

Natural radioactivity of regolith in Mare Crisium

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Abstract—Using data from the Mare Crisium region of the moon recently explored by Luna 24, the reliability of forecasting the composition of surface rocks by remote-control methods is estimated. To determine more accurately the radioactivity distribution pattern across the surface of Mare Crisium, a comparison was made between the orbital and laboratory evaluations of the radioelement content in the regolith of this region. The data on the distribution of radioelements in the soil column brought from Mare Crisium were analyzed within the framework of Th-U and K-U systematics of lunar rocks in the light of the possible regolith formation processes at the Luna 24 landing site.

INTRODUCTION

Comprehensive orbital studies of the lunar surface have shown that, amidst various formations of the eastern part of the moon's visible side, the region of Mare Crisium is of special interest. Its round basin (about 500 km in diameter, with an area inside the crest of the surrounding rim of about 200,000 km²) with a low bottom is characterized by a considerable gravitational anomaly. Although the overall radioactivity level in the moon's eastern maria including Mare Crisium is lower than in western ones; nevertheless, it exceeds, as a rule, the radioactivity level of surrounding highland regions (Trombka *et al.*, 1977). The delivery of a soil column from the southeastern part of Mare Crisium to earth and its analyses have made it possible to understand the nature of the observed radioactivity level contrasts in these regions.

According to the stratigraphic model of the formation of mare basins, the excavation of the Mare Crisium basin apparently took place about 4,000 million years ago (Tatsumoto *et al.*, 1977) during giant impact events which were accompanied by intensive processes of melting and crystallization of the lunar crust. In the opinion of many researchers, processes linked with the chemical separation of rocks enriched, in particular, by potassium, rare earth elements and phosphorus (KREEP), occurred during this period. Undoubtedly the origin and distribution of the rocks of this type on the moon figure prominently in the general genesis of lunar rocks.

One of the approaches to the solution of these problems is linked with studies into the regional features in the distribution of chemical elements, including radioactive ones (K, U, Th) by which KREEP-rocks are enriched. From this point of view it is of interest to analyze the data of X-ray-fluorescent and γ -ray radiometric orbital measurements conducted over the surface of Mare Crisium and the areas adjacent to it and to compare these data with the results of

laboratory analyses of the lunar soil sample brought by Luna 24. Such a comparison will permit the estimation of the reliability of forecasting the type of surface rocks by the maps of elemental composition (and including in particular, the distribution of natural radioactivity levels) for lunar regions covered by the trajectories of orbital stations' flights. The data on the distribution of natural radioelements in regolith of the newly-sampled Mare Crisium region on the moon should also be taken into account while analyzing the K-U systematics of lunar rocks from all sampled regions and in the assessment of the average K, U and Th content for the moon on the whole. If we take into consideration that these values are among the "boundary conditions" for models of the moon's thermal history, then, in the light of the recently revised experimental data on the lunar heat flow (Langseth *et al.*, 1976), it is of interest to compare the estimates of the overall contents of radioelements obtained by various methods.

MARE CRISIUM FROM THE CIRCUMLUNAR ORBIT: ANALYSIS OF X-RAY-FLUORESCENT AND RADIOMETRIC MEASUREMENTS

Some conclusions about the composition of the surface rocks of Mare Crisium, on the territory where the Luna 24 was landed, can be drawn from the known orbital data on X-ray-fluorescent and gamma-spectrometric analysis (Trombka *et al.*, 1977). Table 1 lists the average data on the content of a number of elements and their relationships in the surface layer of regolith in Mare Crisium. For the sake of comparison, data are also given from the elemental mapping of other adjacent eastern maria (Mare Serenitatis, Mare Tranquillitatis and Mare Fecunditatis) and highland areas adjacent to Mare Crisium.

Rather large variations in the chemical element content between individual regions recorded in orbital measurements unfortunately do not allow us to draw unambiguous conclusions about the composition of regolith-forming rocks. A clear-cut difference is recorded only between the rocks of highland and mare regions. However, in Mare Crisium there is a trend towards a rise in the values of Al/Si ratios and towards a decrease in Mg/Si ratios as compared with adjacent

Table 1.

Region	Al/Si	Mg/Si	Fe %	Ti %	K %	U*ppm	K/U
Mare Crisium	0.39 ± 0.11	0.18 ± 0.02	10.5	—	—	—	—
Mare Serenitatis	0.29 ± 0.10	0.26 ± 0.07	10.7	2.6	0.17	0.64	2660
Mare Tranquillitatis	0.35 ± 0.08	0.22 ± 0.04	12.1	2.9	0.11	0.53	2080
Mare Fecunditatis	0.36 ± 0.09	0.23 ± 0.05	10.1	2.2	0.125	0.52	2400
Highland south-west of Mare Crisium	0.51 ± 0.10	0.23 ± 0.05	9.3	0.8	0.12	0.39	3080
Highland south-east of Mare Crisium	0.54 ± 0.09	0.22 ± 0.03	8.6	—	0.10	0.36	2780

*Th/U derived from Th data based on a ratio of about 3.6.

maria, which gives some grounds to suppose that the composition of surface rocks is not quite typical of mare basalts.

For the approximate determination (from the data of elemental mapping) of the type of rocks prevailing in this or that region let us make use of the classification suggested by Gleadow *et al.*, (1974) and Lovering and Wark (1975). According to this classification, lunar surface rocks, depending on the chemical composition, can be subdivided into five basic groups (Table 2) while mare basalts (group II) are subdivided into two subgroups (with the high and the low titanium content). A rather sharply pronounced correlation of the content of natural radioelements with the above-mentioned groups of rocks has been noted by Lovering and Wark (1975). It finds its expression in an increase of the K and U content in the rocks with the transfer from group I to group II, from group II to group III, etc. For the convenience of comparisons of the tabulated materials, the data given in Table 2 are modified by the authors with due account of the specific features of orbital measurements (the values of Al and Mg ratios to silicon and the concentrations of Fe, Ti, K and U are taken in weight per cent).

Passing over to analysis of the data referring to the surface rocks of Mare Crisium, we should take into consideration two additional facts: first, orbital photography in this region has been conducted only over its southern and southwestern part; and, second, until recently we have had at our disposal an incomplete set of the numerical data for this region as compared to other areas (Trombka *et al.*, 1977) (see Table 1).

The comparison of the data available in Tables 1 and 2 leads one to the conclusion that the surface rocks of Mare Crisium can belong to the rocks of only two of the groups considered—group II or group IV, and by the Al/Si and Mg/Si ratios they seem to come even closer to group IV of highland basalts enriched by KREEP-components. Although on the one hand an analysis of the distribution of the radioactivity on the flight paths of Apollo 15 and 16 performed by Trombka *et al.* (1977) characterized the region of Mare Crisium as

Table 2.

	Group I	Group II		Group III	Group IV	Group V
Elements	Anorthosites and gabbro- anorthosites	Mare basalts		Highland basalts		
		Rich in Ti	Poor in Ti	Poor in KREEP	Rich in KREEP	Monzonites and granites
Al/Si	0.75 ± 0.09	0.29 ± 0.03	0.28 ± 0.07	0.55 ± 0.095	0.39 ± 0.09	0.29 ± 0.07
Mg/Si	0.14 ± 0.07	0.27 ± 0.06	0.25 ± 0.065	0.27 ± 0.09	0.21 ± 0.08	0.07 ± 0.055
Fe %	2.8 ± 1.4	14.4 ± 1.1	14.2 ± 2.5	5.4 ± 1.5	6.4 ± 2.1	2.2 ± 1.3
Ti %	0.14 ± 0.15	8.0 ± 1.1	1.3 ± 0.7	0.50 ± 0.28	1.0 ± 0.48	0.36 ± 0.12
K %	0.046 ± 0.30	0.060 ± 0.026	0.062 ± 0.037	0.20 ± 0.14	0.89 ± 0.50	4.78 ± 0.66
U $10^{-4}\%$	0.130 ± 0.136	0.131 ± 0.050	0.22 ± 0.15	1.19 ± 0.77	3.5 ± 1.3	8.0 ± 3.2
K/U	$(3.5 \pm 4.2)10^3$	$(4.4 \pm 2.7)10^3$	$(2.8 \pm 2.5)10^3$	$(1.7 \pm 1.6)10^3$	$(2.5 \pm 1.7)10^3$	$(6.0 \pm 2.5)10^3$

to how most contrast one in comparison with surrounding highlands, on the other hand, Metzger *et al.* (1977) draw the unexpected conclusion that this region has the lowest thorium content among the large eastern maria.

In the light of these facts the interest increases in the data on a direct radiometric analysis of lunar soil from Mare Crisium.

RADIOACTIVE ELEMENTS IN THE LUNAR SOIL COLUMN FROM MARE CRISIUM

At present the data on the natural radioelement content in the Luna 24 lunar soil column have been obtained by two methods: nondestructive gamma-spectrometry with the use of a semiconductor detector and a neutron-activation analysis.

In the first case (Surkov *et al.*, 1977b) the assessment of the overall level of the natural radioelement content at the probe's landing site was made. With this aim in view the average soil sample was measured. It weighed 5 g and actually consisted of ten individual specimens weighing about 0.5 g and selected throughout the depth of the column. The following values were obtained for the K, Th and U contents: 0.035 ± 0.01 (weight %), 1.35 ± 0.35 ppm and 0.4 ± 0.1 ppm, respectively. It should be noted that data given by Surkov *et al.* (1977b) for thorium coincide with the corresponding "orbital" value of 1.4 ppm recently obtained by Metzger *et al.* (1977) for regolith of Mare Crisium by processing a statistically low amount of orbital gamma-spectra information, which earlier had not been considered. Apparently the level of the radioactive element content at the Luna 24 landing site is much lower than the radioactivity level (0.89 ± 0.50 weight % for potassium and 3.5 ± 1.3 ppm for uranium; see Table 2) of highland basalts enriched by KREEP. Consequently, in establishing the main type of the surface rocks in Mare Crisium, the rocks of group IV can be excluded from the analysis. If we add to the above-mentioned analysis the data of ground-based optical-instrumental measurements of lunar spectral reflection which provided an approximate assessment of the overall TiO_2 content in mature mare soils (for Mare Crisium this value is 2 ± 0.5 weight %) (Charette *et al.*, 1974), we can make the final choice in the example of interest to us between two subgroups of group II rocks in favour of Ti-depleted basalts (Table 2).

It is worth noting the resulting conclusion to the effect that the surface rocks of Mare Crisium are represented mainly by mare basalts with the low titanium content which coincides with data of direct petrographic and chemical analyses of Luna 24 samples generally determined as alumina mare basalts with low Ti and alkali content (Barsukov *et al.*, 1977; Tarasov *et al.* 1977).

Let us now consider the data from a neutron-activation analysis (Surkov *et al.*, 1977a), (Barsukov *et al.*, 1977) (Fig. 1 a, b) for the content of Th, U and K in the fine-grained fraction of regolith (dark circles) and in individual fragments of magmatic rocks (circles with points) from selectively taken specimens. Figure 1 compares these data and also Th/U and K/U ratios with the depth distributions of radioelements in soil columns selected by Apollo 15 and Apollo 17 expeditions (Fruchter *et al.*, 1975).

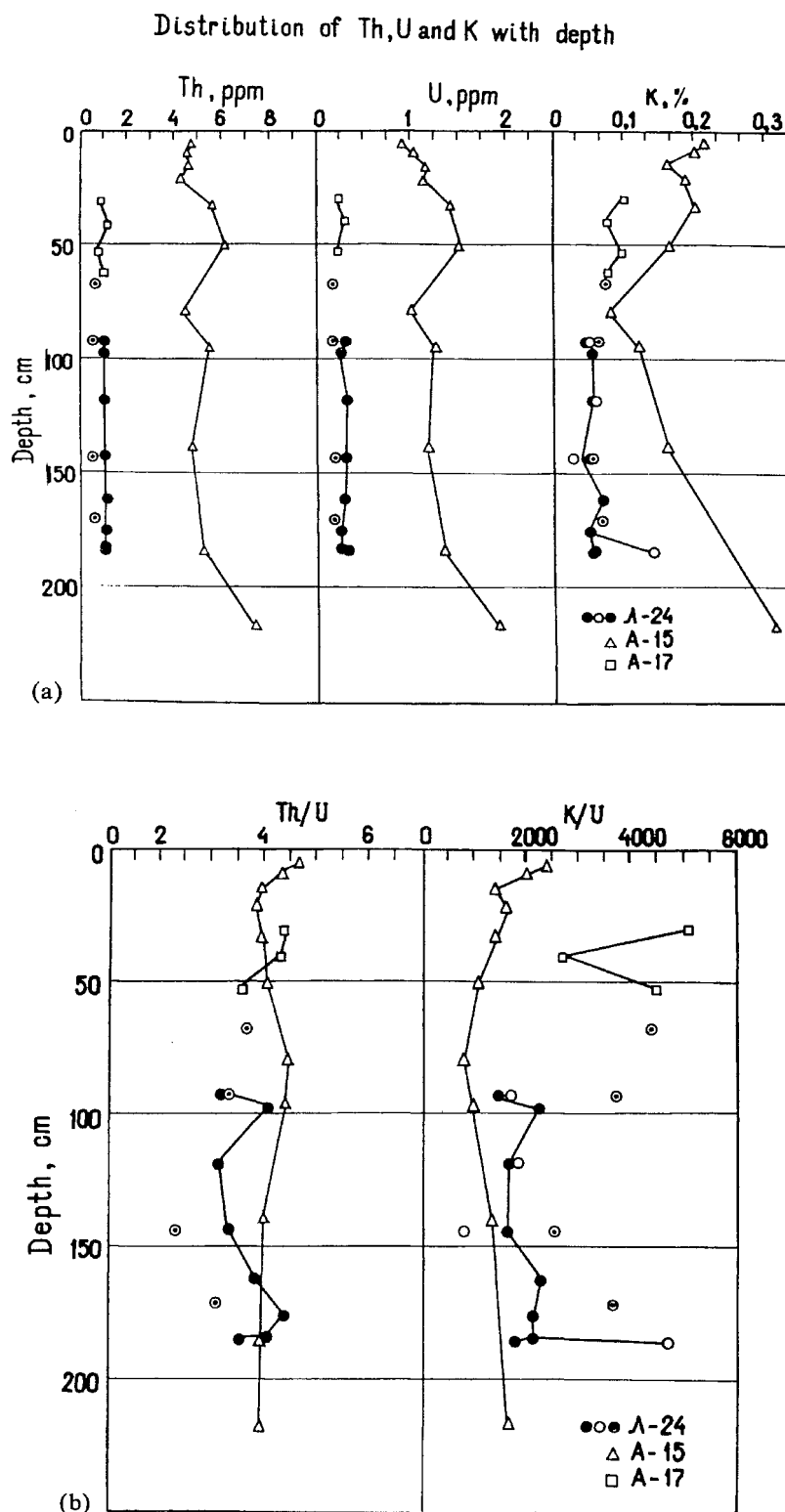


Fig. 1. (a) The distribution of radioelements (the Th, U and K content, ppm) and (b) variations of their ratios (Th/U and K/U by the depth of the Luna 24, Apollo 15 and Apollo 17 soil columns. (The data for the content of K are denoted by unhatched circles is determined by the method of flame photometry).

As is evident from the figure, the entire Luna 24 regolith column is characterized by the rather stable U and Th content (at the level of 0.3 and 1.0 ppm, respectively) with the noticeable variation of potassium contents (0.025–0.141%) by the depth (in particular, the high content of K_2O –0.17% at 184.4 cm mark). One cannot escape noticing the similarity in the character of the distribution in depth and the level of the Th, U and K content in the Luna 24 and Apollo 17 regolith columns in contrast to the Apollo 15 column where four-fold variations in potassium concentrations with depth are recorded (0.077–0.312%) and approximately two-fold variations of uranium (0.90–1.89 ppm) and thorium (4.33–7.35 ppm). While at least some soil layers from the Apollo 15 column are supposed to be enriched by the KREEP-component due to the deposition of ejecta from the craters Aristilles or Autolycus, in the analyzed specimens of the Luna 24 and Apollo 17 columns which have considerably less radioelement content, the content of KREEP is, in all probability, very low. Nevertheless, as evident from the figures, a slight, but regular excess of the Th and U contents in the fine-grained fraction of Luna 24 regolith, as compared to their content in the specimens of magmatic rocks, is due to admixtures of KREEP-components. In this respect the comparison of magmatic rocks and fine-grained fractions of regolith by the potassium content in them is less meaningful due to considerable losses of alkaline metals from mare regolith in the evaporation processes under the effect of exogenic factors (Ivanov, 1977).

The rather monotonous course of the radioelement concentration distribution curves, especially in the upper part of the Luna 24 column (approximately up to the 150 cm mark from the surface), and appreciable variations in the potassium content in deeper layers coincide with the conclusions from the stratigraphic description of the column (Rode *et al.*, 1977) about the homogeneous character of the soil matter in its upper zones and the sharply pronounced stratified nature of its lower horizons. K. P. Florensky *et al.* (1977) revealed the possible causes of such a structure of regolith. In particular, a geological-morphological analysis of the Luna 24 landing site (40 km from the ledge of highland mountains and 18 km from the crater Fahrenheit formed 0.5 to 1.10^9 years ago) points to the possibility that material from the adjacent highland and deep parts of the lava filling of the mare got into the regolith column. At the same time, petrographic studies of the Luna 24 sample (Tarasov *et al.*, 1977) show the extremely limited quantity of highland matter in the soil column. This fact, along with the above-mentioned considerations that KREEP-components are represented in Luna 24 soil sample only as admixtures, are decisive for understanding the pattern of the radioelement distribution in this region—the absence of noticeable contrasts with the overall rise in the radioactivity level over the mare region as compared to the highland area. Such an idea agrees with the general ratios of the content of natural radioelements in the series of rocks (Table 2) when the transfer takes place from anorthosites ($K \sim 0.046\%$, $U \sim 0.13 \cdot 10^{-4}\%$) to mare basalts with low titanium content ($K \sim 0.06\%$, $U \sim 0.22 \cdot 10^{-4}\%$).

TH-U AND K-U SYSTEMATICS OF LUNAR SPECIMENS

An analysis of the natural radioelement content in lunar rocks is usually conducted using the ratios of K to U and Th to U.

The Th-U ratio is used much more rarely since both U and Th display, as a rule, rather low fractionation in lunar materials without deviating considerably from the Th/U range of ratios of 3.6–3.8. Most meteorites and terrestrial rocks are characterized by these values (Surkov and Fedoseyev, 1977). However, lately, while discussing the problems of lunar petrogenesis, researchers have begun to give much more attention to Th-U fractionation.

In collections of the last Apollo expeditions lunar anorthosite rocks with low Th/U ratios in the range of 1–3 were detected by Laul and Fruchter (1976). It has been found out that all the basalts from Apollo 17 collections also have low Th/U ratios (in the 2.1–3.5 range). As it has been shown by subsequent more careful studies, in Apollo 11 basalts poor in potassium the values of Th/U ratios are approximately 10% lower than in basalts enriched by potassium of the same series of specimens. Further studies led to the conclusion that Th will fractionate with respect to U in the crystallization process due to the difference in their separation coefficients, primarily for such an important rock-forming mineral as clinopyroxene (Silver, 1977).

As is evident from the data of Surkov *et al.* (1977a) and Barsukov *et al.* (1977) three of four measured fragments of the magmatic rocks from the Luna 24 column are also characterized by reduced Th/U values up to the minimum value of 2.3 in case of the basaltic fragment selected from a depth of 143 cm. It has been noted by Silver (1977) that in minerals, Th-U fractionation is, as a rule, masked when the KREEP-component is noticeably represented in the rock. However, at low levels of the natural radioelement content, as can also be seen in Luna 24 rocks, Th-U fractionation becomes especially sharply pronounced. No doubt special attention should be given to this fact in further lunar studies, particularly in the light of the low radioactivity level over highland areas on the moon's other side obtained as a result of orbital gamma-measurements. At any rate, the Th/U ratio of 4.0 assumed by some authors, for instance Tera *et al.* (1974), as the average value for the moon, is specifically in the light of the latest Apollo 17 and Luna 24 data, certainly overestimated.

The K-U systematics of rocks more wide-spread in geochemical practice has found its application to lunar studies in elucidating the problems linked with the thermal history and the chemical fractionation of elements in the course of the differentiation of lunar matter (by the ratio of its low-temperature and high-temperature fractions). In particular, with the aid of this systematics attempts are being made to evaluate the average potassium and uranium content and the corresponding K/U ratio for the moon on the whole (Surkov and Fedoseyev, 1977; Toksöz and Johnston, 1977).

Figure 2 gives data in K-U coordinates for lunar specimens from all nine explored areas, adding the results of analysis of the fragments of rocks from the Luna 24 column. A detailed representation of correlation lines plotted on the

basis of regression analysis of various selections characterizing specimens from various regions of the moon can be found in Surkov *et al.* (1978). There it has been pointed out that the region of the intersection of the analyzed correlation lines characterizes the matter of the moon's upper mantle by the K and U content if we suppose the complementary character of the composition of lunar rocks corresponding to them.

In Fig. 2, the addition of the link representing the specimens of primary Luna 24 rocks (specimens of basalt 24067.4–0.12 with K/U of 4350; dolerite 24092, 4–001 with K/U of 3690; gabbro 24190, 1–6.2 with K/U 3670; the basalt specimen 24143, 4–006.1 with K/U of 2550 stands somewhat aloof), supplements the third chain of rocks displaying increased K/U ratios. It is worth noting that the coordinates of the intersection point of two extreme correlation lines (I and III), which most differ from each other by their slopes, correspond to the values of about 0.05 ppm for uranium and about 140 ppm for potassium (for a K/U ratio of 2800). This result agrees rather well with the revised data (0.043 ± 0.006 ppm for uranium) proceeding from the results of direct measure-

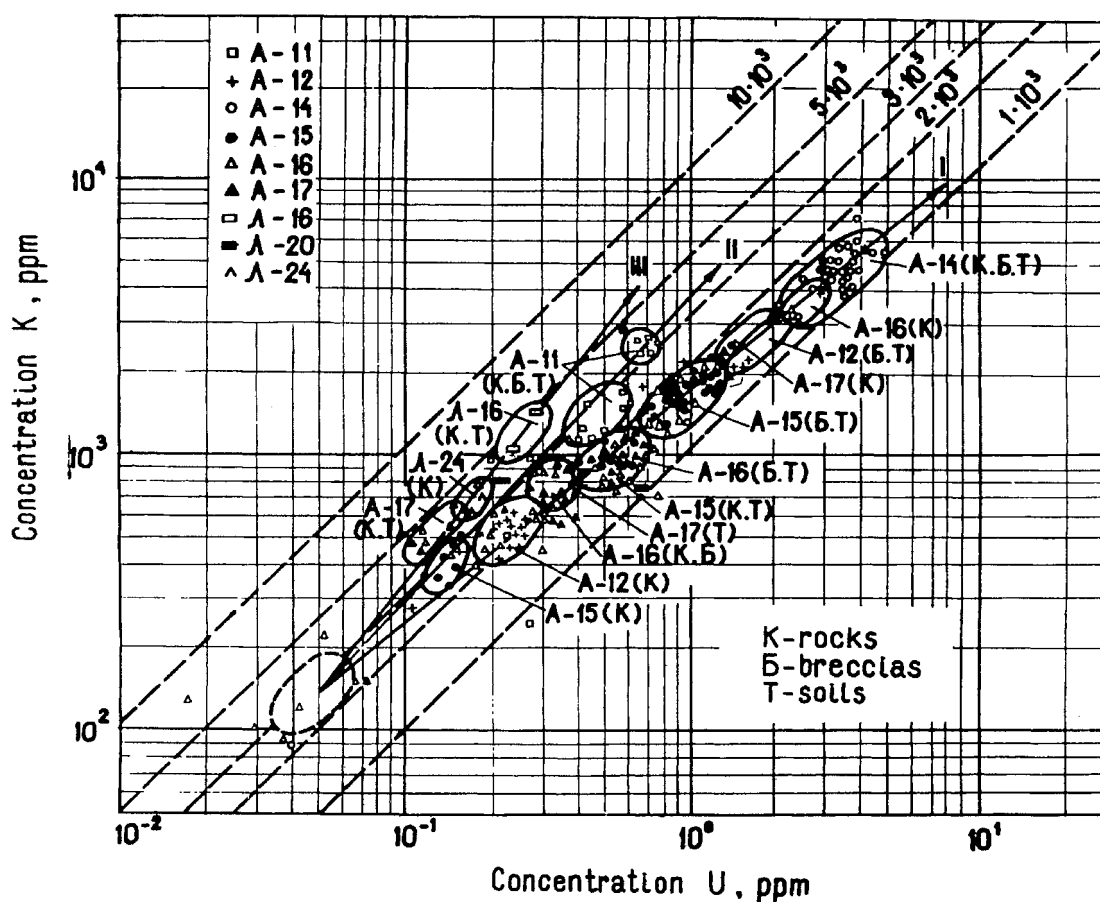


Fig. 2. The potassium-uranium systematics of lunar samples. (K-crystalline rocks, B-breccias, T-fine regolith fractions).

ments of the heat flow on the lunar surface (Langseth *et al.*, 1976).

In this connection it is interesting to compare once again the values of the average values of U and K characterizing the interior of the earth and the moon. In one of our papers dealing with a gamma-spectrometric analysis of lunar soil from the Luna 16 column (Surkov *et al.*, 1972), we have concluded that there is a similarity between average K/U ratios (about $2.8 \cdot 10^3$) for the earth and the moon on the whole, evidence for the kinship of their primary non-differentiated matter.

However, the calculated values of the overall uranium and potassium content on these neighbouring celestial bodies seemed to differ considerably. That is why hypotheses were put forward to the effect that the lunar body could form in an independent circumsolar orbit with its subsequent capture by the earth. In further estimates of the average potassium and uranium content on the moon obtained by various methods, as new information came in, there were trends towards reducing the supposed level of these average contents, and the latest data for K of about 100 ppm (Taylor, 1977) to 140 ppm and U of about 0.020 ppm (Hubbard and Minear, 1976) to 0.050 ppm are considerably lower than the initial data (K of about 250 ppm and U of about 86 ppm).

At present we can state the coincidence of K/U ratios and, as is evident from Table 3, a very close similarity for the values of the average bulk potassium and uranium content in the earth and the moon.

In its turn, this seems to testify quite convincingly in our opinion to the genetic kinship of the matter which formed these two planetary bodies in the course of accretion. This parental matter was equally enriched (by three or four times) by refractory elements and depleted (about four-fold) as far as volatile elements are concerned with respect to the matter of carbonaceous chondrites (C1).

Table 3.

	U, ppm	K, ppm
Earth	0.031 to 0.035 ¹	90 to 170 ²
Moon	0.037 to 0.050 ³	100 to 140 ⁴
Chondrites C1	0.011 ⁵	510 ⁵

¹The average U content is obtained on the basis of the data on the thermal current at the earth's surface (MacDonald, 1964; Tera *et al.*, 1974).

²The limits of the K content are assessed for K⁴⁰ on the basis of the data on the Ar⁴⁰ content in the earth's atmosphere (Hurley, 1968; Larimer, 1971).

³The average content is obtained on the basis of the data on the thermal current at the moon's surface (Langseth, 1976) and from K-U systematics of lunar rocks (the present paper).

⁴The average K content is determined from the K/U ratio (Taylor, 1977) and from the K-U systematics of lunar samples (this paper).

⁵Data from Surkov and Fedoseyev (1977).

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