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HEAT FLOW - HEAT PRODUCTION RELATIONSHIPS IN THE UK AND THE VERTICAL DISTRIBUTION OF HEAT PRODUCTION IN GRANITE BATHOLITHS

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Abstract. Recently the UK heat flow - heat production data-base has been expanded. The linear correlation formerly recognised for southern Britain is now in doubt and there seems no justification for recognising heat flow provinces with characteristic q* and D in the UK. Interpretation of heat flow - heat production data from two voluminous granite batholiths is consistent with geochemical evidence that depth distributions of heat production differ according to magma type.

Introduction

The existence of linear correlations between heat flow (q_o) and surface heat production (A_o) in plutonic and metamorphic terrains from many parts of the world has become well-established in the literature (see summary by Jaupart, 1983). The relationship described originally by Birch et al. (1968) takes the form:

$$q_o = q^* + DA_o,$$

where D is a function of the depth extent of the upper crustal zone of radioelement enrichment and q* represents the heat flow contribution from beneath this zone. Geographic areas within which the relationship is satisfied are known as 'heat flow provinces'.

Heat flow and heat production data reported by Richardson and Oxburgh (1978, 1979) for basement rocks (granite plutons and lower Palaeozoic metasediments) in southern Britain appeared to be linearly related, and the data were interpreted in terms of a classic q_o-A_o heat flow province with $q^* = 27$ mW m^{-2} and D = 16.6 km. Although this value of D is unusually large compared with most other recognised heat flow provinces, the observed relationship gave support to the global applicability of linear q_o-A_o relationships. It was all the more remarkable because the data were derived from several different geological environments and it was difficult to reconcile a common scheme of heat production distribution. Richardson and Oxburgh (1978) concluded that the crustal layer must be relatively unfractionated vertically but varied markedly laterally in terms of its heat production properties.

Since that time further combined q_o-A_o determinations have been made in many parts of the UK during a programme to assess the hot dry rock geothermal potential of the UK (Wheildon et al., 1980; Lee et al., 1984). As a result, the current data-set is more complex and cannot be reconciled in terms of a single UK heat flow province. It is now doubtful whether even southern Britain can be regarded as a single heat flow province (Lee et al., 1987). Here, the UK data-set is reviewed and the validity of linear q_o-A_o relationships examined. In addition, it will be shown that the vertical distribution of heat production in granite batholiths may be inferred from geochemical arguments, entirely independent of linear q_o-A_o interpretations.

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UK Geothermal Map

The new geothermal map of the UK recently published by the British Geological Survey (Figure 1) shows that over much of England, Wales and Scotland the heat flow ranges from 40 to 60 mW m^{-2}. The area-weighted mean for UK is 54 mW m^{-2} (Wheildon and Rollin, 1986). Locally, there are regions where positive heat flow anomalies are associated with: (i) voluminous granite batholiths (labelled EH, LD, WD and SW in inset to Figure 1), (ii) Upper Paleozoic-Mesozoic sedimentary basins (labelled WS, WC, MV, and YL in inset to Figure 1), and (iii) two other areas (labelled BF and just west of YL), where sedimentary basin anomalies are believed to be enhanced by ground-water movement in deep aquifers.

Most of the combined heat flow - heat production determinations are from four regions: the three granite batholiths identified above and the basement of central England and Wales (Figure 1). These are:

(a) The south-west England granite batholith (SW), which is associated with the highest heat flow values (110 to 120 mW m^{-2}) in the UK. The heat flow anomaly is spacially related to the sub-surface form of the batholith (Wheildon et al., 1980). The batholith is of Hercynian age, and comprises peraluminous leucogranites, which were emplaced into low grade Upper Palaeozoic metasediments and volcanics that had been tectonised previously by Hercynian events.

(b) The batholiths of northern England, where the heat flow anomaly extends over both the Lake District (LD) and Weardale (WD) batholiths. They comprise mainly peraluminous leucogranites. The Wensleydale batholith (WN) is a slightly peraluminous biotite granite but has no significant heat flow anomaly. They are all of Late Caledonian (Siluro-Devonian) age and are emplaced into low grade Lower Palaeozoic metasediments.

(c) The Eastern Highlands granite batholith (EH), which is spacially related to a more modest heat flow anomaly. This batholith is also of Late Caledonian age, but was emplaced into the core of an Ordovician metamorphic belt which is believed to be underlain by ancient granulitic crust. It dominantly comprises slightly peraluminous biotite granite, but plutons of dioritic to granodioritic composition also occur, in contrast to the batholiths previously considered.

(d) The central England and Wales region (Figure 1), where data are from low grade metasedimentary basement and

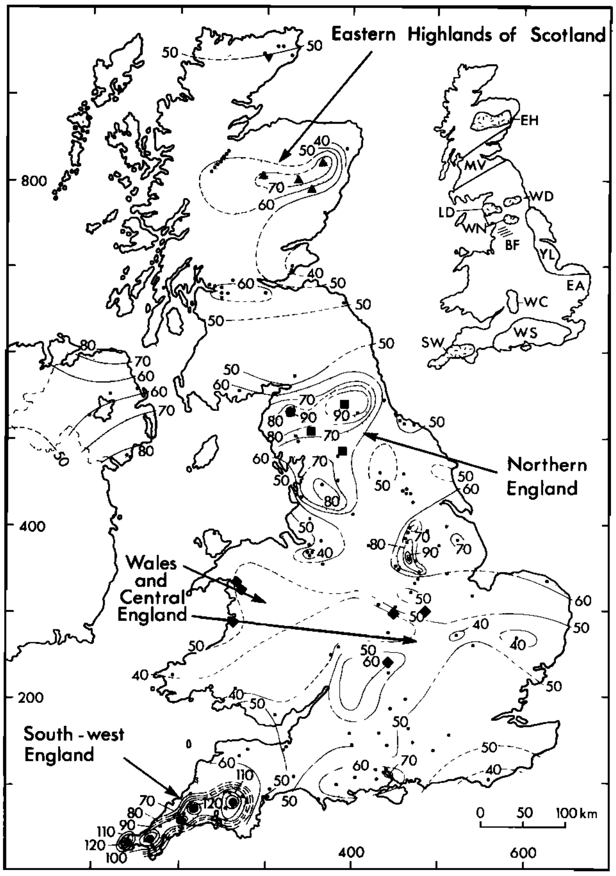

Fig. 1. The simplified UK Heat Flow map based on the Geothermal Map of the UK (British Geological Survey, 1986). Dots indicate locations of heat flow measurements. Filled symbols show sites from which data are plotted in Figure 2. The inset shows granite batholiths and other areas referenced in the text. EH = Eastern Highlands batholith; SW = South-west England batholith; WD = Weardale batholith; LD = Lake District batholith; WN = Wensleydale batholith; WS = Wessex basin; WC = Worcester basin; YL = East Yorkshire and Lincolnshire basin; MV = Midland Valley of Scotland; BF = Bowland Forest Area; EA = East Anglia.

a dioritic intrusion, all of Lower Palaeozoic age. Throughout this area the heat flow is generally low (40 to 50 mW m^{-2}).

Heat flow - heat production relationships

When the current heat flow and corresponding local heat production values are plotted in Figure 2 it is apparent that the data plot as distinct groupings, with little overlap. The form of this graph for the UK data-set has changed considerably from the version that Richardson and Oxburgh (1978, 1979) produced when fewer data were available from high heat production areas (a, b and c above) and the available data apparently followed an almost linear trend (see inset, Figure 2). Superficially at least, it might be argued that there are now two linear trends, one for Scotland, including two points from northern England, the other for much of England and Wales. When examined in more detail, however, each of these trends is little more than a connection between two clusters of data-points, and both trends include the mass of low q_o-A_o data from central England and Wales. A geological case could be made for considering all data from England and Wales where the basement is Proterozoic and younger, separately from those of northern Scotland where the basement is mainly Archaean. Equally, the data from the SW England area, thermally activated last in the Hercynian could be considered separately from data from northern England and central England and Wales last activated in Caledonian times. Added to this problem, the two most southerly data-points from northern England (SH, WN in Figure 2) appear to align with Scottish data whereas the two most northerly data-points (SK, WD in Figure 2) align with south-west England data.

The affiliation of the data from the basement of central England and Wales is not clear. In terms of linear q_o-A_o relationships they occupy a pivotal position. They could be fitted on a line through either the Scottish or the SW England data, but geologically they are from a distinct region, so they might even belong to another, separate heat flow province. Within the cluster of data from these low q_o-A_o basement rocks there does appear to be a positive correlation (Figure 2), but it is not defined well enough to be recognised as a linear relationship. Likewise no such relationship with characteristic q^* and D is discernable for the separate regional data-sets associated with the south-west England and northern England batholiths. Arguably such a relationship could be recognised for the Scottish data (Figure 2), but the slope would be controlled by few data points, one of which (ST) is from the far north of Scotland and plots among the low q_o-A_o cluster. Therefore it is concluded that recognising heat flow provinces as defined by linear q_o-A_o relationships is not appropriate in the context of the present UK data-set.

Distribution of heat production in granite batholiths

Many of the combined heat flow and heat production determinations for the UK are sited on voluminous granite batholiths. The distribution of heat production within those batholiths exerts an important influence on their q_o-A_o relationships. The south-west England and Eastern Highlands batholiths have contrasting thermal properties, featuring, in the former, heat flows of 110 to 120 mW m^{-2} and heat production of 4 to 5 μW m^{-3}, and in the latter, higher heat production values of about 7 μW m^{-3}, but lower heat flows of about 70 mW m^{-2}. It is possible to constrain the vertical distribution of heat production through a simple analysis of these data in combination with off-granite heat flow values which enable high level batholithic contributions to be distinguished from deeper regional contributions.

The difference between on- and off-granite heat flow in SW England is at least 50 mW m^{-2}, and in the Eastern Highlands of Scotland it is about 30 mW m^{-2} (Figure 1). The corresponding difference in heat production between granite and country rocks is about 3 μW m^{-3} in SW England and 5 μW m^{-3} in the Eastern Highlands. A first-order estimate of the depth to which such heat production contrasts might extend may be obtained by dividing the heat flow contrast by the heat production contrast in each case. The result is a depth extent of 17 km in SW England and only 6 km in the Eastern Highlands. Although the parameters used are

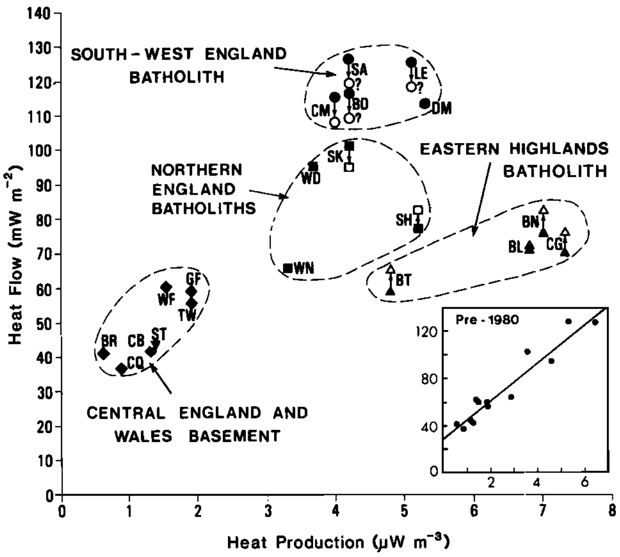

Fig. 2. Heat flow plotted against heat production for UK granites and basement rocks (after Lee et al., 1987). Filled symbols represent measured heat flow, open symbols represent equivalent one-dimensional heat flow. Clusters of data points from specific areas are ringed. The inset shows the pre-1980 correlation (q^* = 27 mW m^{-2}, D = 16.6 km, from Richardson and Oxburgh 1979). Codes identifying data from boreholes into granite are as follows: CM = Carnmenellis Granite, BD = Bodmin Granite, LE = Lands End Granite, SA = St. Austell Granite, DM = Dartmoor Granite, WD = Weardale Granite, WN = Wensleydale Granite, SH = Shap Granite, SK = Skiddaw Granite, CG = Cairngorm Granite, BT = Mount Battock Granite, BL = Ballater Granite, BN = Bennachie Granite, ST = Strath Halladale Granite. Codes identifying data from boreholes into other igneous and metamorphic basement rocks are as follows: CQ = Croft Quarry, BR = Bryn Teg, CB = Coed-y-Brenin, GF = Glanfred, TW = Thorpe-by-Water, WF = Withy Combe Farm.

approximate, they are based on measured values and this simple analysis provides a clear indication that the near-surface abundance of radioelements cannot extend to more than relatively shallow depth in the Eastern Highlands, but should extend to considerably greater depth in SW England. Other factors which may enhance the heat flow in SW England, such as convective transfer of heat, have been considered by Lee et al. (1987) but are not believed to be significant.

The depth extent for the Eastern Highlands batholith derived from an interpretation of gravity data (Rollin, 1984) is about 13 km, much greater than the depth to which the modelled heat production contrast (above) extends. Therefore either the lower portion of the batholith has a low heat production or, more likely, values decrease steadily with depth. Gravity evidence (reviewed by Lee et al. 1987) suggests that the south-west England batholith extends to mid-crustal depths, and in order to explain the high surface heat flow values, heat production must remain fairly uniform with depth.

Independent geochemical evidence (Webb et al., 1985) supports this interpretation that heat production variation with depth occurs to contrasting extents. In the Cairngorm granite, an evolved SiO_2-rich biotite granite, typical of the Eastern Highlands batholith, there is evidence of extensive magmatic fractionation involving enrichment of trace elements such as Nb, Y, heavy rare earth elements (HREEs) and more especially U. Heat production varies from 2.5 to 9 µW m^{-3} across the compositional range 70 to 77% SiO_2. Although the mean surface heat production is estimated as 7.3 µW m^{-3} (taking compositions of borehole samples into account to eliminate effects of near-surface leaching of uranium), a higher proportion of less-evolved rock at depth would considerably reduce the overall bulk heat production. In the Carnmenellis granite, an evolved peraluminous granite, typical of the south-west England batholith, there is again evidence of magmatic fractionation of many trace elements, but abundances of Nb, Y, HREEs do not vary greatly, U increases only slightly, and this is accompanied by a decrease in Th. As a result, surface heat production is nearly uniform between 4.5 and 5 µW m^{-3} throughout the exposed suite of fractionated rocks. From this it is inferred that at depth in less-evolved parts of the batholith the heat production does not differ greatly from surface values. The contrast in trace element, particularly U, fractionation behaviour of the two batholiths is believed to reflect primary differences in magma composition (Webb et al., 1985). Both magmas were rich in fluorine which may complex with heavy metal ions, such as U, causing them to be concentrated in residual melts. This probably occurred during the evolution of the slightly peraluminous magmas of the Eastern Highlands. However, in a strongly peraluminous magma, as in SW England, it is suggested that the formation of aluminofluoride complexes inhibit the complexing of U and consequent magmatic U enrichment (Webb et al., 1985).

In northern England, the Weardale and Wensleydale granite batholiths share a similar tectonic and geothermal environment, but their q_o-A_o data differ. Figure 2 shows that Weardale data (WD) plot near to those of SW England, whereas Wensleydale data (WN) plot closer to those of the Eastern Highlands. Our recent investigations of their geochemistry demonstrates compositional similarities between the magma types from which the Weardale and SW England batholiths evolved, in contrast to those of the Wensleydale and Eastern Highlands batholiths. It is inferred therefore that the two batholiths from northern England have different vertical distributions of heat production that are a function of contrasting types of granite magmagenesis. Such variation in the distribution of heat production cannot be explained readily in terms of a unified scheme such as the exponential decrementation model of Lachenbruch (1970).

Conclusions

In the UK the present heat flow-heat production data-set cannot be interpreted easily in terms of classic heat flow provinces with characteristic q^* and D values. There are at least four thermo-tectonic regions (Lee et al., 1987) represented by the data. The evidence from batholithic regions indicates that primary magma compositions and their evolution are the most important factors in determining q_o-A_o relationships of granite batholiths.

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References

Birch, F., R. F. Roy, and E. R. Decker, Heat flow and thermal history in New York and New England, in: Zen, E-an., W. S. White, T. B. Haddley, and J. B. Thomson, (Eds.), *Studies in Appalachian Geology: Northern and Maritime*, Interscience Publishers, New York, 437–451, 1968.

Jaupart, C., Horizontal heat transfer due to radioactivity contrasts: causes and consequences of the linear heat flow relation. *Geophys. J. Roy. Astron. Soc.*, *75*, 411-435, 1983.

Lachenbruch, A. H., Crustal temperature and heat production: implications of the linear heat flow relation, *Journal of Geophysical Research*, *75*, 3291-330, 1970.

Lee, M. K., J. Wheildon, P. C. Webb, G. C. Brown, K. E. Rollin, C. N. Crook, I. F. Smith, G. King, and A. Thomas-Betts, HDR prospects in Caledonian granites: evaluation of results from BGS-IC-OU research programme (1981-84), *Invest. Geotherm. Potent. UK*, 83pp., Brit. Geol. Surv., 1984.

Lee, M. K., G. C. Brown, P. C. Webb, J. Wheildon, and K. E. Rollin, Heat flow, heat production and thermo-tectonic setting in mainland UK, *Journ. Geol. Soc. Lond.*, *144*, 35-42, 1987.

Richardson, S. W. and E. R. Oxburgh, Heat flow, radiogenic heat production and crustal temperatures in England and Wales, *Journ. Geol. Soc. Lond.*, *135*, 323-337, 1978.

Richardson, S. W. and E. R. Oxburgh, The heat flow field in mainland UK, *Nature*, *282*, 565-567, 1979.

Rollin, K. E., Gravity modelling in the Eastern Highlands granites in relation to heat flow studies, *Invest. Geotherm. Potent. UK*, 17pp., Brit. Geol. Surv., 1984.

Wheidon, J., M. F. Francis, J. R. L. Ellis, and A. Thomas-Betts, Exploration and interpretation of the SW England geothermal anomaly zone, in: A. S. Strub and P. Ungemach, *Proc. 2nd Int. Seminar on results of E C Geothermal Energy Research (Strasbourg, France, 1980)*, Report EUR 7276EN, D. Reidel, Dordrecht, Holland, 456-465,1980.

Wheildon, J. and K. E. Rollin, Heat flow, in: Downing, R. A. and D. A. Gray, *Geothermal Energy: The Potential in the United Kingdom*, HMSO, London, 8-20, 1986.

Webb, P. C., A. G. Tindle, S. D. Barritt, G. C. Brown, and J. F. Miller, Radiothermal granites of the United Kingdom: comparison of fractionation patterns and variation of heat production for selected granites, in: *High heat production (HHP) granites, hydrothermal circulation and ore genesis,* The Institution of Mining and Metallurgy, London, 409-424, 1985.

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