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Relationship among Terrestrial Heat Flow, Thermal Conductivity, and Geothermal Gradient

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Correlation and regression analyses of terrestrial heat flow Q and thermal conductivity K show that Q and K are not independent in many of the continental areas. The refraction of heat flux due to inhomogeneous conductivity, and the proportionality between radioactive heat generation and thermal conductivity are possible explanations.

Introduction

Terrestrial heat flow Q is determined experimentally from thermal conductivity K and geothermal gradient G as

$$Q = K \cdot G$$

where $G = \Delta T/\Delta z$ is the rate of increase of the earth's temperature vertically downward.

The average values of Q in the continental and the oceanic areas are almost equal [*Lee and Uyeda*, 1965; *Horai and Simmons*, 1969]. However, the individual values of Q vary by more than an order of magnitude, from nearly null to more than 8μcal/cm² sec. The origin of the variation of Q can be attributed to the differences in thermal activities in the crust and the upper mantle, hence the measurement of Q is regarded as an important tool to investigate the thermal processes of the earth's interior.

Perhaps the simplest interpretation of the spatial variation of Q is that Q varies proportionally to the amount of heat sources buried underneath. In fact, Q appears to be closely related to the distribution of radioactive elements in the earth's crust in continental areas [*Roy et al.*, 1968]. Since Q is measured near the surface of the earth's crust, it can also be influenced by various near-surface conditions. Factors such as topography and its evolution, past climatic changes, and inhomogeneous distribution of K can significantly affect the observed Q. It may be important to evaluate, and correct if possible, near surface disturbances of Q in order to use heat-flow data to study the interior of the earth.

To gain insight into the problem of heat-flow interpretation, we have run regression analyses on Q, K, and G. Based on this analysis we consider several possible hypothetical models that have some bearing on the nature of the spatial variation of Q.

Data and Analysis

The data used in this study were compiled by *Lee and Uyeda* [1965] and *Simmons and Horai* [1968]. Since the validity of individual values of Q, K, and G are required in the present analysis, those sets of data in which Q is determined from estimated (not directly measured) K were excluded. Oceanic data were also excluded from the present investigation. Because most measurements of heat flow in oceanic areas have been made in the sediments with more or less uniform K, it was anticipated that the Q in oceanic areas is essentially controlled by G.

The analysis was made for various regional provinces in which the crustal thermal condition is assumed to be more or less similar. We followed the division of provinces given essentially by *Lee and Uyeda* [1965]. For each of these provinces, we calculated the correlation coefficient ρ between the variables X and Y and the coefficients A and B in the linear equation $Y = A + BX$, where X and Y are either Q, K, G, or their reciprocals. For comparison with the theoretical models that will be discussed in the next section, the analysis was made for several combinations of the variables.

The results are summarized in Table 1 and shown in Figures 1 to 9. It is rather perplexing

TABLE 1. Correlation $\rho(X, Y)$ and Regression ($Y = A + BX$) Analyses of Heat Flow Q (10^{-6} cal/cm² sec), Thermal Conductivity K (10^{-3} cal/cm sec °C), and Thermal Gradient G (10^{-3} °C/cm)

		$X = 1/K$, $Y = 1/Q$			$X = K$, $Y = 1/G$			$X = K$, $Y = Q$			$X = 1/K$, $Y = G$		
			A_1	B_1		A_2	B_2		A_3	B_3		A_4	B_4
Province	Size of data, n	ρ_1	10^6 cm² sec/cal	10^3 cm/°C	ρ_2	10^3 cm/°C	10^6 cm² sec/cal	ρ_3	10^{-6} cal/cm² sec	10^{-3} °C/cm	ρ_4	10^{-3} °C/cm	10^{-6} cal/cm² sec
North America													
Canadian shield	18	0.34	−1.12±0.54	3.2±3.1	0.70	−1.1±1.6	1.29±0.24	0.41	0.63±0.16	0.05±0.03	0.76	0.02±0.02	0.76±0.14
Interior lowland	28	0.25	−2.07±0.58	17.3±3.3	0.28	−3.7±1.9	1.23±0.27	0.51	0.69±0.27	0.12±0.04	0.77	0.01±0.03	1.45±0.19
Appalachian system	30	0.42	−0.68±0.27	9.5±1.6	0.49	−0.8±1.3	0.89±0.18	0.45	0.65±0.25	0.10±0.04	0.57	−0.01±0.04	1.36±0.23
Cordilleran system	17	0.28	−1.16±0.49	11.4±2.8	0.32	2.5±1.2	0.22±0.13	0.69	0.91±0.30	0.12±0.03	0.79	−0.02±0.05	1.95±0.31
Area of Cenozoic orogeny	80	0.08	−9.30±1.16	71.1±8.0	0.33	−3.6±1.0	0.98±0.13	0.31	0.11±0.53	0.27±0.07	0.50	−0.65±0.10	6.88±0.67
Europe													
Ukrainian shield	4	0.99	−0.15±0.17	10.5±1.2	−0.89	11.4±0.7	−0.26±0.09	0.99	−0.09±0.08	0.12±0.01	−0.89	0.13±0.01	−0.16±0.06
Russian platform	5	0.39	−0.89±0.85	11.6±6.2	0.09	4.2±3.2	0.09±0.36	0.73	−0.43±1.26	0.27±0.14	0.41	−0.16±0.22	2.95±1.58
Area of Caledonian orogeny	8	0.43	−1.52±0.93	11.5±4.3	0.66	−0.7±1.9	1.01±0.34	0.17	1.03±0.49	0.04±0.09	0.36	−0.28±0.22	2.52±0.99
Area of Variscan orogeny	53	0.63	−0.19±0.09	4.2±0.5	0.41	2.3±0.3	0.18±0.05	0.66	0.45±0.22	0.23±0.03	0.29	−0.14±0.06	2.34±0.31
Area of Alpine orogeny	10	−0.43	1.09±0.20	−3.7±1.2	0.90	−1.0±0.7	0.65±0.10	−0.47	2.73±0.41	−0.09±0.06	0.93	−0.16±0.07	3.11±0.42
Japan													
Area of Paleozoic-Mesozoic orogenies	28	0.55	−1.32±0.38	11.7±1.9	0.21	−12.4±3.5	2.95±0.58	0.47	0.36±0.34	0.17±0.06	0.18	−0.33±0.12	3.07±0.61
Area of Cenozoic orogeny	9	0.49	−0.13±0.22	3.6±1.2	0.48	0.7±1.3	0.36±0.19	0.57	0.74±0.73	0.22±0.11	0.69	0.06±0.09	1.70±0.48
Australia													
Australian Precambrian shield	9	0.63	−1.13±0.65	18.8±5.5	0.20	−2.8±5.2	1.37±0.59	0.70	0.12±0.32	0.10±0.04	0.27	−0.03±0.06	1.20±0.52
Australian interior lowland	13	0.96	0.08±0.05	4.0±0.4	0.58	3.8±0.4	0.11±0.05	0.95	0.30±0.16	0.18±0.02	0.60	0.17±0.01	0.30±0.11
Area of Paleozoic-Mesozoic orogenies	5	0.96	0.13±0.09	3.0±0.5	0.79	3.0±0.3	0.13±0.06	0.98	0.31±0.13	0.21±0.02	0.86	0.20±0.03	0.40±0.13
Area of Cenozoic orogeny	3	0.99	0.23±0.06	1.4±0.1	0.99	1.3±0.2	0.23±0.02	0.99	1.34±0.20	0.13±0.02	0.99	0.14±0.02	1.32±0.11
Africa													
South African Precambrian shield	5	0.95	0.43±0.10	5.0±0.9	0.96	4.7±0.8	0.47±0.08	0.97	0.51±0.07	0.05±0.01	0.95	0.05±0.01	0.53±0.10
South African stable basin	7	0.37	0.04±0.30	4.5±1.9	0.88	0.6±1.0	0.66±0.15	0.42	1.10±0.26	0.04±0.04	0.90	0.00±0.04	1.32±0.26
India													
Peninsular shield	7	0.89	−2.75±0.76	26.0±5.4	0.80	26.2±5.4	−2.76±0.74	0.93	−2.21±0.62	0.49±0.09	−0.84	0.61±0.11	−3.06±0.75
All data	339	0.29	−2.04±0.15	17.1±0.9	0.32	1.0±0.4	0.81±0.06	0.40	0.53±0.14	0.17±0.02	0.45	−0.33±0.03	3.69±0.18

that the higher correlations ar
areas where the data are scarc
nite tenency for Q to increa
served in most of the areas. Th
plies that the amount of hea
the crust is not independent o
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models that will be pertinent t
will be considered in the next

DISCUSSION

Conductivity inhomogeneit
higher K may be associated w
cause the flux in a continuous
converge where the conducti
simple model calculation illus
of the problem. Let the shap
tivity anomaly near the surfac
a semi-elliptic cylinder with
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boundary conditions that (1)
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face, and (3) heat flow at gr
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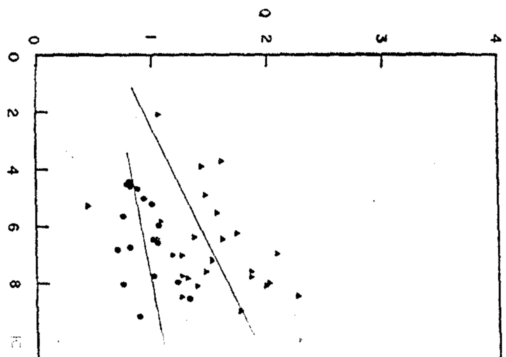

Fig. 1. Heat flow Q (in 10^{-6} ca
thermal conductivity K (in 10^{-}
North America 1: (1) ● Canadi
Interior lowland.

	[illegible]	[illegible]	1.15±0.65	13.3±5.5	0.20	2.8±5.2	1.37±0.59	0.70	0.12±0.32	0.10±0.04	0.27	−0.03±0.06	1.20±0.52
Australian interior lowland	13	0.96	0.08±0.05	4.0±0.4	0.58	3.8±0.4	0.11±0.05	0.95	0.30±0.16	0.18±0.02	0.60	0.17±0.01	0.30±0.11
Area of Paleozoic-Mesozoic orogenies	5	0.96	0.13±0.09	3.0±0.5	0.79	3.0±0.3	0.13±0.06	0.98	0.31±0.13	0.21±0.02	0.86	0.20±0.03	0.40±0.13
Area of Cenozoic orogeny	3	0.99	0.23±0.06	1.4±0.1	0.99	1.3±0.2	0.23±0.02	0.99	1.34±0.20	0.13±0.02	0.99	0.14±0.02	1.32±0.11
Africa													
South African Precambrian shield	5	0.95	0.43±0.10	5.0±0.9	0.96	4.7±0.8	0.47±0.08	0.97	0.51±0.07	0.05±0.01	0.95	0.05±0.01	0.53±0.10
South African stable basin	7	0.37	0.04±0.30	4.5±1.9	0.88	0.6±1.0	0.66±0.15	0.42	1.10±0.26	0.04±0.04	0.90	0.00±0.04	1.32±0.26
India													
Peninsular shield	7	0.89	−2.75±0.76	26.0±5.4	0.80	26.2±5.4	−2.76±0.74	0.93	−2.21±0.62	0.40±0.09	−0.84	0.01±0.11	−3.06±0.75
All data	339	0.29	−2.04±0.15	17.1±0.9	0.32	1.0±0.4	0.81±0.06	0.40	0.53±0.14	0.17±0.02	0.45	−0.33±0.03	3.69±0.18

that the higher correlations are observed in the areas where the data are scarce. However, a definite tenency for Q to increase with K is observed in most of the areas. This observation implies that the amount of heat flowing through the crust is not independent of the property of the medium through which it flows. Possible models that will be pertinent to our observation will be considered in the next section.

Discussion

Conductivity inhomogeneity. A region of higher K may be associated with higher Q because the flux in a continuous medium tends to converge where the conductivity is higher. A simple model calculation illustrates the nature of the problem. Let the shape of the conductivity anomaly near the surface of the earth be a semi-elliptic cylinder with its plain surface at the upper boundary. The steady-state solution of heat flow in this medium under the boundary conditions that (1) the heat flow is continuous on the boundary of the anomalous body, (2) temperature is constant on the surface, and (3) heat flow at great depth, Q_o, is uniform and vertical, is available in the literature. To restrict ourselves to the effect of near-surface geometry, the crustal radioactivity was neglected. Let the conductivities inside and outside the anomalous body be K and K_o. The surface heat flow *inside* the anomalous body Q is given by *Lachenbruch and Marshall* [1966].

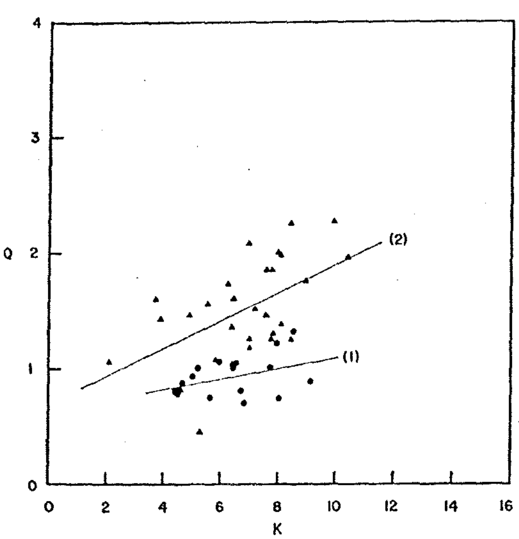

Fig. 1. Heat flow Q (in 10^{-6} cal/cm^2 sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). North America 1: (1) ● Canadian shield; (2) ▲ Interior lowland.

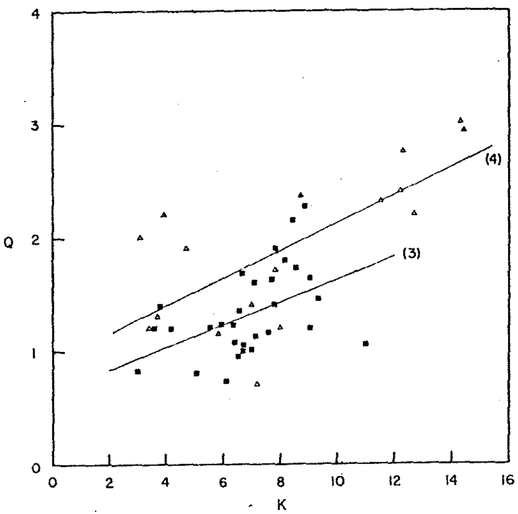

Fig. 2. Heat flow Q (in 10^{-6} cal/cm^2 sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). North America 2: (3) ■ Appalachian system; (4) △ Cordilleran system.

$$Q = (K/K_0)Q_0[(S + 1)/(S + K/K_0)] \quad (1)$$

where S is a parameter related to the geometry of the anomaly ($S = m/n$; m and n are, respectively, the major and minor axes of the semi-ellipsoid). Although (1) is derived for a two-dimensional case, it is easily shown [see, for example, *Carslaw and Jaeger*, 1959, p. 426] that (1) is applicable to more general cases. For example, $S = 2$ implies a three-dimensional hemisphere as well as a two-dimensional vertically elongated ellipsoid. For other cases, $S = 0$ (a half-space of conductivity K_o is overlaid by a thin sheet of anomalous conductivity K) and $S = \infty$ (a thin vertical needle with conductivity K is surrounded with a half-space of conductivity K_o). For each of these cases, the relation between thermal gradient G and thermal conductivity K is given by

$$G = G_0(S + 1)/(S + K/K_0) \quad (2)$$

where $G_o = Q_o/K_o$.

Relationship (1) was linearized by taking the reciprocals of both sides, i.e.,

$$1/Q = 1/(S + 1)Q_o + S/(S + 1)G_oK \quad (3)$$

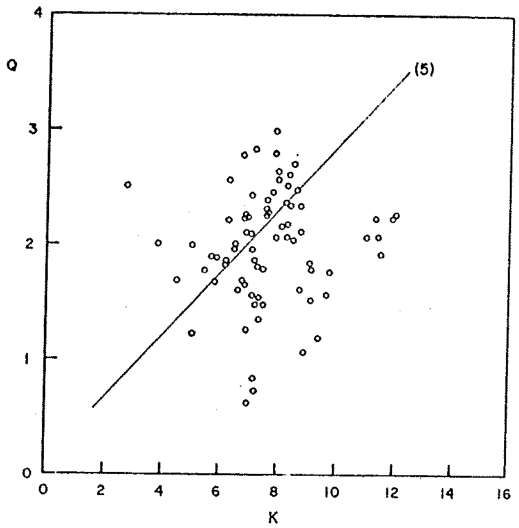

Fig. 3. Heat flow Q (in 10^{-6} cal/cm² sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). North America 3: (5) ○ Area of Cenozoic orogeny. Values of Q more than 4×10^{-6} cal/cm² sec are omitted from the diagram.

which shows that Q, measured inside the conductivity anomaly, certainly increases with K. The data to be compared with (3) are given in the first column of Table 1. The comparison shows that the coefficients given in Table 1 can be interpreted as

$$A_1 = S/(S+1)G_0 \qquad (4)$$

and

$$B_1 = 1/(S+1)Q_0 \qquad (5)$$

Another pair of estimates of the coefficients can be obtained if (2) is converted to

$$1/G = S/(S+1)G_0 + K/(S+1)Q_0 \qquad (6)$$

and compared with the data given in the second column of Table 1,

$$A_2 = 1/(S+1)Q_0 \qquad (7)$$

$$B_2 = S/(S+1)G_0 \qquad (8)$$

Some discrepancies noted between the estimates may imply that the data are inadequate to yield reliable coefficients. The comparison is favorable in such areas as the Australian interior lowland, areas of Paleozoic-Mesozoic and Cenozoic orogenies in Australia, and South African Precambrian shield, where the correlation coefficients are generally high and $A_1 \simeq B_2$ and $A_2 \simeq B_1$. Values of S, estimated from these coefficients, might be related to the regional structures of the earth's crust such as the shapes of batholiths, dykes, or sedimentary layerings. However, detailed analysis of the crude model considered here should not be extended further. For example, due to the deflection of heat flux around the conductivity anomaly, Q is disturbed outside the anomalous body where K is normal (See, for example, Figure 12 (insert) in *Lachenbruch and Marshall*, [1966] for illustration.). This fact makes a rigorous application of our model to the data impossible. The negative coefficients in Table 1 are difficult to explain by this model, because, according to (4) and (5), or (7) and (8), the coefficients must be positive for $G_0 > 0$ and $Q_0 > 0$.

Correlation between thermal conductivity and heat production. In continental areas, a large part of the total radioactive elements, the ultimate cause of terrestrial heat flow, are probably concentrated in the upper layers of the earth's crust. The observed correlation between Q and K can be readily explained if K is positively correlated with the radioactive heat production A.

Let the anomalies of Q, K, G, and A be

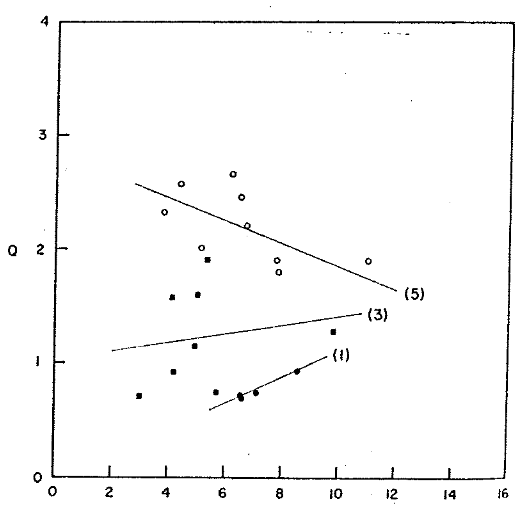

Fig. 4. Heat flow Q (in 10^{-6} cal/cm² sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). Europe 1: (1) ● Ukrainian shield; (3) ■ Area of Caledonian orogeny; (5) ○ Area of Alpine orogeny.

$$\Delta Q = Q - Q_0$$

$$\Delta K = K - K_0$$

$$\Delta G = G - G_0$$

$$\Delta A = A - A_0$$

respectively. Then, the assumptio

$$\Delta Q = h \cdot \Delta A$$

and

$$\Delta A = k \cdot \Delta K$$

where h is the depth to which heat sources are distributed, and stant of proportionality.

Roy et al. [1968] found that lected provinces in the United S of surface rocks are related linear

$$Q = \alpha + \beta A$$

This relation is compatible with (see Table 1) that Q is related to of

$$Q = A_3 + B_3 K$$

if K and A are mutually relate and (11), B_3/β yields an estima

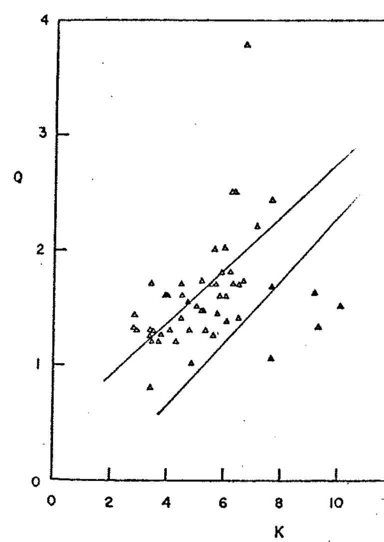

Fig. 5. Heat flow Q (in 10^{-6} cal/ thermal conductivity K (in 10^{-3} c Europe 2: (2) ▲ Russian platform can orogeny; Values of Q more cal/cm² sec are omitted from the di

$$\Delta Q = Q - Q_0$$
$$\Delta K = K - K_0$$
$$\Delta G = G - G_0$$
$$\Delta A = A - A_0$$

respectively. Then, the assumption requires

$$\Delta Q = h \cdot \Delta A$$

and

$$\Delta A = k \cdot \Delta K \qquad (9)$$

where h is the depth to which the anomalous heat sources are distributed, and k is the constant of proportionality.

Roy et al. [1968] found that in several selected provinces in the United States, Q and A of surface rocks are related linearly

$$Q = \alpha + \beta A \qquad (10)$$

This relation is compatible with our observation (see Table 1) that Q is related to K in the form of

$$Q = A_3 + B_3 K \qquad (11)$$

if K and A are mutually related. From (10) and (11), B_3/β yields an estimate of k. For B_3

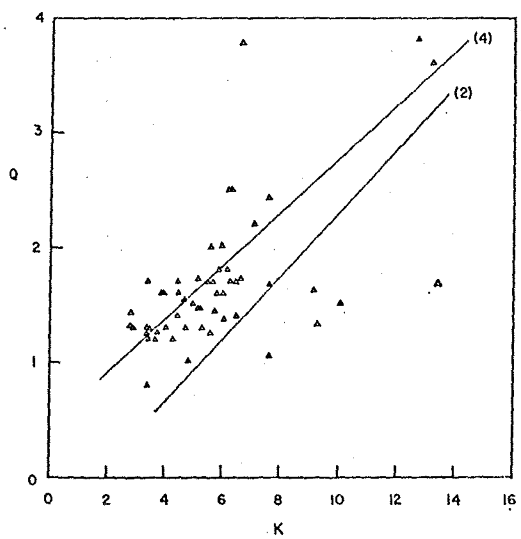

Fig. 5. Heat flow Q (in 10^{-6} cal/cm^2 sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). Europe 2: (2) ▲ Russian platform; (4) △ Variscan orogeny; Values of Q more than 4×10^{-6} cal/cm^2 sec are omitted from the diagram.

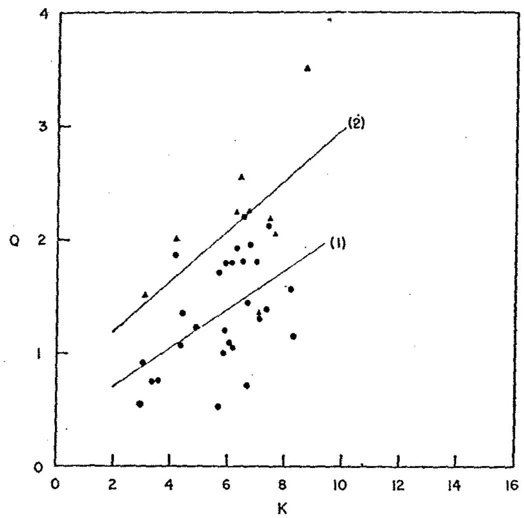

Fig. 6. Heat flow Q (in 10^{-6} cal/cm^2 sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). Japan: (1) ● Area of Paleozoic-Mesozoic orogenies; (2) ▲ Area of Cenozoic orogeny.

$= 0.1 \times 10^{-3}$ °C/cm (see Table 1) and $\beta = 8 \times 10^5$ cm [see *Roy et al.*, 1968], $k = 0.12 \times 10^{-9}$ °C/cm^2 is obtained. The experimental data on thermal conductivity and heat production are not yet adequate to assess independently the reliability of this relationship. However, K and A of igneous rocks are known to vary systematically with chemical and mineralogical composition [see, for example, *Clark*, 1966; *Bullard*, 1961]. Typical values for basalt are $K = 5 \times 10^{-3}$ cal/cm sec °C and $A = 0.1 \times 10^{-12}$ cal/cm^3 sec; typical values for granite are $K = 8 \times 10^{-3}$ cal/cm sec °C and $A = 0.5 \times 10^{-12}$ cal/cm^3 sec. If we assume that K of igneous rock increases in proportion to A as the composition varies from basic (basaltic) to acidic (granitic), then $k = 0.1 \times 10^{-9}$ °C/cm^2.

The agreement of these two independent estimates of k suggests that assumption (9), crucial to this model, is not unreasonable for igneous rocks. On this condition, the relationships among Q, K, and G are

$$Q = K_0(G_0 - kh) + khK \qquad (12)$$

and

$$G = kh + K_0(G_0 - kh)/K \qquad (13)$$

The empirical coefficients given in the third and fourth columns of Table 1 are to be interpreted by (12) and (13) as

$$A_3 = B_4 = K_0(G_0 - kh) \quad (14)$$

and

$$B_3 = A_4 = kh \quad (15)$$

The definition of k and h shows that B_3 and A_4 must be positive. Although the model cannot give a universal explanation of the observed Q–K correlation because of the several negative values of B_3 and A_4, it does provide an explanation of some of the observations in Table 1. In such provinces as the Canadian shield, the Australian interior lowland, areas of Paleozoic-Mesozoic and Cenozoic orogenies in Australia, Precambrian shield and the stable basin of South Africa, the values of A_3 and B_4 are positive and approximately equal. By (14), this implies $G_0 > kh$, which imposes a condition on h, the depth of anomalous heat sources. For $G_0 = 0.3 \times 10^{-3}$ °C/cm and $k = 0.1 \times 10^{-9}$ °C/cm², h is less than 30 km. Even smaller depth seems to be more plausible if we compare the value of kh with the observed values of B_3 and A_4. The estimate of h is in good agreement with the interpretation of *Roy et al.* [1968] that the depth of anomalous heat source distribution, which is given by β in (10), is 7 to 10 km. Negative values of A_3 and B_4 in the Ukrain-

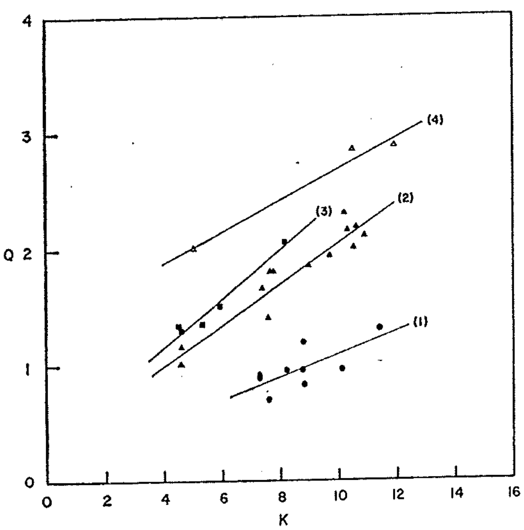

Fig. 7. Heat flow Q (in 10^{-6} cal/cm² sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). Australia: (1) ● Australian Precambrian shield; (2) ▲ Australian interior lowland; (3) ■ Area of Paleozoic-Mesozoic orogenies; (4) △ Area of Cenozoic orogeny.

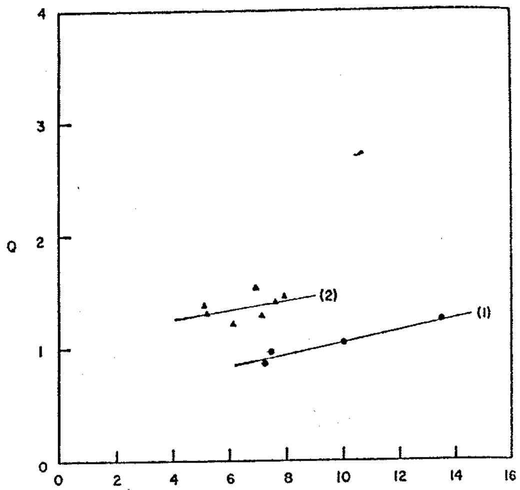

Fig. 8. Heat flow Q (in 10^{-6} cal/cm² sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). Africa: (1) ● South African Precambrian shield; (2) ▲ South African stable basin.

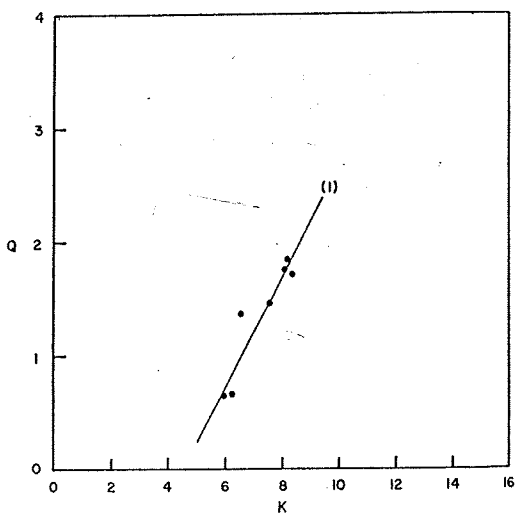

Fig. 9. Heat flow Q (in 10^{-6} cal/cm² sec) versus thermal conductivity K (in 10^{-3} cal/cm sec °C). India: (1) ● Peninsular shield.

ian and the Indian Peninsular Precambrian shields may imply that G_0 is generally small in these areas. It seems desirable to us that the relation of K to A be established experimentally before analyzing in greater detail the heat flow data. Data on K and A of metamorphic and sedimentary rocks are necessary to test the validity of the model in the areas where these rocks predominate.

Summary and Conclu

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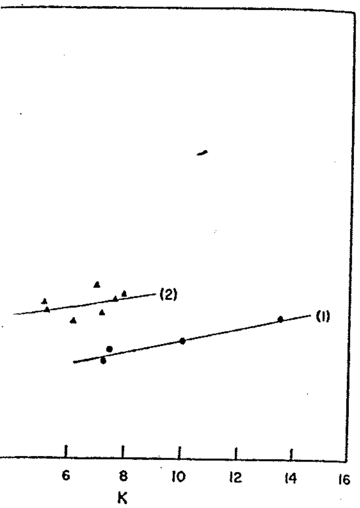

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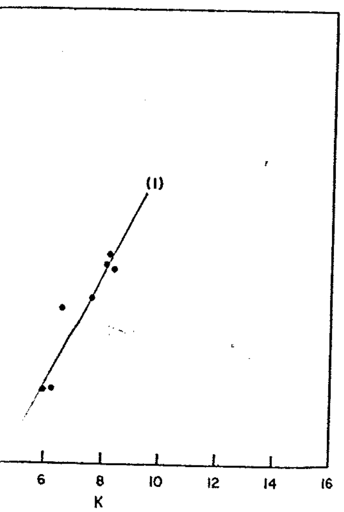

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Summary and Conclusion

Correlation and regression analyses of terrestrial heat flow Q, thermal conductivity K, and thermal gradient G show that Q and K (or, $1/Q$ and $1/K$) are correlated positively in many of the major tectonic provinces on land.

Higher Q will be associated with higher K in the inhomogeneous earth's crust because heat flow converges where the crust is more conductive. Closely spaced heat-flow stations, together with the knowledge of the detailed near-surface crustal structure, will be necessary to evaluate the magnitude and extent of the effect.

The proportionality of thermal conductivity to heat production seems to be the promising explanation of Q–K correlation in the sense that it is compatible with the powerful demonstration of *Roy et al.* [1968] and *Lachenbruch* [1968] that Q is related linearly to heat production A. The validity of this model must be tested experimentally by determining the relationship between K and A in various rocks.

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