Proc. Lunar Planet. Sci. Conf. 11th (1980), p. 669–676.
Printed in the United States of America

Geochemical interpretation of the results of measuring gamma-radiation of Mars

Yu. A. Surkov, L. P. Moskalyova, O. S. Manvelyan, A. T. Basilevsky, and V. P. Kharyukova

Vernadsky Institute of Geochemistry and Analytical Chemistry, Academy of Sciences of the USSR, 47-A Vorobyevskoe Shosse V-334 Moscow

Abstract—Analysis of the data on the natural radioactivity of martian surface material and a comparison with analogous data on Earth, Venus and Moon indicates that there are two fundamentally different types of crustal material on these bodies. Martian volcanic formations with a basalt-like morphology are similar to the basalts on Earth, Moon and probably Venus. This of course does not rule out their specific planetary traits. The ancient formations of Martian terrae differ markedly in thorium and uranium content from the granitic rocks of the earth's continents and from the Venus ancient terrae. They resemble the anorthosite-norite-troctolite association of lunar highlands, and perhaps represent an unknown chemical type of the substance of the planetary crust.

INTRODUCTION

As reported in our earlier papers (Vinogradov *et al.*, 1975; Surkov *et al.*, 1976; Surkov *et al.*, 1979a), gamma-radiation of the martian surface was measured by the Mars-5 probe orbiting the planet. The measurements were taken at a distance of about 2,000 km from the martian surface. Therefore, the measured spectra represent large areas of the planetary surface. The territory mapped is shown in Fig. 1. The external boundary of the hatched band determines the region corresponding to the effective area from which 90 per cent of the gamma-radiation is collected; the internal boundary, 50 per cent of the gamma-radiation. In order to determine the size of this area the fluxes of gamma-quanta were calculated from the planet's spherical layer with uniformly distributed radioactivity (Surkov *et al.*, 1978).

By processing the measured gamma-ray spectra the surface concentration of natural radioelements and some rock-forming elements was determined (Vinogradov *et al.*, 1975; Surkov *et al.*, 1976; Surkov *et al.*, 1979a). Unfortunately, the comparison of these data with data obtained at Vikings 1 and 2 by the X-ray-fluorescence experiment (Toulmin *et al.*, 1977) is difficult because the gamma-ray spectrometric results represent the average concentration of a vast region of the martian surface, while the X-ray fluorescence data characterize the surface composition at the Vikings 1 and 2 landing sites. Nevertheless, one conclusion can

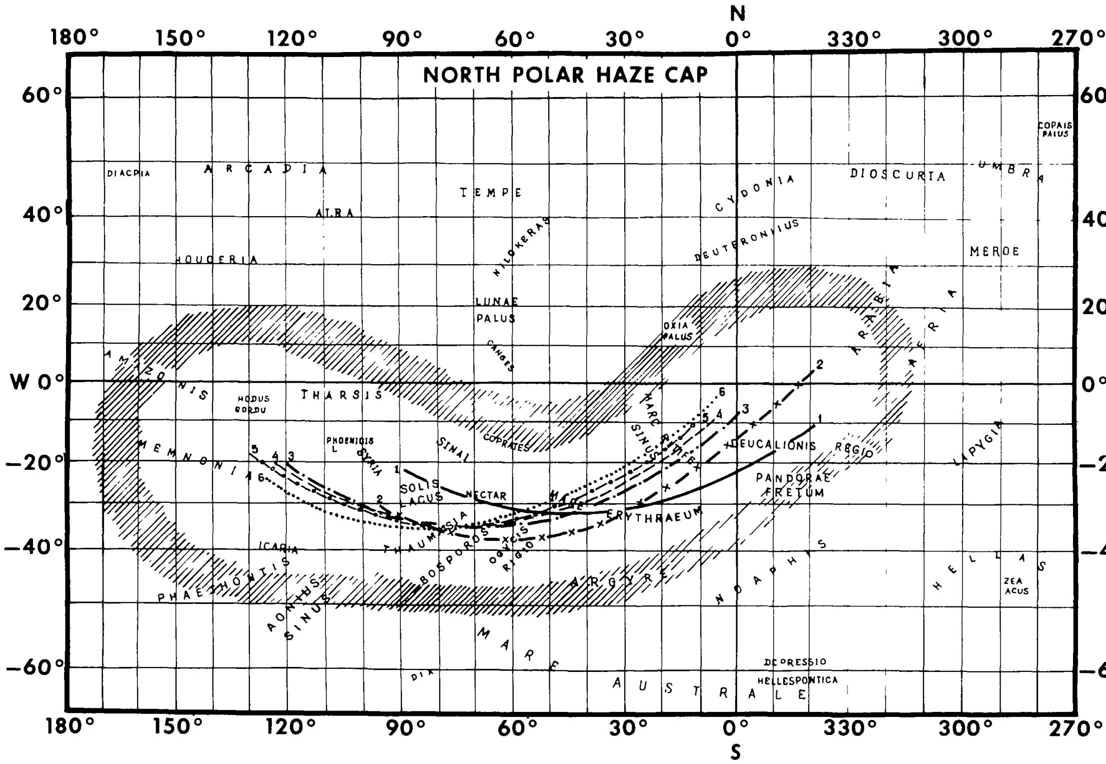

Fig. 1. Territory of Martian surface over which gamma-radiation was measured.

be drawn confidently from the orbital measurements; the content of natural radioelements in martian surface material is similar to igneous rocks of the earth's crust in their basic composition. The data from Viking 1 and 2 on the content of major rock-forming elements seem to buttress this similarity.

Since the region covered by gamma-ray spectrometric measurements is morphologically diverse, we have attempted in this paper to further detail the orbital measurements of thorium and uranium content, taking into account the geological structure of the region under investigation.

THE MODEL

The territory over which measurements were taken can be separated (with a certain amount of generalization) into two principal types of regions: ancient highland formations and younger volcanic formations. Other formations observed on this territory (for instance, valleys of the fluvial type and fields of eolian dunes) cover here a rather small part of the area, and their contribution to the measured gamma-ray flux can apparently be ignored. This map is given in Fig. 2. The presence of a large number of big craters is typical of martian highland formations, and in this respect the highlands of Mars resemble lunar highlands. It is important to determine whether this resemblance extends to the chemical composition.

Volcanic formations surveyed are represented by the Tharsis plateau, including the Arsia shield volcano, and by lowlands relating to the floors of depressions. The former resemble in their morphology the regions of the development of shield basalt volcanism on the earth. The latter look like basalt lowlands in lunar maria (Mutch *et al.*, 1976).

Martian crustal material undergoes surface alteration by weathering, which manifests itself primarily by the planet's reddish color, long known from astronomical observations (Sharonov, 1958). The results of spectrophotometric observations of some regions on the martian surface (McCord *et al.*, 1977a, 1977b) and experimental data at the landing sites of Vikings 1 and 2 (Toulmin *et al.*, 1977) show that rather slightly altered bedrocks of the martian crust outcrop on the surface only in some places in the regions characterized by the low albedo (dark areas), while the rest of the territory (bright areas) is covered on the surface by products of weathering and impact. Judging the results of the X-ray fluorescence analysis of martian soil in combination with data of other experiments, clay minerals of the nontronite-montmoril-lonite type and sulphates of the epsomite

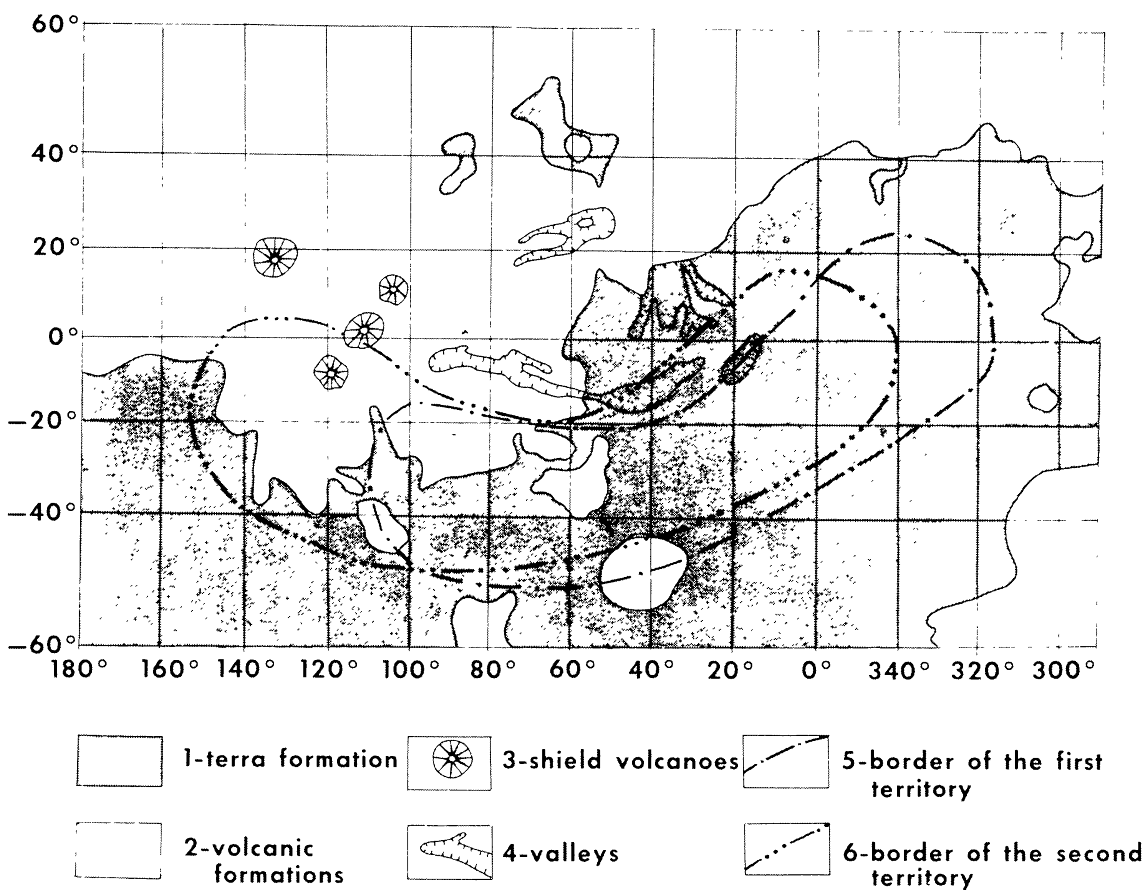

Fig. 2. The map of Mars: 1—ancient terrain formation, 2—volcanic formation, 3—shield volcanos, 4—valleys, 5—border of the first area observed, 6—border of the last area observed.

type figure prominently in the composition of the weathered martian crust. Here, as on the earth, the red color of products of weathering is due to the presence of trivalent iron oxides. Within the territory over which gamma-ray spectrometric observations were made there are dark areas where apparently slightly weathered rocks outcrop and bright areas where weathered material lies in the surface layer.

Thus, the objective was to determine not the average composition of the entire area studied but the composition of highland and volcanic regions separately and bright and dark regions separately. For this purpose we took into account the fact that the spectra measured by the first and last observations were taken over slightly different areas overflown by Mars-5.

These observations differ from each other both in the proportion of the area occupied by ancient cratered terrain and volcanic formations and in the proportion of the area covered by dark and bright regions. That is why two formally alternative versions of the interpretation of these data will be discussed below. Possessing the estimates of the average thorium and uranium content in the area corresponding to each observation, one can calculate the content of these natural radioelements in the two geological subdivisions of the surface. For this purpose one can work out a set of two linear equations which naturally can be solved only with respect to two unknowns.

In the first case it is assumed that differences in the character of gamma-radiation of these areas are due to the difference in the surface portions taken by highland and volcanogenic formations. The solution of the set of equations in this version makes it possible to assess the thorium and uranium content in highland and volcanic formations provided that weathering processes have not had an essential effect on the concentrations of these elements in the surface material.

In the second case the differences in the character of gamma-radiation from the observed regions are accounted for by the difference in the surface portions covered by the dark and bright areas. The solution of the set of equations in this version can give the estimate of the thorium and uranium content in the bedrocks and the products of their weathering provided that the differences in the content of these elements in ancient terrain and young volcanic rocks are insignificant.

The procedure of calculating the thorium and uranium content in surface formations of various types was as follows. If the distribution of natural radionuclides over the volume of rock is uniform, the set of equations assumes the following form:

$$q_x \int_t \int_{s_1} \int_l I(s,l,t) ds\, dl\, dt + q_y \int_t \int_{s_2} \int_l I(s,l,t) ds\, dl\, dt = \bar{q} \int_t \int_{s_1+s_2} \int_l I(s,l,t) ds\, dl\, dt$$

$$q_x \int_t \int_{s_1'} \int_l I(s,l,t) ds\, dl\, dt + q_y \int_t \int_{s_2'} \int_l I(s,l,t) ds\, dl\, dt = \bar{q}' \int_t \int_{s_1'+s_2'} \int_l I(s,l,t) ds\, dl\, dt$$

$I(s,l,t)$ = gamma-ray flux at every orbital point from a unit rock volume and a unit radioelement concentration;

q_x, q_y = concentration of the radioelement in different formations;

$\bar{q}$ = average concentration of the radioelement in the different measured regions;

s_1, s_2, s'_1, s'_2 = areas corresponding to the different formations of the first measured region (s_1, s_2) or of the second measured region (s'_1, s'_2);

l = depth of the rock surface layer emitting gamma-ray (Surkov *et al.*, 1978);

t = time interval of the measurement.

The calculation of the integrals in the set of equations is based on the results of calculating the gamma-ray response flux as a function of the spacecraft's height above the martian surface and the area scanned by the detector.

Proceeding from the probe's altitude variations and the results of these calculations a function was obtained for every measuring session. This function expresses the time dependence of the gamma-ray flux coming from the entire planetary surface scanned by the detector. The integration of this function with respect to the time of measurement represents correspondingly the integrals on the right-hand side of the equations of the worked out set. The calculated dependence of the share of the gamma-quantum flux coming from a unit area of the planetary surface at the distance to the surface has enabled us to determine the contribution of the share of gamma-radiation due to different geological subdivisions of the surface to the overall recorded flux, i.e., to give the values of the integrals on the left-hand sides of the equations.

The results of the calculations for the first version of the interpretation highland-volcanogenic and some data on the thorium and uranium content in typical rocks on Earth, Venus and Moon are summarized in Table 1.

DISCUSSION

It follows from the tabulated data that, as far as the thorium and uranium content is concerned, volcanic rocks of the investigated territories of Mars are close to basalts typical of many geological formations, such as alkali olivine basalts, platform plateau-basalts and geosyncline basalts on Earth. This probably also includes the lunar mare basalts with high potassium content. Terrestrial tholeite basalts and lunar mare basalts with the high titanium content and the moderate potassium content are characterized by the noticeably much lower thorium and uranium content and have no analogues amidst the studied volcanic rocks of Mars.

In accordance with these calculations the highland formations of Mars have lower thorium and uranium content than the investigated martian volcanics and differ greatly from the substance of the earth's granite continents and lunar KREEP which contain much higher contents of these elements. Compared with rocks of the anorthosite-norite-troctolite group (ANT) which are widely developed on lunar highlands, the observed martian highland formations are not appreciably different in thorium and uranium contents.

The content of natural radioactive elements is known to be a good geochemical indicator for the identification of rock types. That is why considerable differences

Table 1. Thorium and uranium content (ppm) in different formations of Mars, Venus, Earth and Moon.

Planet	Type of formation	Th	U	Th/U	Reference
Mars	Young volcanic terrain	5.0±2.5	1.1±0.8	4.5	Surkov[x]
	Ancient terrae	0.7±0.35	0.2±0.14	3.5	This paper
Venus	Supposedly terrain of sheild basaltic volcanism	0.7	0.5	1.4	Surkov *et al.*[x]
	Supposedly ancient terrae	6.5	2.2	3.0	1976
Earth	Ultrabasic rocks	0.08	0.03	2.7	Smyslov 1974[xx]
	Tholeiitic basalts	0.18	0.1	1.8	
	Alkaline olivine basalts	3.9	1.0	3.9	Ronov and Yaroshevsky[xx]
	Platform platobasalts	2.5	0.8	3.1	1978
	Geosyncline basalts	2.4	0.7	3.9	
	Granites, granodiorites, granitic gneisses	15.6	3.9	4.0	
Moon	ANT rocks	0.8*	0.21**	3.8	*Surkov *et al.* 1979b **Taylor, 1978
	KREEP material	9.3	2.8	3.4	Barsukov *et al.*[xxx]
	High Ti and K mare basalts	3.98	0.68	5.8	1979
	Moderate Ti and K mare basalts	1.18	0.64	1.9	
	High Ti and moderate K mare basalts	0.61	0.16	3.9	
	Terrae of equatorial zone	0.4–1.4	—	—	Trombka *et al.*[x]
	Mare basalts	1.2–2.4			1975

[x] Orbital gamma-spectrometry data
[xx] Earth rock analyses
[xxx] Returned lunar sample analyses

between the volcanogenic and highland formations of Mars in the thorium and uranium content should apparently be treated as differences in the general geochemical type of their material. The similarity of the overflown martian volcanic regions, as far as the thorium and uranium content is concerned, to the basalts of some terrestrial and lunar formations should be considered in a broader meaning as the similarity between the types of rocks. This agrees well with the typically basalt morphology of these formations. The similarity of the measured highland formations of Mars, as far as the thorium and uranium content is concerned, to the rocks of the ANT group typical of lunar highlands is in good agreement with the fact that in their morphology and structure the martian crater-studded highlands bear great resemblance to lunar highlands.

Calculations for the second version of the interpretation (bedrocks vs. the crust of weathering) lead to the broad interval of concentration magnitudes which formally includes both positive and negative values. Obtaining negative values of concentrations, which obviously have no physical meaning, may indicate that there is no real correlation between the degree of the weathering of martian rocks and their uranium and thorium content. However, taking into account that drawing boundaries between the dark and bright areas involves a certain element of arbitrariness, and the errors in determining thorium and uranium concentrations are considerable, the question concerning the effect of weathering processes on the thorium and uranium distribution in martian surface rocks remains unresolved.

Thus, an analysis of the data on the radioactivity of martian rock and the comparison of them with analogous data on Earth, Venus and Moon indicates that there are two fundamentally different types of crustal material on all these bodies. Martian volcanic formations with the basalt morphology of the surface are similar to the basalts of Earth, Moon and probably Venus. This of course does not rule out the display of their specific planetary traits. The ancient formations of martian terrae differ markedly in the thorium and uranium content from the granitoid rocks of the earth's continents, and from the Venus ancient terrae. They resemble the anorthosite-norite-troctolite association of lunar highlands, and perhaps represent a yet unknown chemical type of the substance of the planetary crust.

Acknowledgments—The authors would like to express their gratitude to K. P. Florensky, R. O. Kuzmin, N. P. Yermolayev and O. V. Nikolayeva for useful discussions and help in this work.

REFERENCES

Barsukov V. L., Dmitriev L. V., and Garanin A. V. (1979) The main characteristics of lunar rocks geochemistry. In *The Regolith from the Highland Region of the Moon* (V. L. Barsukov and Yu. A. Surkov, eds.), p. 18–30. Nauka, Moscow. (In Russian.)

McCord T. B., Huguenin R. L., and Johnson G. L. (1977b) Photometric imaging of Mars during the 1973 opposition. *Icarus* **31,** 293–314.

McCord T. B., Hunguenin L. L., Mink D., and Pieters C. (1977a) Spectral reflectance of martian areas during the 1973 opposition: photoelectric filter photometry 0.33–1.10 mm. *Icarus* **31,** 25–39.

Mutch T. A., Arvidson R. E., Head J. W., Jones K. Là, and Saunders R. S. (1976) *The geology of Mars*. Princeton Univ. Press, N.J. 400 pp.

Ronov A. B. and Yaroshevsky A. A. (1978) Chemical composition of the Earth crust and its interior. In *Tectonosphere of the Earth,* p. 379–402. Nauka, Moscow. (In Russian.)

Sharonov V. V. (1958) *Nature of the Planets*. State Publications Office of Physical and Mathematical Literature, Moscow. 552 pp.

Smyslov A. A. (1974) *Uranium and Thorium in the Earth's Crust*. Nedra Press, Leningrad. (In Russian.) 231 pp.

Surkov Yu.A., Fedoseyev G. A., and Sobornov O. P. (1979b) Investigations of radioactivity of lunar soil from region of the crater Apollonius C. In *Regolith from the Highland Region of the Moon* (V. L. Barsukov and Yu. A. Surkov, eds.), 534–540. Moscow. (In Russian.)

Surkov Yu.A., Moskalyova L. P., Kirnozov F. F., Kharyukova V. P., Manvelyan O. S., and Shcheglov O. P. (1976) Preliminary results of investigations of gamma-radiation from Mars from Mars-5 observations. In *Space Research* **XVI** (M. J. Rycroft, ed.), p. 993–1000. Academia-Verlag, Berlin.

Surkov Yu.A., Moskalyova L. P., and Manvelyan O. S. (1978) Calculation of the dependence of lunar and Martian gamma ray fluxes on topography and distance to the surface. In *Space Research XVI* (M. J. Rycroft, ed.), p. 301–306. (In Russian.)

Surkov Yu.A., Moskalyova L. P., Manvelyan O. S., and Kharyukova V. P. (1979a) Analysis of the gamma-radiation spectra of martian surface rocks measured by Mars-5 (abstract). 22nd Planetary Meeting of COSPAR, 29 May-9 June, 1979. Bangalore, India.

Taylor S. R. (1978) Geochemical constraints on melting and differentiation of the moon. *Proc. Lunar Planet. Sci. Conf. 9th,* p. 15–23.

Toulmin P., Baird A. K., Clark B. C., Keil K., Rose H. J., Christian R. P., Evans P. H., and Kelliner W. C. (1977) Geochemical and mineralogical interpretation of the Viking inorganic chemical results. *J. Geophys. Res.* **82,** 4625–4634.

Trombka J. I., Arnold J. R., Adler I., Metzger A. E., and Reedy R. C. (1975) Elemental composition of lunar surface according to measurements gamma- and X-ray Radiation on Apollo 15 and 16. In *Soviet and American Conference on Cosmochemistry of the Moon and Planets* (J. H. Pomeroy and N. J. Hubbard, eds.), p. 128–152. Nauka, Moscow. (In Russian.)

Vinogradov A. P., Surkov Yu.A., Moskalyova L. P., and Kirnozov F. F. (1975) Measurements of intensity and spectral composition of gamma-radiation on Mars 5 probe. *Doklady USSR Academy of Sciences* **223,** No. 6. (In Russian.)