

Measurement of radioactive heat generation in rocks by means of gamma ray spectrometry

Vertical distribution of heat source in the island arc crust

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Abstract: Terrestrial heat flow is the sum of the radioactive heat generated in the crust and the heat flow from the mantle. If we can evaluate the radioactive heat generation in the crust more precisely, we can better estimate the heat flow from the mantle and the thermal state in the earth crust. In this study, the authors measured the contents of radioactive elements in rocks of Kohistan volcanic arc, Pakistan and Ichinomegata, northeast Japan. We conclude that low density rocks ($\rho \leq 2.9$) systematically contain much more radioactive elements leading to high heat generation compared with high density rocks ($\rho \geq 3.0$). In the next step, the vertical distribution of radioactive heat generation in the crust was estimated, and the heat generation of the lower crust in the two areas was found to be much lower than previously considered. It means, if the surface heat flow is the same, the estimated temperature at 30 km depth is about 80 °C higher than previous estimates. This temperature change may strongly affect the seismic activity at the depth.

Key words: Heat generation; heat flow; radioactive elements; lower crust.

Introduction. In the study of the thermal evolution of the earth, major candidate processes of energy discharge from the earth are terrestrial heat flow, volcanic activity, hot spring/geothermal activity and earthquakes. The major heat sources in the earth are the decay of radioactive elements, and the gravitational energy released at the time of earth's formation by accretion.

Terrestrial heat flow is the only directly measurable parameter to estimate the thermal state in the earth. The surface heat flow density consists of the so called mantle heat flow and the heat produced in the crust. Therefore, to estimate the mantle heat flow and the temperature structure in the crust more precisely, detailed information of the vertical distribution of radiogenic heat production rate is important.

It is well known that radioactive elements; i.e., U, Th, K are contained mainly in felsic rocks.¹⁾ This feature is explained by the "incompatible" nature of these elements.²⁾ So far, almost all studies concerning the vertical distribution of heat generation have been made in stable continental regions,³⁾ and the study, in tectonically active regions like Japan, is very few.⁴⁾

In order to know the total amount of radioactive heat in the crust, we have to make direct measurements on all the crustal rocks. However, since it is very difficult to obtain the rock samples all the depths, attempts have also been made to infer the vertical distribution of the radioactive heat generation from other parameters. Birch *et al.*,⁵⁾ demonstrated a linear relation between the surface heat flow and the content of radioactive elements of surface rocks. This linear relationship has been theoretically shown to be compatible with the model in which radioactive elements decreased exponentially with depth.⁶⁾

Separate estimations of heat production structure in the crust have also been made by using the empirical relations between the contents of radiogenic heat production and density, and seismic velocity.⁷⁻⁹⁾ In the latter case, Rybach and Buntebarth⁹⁾ formulated the following two linear equations:

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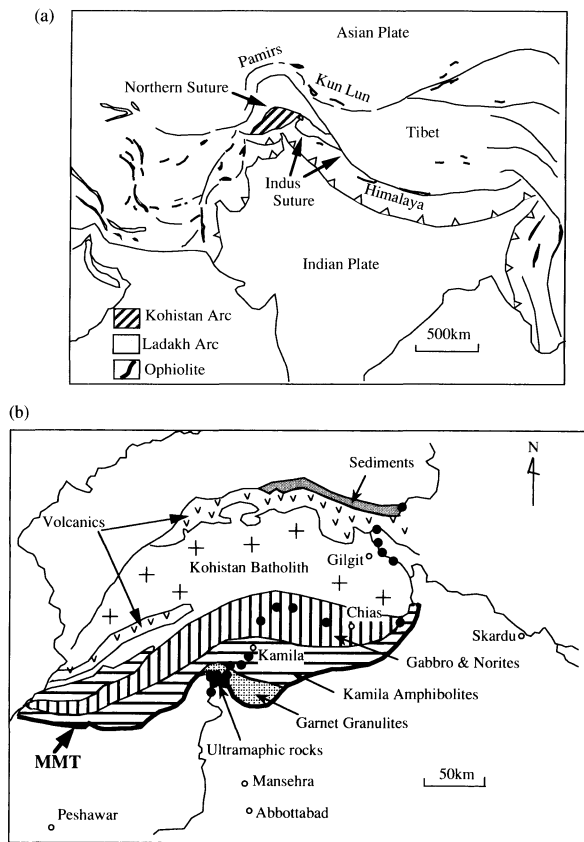


Fig. 1. Fig. 1a shows the location of the Kohistan Arc. Kohistan area belongs to the northern part of Pakistan, which lies between Eurasian and Indian continents. Fig. 1b shows the geological map and the sampling sites with solid circles.

$$\ln A = 12.6 - 2.17V_p \text{ for Precambrian crust, and}$$

$$\ln A = 13.7 - 2.17V_p \text{ for Phanerozoic crust,}$$

where A (10^{-6}W/m^3) is the heat production, V_p (km/s) is the seismic P-wave velocity.

Furukawa and Uyeda⁴⁾ measured the radiogenic heat production of the upper crustal granitic rocks of Hidaka District, Hokkaido, Japan. Where the crustal section is extensively exposed as a result of tectonic movement and erosion associated with the collision of the western and eastern Hokkaido blocks.¹⁰⁾ They concluded that the obtained rate of heat generation and its decrease with increasing depth were similar to those estimated for stable continental areas. However, due to the lack of lower crustal samples, they assumed constant heat generation ($1 \times 10^{-6} \text{W/m}^3$) for the lower crust in their calculation. To the best of the authors' knowledge, no measurement has been made for the lower crustal rocks in tectonically active regions such as island arcs. For the possible mantle rocks, some reports are

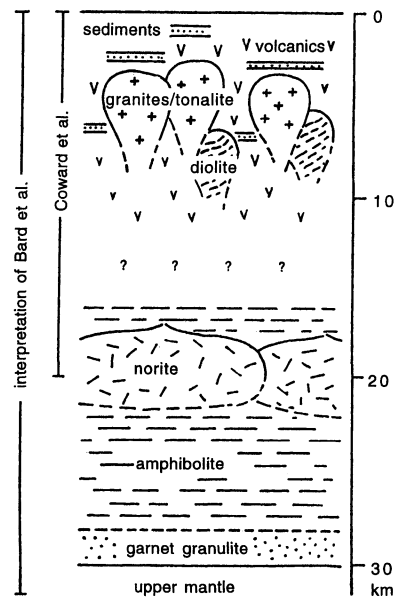


Fig. 2. Schematic geologic column of the Kohistan Arc.

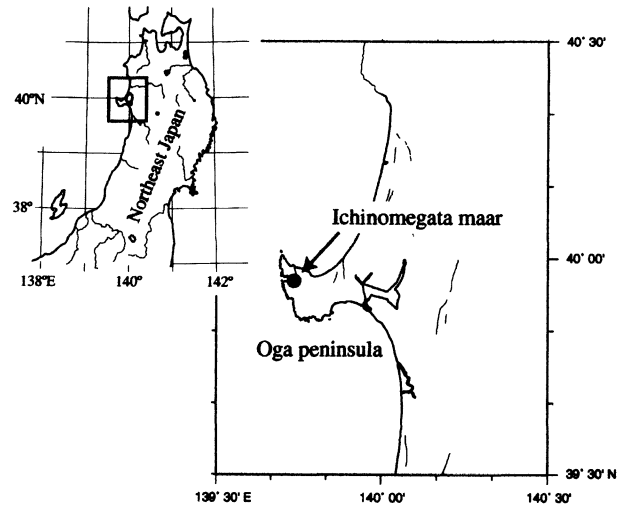


Fig. 3. The location of the Ichinomegata maar, Oga peninsula, northeast Japan.

found.¹¹⁾ Wakita *et al.*,¹²⁾ also reported the results from lherzolite of Ichinomegata maar in northeast Japan.

The main objectives of this paper is to provide some useful information of the vertical distribution of radiogenic elements in the island arc crust. We measured the contents of radioactive elements of the rock samples of the Kohistan Arc, Pakistan, and Ichinomegata maar, Oga peninsula, northeast Japan, by gamma ray spectrometry analysis.

Samples. Kohistan arc is located in the northern part of Pakistan, where Indian subcontinent has been in collision with Eurasia (Fig. 1a). It is considered that

Table I. U, Th, K contents, calculated heat production, density and lithology of Kohistan samples

No.	Sample name	U (ppm)	Error (ppm)	Th (ppm)	Error (ppm)	K (%)	Error (%)	A ($\mu\text{W}/\text{m}^3$)	Error ($\mu\text{W}/\text{m}^3$)	Density (g/m^3)	Error (g/m^3)	Lithology
1	Nilt 10kmN	2.069	0.095	17.800	0.300	2.055	0.041	2.03	0.05	2.81	0.06	Pelitic schist
2	Gligit 11kmS	1.480	0.041	5.800	0.200	1.464	0.036	0.93	0.02	2.74	0.01	Pelitic schist
3	Hunza 70kmS	0.161	0.011	0.299	0.030	0.516	0.016	0.11	0.00	2.70	0.01	Meta-Granite
4	Jaglot 33kmS	8.090	0.150	5.710	0.200	3.003	0.055	2.73	0.06	2.67	0.04	Meta-Granite
5	Gligit 0km	0.797	0.038	8.240	0.190	2.228	0.054	0.98	0.02	2.70	0.02	Granite
6	Dasu 14kmS	0.340	0.080	1.300	0.120	0.190	0.020	0.21	0.02	2.89	0.05	Micro-Diorite
7	Chilas 50kmS	0.038	0.008	0.085	0.008	0.107	0.006	0.03	0.00	2.88	0.03	Diorite
8	Dasu 19kmS	0.080	0.008	0.267	0.013	0.178	0.000	0.06	0.00	2.85	0.01	Diorite
9	Sazin 0km	0.138	0.015	0.327	0.038	0.209	0.008	0.08	0.01	2.90	0.01	Meta-Diorite
10	Hunza 55kmS	0.090	0.019	0.145	0.025	0.178	0.005	0.05	0.01	2.95	0.04	Amphibolite
11	Chilas 25kmS	0.179	0.011	0.493	0.042	0.363	0.008	0.12	0.00	2.93	0.01	Norite
12	Paton 2kmS	0.037	0.007	0.062	0.042	0.123	0.006	0.03	0.00	3.02	0.01	Norite
13	Sazin 30kmS	0.008	0.002	0.024	0.003	0.087	0.000	0.01	0.00	3.14	0.01	Gabbro
14	Paton 1kmN	0.060	0.004	0.123	0.008	0.268	0.005	0.05	0.00	2.94	0.01	Epidote-Amphibolite
15	Paton 1kmS	0.022	0.003	0.033	0.006	0.183	0.004	0.03	0.00	3.47	0.10	Garnet granulite
16	Paton 7.4kmS	0.021	0.002	0.095	0.004	0.037	0.000	0.02	0.00	3.31	0.11	Garnet granulite
17	jijal	0.006	0.001	0.020	0.003	0.004	0.000	0.00	0.00	3.23	0.08	Clinopyroxene

Table II. U, Th, K contents, calculated heat production, density and lithology of Ichinomegata samples

No.	Sample name	U (ppm)	Error (ppm)	Th (ppm)	Error (ppm)	K (%)	Error (%)	A ($\mu\text{W}/\text{m}^3$)	Error ($\mu\text{W}/\text{m}^3$)	Density (g/m^3)	Error (g/m^3)	Lithology
1	Ich-10004	0.680	0.040	0.720	0.090	1.060	0.030	0.34	0.02	2.86	0.07	Meta-Basalt
2	Ich-10003	0.286	0.024	0.765	0.068	0.151	0.010	0.15	0.01	2.93	0.02	Hornblende-gabbro
3	I-464	0.130	0.030	0.320	0.060	0.180	0.010	0.08	0.01	2.91	0.04	Hornblende-gabbro
4	I-1077	0.340	0.007	1.652	0.017	0.328	0.008	0.25	0.05	2.87	0.6	Amphibolite
5	I-402	0.081	0.014	0.113	0.042	0.242	0.012	0.06	0.01	2.91	0.04	Amphibolite
6	I-1043	0.074	0.011	0.056	0.034	0.148	0.012	0.04	0.00	3.12	0.04	Hornblende-gabbro
7	I-661	0.057	0.011	0.090	0.008	0.304	0.011	0.06	0.00	3.07	0.03	Hornblende-gabbro
8	I-1078	0.059	0.007	0.081	0.017	0.078	0.005	0.03	0.00	3.25	0.04	Pyroxene-gabbro
9	Ich-10002	0.098	0.007	0.156	0.013	0.061	0.003	0.05	0.00	3.15	0.08	Pyroxene-gabbro
10	Ich-10000	0.123	0.011	0.068	0.076	0.011	0.002	0.04	0.01	3.12	0.07	Websterite
11	Ich-10005	0.142	0.012	0.095	0.017	0.018	0.002	0.05	0.00	3.24	0.05	Websterite
12	I-1071	0.068	0.007	0.143	0.017	0.219	0.008	0.05	0.00	2.93	0.05	Websterite
13	I-665	0.051	0.005	0.118	0.008	0.020	0.002	0.03	0.00	3.28	0.03	Olivine-Websterite
14	Ich-10001	0.110	0.040	0.110	0.060	0.011	0.003	0.05	0.01	3.37	0.07	Lherzolite
15	I-637	0.029	0.004	0.092	0.013	0.014	0.002	0.02	0.00	3.34	0.09	Lherzolite

Kohistan arc (from southern MMT (Main Mantle Thrust) to Northern Suture) was formed between the late Jurassic and Cretaceous times. Almost complete crustal cross section of this arc is believed to be exposed; progressively deeper structure is outcropped toward south.¹³⁾ Fig. 1b show the geological map. Fig. 2 shows a schematic cross section, and detailed geological setting is described in Coward *et al.*,¹⁴⁾ and Ohta.¹⁵⁾ According to the isotopic dating and palaeomagnetic studies, collision to the Eurasia continent at Northern Suture occurred 75 Ma, and collision at MMT occurred 40-50 Ma.^{13),16),17)} The seismic activity, considered to be of the subduction origin, is still observed at present.¹⁴⁾ Fig. 1b also shows the sampling sites.

Ichinomegata, Ninomegata and San-nomegata, in Oga peninsula, Akita prefecture are maars which erupt-

ed about 10,000 years ago according to C_{14} dating $9,040 \pm 400$ years B.P.¹⁸⁾ Around Ichinomegata maar, xenoliths of various mantle and lower crustal rocks are exposed. Geophysical studies show that the depth of Moho discontinuity around this region is about 25 km.¹⁹⁾ Fig. 3 shows the location of the Ichinomegata region.

Data analysis. The total amount of radiogenic heat in the crust is estimated from the content of uranium (U), thorium (Th) and potassium (K). Since the parent nuclides of the uranium and thorium series emit very low level of gamma-rays, we estimated their contents by gamma ray spectrometry of their daughter nuclides. The high advantages of this method, if germanium semiconductor sensor is used, is high resolution of energy distribution, without performing chemical separation and

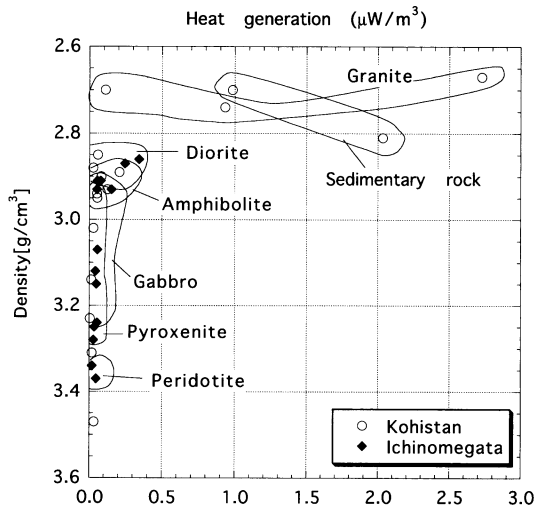


Fig. 4. Correlation between density and radiogenic heat production of Kohistan and Ichinomegata samples. General rock types are also indicated.

the capability of simultaneous measurement of many nuclides.

We measured 17 samples from the Kohistan region, and 15 samples from the Ichinomegata maar region. We used the following peaks to determine the contents; ²¹⁴Pb (295, 352 keV), ²¹⁴Bi (609 keV) for uranium, ²¹²Pb (239 keV), ²²⁸Ac (338, 911 keV), ²⁰⁸Tl (583, 2,614 keV) for thorium, and ⁴⁰K (1,460 keV) for potassium, respectively. The radiogenic heat production values were calculated as follows.²⁰⁾

$$A = \rho (9.52C_U + 2.56C_{Th} + 3.48C_K) \times 10^{-5}$$

where A is the heat production ($\times 10^{-6}$ W/m³), C_U and C_{Th} are the U and Th concentration (ppm), respectively, C_K is the K concentration (%), and ρ the density (kg/m³).

Result and discussion. Tables I and II show the U, Th, K contents, calculated radiogenic heat production and density for the rocks from the Kohistan and Ichinomegata regions, respectively. The results are also shown in Fig. 4. As seen in the tables and Fig. 4, U, Th, K contents and the amount of heat production are large for low density samples. The amount of heat production, in fact, shows an abrupt drop when the density exceeds about 2.8 g/cm³.

Fig. 4 also shows the relationship between heat generation and rock types. Granite and sedimentary rocks show higher values and gabbros, pyroxenites and peridotites show lower values. It is clear that the radionuclides are concentrated in lighter rocks that constitute the upper crust. The results seem to be quite reasonable from the geochemical point of view,²⁾ since U and Th are known to be LIL (Large Ion Lithophil) ele-

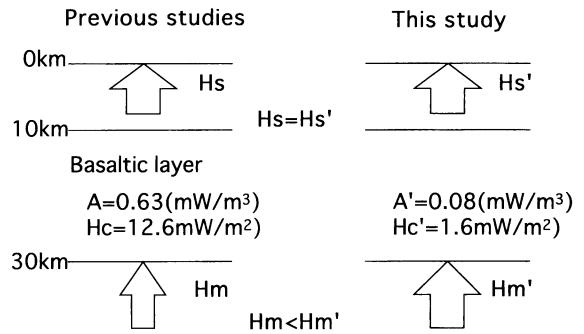


Fig. 5. The effect of heat generation in the lower crust. If the surface heat flow is the same, our model suggests that heat flow from the mantle is higher by order of 10 mW/m² than the previous studies.⁴⁾

ments, and K is a volatile element. All these elements are classified as 'incompatible elements' which can not be easily incorporated into crystal phase during the crystallization differentiation process. In addition, U is easy to move under the influence of meteoric and underground water movements, and Th tends to move under the influence of metamorphic process.

Generally, our results are in agreement with previous studies. However, there is some difference. In previous studies, due to lack of data, it has been customary to model the lower crust by basaltic rocks. In this study, we considered the effect of radiogenic heat production of the lower crust by assuming two models as shown in Fig. 5; the left and right figures show a conventional model and the present model. In our model, the average value of heat generation in the lower crust is taken to be 0.08×10^{-6} W/m³, which is 1/8 of conventional studies.¹⁾ If we adopt the above small value, it results in larger mantle heat flow for the same surface heat flow. If we assume the thermal conductivity of the lower crust as 3.0 W/mK, the temperature at 30 km depth becomes 80~100 deg. Centigrade higher in our model (Fig. 6). The temperature of 80~100 deg. C at 30 km depth may strongly affect the capability of earthquakes generation which is supposed to be controlled by temperature sensitive brittle-ductile transition at the depth.

We can examine the relationship between density and P wave velocity of the Kohistan rocks, using the measurements by Chroston and Simmons.²¹⁾ For the Ichinomegata samples, we apply the general correlation between density and Vp compiled by Ludwig *et al.*²²⁾ Fig. 7 shows the relationship between P wave velocity and heat production in the Kohistan and Ichinomegata samples. Indicated two lines are empirical relations obtained by Rybach and Buntebarth⁹⁾ as mentioned

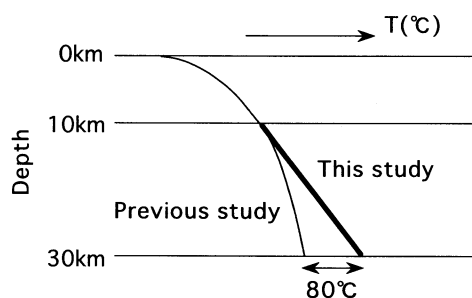


Fig. 6. The difference of the heat generation structure in the lower crust results in changes of about 80 °C in the temperature at 30 km depth. This results can be of considerable importance for the estimate of the thickness of seismogenic layer.

before for Precambrian and Phanerozoic samples. At this stage, it is not clear if our data on relatively young (after Mesozoic era) island arc rocks are systematically different from stable continental data.

Conclusion. In this paper, we present the radiogenic heat production structure of the island arc crust, on the basis of some new measurements of radionuclide concentrations of island arc rocks. The new heat production structure consists of an upper crust with very large heat production values, and a lower crust with very low values. We also present very preliminary results on the relationship between heat generation and P wave velocity. For the next step, we will try to better estimate the heat generation structures in various parts of the world, especially for island arc regions, where the measurements on the accretionally prism rocks may play an important role.

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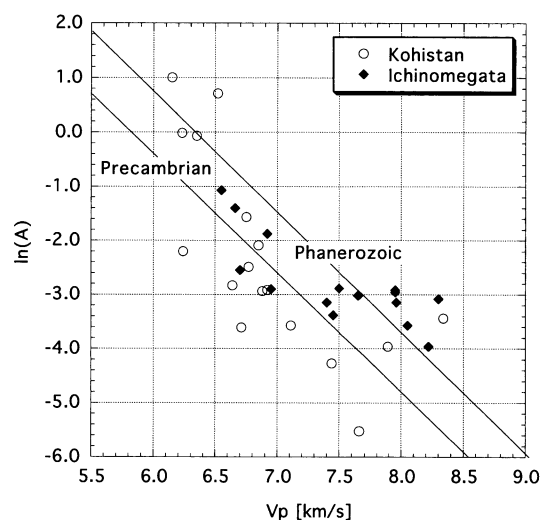


Fig. 7. Correlation between logarithm of heat generation and Vp of the rock samples. The two lines are for rocks from stable continental areas.⁹⁾

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