Outline of a Lunar Chronology

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I. THE ACCUMULATION AND BULK COMPOSITION OF THE MOON

Outline of a lunar chronology

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Introduction

We present here an outline of lunar chronology and evolution based on analyses of the isotopic parent-daughter systems ^{87}Rb-^{87}Sr, U-Th-^{206}Pb-^{207}Pb-^{208}Pb and ^{40}K-^{40}Ar. An overview of the chronology will first be given, followed by an outline of the observational basis. A more complete discussion of ^{40}K-^{40}Ar results and their interpretation is presented in the paper by G. Turner in this volume. While the body of data on lunar materials is limited, the chronology for lunar evolution appears to be rather well defined. The samples which have been investigated represent mare basalts [returned by the Apollo missions (11, 12, 15 and 17) and by the Soviet Luna 16 mission] and terra rocks, which include non-mare basalts, anorthosites, troctolites and norites but are predominantly comprised of complex breccias [returned by Apollo 12, 14, 16 and 17 and Luna 20]. The mare basalts are associated with the late stage lava flows which covered the mare basins. These flood basalts have been broken up by impact processes but for the most part are associated with the local areas and have not been subject to major transport or metamorphism by impact. The highland rocks predate the mare lava flows but are not clearly associated with a particular magmatic or impact process. They may have been excavated from considerable depths and transported over wide distances. Impact metamorphism is certainly one of the critical stages in their development.

The techniques which permit the precise dating of lunar rocks are the result of a rapid development over the past nine years in mass spectrometric techniques, in refined chemical separation methods and mineral separation procedures, and in mineral identification and analysis. These methods have been applied most extensively to lunar problems, but in the future they will undoubtedly be utilized in a new generation of studies of meteorites and of terrestrial samples.

General outline

An overall summary of lunar chronology is given in the cartoon in figure 1. Mare volcanism is a clear manifestation of lunar igneous activity and is directly dated by analyses of basalt samples. The period over which mare basalts were extruded extends from 3.9 to 3.1 Ga. Clasts of mare basalts in the more ancient terra breccias are extremely rare. The rate of basalt flooding appears to have decreased with time between 3.9 and 3.1 Ga and mare volcanism seems to have terminated at about 3.0 Ga. The many suggestions of 'young' mare volcanism

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† Contribution no. 2705.

predicted by several workers based on photogeology have not been susbtantiated. In particular, the Apollo 17, site which was predicted before the mission to yield very young rocks, has instead yielded many basalt samples with ages of 3.8 Ga. The cartoon shown in figure 1, which was originally drafted before Apollo 17, showed a question mark over the small young volcano; the question mark has been deleted. The ages of lunar samples demonstrate that there has been no major lunar volcanism in the last 3.0 Ga. However, this does not necessarily mean that all lunar volcanic phenomena have ceased. This matter is not yet clear and it is important to keep an open mind to the possible continuation of lunar igneous processes into recent times.

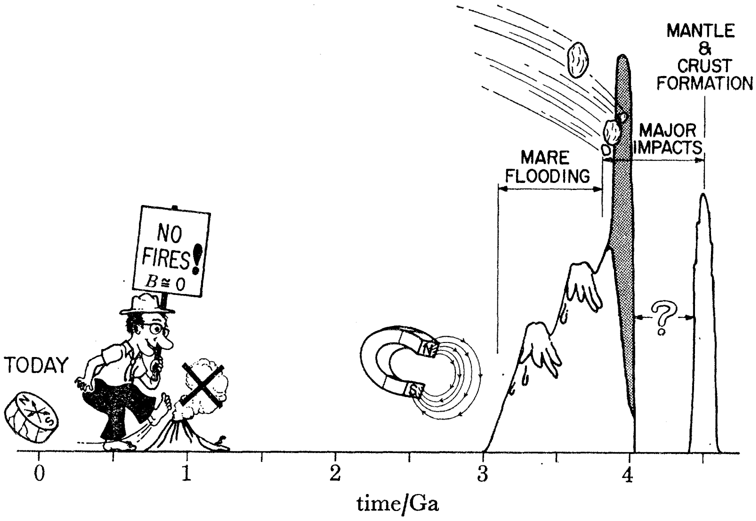

Figure 1. Cartoon showing the chronology of major lunar events as presently known or surmised.

Observations of 'transient' phenomena by several workers have suggested that some gaseous emanations from the lunar interior are occurring today. As we shall argue later, a special mechanism is required which permits the moon to be partially molten over its earlier evolution and then to become cool or rigid enough so as to suppress further volcanism. Rigidity of the lunar crust to support mascons is required while some mare volcanism was still going on.

A distinct period of major lunar igneous activity occurred approximately 4.5 Ga ago. This period is close to the time of formation of the moon and is associated with major lunar differentiation. The evidence for this igneous activity is both inferential and direct. Until recently there had been very little direct evidence of truly ancient lunar magmatic rocks. These ancient rocks occur as fragments within younger breccias or as isolated samples and are not obviously related to broad scale igneous morphologic features. Indeed, our ability to recognize primary lunar morphologic features other than impact basins and late mare floods has been very limited. The inferential data on early lunar processes is strong and is obtained from model ages of total rocks and soils. Demonstration of the existence of major early lunar differentiation and examples of the characteristic rock types produced during this process are of great importance since there are no observations of such processes on the earth and only fragmentary data from diverse meteorites. The duration of this early epoch of planetary differentiation is uncertain but appears to be about 0.2 Ga.

In the interval between about 4.4 and 3.8 Ga there is no *strong* evidence either direct or indirect for igneous activity on the moon. This lacuna in lunar history is indicated by a query mark in figure 1. The validity of assigning a long interval (~ 0.6 Ga) of quiescence following early lunar differentiation remains a fundamental question to be tested by careful observations. Some samples of a highland breccia from the Apollo 16 site yield ^{40}Ar-^{39}Ar apparent ages of up to 4.3 Ga (Schaeffer & Husain 1973). Comparable ^{40}Ar-^{39}Ar ages are observed in samples from highland breccias from the Apollo 17 site. It has not yet been possible to confirm these results by other methods. In some cases the nature of the events dated by the ^{40}Ar-^{39}Ar method is unclear. Because of the steep thermal gradient in the Moon, rocks that are originally at depth may undergo continuous ^{40}Ar loss and the ^{40}K-^{40}Ar system may be measuring the time at which samples were excavated from depth and brought to the surface, where the temperatures are much lower (Podosek *et al.* 1973). In this model the ^{40}Ar-^{39}Ar ages are interpreted as determining the time when fragments were excavated by large impacts during 4.6–4.0 Ga and which escaped recrystallization during the period 4.0–3.8 Ga.

There is abundant evidence of widespread shock metamorphism at a time of *about* 3.9 Ga, apparently in an interval from 4.0 to 3.8 Ga. This episode is reflected in partial to complete isotopic equilibration for all the isotopic systems so far studied. The rock types range from basaltic clasts in breccias to partially and locally recrystallized breccia matrices and to isolated fragments of plutonic rocks. Evidence for metamorphism in this period has so far been found in samples from all sites except Apollo 11 and Luna 16. This metamorphic episode represents a period of major lunar bombardment which has left a distinct imprint on materials covering the whole earth-facing side of the moon. It was first identified by our studies and was called the *terminal lunar cataclysm* (Tera, Papanastassiou & Wasserburg 1974). The question as to whether this was a distinct episode over a very narrow time interval or a series of events over ~ 0.2 Ga is not yet resolved. The terminal lunar cataclysm could represent the Imbrium impact, with a much larger ejecta blanket than predicted or, more plausibly, the formation of several major lunar basins in a highly restricted time interval. The discovery of major impacts at a time of 0.6 Ga after the initial accretion of planetary bodies (with a time constant of 0.01 to possibly 0.10 Ga) is itself of considerable importance. This phenomenon was certainly not predicted and has attracted several workers to propose storage mechanisms for the source of bombarding objects with long time constants (cf. Wetherill 1975). The implications of this late stage lunar bombardment for the cratering histories of all the inner planets have now been recognized by various workers, although the clear-cut applicability of the lunar bombardment time scale to Mercury, Mars and Venus is not self-evident.

The observation of a fossil lunar magnetic field is of major significance (cf. Strangway, Larson & Pearce 1970; Runcorn *et al.* 1970). As indicated in figure 1, the magnetic field was apparently present during the period of lunar volcanism between 3.9 and 3.0 Ga and is absent today. The existence of a field before 3.9 Ga is uncertain, since all of the rocks which are more ancient have been subjected to metamorphism during the terminal lunar cataclysm. The source of the ancient lunar magnetic field is a subject of intense interest, and a possible mechanism for its origin has been proposed (Runcorn & Urey 1973).

Rb-Sr AGES

Methodology

Since the chronology depends to a large extent on the Rb-Sr method, it is desirable to state the basic principles. If a rock system were to start at some arbitrary time with a uniform initial isotopic composition of Sr, then the different constituent phases will initially lie on a horizontal line (see figure 2). If the individual phases remain as isolated systems, they will follow the trajectories as shown by the arrows and will today define a straight line called an internal isochron.

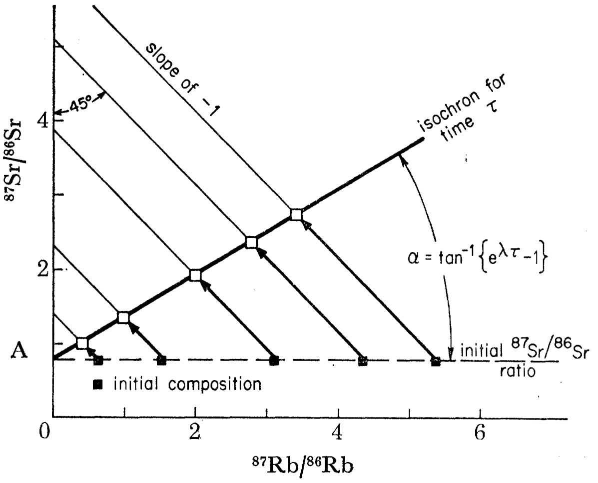

FIGURE 2. Rb-Sr evolution diagram for a set of closed systems with different ratios of Rb/Sr but which initially had the same isotopic composition (point A).

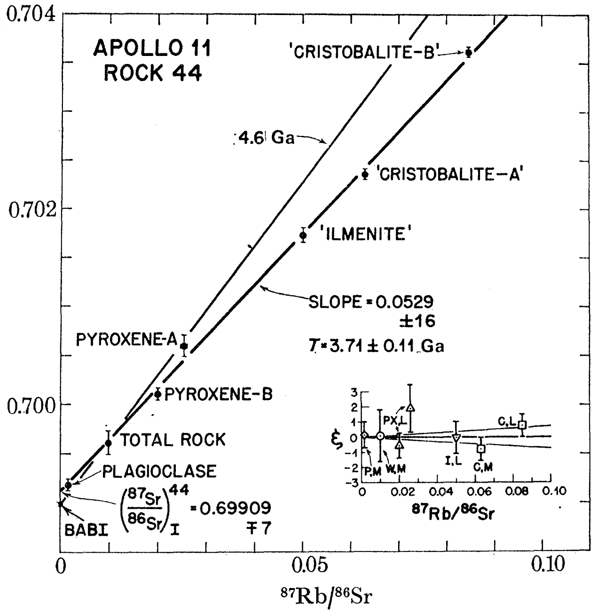

FIGURE 3. Rb-Sr data for a mare basalt from Apollo 11. Note that the initial value is above BABI. A 4.6 Ga line is drawn through BABI. The fractional deviation in $^{87}Sr/^{86}Sr$ of the data points from the best fit isochron are shown in the inset in units of 10^{-4}.

The slope of the line determines the age, and the point of intersection A determines the initial Sr isotopic composition. In every case it is necessary to establish whether a given linear data array is a true isochron representing several distinct phases and not simply a mixture of two end members without a strict time meaning. If the data points do not define a precise line, then the system is complex and neither the age nor the initial Sr are well defined. It should be noted that if, after some time τ', the system were again isotopically homogenized, then the new initial Sr isotopic composition would be increased to the value of $^{87}Sr/^{86}Sr$ for the total rock at the time of homogenization. This increase in the initial value with time will be used in our arguments. Given the initial value for the Moon at the time of formation, then it follows that any excess above this value for the initial $^{87}Sr/^{86}Sr$ value of a lunar rock must represent the passage of time in a lunar reservoir.

In addition to internal isochrons, the concept of model age is very useful. If a value for the isotopic composition of Sr can be chosen that represents the value when the moon was first formed, then we may calculate the model age of a sample relative to the lunar initial value.

For this calculation to be useful, the rock must have a high enough ratio of Rb/Sr so that the enrichment in $^{87}Sr/^{86}Sr$ is much more than the possible range in values of the lunar initial $^{87}Sr/^{86}Sr$. If the rock remained a closed system since the formation of the Moon, then the model age will be the age of the Moon. If the rock was formed with a large enrichment of Rb relative to Sr, then the model age will be close to the crystallization age of the rock. In general the model age is an upper limit to the last time the rock was an open system.

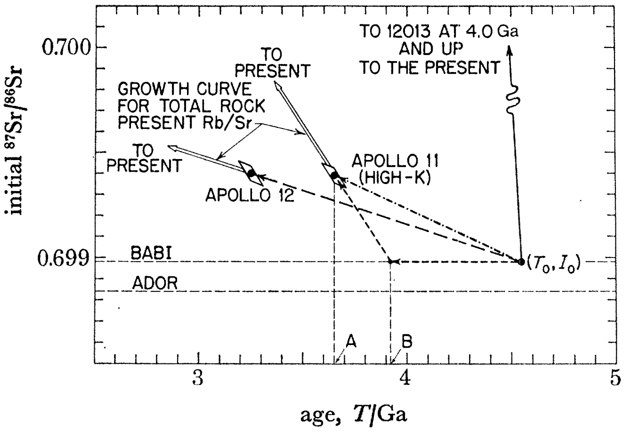

Figure 4. The initial $^{87}Sr/^{86}Sr$ at the time of crystallization for two Apollo mare basalts. Arrows show the sense of the $^{87}Sr/^{86}Sr$ growth curves for each rock with their observed Rb/Sr. The extrapolation of these lines to BABI or ADOR gives the model ages for these respective reference values.

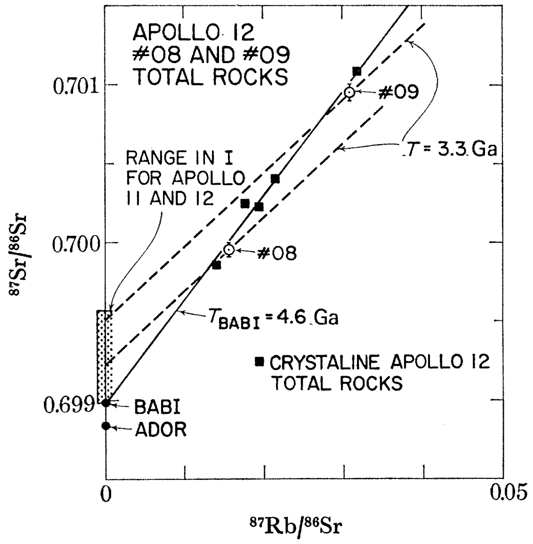

Figure 5. Sr-Rb evolution diagram showing the total rock data for several coarse grained crystalline basalts and two basalt vitrophyres (no. 08 and no. 09). The full line is a 4.6 Ga isochron to BABI. The dashed lines have slopes corresponding to an age 3.3 Ga, which is a typical age for Apollo 12 basalts.

Experimental results

An example of an isochron from a typical mare basalt from Apollo 11 is shown in figure 3. It may be seen that all data points lie on a straight line to within analytical error and define an age of 3.71 Ga. This is much younger than the time of formation of the solar system but is as old as the oldest known terrestrial rocks. Note that the initial value for this rock is significantly above BABI and ADOR (figure 4). This increase in $^{87}Sr/^{86}Sr$ above the primordial solar system value is consistent with the fact that the rock was formed some time after the formation of the Moon and would be produced in a magma source region with Rb/Sr $\approx 0 \pm 004$. In addition, it should be noted that a line through the data point for the total rock and BABI corresponds to a model age of ~ 4.5 Ga. This model age is imprecise because of the low ^{87}Sr enrichment of the total rock; however, this model age is characteristic for the majority of lunar rocks with the exception of the high K rocks of Apollo 11. A comparison of the Rb-Sr evolution for these two rock types is shown in figure 4 where the initial $^{87}Sr/^{86}Sr$ is plotted against the crystallization age. The slope of the line through each total rock point is proportional to the Rb/Sr ratio in the rock. The high-K Apollo 11 rock gives a model age much younger than 4.5 Ga and indicates that the rock was enriched in Rb relative to Sr essentially at the time the lava was formed. The Apollo 12 rock has a model age of ~ 4.6 Ga. Another example may be seen for two basalt vitrophyres from Apollo 12 which appear to lie on a ~ 4.6 Ga line to BABI (figure 5). The approximate rule for most mare basalts is that they have model ages (T_{BABI}) rather close to 4.5 Ga *but with considerable uncertainty*. If this were exactly true it would imply that they were produced without Rb-Sr fractionation from source reservoirs of different Rb/Sr ratios which were isolated near the time of formation of the Moon.

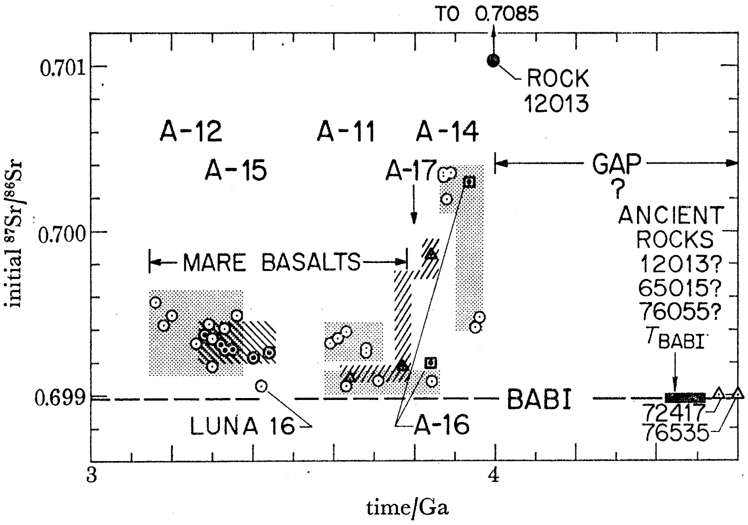

FIGURE 6. Initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ and crystallization ages of mare basalts and two ancient highland rocks (a dunite and a troctolite). Data are also shown for highland igneous and metamorphic rocks. The data from each mission are distinguished by labels or by background markings. Note the apparent absence of any Rb–Sr crystallization ages in the gap.

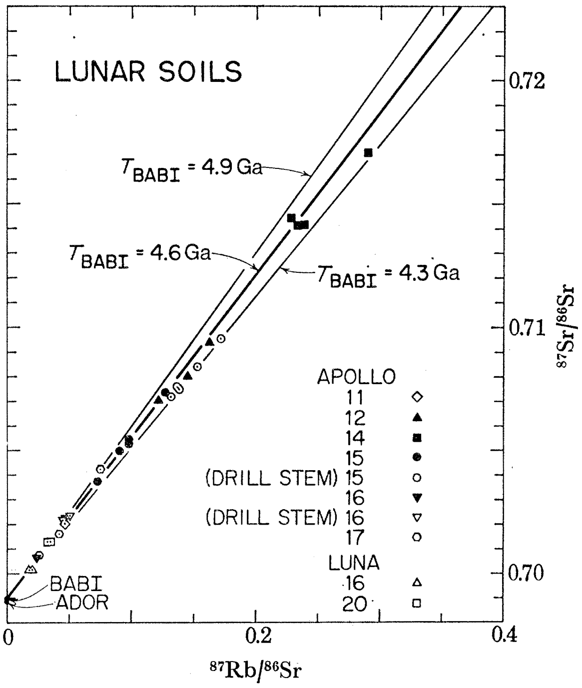

FIGURE 7. Sr-Rb evolution diagram showing data on soils from all lunar missions. There is a very good linear correlation for these highly varied materials, but not a precise isochron. Note the wide range in Rb/Sr which extends to very radiogenic materials.

A summary of the ages and initial values of mare basalts is shown in figure 6. It may be seen that the mare basalts occur in a restricted time interval and all have initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ values only slightly enriched above BABI. Ages for mare basalts have also been determined using the $^{40}\mathrm{Ar}$-$^{39}\mathrm{Ar}$ method, the most reliable results being on mineral separates. Where precise ages have been obtained using both methods, the results are in good agreement. All $^{40}\mathrm{Ar}$-$^{39}\mathrm{Ar}$ ages so far measured on samples from all sites lie in the same restricted time interval as determined from Rb-Sr measurements. The unique green and orange glass spherules found in abundance at the Apollo 15 and 17 sites have yielded similar ages to local basalt flows despite expectations that these samples are products of younger volcanism. They appear to represent only a particular aspect of the general mare effusions during 3.1–3.9 Ga.

Terra basalts and feldspathic basalts from Apollo 14 and 16 give ages which are only slightly older than the upper values found for mare basalts, and estimates of the recrystallization ages for some highland breccias are in the range between 3.8 and 4.0 Ga. Some highland igneous rocks may actually be crystallized from impact melts. Many highland breccias give model ages close to 4.6 Ga, but some highland basalts, which have a high initial Sr, give a precise and distinctly younger model age of 4.3 Ga, indicating significant Rb-Sr fractionation (factor of 2) at the time of formation. There are no highland basalts or breccias which give model ages *much greater* than 4.6 Ga (say 5.6 Ga). This indicates that none of these rocks are Rb poor differentiates of an old reservoir that had a high Rb/Sr ratio.

Lunar soils

One important clue to the early differentiation of the Moon is found in lunar soils. The first hint was given by the Apollo 11 soil, which gave a model age of ~ 4.5 Ga (Lunatic Asylum 1970*a*). In addition, this soil has a much higher Rb/Sr ratio than the common low K basalts. The high K basalts had young model ages (~ 3.8 Ga), which was inconsistent with their making up a significant fraction of the local soil. This indicated that the model ages were controlled by a 'magic' component in the soil rich in Rb, K, U and Th which had originally segregated near the time of formation of the Moon. Subsequent analyses of lunar soils from all the missions have shown consistently the model ages near 4.6 Ga. A summary of the data is shown in figure 7. Considering that the soils are mechanical mixtures from diverse sources and have highly variable Rb content with relatively constant Sr, it is inferred that Rb rich rocks formed near 4.5 Ga and that such rocks are present at or near the surface of the Moon.

An early lunar rhyolite – 12013

Among the samples collected at the Apollo 12 site was a small rock weighing 82 g. The first clear indication that this sample was peculiar came from the γ ray counting which showed this rock to contain 2 % K, 11 parts/10^6 U and 34 parts/10^6 of Th. This rock proved to be a complex breccia with small clots of silica rich material close to rhyolite in composition, as well as clasts of anorthitic plagioclase poor in alkalis. Evidence of local melting could be seen. Several small chips of this rock gave model ages close to 4.5 Ga, but some highly radiogenic chips showed much younger model ages (Lunatic Asylum 1970*b*). Internal isochrons were determined on two different samples weighing 128 and 194 mg. These internal isochrons yielded ages of 3.99 ± 0.05 and 4.01 ± 0.09 Ga (figure 8). The isochrons were parallel but with distinctly different initial values of 0.7085 and 0.7050, demonstrating that the breccia had achieved only local isotopic equilibrium at ~ 4.00 Ga. The total rock model ages near 4.5 Ga and the very high initial values of the internal isochrons suggested that the original K rich material was produced during early lunar differentiation and that this process generated highly radioactive granitic and rhyolitic rocks. The Rb-Sr age of 4.0 Ga and the ^{40}Ar-^{39}Ar age by Turner (1971) were found to be in good agreement and provided the first evidence that 4.0 Ga was a time of significant impact metamorphism.

Ancient clasts in highland breccias

Relict plagioclase fragments in several highland metaclastic rocks were found to contain very primitive Sr which had not equilibrated with Sr in the surrounding matrix during metamorphism (Papanastassiou & Wasserburg 1972*a*). ^{40}Ar-^{39}Ar measurements on these fragments also showed incomplete degassing of the more primitive relicts. Ar released at high temperatures and associated with these relicts yielded ages up to 4.47 Ga and provided evidence that the protolith contained ancient plagioclase (Jessberger, Huneke & Wasserburg 1974).

All the preceding evidence pointed to early lunar differentiation; however, while the arguments are very strong, no direct observations identified ancient individual rocks. A boulder of highland material that was sampled during Apollo 17 provided a fist-sized dunite clast. No age determinations had previously been carried out on dunite samples due to their extremely low Rb and Sr content. An investigation of the lunar dunite (72417) showed the presence of phases with high Rb/Sr. Using only handpicking techniques, it was possible to separate phases with a wide range of Rb/Sr which determined a rather precise isochron (see figure 9). The age determined for this rock was 4.55 ± 0.10 Ga with a precise initial ^{87}Sr/^{86}Sr indistinguishable from BABI. This rock was thus identified as a truly early lunar differentiate (Papanastassiou & Wasserburg 1975). One of the data points was found to lie off the isochron by more than the experimental error. Study of the host breccia showed that the total rock,

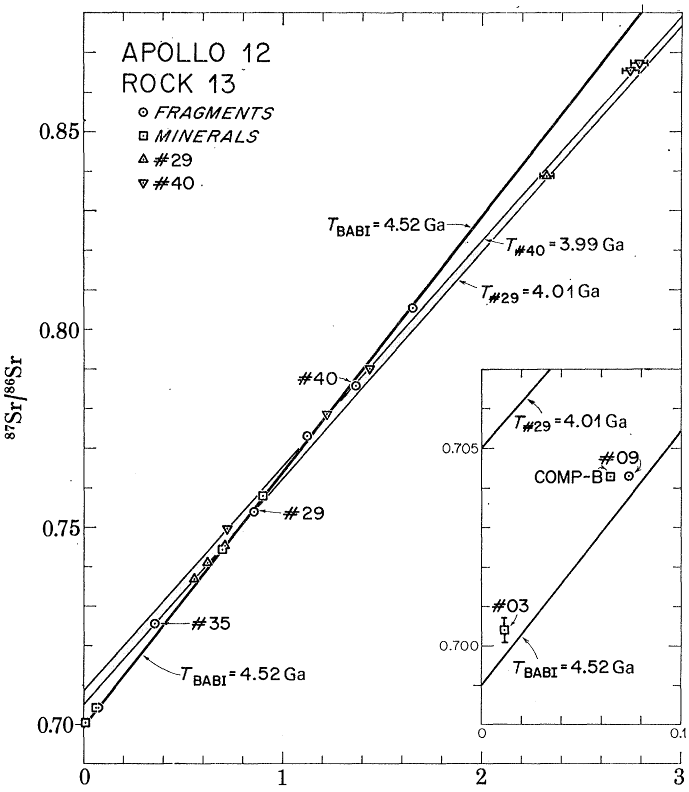

FIGURE 8

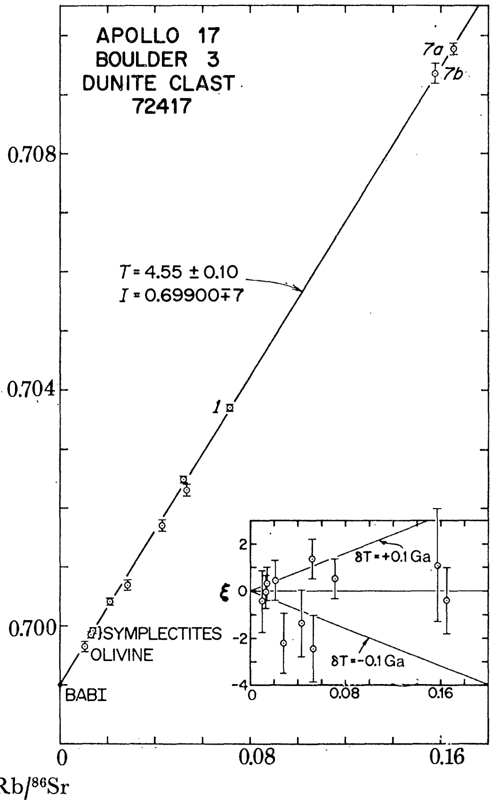

FIGURE 9

FIGURE 8. Sr-Rb evolution diagram for the highly radioactive rock 12013 showing data on 'total rock' chips and of mineral separates. Note the 4.52 Ga reference isochron for total rock chips and the shallower slope of the internal isochrons for rock chips no. 29 and no. 40 corresponding to a recrystallization age of 4.0 Ga.

FIGURE 9. Internal isochron for a dunite clast taken from a highland breccia which was sampled on Apollo 17. Note both the ancient age and the low initial ^{87}Sr/^{86}Sr. The original crystallization age of the dunite appears to have survived metamorphism during the terminal lunar cataclysm (see figure 10).

which has a rather high Rb content compared to the dunite, had a model age of 4.6 Ga. The mineral phases show a general linear trend but clearly did not define an isochron and had obviously been disturbed by element transport. As the dunite was a clast in the breccia, it was necessary to establish whether or not the element migration in the breccia and between the matrix and the clast could have been significant enough to cast doubt on the antiquity of the dunite. An extensive study was carried out on the fine-grained vesicular matrix and on a single plagioclase clast about 3 mm in diameter. Analyses of the matrix, the recrystallized rim of the plagioclase clast in contact with the matrix and of the interior of the plagioclase clast most distant from the matrix were undertaken. It proved possible to determine approximate 'internal' isochrons for each of these microsamples. The results yielded ages of about 3.8 Ga, coinciding with the terminal lunar cataclysm, and showed that the isochrons were offset from one another, indicating that the scale of Rb and Sr isotopic migration was about 1 mm or less.

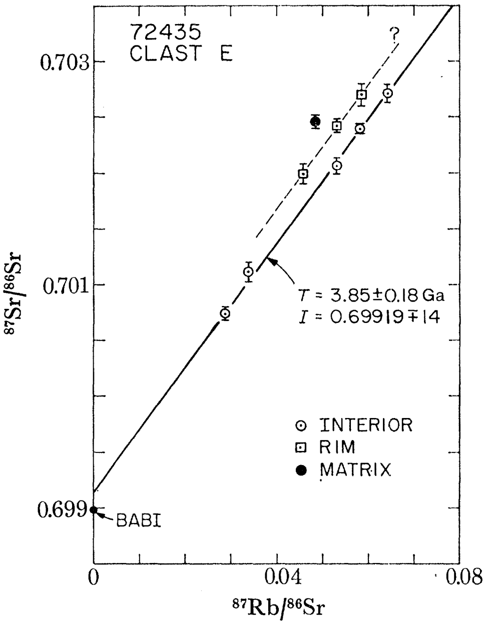

FIGURE 10

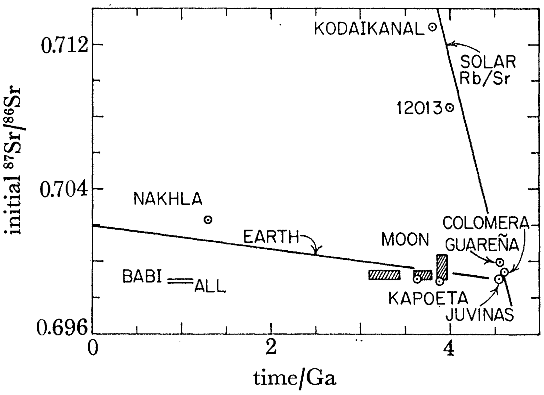

FIGURE 11

FIGURE 10. Sr-Rb evolution diagram showing analyses of a small clast (~ 3 mm in diameter) in the breccia from which the dunite (72417) was taken and showing the restricted scale of isotopic equilibration. The interior of the clast shows isotopic equilibration on a scale of about 1 mm and reflects the relatively young metamorphism. Samples of the same clast adjacent to the contact with K and Rb rich matrix yield a parallel array which is offset. A sample of the nearby fine-grained recrystallized matrix is shown.

FIGURE 11. Graph of the initial ^{87}Sr/^{86}Sr against the time of crystallization or metamorphism for lunar rocks and meteorites. Growth curves for the Earth and the Sun are shown for comparison. The reference initial values for basaltic achondrites (BABI) and Allende inclusions (ALL) are indicated. Note that the range in ages of planetary magmatism and impact metamorphism is quite extensive.

This very limited element migration in a vesicular rock with a recrystallized ground mass is attributed to the absence of H_2O in lunar rocks (Albee & Gancarz 1976). As the dunite was large in size compared to the distance of element migration, it is reasonable to suppose that the original Rb-Sr isotopic pattern of that rock survived the major impact and associated metamorphism at ~ 3.9 Ga.

Subsequent to the discovery of a 4.55 Ga age for the dunite, Papanastassiou & Wasserburg (1976) have determined the Rb-Sr age of a coarse-grained troctolite from Apollo 17 to be 4.60 Ga. Both of these rocks may now be related to early lunar magmatic processes, and further studies will undoubtedly reveal a wider suite of rock types characteristic of early planetary differentiation which have preserved their original formation age through the epochs of major bombardment. Discrepancies between the different dating methods are frequently found for these ancient rocks. This is presumbly due to the different behaviour of each pair of parent-daughter elements in a given rock during metamorphism. This matter is not yet understood and will require further attention if our knowledge of early lunar history is to improve.

Summary of lunar Rb-Sr evolution

A summary figure (figure 11) illustrates the initial $^{87}Sr/^{86}Sr$ and ages of lunar samples and some meteorites. The initial Sr of 12013 is seen to be enormously evolved, lying close to the solar evolution line. Most meteorites have ages near 4.5 Ga. The initial Sr for the eucrites, howardites, angrite and Allende is very primitive; however, some chondrites such as Guarena and iron meteorites show a rather evolved initial Sr.

The approximate evolution curve for the Earth is shown. It can be seen that the field of lunar basalts lies distinctly below this line and demonstrates that the derivation of the Moon from the Earth is an exceedingly implausible hypothesis. Some of the highland rocks lie above the terrestrial growth curve. The meteorite Kodaikanal has a relatively young age of 3.8 Ga and lies in the time band characteristic of lunar impacts and igneous activity. Similarly, some clasts in the Kapoeta breccia are found to lie in this same time band, although other clasts are ~ 4.5 Ga in age. It is conceivable that these meteorites were metamorphosed on their parent planets at about the same time as the Earth–Moon system underwent intense late stage bombardment. On the other hand, the meteorite Nakhla has a very young crystallization age and cannot be related to the earlier bombardment. The extent to which the terminal cataclysmic bombardment of the Earth–Moon system is recorded in the meteorites remains to be seen.

LEAD-URANIUM-THORIUM

One of the important observational constraints on lunar evolution is the Pb-U-Th data on highland rocks and mare basalts. These data have been most significant in: (1) determining the time of isolation of lunar magma reservoirs and the time of early differentiation of the Moon; and (2) demonstrating the temporal relation between a wide variety of terra rocks which were subjected to approximately contemporaneous impact metamorphism. Only in rare cases have crystallization ages been obtained for lunar samples by the Pb-U-Th methods.

In common with all isotopic dating methods, the Pb-U-Th methods provide the determination of an initial isotopic composition as well as an age. The systematics appear more complex because the two lead isotopes ^{207}Pb and ^{206}Pb are the daughter products of the two isotopes of uranium ^{235}U and ^{238}U.

Pb-U systematics

Let us consider a system formed τ years ago and which initially contained no lead but contained uranium of normal isotopic abundance for that time. If this system remains closed, then it will have ratios of $^{207}Pb/^{206}Pb$ and $^{238}U/^{206}Pb$ when observed today, which are a known function of τ. The class of all such systems for arbitrary times defines the concordia curve (see figure 12). Points which lie on the concordia curve yield the same age τ for both ^{207}Pb-^{235}U and ^{206}Pb-^{238}U. Points not on the curve are called discordant (Wetherill 1956). In general, a natural system formed at a time τ will have both U and Pb present. This Pb will be comprised of primordial Pb that was initially present when the Moon formed and of radiogenic Pb produced by U and Th decay prior to τ. This lead is the initial lead similar to the initial Sr for the ^{87}Rb system or 'trapped' argon for the ^{40}K system. If a set of systems or phases were formed at time τ and were initially isotopically homogeneous but contained different proportions of initial lead to uranium, then their ratios of $^{207}Pb/^{206}Pb$ and $^{238}U/^{206}Pb$ today define a straight line isochron extending from the initial $^{207}Pb/^{206}Pb$ on the ordinate to the point on concordia corresponding to the age τ. While various model ages may be calculated for each data point, only the lower point of intersection with concordia has a well defined meaning.

Most data arrays of natural systems will show both a lower and an upper intersection with concordia. The interpretation of the lower intersection is clear, but the interpretation of the upper intersection must be subject to careful scrutiny. In general, the position of a data point on the isochron does not determine an age but is a function of the times τ_0 and τ and the degree of U-Pb fractionation which took place at time τ. If all of the systems had diverse evolutionary paths before τ but were isotopically well mixed at that time, then it would not be possible to infer their history before τ from the isochron. However, if the systems were all formed without any initial radiogenic lead at some time τ_0 and were then recrystallized or fractionated at time τ, then the upper intersection of the isochron with concordia would define τ_0.

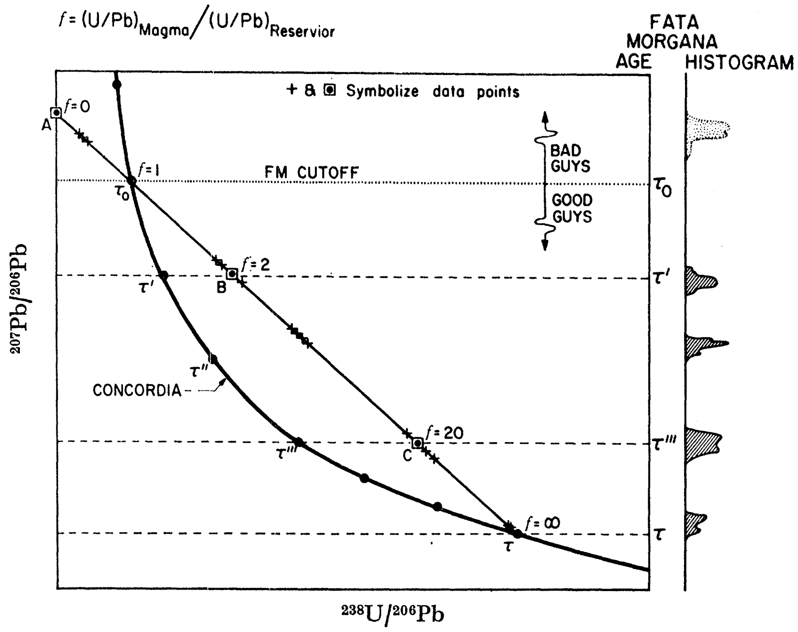

Figure 12. Schematic drawing of the coupled Pb-U evolution diagram exaggerated for clarity. An isochron is drawn from point A (representing the initial $^{207}Pb/^{206}Pb$) to the concordant point at τ, the age of crystallization or metamorphism. The fractionation factor of U relative to Pb is indicated on the isochron for possible derivatives of a single parent magma reservoir formed at τ_0. Representative data points are shown by crosses and yield illusory ^{207}Pb-^{206}Pb ages (τ', τ'', τ''') as indicated by the histogram on the right. Some workers have utilized the ^{207}Pb-^{206}Pb ages with an arbitrary cutoff greater than $\tau_0 \sim 4.6$ Ga.

Highland rocks

All of the data currently available on highland rocks are shown in figure 13 and represent a wide variety of rock types which include terra basalts, anorthosites, a troctolite, and breccias. The sampling localities include Apollo 14, 15, 16 and 17. No attempt was made to screen the data so that the accuracy of some analyses may be of lesser quality. The reference isochron in the figure is the internal isochron for a terra basalt from Apollo 14 (Tera & Wasserburg 1972). Inspection of figure 13 shows that the data form a striking linear array and are consistent with the reference isochron. Considering the diversity of rocks and localities sampled, this is a remarkable Pb-U correlation and strongly suggests a temporal relationship between rocks which are not consanguineous from the viewpoint of igneous petrogenesis. The lower intersection between concordia and the 'isochron' corresponds to a time of about 3.9 Ga, which is an excellent agreement with the Rb-Sr and K-Ar ages for the metamorphism of highland breccias. It should be noted that the ratio of $^{238}U/^{204}Pb$ (μ) observed for the different samples shows a regular trend. Those samples which are most discordant with $^{238}U/^{206}Pb$ near zero have very low values of μ. As the ratio $^{238}U/^{206}Pb$ increases, the μ values also increase rapidly. The observed range in μ is from 9×10^{-1} to 1.5×10^{4}. Those samples with very high μ values are close to the lower intersection with concordia. All of these observations are plausibly explained by an epoch of major lunar impact metamorphism at ~ 3.9 Ga, during which lead (including the primordial isotope ^{204}Pb) was lost from the older pre-existing rocks and distributed over the

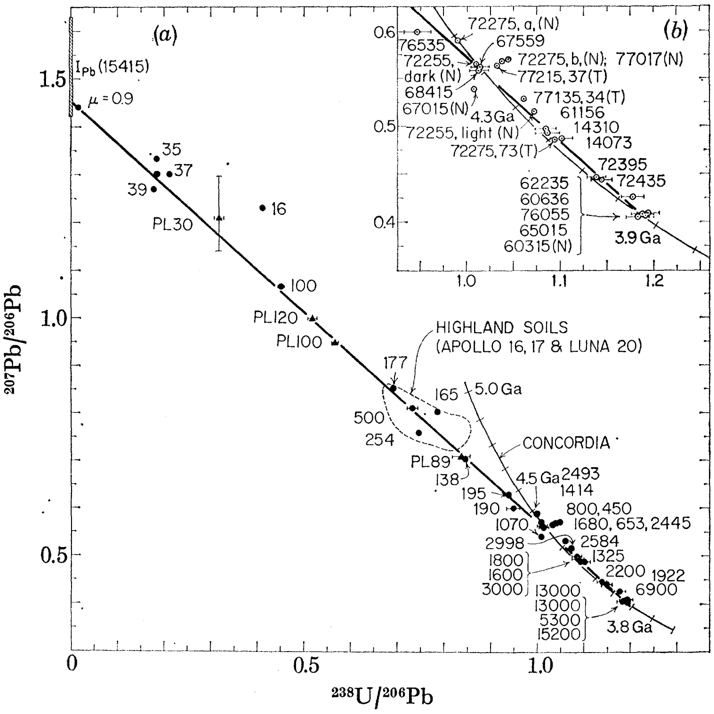

FIGURE 13. Pb-U evolution diagram for highland rocks. Note small curvature of the concordia curve. Plagioclase mineral separates are indicated by PL. The value of $\mu = {}^{238}U/^{204}Pb$ is given by each data point. Inset shows details near concordia and includes sample numbers. Data from this laboratory are shown with error bars.

Moon, while the uranium and thorium, being much less volatile, remained in the rocks (Tera *et al.* 1974). Rocks which suffered almost complete Pb loss would give concordant or nearly concordant ages reflecting the time of the impact and would have very high μ values. The Pb that was removed from these rocks would in part be deposited on various debris, thereby increasing the ^{204}Pb content and decreasing the μ value of this material. The fact that the data do not form a precise array may in part be due to a variety of ages of the target material. The variability of the ages of the target materials is clearly manifested in the wide range in the isotopic composition of 'initial' lead obtained for the anorthosite 15415. In spite of these complexities, the average value for the initial radiogenic $^{207}Pb/^{206}Pb$ at ~ 3.95 Ga appears well defined at $I_{Pb} = 1.45$.

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Because of the variety of selenographic localities that appear to follow the regular Pb-U relations, we must conclude that the impact metamorphic events were intense and widespread enough to dominate the debris blankets over the whole earth-facing side of the Moon. This interpretation is fully compatible with the Rb-Sr and K-Ar results and had first been inferred from Rb-Sr observations on the Apollo 14 and 16 samples (Papanastassiou & Wasserburg 1972). Estimates of the recrystallization ages for highland breccias by Rb/Sr analyses are all in the range of 3.8–4.0 Ga. A comparable range in ^{40}Ar retention ages is determined from ^{40}Ar-^{39}Ar studies of most such rocks. These ages date very large impacts on the lunar surface capable of metamorphosing the rocks during the event or by burial in the hot ejecta blanket or of exhuming them from depths of active metamorphism and degassing. The 3.90 Ga ages on metaclastic rock fragments from the Luna 20 site, which is far removed from Imbrium and least effected by Imbrium ejecta, provide evidence for multiple large impacts during 3.8–4.0 Ga (Podosek *et al.* 1973).

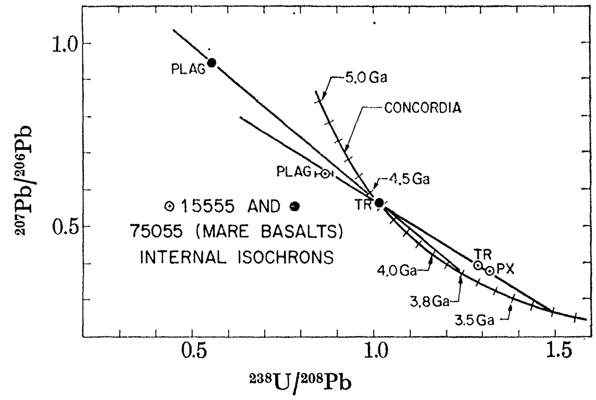

FIGURE 14. Internal Pb-U isochrons for two mare basalts. The Apollo 17 mare basalt has a crystallization age of 3.8 Ga while the total rock lies on concordia at 4.42 Ga. The Apollo 15 basalt has a crystallization age of 3.3 Ga and the total rock is discordant. Note that for both basalts, isochrons of distinctly different ages cross concordia at 4.42 Ga, indicating that this is the time of major lunar differentiation.

Mare basalts

While there are numerous results on total rock samples of mare basalts, there is only limited data for internal isochrons due to the technical difficulty of carrying out contamination-free mineral separations and chemistry on phases low in lead. Two important samples are shown in figure 14. These rocks represent some of the older and younger basalts sampled. The Apollo 15 basalt (15555) defines a good isochron with a crystallization age of 3.3 Ga, which is in reasonable agreement with Rb-Sr and K-Ar ages (Tera & Wasserburg 1975). The total rock is discordant and lies on the chord in a position indicating the enrichment of U relative to Pb (see figure 12 for $f > 1$). The presence of initial Pb is made evident from the position of the plagioclase data point.

The results on the Apollo 17 basalt 75055 also show an isochron (two points only) with an age that is in agreement with the Rb-Sr and K-Ar results. The plagioclase data clearly show the presence of initial Pb. The total rock plots on the concordia curve at the precise point of intersection of the internal isochron of the younger A-15 basalt. The Apollo 17 basalt also gives a ^{208}Pb-^{232}Th total rock model age of 4.42 Ga. These observations may be interpreted to indicate that the mare basalts of different ages were derived from magma reservoirs that were initially formed at 4.42 Ga with essentially no radiogenic Pb.

It should further be noted that this upper point of intersection on concordia is almost precisely the same as determined by internal isochrons on Apollo 14 highland basalts (see figure 13). The rather precise numerical agreement of the upper point of intersection on the concordia curve for terra rocks and mare basalts of different ages strongly suggests that the age of 4.42 Ga is the time of major lunar differentiation.

This value of 4.42 Ga is approximately 0.1 to 0.2 Ga younger than values associated with the formation of meteorites and the presumed formation age of all the other planetary bodies. This younger apparent age also has been found for the Earth, using terrestrial Pb samples of different ages. Assuming the meteorite ages to be correct, we believe this discrepancy to reflect major chemical fractionation processes on the planets subsequent to their formation or else the later accumulation and formation of some planets coupled with major chemical fractionation. These conclusions will require far more stringent testing, but there is little doubt of the general inferences.

The $^{238}U/^{204}Pb$ (μ) of all mare basalts is observed to be quite high ($\sim$ 200); however, the μ of their primary source is not so well defined. In particular, the existence of very low μ sources has been proposed by Tatsumoto *et al.* (1973) for the orange soil from Apollo 17. This may be a key to major chemical layering in the lunar mantle.

Lunar chronology evolution and structure

Isotopic analyses of returned lunar samples have permitted the establishment of a rather comprehensive time scale for the Moon. The Earth and the Moon are the only planets for which extensive information now exists on their history.

The true importance of the lunar time scale is in the inferred relationships between age determinations on particular rocks and the significant events in lunar history. Insofar as the connection between the ages, the rock types and major events in lunar history may be properly ascertained, it should be possible to construct a true model of lunar evolution and structure.

We will attempt here to outline a history of lunar evolution based on the arguments outlined in this paper. Such an attempt must be considered preliminary since far more extensive studies will be required before a true understanding is possible.

An oversimplified view

The protoplanetary bodies from which the Moon formed were separated out of the solar nebula with major chemical fractionation between 5 and 10 Ma after the earliest known condensates as determined from initial Sr values. The actual time of aggregation of the Moon is not precisely known, but the Moon existed as a planetary body at 4.45 Ga, based on mutually consistent Rb-Sr and U-Pb data. This is remarkably close to the ^{207}Pb-^{206}Pb age of the Earth and suggests that the Moon and the Earth were formed or differentiated at the same time. If the Moon formed at 4.55 Ga, the radiogenic Pb produced before 4.45 Ga was either lost by volatilization or was buried in a lunar core with other siderophile elements. In the neighbourhood of 4.45 Ga, the Moon underwent major differentiation to produce a crust enriched in K, Rb, U, Th and associated elements and a mantle which was correspondingly depleted. Fractionation of the rare earths took place during this process and the Eu-depleted and Eu-enriched magma reservoirs were concurrently generated. The distinctive magma reservoirs from which later mare basalts derived were formed about this time. At least a small percentage of the mass of the Moon must have been molten in order to provide a sufficient separation of the fractionated chemical elements. Magmatic processes produced not only a low melting fraction but were extensive enough to produce large masses of cumulate rocks characteristic of basic to ultrabasic magmas. The recent discovery by Lee *et al.* (1976) of abundant ^{26}Al in the early solar nebula at the time of condensation and aggregation can provide the basic heat source for early and rapid melting of planets and small planetesimals.

Major lunar differentiation was completed in 0.1 to 0.2 Ga, and the outer ~ 100 km of the Moon became quite rigid. The rate of volcanism after the initial lunar differentiation was low, and the nature of the volcanic rocks produced were distinct from the later mare basalts. The bombardment rate between 4.4 and 4.0 Ga was very high so that the old lunar crust was highly comminuted and the major primary features were destroyed. An epoch of massive bombardment occurred at about 3.95 Ga. This was the terminal lunar cataclysm which produced sufficient debris of metamorphosed materials as to dominate the age pattern over wide areas of the Moon. After 3.8 Ga the bombardment rate suddenly became quite low, thereby preserving the features of younger lava flows. The large impacts at ~ 3.95 Ga generated zones of weakness that penetrated to depths of 200 km or more and triggered the mare volcanism which flooded the impact basins and large depressions. The basaltic rocks represent partial melts derived from magma reservoirs formed during early lunar differentiation. The basalt flows were in general thin sheets, and thick piles only accumulated in deep basins. The mare basins were repeatedly flooded with basalts over a period of a few hundred million years. Many of the basalts penetrated highly fractured ancient radioactive crustal rocks which were thoroughly assimilated. The basalt flooding peaked immediately after the terminal lunar cataclysm and subsequently decreased as the zones of weakness were healed. At about 3.0 Ga the major fracture zones were closed, and the outer mantle and crust became a rigid barrier.

The deep interior of the Moon today remains at elevated temperatures just at the liquidus, but no tectonic forces exist to permit further volcanism.

The time notation used in this paper is the Ga, which is equal to 1 AE or 10^9 years.

In addition to the data obtained at this laboratory, we have utilized a large amount of data from the literature. These include the Pb-U data of P. D. Nunes and M. Tatsumoto, Sr-Rb data of L. E. Nyquist and of C. J. Allegre on Juvinas. We have profited much from models of lunar differentiation proposed by J. A. Wood and colleagues, by S. R. Taylor and P. Jakes, and by D. Walker and colleagues. All of us have profited from the many ideas and contributions of P. W. Gast.

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