Preliminary data on lunar ground brought to Earth by automatic probe "Luna–16"

A. P. VINOGRADOV

Vernadsky Institute, Moscow, U.S.S.R.

Abstract—Preliminary data are presented on the physical properties, mineralogy, chemistry, and other properties of the regolith sample returned by the unmanned Luna–16 probe from the Sea of Plenty. In general, the data obtained from this mare appear to be quite similar to those obtained from the Sea of Tranquillity (Apollo 11) and the Ocean of Storms (Apollo 12).

THE AUTOMATIC PROBE "Luna–16" returned to Earth a sample of lunar ground taken in the Sea of Plenty, in its northeastern part at 0°41'S. latitude and 56°18'E. longitude approximately 100 km. to the west of Webb Crater (Fig. 1).

Fig. 1. Map of the Moon. (1) Landing site of Apollo 12; (2) landing site of Apollo 11; (3) landing site of Luna–16.

1

GEOCHIMICA ET COSMOCHIMICA ACTA

SUPPLEMENT 2

PROCEEDINGS

OF THE

SECOND LUNAR SCIENCE CONFERENCE

Houston, Texas, January 11–14, 1971
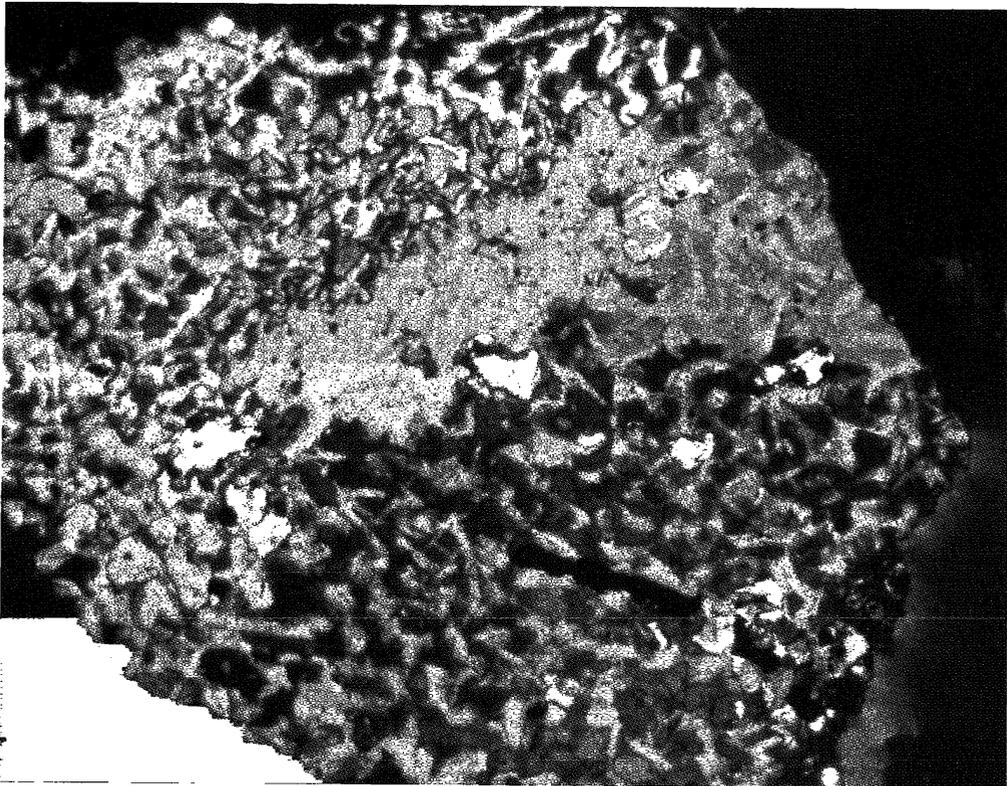
Porphyritic olivine basalt, 12022.

Ophitic basalt, 12057. Width of field = 4 mm.

Thin sections of two Apollo 12 igneous rocks illustrating two typical textures.

PLATE 1.

Skeletal olivine phenocryst in 12009 with dark vitrophyric groundmass. Width of field = 2.5 mm. Courtesy of Dr. Robin Brett.


Thin section of fragment of micrographic granite from soil sample 12070,35, by transmitted polarized light. Width of field = 0.5 mm. The fragment consists largely of intergrown K-feldspar and silica (polymorphs undetermined), which appear gray to black in color. Minor amounts of Fe-rich olivine (Fa_{87}) and pyroxene (ferroaugite) display bright colors. Whitlockite, apatite, and ilmenite are also present. Photograph by J. A. Wood.

PLATE 2.
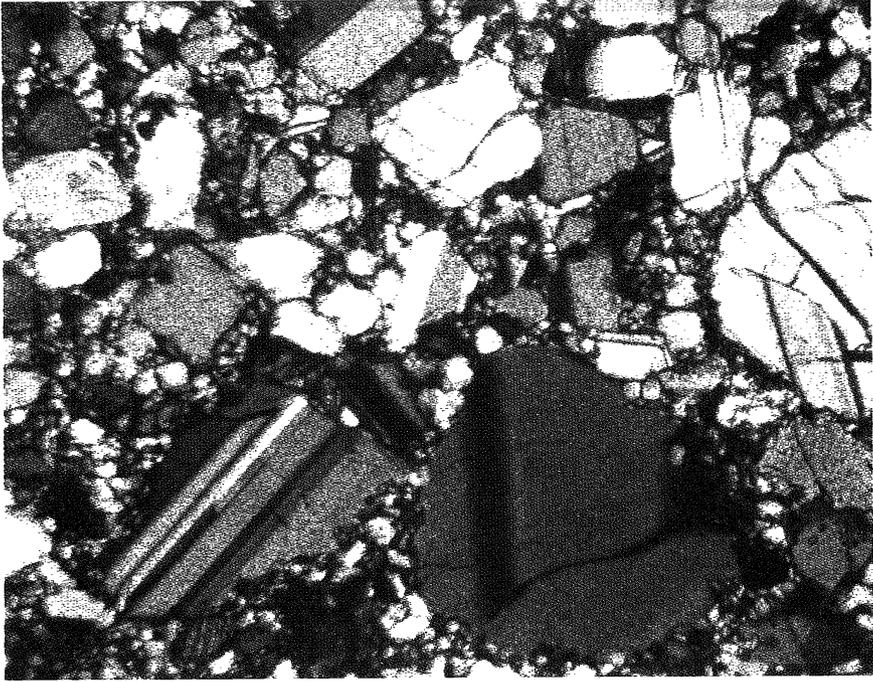
Thin section of fragment of recrystallized noritic breccia from soil sample 12033,23, by transmitted polarized light. Width of field = 0.7 mm. The fragment consists largely of clasts of plagioclase and Ca-poor pyroxene (orthopyroxene and pigeonite), which appear gray to black. One clast of diopsidic pyroxene is visible (brown). Recrystallization has eliminated all pore space in this breccia. Minor minerals include ilmenite, olivine, whitlockite, and zircon. Photograph by J. A. Wood.
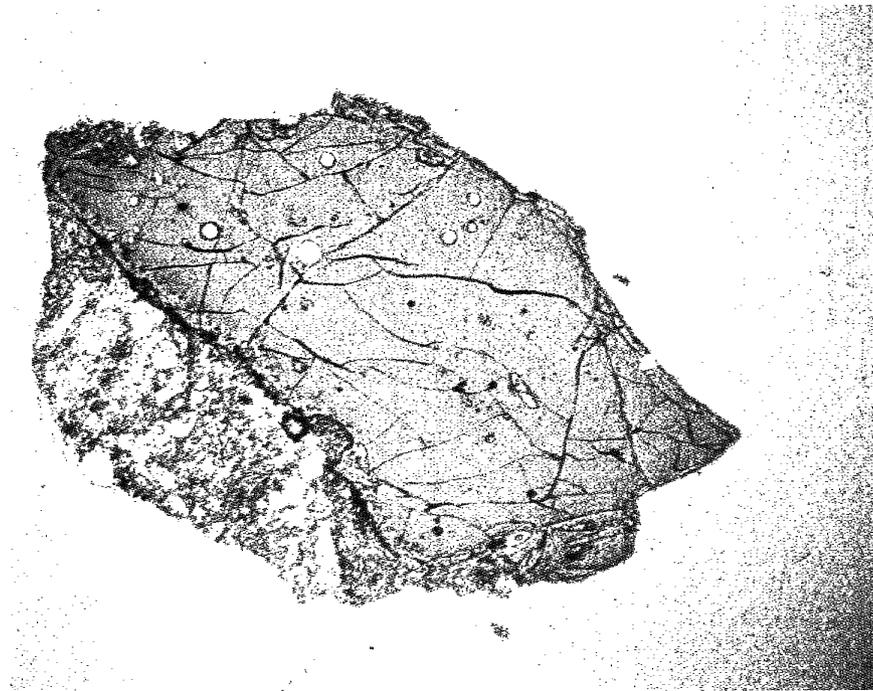
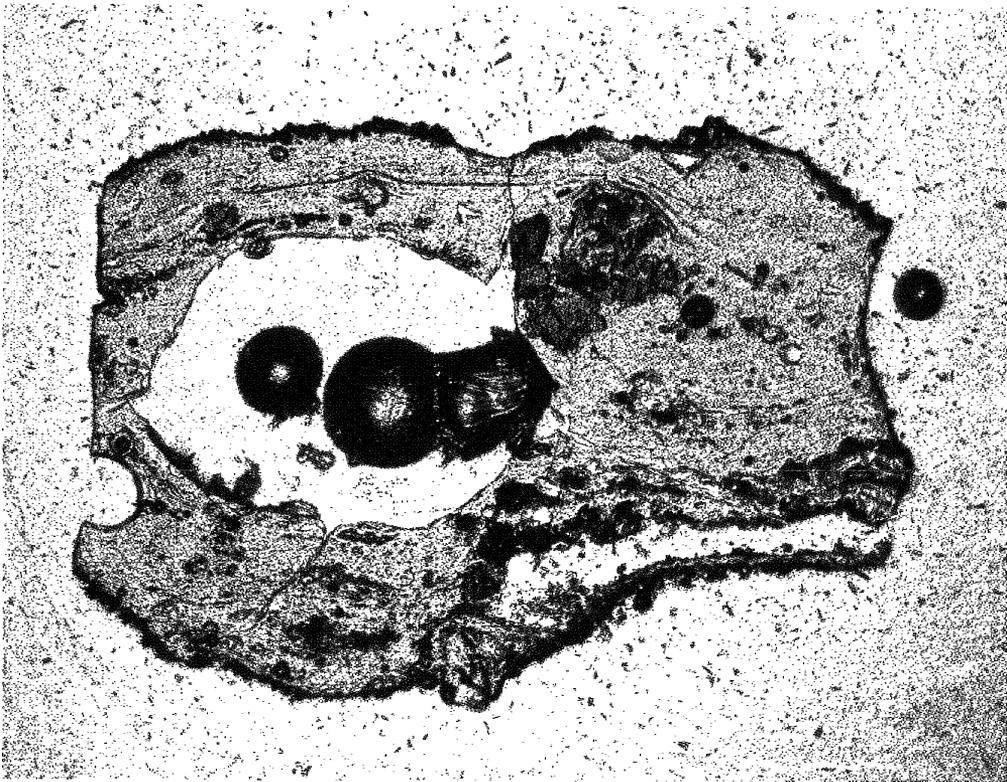Brown glass of KREEP composition attached to rock fragment of plagioclase, orthopyroxene mineralogy. Width of field = 4 mm. Courtesy of Dr. Robin Brett.
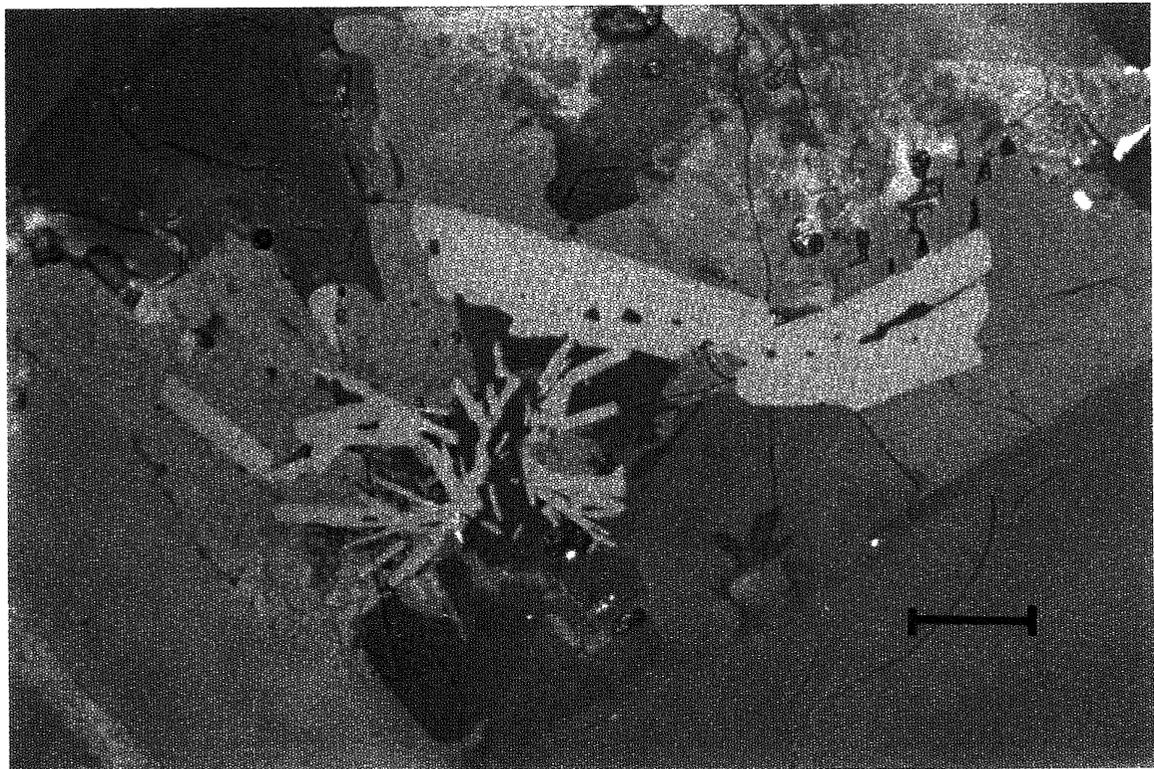
PLATE 3.

Ropy glass fragment with KREEP composition from soil sample 12003. The fine dust coating contains abundant orthopyroxene. Width of field = 1.5 mm.

Thin section of same fragment showing large vesicle and internal flow texture. Courtesy of Dr. David McKay.

PLATE 4.
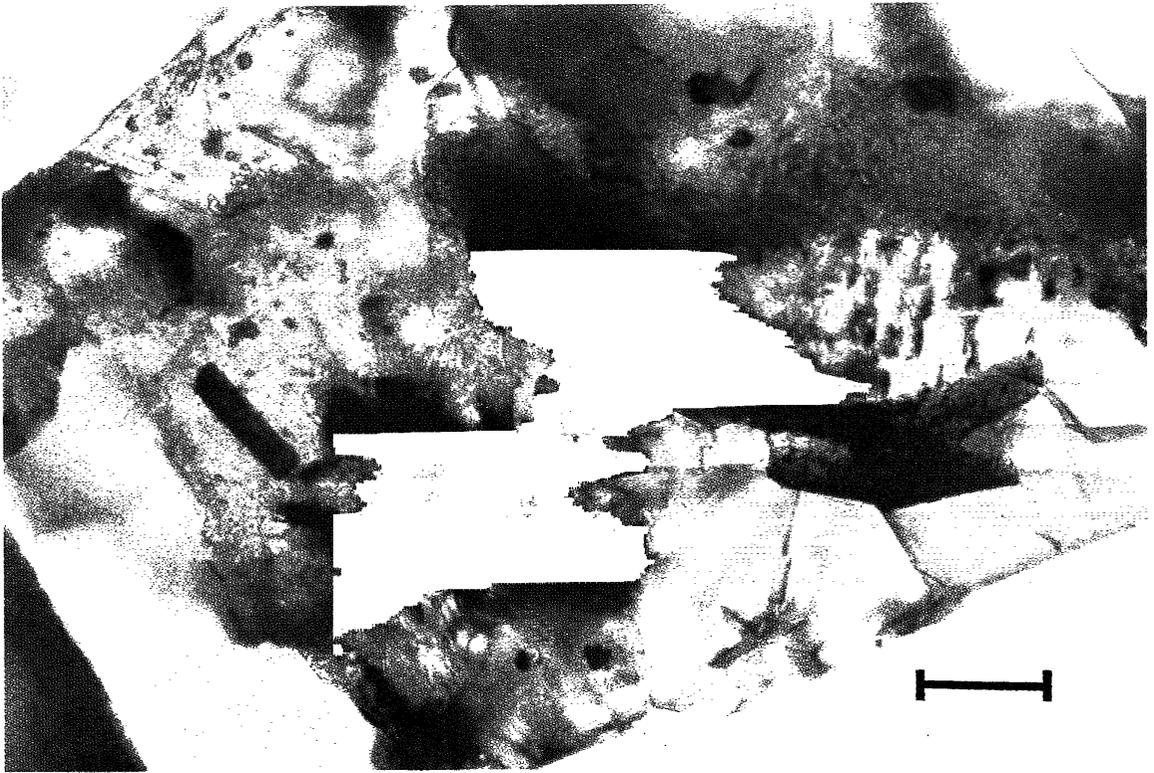
Characteristic occurrence of tranquillityite laths associated with interstitial phases in Apollo 11 basaltic rock 10047,20,A (site A27). (A) (top): Transmitted light photograph showing foxy-red tranquillityite laths. (B) (bottom): Reflected light photograph of same general area showing gray reflecting tranquillityite laths. Associated phases identified in Fig. 1 of "Tranquillityite: A new silicate material from Apollo 11 and Apollo 12 basaltic rocks," by J. F. Lovering *et al.* (pp. 39–45). (Scale bars: 25 μ.)

PLATE 5.

The Sea of Plenty is surrounded by relatively low and subdued hills, which form a diffuse boundary. The Sea is a plain with undulating topography and low relief (100–300 meters). There are no radial systems of large craters in this region. The lunar ground in the Sea of Plenty characterizes a new region in the "sea" surface of the Moon. There are now three large seas on the earthside of the Moon near the lunar equator that have been sampled—the Sea of Tranquillity (Apollo 11), the Ocean of Storms (Apollo 12), and the Sea of Plenty (Luna–16)—making it possible to rather fully recreate the character of the lunar surface material.

The loose surface material from the Sea of Plenty—regolith—was collected with the help of a drill that penetrated to a depth of 35 cm, where the drill encountered hard rock or large fragments of hard rock. A column of regolith filled the tube of the drill. The regolith column had no visible layering and seemed homogeneous (Fig. 2).

Only a small part of the ground at the depth of 35 cm consisted of coarse-grained material. The total weight of regolith brought to Earth by Luna–16 was 101 grams.
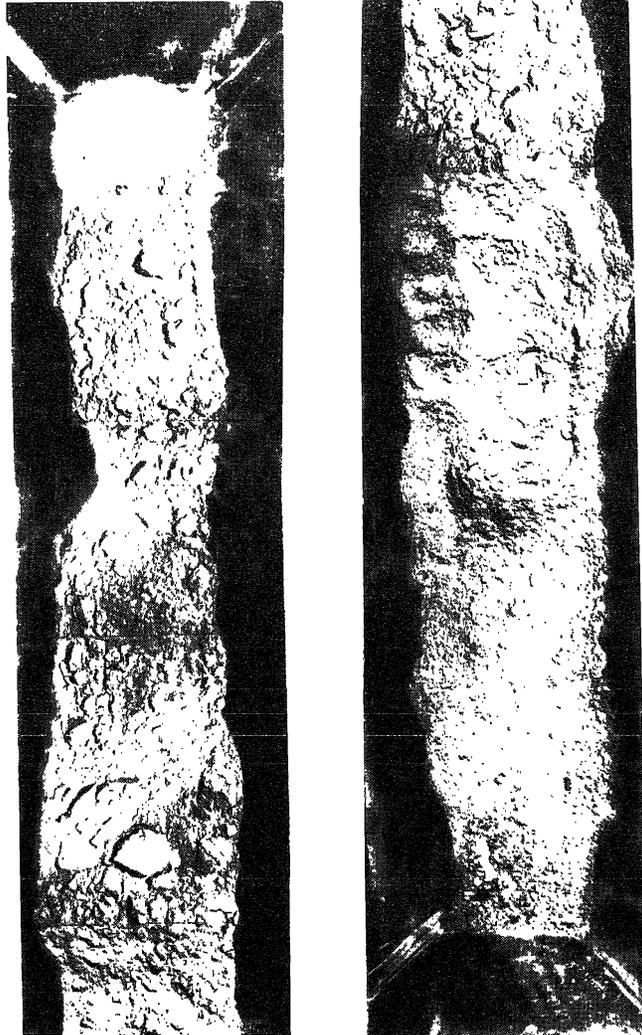

Fig. 2. Photography of lunar ground on a tray in the reception chamber. On the right is the deep part of the column; at the end of the tray coarser material is seen.

As a whole, the regolith is dark gray (blackish) powder with different grain sizes and very cohesive structure. The grains are either melted and rounded or angular. The grain structure of the regolith becomes more pronounced with the depth. Grains ~ 0.1 mm in size are predominant. The numerical distribution of the grains is in good agreement with the power law that governs the distribution of particles at multiple crushing. The median size of grains increases from the surface downward in the regolith column (70 to 120 μ). On this basis and in accordance with its character, the regolith column can be divided into several zones: A, B, C, D, and E. Every zone of the regolith was studied. Zones A and B consist of fine-grain material with a low content of coarse material; they extend from 0 to 15 cm along the column. Zones C and D consist of material with variable grain size and include rock fragments and other particles with size larger than 3 mm; they extend from 15 to 33 cm of the column. Zone E consists of coarse-grained material; it extends from 33 to 35 cm (Fig. 3).

The thickness of regolith layer in the Sea of Plenty is small, ~ 35 cm where sampled and possibly up to 0.5–1 m or a little more, resembling the thickness of regolith in the

Stratigraphic Column of Lunar Soil
(Regolith)

Principal Zones
(Shown is the average size of
fragmented particles less than 1 mm)
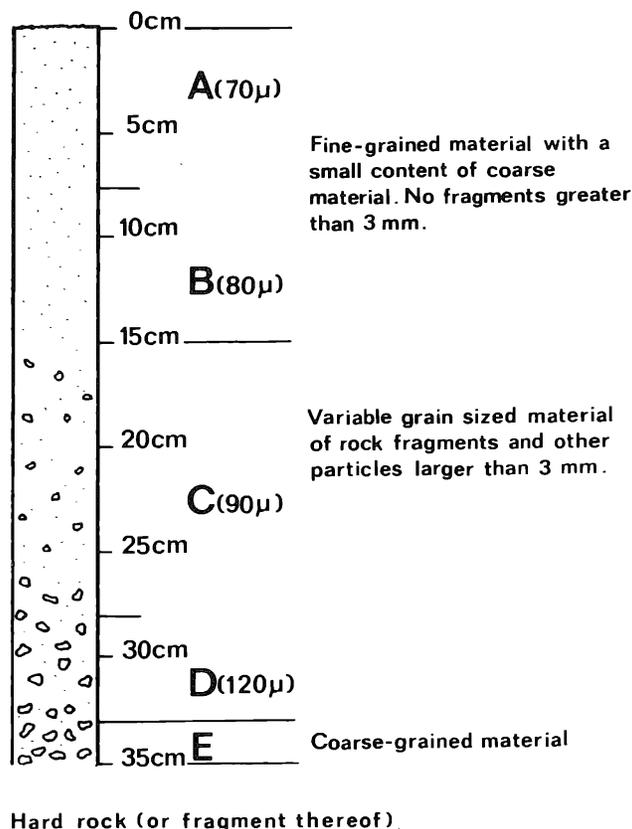

Fig. 3. Schematic column of lunar ground.

Ocean of Storms, which is assumed to be ~ 1–3 m, while in the Sea of Tranquillity it is assumed to be up to 6 m. We probably do not know the true mean thickness of regolith.

A study of physical properties showed that the density of regolith in its natural deposition is ~ 1.17 (1.20) g/cm^3. By mechanical compression its density can be increased to 2.3 g/cm^3. Specific heat capacity is 0.17 (kilocal)/(kg deg.), specific thermal conductivity is 1.9×10^{-3} (kilocal)/(m.hour.deg.), and specific electric resistance is 3.42×10^6 ohm.m, etc. These data are related to the regolith in a 10^{-5} torr environment and with pressure on regolith equal to 160(kg)/(m^2), not to regolith under conditions of natural deposition.

Optical properties were also determined. Albedo for the Sea of Plenty equals on the average 0.069, and in the region close to the landing site of Luna–16 it equals 0.105. Determined on a sample of regolith it equals 0.107. The normal albedo is rather higher for red rays: 0.086 in the ultraviolet region, 0.126 in the near infrared region, and 0.107 in the visible region of the spectrum. The mirror composite is clearly seen in the reflection indicatrix, and the angle of maximum reflection of light is a little larger than the angle of incidence. This regularity becomes stronger with an increase in the length of light waves as well as with a decrease in the angle of lighting.

Regolith—the loose ground of lunar seas—has a very different character under microscopic examination compared with the loose ground of the Earth. Regolith
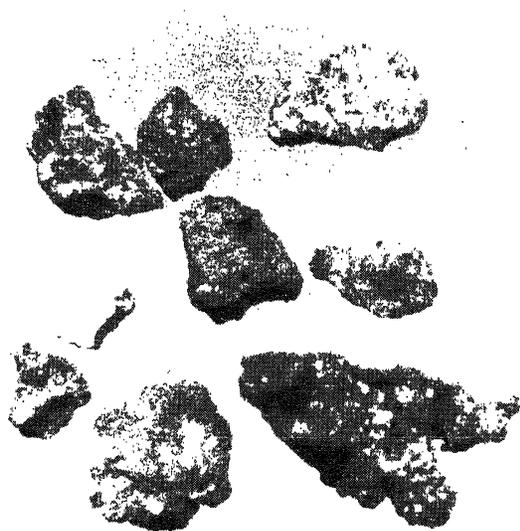
Fig. 4. Large particles of lunar rocks: coarse-grained basalt (gabbro), leucocratic; coarse-grained basalt (gabbro), melanocratic; basalts, partly porous; anorthosite; breccia; slaggy fused particle.
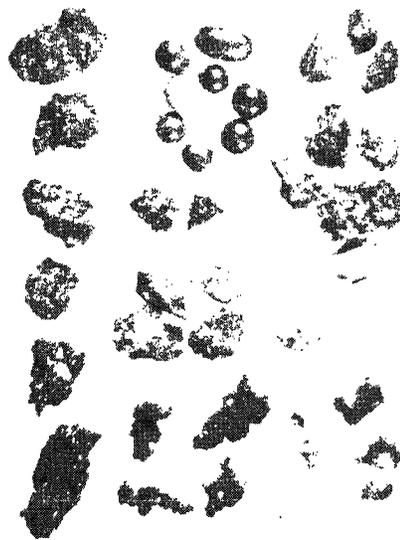
Fig. 5. Groups of most typical particles of lunar regolith from a +0.45 mm fraction: basalt; coarse-grained basalt (gabbro); anorthosites; homogeneous glasses and grains of minerals; globules and spherical formations; brown glasses; breccia; sintered particles; slags and fused particles.

does not resemble the ashes of Earth volcanoes either. There are two main groups of particles: particles of primary magmatic surface rocks of basalt type, which we noted in 1966 when gamma-spectra were obtained from the lunar surface by automatic probe Luna–10 (VINOGRADOV *et al.*, 1966), and particles that underwent noticeable transformations on the surface of the Moon. The first are characterized by a surprisingly fresh appearance that can be observed on Earth only on newly crushed samples of unchanged rocks, they have essentially no traces of rounding and are angular. The latter have clear signs of melting—caked particles of complex form with glassy textures on surfaces, considerable number of glassy spherical shapes, like hardened drops of glass and metallic appearing "cosmic beads" found on Earth. These particles indicate that they were formed from a liquid by rapid cooling. Particles of regolith as seen under the microscope are shown in Fig. 4, and in Figs. 5 and 6, various particles are gathered in groups: gabbro, basalts, anorthosites, breccias, cinders and slags, glasses and monograins, globules, and various particles. It is seen under the scanning electron microscope (Figs. 7 and 8) that large silicate particles are covered with other small particles. The content of various particles in regolith fraction +0.45 is shown in Table 1.

Particles of basaltic rocks are of at least two types, which characterize the conditions of crystallization—fine-grained basalts (with glass) and coarse-grained basalts of gabbro type. They have ophitic textures and comprise about 1/4 of the whole coarse-grained fraction (over 0.45 mm). The main minerals of these rocks are plagioclase, pyroxene, ilmenite, and more rarely olivine. The relative content of the above minerals changes noticeably in various particles. Thus it can be said that volcanic processes occurred on the Moon, erupted the basalts, and evidently formed the lunar crust of currently unknown thickness.
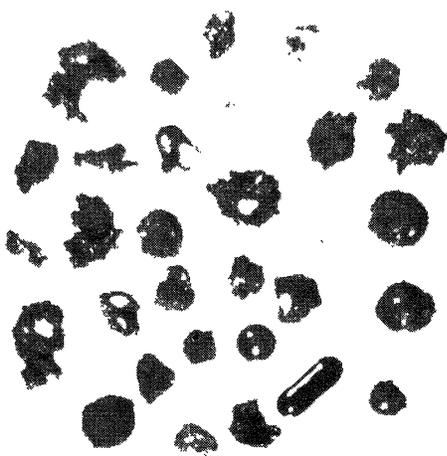

Fig. 6. Various types of particles: globules and spherical formations, glasses, sintered particles.
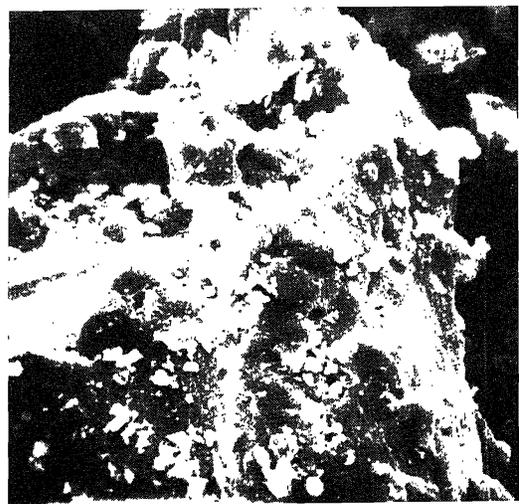

Fig. 7. Raster-type image of particles of regolith fine fraction obtained in the X-ray microanalyzer in secondary electrons. Large silicate particles are covered by smaller ones.

Table 1. Distribution of particles in fraction +0.45 for zones A, B, C, D (numerical %).

Particles	A	B	C	D
Gabbro	13.1	17.5	8.1	15.2
Basalt	7.3	9.0	4.9	7.9
Anorthosite	1.1	3.7	2.5	4.5
Breccia	33.9	41.4	35.5	8.3
Cinders and slags	40.0	17.5	41.8	53.6
Glass and mono-grains	2.3	4.0	6.2	6.1
Globules	1.2	1.3	1.2	1.6
Various	1.2	5.7	—	2.6
Total number of particles	838	297	2351	755
Weight of fraction, in grams	0.230	0.100	0.560	0.260

In our opinion this universal process of effusion of fusible material from the depths of the Moon (with degassing) followed the mechanism of zone melting. There are also feldspar minerals (anorthosites) found as white crystal grains. Their content is small. Their origin even for Earth is not very clear.

Breccia—cemented lithified rocks formed as a result of compressing the finely crushed regolith material—contain in various proportions all components including particles of primary magmatic rocks, iron-and-nickel alloys, etc. Some breccias have particles of a characteristic rounded form, which sometimes have been destroyed by small degrees of compression. Breccias are magnetic and comprise up to 40% of the total number of particles.

Cinders and slags are small caked particles forming aggregates of a very complex irregular branching form. They include all regolith components.

Glasses, glassy and cindered particles. Generally speaking, at least half of all regolith particles has either traces of melting or is cindered on one or more sides. Depending on the composition (content of Fe, Ti, etc.) they have various colors, from dark-brown to black. There are bubble-like slags as well as smooth glazed forms. This is typical lunar-type melting, taking place with instantaneous heating of the whole cold particle.

Hardened drops—globules and like forms. The globules that can be found are different in form—pear-shaped, dumbbell-shaped, etc., as well as in color—transparent, turbid white, greenish, yellow-brown, opaque, often hollow. Their luster ranges from glassy to metallic. Their number increases in the small size fractions. They form at temperatures considerably exceeding the melting point of the rocks, when the rocks are sprayed in a melted state.

Finally, there are mineral grains: plagioclase, olivine, anorthite, pyroxene, spinel, ilmenite, and iron particles. The iron-and-nickel particles in regolith will be discussed later. The content of various minerals is given in Table 2. The content of olivine is rather noticeable in general while the content of olivine in the samples collected by Apollo 11 is considerably lower (Apollo 12 has olivine content similar to Luna-16). The content of ilmenite is close to that of Apollo 12 samples while the samples of Apollo 11 have ilmenite content considerably higher. Regolith contains olivine in the form of separate monocrystallic angular fragments of different color, as well as included in gabbro particles. X-ray photographs indicate the absence of lattice

Table 2. Mössbauer spectra of lunar materials. Fraction of the total area of Mössbauer spectrum for Fe-containing minerals (%).

Sample	Our measurements			U.S.A. (Apollo 11)	
	A3	A3–a	DB	84–14	45–24
Ilmenite	7.7	6.7	9.2	19.7	26.9
Pyroxene	69.0	71.5	65.1	67.6	60.8
Olivine	18.8	16.7	25.5	4.4	6.1
Iron	4.5	5.1	not counted	5.8	2.1
Troilite	≤ 1	≤ 1	≤ 1	≤ 1	≤ 2
Magnetite	≤ 2	≤ 2	≤ 2	1.4	2.1

deformation as well as of twinning effect, that is the absence of stress in the lattice. This is the usual α-modification of olivine which is characterized by irregular distribution of Mg and Fe atoms in its structure. Micro-X-ray-spectral analysis gives the composition shown in Table 3 for the olivine. This is a homogeneous crystal of olivine with iron content of 40 mol. % Fe_2SiO_4 and corresponds to molecular form

$$[Mg_{1.14}, Fe_{0.79}(Ca, Mn, Cr)_{0.02}] SiO_4$$
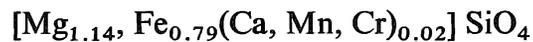
The most widespread mineral in regolith is anorthite, then follows augite and ilmenite. Anorthite is found in the form of fine-grained aggregates in samples of basalt, gabbro, globules and in the fine fraction of regolith. Single monocrystals have not been found. Plagioclase was found in the form of monocrystals of triclinic symmetry.

Fig. 8. Raster-type image of particles of regolith fine fraction obtained on the X-ray microanalyzer, in secondary electrons. Large silicate particle with hexagonal cross-section and traces of growth on the surface are sprinkled with finer material.

Fig. 9. Thin section of coarse-grained basalt (gabbro) in polarized light in crossed nicols (magnification 50). Idiomorphic grains of plagioclase and partly of ilmenite (black), xenophormic pyroxene, and a few olivine segregations.

Table 3. Chemical composition of an
olivine from Luna–16

SiO_2 =	36.0	Cr_2O_3 =	0.15
MgO =	27.5	Al_2O_3 =	0.05
FeO =	33.8	TiO_2 =	0.01
CaO =	0.38	CoO =	0.03
MnO =	0.29	NiO <	0.01
		TOTAL	98.2

Pyroxenes of augite-pigeonite type are found only in rock fragments, where in a number of cases they predominate in basalts and gabbro. The distribution of elements in thin sections of basalt was studied with the aid of X-ray spectrum analysis, which helped to identify the minerals (Fig. 9).

Ilmenite in the bulk sample of regolith sometimes occurs intergrown with augite. Chrome-spinel occurs in the form of monocrystals of dark color. Micro-X-ray-spectral analysis of sample spinel 3-4b (surface analysis, without preparing a slide) gives an uneven distribution of Fe, Ti, Cr, Si, Al, Mg, Ca. There are prominent zones with rock-forming elements and zones with higher concentrations of Fe and Ni; Fe $\sim$ 6%, Ni $\sim$ 1% (Fig. 10). In some spots iron contents up to 66% and nickel up to 6% were
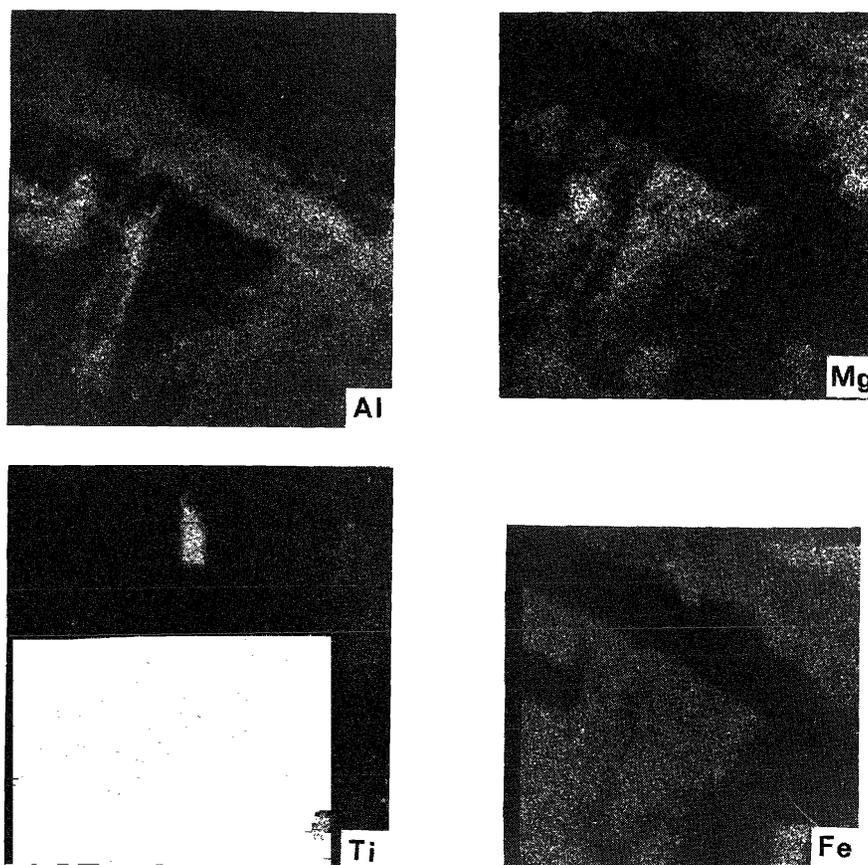

Fig. 10. Photography of a part of thin section of coarse-grained basalt (gabbro) obtained on an X-ray microanalyzer: aluminum distribution; magnesium distribution; titanium distribution; iron distribution. Minerals: Py—pyroxene; Pl—plagioclase; Il—ilmenite.

observed. However, it was impossible to discover nickel in magnetic particles with the help of Mössbauer spectrography. The X-ray analysis of iron particles shows the existence of alpha-iron, i.e. kamacite. We were unable to discover tennite. The volume of iron particles does not exceed 1 % in regolith. At present it is difficult to say anything about the origin of these particles. As shown (Table 4) the content of nickel in regolith in comparison with nickel content in basalts increases by a factor of 5 (on the average) for Luna–16 as well as Apollo 11 and Apollo 12, while the content of cobalt only increases 1.5 times at maximum. At the same time we observe a very low content of platinoids in regolith, while in iron meteorites their content is many hundred times higher than in rocks (Table 5). The chemical analyses have been carried out by several parallel methods: X-ray-spectral (chiefly for the main elements), mass-spectrometry (all elements), spectral and activation method—selectively, for certain elements (Tables 4, 5, 6, and 7).

The variations in the chemical composition of regolith in the four zones are insignificant (Table 7). Much more considerable is the difference in composition between regolith and basalt rock. If we compare the composition of lunar ground

Table 4. Compositional comparison of regolith and crystalline rocks from the three seas (macroelements in %, trace elements ppm).

1	Crystalline rocks			Regolith		
	Sea of Tranquillity Apollo 11* 2	Ocean of Storms Apollo 12† 3	Sea of Plenty Luna–16 4	Sea of Tranquillity Apollo 11 (mean)* 5	Ocean of Storms Apollo 12† 6	Sea of Plenty Luna–16 (mean) 7
SiO_2	41	40	43.8	43	42	41.7
Al_2O_3	12	11.2	13.65	13	14	15.33
TiO_2	10	3.7	4.9	7	3.1	3.39
FeO	19	21.3	19.35	16	17	16.64
MgO	8	11.7	7.05	8	12	8.78
CaO	10	10.7	10.4	12	10	12.49
Na_2O	0.5	0.95	0.38	0.54	0.4	0.34
K_2O	0.12	0.065	0.15	0.12	0.18	0.10
MnO	0.4	0.26	0.20	0.23	0.25	0.21
Cr_2O_3	0.6	0.55	0.28	0.37	0.41	0.28
ZrO_2	0.1	0.023	0.04	0.05	0.09	0.013
NiO	(0.007)	—	0.04	0.03	0.025	—
Rb	2.5	0.64	—	2.2	3.2	5.9
Ba	90	72	206	68	420	114
Sr	110	145	445	90	170	169
Yb	2.5	—	13.7	2.5	—	5.5
Y	250	51	57.9	130	130	17.3
Zr	700	170	300	400	670	347
V	45	88	42.5	42	64	61
Sc	110	50	20	55	47	27
Ni	55	54	147	250	200	190
Co	9	40	29	18	42	53
Cu	5	—	13	—	—	37
Li	15	5.5	—	15	11	10
Ga	6	—	11	—	—	4.9

* Moon Issue, *Science* (1970).
† LSPET (1970).
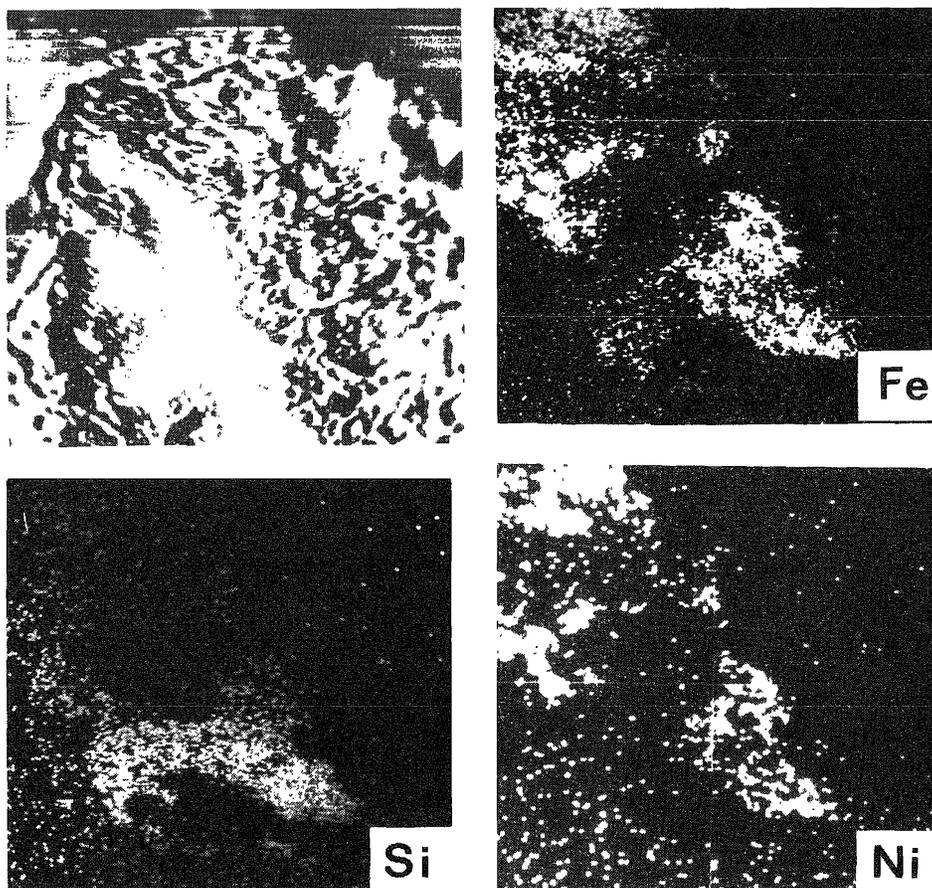
Fig. 11. Raster-type images of a magnetic particle recorded on a X-ray microanalyzer: absorbed electrons; iron distribution; silicon distribution; nickel distribution.

Table 5. Distribution of Au and platinoids in lunar samples (concentrations in ppm).

	Pt	Pd	Ir	Ru	Rh	Au
Basalts	0.02	0.02	—	—	—	0.004
Crystalline lunar rocks						
Apollo 11	—	0.006*	from 0.2* to 0.01	—	—	—
Apollo 11	—	0.1†	—	—	—	0.0016§
Apollo 12	—	—	0.0013‡	—	—	0.0011‡
Luna–16	—	0.027	—	6.3	—	—
In regolith						
Apollo 11	—	0.04†	0.00714*	—	—	0.0021§
Luna–16	—	0.01	—	0.027	0.0037	0.002
In iron meteorites	12.0	3.7	2.8	—	—	1.0

* SMALES et al. (1970).
† MORRISON et al. (1970).
‡ LAUL et al (1970)
§ WÄNKE et al. (1970).

Table 6. Trace element content in regolith zones A, B, C, D and basalt (in weight %, X-ray-spectral method)

Com-ponent	Regolith A	Regolith B	Regolith C	Regolith D	Basalt
SiO_2	41.7	41.2	42.5	41.3	43.8
Al_2O_3	15.32	15.40	15.45	15.15	13.65
FeO	16.80	16.55	16.30	16.90	19.35
CaO	12.20	12.80	12.42	12.55	10.40
MgO	8.73	8.82	8.96	8.60	7.05
TiO_2	3.39	3.46	3.30	3.42	4.90
ZrO_2	0.015	—	0.013	—	0.04
Cr_2O_3	0.31	0.25	0.30	0.26	0.28
MnO	0.21	0.20	0.20	0.22	0.20
Na_2O	0.37	0.36	0.36	0.28	0.33
K_2O	0.10	0.12	0.10	0.10	0.15
S	0.19	0.20	0.18	0.25	0.17

collected by Luna–16 with the samples of lunar rock collected by Apollo 11 and Apollo 12, the difference on the whole are also insignificant, with the exception of Ti, Zr, and certain other chemical elements contained in lunar ground in small quantities (trace elements, Table 4). Note also the high content of F, S, Cl and other volatile elements that dissipated from the Moon (Table 7). However, there are observed in the regolith particles vacuoles possibly containing vulgar gases. They are being studied.

The comparison of chemical composition of regolith and of basaltic rocks from the three seas shows that material has the same character everywhere, with variations in composition both in regolith and in basaltic rocks. The sharpest difference in the composition of the lunar ground collected by Luna–16 is in the low content of Ti. Practically it is the same as in the rocks from the Ocean of Storms (Apollo 12) or almost twice lower than in the Sea of Tranquillity. Variations in the content of Mg and Fe are small (Table 4).

The largest content of Zr was observed in the crystalline rocks of the Sea of Tranquillity, where there was much Ti, Y, Sc. The content of macroelements, as well as Ni and many trace elements, is practically the same in all three seas. The content of Ni in the regolith of the three seas is surprisingly similar. The differences in the composition of regolith and the bedrock of the same sea are of the greatest interest. These differences are repeated for all three seas. For example the content of Fe, Ti, Zr is always higher in the bedrock than in regolith. The content of Ni, on the other hand, is always higher in regolith than in the bedrock (crystalline rock). Similarity the content of Ti in crystalline rock and in regolith shows that regolith was formed on the spot and not supplied from afar (like volcanic ashes). The quantity of Ca increases in regolith, as does Al_2O_3. Thus, regolith is enriched with plagioclase and it is poorer in pyroxene, olivine, ilmenite (and spinel), i.e., crystalline rocks are more mafic than regolith. Rare lithophylic elements are contained in larger quantities in the crystalline rocks of the Sea of Tranquillity.

We have already drawn attention to a low content of gold and platinoids in regolith. There are not many data on these elements, but one can see the distribution of gold and platinoids in the lunar rocks (Table 5).

Table 7. Trace element content in regolith zones A, B, C, D and basalt collected by Luna–16
(mass-spectral and spectral investigations) (ppm)

	Regolith A 1	Regolith B 2	Regolith C 3	Regolith D 4	Basalt 5
Li	—	10	—	10	—
Be	—	2.8	2	2.7	—
F	265	292	246	277	181
B	4.5	3.9	6	4.6	5
P	—	254	—	200	511
Sc	27	33	23.3	25	20
Cl	66	74	36	72	—
V	64	73.5	55.3	55	42.5
Co	68	56	44	61	29
Ni	190	137	250	178	147
Cu	36	39.8	35	36	13
Zn	10	20	33	21.5	26
Rb	3	6.3	5.5	—	—
Sr	90	156	—	182	445
Cs	0.06	0.26	—	0.08	0.75
Zr	350	334	354	346	—
Hf	1.1	3.6	1.2	1	0.3
Mo	7	12	3.6	5	1.2
Ga	11	—	4.9	—	1.2
Ge	1.3	1.2	1.2	1.5	2.5
As	0.4	0.36	0.6	0.3	2.9
Se	0.45	0.5	—	0.4	0.7
Br	0.26	0.27	0.24	0.33	1.3
Ru	0.03	0.044	0.01	—	6
Rh	—	0.0037	—	—	—
Pd	0.0086	0.012	—	0.01	0.027
Ag	0.05	0.059	0.02	0.07	0.2
Cd	1	0.75	1	1.3	—
In	0.06	0.025	0.086	0.08	—
Ba	42	259	37	48	206
Sn	1.6	1.4	—	2	4
Sb	0.4	0.3	0.7	0.35	0.5
Te	0.2	—	0.15	0.2	—
W	—	4.7	5.3	7.5	9
Au	0.0033	0.0013	0.003	—	—
Tl	0.3	0.2	—	0.5	—
Pb	6.4	6.6	7	6	7.7
I	0.15	—	0.26	0.14	—
Y	45	49	50	56	58
La	7.3	8	7.4	7.2	7.7
Ce	21	26	24	23	24.6
Pr	4.5	4.7	4.6	4.5	4.8
Nd	20	28	21	23	25
Sm	5.6	6.8	6.2	6.8	7.1
Eu	1.6	1.2	1.3	1.4	1.2
Gd	6.0	4.7	4.6	5.8	4.8
Tb	0.75	1.0	0.9	0.9	0.9
Dy	5.0	5.3	5.0	5.0	5.2
Ho	2.0	2.2	1.9	1.8	2.0
Er	5.0	5	5.0	4.7	5.0
Tm	0.4	0.4	0.4	0.4	0.4
Yb	3.5	3.6	3.5	3.5	3.6
Lu	0.28	0.3	0.3	0.3	0.3

The determination of rare earths has not been finished yet. The isotopic analysis Li^7/Li^6 for regolith is 12.28 ± 0.03; K^{39}/K^{41}, 14.00 ± 0.18; Rb^{85}/Rb^{87} for mean sample is 2.57 ± 0.04. That is to say that the isotopic content is in agreement with the

isotopic content of these elements on Earth. At the same time there were observed disturbances of isotopic content of lithium in meteorites.

As is known, spallation products occur under the influence of solar wind. We have also discovered in regolith Na^{22}, Al^{26}, etc. (Al^{26} gives 173 ± 113 disint. min. kg). This work is being continued. We would like to have data for both zone A and the deeper part of zone D. It would enable us to explain many things.

In this connection it would be of interest to note that the infrared spectrum of regolith showed the existence of a wide structureless band of absorption in the region of oscillation of silico-oxygen bonds. Heating of a regolith sample to 1000°C in argon results in the appearance in infrared spectrum with a distinct structure—separate bands connected with the absorption of isolated SiO_4 groups, frame silicates, etc. Consequently it could be assumed that the regolith material had been irradiated, and that the effects were removed by heating.

Solar wind influences lunar rocks, causing their metamictization and the appearance of spallation products, to a small depth—3–5 cm. Therefore, we decided to measure the induced activity in the upper layers of regolith as well as in its base. The results could contribute to the explanation of the history of regolith accumulation.

Regolith contains inert gases of unusual composition whose content does not vary with depth in the regolith (zone D, Table 9). The prominent component of the gases are solar wind gases. Their composition is much different from the composition of Earth gases and gases in meteorites. The concentration of the gases is very high, several order of magnitude higher than in Earth objects or meteorites. The content of He and Ne coincides with their content in certain meteorites rich in inert gases. Particularly outstanding is the isotopic composition of Ar ($Ar^{40}/Ar^{36} \sim 1$, and $Ar^{36}/Ar^{38} = 5.25$) which corresponds to that on Earth. The quantity of Ar^{40} is 4–5 times greater than found in rocks as a result of disintegration of K^{40}. The isotopic composition of Xe is also different from that of the Earth and is being studied further. The content of inert gases in the material from the Sea of Plenty is closer to regolith from the Sea of Tranquillity. The first evaluation of the age of the Moon was carried out by the Rb/Sr method, in crystalline rock in the fine fraction of regolith, and the results are 4.85×10^9 and $4.25 \times 10^9 \pm 0.75 \times 10^9$ years. The mean isochron values are 4.45 and $4.65 \times 10^9 \pm 0.5 \times 10^9$ years. Thus the absolute age of the samples from the three seas are very close to each other, i.e., the age of the Moon corresponds to the age of the Earth. The same values were obtained by Pb^{206}/Pb^{207}. It was difficult to calculate the age by K/A. Of particular interest is the exposure age of regolith.

Table 8. Content of Th and U (in ppm)

Regolith Apollo 11	Regolith Apollo 12	Regolith Luna-16	Crystalline rocks Apollo 11	Crystalline rocks Apollo 12	Crystalline rocks Luna-16
2.24 ± 0.06	6.0 ± 0.6	0.474 ± 0.05*	2.9 ± 0.4	0.88 ± 0.09	1.14 ± *
0.59 ± 0.02	1.5 ± 0.2	0.1 ± 0.01*	0.7 ± 0.1	0.24 ± 0.035	0.2 ± *
3.8	4.0	4.7	4.0	3.7	5.7

* Determined by mass-spectral method.

Table 9. Content and isotopic composition of inert gases in lunar soil samples (fine fractions)
(in 10^{-8} cm^3)

	Sea of Plenty sample 7–1 g	Apollo 11		
		FUNKHOUSER et al. (1970)	REYNOLDS et al. (1970)	HINTENBERGER et al. (1970)
He^4	18,000,000	11,000,000–19,000,000	29,000,000	20,000,000
He^4/He^3	2670	2430–2540	2130	2550
Ne^{20}	340,000	200,000–313,000	530,000	221,000
Ne^{20}/Ne^{22}	12.80	12.4–12.8	12.85	12.7
Ne^{21}/Ne^{22}	0.0332	0.0316–0.0340	0.0332	0.0333
Ar^{40}	53,000	38,500–40,800	57,000	41,000
Ar^{40}/Ar^{36}	0.98	1.1–1.2	1.126	1.10
Ar^{36}/Ar^{38}	5.26	5.20–5.17	5.19	5.15
Kr^{84}	22	21–20	37	21
Xe^{132}	8.5	10–4.1	4.6	2.87

Thus the lunar rocks of the three seas are of the same general type—basalts, with compositional variations dependent on the conditions of their melting, and regolith, with variations dependent on its rather different history in the subsequent period.

The rocks from the Sea of Plenty are closer to the composition of the rocks from the Ocean of Storms. But on the other hand the inert gas content of the regolith is closer to that of the regolith from the Sea of Tranquillity, etc.

Let us make certain preliminary conclusions. It is still too early to state the final opinion on the character of processes on the lunar surface. We will base ourselves on the data obtained during the study of the sample collected by Luna–16 from the Sea of Plenty and, certainly, compare it with the data obtained by Apollo 11 and Apollo 12. The material from all three seas—the Sea of Tranquillity, the Ocean of Storms, and the Sea of Plenty—is surprisingly similar in its petrological, mineralogical, and chemical composition, though certain details are different. Huge lunar seas situated along the lunar equator are depressions filled with lava. During the early period of extensive volcanic activity on the Moon a huge amount of basaltic rocks, accompanied by the dissipation of gases, flowed onto the lunar surface. Depending on the conditions of the flow, its temperature, depth, etc. there were created lunar surface rocks, of the same basalt type, with variable contents of Fe, Ti, Zr, Ba, and other elements. The content of iron in the magma also played a certain role in this endogenous process. Possibly there can be found on the Moon rocks derivative of basalts (anorthosites, rhyolites, etc.). We do not know the exact thickness of the basalt crust of the Moon. The absolute age of the surface rocks of the Moon, or to be more precise, the age of the Moon, for all practical intents and purposes corresponds to the age of the Earth. The lunar seas are covered with a layer of regolith. Evidently its thickness varies considerably. In the Sea of Plenty, where collected by Luna–16, it did not exceed 0.5. The variations probably are limited to the first several meters. As we have seen regolith is a heterogenous mixture of rock fragments, minerals of various sizes, shapes and colors and melted as well as angular particles. With depth the ratio of various fragments changes, though it is not possible to note any stratification of material.

Regolith material is the result of crushing lunar rock under conditions of high temperature, causing not only the formation of melted particles of regolith but also

the formation of spheroids. Regolith is different from the volcanic sand of Earth volcanoes. As we have already seen, the composition of regolith is rather different from that of crystalline rocks of the Moon. It contains a lower amount of mafic elements. Consequently it should have a lower melting point than primary basalt rocks. Before touching upon the problem of the formation of regolith, let us recollect the main factors of lunar "weathering." Firstly, there is the fluctuation of lunar temperature for the surface rocks of the Moon during thousands of millions of years from the lunar day to the lunar night (in the range $\pm$ 100°C). Secondly, the surface rocks of the Moon are irradiated by solar wind and galactic cosmic rays. Further, the lunar rocks exist in vacuum and finally, encounters with meteorites are possible. Possibly the fluctuation of temperature in some way influences the strength of the surface rocks of the Moon, but we are unable to evaluate it at present. The effect of solar wind and galactic irradiation is considerably larger. Firstly, our observations indicate that the whole regolith down to 35 cm depth bears traces of the influence of solar wind. The regolith sample from zone D contained a great amount of solar-wind inert gases. The infrared spectrum of regolith also gave evidence of its irradiation. And lastly we should, of course, wait for the results of determination of spallation products in deep layers of regolith. This indicates, preliminarily, either the mixing of regolith in place, or that the layers of regolith depict the history of formation. The irradiation does not penetrate deep inside, only through a few centimeters of material. On the basis of observations and study of the so-called metamictness in minerals containing radioactive elements it follows that they loose their strength, their crystalline lattices undergo deformation, etc. But irradiation does not lead to the complete destruction of minerals. We are trying to discover metamictness in regolith particles.

Irradiation begins its work mainly after the crushing of the material. Therefore, solar wind does not take a direct part in the process of crushing of the material and the formation of regolith (its melting), but it does influence the strength of the material. Usually the formation of lunar seas and, therefore, the formation of regolith which fills them, is connected with the impacts of meteorites. It is interesting to visualize the process of impact of a swarm of meteorites on the earthside of the Moon in the region of the contemporary lunar seas situated along the equator. It is difficult to explain why they fell only on the visible, most concave, side of the Moon. The most reliable evidence of the "work" of meteorites would have been their discovery on the lunar surface. However, meteorites and micrometeorites impact the Moon with cosmic velocities. Experiment and calculations show that one gram of meteorite is capable, under such conditions, of disintegrating 2–3 orders of magnitude more lunar rock. During this process rock particles fly with great speeds and have a wide range of velocities. A part of them could leave the Moon and reach the Earth (for instance Eucrites). While trying to find an explanation for the formation of regolith, we must always remember this situation with the balance of lunar matter. Nevertheless, a portion of meteorite matter, however small, is left on the surface of the Moon. Above we gave preliminary data on the finding of meteorite matter in regolith. Undoubtedly it can be discovered. But still it is not sufficient for the explanation of the formation of the whole regolith on the Moon.

I would like to draw your attention to another thing. The most distinctive feature in the endogenous process of the flowing of melted basalt rocks on the Moon is the immediate contact with extreme space vacuum. The magma of the Moon comes to the crust and breaks through it. Liquid magma and its gases rush into vacuum. This must result in the spraying of liquid magma and simultaneous loss (with a great speed) of its gases and volatile substances. We would like to follow this approach (parallel with other motives) of finding the origin of regolith by staging certain experiments. All the more so because the crucial problem of the character of the balance of lunar matter is important for the understanding of geochemical processes on the Earth, particularly during the first thousand million years of its evolution.

REFERENCES

FUNKHOUSER J. G., SCHAEFFER O. A., BOGARD D. D., and ZÄHRINGER J. (1970) Gas analysis of the lunar surface. *Science* **167**, 561–563.

HINTENBERGER H., WEBER H. W., VOSHAGE H., WÄNKE H., BEGEMANN F., VILSCEK E., and WLOTZKA F. (1970) Rare gases, hydrogen, and nitrogen: Concentrations and isotopic composition in lunar material. *Science* **167**, 543–545.

LAUL J. C., KEAYS R. R., GANAPATHY R., and ANDERS E. (1970) Abundance of 14 trace elements in lunar rock 12013,10. *Earth Planet. Sci. Lett.* **9**, 211–215.

LSPET (LUNAR SAMPLE PRELIMINARY EXAMINATION TEAM) (1970) Preliminary examination of lunar samples from Apollo 12. *Science* **167**, 1325–1339.

Moon Issue (1970) *Science* **167**, 417–719.

MORRISON G. H., GERARD J. T., KASHUBA A. T., GANGADHARAM E. V., ROTHENBERG A. M., POTTER N. M., and MILLER G. B. (1970) Multielement analysis of lunar soil and rocks. *Science* **167**, 505–507.

REYNOLDS J. H., HOHENBERG C. M., LEWIS R. S., DAVIS P. K., and KAISER W. A. (1970) Isotopic analyses of rare gases from stepwise heating of lunar fines and rocks. *Science* **167**, 545–548.

SMALES A. A., MOPPER D., WEBB M. S. W., WEBSTER R. K., and WILSON J. D. (1970) Elemental composition of lunar surface material. *Science* **167**, 509–512.

VINOGRADOV A. P., SURKOV YU. A., and CHERNOV G. M. (1966) Investigation of the intensity and spectral composition of lunar gamma ray by Luna–10. *Dokl. Acad. Sci. USSR* **170**, No. 3.

WÄNKE H., BEGEMANN F., VILSCEK E., RIEDER R., TESCHKE F., BORN W., QUIJANO-RICO M., VOSHAGE H., and WLOTZKA F. (1970) Major and trace elements and cosmic-ray produced radioisotopes in lunar samples. *Science* **167**, 523–525.