THE INNER STRUCTURE OF THE MOON

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Summary

Our knowledge of the composition and constitution of the Moon has increased enormously on the results of the APOLLO project over the past years. For the research of the Moon's interior the most reliable information can be obtained by the analysis of the lunar seismological observations. A brief summary is given of the essential results and data obtained from these seismological observations and from the most important thermal, magnetic, gravitational and radioactive measurements. The main conclusion which can be drawn from these concerning the inner structure of the Moon has been summarized by the authors. Finally a brief summary is given of the main results of the petrological and mineralogical investigations and of the material composition of the Moon.

In the course of our present investigations the knowledge of the inner structure of the Moon is necessary in order to recognize on the basis of eventual analogies to what extent the inner structure and the material structure of the Earth are general features in the Solar System. Though the investigation of planets similar to the Earth would be more interesting for us, up to the present time only very few information is available of the physical features of the planets. In contrast to that, mainly as the results of the APOLLO experiments, an essentially greater number of data are known of the Moon (though in themselves they are rather insufficient).

Researching the inner structure of the Moon—in addition to the gravitational, thermal, magnetic, radioactive and celestial mechanical observations—the most reliable information can be obtained, similarly to the research of the Earth, by the analysis of the propagation of the seismic waves and by the investigations of the rock samples collected on the Moon. Thus, our conceptions concerning the inner structure of the Moon are based on scientific data only after the collection of lunar rocks during the APOLLO experiments, after the location of seismometers on the surface of the Moon and after the evaluation of the seismograms of several moonquakes. However, it is important to note that on the basis of the observations made up to the present time only very uncertain consequences can be drawn concerning the inner

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structure of the Moon, particularly with reference to greater depths. For more precise and more reliable consequences, placing of several seismological observatories and the observation and evaluation of a great number of moonquakes would be required.

In the followings a brief summary will be given of the essential results and data obtained thus far by these measurements, and also of the conclusions which can be drawn from them concerning the structure and material build-up of the Moon.

The first and at the same time the most important problem is, how far is the inner structure of the Moon similar to the particular structure of the Earth which latter has been shortly summarized by us already earlier [1] i.e. whether a separation of crust—mantle—core exists also in case of the Moon, and whether also the Moon has—similarly to the Earth—the liquid outer core and the solid inner core.

In order to answer this question let us first survey the results of seismological observations carried out on the surface of the Moon. For the investigation of the moonquakes the APOLLO astronauts established a network consisting of four seismic stations equipped with four seismometers on each station, located at the landing sites of APOLLO missions 12, 14, 15 and 16. These stations have recorded the seismic data on the Moon for more than five years up to October 1977 and transmitted the obtained information to the data centre on the Earth [2]. It was proved already by the first observations that the Moon has less seismic activity than the Earth. In contrast to the several hundreds of earthquakes observed on the Earth a day, the average number of moonquakes occurring daily on the Moon is only 1–2. These moonquakes is about 1–2 magnitude on the Richter scale. Three types of natural lunar seismic events are available for analysis: meteorite impacts, near surface, and deep focus moonquakes.

The results of the seismic investigations are discussed by an extensive literature [3], however, the most important achievements of this literature can be summarized even in a single figure. This can be seen in Fig. 1 where the velocities of longitudinal and transverse waves as a function of depth below the moon's surface are shown on the basis of the results of two different research teams. This Figure affords the most important information for the research of the inner structure of the Moon. (It must be noted here that the stepped shape of these curves is due to the method of calculation and has no physical meaning at all—only the course of the curves has an importance for us.)

It can be seen in Fig. 1 that the properties of the seismic waves are known rather exactly in smaller depths. However, at depths exceeding a few hundreds of kilometres the uncertainty is significantly increasing, and the velocity conditions of the innermost lunar regions are practically unknown. On comparing the variation of seismic velocities with depth of the Moon with that

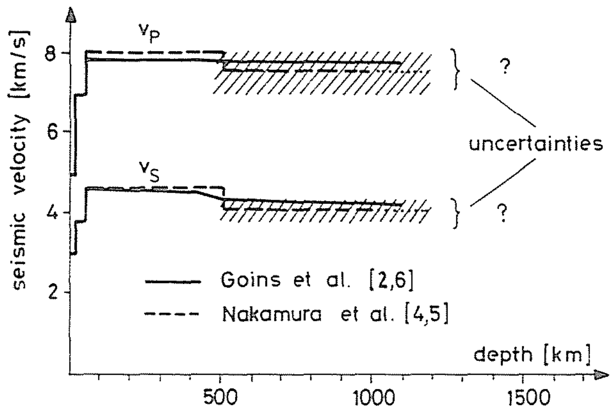

Fig. 1

of the Earth, a striking similarity appears in the uppermost 100 km region. From this it may be concluded that the structure of the crust of the Moon is similar to that of the Earth, and—since according to Fig. 1 a major increase of seismic velocity occurs between a depth of 55–60 km in average—this depth may be considered as the lower boundary of the lunar crust. Still, this depth is not identical everywhere. The above given depth is only a mean value varying between about 30 and 110 km. Comparing the above discussed results of the seismic measurements with the gravity and the topography of the Moon we can experience that the law of isostasy is to all probability valid also in case of the Moon's crust since there are large variations in crustal thickness, ranging from 30–55 km beneath mascons to 90–110 km in the farside highlands. It is interesting to note here that the average crustal thickness of the Moon is greater on the farside that on the nearside. It follows that the centre of mass of the Moon does not coincide with its geometrical centre, the deviation is about 2.5 km.

Let us now examine further the consequences which can be drawn concerning the deeper structure of the Moon on the basis of the velocity-depth function of the seismic waves shown in Fig. 1. Whereas the mooncrust can be defined with a suitable certainty on the basis of the seismic velocities nothing can be stated concerning the structure of the deeper regions because—just according to Fig. 1 the velocity-depth function is known very uncertainly below about 500 km and practically not at all at depths below 1000–1100 km. Accordingly, up to the present a great number of models differing from each other have been suggested for the inner structure of the Moon. A common feature of these models is they do not consider the mantle of the Moon to be homogeneous, and thus the mantle of the Moon is divided to two parts (upper and lower mantle) or eventually to three part (upper, middle and lower lunar mantle). It is surprising that the majority of these models presumes the existence of a lunar core similar to the Earth's core although up to the present no evidence of that is available.

The most probable structural units of the Moon's interior are summarized in Fig. 2 on the basis of seismological observations. The boundary

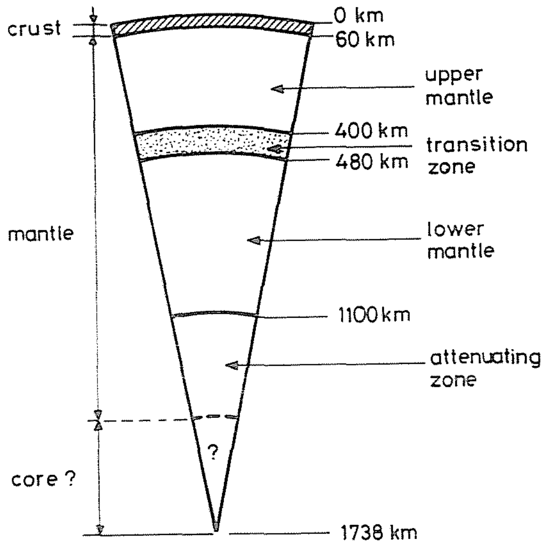

Fig. 2

surfaces can be defined according to the data of Table 1 on the basis of the velocity model of Goins et al. [2]. Considering a mean crustal thickness of 60 km, the upper mantle is extending from 60 to about 400 km depth. Between the depth of 400 and 480 km a relatively quicker decrease of seismic velocities is experienced. This region is denoted as transition zone which is separating the upper and lower lunar mantles. The lower boundary of the lower lunar mantle is uncertain but according to some researchers this mantle may be presumed to be at a depth of 1000 km or according to others at a depth of 1100 km. The

Table 1

Depth [km]	v_P [km/s]	v_S [km/s]
60	7.75	4.57
400	7.65	4.37
480	7.6	4.20
1100	7.6	4.20

existence of this boundary somewhere at a depth of 1000–1100 km is rendered probable by two observations. On one hand, the major part of the natural moonquakes is occurring in the region of depths between 700 and 1100 km, and up to the present no focus of moonquakes were recorded deeper than 1100 km [2]. On the other hand, according to other observations the strong attenuation of the seismic waves can be observed at a depth of 1100 km—which used to be characterized otherwise by the Q quality factor, being in fact the reciprocal value of the amplitude decrease of the seismic waves [7]. The dependence on depth of the Q values related to the P waves is summarized in Table 2 [2]. The region below 1100 km is denoted as attenuating zone—due to the strong absorption of seismic waves at a depth of 1100 km which appears also in the Table—and this depth is considered by some scientists as the lower boundary of the lower mantle. However, the thickness of this attenuating zone cannot be determined now on the basis of the available data. Thus no seismological evidence are yet at our disposal for the depth of the lunar core and even for its existence either. In general, the Moon's core is mentioned only by researchers who are supposing that the Moon have to possess a core to the analogy of the Earth's core and who are explaining the existence of the core—mantle discontinuity of the Earth by compositional change (an iron-nickel core), taking no notice of the fact that in case of the Moon a physical phase transition is essentially more probable [1, 8]. The boundary between the lunar mantle and the core is presumed generally to be at depths of 1400 km [3] though in case of the Moon at such a low depth it is difficult to assume such pressure and temperature parameters at which a physical phase transition would take place.

On summarizing briefly the results of the seismological investigations: only the boundary between lunar crust and lunar mantle occurring at a mean depth of 55–60 km can be defined with certainty. Furthermore, it is very probable that the lunar mantle has no homogeneous structure but can be divided into at least two parts: an upper and a lower (or external and inner) lunar mantle. Between the external and inner lunar mantles—instead of a sharp discontinuity—there is a transition zone between the depths of about 400 and 480 km. Though the lower boundary of the inner lunar mantle is uncertain, a further discontinuity may be presumed at a depth of 1000–1100 km where—on

Table 2

Region	Depth [km]	Q
Crust	0 – 60	5000
Upper mantle	60 – 400	4000
Lower mantle	400 – 1100	1500
Attenuating zone	> 1100	< 500

one side no moonquakes are occurring already and, on the other side, the elastic waves are strongly absorbed. This region is denoted as absorption (attenuating) zone. At present there are still no seismological evidences for the thickness of the absorption zone and for the existence of other boundaries (and thus for the existence of a lunar core).

Also the results of lunar magnetic measurements carried out by various satellites are of prominent importance. According to these investigations only a very weak magnetic field can be measured on the Moon originating almost solely from the magnetization of the superficial rocks [3, 11]. A magnetic field similar to the Earth's dipole field, originating from the interior of the Moon is completely absent. This points to the fact that the inner structure of the Moon is fundamentally differing from that of the Earth and thus it is not worth presuming at all means also in case of the Moon a terrestrial structure of crust—mantle—core, and the existence of an external liquid core of plasmatic state similar to that existing on the Earth, and the existence of a solid inner core can be precluded at a high probability.

From the aspect of the investigation of the material composition the knowledge of the inner density distribution of the Moon is very important. According to the measurements the mean density of the Moon is 3344 (± 2) kg/m^3 whereas the density of the lunar crust is a value between 2700 and 3000 kg/m^3 [3, 9]. From this it follow unequivocally that on proceeding towards the centre of the Moon the density is increasing. This is confirmed also by the 0.392 (± 0.002) values of the lunar moment of inertia [10]: namely, if the density distribution would be homogeneous, the value of the lunar moment of inertia would be 0.4. Consequently it is obvious that materials of higher density are located near the centre of the Moon. According to calculations—on presuming that the densities of the upper and lower lunar mantles are homogeneous—the most probable mean density of the upper lunar mantle at depths between 60 and 400 km would be 3300 kg/m^3 whereas the mean density of the lower lunar mantle at depths below 400 km would be 3490 kg/m^3 [3]. If a lunar core existed at all, it would be very difficult to estimate its density. Namely, in case of a lunar core of a radius of about 300 km, its volume would be hardly one two-hundredth part of the total lunar volume. Thus, on presuming a very great error in the density of the core, this would be hardly perceptible in the total mass and in the moment of inertia on cheking the values.

Lastly we must deal here briefly also with the thermal conditions of the Moon. The fundamental informations were afforded by the heat flux measurements of APOLLO 15 and 17. At the landing site of APOLLO 15 a heat flux of 21 mW/m^2 on the other hand at the landing site of APOLLO 17 a heat flux of 14 mW/m^2 were measured [3]. Obviously it is impossible to draw reliable conclusions from these two measurements concerning the entire surface of the Moon but a mean heat flux value of about 18 mW/m^2 referred to the entire surface of the Moon appears to be quite real though this value is surprisingly high in case of the Moon. From these two measurements the following conclusions can be drawn: on one hand it may be taken for certain that the heat flux from the inside of the Moon towards the surface originates from the decay of radioactive elements (presumably first of all from U and K) which are distributed probably irregularly as indicated by the significant difference between the two measured results; and on the other hand, the heat energy originating from the radioactive decay may start also some tectonical processes in the inside of the Moon. It may be imagined e.g. that some of the moonquakes is related to this fact i.e. the Moon is not completely "dead"—as assumed earlier—but rather a celestial body being active to certain extent [12]. At the same time it may be presumed that also the existence of the absorption zone at a depth of 1100 km is due to a higher concentration of the radioactive elements. It may be imagined that on the effect of the radioactive heat production the rocks present in this region are partial melted, and thus no moonquakes can occur in this depth, and also the amplitude of the seismic waves decreases significantly.

In the foregoings a brief summary has been given on all of the physical informations from which conclusions may be drawn concerning the inner structure of the Moon. It appears that our present knowledge is still rather poor; only the structure of the uppermost layer of the Moon has been recognized at a considerable certainty, and our knowledge rapidly decreases with the increase of the depth.

In order to recognize the inner material structure and the chemical composition of the Moon knowledge of the various physical parameters as functions of the depth and also the superficial lunar rocks—first of all their all geological and mineralogical characteristics—must be exactly known.

In the investigation of the lunar rocks a decisive role has been played by the APOLLO program since in the course of the six landings on the Moon—by means of a well-planned and careful selection—about 384 kg of lunar rocks was transported to the terrestrial laboratories for studying purposes [13]. (In addition about 0.1 kg of moon dust has been delivered by the LUNA 16 and 20 for analysis.) At the same time, only the commander and the service modul of the APOLLO 15 prepared a geochemical map of 38% of the lunar surface. In the followings a brief summary will be given of the results of the main petrological investigations.

The rocks to be found on the surface of the Moon are of volcanic origin. These primary rocks which have been crystallized from the magmatic material are transformed on the lunar surface by cosmic effects. The original rocks are broken and cut to pieces by meteorite impacts. Moreover, these rock fragments and the moon dust are melted again and cemented to breccias by meteorite impacts of higher energy. A particularly characteristic lunar material is the moon dust consisting of rock fragments of a size of 10 – 100 microns formed on the effect of the bombardment by micrometeorites. The flatter areas are covered by a 5 – 25 cm thick layer of this moon dust.

The magmatic rocks of the Moon had not been exposed to such transforming effects as those to which the rocks of the Earth had been exposed in the atmosphere rich in water and oxygen.

Therefore, the chemical composition of the rocks on the Moon remained unchanged in lack of erosive processes, the various rock types having been mixed up only mechanically; including also some components originating from meteorites [14].

Two major petrologic provinces can be distinguished on the lunar surface the anorthositic lunar highlands which are known as terra regions cutting into strips by light-coloured craters, and the dark colour basaltic mare regions. The rocks of the mare regions are the so-called mare-basalts whereas the rocks of the terra regions are the anorthosites and other rocks very rich in feldspars. On comparing their chemism with that of the adequate terrestrial rocks it appears that the iron, titanium and chromium contents of the mare-basalts are strikingly higher than those of the terrestrial basalts but they are poorer in silicates—i.e. on using the traditional expression: the lunar rocks are more basic than their terrestrial equivalents [14]. Iron present in the mare-basalts consists almost exclusively of bivalent Fe^{2+} and some metallic iron whereas in the basalts of the Earth also significant amounts of trivalent ferric iron are always present. From this it may be concluded that the lunar rocks had been formed under reductive conditions poor in oxygen and other volatile substances. The content of CaO and Al_2O_3 of the mare-basalts is similar to those of the terrestrial unsaturated olivine-basalts [14]. The terra-rocks very rich in lunar feldspare are standing nearest to the anorthosites, norites and trocktolites of the Earth, according to their chemism and mineral composition. A fundamental difference between the lunar and the terrestrial anorthosites is that the lunar rocks are richer in calcium i.e. the feldspars (plagioclasses) of the lunar anorthosites are almost completely anorthites whereas those of the terrestrial rocks are rather bytownite and labradorite [14].

At the comparison of the rocks of the mare and the terra regions it appears that the mare-basalts are sharply distinguished from the terra rocks by their high iron content and richness in titanium and chromium whereas the anorthositic terra rocks are being characterized mainly by their high aluminium content [15].

Now let us examine the rock-forming minerals found in the various lunar rocks. The number of minerals found—or more exactly, recognized up to the present—on the Moon is rather small when compared to the about 80 varieties of minerals found in meteorites or to the 2100 mineral types to be found on the Earth. In Table 3, besides the three main rock-forming minerals, 28 different

Table 3

Summarizing table of minerals of the lunar rocks according to Sz. Bérzi [14]

1. Main rock-forming minerals:	
pyroxenes	$(Mg, Fe, Ca)_2 Si_2O_6$
plagioclase	$(Ca, Na) AlSi_4O_8$
olivines	$(Mg, Fe)_2 SiO_4$
2. Accessory minerals:	
ilmenite	$FeTiO_3$
chromite	$FeCr_2O_4$
ulvite	Fe_2TiO_4
spinel	$MgAl_2O_4$
chrompleonaste	$(Fe, Mg) (Al, Cr)_2O_4$
perowskite	$CaTiO_3$
edysanalyte	$(Ca, Ce) (Ti, Nb, Fe) O_3$
rutile	TiO_2
niobium-REE*-rutile	$(Nb, Ta) (Cr, V, Ce, La) TiO_2$
baddeleyite	ZrO_2
zircon	$ZrSiO_4$ + REE*, U, Th, Pb
quartz	SiO_2
tridymite	SiO_2
christobalite	SiO_2
potash feldspar	$K(AlSi_3O_8)$
hyalophane	$Ba (AlSi_3O_8)$
apatite	$Ca_5 (Fe, Cl) (Po_4)_3$ + REE*, U, Th, Pb
whitlockite	$Ca_3(Po_4)_2$ + REE*, U, Th
zirkelite	$CaZrTiO_5$ + Y, REE*, U, Th, Pb
amphibole	$(Na, Ca, K) (Mg, Fe, Mn, Ti, Al)_5 Si_8O_{22}(F)_2$
iron	Fe
taenit	(Fe, Ni, Co)
copper	Cu
troilite	FeS
cohenit	Fe_3C
schreibersite	$(Fe, Ni)_3P$
corundum	Al_2O_3
goethite	$HFeO_2$
3. New minerals to be found on the Moon only:	
armalcolite**	$(Fe, Mg) Ti_2O_5$
tranquillityte	(Fe, Y, Ca, Mn) Ti Si Zr Al Cr O_3
piroxferroite	$CaFe_6 (SiO_3)_7$

* REE = rare earth elements

** from the abbreviation of the names of the three APOLLO 11 astronauts: Armstrong, Aldrin and Collins accessory lunar minerals and three further new minerals are listed which latter are occurring only in the Moon and were still unknown up to the present [14]. A quick survey of the list of the lunar minerals indicates that they are belonging mostly to the type of magmatic crystallization. Further, also their richness in iron, titanium, aluminium, calcium, magnesium, zirconium, uranium and thorium, and in rare earth elements is conspicuous; whereas—in comparison to the minerals of the Earth—their silicate content is low and their content of oxygen and volatile substances is very low.

The problem emerging here is whether we may generalize on the basis of the data of rock samples collected on the Moon surface from only 8 locations, and, respectively, whether we may draw conclusions from the analytical data of these rock samples concerning the whole surface of the Moon. However, the orbital measurements of the X-ray and gamma-radiations indicated that we may generalize. Namely, these measurements pointed to a global anorthositic lunar core and the basins filling-up by mare-basalts [15].

In order to draw conclusions concerning the material composition of the inner parts of the Moon on the basis of the knowledge of the superficial rocks an exact knowledge of the function of several physical parameters—mainly of density, pressure and temperature—plotted against the depth is required. Though the density-depth and the pressure-depth functions could be determined from the seismic measurements [8], it has been shown in the foregoings that the seismic velocity-depth function is known adequately at most down to some hundreds of kilometres. Conditions are even worse in case of the temperature-depth function, since only very rough estimations are available concerning the inner temperature distribution of the Moon.

Still, on the basis of the results of high-pressure experiments carried out in laboratories and of the approximate knowledge of the physical parameters of the Moon it may be stated to all probability that even in the deepest parts of the Moon no physical phase transition may be imagined, and at most some isochemical phase transition may be presumed [15]. Thus at the spots of the velocity jumps shown in Fig. 1 most of all the appearance of novel rock layers having a different chemical composition or eventually an isochemical phase transition may be assumed.

On the basis of the knowledge listed is the foregoings the only statement appearing to be certain is that in the mare regions a basalt layer of a mean thickness of 20 km is laying upon the surface of the Moon, and that below it the crust is continued probably by an anorthositic gabbro zone of 40 – 50 km thickness. In the terra regions the upper layer is anorthosite and anorthositic gabbro, respectively. Its thickness is 70 – 100 km, exceeding even a thickness of 100 km at the farside of the Moon. Below the lunar crust presumably a mantle of pyroxenite follows in both the mare and the terra regions [15].

Lastly it is worth to mention also some data of the history of the Moon. According to the radioactive age determinations carried out with rock samples, the age of the Moon is about 4500 million years i.e. the Moon has the same age as the Earth. However, with respect to the geochemical differences between the terrestrial and the lunar rocks it is rather difficult or even impossible to presume a terrestrial origin for both rock types. Consequently, the theory according to which the Moon has been formed by fission of its mass from the Earth, is incorrect. The results of the APOLLO experiments are confirming that the Moon has been formed either together with the Earth or quite independently of the Earth as an independent celestial body which has been later captured by the Earth's gravity field. The lack of volatile elements and the relative enrichment of titanium and zirconium in the lunar rocks are pointing however to the fact that the Moon must have been of a very high temperature in the past and a very intensive magmatic differentiation must have been taken place on it.

Still, in order to exactly clear up the inner structure, development and history of the Moon, a great number of lunar expeditions and an immense research work are required.

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