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USING HEAT FLOW MEASUREMENTS TO ESTIMATE AND VERIFY THE TOTAL RADON HAZARD POTENTIAL OF GRANITES, SOUTHEASTERN UNITED STATES

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ABSTRACT

Determining the radon hazard potential posed by large rock units can be done using large-scale soil gas and groundwater surveys. However, an easier approach or some independent demonstration that all radon is being inventoried is often desired. One method is to use existing geologic mapping, rock and soil uranium contents, and to rely on the observed positive correlation between uranium and radon contents. However, heat flow measurements can also be used. The most important modification of Earth heat flow from the mantle in the southern Appalachian Piedmont is the heat contributed by the average radioactive element content in the rocks within a few kilometers of a heat flow measurement site. Thus the added heat flow is a crustal-scale measure of uranium, which is both an important contributor to crustal heat production and the parent of ^{222}Rn. Soil gas and groundwater radon contents for 10 heat flow sites in North Carolina, South Carolina, and Georgia show an increase of groundwater and soil gas radon with increasing heat flow. Those rocks associated with lower than expected radon contents are interpreted as having either uranium that was preferentially lost during soil formation or was unsuitably sited for radon emanation into the groundwater and soil gas.

INTRODUCTION

The sources of most indoor radon are the underlying soil, rocks, and groundwater. The parent of ^{222}Rn, the only isotope of radon sufficiently abundant to be hazardous, is uranium. Thus the potential radon hazard of an area should vary with available uranium which, in turn, is controlled by bedrock composition, either directly or indirectly as parental material of the soil and the host for groundwater. Positive correlations between environmental uranium and radon concentrations have been shown in several studies of both soil gas (Schumann and Owen 1988; Agard and Gundersen 1991) and ground water (Loomis et al. 1988; Brutsaert et al. 1981). However, there is variability which is attributed difficulties in estimating uranium contents, secondary uranium migration, differing radon emanations, hydrogeologic characteristics and rock or soil structures, meteorologic effects, etc.

Relying on the positive correlation between uranium and radon contents, it would be useful to be able to [1] predict the radon hazard potential of an area using the existing geologic mapping and geochemical data, and [2] have some independent demonstration that all radon is being inventoried in such large-scale assessments. These could be accomplished by averaging the uranium contents of a large number of samples collected from the bedrock unit. However, a heat flow measurement could also be used. The most important modification of Earth heat flow from the mantle in the southern Appalachian Piedmont is the heat contribution from the decay of radioactive elements in the crust. The heat added to that from the deep interior of the Earth is a crustal-scale averaging of the heat contribution from decay of radioactive elements such as uranium, the parent of ^{222}Rn.

Demonstrating that heat flow measurements would predict or test the potential radon hazard posed by a large rock unit requires a heat flow measurement and a commensurate large-scale survey to obtain an estimate of the radon production associated with the rock unit. Fifteen rock units in the southern Appalachians containing heat flow determination sites (Fig. 1) have been investigated to obtain soil gas and groundwater radon concentrations for this study. Fourteen of the sites are located in 9 granite plutons, 1 site is in metavolcanic wall rocks of the granites. Granites invariably head any list of rock types with higher than average uranium contents and posing a greater than normal radon hazard. This and the fact that granites are relatively homogenous rock units made them an attractive investigative target. Such a study also provides an opportunity to demonstrate that granites exhibit a range of behaviors. This radon behavior characterization of large-scale rock units is different from most radon investigations which examine variations of specific sites.

METHODS

The procedures and equipment used for collecting soil gas and groundwater radon samples are those described by Reimer (1991). Sample depth for soil gas radon was 0.75 m. Groundwater samples are from wells deeper than 30 m, groundwater from shallower bored or hand-dug wells have lower radon contents that are comparable to the soil gas contents. Water was run until it was being pumped from the ground. This was checked by measuring water temperatures which are generally <18°C in the ground. Radon was measured in 20 cc of gas sample using Lucas cells and a Bondar-Clegg & Co., Ltd. model RE-279 alpha-scintometer. Counting was begun five minutes after injection of gas into the Lucas cell. Two minute counts were taken and recorded until a reading was obtained that is lower than the previous one. At that point, a succession of five (5) 2-minute counts were taken and used for the radon concentration determination.

Heat production and heat flow values were obtained from Costain et al. (1986). Heat production, A, was calculated using Rybach's (1973) equation:

$$A, \mu W m^{-3} = 0.133 \bullet \rho, g\ cm^{-3} \bullet [0.718\ U, ppm + 0.198\ Th, ppm + 0.262\ K, wt\ \%] \qquad \text{(Eq. 1)}$$

Uranium, thorium, and potassium contents were determined by gamma-ray spectrometry. Heat flow, Q, was obtained as a product of two measured parameters:

$$Q = \beta k \qquad \text{(Eq. 2)}$$

where β is the vertical temperature gradient measured in a drillhole and k is the thermal conductivity measured on the recovered core. The uranium contents of the bedrock are from unpublished uranium determinations used for the heat production values of Costain et al. (1986), unpublished data of Speer, and with additional data from Wenner and Spaulding (1982) for the Elberton, GA granite. Groundwater radon contents for the Elberton, GA and Rocky Mount, NC granites are from Simones (1990) and Pascarella (1989) respectively.

RESULTS

Table 1 presents the bedrock uranium contents, heat productions, heat flows, and soil gas and groundwater radon contents for 15 granites. In cases where differing lithologies within a pluton have significantly differing values, these are reported separately. The number of determinations (N) are given for the bedrock uranium, soil gas and groundwater radon contents. Bedrock uranium and heat production values are arithmetic means. Because the soil gas and groundwater radon contents can widely range, the median, arithmetic, geometric means, minimum, and maximum values are reported for each. Geometric means are used for the plots in this paper. Geometric means are considered more representative for comparative purposes because just a few high or low values can significantly skew the arithmetic mean and a few central values can control the median. However, each of these measures of central tendencies track each other closely (Table 1) and would give similar plots used in the following discussions.

DISCUSSION

Birch et al. (1968) empirically found a linear relationship between Earth surface heat flow (Q) and surface heat production (A). They expressed this relationship as:

$$Q = Q^* + D \bullet A. \qquad \text{(Eq. 3)}$$

D, the slope, has a dimension of length and is related to the thickness of the surface layer (crust) enriched in heat-producing radioactive elements. Q* is the reduced heat flow and is interpreted as the heat contribution from beneath the enriched surface layer (Fig. 2). D has been interpreted as either [1] the thickness or depth of a layer uniformly enriched in radiogenic heat sources or [2] a number characterizing the exponential distribution of heat-producing elements with depth. There is no agreement on which meaning of D is correct and the meaning may be rather complex (Jaupert et al. 1981; Huestis 1984;Vasseur and Singh 1986). Luckily the interpretation of D does not bear on this study. What is important is the repeatedly found linear relationship between heat flow and heat production. This linear relationship can be viewed as a result of adding heat from radioactive elements in near surface rocks to the flow of heat from the Earth's deeper interior. It is also important that this added heat flow represents a sampling of the radiogenic heat sources in a crustal-scale section of the Earth; the vertical extent of this sample extends to the base of the crust whereas the horizontal extent is at least the areal half-size (radius) of the plutons, or greater than a few kilometers.

The internal heat source of a rock is the decay of radioactive elements; isotopes of U, Th, and K are the most important. Using Eq. 3 and the average uranium, thorium, and potassium contents of 600 granite samples from the southern Appalachians (4.9 ppm, 20.4 ppm, and 3.8 wt. %) shows that, on average, uranium and thorium contribute most of the heat in subequal amounts of 41% and 47% while potassium accounts for about 12%. Because the Th/U ratio has a nearly constant value of 4 for these granites, the relationship between uranium and heat production is linear (Fig. 3). The same is true for thorium but only uranium, the parent of radon, will be considered further.

Fig. 4a shows the linear relationship between heat flow and heat production for the southern Appalachian granites investigated for this study. For the line drawn in Fig. 4a, $Q^* = 29.2$ mWm^{-2} and D = 7.7 km. Because of the nearly one-to-one relationship between rock uranium contents and heat productions (Fig. 3), there is also a good positive correlation between heat flow and rock uranium content (Fig. 4b). Two granites lie well off and another a little off the linear trend defined by most granites in Fig. 4a. Either the heat flow determination is incorrect for these granites, or heat-generating radioactive elements have been gained (Pageland, SC) or lost (Castalia, SC) in the near surface rock. Geologic evidence would indicate element mobility in these two cases (Costain et al. 1986) but, for the remaining granites, the linear relationship shows that the sampling and the uranium determinations have produced a good estimate of the uranium content of that volume of the crust sampled by the heat flow determination.

Fig. 5a is a plot of the rock uranium and groundwater radon contents of 10 granites. Nine granites define a trend of increasing groundwater radon content with increasing uranium content of the host rock. This is an expected relationship. The Rocky Mount, NC granite falls outside the cluster of points and could be explained by either [1] an underestimation of groundwater radon content, [2] an overestimation of the average rock uranium content, or [3] uranium occupying a site in the granite from which radon emanation is difficult. Fig 5b. is the derivative plot of heat flow and groundwater radon contents. It shows the same relationships as Fig. 5a and the Rocky Mount values still lie outside the trend of the other granites. This, and the fact that the Rocky Mount, NC granite belongs to the linear relationship of heat flow and heat production, indicates errors in estimation of the radon content of the groundwater or low emanation coefficient for radon.

Fig. 6a is a plot of the rock uranium and the soil gas radon contents for 17 granites. Fifteen granites show increasing soil gas radon with increasing rock uranium contents. This indicates that for most granites the relative uranium content variations of the parent rocks persist through soil formation processes. The Rocky Mount, NC and Cuffytown Creek, SC plutons lie outside the linear cluster of other values and could be explained by either [1] an underestimation of soil gas radon contents, [2] an overestimation of the average rock uranium contents, [3] preferential loss of uranium during the soil formation as compared to the other granites, or [4] uranium sited unsuitably for radon emanation. Because these two granites belong to the linear relationship of heat flow and heat production (Fig. 4a), it is unlikely that an overestimation of rock uranium content was made. Fig 6b. is the derivative plot of heat flow and soil gas radon contents. The Rocky Mount, NC and Cuffytown Creek, SC granite values still lie outside the trend of the other granites, and are joined by the Castalia, NC and Rolesville, NC granites. The Cuffytown Creek, SC and Rocky Mount, NC granites are interpreted as having preferential loss of uranium during the soil formation or uranium unsuitably sited for radon emanation. Evidently the Castalia, NC and Rolesville, NC granites have lost uranium in near-surface rocks; soil gas radon contents reflect the uranium contents of the near surface rocks (Fig. 6a) but not the crustal-size sample of the granite measured by the heat flow (Fig. 6b). This same interpretation was also made from the heat flow-heat production relationship of the Castalia, NC granite (Fig. 4a). Similar arguments could be made for the Pageland, SC granite in that soil gas radon contents reflect the uranium contents of the near surface rocks (Fig. 6a) but not the crustal-size sample of the granite measured by the heat flow the heat flow-heat production relationship (Fig. 4a). It is probably fortuitous that the uranium and thorium contents and weathering processes caused the Pageland, SC to plot in the cluster of other granites in the heat flow-soil gas radon plot (Fig. 6b).

CONCLUSIONS

The granites have a range of soil gas and groundwater radon values (Table 1) which can be explained largely by the range in uranium contents of the parent or host rock (Figs. 5a & 6a). This is confirmed by the increase of soil gas and groundwater radon contents with increasing heat flow associated with each granite (Figs. 5b & 6b). Heat flow is dependent on the heat production of rock unit (Fig. 4a), which, in turn, is dependent on the uranium content (Fig. 3) of the large volume of crust sampled by the heat flow measurement. Variations in this relationship can result from preferential uranium loss or gain during soil formation or groundwater leaching or differing coefficients of radon emanation.

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Table 1.

Pluton	rock U		Heat Prod.	Heat Flow	Soil gas radon, kB m^{-3}						Groundwater radon, kB m^{-3}					
						mean		range				mean		range		
	ppm	N	μWm^{-3}	mWm^{-2}	med.	arith.	geom.	min.	max.	N	med.	arith.	geom.	min.	max.	N
Clouds Creek, SC	3.3	3	2.0	...	31.7	35.3	28.3	4.3	109.6	21	...	...	...	...	...	...
Cuffytown Creek, SC	10.1	22	5.2	67.7	40.5	50.2	42.7	14.4	128.2	23	1137.6	1242.7	1012.8	283.3	2478.9	7
Castalia, NC	4.8	16	2.3	60.7	45.2	58.4	43.6	9.3	277.9	90	...	...	...	...	...	...
Elberton, GA	3.4	56	...	...	64.9	77.0	67.2	24.2	193.8	27	214.2	269.5	201.5	30.5	787.1	33
Liberty Hill, SC																
coarse	2.8	28	2.3	45.9	65.0	72.1	63.5	20.1	205.8	43	99.8	142.7	101.1	13.4	471.3	12
fine	4.5	7	...	...	79.1	93.0	75.1	29.5	250.8	7	729.6	887.9	729.5	294.4	1547.6	7
Mount Airy, NC	1.7	20	1.0	...	11.9	17.0	14.1	7.3	44.2	9	107.5	102.9	100.9	71.9	124.4	9
Pageland, SC	5.4	26	3.1	40.1	66.5	77.0	59.1	17.9	217.9	13	...	...	...	...	...	...
Rocky Mount, NC	6.5	8	3.4	59.6	31.2	56.0	35.4	4.0	249.8	18	177.6	245.6	193.3	40.7	666.0	47
Rolesville, NC	4.5	64	2.5	49.8	32.2	43.5	31.7	5.3	258.7	86	515.8	497.3	491.0	389.8	624.4	6
Roxboro, NC	2.6	49	1.6	39.3	44.5	26.4	44.5	22.7	102.2	13	...	...	...	...	...	...
Slate Belt, NC	3.3	13	1.4	40.3	63.2	63.8	54.0	17.8	160.0	10	...	...	...	...	...	...
Siloam, GA	7.6	55	4.6	64.3	89.0	151.6	107.7	23.3	614.5	53	...	...	...	...	...	...
Sims, NC	8.3	8	...	...	84.7	96.5	85.3	25.2	234.6	23	749.3	894.5	759.8	181.2	2438.1	28
Stone Mountain, NC	1.5	3	...	...	24.5	15.7	19.1	4.5	54.8	8	...	...	...	...	...	...
Winnsboro, SC																
coarse	2.7	22	...	...	36.1	43.4	38.5	14.8	81.7	18	97.1	135.0	108.7	61.2	330.7	5
medium	6.0	38	4.2	62.0	80.7	93.2	83.5	30.4	209.7	29	938.1	1074.0	735.1	51.1	1777.5	7

1. heading abbreviations: ppm = parts per million, N = number of samples, Heat Prod. = Heat Production, med. = median, arith. = arithmetic mean (average), geom. = geometric mean, min. = minumum, max. = maximum
2. data not collected by the authors: rock U content, heat production, and heat flow from Costain et al. (1986); groundwater data for the Elberton, GA granite from Simones (1990), groundwater data for the Rocky Mount, NC granite from Pascarella (1989)

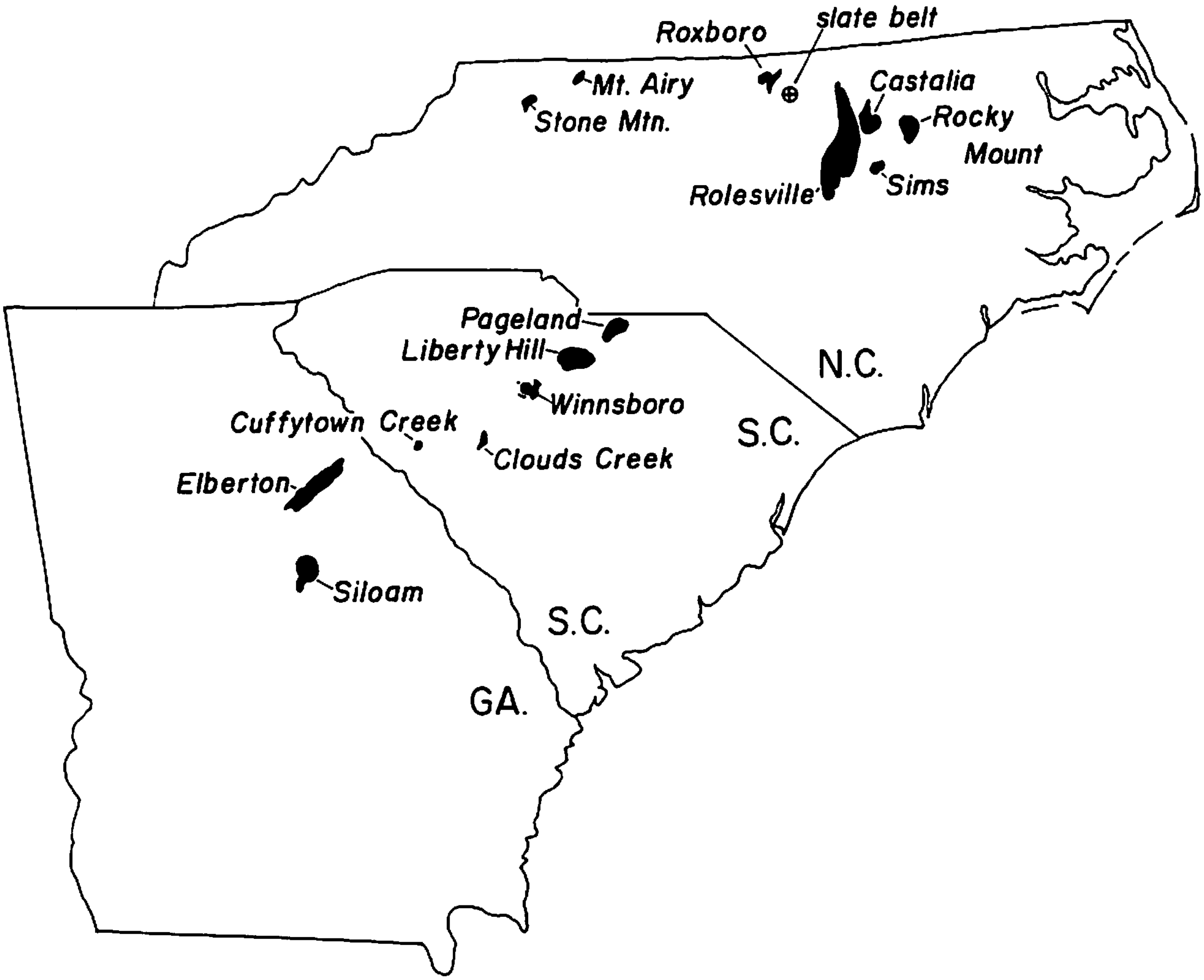

Fig. 1. Location map of the rock units in the southern Appalachians investigated for this study. Proper names are granite bodies. The drill hole symbol (⊗) is the location of the heat flow site in the slate belt country rock.

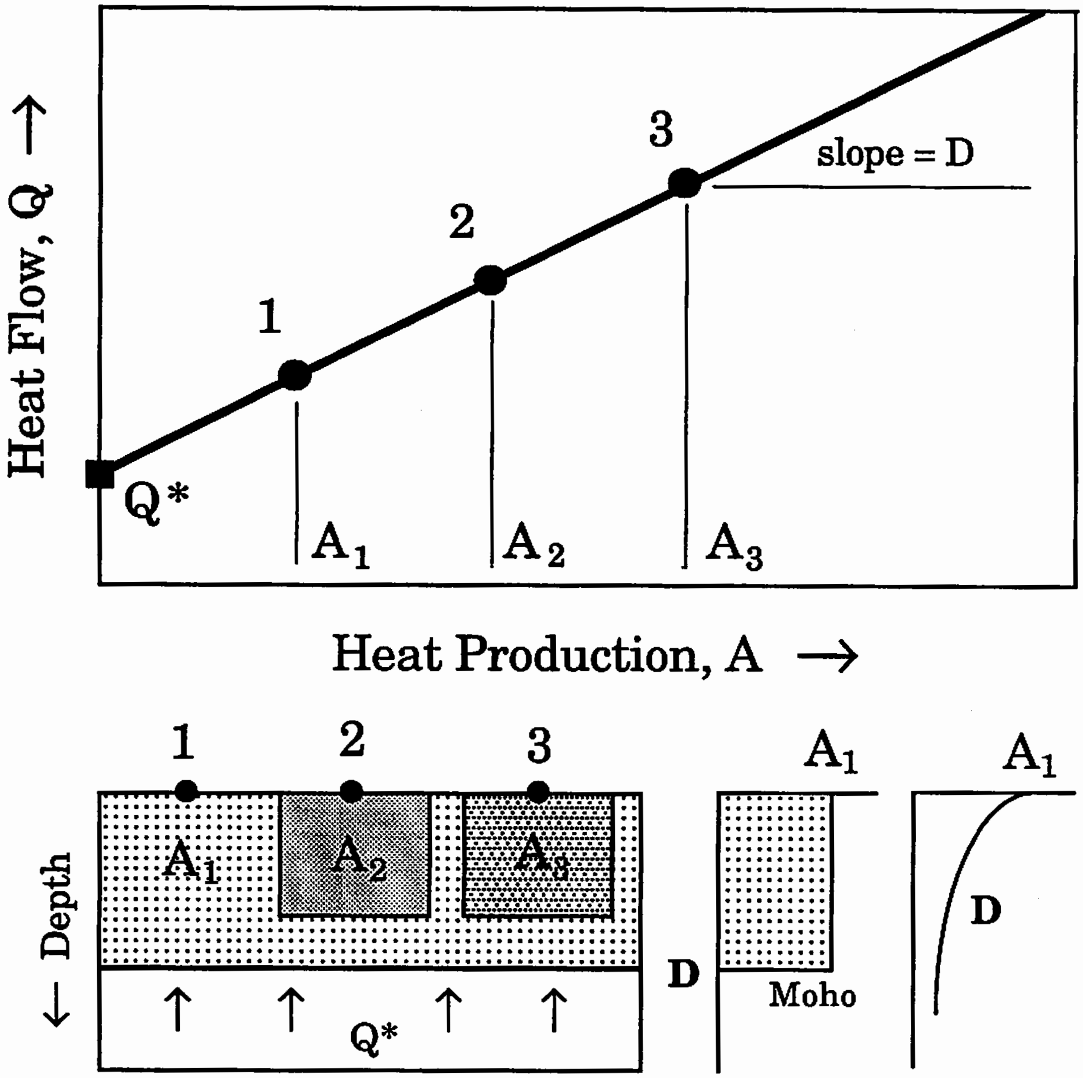

Fig. 2. Explanation heat flow (Q) versus heat production (A) diagram (after Vigneresse 1988). Surface heat flow values at locations 1, 2, and 3 cluster along a linear trend for which the intercept is the reduced heat flow (Q*) coming from beneath the surface layer (crust, square stipple). The surface layer has a heat production of A1, which is higher than the interior, and can contain units of even higher heat productions (A2, A3) that increase the heat flow. The slope of the line, D, is either the thickness of the surface layer or corresponds to an exponential distribution of heat production with depth.

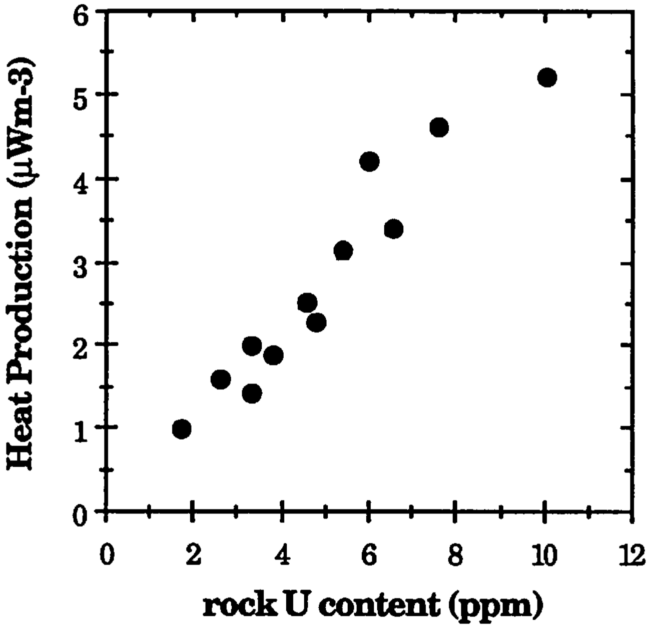

Fig. 3. Relationship between heat production and rock uranium content for the granites of Table 1.

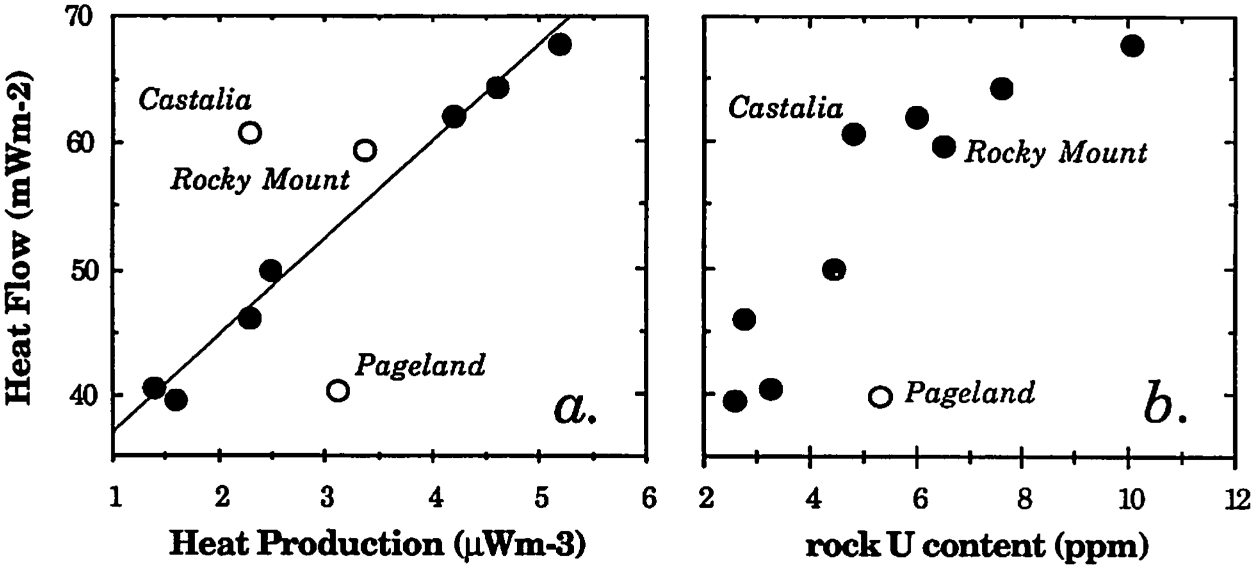

Fig. 4. Relationship between heat flow and (a) heat production and (b) rock U content for the granites of Table 1.

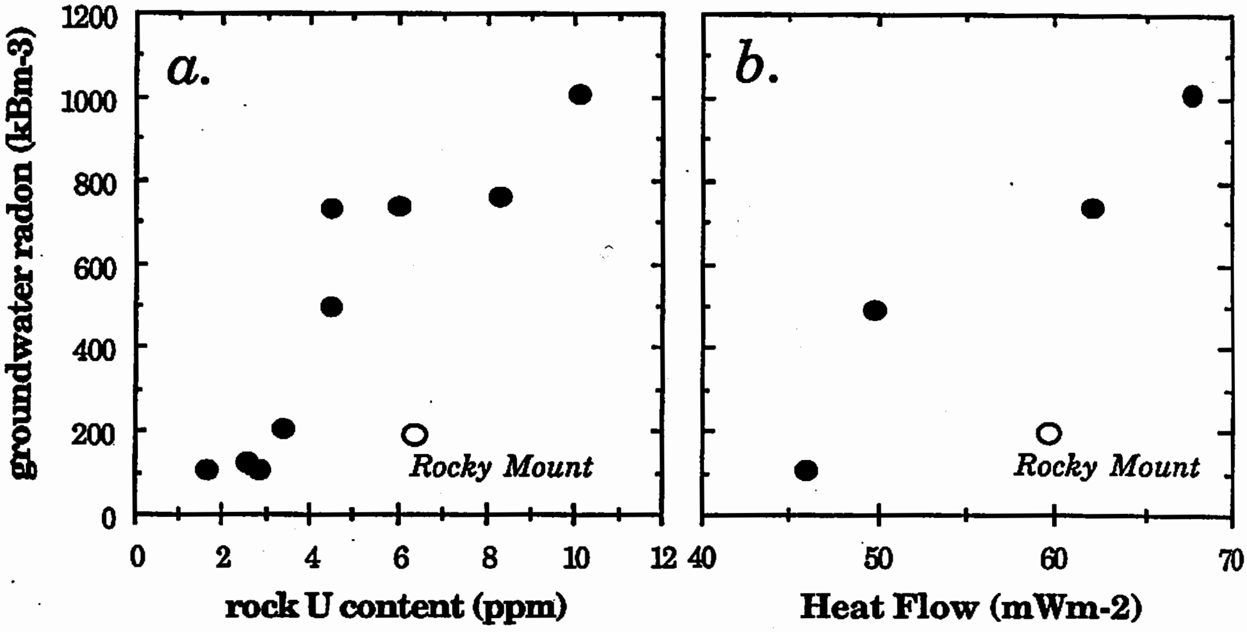

Fig. 5. Relationship between groundwater radon content and (a) rock uranium content and (b) heat flow for the granites of Table 1.

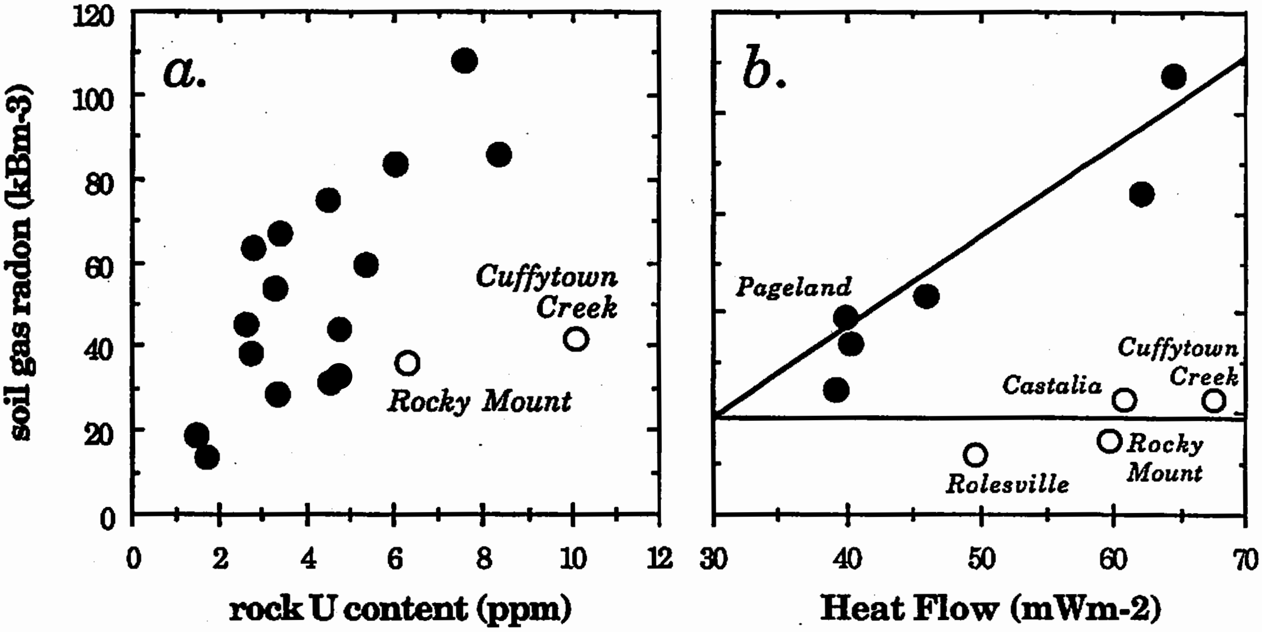

Fig. 6. Relationship between soil gas radon content and (a) rock uranium content and (b) heat flow for the granites of Table 1.