

# Differentiation of the Matter of the Moon

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In the past few years it has become possible to study lunar materials directly because surface rocks of the Moon have been returned by man and by automatic spacecraft. A tremendous number of new facts have been accumulated about the properties and composition of lunar crustal rocks. There is a great general similarity between the surface rocks of the Moon and the basic rocks of the Earth's crust, such as tholeiitic basalts, although certain differences have been found between lunar and terrestrial rocks. It is the differences between lunar and terrestrial rocks to which the current report essentially addresses itself. From comprehensively studying laboratory materials, the scientific literature on the composition of lunar rocks, and hypotheses concerning the formation of the matter of the Moon, etc., we have been forced involuntarily to turn to the cardinal question, which is of exceptional significance for our understanding of the evolution of the solar system: are the differences observed in the surface rocks of the Moon the result of the uniqueness of the differentiation of lunar material into concentric layers, or a result of the early preplanetary separation of the matter of the Sun, which occurred in the protoplanetary cloud? We have available only surface rocks from the Moon. Is it possible, by studying the surface rocks of the Moon and the other planets, to gain an idea of the chemical structure of the matter within the Moon? This will be determined later. In any case, a comparative physical and chemical study of surface and near-surface rocks of

the Earth and Moon and various types of meteorites, as well as a search for possible genetical processes, forms the main approach to answering the question stated above.

I must recall some of the basic physical-chemical data concerning the terrestrial planets. Apparently, all of the terrestrial planets and the Moon have concentric layered structures. Some of them—the Earth, Venus, and Mercury—have dense cores, probably of an alloy of Fe and Ni with admixtures of certain other siderophilic elements. This affirmation is based, as we will see later, on the wide distribution of iron, on studies of its behavior during the evolution of the solar plasma, and on studies of the metallic phase of various meteorites. On the other hand, attempts to replace these concepts of the FeNi core of the planets with a silicate core or any other core have not been successful because, for example, no jump in density occurred when silicates were compressed under pressures of millions of atmospheres. The ratio  $\text{FeNi}_{\text{met}}/\text{silicate}$  (metal/silicate), as we know, differs rather widely for different terrestrial planets and, as a result, so do the densities of the planets. Here we first encounter a sharp difference between the composition of the planets and the composition of the Sun, at least for Fe and the siderophile elements. We will return to this question later in our analysis of ways to form the FeNi cores of planets. The mantles of the planets represent the silicate phase of planetary material. We can assume that the mantle is either “whole” solar material, not subjected to separation in

the protoplanetary cloud, or that it represents some portion of the solar plasma. Doubtless, this is an ultrabasic substance similar in composition to stony meteorites. However, we have never studied it directly in any objective way, since very little has been obtained. From beneath the Earth's crust and from the rift valleys of the midoceanic ridges, rock has been obtained (from the upper mantle of the Earth) which is ultrabasic in nature (rich in Mg and Fe and with little Al), i.e., harzburgites and lherzolites (ref. 1). Possibly the composition of the mantles of the planets varies somewhat like the compositional variations of rocky chondritic meteorites of various types, but doubtless the composition remains similar to terrestrial ultrabasic rocks. However, flows of basic rock similar to terrestrial primitive tholeiitic basalts apparently occur on all terrestrial planets. This follows directly from data for the Earth and Moon. Based on photographs of the landscape of Mars (polar caps with CO<sub>2</sub>) and particularly remarkable of Mercury, the same type of planetary surface has been observed, i.e., with tremendous craters. Finally, we cannot imagine the absence of lava flows on Venus where the atmosphere, due to the "greenhouse effect," contains (according to our calculations) all of the probable "reserve" of carbon of the entire planet in the form of CO<sub>2</sub>, which could have resulted only from volcanism. Consequently, the phenomena of magmatism, effusion of basaltic lava, and accompanying degassing, occur on all planets. In other words, basaltic crusts form on all of the planets. The thickness and composition of these crusts are only just now beginning to be studied. The landscape of all terrestrial planets is surprisingly similar. In addition to volcanic craters, a tremendous mass of craters of all sizes has been produced as a result of meteorite impacts. People first became familiar with the "lunar" landscape on the Moon. It was then discovered on Mars, and recently on Mercury. On Earth, meteorite craters have been partially (particularly before the atmospheric age) eroded, and are presently hidden beneath thick sediments.

Some have been retained and are well known, as, for example, the huge Canyon Diablo meteorite crater in the United States and the Alae Crater in Hawaii and many others. Finally, under the influence of various factors on the various planets, layers of fine-grained materials have developed on their surfaces and cover the planets: soil on Earth, regolith on the Moon, and dust on Mars. The Moon's regolith, which was formed by thermal explosions caused by meteorite impacts, reaches several meters in thickness. On Venus there are probably thick sediments covering its surface as a result of the corrosive influence of the carbon dioxide atmosphere and the "greenhouse effect" on the destruction of magmatic rock. Radar studies of Venus show altitude differences of not over one kilometer. Craters 33–160 km in diameter, with depths of up to 400 m, have been discovered on Venus (ref. 2). Mountains on the Moon, Mars, and Earth, however, reach 10 km in height. The nature of the landscape is influenced by many factors. Also, depending on the mass of the planet and its distance from the Sun, on life, on solar, cosmic, and galactic radiation, and on many other factors, various atmospheres develop or are finally lost.

The seismic observations of Apollos 14, 15, and 16 have indicated that, by analogy with the structure of the Earth, the lunar crust is ~ 25 km thick. We recall that the thickness of the Earth's crust is ~ 40 km on the continents and 6–8 km beneath the ocean floor, amounting to ~ 1 percent of the thickness of the entire silicate mantle of the Earth (ref. 3). There is therefore considerable interest in the seismic data recently produced by Apollo 17, indicating that, for example, the thickness of the basaltic rocks in the Taurus-Littrow Valley is only a little more than one kilometer, totaling 1860 meters. The problem of the thickness of the crust remains open. Reflections of seismic waves were received from deeper horizons as well, but their significance is not sufficiently clear. The central portion of the Moon is apparently melted and does not transmit seismic shear waves. Many are inclined to believe that the entire area of

the core is like the asthenosphere of the Earth, with low seismic conductivity (ref. 4).

There is every reason to believe that the Moon has no FeNi core. Let us begin with the fact that the density of the Moon is 3.34 (10 percent of the density is probably a result of gravitational compression). The density of stony meteorites (chondrites containing  $\sim 12$  percent metallic alloy) is  $\sim 3.58$ – $3.6$ , i.e., higher than that of the Moon. The solar plasma flowing around the Moon is not perturbed. The Moon has no global magnetic field. Later, we will show that the Moon was formed in a cloud with reduced quantities of FeNi and therefore the Moon not only has no FeNi alloy at its center, but also contains significantly lower quantities of the 10 siderophilic elements that ordinarily accompany metallic iron than, for example, the rocks of the Earth.

It should be recalled that the metallic iron contained in stony meteorites is not sufficient to form the iron-nickel cores of the planets. A solid addition of tremendous fragments of metallic iron—iron meteorites—is required.

The Moon has an asymmetrical surface structure. About 30 percent of its visible area is occupied by so-called lunar maria and the remaining area by a mountainous continental portion. On the back side of the Moon only  $\sim 2.5$  percent of the area consists of maria and all of the rest is mountainous relief. The force of gravity on the Moon is one-sixth that of the Earth, which is of particular interest in connection with the process of upthrusting of lunar magma to the surface. The temperature at the center of the Moon, according to various extrapolations (for example, based on the electrical conductivity of "dry" lunar rock), is probably not presently over  $1000^{\circ}$ – $1500^{\circ}\text{C}$ . The expected heat flux at the surface of the Moon would be about one-sixth of the mean heat flux on the Earth. However, measurements have yielded a heat flux from the surface of the Moon that is one-half that of the Earth (ref. 5). The temperature gradient differs significantly from the terrestrial gradient (Moon,  $1^{\circ}$ – $4^{\circ}\text{C}/\text{meter}$ ; crust,  $0.01^{\circ}\text{C}/\text{meter}$ ).

On the Moon, the terrestrial factors of rock weathering are absent. Water has participated little in geological processes on the Moon. On the Moon quite different factors cause the destruction of rock: variations in temperature between lunar day and night; the solar wind; the cosmic, solar, and galactic radiation; and meteorite and micrometeorite impacts. Finally, the surface relief of the Moon is changed by volcanism and lava flows, which were most intensive during the first billions of years, up to 3.0 billion years ago. Some of the circular lunar maria such as Mare Imbrium, Serenitatis, Humorum, Nectaris, and Crisium have positive gravity anomalies (ref. 6). It is assumed that below these maria at depths of  $\sim 100$  km there are denser rocks, the so-called mascons. According to the thinking of many scientists they are of extralunar origin, i.e., planetesimals which struck the Moon during the last stage of its accretion. The surface of the Moon, particularly its highland portions, is covered with many craters. There are no lines of mountains on the Moon, the mountainous relief being created by circles of mountains, crater walls, over 10 km high.

Craters on the Moon have been caused by two different processes. One is ancient volcanic activity, which was confirmed after man visited the Moon and found that the surface rocks are of magmatic origin. There are direct observations of frozen lava flows on the Moon, for example, in the crater Aristarchus and elsewhere. Other craters were formed as a result of meteorite impacts or the impacts of stones ejected by explosive volcanism. The impact nature of craters has been proven by the finding of fragmental meteoritic material on the surface of the Moon, and by direct observation in our own time of the formation of a crater on the Moon, which was observed upon impact of a meteorite two years ago (ref. 7).

However, there is no generally accepted visual evaluation of craters as to their origin. Obviously, the small craters of precise circular shape, up to 1 km in diameter and surrounded frequently by rock fragments, are of impact origin. On the other hand, the

impact mechanism is credited with the formation of certain circular lunar maria by impact of planetesimals. The influence of meteorite impacts on changes in rocks on the surface of the Moon is tremendous. On the lunar surface, particularly in the continental areas, we have encountered large numbers of primary magmatic lunar rocks that have been crushed and metamorphized by impact mechanisms, particularly basalt-type rocks, to form various types of breccia, slag, and, finally, the fine-grained powder called regolith, which covers the entire surface of the Moon in a layer reaching a thickness of several meters in places. The grains of rocks in the regolith are melted, or have glass-covered surfaces, or are in the form of drops. The glass has various compositions and colors. The impact of meteorites causes a thermal explosion and temperatures reach several thousands of degrees C. Lunar rocks have properties quite unusual for terrestrial rock, i.e., tremendous density, the appearance of nonrusting iron, etc. The rock fragments take on remarkable forms due to micrometeorite impacts. The metamorphism of surface rocks on the Moon arises under the influence of meteorite and micrometeorite impacts, greatly complicates the surface processes, and causes complete or partial remelting of the primary magmatic rocks of the Moon, with subsequent formation of breccia, etc.

As a result of the continuous study of lunar rocks, the possibility has arisen of determining unique petrologic provinces on the Moon; and by determining the absolute age of rocks from various areas of the Moon, it has become possible to determine the more ancient and younger petrographic areas of the Moon. For example, it has been found that rocks from the Fra Mauro province are older than the material from Mare Imbrium.

In order to approach the solution of the problem of which process was predominant in the formation of lunar rocks, and in their composition (either separation of matter in the protoplanetary nebula or fractional differentiation of lunar material during formation of the Moon's crust), we must first of all obtain comprehensive data on the nature

of the most ancient, unchanged primary crystalline magmatic rocks of the Moon. Therefore, our attention will next be concentrated primarily on (1) analysis of the composition of just these unchanged or little changed magmatic surface rocks of the Moon and (2) comparison with the tholeiitic basalts of the Earth and feldspar achondrites. The lunar mare basalts have many features in common with the tholeiitic basalts of the Earth. They also poured out directly from the underlying layer of ultrabasic "meteoritic" rock. However, breccias, regolith, and other clastic material, of course, are of considerable interest in light of the problem at hand.

## The Lunar Rock Collection

Let us briefly recall the nature of the lunar surface rocks returned by Apollos 11, 12, 14, 15, 16, and 17 and by Luna 16 and Luna 20.

### MARE SAMPLES

Apollo 11 Mare Tranquillitatis, southwestern portion, 10 km from the Crater Sabine D, 0°41'15" N.; 23°26' E.

They are magmatic rocks in the form of two varieties of basalt, one with subophitic texture, basalt type A, and one with granular texture, basalt type B (microgabbro). They differ slightly in mineralogical and chemical composition (see table 1). Basalt type A is richer in Rb, REE, Y, and other trace elements (see table 1). These basalts are also rich in FeO and TiO<sub>2</sub> (almost 11 percent) and contain low concentrations of alkalis in comparison with primitive terrestrial tholeiitic basalts (see table 1). Fragments of anorthosite were found in the Apollo 11 regolith. We will return to the rocks of the anorthositic series somewhat later.

Apollo 12 Oceanus Procellarum, northwestern edge, near Surveyor Crater: 23°4' W., 3.2° S., 120 km from the crater Lansberg.

Fine-grained and medium-grained basalts are encountered. However, these basalts are less differentiated than the Apollo 11 basalts and contain still more FeO, but less TiO<sub>2</sub>. In addition, the regolith contains a variety of nonmare basaltic fragments (with increased content of Al<sub>2</sub>O<sub>3</sub> and CaO) and grains of anorthositic rock.

Apollo 15 On the edge of Mare Imbrium in the bay Palus Putredinis; 26°06'04" N. and 3°39'10" E. between the Apennine Front and Hadley Rille.

The Mare basalts are like those of Mare Imbrium and Serenitatis. Various types of basalts are found, some rich in dark-colored pyroxenes, and others with olivine. This mission discovered a flow of mare basalt lava 30 feet thick (rille edge) (see table 1). Here also were certain basaltic fragments containing larger quantities of Al<sub>2</sub>O<sub>3</sub> and CaO and less FeO and MgO in comparison with typical mare basalts from Apollo 11, 12, and 15, i.e., the so-called nonmare basalts (see table 1), as well as fragments of anorthositic rock.

Apollo 17 Southeastern edge of Mare Serenitatis, south of Littrow Crater and the Taurus Mountains; 20°10' N., 30°46'58" E., in a valley.

These are a complex group of rocks, of pulverized and clastic type. The crystalline basalts have textures similar to the basalts of Apollo 11 type B (see table 1), i.e., they repeat the mare basalt compositions from other mare areas.

Luna 16 Mare Fecunditatis, northeastern portion, 13°41' S. and 56°18' E.; 100 km west of Webb Crater.

Regolith with varied grain size was returned. Among the fused regolith grains, there are angular fragments of fresh-looking, unfused basalt. In composition, they are also typical mare basalts. Rare grains of anorthositic rock also occur.

## CONTINENTAL SAMPLES

Apollo 14 Shore of Mare Imbrium and Fra Mauro Ridge, 3°40'24" S., 17°27'55" W.

Rocks were returned from a continental area of the Moon. These were highly altered, clastic rocks. Their composition and history are exceptionally complex. Only one ~ 50-g rock was found to be a fragment with the texture of primary basalt. The basalts are distinguished by their high content of Al<sub>2</sub>O<sub>3</sub> and CaO and their low content of FeO and TiO<sub>2</sub>. Some of them contain significant quantities of K, REE, and P and are called KREEP basalts (or norites). The material contained primarily light-colored rocks of the anorthositic series.

Apollo 16 Highland area, region of the old Descartes Crater (8°59' 34" S. and 15°30'47" E.).

These rocks are quite varied, of complex composition, and clastic in nature. The breccias are fused and recrystallized. All rocks were divided into four types: (1) cataclastic anorthosites, (2) partially fused breccias, (3) polymict breccias, and (4) igneous rocks with a high degree of metamorphism. Our attention is currently drawn to the last type of rock. These are crystalline rocks with various degrees of homogeneity. Their composition varies. Plagioclase predominates. On the other hand, KREEP basalts were returned (see table 1).

Luna 20 Highland area between Mare Fecunditatis and Mare Crisium; 3°32' N. and 56°23' E.

Luna 20 returned soil from a continental area in which particles of light anorthositic-type rock predominated. Particles with good basaltic texture were also found.

A petrological classification of the lunar gabbro-basalts is not yet agreed upon, and the same types of basalts continue to be called by different names, for example, nonmare basalts or norites. Apparently the lunar gabbro-basalts can be separated into 8 or 10

Table 1.—*Lunar Basalts From Various Sites: Chemical Composition in Weight Percent (data from various authors)*

Type of Rocks	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Cr <sub>2</sub> O <sub>3</sub>
<b>Mare Basalts</b>											
Mare Tranquillitatis, Apollo 11 <sup>(1)</sup>	40.3	10.8	7.52	18.06	0.2	6.97	11.76	0.40	0.22	—	—
Mare Tranquillitatis, Apollo 11 <sup>(2)</sup>	42.8	10.5	11.84	17.15	0.2	6.47	7.34	0.48	0.10	—	—
Oceanus Procellarum, Apollo 12 <sup>(3)</sup>	45.0	2.97	9.76	19.7	0.27	10.9	9.97	0.33	0.05	0.09	0.50
Mare Imbrium, Palus Putredinus, Apollo 15 <sup>(4)</sup>	45.0	2.54	8.9	22.21	0.30	9.08	10.27	0.28	0.03	0.08	—
Mare Serenitatis, Taurus-Littrow, Apollo 17 <sup>(5)</sup>	37.19	13.14	8.7	19.62	0.28	8.52	10.43	0.32	0.04	0.09	0.42
Mare Fecunditatis, Luna 16 <sup>(6)</sup>	42.95	5.5	13.88	20.17	0.21	6.05	10.8	0.23	0.16	0.14	0.24
<b>Highland Basalts</b>											
Fra Mauro, Apollo 14 <sup>(7)</sup>	48	1.5	12.0	16	0.29	8.4	12	0.58	0.14	—	0.44
Crater Descartes, Apollo 16 <sup>(8)</sup>	45.40	0.32	28.63	4.25	0.06	4.38	16.39	0.41	0.06	0.07	—
Taurus-Littrow, Apollo 17 <sup>(9)</sup>	48.5	0.95	17.2	11.4	—	8.94	11.6	0.40	0.25	—	—
<b>KREEP Basalts</b>											
Fra Mauro, Apollo 14 <sup>(10)</sup>	50	1.3	20	7.7	0.14	8	11	0.63	0.53	—	—
Crater Descartes, Apollo 16 <sup>(11)</sup>	47.18	1.04	19.98	7.91	0.12	10.34	12.03	0.44	0.32	0.40	—
<b>Earth Basalts</b>											
Oceanic Tholeiitic Basalts (276 cases)	49.15	2.09	15.09	7.58 (+Fe <sub>2</sub> O <sub>3</sub> 3.35)	0.17	7.75	10.61	2.23	0.3	0.23	—
<b>Meteorites</b>											
Basaltic achondrites (12 cases) <sup>(12)</sup>	49.0	0.61	11.95	18.05	0.52	9.73	9.03	0.40	0.05	0.11	0.48
Chondrites (94 cases)	38.04	0.11	2.50	12.45	0.25	22.84	1.95	0.98	0.17	0.21	0.36

NOTES: (1) Data of Wänke (see bibliography) (refs. 8–11)  
 (2) Data of Wänke (refs. 8–11)  
 (3) Data of Cuttitta et al. (refs. 12 and 13)  
 (4) Data of A Preliminary Description (ref. 17)  
 (5) Preliminary Exploration Team (70215,2) (refs. 15–17)  
 (6) Data of Vinogradov (refs. 3, and 18–28)  
 (7) Data of Preliminary Scientific Report (14053) (refs. 29 and 30)  
 (8) Data of Preliminary Exploration Team (68415,6) (refs. 15–17)  
 (9) Data of Taylor (77275) (refs. 31–35)  
 (10) Data of Preliminary Scientific Report (14310) (refs. 29 and 30)  
 (11) Data of Hubbard et al. (65016,45) (refs. 36–38)  
 (12) According to calculations performed for the author by G. P. Vdovykin.

groups. However, this has not yet been done. Therefore, we will use the mineralogical and chemical composition for comparison, and compare the lunar gabbro-basalts on the one hand with the achondrites, rich in Ca and feldspar; and, on the other hand, with primitive terrestrial tholeiitic basalts-oceanic olivine-basalt associations. There is a ten-

dency to classify basalts—more precisely—to divide them into groups or types, according to the content of FeO, TiO<sub>2</sub> or Al<sub>2</sub>O<sub>3</sub>, etc.

The texture of basalts depends on the conditions of crystallization, primarily temperature and time. It varies as a function of pressure, content of volatiles in the magma, etc.

Chemical compositions are presented in

table 1. They are nonaveraged individual data for various basalt types according to various authors. First, the primary attention of researchers was drawn to material from the lunar mare. Attention was given to the high content of FeO and TiO<sub>2</sub> in various types of mare basalts, as well as to the very low content of alkalis. The content of FeO is over 25 percent, approximately double the mean content of FeO in terrestrial tholeiitic basalts. One can consider that the content of FeO in all mare basalts is distinctly higher than in terrestrial tholeiitic basalts, as well as in the Ca-rich feldspar achondrites. Therefore, the ratio (100 Mg/Mg + Fe) is higher on Earth. The presence of Fe<sub>2</sub>O<sub>3</sub> in lunar basalts is doubtful. The fugacity of O<sub>2</sub> for lunar rocks is 10<sup>-23</sup>, and for terrestrial basalts is 10<sup>-11</sup>. The Ca-rich feldspar achondrites occupy an intermediate position.

In order for Fe<sub>2</sub>O<sub>3</sub> or Fe<sub>3</sub>O<sub>4</sub> to form in the protoplanetary cloud, the partial pressure of O<sub>2</sub> would have to be changed by several orders of magnitude in comparison with the P<sub>O<sub>2</sub></sub> (partial O<sub>2</sub> pressure) for the formation of FeO, which would also greatly influence the valency states of many other metals.

Furthermore, the rocks of the Moon and their minerals contain metallic Fe as well as Ti and Cr in trivalent form, etc., indicating the deeply reducing conditions during accretion of the Moon.

The presence of large quantities of FeO in the mare basalts has a considerable influence on the physical properties of the magma. First of all, Fe<sup>2+</sup> significantly reduces the melting point of minerals, and consequently of basalts, due to the exceptional ease with which Fe<sup>2+</sup> isomorphically replaces many divalent and other ions. Secondly, due to the presence of large quantities of FeO a series of iron minerals is formed. Further, a still more interesting effect occurs in the lunar basalts because of the large quantities of TiO<sub>2</sub>, which also forms a number of minerals which are unusual for terrestrial basalts, ortho- and para-armacolite, tranquillityite, zirkelite, pseudobrookite, etc., a compound with Cr, -spinel, and with ZrO<sub>2</sub> and other of its analogues. The primary Ti mineral in the

lunar basalts is ilmenite. The content of TiO<sub>2</sub> in the mare basalts reaches 13 percent, i.e., 100 times its content in the chondrites. Since ilmenite easily exchanges, many other minerals containing Ti are also found, and interesting processes occur. For example, it has been experimentally proven that plagioclase and olivine do not form liquids, but with high contents of TiO<sub>2</sub> and clinopyroxene, a silicate fluid is formed. All together, this results in a group of minerals in the lunar basalts which would be unusual for their terrestrial analogues. In the tholeiitic basalts the average TiO<sub>2</sub> concentration  $\cong$  2 percent, and in the Ca-feldspar achondrites there is very little,  $\cong$  0.5 percent TiO<sub>2</sub>, indicating the peculiarities of the genesis of these achondrites.

The lunar basalts have at least an order of magnitude less alkali, particularly K, than the tholeiites. The Ca-feldspar achondrites contain still less K than the lunar basalts. This deficiency of K and, as we will see below, of other alkalis is explained by their loss either in the process of accretion or in the process of differentiation of lunar material. Since a similar loss is noted for many other easily volatilized chemical compounds and elements, we will return to this question specially somewhat later. We must recall that there are no hydrate minerals. A number of the peculiarities of the process of formation of lunar basalts indicate the slight participation of water in them, or its total absence, which also differentiates the magmatic processes on the Moon from those of terrestrial magmatism.

The content of other primary oxides in mare basalts is to some extent monotonous. I have in mind here SiO<sub>2</sub>, MgO, CaO, and to some extent Al<sub>2</sub>O<sub>3</sub>. This is also true of the nonmare basalts from the highland areas of the Moon (norites). These highland nonmare basalts (norites) have been significantly less studied; however, it is these rocks which create the primary background for the composition of the surface rocks of the Moon, since highland areas occupy its entire backside—in all, over 70 percent of the surface.

The nonmare basalts (norites) have significantly higher contents of the feldspar

molecule and therefore much higher contents of  $\text{Al}_2\text{O}_3$ , and particularly of  $\text{CaO}$ , than the lunar mare basalts; and at the same time, lower contents of  $\text{FeO}$  and  $\text{TiO}_2$ . The remaining primary elements— $\text{SiO}_2$ ,  $\text{MgO}$ ,  $\text{Cr}$ ,  $\text{Na}$ ,  $\text{K}$ , and  $\text{Mn}$ —are found in the nonmare basalts in quantities comparable to those of mare basalts, and with the known variations and tendencies. Among the rocks obtained from the Fra Mauro province and in the samples from other areas as well the so-called KREEP basalt was found, particularly in samples from Mare Procellarum. They differ in composition, structure, and texture from the other basalts. The composition and method of their formation will be discussed later as we study the behavior of trace elements in lunar rocks.

The nonmare basalts (norites) show a tendency toward enrichment with the feldspar molecule and, consequently, higher contents of  $\text{Al}_2\text{O}_3$  and  $\text{CaO}$ , a characteristic which is still more completely realized by the formation on monomineralic anorthosite in the highland areas. The process of melting and raising basalt magma to the surface of the Moon and the formation of the basalt crust is basically similar to such processes on Earth. However, some of the conditions of formation and rise of magma and its crystallization on the Moon show significant differences. As indicated by a study of magma crystallization, the precipitation of various minerals occurs primarily in the range of  $1025\text{--}1310^\circ\text{C}$ . According to direct determinations lava usually solidified at  $\sim 1200^\circ\text{C} \pm 50^\circ$ . Because of the low gravitational force and low viscosity, the magma rose quickly. Xenoliths are practically absent. The pressure at which magma crystallized on the Moon was only a few kbar (3–10 kbar);  $\text{H}_2\text{O}$  and the volatiles common in terrestrial magmatic processes were significantly less abundant, i.e., a “dryer” process occurred. There are few vesicles in the lunar rocks, because of the tremendous vacuum on the surface of the Moon. However, we cannot exclude the participation of traces of  $\text{H}_2\text{O}$  in the processes of lunar differentiation. Magma rose from a depth of several hundreds of

kilometers, depending on the nature of the basalts (content of  $\text{Ti}$ ,  $\text{Al}_2\text{O}_3$ , olivine, etc.). It is assumed that with the high  $\text{Al}_2\text{O}_3$  content, basalts must have risen from depths of over 400 kilometers in order to provide for the extraction of  $\text{Al}_2\text{O}_3$  from depths in large quantities. On the other hand, the presence of large quantities of olivine in the basalts indicates a shallow depth of origin because olivine breaks down at 3 kbar. The presence of tridymite and cristobalite in some lunar rocks indicates high temperatures and low pressures and, consequently, the depth of the magma sources. Cooling must have occurred quite rapidly, as indicated by the texture of the complex basalts, the disordered nature of the plagioclase, and other factors. Under the near-surface conditions, the depth of crystallization differentiation could not have been great. Probably, the variety of basalt types is most closely related to the temperature and depth of melting. Some variety in the composition of the basaltic rocks resulted from meteorite impacts which caused remelting or partial melting of the lunar material and the formation of various types of breccia. Our attention is drawn to the unusually high content of  $\text{Ni}$  for certain crystalline magmatic rocks, for example, in the specimens of KREEP basalts, etc. We should also note that the maximum of the magmatic process occurred in time intervals of  $4.5$  to  $3 \times 10^9$  years, when the young Moon was producing heat as a result of the decay of  $\text{K}^{40}$ , primarily  $\text{U}^{235}$ , and also  $\text{U}^{238}$  and  $\text{Th}^{232}$  by approximately one half an order of magnitude higher than today. The absolute ages of lunar rocks indicate that volcanism practically stopped on the Moon by  $3$  to  $2.5 \times 10^9$  years. We will return once more to the reason for this sharp reduction in magmatism and thickness of the basaltic crust of the Moon, when we study the behavior of the radioactive elements in lunar rocks.

## Anorthosites

Anorthosites were discovered on the Moon primarily in the lunar highlands, and accord-



Table 2.—*Anorthositic Rocks From Various Sites on the Moon: Chemical Composition in Weight Percent (data from various authors)*

	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Cr <sub>2</sub> O <sub>3</sub>
Apollo 11 <sup>(1)</sup>	46.0	0.3	27.3	6.2	0.1	7.9	14.1	0.3	tr.	—	0.2
Apollo 14 <sup>(2) (3)</sup>	43.50	0.19	23.29	4.56	0.06	15.82	12.27	0.28	0.06	0.03	—
Apollo 15 <sup>(3)</sup>	44.08	0.02	36.49	0.29	0.60	0.09	19.68	0.34	0.01	0.01	—
Apollo 16 <sup>(4)</sup>	43.97	0.02	35.83	0.36	0.00	0.25	18.95	0.34	0.01	—	tr.
Apollo 17 <sup>(5)</sup>	42.7	0.0	34.9	0.2	—	0.1	19.1	0.01	0.1	0.2	—
Luna 16 <sup>(6)</sup>	42.9	0.02	36.0	1.99	0.01	2.52	18.1	0.36	0.02	0.03	0.01
Luna 20 <sup>(7) (8)</sup>	44.2	0.32	19.1	6.91	0.12	13.37	13.3	0.48	0.47	0.17	0.18
Terrestrial Anorthosite	54.54	0.52	25.72	1.72	0.02	0.85	9.62	4.66	1.06	0.11	—

NOTES: (1) Wood et al. (refs. 40–42)  
 (2) Chao et al. (ref. 43)  
 (3) Preliminary Description (ref. 17)  
 (4) Juan et al. (ref. 44)  
 (5) Stoeser et al. (ref. 45)  
 (6) Keil et al. (ref. 46)  
 (7) Vinogradov (refs. 3 and 18–28)  
 (8) Troctolite

ingly the old concepts concerning a primary terrestrial anorthosite crust were extended to the Moon (ref. 39).

Lunar anorthosites were found at a number of landing sites (see table 2). Anorthosites have not been found in meteorites. These are usually light-colored rocks of practically monomineralic composition. Lunar anorthosites contain Ca-rich anorthite, AN 96–98. They contain a great deal of Al<sub>2</sub>O<sub>3</sub>, up to 35 percent, and CaO up to 20 percent. Their content of FeO is quite low in comparison with the basalts. Alkalies are generally sparse and less than in terrestrial anorthosites, particularly K<sub>2</sub>O and Na<sub>2</sub>O. The content of all trace elements is also lower. However, exceptions are known—for example, the rocks from the Apollo 16 collection.

The anorthosites of the Moon have an anomalously high content of Eu. The content of all other REE is presented in the table (see table 2). The texture of lunar anorthosites is reminiscent of the texture of the massive stratoform anorthosites on Earth. They have cumulative structure and there is no orientation of crystals. Norites and anorthosites are found in joint associa-

tion. However, contact of anorthosites with other rocks on the Moon has not been described as a layered structure. Thus on the Moon, and probably particularly on its far side, we find a unique series of rocks; gabbro-basalts-norites-anorthosites. The age of the anorthosites is great, from 3.5 to 4.2 × 10<sup>9</sup> years (refs. 43, 47, and 48). Anorthosites are generated when tremendous masses of gabbro-basalts are melted under high heat flow conditions and anorthite crystals float upward from the magma. Yoder studied the phase diagram of diopside-anorthite-water and showed the possibility of accumulating floating anorthite to form anorthositic rocks (ref. 49).

Anorthositic rocks are somewhat varied in composition and are subdivided into anorthosites, gabbroic anorthosites, anorthositic gabbros, and troctolites. The magmatic origin of these rocks follows from the high formation temperatures of their pyroxenes and pigeonites. This is also confirmed by their association with rocks with lower melting points and slight enrichment with O<sup>18</sup> (ΔO<sup>18</sup> ≅ 6 parts per mil).

On Earth, anorthosites are found in an-

Table 3.—*Mean Content of Siderophile Trace Elements in Lunar Basalts (ppm)*<sup>(1)</sup>

	Ga	Ge	As	Sn	Sb	Cu	Co	Ni
<b>Mare Basalts</b>								
Apollo 11 A	3.92 (22) <sup>(2)</sup>	0.73 (8)	0.046 (5)	0.5 (2)	0.0056 (1)	10 (20)	45.3 (24)	11.46 (7)
Apollo 11 B	4.12 (15)	0.63 (2)	0.036 (2)	1.2 (1)	0.0072 (1)	—	13.25 (22)	11.5 (9)
Apollo 12	4.2 (37)	0.00 (14)	0.013 (12)	0.2 (5)	0.08 (8)	9.6 (37)	47.2 (63)	46 (31)
Apollo 15	3.86 (29)	0.012 (11)	—	0.19 (1)	0.00032 (7)	11 (16)	55 (33)	65 (25)
Apollo 17	—	0.00147 (2)	—	—	0.00011 (2)	3 (3)	25 (5)	1 (2)
Luna 16	4.4 (6)	1.8 (2)	1.6 (2)	2.3 (2)	0.35 (2)	19 (2)	19.5 (4)	113 (2)
<b>Highland Basalts</b>								
Apollo 14	3.8 (8)	0.47 (1)	0.86 (3)	—	1.7 (3)	17.3 (16)	30.5 (25)	161 (22)
Apollo 16	3.0 (11)	0.022 (1)	—	—	0.00021 (1)	6.7 (10)	29.6 (15)	343.4 (24)
<b>KREEP Basalts</b>								
Apollo 14	4.25 (2)	0.086 (1)	—	—	—	11 (1)	23.5 (2)	175 (3)
Apollo 16	4.17 (2)	—	—	—	—	10.8 (1)	48 (2)	890 (2)
<b>Terrestrial Basalts</b>								
Tholeiitic Basalts	18.5 (50)	1.46 (13)	—	1 (10)	—	97 (94)	42 (87)	114 (116)
<b>Meteorites</b>								
Ca-Achondrites	1.85 (21)	0.25 (5)	0.05 (1)	—	0.01 (1)	8.0 (16)	12.36 (39)	1 ---
Chondrites	5.0	10	2	5	0.1	120	700	145

NOTES: (1) Data used for specimens of various missions were taken from the following references:

Apollo 11: 8 and 50–62  
 Apollo 12: 9, 12, 32, 50, 59, and 63–71  
 Apollo 14: 10, 30, 37, 58, 68, and 72–79  
 Apollo 15: 13, 34, 47, 58, and 80–86  
 Apollo 16: 15 and 87–93  
 Apollo 17: 34, 35, and 94–96  
 Luna 16: 20, 21, 28, and 97

(2) Each figure in parentheses indicates number of determinations.

cient shields (around platforms and in the base of platforms) of Precambrian age, for example in the Ukraine, in Canada, etc. They are also found in gabbros, which are often layered, and in which the light portion frequently corresponds in composition to anorthosite. The thickness of rock associated with anorthosites on the Earth is several kilometers and only ~ 10 percent actually consists of anorthosites. All of this forces me to think

that the thickness of anorthosite layers on the Moon is not great.

## Trace Elements

The content of trace elements in lunar rocks, in comparison with the content of these elements in meteorites and tholeiite basalts of the Earth, represents a significant

Table 4.—*Partial Pressure of Oxygen ( $PO_2$ ) in the Reversible Equilibrium of Metals With Their Oxides (at the melting temperature of Fe, 1803 K)*

Elements	$PO_2$ (atmospheres)	Elements	$PO_2$ (atmospheres)
La-La <sub>2</sub> O <sub>3</sub>	$3.2 \times 10^{60}$	Mn-MnO	$4 \times 10^{-15}$
Ta-Ta <sub>2</sub> O <sub>5</sub>	$2 \times 10^{-41}$	Y-Y <sub>2</sub> O <sub>3</sub>	$4 \times 10^{-14}$
Nb-NbO <sub>2</sub>	$6.3 \times 10^{-34}$	Cr-Cr <sub>2</sub> O <sub>3</sub>	$1 \times 10^{-13}$
Th-ThO <sub>2</sub>	$2 \times 10^{-28}$	Zn-ZnO	$3.2 \times 10^{-12}$
Be-BeO	$1 \times 10^{-25}$	W-WO <sub>2</sub>	$1 \times 10^{-11}$
U-UO <sub>2</sub>	$1.2 \times 10^{-24}$	Mo-MoO <sub>2</sub>	$7.4 \times 10^{-9}$
Ba-BaO	$2 \times 10^{-23}$	Fe-FeO	$4 \times 10^{-9}$
Sc-Sc <sub>2</sub> O <sub>3</sub>	$5 \times 10^{-23}$	Ga-Ga <sub>2</sub> O <sub>3</sub>	$n \times 10^{-9}$
Al-Al <sub>2</sub> O <sub>3</sub>	$5 \times 10^{-23}$	As-As <sub>2</sub> O <sub>3</sub>	$3.2 \times 10^{-8}$ (542K)
Zr-ZrO <sub>2</sub>	$1 \times 10^{-22}$	In-In <sub>2</sub> O <sub>3</sub>	$3.2 \times 10^{-8}$
Ti-TiO <sub>2</sub>	$7.9 \times 10^{-10}$	Sn-SnO <sub>2</sub>	$7 \times 10^{-7}$
Si-SiO <sub>2</sub>	$6.3 \times 10^{-17}$	Ge-GeO <sub>2</sub>	$2 \times 10^{-7}$
		Ni-NiO	$2 \times 10^{-5}$
		Sb-Sb <sub>2</sub> O <sub>3</sub>	$1.3 \times 10^{-5}$
		Co-CoO	$6.3 \times 10^{-4}$
		Cu-Cu <sub>2</sub> O	$2 \times 10^{-4}$
		(Pt,Pd,Ir,Os, Ru,Rh,Au)	

fund of information about the formation conditions of lunar material. In the process of condensation and agglomeration of the matter of the protoplanetary cloud, definite phases occur, which we encounter, for example, in meteoritic material, namely metallic FeNi, which contains a characteristic set of siderophilic trace elements (Ga, Ge, As, Sb, Sn, Cu, Co, Ni, and Au) and platinoids, a silicate phase, and a sulfide phase, as well as gases and volatile substances with high vapor pressure (In, Tl, Hb, Pb, Bi, etc.). During differentiation of the silicate material of planets (mantles) refractory elements such as Ba, Zr, Nb, Hf, Y, REE, Sc, Ta, Ti, and Be are differentiated into the gas phase and the easily melted phase. Obviously, the behavior of these groups of chemical elements must also be studied in the processes of formation of a celestial body, i.e., in the processes of accretion and then in the crystallization differentiation of planetary and lunar material.

### Siderophile Elements

Iron is found in lunar rocks, chondrites, and other meteorites in the form of metallic

Fe (primarily in meteorites) and in the form of FeO. In lunar rocks and meteorites (chondrites) Fe is not in higher oxidation states, for example Fe<sub>3</sub>O<sub>4</sub> and Fe<sub>2</sub>O<sub>3</sub>, since oxidation of Fe to this valence would require an O<sub>2</sub> partial pressure and order of magnitude higher than that required for the production of FeO. This characterizes the protoplanetary cloud. Metallic iron forms continuous solid solutions with almost 70 chemical elements. However, metallic Fe in meteorites is always accompanied by a more limited composition of these elements (ref. 22).

We can see from table 3 that many siderophilic elements are converted to oxides by a quite negligible shift to the left in the equilibrium  $H_2O/H_2 = 1$  in the protoplanetary cloud. These include all elements located in table 4 above the Fe-FeO system. Because of this characteristic, these oxides are not dissolved in vapors, liquids, or metallic iron and are not encountered in them. Those chemical elements which dissolve in Fe are located below the Fe-FeO system in the table, i.e., Ga, Ge, As, Sn, Sb, Co, Ni, the platinoids, Au, and certain others, which actually are systematically strongly concen-

trated in all metallic phases of meteorites, and obviously so in the FeNi cores of the planets. This is why such widespread siderophilic elements as Ti, Mn, Cr, V, and many others are not concentrated in the metallic iron of the meteorites. Therefore, for example, it is impossible to imagine that the initial iron in celestial bodies was in the form of FeO and that it was substantially reduced by CO or other means within the planets to Fe, since FeO does not concentrate the many siderophile elements mentioned above, including Ni particularly; and therefore reduction of FeO would produce only pure metallic Fe without the siderophile trace elements. However, such pure metallic Fe is completely unknown in meteorites. Naturally, the metallic FeNi alloy in celestial bodies might to some extent be subjected to oxidation, as a result of various processes, with the result that the siderophile trace elements concentrated in the metallic Fe would enrich the other phases of the cosmic material. The silicate phases of meteorites are many times poorer in these siderophile elements than the metallic FeNi phase.

Before us is a table giving the contents of these siderophilic elements in the basaltic rocks of the Moon, the Earth, and various meteorites. There is no doubt about the lower content of all of these elements in the crystalline basalts of the Moon in comparison with the tholeiitic basalts of the Earth, and, of course, the chondrites. For example, the content of Ni is higher in terrestrial olivines, etc. The stability of the parallel increase of MnO and FeO is surprising. As concerns the nonmare basalts and KREEP basalts, as we have already mentioned, the presence of large quantities of Ni and other siderophile elements and Pt is obviously a result of contamination with nonlunar meteorite matter. The content of siderophile trace elements in Ca-rich feldspar achondrites is still lower. They are closer in this respect to the lunar basaltic rocks.

The low content of siderophile elements that accompany metallic iron indicates a deficit of metallic iron in the lunar material in comparison with analogous terrestrial rocks.

On the other hand, lunar rocks contain approximately 1.5 to 2 times more FeO than do terrestrial tholeiitic basalts. This also characterizes the evolution of conditions in the protoplanetary cloud where the center of accretion of lunar material arose. We will return to this question later.

## The Platinoids and Gold

The platinoids and gold are also typical siderophile elements; they dissolve in Fe and are concentrated in it. One needs only to examine table 5 to become convinced that their content in crystalline lunar rocks is extremely low. We see that the content of the platinoids and Au in the metallic iron of the meteorites is thousands of times higher than in the silicate crystalline rocks of the Moon and Earth. The platinoids and Au are distributed approximately 70 percent in the iron phase, 20 percent in tellurite, and 10 percent in the silicate phase in the meteorites. The even platinoids predominate. Suffice it to say that the content of FeS in the lunar rocks is negligible. The higher content of platinoids and Au in the regolith, in comparison with crystalline rocks in the lunar regolith, is explained by the addition of meteoritic material. Calculations show that approximately 2.5 percent of the material of stony meteorites is present in the lunar regolith (which is equivalent to 0.25 percent meteoritic FeNi) (ref. 28). The content of platinoids and Au in the regolith and breccias of mare origin is higher than that of the regolith from the highland areas. The content of platinoids and Au in terrestrial tholeiites and Ca-rich feldspar achondrites is on the same order of magnitude as in lunar basalts. The lower content of platinoids and Au in the lunar basalts also indicates a deficit of metallic iron on the Moon, as do the other siderophile elements.

## Refractory Oxides

Table 6 presents those refractory microelements for which reliable concentration data are available for lunar basalts. All of

Table 5.—*Mean Content of Platinoids and Gold in Lunar Basalts (ppb)*<sup>(1)</sup>

	Ir	Pd	Os	Rh	Ru	Pt	Au
<b>Mare Basalts</b>							
Apollo 11 A	0.68 (13) <sup>∞</sup>	56 (5)	0.42 (4)	—	—	—	0.72 (18)
Apollo 11 B	0.11 (5)	2.2 (5)	0.26 (2)	—	—	—	0.25 (13)
Apollo 12	0.44 (20)	<1 (5)	0.65 (19)	0.21 (4)	70 (10)	—	0.598 (20)
Apollo 15	0.04 (9)	—	—	—	—	—	0.094 (9)
Luna 16	—	27 (1)	—	—	—	—	—
Apollo 17	0.002 (2)	—	—	—	—	—	0.017 (2)
<b>Highland Basalts</b>							
Apollo 14	1.99 (4)	0.1 (1)	—	—	—	—	1.48 (3)
Apollo 16	0.081 (4)	—	—	—	—	—	0.127 (4)
<b>Terrestrial Basalts</b>							
Tholeiitic Basalts	0.4 (13)	—	—	—	—	—	7.7 (16)
<b>Meteorites</b>							
Ca-Achondrites	1.2 (21)	1.0	0.5	0.2	1.0	2.0	10.0 (21)
Chondrites	630 (25)	950 (19)	700 (21)	200 —	880 (17)	1350 (18)	180 (24)
Troilite	1320 (15)	3190 (15)	1540 (15)	—	3410 (15)	3740 (18)	1196 (16)
Metallic phase of chondrites	3660 (17)	4610 (17)	3300 (16)	—	4675 (16)	8770 (17)	1120 (16)

NOTES: (1) Data used for various missions were taken from the following references:

Apollo 11: 8, 50, 52-54, 58-60, 62, 63, 98, and 99

Apollo 12: 9, 50, 56, 58, 63-65, 68, 99, and 100

Apollo 14: 10, 58, 68, and 72

Apollo 15: 58, 80, 83, 90, 91, 96

Apollo 16: 34, 35, and 94-96

Luna 16: 20, 21, and 28

(2) Each figure in parentheses indicate number of determinations.

these metals and their oxides melt at temperatures of over 2000° C and boil at temperatures up to 5000° C. Within this range of temperatures, they condense from vapor in the protoplanetary cloud. They are all easily oxidized at very low O<sub>2</sub> pressures (in the table they fall above the Fe-FeO system). The table gives us an idea of the content of these oxides in the lunar rocks, terrestrial tholeiites, and meteorites. The refractory elements (oxides) are found pre-

dominantly in the basaltic rocks of the Moon. We have already mentioned the accumulation of TiO<sub>2</sub> in the lunar basalts. In terrestrial tholeiites, the content of refractory elements is significantly lower. In the achondrites, it is practically identical to that of the terrestrial basalts. However, the degree of enrichment with rare refractory elements varies. The concentration of Sc and Y, for example, is low. The concentrations of Ba, Ti, REE, Nb, Be, and other elements are

Table 6.—*Mean Content of Refractory Trace Elements in Lunar Rocks (ppm)*<sup>(1)</sup>

	Ba	Zr	Nb	Y	Sc	Ta	Hf	Ti (percent)	Be
<b>Mare Basalts</b>									
Apollo 11 A	285.5 (37) <sup>(2)</sup>	617.8 (18)	29.9 (9)	155.8 (13)	74.83 (24)	2.0 (17)	17.4 (20)	6.0 (13)	2.7 (8)
Apollo 11 B	158.8 (34)	412.4 (20)	26.86 (7)	135.4 (14)	103.6 (26)	2.0 (18)	16.6 (23)	5.6 (12)	4.1 (4)
Apollo 12	102.7 (59)	146.5 (34)	9.7 (29)	53.0 (25)	51 (60)	0.42 (26)	3.62 (43)	2.0 (32)	1.32 (16)
Apollo 15	65.59 (32)	91.3 (34)	8.6 (29)	27.0 (27)	40.4 (28)	0.45 (14)	2.50 (20)	1.4 (14)	1.0 (19)
Apollo 17	57 (1)	—	—	—	—	—	—	7.8 (1)	—
Luna 16	220 (11)	300 (3)	15 (1)	89.0 (2)	39 (7)	—	3.00 (5)	3.0 (3)	1.2 (1)
<b>Highland Basalts</b>									
Apollo 14	534 (11)	807.8 (17)	43.6 (16)	182.3 (16)	34 (21)	3.1 (3)	16.7 (6)	1.2 (4)	3.3 (6)
Apollo 16	223 (17)	500.5 (19)	27.4 (14)	76.4 (15)	9.8 (14)	1.3 (5)	29.4 (14)	0.51 (1)	3.7 (3)
Apollo 17 (1)	150.0 (1)	250 (1)	11 (1)	31 (1)	11 (1)	—	3 (1)	0.3 (1)	—
<b>KREEP Basalts</b>									
Apollo 14	808 (3)	911.5 (2)	43 (1)	170 (2)	—	—	21 (1)	—	—
Apollo 15	686 (1)	—	—	—	—	—	—	—	—
Apollo 16	466 (1)	840 (1)	33 (1)	120 (1)	14.2 (2)	—	16.2 (2)	0.7 (1)	5.2 (512)
<b>Terrestrial Basalts</b>									
Tholeiitic Basalts	23.3 (88)	105 (51)	<30 (10)	31.7 (64)	43 (23)	—	20	1.25 (276)	—
<b>Meteorites</b>									
Ca-Achondrites	35	46	<30 (10)	22 (4)	26 (40)	0.1	0.8	0.46	0.1
Chondrites	6	7	0.3	2	8	0.02	0.2	0.065	0.04

NOTES: (1) See following references regarding specimens of various missions:

Apollo 11: 8, 31, 51, 54-61, and 101-107  
 Apollo 12: 9, 12, 32, 36, 56, 58, 59, 64-67, 69, 71, 106, and 108  
 Apollo 14: 10, 30, 33, 37, 58, 73-75, 77-79, 109, and 110  
 Apollo 15: 13, 34, 38, 47, 58, 82, 86, 91, and 111  
 Apollo 16: 15, 87-89, 91-93, and 111-114  
 Apollo 17: 34, 35, 94, and 96  
 Luna 16: 20, 21, 28, 97, and 115-118

(2) Each figure in parentheses indicates number of determinations.

more than a hundred times greater than their concentrations in chondrites. The question arises as to whether rapid extrusion and cooling of the magma on the Moon could cause this enrichment. According to all available data, the nonmare basalts of the Moon are quite rich in these refractory substances. However, it is interesting to note that the

content of refractory oxides in the basalt returned by Apollo 15 is practically identical to that of terrestrial tholeiitic basalts and Ca achondrites. Lunar basalts contain TiO<sub>2</sub> at levels of up to 13 percent, primarily in the form of the ilmenite. Zr and Hf follow the Ti minerals, such as FeTiO<sub>3</sub>, to a significant extent. However, they contain 6 to 8 times

more Zr than terrestrial ilmenite (0.058 percent Zr). Ba is concentrated in the feldspars of lunar basalts. The ratios of Zr/Hf and Nb/Ta, and of similar pairs of isomorphous elements are similar to their ratios in terrestrial basalts. Nb and Ta are enriched in Fe minerals and are also distributed in MgFe minerals. Nb and Zr do not form their own minerals in lunar rocks. The entire range of rare earths must also be considered refractory. Table 7 shows the significant excess of rare earths in lunar rocks in comparison with terrestrial rocks and Ca achondrites. The last two contain practically identical low contents of the rare earths.

In comparison with the chondrites, the basalts of the Moon have a relatively higher content of the heavier rare earths. The anomalous behavior of Eu among the other rare earths is now well known. Its content is decreased in pyroxenes and increased in plagioclases (see anorthosites). This indicates once more that the magma was liquid. Here also the increase in the content of rare earths reaches 100 fold or more—for example, for La, Ce, Nd, and others. The rare earths, like the other refractory oxides, are more abundant in nonmare basalts. One should note that the refractory elements and their oxides are not concentrated in the regolith. Also, on the average, a single-event process (melting of tholeiitic basalts of the Earth, etc.) causes up to twentyfold enrichments of some elements. Consequently, enrichment by 100 times in lunar rocks requires a content of refractory elements in the Moon 3 to 5 times higher than in chondrites.

## Radioactive Elements

Because of the many absolute age determinations of lunar rocks by the U-Pb and U-He method, a number of determinations of U, Th, and K have been made (see table 8). The mean data indicate a significant excess in the content of U and Th in lunar basalts of various types, in comparison with terrestrial tholeiitic basalts and Ca achondrites. The content of U and Th is particularly

high in the nonmare basalts (norites) and KREEP basalts. Therefore, the K/U ratio for nonmare basalts is  $\sim 1500$  and for the mare territories  $\sim 2000$ . U and Th are unevenly distributed in lunar rocks. We consider it probable that the minimum content of U in mare basalts is 0.20 ppm, i.e., some 20 times higher than in chondrites. The arithmetic mean content in all basalts of the Moon is higher, up to 0.6 ppm. Many data indicate 0.1 to 0.2 ppm U in terrestrial tholeiitic basalts. On the Earth, the effusion of primitive tholeiitic basalts is reminiscent of the single-event melting process that produced mare basalts on the Moon. The content of U and Th in the lunar rocks parallels the increase of other lithophile elements, for example, in the nonmare basalts. However, what process increased the U content to 3.5 ppm and higher, as has occurred in certain provinces on the Moon, remains unclear. In the continental areas of the Earth the first stage of U concentration (production of basalts) is followed by a second stage of enrichment, i.e., granitization. Granitization increases the U content to 3 ppm and higher in granites (produced by conversion at depth of a portion of the basaltic substrate of the basalts during the complex process of granitization), i.e., it is increased by another 10 times in the crust of the Earth, a total of  $\sim 100$  times. Processes occur in the Earth's crust with fluxing agents ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , etc.) not present on the Moon, where the processes are more primitive. Th increases in the lunar basalts in parallel with U. The redistribution of U, Th, and K into the various rocks of the Moon, and particularly the accumulation of U and Th at the periphery in the lunar crust, as we will see below, has significantly disrupted the primitive thermal balance of the Moon and allows us to draw certain important conclusions. These will be discussed later.

## The Loss of Volatiles from the Moon (Deficient Elements)

We see the greatest deficit of elements, generally volatile at elevated temperatures,

Table 7.—Mean Content of Rare Earth Elements in Lunar Rocks (ppm)<sup>(1)</sup>

	La	Ce	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Pr
<b>Mare Basalts</b>														
Apollo 11 A	22.7 (31) <sup>(2)</sup>	70.64 (29)	62.68 (16)	21.4 (27)	2.48 (28)	26.9 (14)	4.9 (19)	37.5 (17)	5.9 (16)	20.9 (14)	2.3 (4)	18.0 (28)	2.8 (26)	14.52 (5)
Apollo 11 B	12.4 (22)	43.4 (21)	47.2 (16)	16.2 (21)	2.3 (21)	21.8 (14)	3.2 (14)	30.2 (15)	6.0 (10)	13.8 (14)	1.8 (2)	15.3 (20)	2.2 (18)	11.68 (4)
Apollo 12	7.7 (48)	22.4 (48)	15.6 (34)	4.8 (54)	1.2 (54)	7.1 (27)	1.55 (38)	9.0 (42)	1.75 (29)	5.9 (30)	0.93 (12)	5.2 (54)	0.77 (43)	3.46 (20)
Apollo 15	5.54 (28)	16.9 (14)	11.65 (13)	3.78 (29)	0.96 (29)	5.24 (1)	0.74 (15)	5.48 (13)	3.45 (2)	3.2 (13)	0.4 (1)	2.4 (29)	0.36 (24)	2.0 (1)
Apollo 17	5.1 (1)	—	—	8.7 (1)	1.6 (1)	—	2.2 (1)	13 (1)	—	—	—	—	—	—
Luna 16	15.6 (5)	43.4 (10)	32.6 (5)	9.18 (10)	2.8 (10)	12.3 (7)	2.0 (4)	12.78 (10)	3.0 (6)	3.9 (7)	0.9 (1)	6.43 (10)	1.04 (9)	16.00 (1)
<b>Highland Basalts</b>														
Apollo 14	46.7 (19)	51.5 (7)	36 (4)	8.9 (7)	1.3 (5)	12.7 (5)	1.7 (3)	14.7 (5)	1.9 (3)	4.7 (4)	—	12.2 (7)	0.81 (8)	4.3 (3)
Apollo 16	52.6 (9)	67.4 (11)	36.9 (10)	11.14 (11)	1.6 (11)	4.43 (7)	2.54 (4)	26.7 (11)	3.28 (4)	6.84 (6)	—	7.2 (11)	1.2 (10)	—
Apollo 17	11.0 (1)	31 (1)	15 (1)	4.5 (1)	1.5 (1)	5.4 (1)	0.85 (1)	5.4 (1)	1.3 (1)	3.6 (1)	0.5 (1)	3.4 (1)	0.4 (1)	4.0 (1)
<b>KREEP Basalts</b>														
Apollo 14	60.8 (9)	173.6 (6)	90 (4)	26.7 (5)	2.2 (6)	34.5 (2)	5.5 (3)	32.2 (5)	7.6 (3)	22.4 (4)	3.0 (1)	20.0 (6)	2.9 (5)	23 (1)
Apollo 15	75.2 (4)	191.2 (6)	116 (6)	32.4 (6)	2.65 (6)	39.2 (4)	—	42.3 (5)	—	25.3 (6)	—	22.2 (6)	3.4 (3)	—
Apollo 16	48.0 (6)	139.2 (6)	74.7 (6)	23.0 (6)	1.87 (6)	25.6 (6)	4.40 (2)	29.65 (6)	5.2 (2)	17.84 (5)	1.4 (1)	15.32 (5)	2.31 (3)	—
<b>Terrestrial Basalts</b>														
Tholeiitic Basalts (64)	3.36	10.3	9.87	3.49	1.26	5.05	0.86	5.22	1.24	3.48	0.53	3.20	0.49	1.87
<b>Meteorites</b>														
Ca-Achondrites (4)	3.7	9.7	7.0	2.3	0.72	3.1	0.57	3.8	0.80	2.3	0.38	2.0	0.35	1.4
Chondrites (20)	0.3	0.84	0.58	0.21	0.074	0.32	0.05	0.31	0.073	0.21	0.053	0.17	0.031	0.12

NOTES: (1) See following references for data on specimens of various missions.

Apollo 11: 8, 54–57, 59, 61, 102, and 105

Apollo 12: 36, 56, 64, 65, and 70

Apollo 15: 34, 38, 77, 82, 86, and 91

Apollo 16: 38, 89, 91, 92, and 114

Apollo 17: 34, 35, 89, 94, and 96

Luna 16: 20, 21, 28, 116, 118, and 119

(2) Each figure in parentheses indicates numbers of determinations.



Table 8.—*Mean Content of U, Th, K in Lunar Rocks (ppm.)*<sup>(1)</sup>

	U	Th	K	K/U
<b>Mare Basalts</b>				
Apollo 11 A	0.55 (35) <sup>∞</sup>	2.7 (30)	2140 (11)	3890
Apollo 11 B	0.33 (22)	1.63 (24)	1330 (9)	4030
Apollo 12	0.641 (70)	1.39 (54)	501 (38)	783
Apollo 15	0.153 (14)	0.5 (2)	375 (7)	2451
Apollo 17	0.14 (11)	0.4 (9)	507 (8)	3620
<b>Highland Basalts</b>				
Apollo 14	0.58 (4)	2.3 (3)	2444 (3)	4214
Apollo 16	1.18 (15)	5.09 (11)	238 (1)	200
Apollo 17	0.5 (1)	1.8 (1)	900 (1)	1800
<b>KREEP Basalts</b>				
Apollo 14	3.2 (9)	10.6 (10)	3924 (5)	1226
Apollo 15	3.39 (6)	—	—	—
Apollo 16	2.09 (6)	9.2 (1)	3100 (1)	1550
<b>Terrestrial Basalts</b>				
Tholeiitic Basalts	0.20	0.62	2490	12 450
Ca-Achondrites	0.1	0.41	400	4000
Chondrites	0.012	0.04	850	70 833

NOTES: (1) Data regarding various missions were taken from the following references:  
 Apollo 11: 8, 55, 57-59, 60, 61, 101, 106, and 120-123  
 Apollo 12: 9, 32, 56, 58, 59, 64, 65, 67, 69-71, 100, 124, and 125  
 Apollo 14: 10, 33, 37, 58, 73, 75, 77, and 126  
 Apollo 15: 34, 38, 58, 83, and 86  
 Apollo 16: 15, 38, 87, 90-92, and 127  
 Apollo 17: 34, 35, and 94-96  
 (2) Each figure in parentheses indicates numbers of determinations.

compounds, in comparison with terrestrial basalts and meteorites:

1. H<sub>2</sub>O, CO<sub>2</sub>, H<sub>2</sub>S, and many other gases
2. Alkalies: K, Na, Rb, and others
3. Halogens: F, Cl, and others
4. Metals with high vapor pressure: In, Ti, Pb, Bi, Hg, and others

## GROUP 1

Kinetic calculations show that practically all gases up to mass 40 are lost from the Moon into space. However, the nuclei of neutral gases, N<sub>2</sub> and others, are implanted in the rocks of the Moon by the solar wind.

H<sub>2</sub>O, CO<sub>2</sub>, and other gases: A multitude of available data make it easy to see that the Moon contains a markedly lower quantity of H<sub>2</sub>O, CO<sub>2</sub>, S, and other ordinary gases in comparison with their content in the terrestrial rocks. The vesicles of lunar rocks have been found to contain CO<sub>2</sub>, H<sub>2</sub>, and N<sub>2</sub> in negligible quantities. Traces of H<sub>2</sub>O have not been found with sufficient accuracy. This does not mean that H<sub>2</sub>O and the other gases are totally absent in the lunar rocks. In the basalts of the Moon, the content of H<sub>2</sub>O is generally considered to be on the order of 0.01 to 0.1 percent. This is markedly less than the content of H<sub>2</sub>O in the magmatic rocks of Earth. However, the entire course of chemical reactions in the crust of the Moon directly indicates the deficit of H<sub>2</sub>O. The regolith does not accumulate H<sub>2</sub>O in comparison with the crystalline rocks. This means that the shortage of H<sub>2</sub>O, C, N, and other elements is not a result of their loss during the differentiation of lunar material, but more probably is related to the accretion of lunar material, where the loss of H<sub>2</sub>O occurred during the condensation and agglomeration of lunar material. The basic reasons might be the high temperature of accretion and an H<sub>2</sub>O/H<sub>2</sub> ratio less than 1.

## GROUP 2

The second group consists of the alkalies Na, K, Rb, and others. As we can see from

in the lunar basalts—a deficit greater than that in the tholeiitic basalts of the Earth or even the ordinary chondrites. The deficit in lunar rocks has been noted for the following groups of chemical elements or their

Table 9.—*Mean Content of Elements With High Vapor Pressure in Lunar Rocks (ppb)<sup>(1)</sup>*

	In	Tl	Hg	Pb (ppm)	Bi
<b>Mare Basalts</b>					
Apollo 11 A	13.0 (6) <sup>en</sup>	0.80 (3)	9.01 (2)	1.0 (16)	0.38 (3)
Apollo 11 B	86 (4)	0.45 (2)	0.60 (1)	1.14 (17)	0.16 (1)
Apollo 12	2.1 (31)	0.36 (16)	6.0 (8)	0.5 (1)	0.55 (5)
Apollo 15	1.06 (11)	0.46 (7)	—	0.5 (1)	0.24 (7)
Apollo 17	—	0.23 (2)	—	—	0.07 (2)
Luna 16	12 (1)	—	—	0.33 (1)	—
<b>Highland Basalts</b>					
Apollo 14	10.75 (2)	1.4 (1)	—	10.2 (4)	0.28 (1)
Apollo 16	40 (2)	0.36 (1)	—	3 (1)	0.08 (1)
Apollo 17	—	—	—	1.7 (1)	—
<b>KREEP Basalts</b>					
Apollo 12	1.25 (1)	6.0 (1)	—	—	4.6 (1)
Apollo 14	75 (2)	10 (1)	—	—	0.39
<b>Terrestrial Basalts</b>					
Tholeiitic Basalts	77 (13)	—	—	2 (20)	—
<b>Meteorites</b>					
Ca-Achondrites	5.0 (25)	11.0 (20)	—	0.5 (?)	3.14 (19)
Chondrites	1.0	1.0	—	0.3	3.0

NOTES: (1) Data used were taken from the following references:

- Apollo 11: 8, 52, 54, 62, 106, 123, and 128
- Apollo 12: 9, 50, 63-65, 68-70, 100, and 125
- Apollo 14: 10, 33, 68, 72, 78, and 79
- Apollo 15: 34, 80, 83, and 84
- Apollo 16: 87, 90, and 92
- Apollo 17: 34, 35, and 96
- Luna 16: 20, 21, and 28

(2) Each figure in parentheses indicates numbers of determinations.

table 1, the content of alkalis, particularly K, is significantly lower in lunar basalts than in terrestrial tholeiitic basalts or even in ordinary chondrites. Only the Ca-feldspar achondrites have lower contents of alkalis than lunar basalts. On the other hand, the regolith overall does not accumulate alkalis

in all known cases, but rather shows the same slight variations as the crystalline lunar basalts. It is of course possible to assume a loss of alkalis during the thermal events that accompany the formation of fragments of regolith, glasses, etc., as well as breccia. These losses, however, could not be compar-

able with the quantities which might have been present in lunar rock by analogy with terrestrial rocks. It is well known from everyday experimental experience that when basalts and other rocks are heated they lose primarily alkalis, namely K and others. All of this together indicates that it is most probable that the alkali losses result from conditions of the accretionary process, not from differentiation of the lunar material. At the same time, we should note the local fact of increased K content in the KREEP basalts during formation of lunar crustal rocks.

### GROUP 3

The third group is the halogens F, Cl, and others. Their contents vary in the crystalline rocks of the Moon. A number of data indicate that their concentrations are sometimes significant. For example, F and Cl parallel the contents of other volatile elements, such as Ge, in the mare regoliths and particularly in the highland regoliths (even those consisting primarily of grains of anorthositic rock, e.g., Apollo 16). It is of interest that the content of all halogens, as a rule, increases several fold in the regolith (ref. 127); therefore, their loss occurs upon breakup of crystalline basalts and their hydrogen compounds in the volcanic exhalations of ancient lunar volcanism.

### GROUP 4

Group 4 consists of metals such as In, Tl, Hg, Pb, Bi and others (table 9) that have high vapor pressures (see table 10). This group is interesting in that Tl, Hg, Pb, and Bi do not produce solid solutions with metallic Fe. The element In alloys only to a limited extent with Fe. On the other hand, group 4 metals require higher O<sub>2</sub> partial pressures for oxidation than does metallic Fe. Therefore, under reducing conditions in the accretionary process, and also in the chemical differentiation of lunar material and formation of a lunar crust, these elements are scattered among the various phases and are generally easily mobile at elevated temperatures. In any case, it has been noted that the regolith, particularly from the highland areas, contains Tl, Zn, Hg, Pb, and other similar elements in significantly higher quantities than do the crystalline rocks from which it was formed. This means that they are dispersed in a fashion similar to the dispersion of Hg and I on Earth. This does not exclude the possibility of loss of these elements in the accretionary stage as well, but it seems to me today difficult to determine the share of these losses in each individual process.

Thus, it seems to me that some of the volatile elements or their compounds were primarily lost in the process of accretion, for

Table 10.—*Melting Points, Boiling Points, and Vapor Pressures of the Metals In, Tl, Pb, Hg, and Bi (Fe for comparison) at 25° C and 1500° C*

Metals	Melting Point		Boiling Point		Vapor Pressure (atm)	
	°C	K	°C	K	T = 25° C (298 K)	T = 1500° C (1773 K)
In	156	429	2000	2273	$3.3 \times 10^{-37}$	$3.5 \times 10^{-2}$
Tl	303	576	1457	1730	$8.2 \times 10^{-28}$	1.3
Pb	327	600	1725	1998	$2.7 \times 10^{-29}$	$2.2 \times 10^{-1}$
Hg	-38	235	357	630	$4.2 \times 10^{-6}$	$1.1 \times 10^{-3}$
Bi	271	544	1560	1833	$1.3 \times 10^{-27}$	$6.3 \times 10^{-1}$
(Fe)	1539	1812	2857	3130	$6.3 \times 10^{-66}$	$1.4 \times 10^{-5}$

example, H<sub>2</sub>O and alkalis; while other elements were probably lost in both processes, for example, the inert gases, halogens, and elements with high vapor pressures. However, this loss did not cause them to escape from the Moon in significant quantities.

## Brief Conclusions

Thus, in comparing the basaltic surface rocks of the Moon with terrestrial tholeiitic basalts and ordinary chondrites we have discovered a number of facts important in principle:

1. There is an excess of the so-called refractory chemical elements, including the group of truly refractory elements, the rare earths, U, and Th, in comparison with their content in primitive terrestrial basalts and chondrites.
2. The so-called siderophilic elements have lower contents in the lunar surface rocks than in terrestrial rocks.
3. The low alkali content (Na, K, Rb) in lunar rocks is established.
4. There is a low content of H<sub>2</sub>O and the ordinary gases CO<sub>2</sub>, halides, etc.
5. The low content of metals with high vapor pressure, (In, Tl, etc.) has been established. The primary question is, which processes have caused in one case an abundance and in another case a deficit of certain chemical elements in the lunar surface rocks?

As is well known, the mean composition of the Sun is similar if not identical to that of stony meteorites, i.e., chondrites, if we exclude the mass of ordinary gases. Because of this, many scientists have developed the so-called chondritic model of the Earth and the other planets: in other words, it is considered that all of the matter of the Sun, without separation, is included in the composition of the terrestrial planets. However, the differences already known in the contents of metals in the cores of the planets have caused critical discussion. The chondritic model also includes other unanswered questions, such as the sharp difference in the Sr<sup>86</sup>/Sr<sup>87</sup>

ratio between chondrites (0.7480), terrestrial rocks (tholeiite basalts), and lunar basalts (norites, anorthosites) (0.6990–0.7036). Furthermore, particular attention has been drawn to the huge lunar deficit of K, etc. As we have just seen, dissimilarities in the chemical composition of the rocks of the Moon and the Earth, and of chondrites are still greater. If we exclude from consideration the influence of the meteoritic and planetesimal impacts, which have caused tremendous destruction of the structures of lunar surface rocks during the formation of regolith and breccias, and the influence of impact metamorphism on lunar rocks, which however has relatively little changed their mean compositions, then two main processes may be responsible for changes in the composition of lunar rocks: (1) the very process of accretion of lunar material, and (2) the process of differentiation of the substance of the Moon into concentric layers (formation of the crust). It seems to us that study of the process of accretion makes sense only if we relate the origin of the Moon to that of the Earth, namely to the Earth-Moon system. Otherwise, everything becomes quite abstract. Therefore, we suggest that the center of condensation of lunar material arose near the Earth. Every celestial body in this system developed according to two different models—the Earth with its heavy inner metal core and the Moon without a heavy metal core.

Let us examine what conditions must be satisfied by the formation of the Moon from a protoplanetary cloud, having in mind our preliminary geochemical analysis. According to all data mentioned above, the protoplanetary cloud was rather homogeneous. The first condition for formation and growth of the Moon would have to be its formation near a large celestial body, under whose influence it was born, evolved, and had its growth interrupted. Most probably, such a body is either the Sun or the Earth. I would prefer not to discuss here the problems of celestial mechanics that arise, nor other hypotheses about the formation of the Moon, based purely on mechanics. Why did the

Moon, if it was near the Sun, avoid capture by the Sun, and subsequent death? Further, what caused it to move away from the tremendous mass of the Sun and approach the Earth? Its capture by the Earth would require deceleration of the Moon near the Earth and its transition into an elliptical orbit around the Earth, and so forth.

Secondly, for the preferential condensation of refractory chemical elements or their compounds (they are 3 to 5 times greater on the Moon than in chondrites) during the process of the Moon's accretion requires very high temperatures of the gases in the protoplanetary cloud—on the order of at least  $1500^{\circ}$  to  $2000^{\circ}$  C at the center of accretion of the Moon. This could occur easily only near the Sun, at a certain distance. However, the temperature of the area of accretion of the Moon must have evolved rather quickly, as did the Moon itself, reaching a rather low temperature by the end of accretion, generally markedly below  $1500^{\circ}$  C. The Sun, however, had only just begun to heat up, and could not have provided this sort of temperature variation. The temperature of the protoplanetary cloud near the Sun could not have fallen at the rate with which the Moon grew. Therefore, formation and growth of the Moon near the Earth and under its influence, is more acceptable (ref. 129).

In this case, the initial high temperature of the protoplanetary cloud at the center of accretion of the Moon can be easily explained by a somewhat earlier beginning of condensation of lunar material than the beginning of condensation of the Earth and the other planets, or by effects which cause local temperature increases in the protoplanetary cloud at the center of accretion of the Moon, which is near the Earth.

We suggest (ref. 22) that the core of the Earth and the other terrestrial planets arose at first independently and directly from the vapor phase of the protoplanetary cloud and condensed at a temperature of less than  $1500^{\circ}$  C. With global separation of matter in the protoplanetary cloud, the magnetic field would have a significant influence on the separation of ferromagnetic particles from

dielectrics. We must not forget here that the past magnetic field between the planets of the solar system had an intensity thousands of times greater. Further, Fe particles easily fuse together upon collision, because of the great thermal conductivity of the alloy, and form larger fragments. Recall that at the present time such chunks of FeNi, meteorites weighing up to hundreds of tons, are still falling on the Earth, whereas silicate matter—stony meteorites—reaches the Earth with masses of not over a few kilograms. It was these very chunks of alloy which formed the cores of the planets. We do not share the common opinion that all of the matter of the planets participated in the process of differentiation of the planets into concentric layers. Only the silicate portion (mantle) participated; the metal core already existed. Otherwise, as the process is usually imagined, the silicate material from the central parts of the planet would rise to the periphery while the FeNi alloy moved to the center of the planet, and temperatures for the Earth would reach, for example,  $\sim 3000^{\circ}$  C. There is no known method to carry away this heat. Furthermore, such differentiation temperatures of the Earth have never been observed, either directly or indirectly. As argued above, we suggest a model of the Moon without a heavy metal core. To some extent, to answer the question of why the Moon has no metal core is to answer a similar question: How have the Ca-poor (ordinary) achondrites been formed? They contain little or no metallic iron or FeS and have lost their structure. It seems to us that enrichment of refractory elements and impoverishment in siderophilic elements and the loss of volatile substances are all aspects of a single process of accretion in a system of two celestial bodies—a process that uninterruptedly occurred in time and space at different stages of development in the evolution of the Earth-Moon system.

Thus, two centers of accretion, one near the other, arose almost simultaneously—the Earth with its metal core and the Moon with no core. The temperature of condensation of the lunar material was higher. Probably at a temperature of  $2000^{\circ}$  C or higher, the oxides

of the refractory elements condensed preferentially. The ratio  $H_2O/H_2 = 1$  in the cloud was shifted to the left negligibly, but sufficiently to convert all of these and many other metals into oxides. Thus, solid dust was formed at significantly lower temperatures in comparison with the higher temperatures of the surrounding gas. The difference in temperature of the solid particles and gas reached several hundreds of degrees (ref. 130). At the same time, a similar process occurred at the center of accretion of the Earth, either in a shorter period of time or at a comparatively lower temperature. Thus, refractory elements and their oxides condensed during the accretion of the Moon, accompanied by the loss of gases,  $H_2O$ , volatile alkalis, and elements of high vapor pressure at the relatively high temperatures near the Earth. During this time, as the temperature of accretion of the Moon dropped, the metallic Fe in the lunar cloud condensed and was lost by magnetic separation. Because of the other properties of FeNi, it came under the influence of Earth's gravity. The growth of the Earth probably occurred more rapidly than the growth of the Moon, and as soon as the Earth accumulated significant mass it began to have a great influence on the accretion of the Moon. The second stage of accretion of the Moon occurred at relatively low temperatures and higher  $O_2$  partial pressures, and under the influence of the gravitational force of the Earth, which significantly limited the accretion of the Moon. Thus, the Moon was deprived of volatile materials from the beginning of its accretion, particularly since the accretion of the Moon soon stopped due to the formation of the nearby massive Earth.

During the first stage, the condensing Fe vapors dissolved the siderophile elements from the dust particles because the partial pressure of  $O_2$  was insufficient for their oxidation.

Thus, the accretion of the Moon occurred under the influence of the accretion of the Earth. During the first, high-temperature stage, this resulted in the accretion of refractory elements into the body of the Moon.

During the second stage, the dimensions of the Earth reached many hundreds of kilometers and the gravitational force of the Earth increased significantly, interfered with the accretion of the Moon, and caused the loss of Fe and many siderophile elements. Lower accretion temperatures caused a greatly decreased intensity of accumulation of volatile substances by the Moon.

During the third stage, growth occurred such that condensation occurred significantly below  $1500^\circ C$ . The Moon returned to conditions of the protoplanetary cloud that were in common with those for the Earth. Then, growth of the Moon decreased and stopped completely.

I do not doubt that a great deal of what occurred in the Earth-Moon system can be calculated when our considerations become more quantitative.

Let us now see how the differentiation of lunar material could be reflected in the composition of the surface rocks of the Moon. According to various estimates, the thickness of the lunar crust is  $\sim 25$  km (ref. 4). Deeper, there is a layer with low seismic velocity. We have examined the crust of the Moon in a somewhat one-sided manner, mainly from the history of the lunar mare, even though the continental crust predominates in the lunar exterior. We have characterized the continental crust as a profile of mare gabbro-basalts—norites—anorthosites. In connection with this, the behavior of individual elements in this profile has definite tendencies (for example, Fe, Ti, Cr, Al, Ca, etc.) as we saw above. We share the opinion of many researchers that the formation of anorthosites was a result of cumulation and flotation of feldspar crystals from norite-type rock.

If we held to the strictly chondritic model for the Moon, in other words, starting with a primary substance with the composition of the Sun, the enrichment of various elements in lunar rocks (sometimes by hundreds of times relative to chondrites) would force us to consider the thickness of the crust to be but a few kilometers. We now assume, for a number of elements, that the entire Moon is

rich in these elements relative to chondrites, and this conflict is removed. Magmatic activity on the Moon leads to lava flows and the formation of gabbro-basalts similar to the magmatic rocks of the Earth. The known variety of these rocks is related to the enrichment of the Moon with lithophile refractory elements and the loss of a portion of the siderophile elements. At the same time, the depth of formation of magma on the Moon, its rate of rise, the temperature of the magma, and, finally—very importantly—the variety of conditions of surface crystallization of the magma, are reflected primarily in the structure and texture of the rock, and expand this variety. We have turned our attention to the significance of the high content of FeO, TiO<sub>2</sub>, etc., in reducing the temperature of crystallization of the magma. The ratios of isomorphic pairs of chemical elements K/Rb, Ca/Sr, REE/Y, Zr/Hf, Nb/Ta, Th/U, and many others approach the ratio in the tholeiite basalts of the Earth, with small deviations. There are no deviations in the even-odd behavior of the rare earth elements or of the platinoids. The isotopic ratios for the chemical elements are not disturbed, except for similar changes in the rocks of the Earth (changes in D/H<sub>2</sub> ratio or O<sup>16</sup>/O<sup>18</sup> ratio, due to various reactions at low temperatures). The geological and geochemical processes on the Moon are significantly more primitive than the processes involved in formation of the crust of the Earth and processes within the Earth's crust itself. A full petrological model of the crust of the Moon can be produced by development of a quaternary diagram for silicates, plus TiO<sub>2</sub>.

The thermal history of the Moon was exceptionally significant.

According to our ideas set forth above, U and Th were carried from the internal areas to the peripheral rocks of the Moon (see table 8) during magmatic activity, i.e., up to 3 billion years, when the production of heat was  $\sim 1/2$  greater. This redistribution of U and Th leads to their concentration in narrow surface and near-surface layers of the Moon, and the heat which they generated was lost primarily into surrounding space.

Actually, the Moon, which conducts heat poorly, has a high thermal gradient for rock. Therefore, one expects a heat flux from the surface of the Moon of  $\sim 1/6$  the heat flux of the Earth, whereas the measured heat flux was found to be  $\sim 1/2$  that of the Earth (ref. 5). All of this forces us to believe that intensive magmatic activity on the Moon ended some  $3 \times 10^9$  years ago. Incidentally,  $\sim 500$  volcanoes are still active on Earth.

We have come to the conclusion that in order to understand the processes on the Moon, we cannot use the chondritic model even though it retains its significance for the study of the planets of our solar system. In this regard, I would like to note that the rejection of the chondritic model for the Moon will doubtless influence our conceptions of the processes of condensation of other celestial bodies in the protoplanetary solar cloud as well.

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