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Heat flow, heat production and thermo-tectonic setting in mainland UK

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Abstract: New heat flow data for the United Kingdom, together with additional heat flow and heat production determinations for Caledonian-age granites, have led to a revision of the UK heat flow map and a re-examination of the relationship between heat flow (q_0) and heat production (A_0) for granites and basement rocks. Previously recognized broad belts of above-average heat flow are now resolved into separate zones which reflect, to a greater extent, the geological structure and tectonic history of the UK. The zones of highest heat flow are spatially associated with voluminous, high heat production granitoid batholiths in SW England, northern England and the Eastern Highlands of Scotland. A single linear correlation between q_0 and A_0 is no longer tenable and an analysis in terms of broad heat flow provinces, each with a characteristic upper-crustal heat production distribution and deep heat flow contribution, is also considered to be an oversimplification. On the q_0–A_0 plot, the data form four separate clusters; three corresponding to the granite batholiths in SW England, northern England and the Eastern Highlands of Scotland, and the fourth to the basement rocks of central England and Wales. An explanation of the q_0–A_0 data is proposed in terms of the crustal structure and thermo-tectonic setting of each area. In the case of the granite batholiths the data reflect the contrasting depth extent and radioelement–depth functions of the intrusions. These parameters in turn are related to the magmatic evolution and emplacement history of each batholith and the nature of the crust into which they were emplaced.

Heat flow through the surface of the Earth can be regarded as the sum of various contributions: principally (1) a sub-crustal component which is related to lithospheric thickness and the time since the last major thermal activation (Polyak & Smirnov 1968; Chapman & Pollack 1975; Sclater *et al.* 1980), and (2) a contribution due to heat production from the decay of uranium, thorium and potassium isotopes within the crust. The heat-producing elements are relatively concentrated towards the Earth's surface and the crustal component can be regarded as the sum of contributions from regionally variable lower crustal sources and locally variable upper crustal rocks. Finally, the true conductive heat flow field may be perturbed by lateral heat transfer owing to fluid movement and convection on both local and regional scales.

Since the reviews of the UK heat flow field by Richardson & Oxburgh (1978, 1979), six new combined heat flow (q_0) and heat production (A_0) determinations have been made on Caledonian-age granites in the English Lake District and the Eastern Highlands of Scotland (Wheildon *et al.* 1984a, 1984b; Lee *et al.* 1984; Webb & Brown 1984a, 1984b), together with 29 separate heat flow measurements in other parts of Britain (Burley *et al.* 1984). The new data bring the total of heat flow observations listed in the British Geological Survey's (BGS) geothermal catalogue to 188 (Burley *et al.* 1984). A new heat flow map based on these values, together with about 100 estimates from temperature observations in deep boreholes, has been published by the BGS and is shown in Fig. 1. Details of the new heat flow and heat production data from the granite sites are included in Table 1. The purpose of this paper is to re-examine the form of the UK heat flow field in the light of these new data and to put forward a revised interpretation of q_0–A_0 relationships for British granites and basement rocks.

The heat flow map

The arithmetic mean of all UK heat flow observations is $69 \pm 28\,mW/m^2$, but this value is heavily influenced by the large number of measurements over the high heat flow zone in SW England. The new area-weighted (10 km grid) mean heat flow in the UK is $54 \pm 12\,mW/m^2$ (Wheildon & Rollin 1986).

The broad belts of above-average heat flow over northern and SW England previously recognized by Richardson & Oxburgh (1978, 1979) are now resolved into well-defined zones (Fig. 1) that reflect, to a much greater extent, the geological structure and tectonic history of the UK. In particular, the zones of highest heat flow are spatially associated with voluminous, high heat production granitoid batholiths as follows:

SW England. Heat flow over the Cornubian batholith (of Hercynian age) is around twice the UK area-weighted mean. The field is well defined by about 40 heat flow observations and the shape of the high heat flow anomaly is closely related to the space-form of the batholith (Wheildon *et al.* 1980, 1981).

Northern England. The main heat flow anomaly occurs over the Lake District and Weardale Caledonian batholiths (Lee *et al.* 1984), but extends south into the Bowland Forest area where evidence for a buried granite is lacking and convective groundwater circulation may contribute to elevated values. The new heat flow value of $101\,mW/m^2$ at Skiddaw (Table 1) is the highest recorded over a UK granite outside SW England. The Wensleydale Granite, where the heat flow is $65\,mW/m^2$ (England *et al.* 1980), lies outside the zone of highest values.

Eastern Highlands of Scotland. New heat flow data from four Caledonian-age granites, which are part of the Eastern

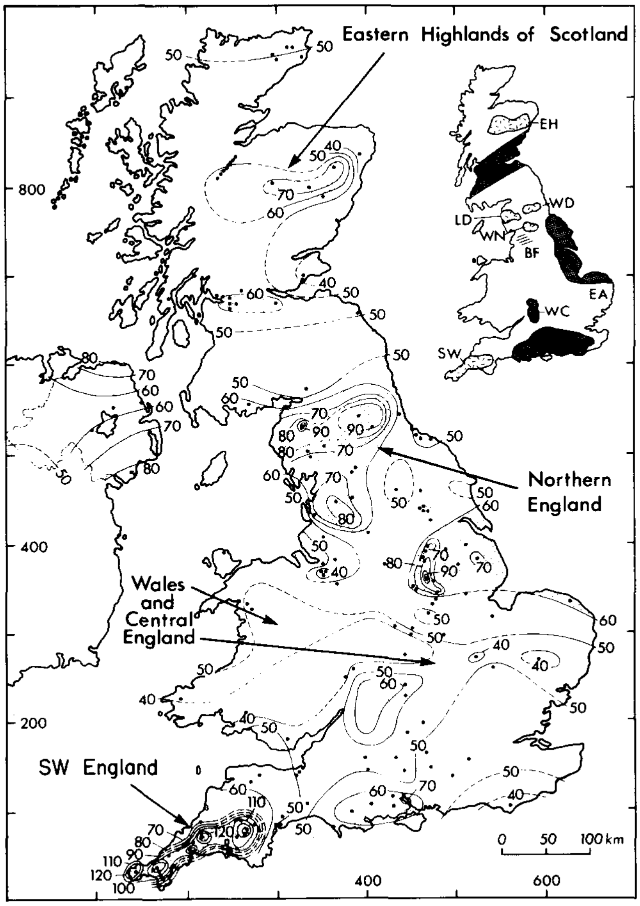

Fig. 1. Heat Flow map based on the Geothermal Map of the UK (BGS 1986). Dots indicate the locations of heat flow measurements. Inset shows granite batholiths, sedimentary basins and other areas referred to in text: EH, Eastern Highlands batholith; WD, Weardale batholith; LD, Lake District batholith; WN, Wensleydale batholith; SW, SW England (Cornubian) 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.

Highlands batholith, are in the range 59–76 mW/m^2 (Table 1). Although these values are not as high as those observed over the batholiths in zones a and b, they define a zone of higher than average heat flow in Scotland which is closely related spatially to the Eastern Highlands batholith.

Outside these three zones, variations in the heat flow field are thought to reflect lateral bulk heat production variations within the upper and lower crust, possibly superimposed on regional variations in the heat flow component from beneath the crust (see below), combined with secondary anomalies related to groundwater movement. A large area dominated by lower than average heat flow extends from the folded lower Palaeozoic strata of Wales, across central England to East Anglia, and is consistent with the presence of moderate to low heat production basement rocks (Richardson & Oxburgh 1978). A few low heat flow values also occur over the relatively low heat production Moine and Dalradian basement of the Scottish Highlands (Richardson & Powell 1976), away from the influence of the Eastern Highlands batholith. Secondary heat flow highs occur over E Nottinghamshire and Lincolnshire, the Midland Valley of Scotland, and the Wessex and Worcester Mesozoic sedimentary basins. The more localized anomalies probably reflect groundwater movements associated with specific structures. However, whether the larger scale anomalies reflect regional groundwater movement or variations in crustal heat production and sub-crustal heat flow is difficult to ascertain. Evidence that the heat flow field is perturbed by large-scale groundwater movement within the North Sea basins (Andrews-Speed *et al.* 1984) suggests that this may also be an important factor in onshore basins.

The relationship between heat flow and heat production

An empirical linear correlation between surface heat flow (q_0) and surface heat production (A_0) in plutonic and metamorphic terrains has been demonstrated in many parts of the world (e.g. Birch *et al.* 1968; Roy *et al.* 1968; summary by Jaupart 1983). The relationship takes the form:

$$q_0 = q^* + DA_0, \qquad (1)$$

where D has the dimension of length and is a function of the depth extent of a crustal zone of enrichment of heat producing elements, and q^* is the 'reduced' heat flow representing the contribution from beneath this enriched zone. Where the relationship is satisfied over large geographic areas, known as 'heat flow provinces', it may be implied that D and q^* are constants. Typical values of D from provinces throughout the world are in the range 4–16 km and typical values of q^* lie in the range 18–32 mW/m^2 (Jaupart 1983). Several different models for the distribution of radioelements with depth satisfy the linear relationship. The two most commonly proposed are the step function (i.e. a constant distribution down to depth D) and an exponential decrease (extending at least to depth $3D$). The exponential model (Lachenbruch 1970) takes the form:

$$A_z = A_0 \exp(-z/D), \qquad (2)$$

where A_z is the heat production at depth z.

In recent years the validity and meaning of equation (1) has been the source of much debate. In particular England *et al.* (1980) suggested that heat production and refraction contrasts between granitic plutons and country rocks lead to an overestimate of the true value of q^* and an underestimate of the true depth scale, D. Jaupart (1983) emphasized the effects of alteration and leaching of radioactive elements in near-surface rocks leading to an underestimate of true A_0 values. Moreover he suggested that the observed linearity of the plot of q_0 against A_0 is enhanced by the effects of lateral heat transfer between upper-crustal blocks of contrasting heat production.

Prior to the recognition of many of the problems associated with linear q_0–A_0 relationships, Richardson & Oxburgh (1978, 1979) observed a linear relationship with the parameters $q^* = 27\ mW/m^2$ and $D = 16.6$ km for southern Britain. While discussing possible mechanisms for the apparently high value of D compared with other parts of the world, they recognized that a q_0–A_0 correlation incorporating data from several tectonic environments could not be attributed easily to a single cause of crustal fractionation.

Table 1. *Heat flow and heat production data for UK granites and basement*

Granite	No. of heat flow measurements	Mean observed heat flow (a) (mW/m^2)	Equivalent one-dimensional heat flow (b) (mW/m^2)	Heat production ($\mu W/m^3$)
South West England				
Carnmenellis	10	115 ± 7	108	4.0 ± 0.5 (d)
Bodmin	5	116 ± 5	109	4.2 ± 0.9 (d)
Land's End	3	125 ± 3	118	5.1 ± 0.2 (d)
St. Austell	2	126 ± 0.5	118	4.2 ± 0.9 (d)
Dartmoor	6	113 ± 9	113	5.3 ± 0.5 (d)
Northern England				
Weardale	1	95	95	3.7 (e)
Wensleydale	1	65	65	3.3 (e)
*Shap	1	78	82	5.2 (f)
*Skiddaw	1	101	95	4.2 (f)
Scotland				
*Cairngorm	1	70	76	7.3 (f)
*Mount Battock	1	59	65	4.8 (f)
*Ballater	1	71	72	6.8 (f)
*Bennachie	1	76	82	7.0 (f)
Strath Halladale (c)	1	43	43	1.4 (g)
Basement in central England and Wales				
Croft Quarry (Quartz Monzonite)	1	37	37	0.9 (h)
Bryn Teg (Late Pre-Cambrian)	1	41	41	0.6 (h)
Coed-y-Brenin (Ordovician)	1	42	42	1.3 (h)
Glanfred (Silurian)	1	59	59	1.9 (h)
Thorpe-by-Water (Lower Palaeozoic)	1	57	57	1.9 (h)
Withy Combe Farm (Lower Palaeozoic)	1	60	60	1.5 (h)

Notes

(a)* = New data (Wheildon *et al.* (1984*a*, *b*), summarized by Lee *et al.* (1984)). Other sources of heat flow data as follows: SW England from Wheildon *et al.* (1980, 1981); Weardale and Wensleydale from England *et al.* (1980); central England and Wales from Richardson & Oxburgh (1979); Strath Halladale Granite from the BGS Geothermal Catalogue. Standard deviations refer to the mean of mean values for each borehole.

(b) Equivalent one-dimensional heat flow values were derived as follows: the Shap, Skiddaw, Cairngorm, Mount Battock, Ballater and Bennachie granites from the thermal models developed by Wheildon *et al.* (1984*a*, *b*); the Carnmenellis Granite from the model given by Wheildon *et al.* (1980, 1981); the Bodmin, Land's End and St Austell granites are of similar size to the Carnmenellis Granite and the observed heat flow is assumed to be enhanced by the same amount (6%); the Dartmoor Granite is larger and the average observed value is assumed to be equivalent to the one-dimensional heat flow; the Weardale and Wensleydale granites from models by England *et al.* (1980); all other observed values are assumed to present one-dimensional heat flow.

(c) The Strath Halladale Granite is in *northern* Scotland.

(d) Heat production values are the mean ot the data from 100 m deep heat flow boreholes (Wheildon *et al.* 1980, 1981). Values were derived from borehole chippings and probably underestimate the true heat production.

(e) Heat production value from borehole core (analyses by the Open University, reported in Lee *et al.* (1984)).

(f) Preferred heat production value for the intrusion based on borehole and surface material, from Webb & Brown (1984*a*, *b*).

(g) Heat production calculated from source data by Storey & Lintern (1981).

(h) Heat production reported by Richardson & Oxburgh (1978).

The revised UK data set

The new heat flow and heat production data for the Lake District and Eastern Highlands granites are given in Table 1, together with previously published data for UK granites and basement rocks. The revised q_0–A_0 plot for the UK is shown in Fig. 2.

It is immediately apparent that the single linear correlation previously identified for southern Britain (Richardson & Oxburgh 1978, 1979) is not appropriate for the UK as a whole. Division into two 'heat flow provinces', with $q^* = 28.3\ mW/m^2$ and $D = 16.4$ km in England and Wales and $q^* = 35.2\ mW/m^2$ and $D = 5.9$ km for the Scottish Highlands is possible (Fig. 2), but when the data are examined more closely this probably also represents an unjustified oversimplification. For example, in the northern 'province', the data relate mainly to the Eastern Highlands batholith, with a single low point from the Strath Halladale Granite in northern Scotland. On the other hand, the southern 'province' incorporates data from three distinct regions; the SW England and northern England granite batholiths, together with a third zone comprising the pre-Caledonian metasediments, metavolcanics, and minor Caledonian intrusions of the English Midlands and Wales. The data subsets for these zones form separate clusters in Fig. 2, and in none of them is there sufficient information to

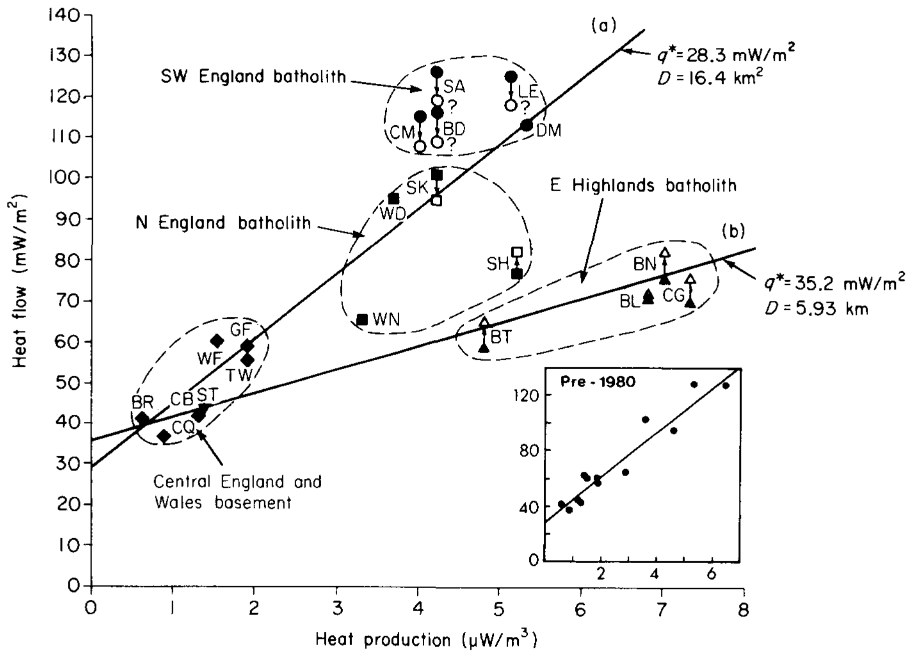

Fig. 2. Plot of heat flow against heat production for UK granites and basement rocks compiled from data listed in Table 1. Solid symbols represent measured heat flow, open symbols represent equivalent one-dimensional heat flow. Clusters of data points from specific areas are ringed. Line (a) is a linear regression of all the data from England and Wales. Line (b) is a linear regression of data from the Eastern Highlands and Northern Scotland. Both are based on the equivalent one-dimensional heat flow values listed in Table 1. D and q^* are defined in the text. The inset shows the pre-1980 correlation ($q^* = 27$ mW/m^2, $D = 16.6$ km, from Richardson & Oxburgh 1979). Codes identify granites and/or boreholes 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; CQ, Croft Quarry; BR, Bryn Teg, CB, Coed-y-Brenin; GF, Glanfred; TW, Thorpe-by-Water; WF, Withy Combe Farm.

define reliable individual q_0–A_0 correlations (Lee *et al.* 1984; Lee 1986*a*).

Taking the data set as a whole, the four clusters recognized on Fig. 2 represent two distinct geological populations: (i) the basement rocks of central England and Wales, and (ii) the large granite batholiths of SW England, northern England, and the Eastern Highlands of Scotland. Moreover, each of the three batholithic areas has its own distinct tectonic and thermal history, as have the basement rocks of central England and Wales. In view of these differences, and the recent discussions on the interpretation of q_0–A_0 plots summarized above, we suggest that the UK data are best considered in terms of the crustal structure and regional thermo-tectonic setting of each area, rather than defining artificial 'heat flow provinces' with characteristic values of q^* and D. In order to examine the parameters which give rise to the observed q_0–A_0 data, the four regions are compared and contrasted below.

The Eastern Highlands of Scotland and SW England

From Fig. 2, the most extreme contrast in q_0–A_0 values is between SW England and the Eastern Highlands of Scotland. The mean heat flow over the SW England batholith exceeds that over the Eastern Highlands batholith by 40–50 mW/m^2 whereas the mean heat production of the Eastern Highlands granites is greater by 2–3 μW/m^3 (Table 1). In addition, mean *off-granite* heat flow values appear to be some 20–30 mW/m^2 higher in SW England than in the Eastern Highlands (Fig. 1). This contrast in off-granite values represents the difference in contribution from deep heat sources if similar upper-crustal radiothermal properties and thicknesses are assumed. However, the heat production of the mainly pelitic Devonian low-grade metasediments of SW England (Wheildon *et al.* 1981) is greater (probably by at least 0.3 μW/m^3) than that of the mainly psammitic Moine and Dalradian medium-to high-grade metasediments (Richardson & Powell 1976) that envelop the Eastern Highlands batholith. If this contrast extends to mid-crustal depths in both regions, part of the difference in surface off-granite heat flow may be accounted for, and the full 20–30 mW/m^2 must be regarded as a *maximum* difference for deep sources.

The deep-source contribution in SW England might be expected to be larger because of two factors. Firstly, the Eastern Highlands batholith was emplaced into the already uplifted core of a metamorphic belt where the lower crust is likely to be comparable to the radioelement-depleted Lewisian granulite (Bamford *et al.* 1978; Watson & Plant 1979) which formed the Archaean basement to late-Proterozoic sedimentation in the NW Highlands. In contrast, the SW England batholith was emplaced into a tectonically thickened, but not greatly uplifted, pile of sediments where the metamorphic lower crust is unlikely to be particularly radioelement-depleted. Secondly, the time since thermal activation is greater in the Caledonian province (metamorphism c. 500 Ma: late granites c. 400 Ma), than in the Hercynian province (c. 300 Ma), although this difference would account for only small (5 mW/m^2) present-day contrasts in residual heat flow (Polyak & Smirnov 1968; Chapman & Pollack 1975).

If the maximum difference in the heat flow contribution from deep sources is 20–30 mW/m^2, then the remainder of the contrast in surface *on-granite* heat flow (i.e. at least 20 mW/m^2 of the 40–50 mW/m^2 observed) between the Eastern Highlands and SW England batholiths must arise from within the batholiths themselves. The most probable causes for such differences are (i) contrasting radioelement-depth functions (i.e. different vertical heat production profiles) and/or (ii) unequal granite depth extents.

If the heat production at depth was to be maintained at surface values in both batholiths, a difference in depth extent of about 7 km (e.g. 15 km in SW England and 8 km in the Eastern Highlands) would be needed to account for the minimum batholith-related heat flow difference of 20 mW/m^2. Gravity modelling suggests that both batholiths extend to similar depths (between 9 and 20 km in SW England (Tombs 1977) and about 13 km in the Eastern Highlands (Rollin 1984)) but neither interpretation can be considered a reliable guide to absolute depth extent. The supposed westward thinning of the Cornubian batholith (Tombs 1977) is not compatible with the relatively uniform heat flow and heat production across the batholith (Wheildon *et al.* 1980, 1981), and may be due to the use of an inappropriate background field for the gravity interpretation. Similar difficulties exist in Scotland and the thickness of 13 km should probably be considered to be a maximum. Nevertheless, the gravity evidence suggests that the SW England batholith is unlikely to be twice as thick as its Eastern Highlands counterpart and although a difference in depth extent might explain part of the contrast in the batholith-related heat flow, it is unlikely to account for all of it. We consider it likely that a contrast in radioelement-depth functions is responsible for much of the difference in on-granite heat flow, and this is a feature of thermal models developed by Wheildon *et al.* (1980, 1981, 1984*b*) for the two areas. They showed that in SW England, surface heat production values must continue to 15 km depth unchanged if the heat input from beneath this depth is to be compatible with off-granite regional values. In the Eastern Highlands, if the batholith is assumed to extend to 13 km, its heat production must diminish rapidly with depth, otherwise on-granite heat flow values would be very much greater (by 30–40 mW/m^2) than observed values. Thermal models suggest that an exponential decrease with a scale length of 7–10 km would be compatible with the observed values of q_0 and A_0 from the Eastern Highlands batholith (Wheildon *et al.* 1984*b*). However, reliable heat production data are not available over a sufficiently large vertical range to directly verify this proposition (Webb & Brown 1984*b*).

Two further possible causes for the higher granite-related heat flow in SW England require consideration. Firstly, there is the possibility of a root zone enriched in radioelements beneath the Cornubian batholith, as suggested recently for granites in southeastern Australia (Sawka & Chappell, in press). This is difficult to evaluate, but if true, implies that the overall distribution of radioelements is fundamentally different to that within and beneath the Eastern Highlands batholith. Secondly, there is the possibility of convective groundwater circulation within or beneath the SW England batholith. A *major* deep-seated convection system seems unlikely in view of the results of studies of groundwater geochemistry (Edmunds *et al.* 1984) and the close correlation between the heat flow anomaly and the form of the SW England batholith (Wheildon *et al.* 1980, 1981). Moreover, recent helium isotope studies (Hilton *et al.* 1985) support the view that the high heat flow over the batholith is largely of radiogenic crustal origin. It would seem, therefore, that the difference in granite-related heat flow values between the SW England and Eastern Highlands batholiths is due to either a contrast in vertical heat production profiles or very different granite depth extents, or, more likely, a combination of both.

Northern England and central England/Wales

The geological setting of the northern England Caledonian batholiths (Weardale, Wensleydale and Lake District) shares some features in common with that of the SW England Hercynian batholith. In particular, they were emplaced within relatively juvenile crust (Hampton & Taylor 1983), and there is no evidence for ancient, high-grade, geochemically-depleted metamorphic crust underlying the rather low-grade, metamorphic rocks at the level of batholith emplacement. Also, unlike the Eastern Highlands, the main compressive events in northern England occurred around the same time as batholith emplacement (Soper 1986). On-granite heat flow values show a wider range, for a given heat production, than in either SW England or the Eastern Highlands (Fig. 2). Unlike those areas, however, the data from northern England relate to three distinctly separate batholiths, and, while recognizing the dangers of placing too great an emphasis on single q_0–A_0 determinations, it seems likely that the wide range of q_0 and A_0 values reflects the individual characteristics (i.e. depth extent, radioelement-depth function and magmatic history) of each pluton. Overall, heat flow values are lower than in SW England and this may reflect a generally shallower granite depth extent (around 9 km), as suggested by gravity interpretations (Bott 1967, 1974; Wilson & Cornwell 1982; Lee 1986*b*), and/or a more rapid decrease in heat production with depth, particularly for the Shap and Wensleydale granites.

In the fourth discrete area for which q_0–A_0 data are available, namely central England and Wales (Fig. 2), no *extensive* granite batholiths (similar to those found in the other three areas) are known. The granites that do occur are relatively small and those that have been analysed are poorly radiothermal (Lee *et al.* 1984). The generally low heat flow values are near the global average for 500–600 Ma old crust that has not been subsequently reactivated. The q_0–A_0 data are mainly from low-grade metavolcanic and metasedimentary basement and are consistent with a simple crustal model in which the poorly radiothermal upper crust is relatively unfractionated in heat producing elements (cf. Richardson & Oxburgh 1978, 1979).

Factors affecting the q_0–A_0 characteristics of granite batholiths

In areas such as Britain, where the highest heat flow values are associated with radiothermal batholiths, recognition of the characteristics of high heat production granites is important for identifying future target areas for 'hot dry rock' geothermal investigations (Lee *et al.* 1984; Lee 1986*a*). In particular it is necessary to recognize the factors which distinguish potentially geothermally-viable granites, such as the Cornubian and Weardale batholiths, from non-viable ones such as the Eastern Highlands batholith. In addition to total intrusive volume and depth extent, the heat flow contribution from heat production within a batholith depends on the large-scale distribution of radioelements and the bulk radiothermal capacity of the intrusion.

Factors affecting the radioelement content of parental magmas, which gives rise to the *bulk* radiothermal character of the batholith, are the nature of the magma source region (especially its composition), the prevailing geothermal regime, the degree of melting and melt-residue separation, and the extent of subsequent contamination. The Eastern Highlands batholith was emplaced into the interior of an uplifted and cooling metamorphic belt which had been thickened and thermally activated some 80–100 Ma earlier. Geochemical characteristics of these granites suggest a mature continental arc environment (Brown *et al.* 1984), and isotopic evidence (Harmon *et al.* 1984) suggest an origin involving both mantle and granulitic lower crust for many of the Grampian granites. A granulitic lower crust would be depleted in volatile constituents and radioelements (Watson & Plant 1979; Heier 1979) and would contribute little of these components to a parental magna. In SW England, the batholith was emplaced shortly after deformation and metamorphism, and before significant uplift had taken place. A combination of geochemical and isotopic evidence (Davies 1983; Stone & Exley 1985; Hampton & Taylor 1983) suggests that this highly peraluminous batholith had a dominantly crustal source of late Proterozoic age. In contrast to the Eastern Highlands, there is no evidence that the lower crust in SW England had been previously depleted in volatiles or radioelements. Therefore, when heated up as a result of the structural thickening, prograde metamorphism would have liberated volatiles (especially H_2O), assisting melt formation in the lower crust and the incorporation of incompatible elements (including U), so giving rise to a parental magma with a higher radioelement and water content than that of the Eastern Highlands batholith.

The radioelement *distribution* within a batholith is further affected by the crystal-liquid fractionation and emplacement history of individual parts of the batholith, the behaviour of volatiles during crystallization, and sometimes by post-crystallization hydrothermal alteration (Webb & Brown 1984*a*, 1984*b*; Albarede 1975). The scale at which radiothermal properties make a significant contribution to the total heat flow, however, is large and more likely to reflect radioelement distributions due to magmatic and crystallization processes, rather than more localized hydrothermal processes. The variation of uranium with magmatic evolution is often difficult to assess from surface samples because uranium is mobile under oxidizing conditions and easily leached in the weathering zone. However, Webb *et al.* (1985) have recognized parallels in the behaviour of uranium and generally immobile high field strength elements, such as Nb, Ta, Y, Yb, in the Carnmenellis Granite (part of the Cornubian batholith) and the Cairngorm Granite (part of the Eastern Highlands batholith). Such observations, in conjunction with limited

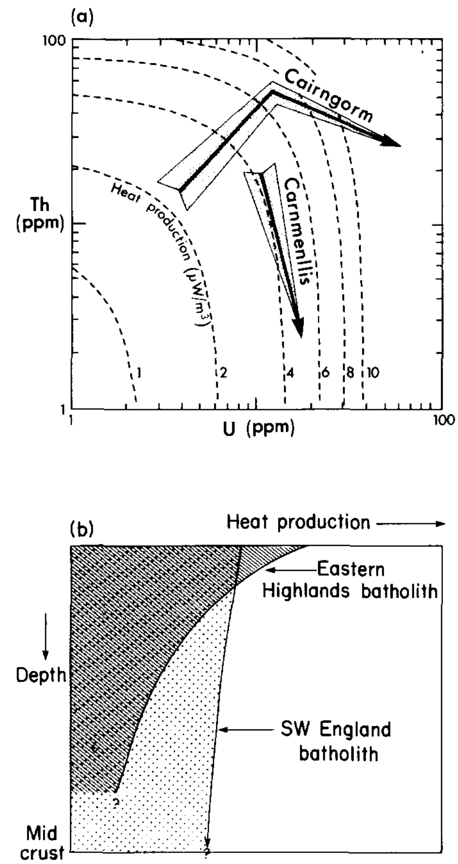

Fig. 3. (**a**) Proposed fractionation paths in U,Th space for the Cairngorm and Carnmenellis Granites, representing the Eastern Highlands and SW England batholiths, respectively (after Webb *et al.* 1985). U,Th space is contoured for heat production assuming a constant potassium content of 4% in granites. Arrow heads indicate the direction of fractionation. More evolved products of a fractionation series are volumetrically less important than less-evolved representatives, therefore the width of the bands reflects the greater volume of less evolved rock expected at depth within a granite batholith. (**b**) Schematic representation of conjectural heat production/depth profiles for the Eastern Highlands and SW England batholiths, based on the fractionation paths in (a) and geothermal models for the two areas (see text for references). For each curve the area of ornament represents the contribution to surface heat flow from heat production within the batholith.

subsurface sampling of these intrusions, have led them to model magmatic-evolution paths for radioelements (Fig. 3a) which suggest that heat production varies little with magmatic evolution in the former but to a large extent in the latter. Combining this with the assumption that granites, on a large scale, become less evolved downwards, provides a possible explanation for a more rapid decrease in heat production with depth in the Eastern Highlands batholith compared with its SW England counterpart (Fig. 3b). Such differences in radioelement-depth functions must be related to contrasting geochemical evolution of the magmas. Webb *et al.* (1985) suggested that in the magmas of the Eastern Highlands, fluorine was available to complex uranium and consequently promote uranium enrichment in the more evolved but smaller-volume fractionation products which crystallized at high levels within the batholith. In contrast, in the more aluminous magmas of SW England, fluorine formed alumino-fluoride complexes and was not available to complex and enrich uranium during melt evolution, giving rise to a more uniform distribution of uranium in the batholith.

The setting of the Caledonian batholiths in northern England shares some of the features of the SW England tectonic environment, particularly in relation to the relatively juvenile nature of the lower crust and the relative timing of the major compressional events (see above). However, some of the geochemical characteristics, such as peraluminosity and the degree of primary uranium enrichment, are transitional between those of the Eastern Highlands and SW England batholiths (Webb *et al.* 1985). The q_0–A_0 signatures of the northern England granites, as a group, presumably reflect these factors, together with others related to the specific plate-tectonic evolution of the southern Caledonian province. The location of the individual data points on the q_0–A_0 plot (Fig. 2.) might suggest that the Shap and Wensleydale granites have characteristics in common with those of the Eastern Highlands batholith, while the Skiddaw and Weardale granites have characteristics in common with those of the Cornubian batholith. Finally, the relatively small and poorly-radiothermal granites of central England and Wales contrast with those of the other three areas in that they were probably not associated with extensive crustal thickening and consequent incorporation of volatile constituents from prograding crustal materials.

Conclusions

A single linear correlation between heat flow and heat production is not tenable for the UK as a whole and division into two 'heat flow provinces' is probably also an oversimplification. Four data clusters are apparent on the q_0–A_0 plot (Fig. 2), three of which relate to granite batholiths (from SW England, northern England and the Eastern Highlands of Scotland, respectively) and the fourth which relates to the basement rocks of central England and Wales. Rather than define artificial heat flow provinces, with characteristic values of q^* and D, the data are probably best explained in terms of the separate thermo-tectonic development of each area. In practice the concept of a 'thermo-tectonic province', characterized by a distinct geological, tectonic and thermal history, might be more appropriate for interpreting q_0–A_0 data than the concept of a 'heat flow province', with its origin in the questionable linear correlation between heat flow and heat production.

The present UK data set contains limited data from four recognizable 'thermo-tectonic provinces'. However, the data are insufficient to examine intra-province variations, either between intrusions of different ages or between granite batholiths and their crustal envelopes. The present data suggest that granite intrusions born of the same tectonic environment share similar overall controls on their bulk radioelement content and radioelement distribution. Thus their q_0–A_0 signatures are likely to have more in common with each other than with granites from a different 'thermo-tectonic province'. However, it seems reasonable to expect that different plutons within the same province, or even different intrusions within a single composite batholith, *may* exhibit different thickness and/or radioelement-depth functions which reflect local emplacement history and source differences, and the evolution of the orogenic belt with time. Furthermore, the radioelement distribution within surrounding basement rocks should reflect the original composition and pre-batholithic history of those rocks, and their subsequent reworking during the evolution of the orogenic belt.

Previously recognized criteria for identifying the most radiothermal granite batholiths as potential targets for hot dry rock geothermal exploration (Brown *et al.* 1979, 1982; Lee *et al.* 1983) include: (i) high primary abundances of radioelements (i.e. high, evenly distributed surface heat production) and (ii) large intrusive volume and a depth extent of many kilometres (as indicated by large negative gravity anomalies). The first of these should now be extended to include evidence for high *bulk* heat production (i.e. high surface heat production combined with a relatively constant radioelement-depth function) as deduced from geochemical studies of magmatic evolution (Webb *et al.* 1985) and consideration of both the prevailing tectonic environment and the radiothermal character of the crust into which the batholith was emplaced. The highest heat flow values in the UK are associated with highly radiothermal peraluminous granite batholiths which became enriched in incompatible radioelements during partial melting of hydrous, undepleted, and relatively juvenile lower crust.

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