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Gamma ray spectrometry of rocks from a volcanic sequence penetrated by the SG-1 borehole and the radiogenic contribution to the total heat flow

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Abstract. Results derived from gamma-ray spectrometry studies of volcanic rocks in a depth interval of 3540–8150 m are presented. The rocks are shown to have low concentrations of radioactive elements, which is consistent with the clarke of basic igneous rocks close to calc-alkalic series of present island-arc systems. Potassium is present in all rocks of the volcanic sequence, whereas uranium and thorium are absent in some of its beds. Maximum U and Th concentrations are $4{\times}10^{-4}\%$ and $6{\times}10^{-4}\%$, respectively. The Mesozoic sequence was subdivided into seven groups in accordance with associations of radioactive elements. The distribution of radioactive elements and their associations along the SG-1 section can be accepted as criteria for the differentiation of the volcanic sequence. Estimates of the radiogenic heat generation calculated for rocks of the volcanic sequence point to a considerable contribution of the radiogenic heat to the total heat flow. No proportionality exists between the radiogenic heat generation in the crust and measured heat flow.

Problems of the thermal regime and radioactivity require interrelated approaches to their study. Works on the geochemistry of radioactive elements often do not include the analysis of the thermal state of crustal structures and blocks; vice versa, geothermal regime studies us either too general or too fragmentary data on the radioactivity of the Earth's substance.

A detailed comparative analysis of radioactivity and thermophysical properties of minerals, rocks and Earth's shells can be found in [*Smyslov et al.,* 1979], where the relation between the radiogenic (crustal) and mantle components of the heat flow was shown to largely depend on structural features and other factors such as the crustal thickness, amount of the radiogenic heat generation, intensity and volumes of deep thermal energy influx from subcrustal zones etc. The comparative analysis between characteristics of temperature field radioactivity variations showed that the radiogenic heat generation in the crust is not directly proportional to the measured heat flow and that the contribution of the radiogenic (crustal) component to the total heat flow varies from 60 to less than 10%. Apparently, 50–60% is a maximum value of the radiogenic heat contribution within continents. *Aliev* [1988] showed that a temperature rise in depression structures of the Earth depends not only on the heat-screening effect of the sedimentary cover but also on the heat flow intensity in the mantle and crust.

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Combined geothermal studies of the overdeep Saatly (SG-1) borehole revealed a complex relationship between temperature and depth [*Aliev and Mukhtarov,* 2000]. Since the temperature (T) increases more slowly than the depth (H), this relationship was described by the parabola equation [*Aliev et al.,* 2000]

$$T = a_0 + a_1 H + a_2 H^2 \ , \tag{1}$$

where a_0, a_1, and a_2 are parameters estimated by the least-squares method (a_0 = 13.93, $a_1 = 1.69{\times}10^{-2}$, and $a_2 = -7.8{\times}10^{-8}$). The prediction of deep temperatures should take into account the heat flow value and radiogenic heat contribution.

The radiogenic heat is one of the main components of the Earth's internal energy. However, its contribution to the total heat flow depends on the concentration, composition and occurrence type of radioactive elements in rocks.

The radioactivity of volcanic cores (the collection of Prof. R. N. Abdullaev and S. A. Salakhov) from a 3540–8150-

Table 1. Performance parameters of the SARI-2 spectrometer

Element	Gamma-ray source nuclide	Energy, MeV	Windows, MeV	Sensitivity threshold		Error, %	Clarke of main rocks	
				%	Bq/kg		%	Bq/kg
Thorium	$^{208}_{81}Tl$	2.62	2.51–2.72	8×10^{-5}	3.5	12	3×10^{-4}	12
Uranium	$^{214}_{83}Bi$	1.76	1.68–1.85	2×10^{-5}	2.5	10	0.5×10^{-4}	6
Potassium	$^{40}_{19}K$	1.46	1.41–1.51	1×10^{-2}	3.2	10	0.8	240

m interval of the SG-2 section was measured on the mass spectrometer SARI-2 at the radiometric laboratory of the Institute of Geology, National Academy of Sciences of Azerbaijan. The technical performance of the mass spectrometer is characterized in Table 1. The measuring methods and software were developed at the same laboratory. Tests determining the instrument sensitivity and measurement uncertainties were performed with generally accepted methods using standard benchmarks.

The methods applied in this study guarantee a high sensitivity of gamma radiation source elements within an energy range of 0.5–3.0 MeV. If an element was not detected (n.d.), this means that either its concentration is lower than the sensitivity threshold or it is altogether absent. The gamma-ray spectrometry results from the cores measured on the SARI-2 apparatus are presented in Table 2. The volcanic rocks are distinguished by low concentrations of radioactive elements, which is consistent with the clarke of basic igneous rocks [*Vinogradov,* 1962] close to calc-alkalic series of present island-arc systems. Potassium in small amounts is present in all volcanic rocks. Uranium and thorium have not been detected in some beds. Maximum concentrations are not higher than 4×10^{-4}% for uranium and 6×10^{-4}% for thorium.

Mathematical treatment of the radiometric results revealed a nonuniform distribution of radioactive elements in the volcanic sequence. A complex shape of curves showing the variation in the concentration of radioactive elements (Figure 1) and disagreement between the arithmetical mean, mode and median are evidence of postvolcanic processes that affected the distribution of radioactive elements in the rocks. The absence of a simple mathematical function describing U and Th concentrations that have high coefficients of variation is a geochemical feature characteristic of radioactive and trace elements in altered rocks [*Smyslov,* 1974]. The most frequent U and Th concentrations are $(0–0.5)\times10^{-4}$%; less frequent values are 2×10^{-4}% for U and 1×10^{-4}% for Th. The potassium distribution in the volcanic sequence is close to a normal distribution with a bimodal characteristic and has coinciding arithmetical mean and median. All this indicates that the volcanic sequence formed under various geochemical conditions and postvolcanic processes favorable for metamorphism of the rocks played a substantial role.

The Th-U ratio in the volcanic sequence has very low values, indicating an intense Th withdrawal. It is consistent with the crustal clarke (3.86) only in an interval of 4108–4670 m. Apparently, premetamorphic Th and U distributions were uniform throughout the section studied.

The volcanic sequence is represented by a complex of basic rocks with nearly invariable petrological properties and mineral composition [*Abdullaev and Salakhov,* 1999; *Nartikoev et al.,* 1985], which complicates its differentiation. It is equally difficult to differentiate the volcanic sequence in accordance with the metamorphic grade of its rocks. Due to disequilibrium and a weak extent of alterations in rocks, only three intervals with poorly constrained boundaries were identified [*Glagolev et al.,* 2000].

Abdullaev et al. proposed an associative approach to the differentiation of the Mesozoic sequence in an interval of 2800–8264 m based on types of rock associations with due regard for the abundances of main rocks [*Alizade et al.,* 2000]. This approach proved highly effective and we identified seven groups in the same depth interval based on associations of radioactive elements. These are K-U-Th, U-K, Th-U-K, K, U-Th-K and Th-K associative groups. Results of differentiating the Mesozoic sequence into members in accordance with rock associations and into groups in accordance with associations of radioactive elements.

A nearly perfect coincidence of intervals and thicknesses of members differing in rock associations with groups indicates that rock associations and distributions of radioactive elements formed under the action of postvolcanic processes and are closely interrelated (Figure 2). Thus, member I (2830–3540 m) is represented by limestones with sills of basalt and andesitic basalt. Concentrations of radioelements in the limestones do not exceed 0.5% for K and 2×10^{-4}% for U and Th. "Pure" rocks in this member are distinguished by a minimum radioactivity. Against the background of a low and fairly uniform radioactivity of about 6 μR/h, the gamma-ray log exhibits intervals of markedly higher radioactivity values reaching 11–13 μR/h (2883–2885, 2889–2891, 2905, 2966–2968, 3000–3055 and 3145–3168 m). Higher fracturing and contamination of the limestone by various admixtures have been established in these intervals. Higher concentrations of K (to 2.8%) and Th (to 4.4×10^{-4}%) are observed in andesites at depths of 3040–3045 m. This is associated with the presence of accessory minerals and an abrupt increase in the P_2O_5 concentration [*Nartikoev et al.,* 1985]. By radiometric characteristics, this member is classified as the K-Th-U group, i.e. its radioactivity is due to the presence of all three elements.

Member II (3540–4100 m) is represented by fine-porous basalts with variegated basaltic scoria, i.e. by basic rocks. Thorium is absent in this member because it contains no accessory minerals (except for a 3705–3710-m interval with 0.4×10^{-4}% Th), and the U concentration varies around

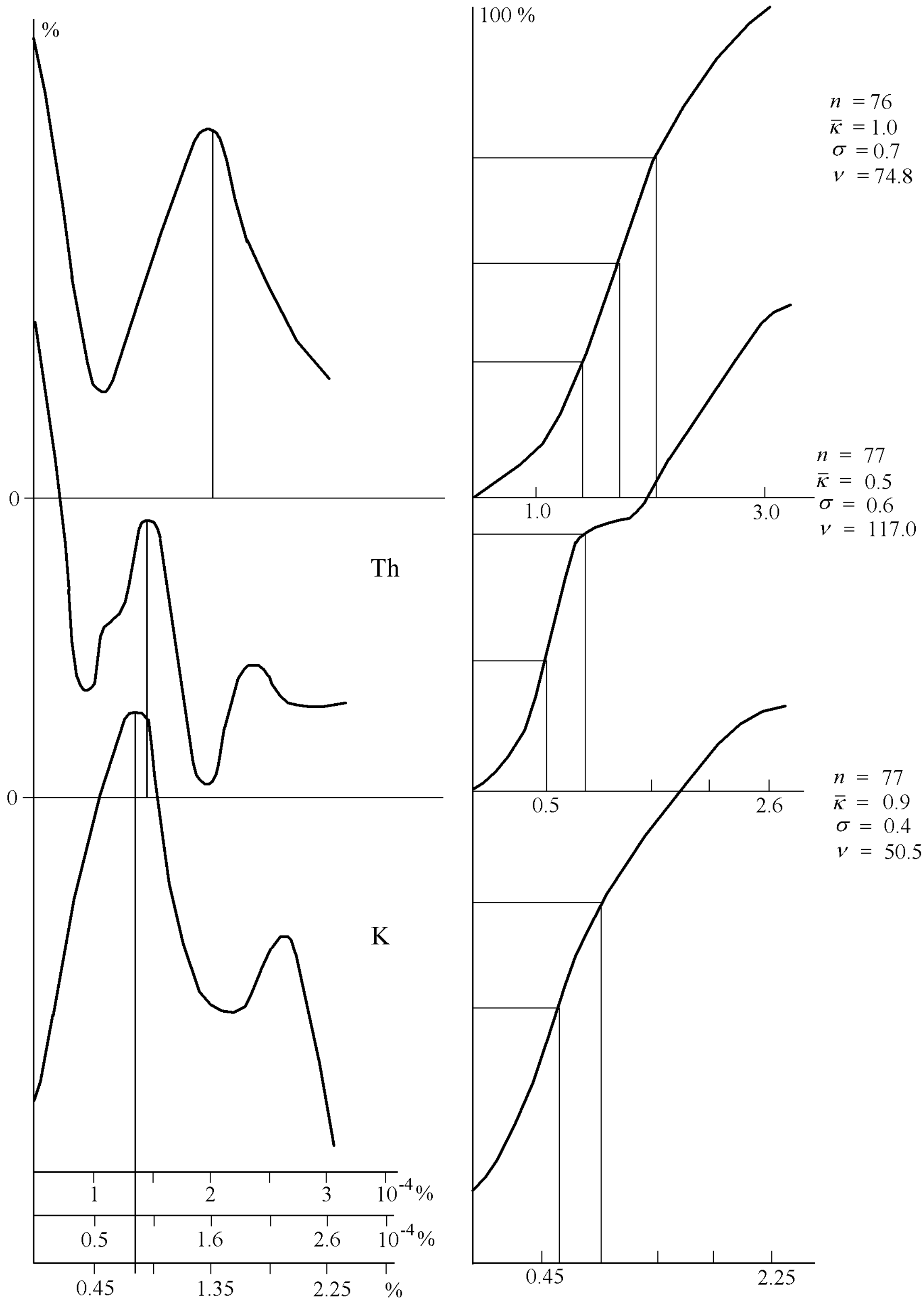

Figure 1. Variational and cumulative curves of concentrations of radioactive elements in rocks of the volcanic sequence penetrated by the SG-1 borehole.

Table 2. Specific activity, average concentrations of radioactive elements and geothermal parameters of rocks from members of the volcanic sequence penetrated by the SG-1 borehole (a depth interval of 3540–8156 m)

Members	Interval and thickness, m	Rocks	Density ρ, kg/m^3	Activity A, Bq/kg	Concentration of radioactive elements, %			Radiogenic heat generation Q_0 μW/m^3	Radiogenic heat flow density q_r mW/m^2	Heat flow q_0, mW/m^2	Deep heat flow q_d, mW/m^2	Radiogenic heat contribution, %
					U$\times 10^{-4}$	Th$\times 10^{-4}$	K					
II	3540–4100 560	Fine-porous basalts	2660	43.3	2.0	n.d.	0.8	0.59	0.33	22.95	22.57	1.44
III	4100–4850 750	Porphyritic basalts	2730	38.7	0.9	1.2	0.8	0.41	0.31	31.90	31.59	0.97
IV	4850–5220 370	Basalts andesitic basalts	2725	46.4	1.0	0.3	1.4	0.42	0.16	34.56	34.4	0.46
V	5220–5428 208	Basalts, andesitic basalts, alternating lavas and tuffs	2730	20.1	0.4	0.7	0.5	0.21	0.04	33.60	33.56	0.12
	5428–6075 647	Andesites, andesitic basalts	2750	11.6	n.d.	n.d.	0.5	0.05	0.003	31.02	31.02	0.01
VI	6075–6775 700	Dacites and their tuffs	2760	16.9	0.2	0.1	0.6	0.12	0.084	40.70	40.62	0.21
VII	6775–8148 1373	Alternating diorites and andesites	2720	31.4	n.d.	0.4	1.26	0.15	0.21	41.67	41.46	0.50
	8148–8156 8	Acidic extrusive rocks	2700	32.4	2.8	n.d.	0.12	0.74	0.06	48.70	41.64	0.14
Average over a 4616-m volcanic sequence			2719	30.1	0.6	0.2	0.9	0.26	0.75	35.0	33.80	3.48

2.1×10^{-4}%, which is much greater than the clarke of basic rocks (0.5×10^{-4}%). The K concentration in rocks of this member is about 0.85%, complying with the clarke of basic rocks (0.8%). The K concentration increases to 2–3% in depth intervals of 3628–3630 and 3660–3666 m, where its concentrators are secondary hydromica and chlorite. The boundary between members II and III is fixed at a 4100-m depth by the appearance of thorium related to secondary transformations of basalts. Thus, by radiometric parameters, member II is classified as the U-K group and has a thickness of 560 m, i.e. exceeds by 200 m the value constrained from rock associations.

Member III (4100–4850 m) consists of strongly altered basalts and andesitic basalts and is dominated by porphyry olivine-pyroxene-plagioclase basalts; alternating lava and lava breccia flows are noted and coarse-grained porphyry varieties occur. In some intervals (particularly in the upper part), the rocks are intensely brecciated. The upper boundary of this member is constrained by appearing thorium, after which beds containing all types of radioactive groups alternate. Since core samples in this interval were taken intermittently, boundaries between the alternating beds are difficult to fix. For example, U and Th are absent in a depth interval of 4680–4692 m and 0.72% K are only present. In a 4714–4719-m interval, K and U concentrations increase to 1.89% and 2.76×10^{-4}%, respectively, and thorium is absent. U is absent at depths of 4817–4824 m, where 2.24×10^{-4}% Th and 0.33% K are present. Andesitic basalts contain, albeit in small amounts, all three elements: U, $(0.63–1.48)\times10^{-4}$%; Th, $(0–0.43)\times10^{-4}$%; and K, 1.3–1.6%. Strong variations in the radioelement abundances indicate compositional instability of the volcanic sequence, which was variously subjected to metamorphic processes. Average concentrations of U, Th and K in this member are, respectively, about 0.35×10^{-4}%, 2.58×10^{-4}% and about 0.81%. The K concentration increases to 1.7% in samples containing plagioclase and numerous calcite veinlets. A higher Th concentration in this interval is due to strong metamorphism. Thorium disappears once again at a depth of 4850 m, indicating a change in the postvolcanic activity. Rocks of the U-K group appear. The boundary of member III is fixed at this depth, where one rock association gives way to another and the K concentration sharply changes here from 0.3 to 1.3%. As regards the radiometric characteristics, member III is represented by alternating U-Th-K, Th-K, K and K-U-Th associations.

Member IV (4850–5220 m) consists of rocks varying within a wide range. Hornblende andesites and trachyandesites occur along with pyroxene-plagioclase basalts. All basalts and andesites are mainly present in the igneous facies. A characteristic feature of this interval is intense brecciation and zeolitization of its rocks. The latter gives rise to a higher U concentration in the middle part of the interval (1.2×10^{-4}% to 1.5×10^{-4}%). A relatively high K concentration (1.1–1.6%) is observed in this member. Thorium in minor amounts occurs in some intervals. U and K concentrations decrease toward the bottom of this sequence, and Th somewhat increases. Radiometrically, this member can be classified as a K-U-Th group dominated by K and U. Uranium disappears at a depth of 5220 m and thorium appears in small amounts (0.9×10^{-4}%). The K concentration becomes less than 1%. Based on these determinations, the lower boundary of member IV should be fixed at a depth of 5220 m.

Member V (5220–6075 m) belongs to a Jurassic volcanic complex. The upper part of this member (5220–5428 m) varies in composition of strongly altered basalts. Rocks in this interval contain in small amounts alternating uranium (to 0.75×10^{-4}%) and thorium (to 1.3×10^{-4}%). Potassium is everywhere present but its concentration is substantially lower than in member IV and varies around 0.4%. As regards rock associations, this interval lies within member V (5200–6000 m), but the radiometric evidence implies that this part should be classified as either an individual member or a 208-m-thick transitional contact zone between members IV and V. The upper part of this member is clearly constrained a lower K concentration, and U and Th concentrations vanish at a depth of 5428 m. Possibly, a closer examination of its rock associations will enable the identification of this member. Radiometrically this member belongs to the Th-K-U group.

At a depth of 5428 m, the K concentration rises to 1.04%, and U and Th disappear. Radioactivity in a 5428–6075-m interval is due solely to potassium, although it is present in small amounts (about 0.5%). Both upper and lower boundaries of this member are distinguishable as "K peaks" with a K concentration reaching 1.5%. Basalts change their color at the boundary, they become lighter and calcite and quartz veinlets appear. According to the radiometric scale, this interval of member V relates to the K group. The difference between the lower boundary positions determined from rock associations and radioactivity is insignificant (25 m).

Member VI (6075–6775 m) is mainly represented by andesites (pyroxene-plagioclase and amphibole-pyroxene-plagioclase varieties) with subordinate andesitic basalts. Strongly brecciated andesites and andesitic basalts alternate in its upper part. Six cores were taken from this member 700 m thick. Its rocks contain very small amounts of U, Th and K; only in one sample does the K concentration reach 1.56%.

Uranium, thorium and potassium are present in small amounts in a depth interval of 6178–6183 m (0.22×10^{-4}%, 0.43×10^{-4}% and 0.94%, respectively); at greater depths the radioactivity decreases. Uranium and thorium are absent in a 6208–6212-m interval, and the K concentration does not exceed 0.75% there. The lower boundary of the member (6777–6779 m) is recognizable as a K peak (1.12%).

Member VII is represented by dacites and their tuffs alternating with pyroxene-plagioclase andesites and andesitic basalts. The rocks are strongly altered, but their primary porphyritic texture and lava facies are reliably recognizable. Samples from only three intervals of this member (7732–7743, 8038–8050 and 8148–8150 m) were measured. Rocks of the member contain potassium in appreciable amounts (1.12–1.52%), thorium in several intervals (0.18×10^{-4}% to 1.63×10^{-4}%) and no uranium. Its lower part is classified as a U-K group, because it consists of acidic extrusive rocks penetrated by numerous small intrusive bodies. Uranium (2.8×10^{-4}%) appears in this interval (8148–8156 m) and the K concentration decreases to 0.12%.

Differentiation according to rock associations (R. N. Abdullaev and S. A. Salakhov)			Differentiation according to associations of radioelements (Ch. S. Aliev and T. A. Zolotovitskaya)					Activity,	Radiogenic
Member	Depth interval and thickness, m	Rock associations	Depth interval and thickness, m	Groups (associations of radioelements)	Concentrations of radioactive elements, %			$A_0 \times 10$ Bq/kg	heat generation
					$U \times 10^{-4}$	$Th \times 10^{-4}$	K		
I	2830–3540 710	Carbonate series: limestones, sills of basalts and andesitic basalts	2830–3540 710	K-Th-U					
II	3540–3900 360	Fine-porous volcaniclastic basalts	3540–4100 560	U-K					
III	3900–4850 950	Porphyry basalts with alternating lavas and volcanic breccia	4100–4850 750	U-Th-K Th-K K K-U-Th					
IV	4850–5200 350	Wide range of rocks (basalts, andesites, trachyandesites)	4850–5220 370	U K Th					
V	5200–6100 900	Large- and coarse-grained porphyry basalts and andesitic basalts with alternating lavas and volcanic breccia	5220–5428	Th-K-U					
			5428–6075 647	K					
VI	6100–6800 700	Strongly brecciated andesites and andesitic basalts; alternating lavas, tuffs and tuffaceous siltstones including radiolarian	6075–6775 700	U K Th U-Th-K					
VII	6800-8267 1467	Dacites and their tuffs; alternating tuffs and their breccias; alternating diorites, andesites and volcanic breccias penetrated by intrusions; acidic extrusive rocks	6775–8100 1325	K-Th					
			8148–8156 8	U-K					
Average over the volcanic sequence 4616 m thick									

Figure 2. Differentiation of the SG-1 geological section according to rock associations, associations and concentrations of radioactive elements, activity and radiogenic heat generation.

Thus, the distribution and associations of radioactive elements along the SG-1 section can be adopted as criteria for differentiating the volcanic sequence. These criteria provide additional constraints on the position of boundaries between members, which is very important for studying geothermal conditions throughout the Middle Kura basin and primarily for estimating the radiogenic heat contribution to the total heat flow in the crust.

The radiogenic heat generation was calculated by the well-known Birch formula from U, Th and K concentrations measured in each bed:

$$Q_0 = \rho(aU + bTh + cK) \ , \tag{2}$$

where Q_0 is the energy released in the unit volume, ρ is density, and a, b and c are coefficients of heat generation in unit volume during the U, Th and K decays, respectively. Their values in natural coefficients are $a = 0.97\times10^{-4}$, $b = 0.27\times10^{-4}$ and $c = 0.36\times10^{-8}$ W/kg.

The radiogenic heat flow density was determined by the formula

$$q_{\mathrm{p}} - \Sigma Q_{0\mathrm{i}} h_{\mathrm{i}} \ , \tag{3}$$

where h_{i} is the thickness of an ith bed. Results of the calculations are presented Table 2, where geothermal parameters of the volcanic sequence are given along with mean concentrations of radioelements in the beds.

The heat flow density (the thermal energy flowing through the unit area) was found by the formula

$$q_0 = \lambda \, \mathrm{grad} T \ , \tag{4}$$

where λ is the thermal conductivity ($\lambda = 2.44$ Wm^{-1} K in the volcanic sequence studied) and grad$T$ is the temperature gradient.

The heat flow generally increases with depth. Its value varies from about 14.3 to 17.0 mW/m^2 in upper parts of the section 500–1000 m) [*Aliev and Mukhtarov,* 2000]. The heat flow density within the drilled part of the volcanic sequence increases from 23 mW/m^2 (3540–4100 m) to 48.6 mW/m^2. However, the heat flow density does not increase everywhere in the section and there are intervals in which it is smaller compared to the overlying beds. For example, such a "negative anomaly" is observed in the K member in which the activity is lowest.

Low concentrations of radioactive elements in rocks of the volcanic sequence predetermined an insignificant contribution of radiogenic heat to total heat flow. The radiogenic heat generation data obtained in our study are, on average, lie within the range typical of basaltic layers in the continental crust (0.31–0.41 μW/m^3) [*Smyslov et al.,* 1979].

Conclusion

The knowledge of the energy conservation conditions in the lithosphere and the energy relations between endogenous and exogenous processes influencing the geological evolution of the Earth is vital to the study of regional metamorphism, tectonic processes, formation of mineral deposits, etc. The direct investigation of the thermal regime in beds penetrated by the SG-1 borehole provided constraints on the energy accumulation by sediments in the region studied. The following results were derived from the study of the geothermal regime in the volcanic sequence.

1. The Middle Kura depression is an area of a lower heat flow (23 to 41 mW/m^2) and the crust is heated due to the mantle heat flow because the radiogenic contribution to the total heat flow is as small as 3.5%.

2. Data on the radiogenic heat generation in the Jurassic volcanic sequence can be ignored in estimating the heat flow from the basement.

3. At the present stage of the Earth's temperature field development, such a regime is characteristic of depression structures filled with Mesozoic-Cenozoic sediments.

4. Due to a low value of the heat conductivity, such structures are favorable for the accumulation of both heat and hydrocarbons.

5. The heat flow generally increases with depth, but geotectonic reconstructions and deep heat estimation should take into account the presence of anomalous heat-generating zones in the crust associated with changes in the geothermal gradient; the latter can increase in the presence of acidic rocks enriched in radioactive elements and decrease if ultrabasic or basic rocks depleted in radioelements prevail.

6. In elucidating the formation conditions of the geothermal regime, one should take into consideration a nonuniform distribution of heat sources in the crust and subcrustal zones. The distribution pattern of radioelements in various types of rocks is a factor controlling the appearance of anomalous geothermal regimes.

7. The estimation of the radiogenic contribution to the thermal regime of the crust should also account for the fact that the radiogenic heat generation in the crust is not directly proportional to the measured heat flow.

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