Jour. Korean Inst. Mining Geol.
Vol. 26, No. 3, p. 371-382, 1993.

A Study on the Heat Generation and Thermal Conductivity of Crustal Rocks

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ABSTRACT: Compilations of thermal conductivity and radiogenic heat production on 20 typical rock types provide a convenient summary. These compilations allow estimates to be made of the radioactive heat generation for the continental crust and thus heat flow anomalies of tectonic origin to be isolated.

INTRODUCTION

The temperature distribution in the continental lithosphere affects many physical parameters including density, thermal conductivity, and seismic velocity. Temperature-depth calculations, however, are sensitive to the vertical distribution of radiogenic heat production and thermal conductivity, neither of which can be measured directly at depths more than a few kilometers. In order to facilitate thermal modeling, I have made an extensive compilation of radiogenic heat production and thermal conductivity for rocks grouped into 21 types.

The major compilations of thermal and physical properties of rocks and minerals are those by Clark et al. (1966), Kappelmeyer and Haenel (1974), and Roy et al. (1981). Clark et al. (1966) made the first comprehensive compilation of data on seismic velocity, thermal conductivity, and the content of U, Th, and K in rocks. Kappelmeyer and Haenel (1974) extended the earlier compilations of thermal conductivity and heat production; Roy et al. (1981) also extended the compilation of seismic wave velocity. The thermal conductivity of sedimentary rocks has been emphasized by Sekiguchi (1984) and Vacquier (1984). Drury et al. (1984) presented a summary of thermal diffusivity determinations.

The importance of heat production measurements for geothermal studies was initially emphasized by Birch (1954) with his investigation of the relationship between heat production and the abundance of U, Th, and K. Clark et al. (1966) reported the U, Th, and K content of both meteorites and commonly occurring rocks. The study of U, Th, and K was continued by Lambert and Heier (1967) who generalized available measurements to characterize the heat generation properties of continental crust.

The type of heat production studies initiated by Birch and co-workers was soon extended globally. Both Birch et al. (1968) and Roy et al. (1968) had focused on heat production in granitic rocks with application to the New England region of the United States. Swanberg et al. (1974) studied heat production in Norway. Bunker et al. (1975) studied Australian crystalline rocks. Lachenbruch and Sass (1977) studied the conterminous United States. Jaupart et al. (1981) made 39 new measurements in several different geologic environments in igneous, metamorphic, and metasedimentary rocks, basing their studies in New Hampshire.

Rybach (1976) began to investigate the relationship of heat production and P-wave velocity. Building upon this early study, Rybach and Buntebarth (1982) studied the relationship between density, seismic velocity, heat generation, and mineralogical constitution. Rybach and Buntebarth (1984) showed the considerable heat production variations with rock type and the geologic age of the rocks. Cermak (1989) suggested that the uppermost crust is dominated by microcracks which allowed a certain redistribution of radioactive elements by deep circulation of groundwater.

Turning to the area of thermal conductivity, we find early studies by Clark et al. (1966) which focused upon the variation of conductivity in different rocks at 20℃. Kanamori et al. (1968) measured thermal conductivity at high temperatures. Schatz and Simmons (1972) continued this study as did Scharmeli (1982). Cermak (1982) studied the thermal conductivity/temperature relationship in granitic and basaltic rocks. Royden et al. (1983) investigated the relationship between thermal conductivity and depth for sedimentary rocks.

There are only minor limitations in the existing

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compilations of thermophysical properties of rocks. Owing to continued work in measuring thermal properties, however, it is possible to extend the rock types that have been studied, and to broaden the sampling locations.

The study presented here seeks to augment previous work first by making a comprehensive compilation of heat production, thermal conductivity, and P-wave velocities. I have also been concerned with investigating variations of heat production and thermal conductivity with depth. The possibility of a significant relationship between P-wave velocity and heat production was also examined.

DATA

Heat production data for 21 rock types are listed in Table 1. It should be noted that the data are far more abundant for felsic igneous rocks than for basic rocks. In compiling the vast amount of data, I found that many of the sources quoted were secondary and the reported values differ sometimes from the original values. Wherever possible, I have gone beyond these secondary sources to the original ones. The possibility that these rock types are contaminated so that their present content of U, Th, and K differs from their original amount, should be kept in mind.

Table 2 summarizes the mean and standard deviation for thermal conductivity of 20 rock types. Unfortunately, porosity which is among the most important factors influencing thermal conductivity, has not been reported by the original investigators in most cases.

Significant additions have been made to seismic velocity data for rocks and these are noted in Table 3. Wherever feasible, I have selected original data reported from tables rather than graphs. Both laboratory and field measurements are included.

ANALYSIS AND DISCUSSION

Radioactivity

Heat production data for igneous rocks shows that U, Th, and K are strongly concentrated in granitic rocks. Granite and syenite have the highest heat production (3.6 μ Wm^{-3}) of common rock types although heat generation is variable as indicated by their large range of values.

Heat production in basalt is only one-third that in granodiorite. In fact, heat production values show a consistent decrease from felsic to ultramafic rocks. Metamorphic rocks show a similar trend toward heat production decrease as the rocks become more mafic. In amphibolite and granulite, heat production is low and varies only slightly from 0.08 to 1.51 μ Wm^{-3}.

Sedimentary rocks also exhibit a low variability in heat production when compared to felsic igneous rocks. Limestone has the lowest heat production of the common sedimentary rock type; shale and sandstone have the highest heat production. As the distribution of U and Th is affected by water migration, permeable sedimentary rocks such as sandstone shows considerable variation in heat production.

Amphibolite, granulite, and gabbro associated with lower crust have a mean heat production range of 0.68 to 1.1 μ Wm^{-3}. However, it is probable that these values do not represent the entire lower crust, although to date the investigation of the lower crust has been limited. Nicolaysen et al. (1981) have suggested that lower crust heat production is 0.56 μ Wm^{-3}, which falls into the range of 0.03 to 1.1 μ Wm^{-3} compiled in Table 1. When rock types are weighted as to their probable abundance in the lower crust, the range of heat production values is about 0.3 to 0.7 μ Wm^{-3} (Chapman, 1986). In computing crustal geotherms, Chapman (1986) assumed the lower crust heat production to be 0.45 μ Wm^{-3}. For the upper mantle, a heat production value of 0.03 μ Wm^{-3} is probable, with a range of 0.005 to 0.08 μ Wm^{-3}.

The relationship between heat production and P-wave velocity was also investigated. Data compiled by original investigators were compiled and new calculations were made for their means and standard deviations. Using the heat production and V_p values in Tables 1 and 3, the relationship between V_p and heat production A is shown in Fig. 1. Because crustal seismic velocities are sensed remotely by refraction and reflection experiments, and are not restricted to regions where samples are available, Fig. 1 can be used to estimate heat production in the crust.

In general, P-wave velocity shows a correlation with heat production. Because compressional wave velocities increase with increasing mafic content of igneous rocks, heat production values and V_p values show an inverse relationship. From this study the relationship between heat production and P-wave velocity emerges in the following equations:

Table 1. Rock types and heat production values.

Rock Type	N	n	A_o (range) (μ Wm^{-3})	A_o (mean± s.d.) (μ Wm^{-3})	Reference
Granite	70	958	0.59~9.29	3.6± 1.0	4, 6, 8, 9, 13, 14, 15, 16, 20, 24, 30, 31, 41, 43, 44, 46, 48, 49, 50, 51, 52, 53, 56, 59
Granodiorite	19	392	0.80~6.00	2.6± 1.0	6, 7, 8, 10, 12, 14, 20, 25, 32, 39, 41, 46, 47, 48, 49, 50, 57
Monzonite	13	50	0.60~4.87	2.1± 0.7	12, 14, 16, 39, 49, 50
Quartz-Monzonite	9	80	0.86~2.96	2.1± 0.7	12, 32, 44, 50, 52
Basalt	15	93	0.17~3.72	0.9± 0.3	4, 8, 12, 25, 35, 45, 46, 50, 54, 56
Andesite	4	18	0.65~2.52	1.4± 0.8	12, 20, 46, 50
Rhyolite	14	16	0.55~5.58	2.9± 1.1	12, 50
Limestone	4	88	0.04~0.62	0.5± 0.2	8, 21, 22, 40, 46, 47
Shale	5	326	0.23~2.18	1.5± 1.0	1, 8, 21, 22, 46, 47, 57
Sandstone	5	327	0.33~3.80	1.8± 1.0	8, 46, 47, 57
Diorite	9	94	0.16~3.36	1.7± 0.7	8, 16, 20, 24, 31, 46
Quartz-Diorite	9	14	0.13~2.56	0.9± 0.5	13, 26, 32, 33, 46, 50
Syenite	5	54	0.43~6.19	3.6± 0.8	4, 8, 13, 30, 41, 48
Gabbro	11	71	0.04~1.10	0.7± 0.3	4, 8, 9, 20, 25, 31, 46
Gneiss	20	513	0.67~5.00	2.3± 0.7	8, 9, 12, 24, 30, 42, 43, 46, 48, 49, 57
Schist	18	381	0.06~3.29	2.1± 0.5	2, 8, 9, 43, 46, 57
Amphibolite	10	134	0.08~1.51	1.1± 0.6	8, 9, 19, 23, 27, 43, 46
Granulite	12	77	0.34~1.00	0.68± 0.18	8, 19, 20, 23, 27, 46, 57
Eclogite	7	7	0.021~0.16	0.08± 0.05	29, 34, 35, 36, 55
Peridotite	20	54	0.002~0.39	0.03± 0.02	4, 5, 8, 17, 28, 29, 34, 37, 38, 46, 56, 58
Dunite	11	11	0.0008~0.08	0.005± 0.004	3, 11, 18, 22, 29, 34, 35, 37, 46, 56, 58

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55. Tilton and Reed., 1963
56. Verhoogen et al., 1970
57. Vitorello et al., 1980
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59. Wright et al., 1980

N is number of localities for data set. n is number of sample. A_o is heat production.

$$\ln A = 16.68 - 2.63\ V_p \quad (\gamma = -0.98,\ \text{for plutonic rocks}) \qquad (1)$$

$$\ln A = 14.09 - 2.17\ V_p \quad (\gamma = -0.89,\ \text{for plutonic and metamorphic rocks}) \qquad (2)$$

where γ is the correlation coefficient. These results are similar to those of Rybach and Buntebarth (1982) determined on specific rock types whose seismic velocities were measured at pressures of 50, 100, and 200 MPa. Sedimentary and metamor-

Table 2. Rock types and thermal conductivity.

Rock Type	N	n	k_o (range) (Wm^{-3} K^{-1})	k_o (mean± s.d.) (Wm^{-3} K^{-1})	Reference
Granite	49	1,971	1.50~5.80	2.8± 0.8	2, 5, 7, 11, 12, 13, 16, 21, 26, 28, 29
Granodiorite	22	281	1.63~3.50	2.8± 0.4	1, 5, 6, 12, 16, 26, 29
Monzonite	2	9	2.86~3.07	3.0± 0.1	6, 12
Quartz-Monzonite	8	278	1.60~3.99	3.3± 0.4	1, 5, 6, 26
Basalt	48	126	1.12~5.20	1.8± 0.2	1, 2, 5, 6, 7, 9, 12, 15, 19, 26, 28
Andesite	20	874	1.06~4.86	2.4± 0.7	6, 9, 14, 16, 26, 28, 29
Rhyolite	16	436	1.58~4.33	3.1± 0.6	5, 6, 9, 14, 26, 28, 29
Limestone	90	903	1.27~6.26	2.7± 0.7	2, 5, 6, 7, 12, 18, 19, 24, 25, 26, 27, 28, 29
Shale	49	433	0.91~5.12	2.2± 1.2	4, 5, 7, 8, 11, 12, 20, 23, 24, 28, 29
Sandstone	121	879	0.84~7.98	2.7± 1.3	4, 5, 7, 11, 12, 17, 23, 24, 25, 26, 27, 28, 29
Diorite	10	272	1.92~4.10	2.5± 0.6	12, 14, 26, 29
Quartz-Diorite	4	19	2.10~3.27	2.8± 0.4	1, 11
Syenite	7	14	1.50~5.20	2.5± 0.5	3, 5, 12
Gabbro	24	256	1.50~4.00	2.3± 0.3	3, 5, 9, 12, 26
Gneiss	30	619	1.13~5.75	2.6± 0.8	5, 11, 13, 18, 20, 26, 29
Schist	28	181	1.20~6.17	3.2± 0.9	5, 9, 11, 22, 26, 28, 29
Amphibolite	9	74	1.82~4.73	3.3± 0.4	5, 9, 26
Eclogite	5	5	2.46~4.20	3.2± 0.2	10, 12
Peridotite	6	10	2.50~4.60	3.7± 0.6	3, 5, 10, 12
Dunite	9	11	3.50~5.20	4.2± 0.8	5, 10, 12, 19

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27. Sass et al., 1971
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N is number of localities for data set. n is number of sample. k_o is thermal conductivity.

phic rocks show a wide variation in P-wave velocity and heat production and diverge from the $A-V_p$ trend of igneous rocks because of the effects of constituent minerals and water. In my evaluation of the data at this time, there is uncertainty about its significance because of the considerable scatter from the regression line.

Constituent minerals in rocks play an important role in heat production variation. Radioactive elements, for example, are highly concentrated in biotite and hornblende. As shown in Fig. 1, vertical changes in heat production are associated with concentrations of such radioactive constituent minerals. Also, the effects of water play an important role in the distribution of radioactive elements. Smithson and Decker (1973) have shown that heat production is about three times greater in hydrous crystalline rocks than in rocks with only anhydrous mineral phases.

Although the data show considerable scatter, Table 1 suggests that amphibolites generate considerably higher heat production than granulites while the rate of heat production is quite similar between granulites and gabbro. Granulites are believed to have been depleted of U, Th, and water by partial melting as their constituents were preferentially incorporated into upper crustal levels. Partial melting may be a necessary condition for the formation of totally anhydrous granulites (Fyfe, 1973).

Thermal Conductivity

Table 3. Rock types and P-wave velocity.

Rock Type	N	V_p (range) (km s^{-1})	V_p (mean± s.d.) (km s^{-1})	Reference
Granite	53	3.3~6.4	5.9± 0.4	1, 3, 6, 9, 10, 18
Granodiorite	11	4.6~6.4	6.0± 0.2	1, 6
Monzonite	1	(5.3)		1
Quartz-Monzonite	3	5.0~6.5	5.9± 0.1	6, 11, 15
Basalt	19	3.8~7.0	6.2± 0.2	1, 3, 6, 11, 18
Andesite	3	5.1~5.6	5.2± 0.1	1, 6
Limestone	26	1.7~7.1	5.8± 0.7	1, 6
Shale	7	1.7~4.7	3.8± 0.4	1, 6
Sandstone	29	1.4~6.2	4.3± 0.8	1, 6, 16, 17
Diorite	5	5.4~6.5	6.0± 0.4	1, 6
Quartz-Diorite	2	5.1~6.6	6.3± 0.1	6
Syenite	5	5.3~6.7	6.1± 0.5	1, 6, 15
Gabbro	13	5.9~7.2	6.7± 0.3	1, 3, 6, 11
Gneiss	17	2.4~7.5	6.2± 0.4	1, 4, 6, 10, 15
Schist	12	2.6~7.5	6.4± 0.5	1, 6
Amphibolite	16	3.1~8.0	7.2± 0.2	1, 3, 6, 7, 9, 10, 15
Granulite	8	5.0~7.8	7.4± 0.2	3, 4, 8, 9, 12, 13, 14, 15
Eclogite	14	5.2~8.1	7.8± 0.2	1, 2, 3, 5, 6, 12, 18
Peridotite	10	7.5~8.4	7.9± 0.3	1, 6, 9, 10, 18
Dunite	17	6.0~8.6	8.1± 0.3	1, 2, 3, 6, 10

Sources: See References

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N is number of localities for data set. V_p is P-wave velocity.

Table 2 presents thermal conductivity data according to rock type. The data show much complexity since thermal conductivity is influenced by the complex composition and structure within the continental crust. The factors influencing this thermal conductivity are composition, temperature, and pressure. The most important control on thermal conductivity is the mineral abundance and composition. The average thermal conductivities are given by Sass et al. (1971) and Roy et al. (1981) for quartz (5.9 Wm^{-1} K^{-1}), biotite (2.0 Wm^{-1} K^{-1}), and feldspar (2.5 Wm^{-1} K^{-1}).

The average values of some rocks are given by Cermak and Rybach (1982) for diorite (2.91 Wm^{-1} K^{-1}), granodiorite (2.65 Wm^{-1} K^{-1}), gabbro (2.63 Wm^{-1} K^{-1}), amphibolite (2.46 Wm^{-1} K^{-1}), gneiss (2.44 Wm^{-1} K^{-1}), and granitic upper crust (3.0 Wm^{-1} K^{-1}). The thermal conductivities are given by Chapman (1986) for granulite (2.4~2.9 Wm^{-1} K^{-1}) and for generalized lower crust (2.6 Wm^{-1} K^{-1}).

Thermal conductivity of rocks at crustal temperatures varies inversely with temperature according to the relation

$$k\ (T)=k_o/(1+bT) \tag{3}$$

where T is temperature in Celsius, b is a constant, and k_o is a thermal conductivity measured at 0℃. Temperature coefficients b are 1.5×10^{-3} and 1.0×10^{-4} K^{-1} for the upper and lower crust respectively (Chapman, 1986). Zero temperature values k_o are 3.0 and 2.6 Wm^{-1} K^{-1} for the upper and lower crust.

Also, the influence of pressure on thermal conductivity may be due to the limitation of movement of water when cracks are closed. However, the effects of pressure on thermal conductivity are still not well understood. Beck et al. (1976) reported experimental results for thermal conductivity over a specific pressure/temperature range. It may be that the relative effects of pressure and temperature depend on crustal depth. Stress, by closing microc-

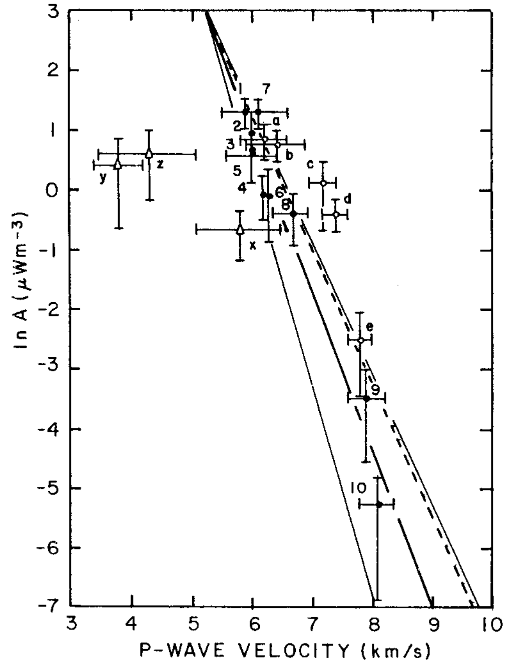

Fig. 1. The relationship between heat production A and P-wave velocity V_p. Closed circles represent (1); granite, (2); granodiorite, (3); quartz-monzonite, (4); basalt, (5); diorite, (6); quartz-diorite, (7); syenite, (8); gabbro, (9); peridotite, and (10); dunite. Open circles represent (a); gneiss, (b); schist, (c); amphibolite, (d); granulite, and (e); eclogite. Triangles represent (x); limestone, (y); shale, and (z); sandstone.

racks, affects thermal conductivity in a manner similar to seismic velocity increase. This is of definite significance.

The mean thermal conductivity of 20 rock types dicates a range from 1.8 to 4.2 $Wm^{-1} K^{-1}$. Considering the composition of the crust, an appropriate range for the upper crust is from 2.5 $Wm^{-1} K^{-1}$ to 3.0 $Wm^{-1} K^{-1}$. The thermal conductivity range probable in lower crustal rocks is from 2.3 to 3.3 $Wm^{-1} K^{-1}$. The lowest is gabbro at 2.3 $Wm^{-1} K^{-1}$, then diorite at 2.5 $Wm^{-1} K^{-1}$, gneiss at 2.6 $Wm^{-1} K^{-1}$, quartzdiorite at 2.8 $Wm^{-1} K^{-1}$, with the highest values for amphibolite at 3.3 $Wm^{-1} K^{-1}$.

It has been shown that thermal conductivity at varying depths is influenced by the types of rocks occurring there. Depending upon rock type, thermal conductivity increases slightly with depth. So far, a satisfactory explanation of this trend has not been advanced. However, I find that higher variability exists in felsic rocks than in mafic. The porosity of sedimentary rocks gives them lower thermal conductivity than igneous or metamorphic rocks.

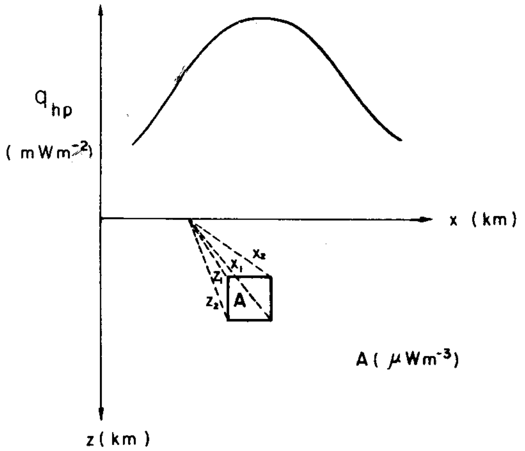

Fig. 2. The vertical sheet with heat production (A).

Mean Radioactive Heat Flow

The calculation of residual surface heat flow and heat flow anomaly due to the heat source distribution may be complicated by several factors. However, this problem can be alleviated to a certain degree if an accurate model of the earth's crust and the heat source distributions of typical rock types are available.

An accurate model of the earth's crust depends upon collecting rock samples in a way that faithfully reflects their formation. To do this, a method should be developed to determine the average composition of rocks in a given lithosphere according to the layering of its crusts as follows: (1) by analyzing the available rock types; (2) by determining the proportion of their occurrence; and then (3) by assigning this proportion to the crustal model. This process is not intended to represent a detailed and complete summary of all pertinent influences upon the crust but simply to provide a working estimate of lithospheric temperatures. The model should be applied to regions where a steady state can be expected to exist, as in the case of stable continental crusts.

The problem of estimating a residual surface heat flow or heat flow anomaly occurs quite regularly in heat flow provinces dealing with radioactive heat flow. The mean radioactive heat flow (q_{hp}) has been calculated using the following procedures. Let us consider a thin vertical sheet with heat production (A) as shown Fig. 2. Simmons (1967) has

Table 4. Comparison of heat production (A_o) and seismic velocity (V_p).

Rock Type	A_o	mean± s.d.		V_p	mean± s.d.
	(μ Wm^{-3})	range		(km s^{-1})	range
	1	2	1, p=50 MPa	1, p=100 MPa	2
Granite	2.81± 0.97	3.6± 1.0	5.84± 0.16	6.11± 0.33	5.9± 0.4
	0.806–4.65	0.59–9.29	5.52–6.04	5.49–6.68	3.3–6.4
Granodiorite	2.50± 1.25	2.6± 1.0	5.93± 0.18	6.10± 0.17	6.0± 0.2
	0.628–4.41	0.8–6.0	5.66–6.30	5.84–6.41	4.6–6.4
Monzonite		2.1± 0.7			(5.3)
		0.6–4.87			
Quartz-Monzonite		1.9± 0.8			5.9± 0.1
		0.86–2.97			5.0–6.5
Basalt		0.9± 0.3			6.2± 0.2
		0.17–3.72			3.8–7.0
Andesite		1.4± 0.8			5.2± 0.1
		0.65–2.52			5.1–5.6
Limestone		0.5± 0.2			5.8± 0.7
		0.04–0.62			1.7–7.1
Shale		1.5± 1.0			3.8± 0.4
		0.23± 2.18			1.7–4.7
Sandstone		1.8± 1.0			4.3± 0.8
		0.33–3.80			1.4–5.6
Diorite	0.877± 0.28	1.7± 0.7	6.26± 0.27	6.60± 0.42	6.0± 0.4
	0.472–1.32	0.16–3.36	5.84–6.57	5.97–7.15	5.4–6.5
Quartz-Diorite	0.88± 0.28	0.9± 0.5	6.26± 0.25	6.60± 0.42	6.3± 0.1
	0.472–1.32	0.13–2.56	5.84–6.57	5.97–7.15	5.1–6.6
Syenite		3.6± 0.8			6.1± 0.5
		0.43–6.19			5.3–6.7
Gabbro	0.06± 0.125	0.7± 0.3	6.19± 0.74	6.94± 0.43	6.7± 0.3
	0.007–0.345	0.04–1.10	5.05–7.06	6.37–7.69	5.9–7.2
Gneiss		2.3± 0.7			6.2± 0.4
		0.67–5.0			2.4–7.5
Schist		2.1± 0.5			6.4± 0.5
		0.06–3.29			2.6–7.5
Amphibolite	0.37± 0.18	1.12± 0.6	6.30± 0.27	6.92± 0.20	7.2± 0.2
	0.154–0.701	0.08–1.51	5.92–6.66	6.58–7.09	3.1–8.0
Granulite		0.68± 0.18			7.4± 0.2
		0.34–1.00			6.4–7.8
Eclogite		0.08± 0.05			7.8± 0.2
		0.021–0.16			5.2–8.1
Peridotite	0.017± 0.009	0.03± 0.02	7.71± 0.20	8.22± 0.28	7.9± 0.3
	0.001–0.026	0.002–0.39	7.47–7.99	7.99–8.62	7.5–8.4
Dunite		0.005± 0.004			8.1± 0.3
		0.0008–0.08			6.0–8.6

1 is the data set from Rybach and Buntebarth (1982) and 2 is new determinations from this study.

shown the relationship of gravity (g) to q_{hp} to be:

$$q_{hp}=gA/2\pi G\rho \tag{4}$$

where G is the gravitational constant and ρ is density. This equation is valid for steady-state conditions.

The gravitational attraction of a two-dimensional, very thin vertical sheet is given by

$$g=-2G\int\int_{s}\frac{(z-z')}{(x-x')^2+(z-z')^2}\rho\ dx'\ dz' \tag{5}$$

where x is the horizontal distance, z is the depth, and primes show new coordinates.

Using the identity,

$$g=-G\rho\Big[\Big(\beta\ \ln(\beta^2+(z-z_2)^2)-2\beta$$

$$
\begin{aligned}
&\quad +2(z-z_2)\ \tan^{-1} \left.\frac{\beta}{(z-z_2)}\right)_{x_1}^{x_2} \\
&-\Big(\beta\ \ln(\beta^2+(z-z_1)^2)-2\beta \\
&\quad +2(z-z_2)\ \tan^{-1} \left.\frac{\beta}{(z-z_1)}\right)_{x_1}^{x_2}\Big] \qquad (6)
\end{aligned}
$$

where β is $x-x'$, the mean radioactive heat flow (from equation 4) becomes

$$
\begin{aligned}
q_{hp}=-\frac{A}{2\pi}\,&[(x-x_2)\,[\ln\ \{(x-x_2)^2+(z-z^2)^2\} \\
&-\ln\{(x-x_2)^2+(z-z_1)^2\}] \\
&+(x-x_1)[\ln\{(x-x_1)^2+(z-z_1)^2\} \\
&-\ln\{(x-x_1)^2+(z-z_2)^2\} \\
&+2(z-z_2)\{\tan^{-1}\frac{(x-x_2)}{(z-z_2)}-\tan^{-1}\frac{(x-x_1)}{(z-z_2)}\} \\
&+2(z-z_1)\{\tan^{1}\frac{(x-x_1)}{(z-z_1)}-\tan^{1}\frac{(x-x_2)}{(z-z_1)}\}] \qquad (7)
\end{aligned}
$$

Using cells of assigned heat production value, which reflect a geologic cross-section q_{hp} values can be brought into comparison with the calculated heat flow values by finite difference method.

SUMMARY

Heat production is high in felsic rocks and low in mafic rocks. However, heat production in igneous and metamorphic rocks shows a large variation depending on the constituent minerals in the rock and upon the effects of water. Also the temperatures and pressures that occurred during the magma solidification have a strong bearing upon the distribution of U, Th, and K. When we analyze the thermal conductivities of 20 common rocks, we do not find the broad range of difference that we do when we conduct heat production analysis of the same rock types.

Further experimental work should be done to understand better the unique thermal conductivity of each rock type. We can confidently assert that the porosity and water content in a given rock affects its thermal conductivity. However, we must be cautious in our current application of the data. It has been almost exclusively developed in laboratory settings and as yet it is uncertain whether it can simply be applied to the natural setting.

Since a single rock type can exhibit a broad range of thermal conductivities under different conditions, a simple conductivity cannot be applied simply to each rock type. It is not the rock type but the percentage of constituent minerals which is the key influence on thermal conductivity.

The results of my study of the relationship between heat production and P-wave velocity coincide nicely with those of Rybach and Buntebarth (1982) except that in my compilation (Table 4), the V_p values range between 50 MPa and 100 MPa. Press (1966) has suggested that reliable comparisons between field and laboratory measurements show fairly good consistency between the two. In my study of heat production/P-wave velocity, I have found this to be true.

In general, seismic velocity decreases with temperature and increases with pressure, but effects of temperature are more difficult to determine because of thermal expansion and the consequent loosening of the structure. The opening of new cracks and the widening of old cracks cause large decreases in seismic wave velocity (Kern, 1978). The increase of compressional wave velocity with pressure may be attributed to compaction of pore space. The initial rapid increase of seismic wave velocity can be explained as a result of compaction caused by closure of grain cracks. Also, V_p depends upon such elastic parameters as bulk modulus and rigidity because the constituent minerals, quartz, feldspar, pyroxene, and olivine, show quite different elastic moduli.

A better understanding of the relationship between radioactivity and surface heat flow can be achieved by estimating crustal cross-sections through well studied areas. Equation (7) in this study is a good estimator to obtain radioactive heat flow and residual surface heat flow within specific heat flow provinces.

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Manuscript received 12 March 1993

지각 구성 암석의 열생산량과 열전도도에 관한 연구

한 욱

요 약: 지각을 구성하는 20개의 전형적인 암석에 대하여 열전도도와 방사성 원소에 의한 열 생산량을 종합적으로 분석·연구함으로서 대륙 지각에서 방사성원소의 열 생산량과 구별되는 지구조운동에 의한 지열류량 이상 (anomaly)을 평가하였다.