming from the mantle. If the mantle heat flow can be assumed to be similar in all continental areas (cf. Clark & Ringwood 1964) an important upper limit to the mantle heat flow is set by the lowest reliable surface heat flows measured. That the deep crust and upper mantle is similar under the basic greenstone and granitic shield areas is suggested by the gravity measurements of Everingham (1965) and the electrical conductivity data of Everett & Hyndman (1967).

The Kalgoorlie greenstone area is the largest region of basic, low radioactivity rocks in the Western Australian shield. The basic rocks appear to persist at least to a depth of 4km (Everingham 1965) implying that the high radioactivity surface layer is absent. The total crustal radioactivity and crustal heat production should therefore be as low as anywhere on the Australian continent and very low heat flows are to be expected.

Near surface temperature disturbance

It was first recognized by Diment (1965) that anomalously low temperature gradients in the top 50 to 200m of boreholes was a common occurrence. He emphasized that shallow boreholes, less than 200m deep, may give unreliable heat flow values. He suggested the cause was probably flow of groundwater through the boreholes or a climatic change. Groundwater movement undoubtedly causes disturbed temperature profiles, but it is difficult to understand how water flow could give such a constant form of temperature disturbance in widely different areas and structures. Diment & Weaver (1964) concluded that the low near surface gradients at Puerto Rico were due to the clearing of heavy tropical vegetation. Hyndman (1967) suggested a similar clearing of vegetation for the low near surface temperature gradients in several boreholes in Queensland.

The dependence of mean ground surface temperature on vegetation is a complex problem in microclimatology (e.g. Geiger 1950) but one important fact is evident: ground covered by heavy vegetation will have a lower mean ground temperature than grassland or bare ground. It is then easy to explain why no high temperature gradients near the surface, associated with a decrease in surface temperature, are observed. Heavy vegetation may be removed suddenly, either by clearing for agriculture or by bush fires, but heavy vegetation will generally take a number of years to grow again.

In southwestern Australia, anomalously low near surface temperature gradients appear in the top 50 to 200m of most of the heat flow boreholes that have been measured (Howard & Sass 1964, Sass 1964, Hyndman et al. 1967). An increase in mean annual surface temperature about 75 years before the measurements will explain most of these temperature profiles. This time corresponds to the beginning of the gold rush to southwestern Australia, when large amounts of timber were cut for mine pit props and for firewood, and burning off to facilitate prospecting occurred. The areas where boreholes for heat flow measurements are available usually are the same as those that were first prospected and mined at this time. Agricultural clearing also became common 50 to 100 years before the measurements, particularly within 300 km of the west coast. Around Kambalda a large number of small mines and prospects were first worked about 75 years ago.

The borehole temperature profiles presented here for Kambalda all have low gradients near the surface which can be explained by an increase of 1°C in mean annual surface temperature about 75 years before the measurements. The theory for such a sudden change is given by Lachenbruch (1957) or Carslaw & Jaeger (1959). We have estimated the diffusivity of the rocks to be about 0.015 cm²/s. The measured and corrected temperatures are given in Fig. 1. The temperature profile for Kalgoorlie hole SE 13 (Fig. 3) also shows a low temperature gradient in the top 50m.
Kambalda

Kambalda is a new nickel mine recently opened by Western Mining Ltd. about 75 km southeast of Kalgoorlie in the Kalgoorlie greenstone belt (long. 121° 41' E, lat. 31° 17' S). Seven boreholes were measured to depths ranging from 125 to 275 m. They lie approximately in a N–S line 400 m long. The mine is a newly-developed prospect so little geological information is available but the region consists of fairly strongly folded sequences of porphyry, serpentine and basalt. The bedding intersected by the holes generally dips less than 45°.

The pronounced curvature in the upper 150 m of the temperature profiles discussed in the previous section, is evident in all of the holes (Fig. 1). There is no associated systematic variation of conductivity and it seems unlikely that water flow could produce such a uniform disturbance in seven holes. The surface temperature obtained...
from extrapolating the temperatures from below 150 m is about 22.0°C which is in good agreement with that from SE 13 (22.4°C, see below) and SE 4 (22.5°C, Sass 1964), near Kalgoorlie. The temperatures have been corrected on the basis of a 1°C surface temperature increase about 75 years before the measurements. The uncorrected gradients from temperatures below 150 m and the corrected gradients from temperatures below 90 m are given in Table 1. The mean is weighted according to the measured lengths of the holes.

Table 1

<table>
<thead>
<tr>
<th>Borehole</th>
<th>KD 18</th>
<th>KD 7</th>
<th>KD 23</th>
<th>KD 8</th>
<th>KD 5</th>
<th>KD 20</th>
<th>KD 6</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>274</td>
<td>242</td>
<td>208</td>
<td>195</td>
<td>181</td>
<td>178</td>
<td>122</td>
<td>9.1</td>
</tr>
<tr>
<td>Uncorrected gradient (°C/km)</td>
<td>9.1</td>
<td>9.6</td>
<td>8.7</td>
<td>9.7</td>
<td>8.3</td>
<td>7.7</td>
<td>9.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Corrected gradient (°C/km)</td>
<td>9.3</td>
<td>9.3</td>
<td>8.8</td>
<td>8.5</td>
<td>8.6</td>
<td>9.2</td>
<td>8.6</td>
<td>9.0</td>
</tr>
<tr>
<td>Uncorrected heat flow (μcal/cm²s)</td>
<td>0.69</td>
<td>0.73</td>
<td>0.66</td>
<td>0.74</td>
<td>0.63</td>
<td>0.59</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td>Corrected heat flow (μcal/cm²s)</td>
<td>0.71</td>
<td>0.71</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.70</td>
<td>0.65</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Thermal conductivities were measured on 27 samples from the core at uniform intervals in the holes. The measurements were made on a 32 mm diameter, 6 mm thick disks with a conductivity apparatus of the type described by Birch (1950). The instrument is to be described elsewhere. A part of an intercomparison between this instrument and the divided bar apparatus constructed by Beck (1957), seven of the above samples were measured first on the Beck divided bar (35 mm in diameter) then reduced in diameter to 32 mm and remeasured on the Birch type instrument. The agreement is within 2 per cent on all samples.

The three main rock types were represented in approximately the proportions they appear in the holes. There is a barely significant difference in the mean conductivities (porphyry, 7.8; serpentinite, 7.8 and basalt, 7.1 mcals/cm²°C). The
basalt which has a slightly lower conductivity than the other rock types appears in only about 15 per cent of the hole intersections. Fig. 2 shows the measured conductivities. The harmonic mean for the samples was 7.61 ± 0.18 (arithmetic mean 7.74). The harmonic mean conductivity has been combined with the corrected and uncorrected temperature gradients to give the heat flows of Table 1.

The mean heat flow from the uncorrected temperatures is 0.69 ± 0.02 μcal/cm²s and that from the corrected temperatures is 0.69 ± 0.01. The only major uncertainty in this value lies in the disturbed near surface temperatures. As mentioned above, temperature disturbances of the type observed in these holes are common in southwest Australia. None of the disturbances in other areas penetrate to depths greater than 150 m so the temperatures below that are probably reliable in these holes.

![SE-13 conductivity graph](https://academic.oup.com/gji/article-abstract/14/1-4/479/743931)

**Fig. 3.** Temperatures and thermal conductivities measured in drill hole SE 13 near Kalgoorlie.
Kalgoorlie

Borehole SE 13, drilled by Western Mining Ltd. 10 km southeast of the main Kalgoorlie at long. 121° 26', lat. 30° 41', is presently the deepest diamond drill hole in Australia, 2770 m in length, but it was only possible to measure the top 1250 m. This measured portion is nearly vertical. The hole is in the region of the four shallower holes reported by Sass (1964), but is sufficiently distant from Hannan's Lake to avoid the disturbance that appeared in the temperatures he measured. The temperature profile is very linear, except for the top 100 m which exhibits a curvature similar to that at Kambalda (Fig. 3). The least squares temperature gradient is 9.26 ± 0.05 °C/km.

The borehole penetrates the western limb of a steeply dipping synclinal structure of altered basic and ultrabasic rocks. From 0 to 340 m it intersects Williamstown Dolerite and from there to the depth measured, Paringa Basalt. Thermal conductivities were measured on the divided bar apparatus constructed by Beck (1957) (see also Sass 1964). The harmonic mean conductivity for 20 core samples at 61 m intervals in the hole was 8.81 ± 0.23 mcal/cm s °C (arithmetic mean, 8.91). The conductivities increase slightly with depth. This mean compares with Sass's mean for four holes of 10.1 ± 0.1 and his mean conductivity for SE 4, the nearest hole to SE 13 (500 m to the southeast), of 9.24 ± 0.4. The high conductivities appear to be due to carbonates and quartz in the altered rocks.

The harmonic mean conductivity and least squares temperature gradient give a heat flux of 0.82 ± 0.03 µcal/cm² s. This compares with Sass's corrected average for the area of 0.95 ± 0.01 and his value of 0.88 for SE 4. Both the temperature gradient and mean conductivity found in SE 13 are lower than the mean values found by Sass for his four holes. The difference is least in comparison with the nearest hole SE 4. A small but significant trend in heat flow is apparent in this area. The very high conductivities in the higher heat flow holes (10 mcal/cm s °C) compared with lower values common in other parts of the Kalgoorlie greenstone belt (7 to 8) suggests a country rock effect. Heat is refracted to flow out preferentially through regions where the rocks have exceptionally high conductivity.

Howard & Sass (1964) found a heat flow of 0.89 in the Kalgoorlie mines. We consider that this value plus the results from Sass's holes and SE 13 indicate a mean heat flow of about 0.88 for the Kalgoorlie area.

Discussion

The heat flow of 0.69 µcal/cm² s at Kambalda is the lowest Australian heat flow so far measured and is among the lowest of the reliable continental values (Lee & Uyeda 1965). Kambalda is in the centre of the Kalgoorlie greenstone belt where the low radioactivity basic rocks appear to be thicker than elsewhere in the Australian shield. Another low value of 0.72 has been found by Howard & Sass (1964), 11 km south of Coolgardie. If the upper 150 km of their borehole which is subject to a temperature disturbance of the type described above is ignored, a slightly higher value of about 0.80 is obtained. Around Kalgoorlie where higher heat flows have been measured, the low radioactivity greenstones are probably thinner although still must be more than about 3 km thick. The higher heat flows in this area may be associated with high thermal conductivities.

We hesitate to draw conclusions on the basis of one or two heat flow measurements but very low heat flows (0.80 or less) are now fairly common for shields. There are now at least eight published shield values of 0.80 or less, which is about 15 per cent of the shield heat flows reported (Lee & Uyeda 1965). The heat flow from the mantle under Kambalda is not likely to be greater than 0.4 µcal/cm² s and may be less. Even on the basis of the radioactivity profiles of Hyndman et al. (1967) which show a
shield deep crust very strongly depleted in radioactive elements, at least 0.3 μcal/cm²s must be generated in the crust. If the heat flows at Kambalda and other areas with surface heat flux of 0.8 or less are in equilibrium with heat production in the crust, we conclude that either (i) the mantle is fundamentally different under these areas compared with other continental areas; or (ii) the heat flux from the mantle beneath the continents of 0.5 to 0.6, which Clark & Ringwood (1964) obtained by geophysical and geochemical considerations, needs to be re-evaluated.

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References


