Further data on the South-west England heat flow anomaly

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Summary. Temperature gradients and thermal conductivities were determined for a number of exploration boreholes in South-west England in order to verify and further delineate the anomalously high heat flow which has been reported. A pattern is emerging of an anomalously high geothermal gradient and heat flow of about 40°C km⁻¹ and 126 mW m⁻² respectively over the Hercynian granite batholith, with normal values adjacent to it. A synthesis of related data indicates that the heat flow anomaly is associated with convection of hydrothermal fluids and although the mechanism is not well understood it may be caused by a combination of above average natural radioactive heat generation coupled with deep, permeable fracture systems within the batholith.

Introduction

Anomalously high heat flow values based on temperature measurements made at various levels in two mines, have been reported from South-west England (Tammemagi & Wheildon 1974). It is the purpose of this study to verify the above results utilizing data obtained from surface exploration boreholes, and also to further delineate the zone of high heat flow. In all, nine mineral exploration boreholes have been investigated, of which six have yielded useful results.

In addition, Barrow (1974) has statistically analysed temperature measurements made in Cornish mines in the previous century, and investigations of the heat production of the granites of South-west England have been performed (Tammemagi & Smith 1975). This study will synthesize the currently available data in an attempt to delineate and explain the South-west England heat flow anomaly.

South-west England is composed of intensely folded Ordovician to Carboniferous shales and slates into which are intruded a series of Hercynian granite plutons. Gravity surveys (Bott & Scott 1964) indicate that these granites are linked at shallow depth, forming a large batholith which dominates the geography of the peninsula. The outcrops of five major

plutons are shown in Fig. 1. Associated with the granitic intrusion is Cu–Sn–Pb–Zn mineralization. A comprehensive description of the geology of the region is given by Edmonds, McKeown & Williams (1969).

**Method**

An attempt was made to obtain temperature data and conductivity samples from all mineral exploration boreholes as they became available. Fig. 1 shows the locations of the six boreholes from which useful data have been derived. Four of the boreholes (E, I, O, P) are located east of Redruth, Cornwall and two (IGS–2, BKM–4) are situated north of South Molton, Somerset. Preventing boreholes from collapsing after the removal of the driller’s casing so that temperatures could be measured, was the major problem in the acquisition of data. Although borehole E was kept open by inserting a short length of plastic tubing in the top of the hole, this method generally proved unsatisfactory. Subsequently plastic tubing was inserted into the complete length of two boreholes; although this prevented collapse of the borehole it did not stop vertical ground water movement between aquifers at different horizons and the data from one site was rejected while the temperature gradient of the other (I) suffered local perturbation (see Fig. 2). The ultimate solution was to insert 1½-in steel...
pipe into the borehole and to seal the annulus between the pipe and rock with cement. Boreholes O, P and IGS-2 were preserved in this fashion and at the IGS site, the techniques arrested a slight flow of water which was issuing from the borehole. The temperatures of borehole BKM-4 were measured before the drilling casing had been removed.

Temperatures were determined to a relative precision of \( \pm 0.01^\circ \text{C} \), generally at 6-m intervals, using a thermistor resistance thermometer. Measurements were usually made shortly after drilling ceased and repeated a few months later, but for the hole BKM-4 it was not possible to repeat measurements. The temperatures are plotted as a function of vertical depth in Fig. 2. Least-squares methods were used to calculate temperature—depth gradients and the results, along with drilling dates, grid references and other data are listed in Table 1.

![Figure 2. Temperatures as a function of vertical depth. In order to place the temperature profiles of all boreholes on the same plot, some have been shifted to the right. For correct temperatures subtract the amount indicated for each profile.](https://academic.oup.com/gji/article-abstract/49/2/531/587398)

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Gradient ( (^\circ \text{C} \text{ km}^{-1}) )</th>
<th>( T(0) ) ( (^\circ \text{C}) )</th>
<th>Conductivity ( (\text{W m}^{-1} \text{C}^{-1}) )</th>
<th>Heat flow ( (\text{mW m}^{-2}) )</th>
<th>Heat flow* ( (\text{mW m}^{-2}) )</th>
<th>Drilling dates</th>
<th>Measuring dates</th>
<th>National grid reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJ-E</td>
<td>47.2</td>
<td>9.4</td>
<td>2.89</td>
<td>136.5</td>
<td>144.9</td>
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<td>29/12/73</td>
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<tr>
<td>WJ-1</td>
<td>42.5</td>
<td>9.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>15/2/74–</td>
<td>8/9/74</td>
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<tr>
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<td>11.1</td>
<td>2.70</td>
<td>113.1</td>
<td>119.8</td>
<td>10–21/6/74</td>
<td>22/6/74</td>
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</tr>
<tr>
<td>WJ-P</td>
<td>42.3</td>
<td>11.4</td>
<td>2.99</td>
<td>126.0</td>
<td>134.0</td>
<td>26/6/74–</td>
<td>10/7/74</td>
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<tr>
<td>IGS-2</td>
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<td>9.1</td>
<td>4.38</td>
<td>54.0</td>
<td>57.4</td>
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<td>3.44</td>
<td>55.3</td>
<td>59.0</td>
<td>6–21/11/74</td>
<td>22/11/74</td>
<td>SS723323</td>
</tr>
</tbody>
</table>

*Corrected for palaeo-climate.
Boreholes O, P, E and 1 are situated east of Redruth, Cornwall and intersect lower Devonian Mylor slates and silts which are cut by occasional elvandykes (orthoclase and quartz-porphyries) (Rayment, Davies & Willson 1971).

Borehole BK-4, north of South Molton, Somerset, is located in the Pickwell Down Beds, which are of a middle Famennian age in the upper Devonian. Sandstones, with occasional shale, are intersected. The IGS-2 borehole near Simonsbath, Somerset penetrates into the Ilfracombe Beds. These consist of interbedded blue-grey slates, sandstones and limestones of Frasnian age in the upper Devonian. A well-developed cleavage is present and a fracture zone is intersected near the bottom of the hole (Edmonds et al. 1969; K. Beer, private communication).

Thermal conductivities were measured on core samples from boreholes O, P, E and BKM-4 using a divided-bar apparatus and standard techniques (see Tammemagi & Wheildon 1974, for details) and the results are depicted in Fig. 3.

Due to the foliated nature of the country rock at the IGS-2 borehole, the calculation of the conductivity was more complex. Conductivity was measured on 13 core samples and for

Figure 3. Histograms showing number of samples per arbitrary range of 0.42 W/m°C. Arrows indicate harmonic means and numbers in brackets show the number of samples.
five of these, conductivity was determined in two known directions by preparing two discs, cut in different orientations and measuring in the usual way using the divided-bar apparatus. By applying the formula (Kappelmeyer & Haenel 1974, p. 57)

\[ K_\theta = K_\parallel \cos^2 \theta + K_\perp \sin^2 \theta \]  

(1)

where \( \theta \) represents the angle to the axis normal to the plane of bedding, \( K_\parallel, K_\perp \) and \( K_\perp \) could be determined for the five cores from which two conductivity values were available. (The \( K \) subscripts represent the vertical direction and parallel and perpendicular to foliation respectively). The ratio \( K_\parallel/K_\perp \) for these five samples yielded an average of 2.39 and \( K_\parallel \) was calculated for the remaining eight samples by applying this ratio and equation (1). Thus a total of 13 conductivity values in the vertical direction were determined and are illustrated in histogram form in Fig. 3. The harmonic mean is 4.38 W/m°C.

It is felt that individual conductivity values were determined to an accuracy of ±4 per cent or better.

Results

For the three boreholes which were cased in steel and cement (O, P and IGS-2) temperatures were measured approximately one day after drilling ceased and again about two months later. The temperature readings for boreholes O and P showed minimal change over the intervening time interval (less than 2 per cent change in the temperature gradients) and it is concluded that for practical purposes, thermal equilibrium was established by the time the first measurements were made. This is in contrast to theoretical arguments. The boreholes in this study were all of relatively shallow depth with relatively small radii and their drilling operations were of an intermittent character rather than continuous. These factors may account for the minimal effect of the drilling disturbance; in addition, practical observations have indicated that recovery times are generally less than predicted theoretically (Kappelmeyer & Haenel 1974, p. 188). The initial temperature readings at the IGS hole were disturbed by vertical water flow whereas the final readings were not, thus, it is not possible to estimate recovery time there.

Funds were not available to preserve the borehole BKM-4 by inserting steel pipe and cement so that measurements were made after an overnight pause in drilling but before the removal of the drilling casing and the inevitable collapse of the hole. Fig. 2 shows the results, and although the borehole is shallow, the temperatures appear to yield a representative gradient. Since boreholes O and P showed negligible drilling disturbance after one day it has been assumed that BKM-4 was similarly unaffected.

Neither the temperature data nor the conductivities for boreholes E, O, P, BKM-4, IGS-2 indicated any significant variations with depth and therefore, heat flows have been calculated by combining geothermal gradients calculated by least-squares techniques with the harmonic means of the conductivities. Topographic corrections were deemed unnecessary, however corrections for palaeoclimate (as outlined in Tammemagi & Wheildon 1974) were applied. The results are presented in Table 1.

The heat flows for the three Cornish boreholes are in reasonable agreement and yield average values of 125.2 mW m⁻² (uncorrected) and 132.7 mW m⁻² (corrected for palaeoclimate). These values are dramatically in excess of the world mean heat flow of 61.6 mW m⁻² (Lee 1970) as well as that expected for an area which has been stable since the Hercynian (50–59 mW m⁻², Polyak & Smirnov 1968). The high heat flow, uncorrected average of 129.0 mW m⁻², determined by Tammemagi & Wheildon (1974) using data acquired in mines is thus verified. Due to water flow perturbations, a heat flow value was not calculated for
borehole I. However a least-squares linear fit to the temperature data yields a gradient of 42.5°C km⁻¹, providing further confirmation of the high geothermal gradient regime of this area.

The heat flow values of 55.3 mW m⁻² (uncorrected) and 59.0 mW m⁻² (corrected) calculated for borehole BKM-4, are in reasonable agreement with the values of 54.0 and 57.4 mW m⁻² for IGS-2 and with that expected for such a geological environment (50–59 mW m⁻² Polya & Smirnov 1968).

Summarizing all the available data from South-west England, anomalously high heat flow has been observed at Geevor Mine, South Crofty Mine and boreholes O, P, E, and I. Normal heat flows have been determined at the Wilsey Down, IGS—2 and BKM—4 boreholes.

Errors

Any significant errors that may possibly be associated with the above quoted values are not caused by lack of precision in the measurement techniques. However, uncertainties may arise from two other fundamental sources. Firstly, the thermal conductivity of rocks can be quite variable, especially for the relatively small samples used in standard divided bar techniques, and a reasonably large number of samples must be measured to achieve a representative value. The degree of scatter is illustrated by the standard deviations of the conductivity values, which for this study were of the order of 10–20 per cent. The linearity of the temperature profiles indicated that there were no major changes in the conductivities within any one borehole and it is thus felt that the number of conductivity samples were sufficient to yield meaningful values.

Another source of uncertainty may be introduced by ground water flow, or other transient phenomena, disturbing the temperature values. These are generally near-surface effects and can be minimized by utilizing boreholes of sufficient depth. Of the four holes located near the Carnmenellis pluton (O, P, E, I), borehole I is clearly disturbed by water flow between the depths 150 and 225 m. The other borings show no such tendencies and the similarity of their gradients (and their conductivities) indicates that a valid heat flow ±10 per cent, has been calculated for this region. The borehole IGS—2 in Somerset intersected a fault near its bottom which originally issued water. Although the water flow ceased when the steel pipe was cemented into position, the possibility that water flow at depth is disturbing the measured temperatures cannot be eliminated. Borehole BKM-4 is not very deep, however since IGS—2 and BKM—4 yield similar temperature gradients it is felt that the heat flow of 54 mW m⁻² is accurate to about ±20 per cent and is representative of this region.

Discussion

The high heat flows encountered in South-west England are not typical of stable areas well away from tectonic plate margins and thus plate tectonic theory does not offer a framework by which to explain them. The underlying cause is therefore of fundamental interest.

The first step is to attempt to outline the extent of the zone. Barrow (1974) has statistically reappraised temperature measurements made in 111 mines in Western Cornwall in the previous century (Henwood 1843). Using least-squares methods he calculated an average thermal gradient of 41°C km⁻¹ which is in good agreement with the values reported in this study. Thus the sites of the old mines are a useful aid in delineating the zone of high heat flow; this area is outline in Fig. 1.

Although the evidence at this stage is not complete, all the heat flow data obtained over the granite batholith yield anomalously high geothermal gradients as is supported by the
compilation by Barrow (1974) of temperature data from mines of the previous century. In contrast heat flows measured to the side of the batholith are normal. Far more data are required, particularly in the vicinity of the St Austell, Bodmin Moor and Dartmoor plutons, but a distinct pattern is emerging where heat flows over the batholith are anomalously high, while heat flows adjacent to it are normal. If this extrapolation is valid, then the batholith must play a central role in any theory which seeks to explain the heat flow anomaly.

Although the South-west England thermal zone is the first of its kind to be reported in the British Isles, several similar regions exist in Europe. In north-western Czechoslovakia an area with heat flow as high as 184.7 mW m$^{-2}$ is associated with thermal springs (Cermak 1968). A heat flow high in the Upper Rhinegraben of Germany has been identified (Haenel 1971). A prominent thermal high is also located in the Hungarian Basin (Boldizsar 1964) with geothermal gradients exceeding 70°C km$^{-1}$ over large areas. These high gradients have allowed the commercial exploitation of thermal energy. Although the geothermal gradient in South-west England is considerably lower (40°C km$^{-1}$) it is still sufficiently high to warrant investigation as a potential energy resource. Technology does not yet exist for extracting heat from hot dry rocks but research into solving that problem is receiving attention and the method may become viable in the near future (e.g. Smith 1973). A listing of European geothermal areas is not very helpful since the geological settings are not the same as in South-west England. Only in the case of the German anomaly is a granite body involved. In that case the anomalous heat flow is postulated to be caused by the relatively high radioactivity of the batholith (Haenel 1971).

The radioactivity of the South-west England batholith, however, does not appear capable of causing the entire heat flow anomaly according to calculations by Tammemagi & Wheildon (1974). Their calculation assumed conductive heat transfer and required a knowledge of the heat generation of the batholith and of the country rock. At that time heat generation samples were only available from two localities but a comprehensive investigation of the heat generation of the region has since been performed (Tammemagi & Smith 1975). The results verify the previous assumption and thus although the granite is relatively highly radioactive uniformly along its length, it is not sufficiently radioactive to account for all the heat flow. Thus, some other mechanism, associated with the granite batholith, must be sought.

Although not common, high heat flows associated with granite intrusions have been observed elsewhere and a particularly noteworthy example is the Marysville, Montana geothermal anomaly. A thorough geophysical study and drilling program indicate that the high heat flows at this region (up to 835 mW m$^{-2}$) are caused by hydrothermal convection through major fractures in the Cenozoic Empire Stock (Blackwell et al. 1974).

It appears that this may be the cause in South-west England also. Hot waters ranging in temperatures from 24 to 47°C have been reported in Wheal Jane, Mount Wellington Mine, South Crofty Mine, borehole C-28 (Mt Wellington) as well as in several mines of the last century (e.g. see James 1944). All these sites lie over the batholith and it appears that the convective upwelling of thermal waters may be associated with the high heat flow. The driving force for the Marysville Montana anomaly is postulated to be cooling magma at considerable depth; this solution is untenable for the much older granites of South-west England. However deep fractures and major faults exist in the region. Stable isotope studies of the thermal waters are recommended as they may determine the depth of the system, the period of the convection cycle as well as determining any juvenile component. Evidence that deep fracture systems exist in South-west England is also forthcoming from studies of seismicity. There are two areas of earthquakes in the peninsula and their centres are shown in Fig. 1. One area is coincident with the Lands End and Carnmenellis plutons while the other lies to the north-east (Davison 1924).
The sharp transition from high to normal heat flow is not understood, although a similar phenomenon occurs in Marysville, Montana where a second stock acts as a boundary to the anomalous zone (Blackwell et al. 1974). Major faults in South-west England cut across both granite and country rock yet thermal waters appear to be restricted to the batholith. Perhaps the granite, structurally more competent, can support open fractures at depth which act as conduits for water, whereas the country rock cannot, or perhaps the natural radioactivity of the granite provides sufficient heat to drive the convection cell.

Conclusion

Anomalously high heat flow in South-west England has been verified. Further work is required in delineating the zone, but by extrapolating current data, it appears that high heat flow is associated with the granite batholith with normal values adjacent to it. Convection of hydrothermal waters through deep fracture systems may be the underlying cause although the driving heat source has not been identified. It may be that the heat generated by the high levels of natural radioactivity in the granite batholith is sufficient to cause convective flow through deep and permeable fracture systems.

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References


