30 July 1971, Volume 173, Number 3995 SCIENCE

Of Time and the Moon

Dating of lunar materials reveals the early history of an observable planetary body.

George W. Wetherill

The American cool was becoming a narcotic. The horror of the Twentieth Century was the size of each new event, and the paucity of its reverberation.—NORMAN MAILER, *Of a Fire on the Moon*

The current series of Apollo lunar missions, together with the unmanned Surveyor, Orbiter, and Soviet missions, permit for the first time a rather detailed study of the formative stage of a planetary body. Prior to the Apollo landings, many National Aeronautics and Space Administration and National Academy of Sciences study groups produced documents predicting that lunar exploration would enable us to understand the origin of the moon, the earth, and the solar system. To some, these statements probably seemed to be exaggerations calculated to persuade Congress and the public to provide the necessary financial support. But to a large measure these predictions have proven to be true, and it may be expected that lunar data will both supplement and supplant meteoritic data as the primary source of information about the origin and early history of the earth and solar system. For this reason, the continuing supply of data obtained from the returned lunar samples, from the geophysical instruments emplaced on the lunar surface, and from the experiments to be carried out in lunar orbit deserve to be followed closely by the scientific community, particularly by earth scientists. This new source of information comes at a time when earth scientists are to some extent overwhelmed with the necessity of incorporating into their thinking new concepts, particularly those arising from the discovery of sea floor spreading and plate tectonics. This wealth of understanding concerning the origin and evolution of the earth, as well as fundamental earth processes, may well lead to a renaissance in earth science, especially at a time when great concern as to the future of the earth should serve as an incentive to understanding our planet.

The author is professor of geophysics and geology in the Department of Planetary and Space Science, University of California, Los Angeles 90024.

Rb-Sr Evidence for Primordial Geochemical Differentiation

Measurements on samples returned from Apollo 11 and 12 have shown that the composition of the source of lunar rocks differs significantly from the average composition of the solar system, as indicated by the composition of the sun and of the most abundant and least differentiated class of meteorites, the chondrites. Furthermore, this difference was established very early in the history of the solar system, 4.5×10^9 to 4.6×10^9 years ago. It is quite likely that this primordial differentiation, which depleted the moon of relatively volatile elements such as potassium, rubidium, and lead, took place in the solar nebula, or in a protomoon, prior to the final accretion of the moon.

Evidence for this primordial fractionation is provided by the isotopic composition of strontium separated from lunar rocks and minerals. Radiogenic ^{87}Sr is generated by the beta decay of ^{87}Rb, with a half-life of 5×10^{10} years, so that the ratio of ^{87}Sr to the nonradiogenic isotope ^{86}Sr increases with time. The rate at which this ratio increases is proportional to the ratio $^{87}Rb/^{86}Sr$. The lowest $^{87}Sr/^{86}Sr$ ratio found in any natural sample is in the achondritic meteorite Angra dos Reis and is equal to 0.69884 ± 0.00004, which indicates that this ratio was at least this low at the time of contraction of the solar nebula. Similar measurements on the more abundant basaltic achondrite meteorites give an only slightly higher value of 0.69898 (*1*). Measurements on the chondrite Guareña (4.53×10^9 years old) (*2*) show that, at the time chemical equilibrium was established within this meteorite sample, the ratio $^{87}Sr/^{86}Sr$ had risen to 0.69995. For a typical chondritic $^{87}Rb/^{86}Sr$ ratio of 0.75, this increase of ~ 0.001 requires only 100 million years; and for a solar $^{87}Rb/^{86}Sr$ ratio of 2.25, it requires only about 30 million years. Furthermore, measurements in chondrites of ^{129}Xe, formed by the decay of the now extinct (17-million-year half-life) natural radioactivity ^{129}I, show that the parent body of the chondrites crystallized within approximately 100 million years of the time of formation of the solar nebula, from which the sun and planets subsequently formed (*3*). Consequently, any object less than 4.5×10^9 years old which has had a ratio of $^{87}Sr/^{86}Sr$ less than about 0.700 was derived from a source which underwent a significant depletion in Rb relative to Sr within the first 100 million years of solar system history.

Initial $^{87}Sr/^{86}Sr$ ratios for typical lunar rocks and minerals are shown in

Fig. 1. Knowledge of their present $^{87}Sr/^{86}Sr$ ratios, together with their age (discussed later), permits extrapolation of the $^{87}Sr/^{86}Sr$ ratio of each sample back to that at the time of its formation; this initial ratio is given by the intercepts on the ordinate of the lines representing the growth of $^{87}Sr/^{86}Sr$ with time for each of these samples. All of these initial values are less than the value for the chondrite Guareña, and but slightly higher than the ratio found in the chondrite Angra dos Reis. In fact, for some of the samples (for example, the plagioclase feldspar from basalt sample 10017) even the *present* $^{87}Sr/^{86}Sr$ ratio is less than 0.700, and the extrapolation back to the even lower initial ratio is insensitive to any possible error in the age of the sample. These results show that the source from

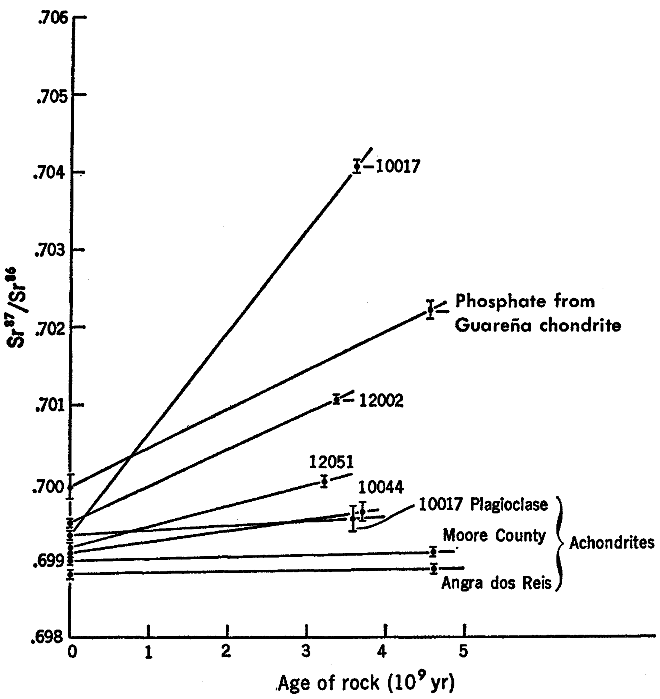
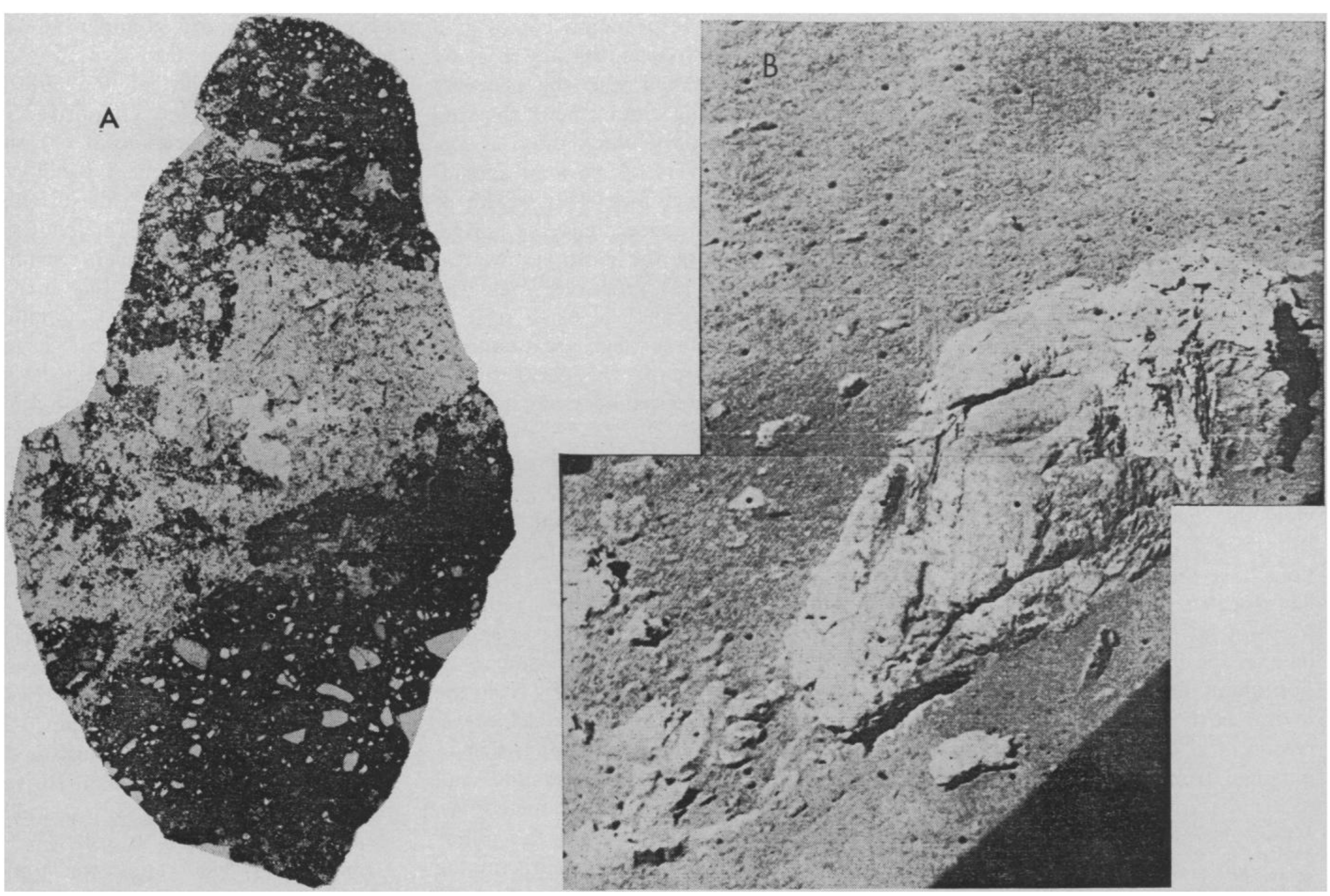


Fig. 1 (left). Extrapolation of measured $^{87}Sr/^{86}Sr$ ratios back to the value at the time of formation of the rock. The initial values for lunar rocks fall between the values found for achondritic and chondritic meteorites (Data primarily from Wasserburg and co-workers).

Fig. 2 (below). (A) Thin section of lunar rock 12013, a breccia containing light and dark regions with numerous included rock fragments. Horizontal dimension of thin section is 1.2 centimeters. Total weight of rock is 82 grams. (B) Large lunar rock (~ 50 centimeters) with light and dark portions, photographed by Surveyor I, in western Oceanus Procellarum.



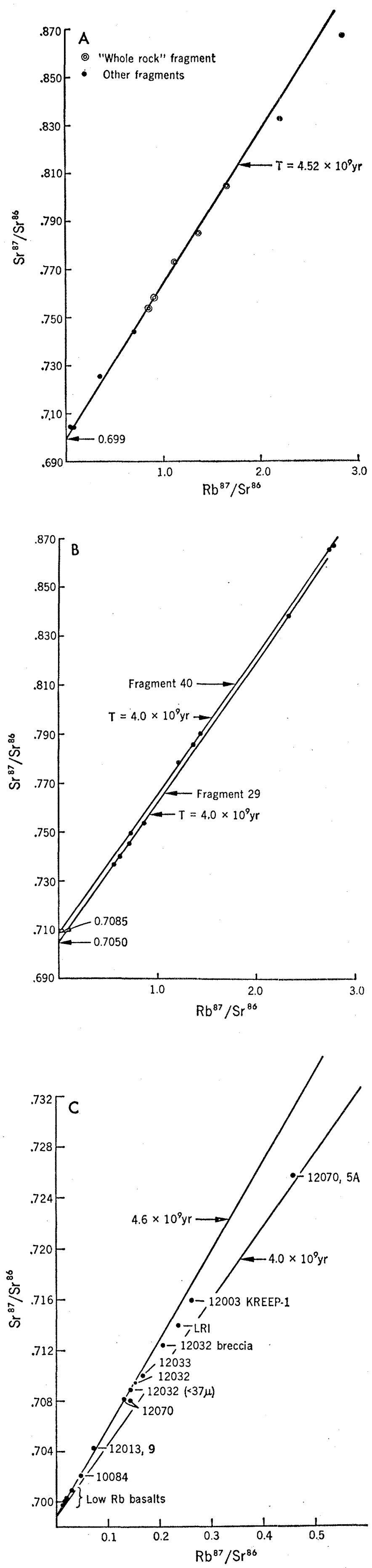


Fig. 3. (A) Rubidium-strontium data of Asylum (*5*) for rock fragments from rock 12013. The points lying along the isochron marked "4.52×10^9 years" represent material that has been enriched in Rb relative to Sr very early in lunar history. (B) Rubidium-strontium data of Asylum (*5*) for minerals separated from fragments of rock 12013. The mineral points lying on the two distinct isochrons are interpreted to be part of $\sim 4.5 \times 10^9$ year-old rocks which were metamorphosed 4.0×10^9 years ago. (C) Rubidium-strontium data for materials separated from the lunar soil indicate that these soils contain a component which was involved in differentiation very early in lunar history.

which these rocks were derived has not had a chondritic $^{87}Rb/^{86}Sr$ ratio since the formation interval of the solar system. This depletion in Rb relative to Sr could have taken place in that portion of the solar nebula which subsequently accumulated to form the moon, or alternatively, the region in the moon from which these basalts were derived was depleted in Rb immediately following formation of the moon, with the concomitant enrichment in Rb of some other portion of the moon, presumably a region nearer the surface. Because of their chemical similarity a similar depletion in K should also have occurred.

Rb-Sr Evidence for Subsequent Early Geochemical Differentiation

Regardless of the site of lowering of this primordial Rb/Sr ratio, there is evidence that, in addition, some portions of the moon underwent a possibly subsequent, but nevertheless, early, enrichment in Rb relative to Sr. This is most clearly shown by rock 12013, collected on the Apollo 12 mission. Studies of thin sections of this rock (Fig. 2A) indicate that this is a breccia consisting of dark fragments, which have been intruded by a matrix of lighter material. Analyses of this rock (*4*) show that neither the light nor the dark portions of this rock are similar in composition to the more common mare basalts returned by Apollo 11 and 12. Rock 12013 is enriched in the elements K, Rb, Ba, and the rare earths by a factor of about 10.

At the time this rock was found, it seemed possible that it was an extreme differentiate occurring at the top of a layered igneous body, the average composition of which was more similar to the basaltic rocks at this site. However, subsequent Rb-Sr measurements indicate that this rock is considerably older than the basaltic rocks, which have an age of 3.3×10^9 years. Figure 3A shows the results of Rb-Sr measurements carried out by Asylum (*5*) on individual fragments from this rock, plotted on a Sr evolution diagram. The open circles represent fragments of "whole rock systems," and the closed circles are fragments more likely to be similar to mineral separates. If $^{87}Rb/^{86}Sr$ ratios are plotted against $^{87}Sr/^{86}Sr$ ratios for each of an assemblage of closed chemical systems a straight line will result if all of the systems had the same $^{87}Sr/^{86}Sr$ ratio at some time in the past (*6*). The slope of this line is a function of the time elapsed since all of these systems had their common ratio, and the initial ratio itself is given by the intercept of this line with the ordinate. Such would be the case for a group of rocks separated from a common magma source, an assemblage of minerals crystallizing from a melt, or a metamorphic assemblage of minerals forming in chemical equilibrium as a result of a metamorphic event subsequent to the original crystallization of the rock. The "whole rock" points in Fig. 3A fall along the line marked "4.52×10^9 years," so that all of these fragments were probably involved in a fractionation of Rb relative to Sr at this time in the past, and at that time they possessed a common $^{87}Sr/^{86}Sr$ ratio equivalent to that found in achondritic meteorites. This age is the same as that obtained by similar measurements on minerals separated from chondrites (*1, 2, 7*) or on measurements on whole meteorites (*7, 8*), and represents a time during the formation interval of the solar system.

Similar data obtained from individual minerals separated from two rock fragments of sample 12013 are plotted in Fig. 3B. These also fall along straight lines, but with slopes corresponding to an age of 4.0×10^9 years, which may be interpreted as a time of subsequent metamorphism, possibly related to the time at which the fragments were assembled into a breccia. This age of 4.0×10^9 years has also been obtained by K-Ar measurements (*9*).

It does not seem likely that rocks similar to 12013 are extremely rare. An 83-milligram fragment (LR-1) similar to some parts of 12013 has been found in a soil sample from Apollo 11 (*10*).

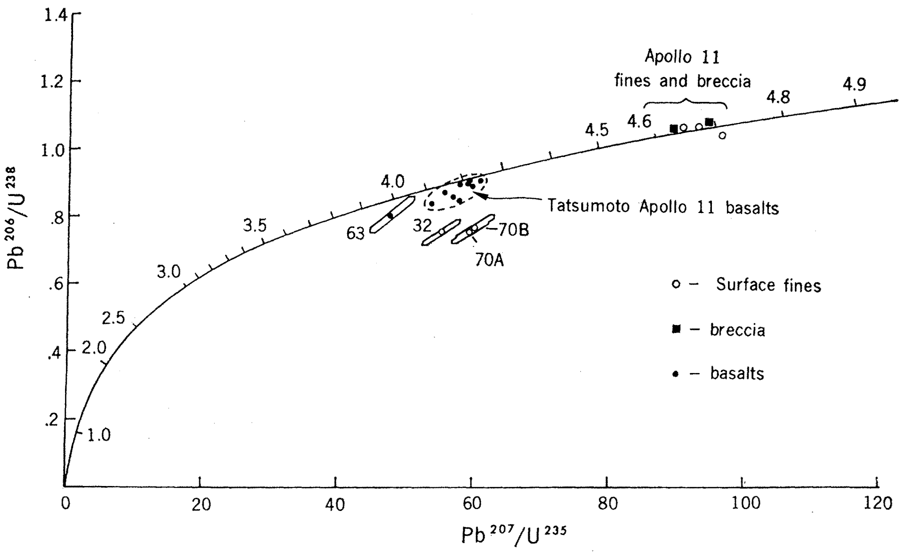


Fig. 4. Uranium-lead data for lunar rocks. All of the Apollo 11 fine soil and breccia give essentially concordant ages of 4.6×10^9 to 4.7×10^9 years. The Apollo 11 basalt data of Tatsumoto (*16*) gives "apparent" U-Pb ages of $\sim 4 \times 10^9$ years, which are actually not in conflict with 3.6×10^9 year Rb-Sr and K-Ar ages on these same rocks, as discussed in text. A typical Apollo 12 rock (12063) gives slightly younger apparent ages.

Measurements of various soil samples from Apollo 12 (Fig. 3C) indicate that the Rb and radiogenic Sr of soil at the Apollo 12 site are entirely dominated by a 4.5×10^9 year old component, and individual rock types [microbreccia (*11, 12*) and "KREEP" glass (*13*)] separated from these soil samples are even richer in this component. Apollo 11 soil, while containing less Rb and less radiogenic ^{87}Sr, nevertheless also falls on the 4.6×10^9 year line (isochron) in Fig. 3C (*10*). Rocks resembling 12013 in appearance have also been photographed by Surveyor I (Fig. 2B). It seems very likely that lunar igneous rocks are not limited to the common mare basalts, but also contain abundant differentiated rocks of varied compositions, many of which differentiated very early in the history of the moon and the solar system.

U-Pb and Th-Pb Evidence for Early Geochemical Differentiation

Additional evidence for primordial differentiation may be obtained from measurements of radiogenic Pb from lunar materials and its associated parent isotopes of uranium and thorium. The isotopic composition of Pb from lunar rocks and soil samples is entirely different from that found in analogous terrestrial materials. Lunar rocks have much higher ratios of the radiogenic isotopes ^{206}Pb, ^{207}Pb, and ^{208}Pb, relative to the nonradiogenic isotope ^{204}Pb (*14–16*). This is because the lunar abundance of ^{204}Pb is lower than that found in similar terrestrial rocks by a factor of the order of 100. These data indicate that the moon has been very much depleted in the relatively volatile Pb, and that essentially all of the Pb on the moon has formed as a consequence of the radioactive decay of U and Th.

The isotopic composition of Pb can also be used to show that this gross depletion of Pb relative to the refractory U and Th also took place very early in lunar history, quite likely during the process of lunar formation. The parent of ^{207}Pb, ^{235}U, is quite short-lived (its half-life is 0.7×10^9 years), and consequently is nearly, but not quite (unfortunately?) an "extinct" radioactivity. Highly radiogenic Pb very rich in ^{207}Pb, as is the case for lunar Pb, must therefore have formed very early in the history of the solar system, prior to the decay of most of the ^{235}U.

A quantitative extension of this qualitative argument leads to the conclusion that this early depletion in Pb relative to U and Th took place between 4.6×10^9 and 4.7×10^9 years ago. Figure 4 shows the results of U-Pb analyses of Apollo 11 soil samples plotted on a "concordia" diagram. The Pb isotopic composition has been corrected for primary Pb by subtraction of a component with the isotopic composition of primordial Pb, as given by Pb from the troilite (FeS) of iron meteorites (*17*). Because the lunar ratios of $^{206}Pb/^{204}Pb$ (~ 262) and $^{207}Pb/^{204}Pb$ (~ 171) are so high, the result is insensitive to this correction. The concordia curve is the locus of chemical systems for which the ages calculated from the ratio $^{206}Pb/^{238}U$ are the same as those calculated from the ratio of $^{207}Pb/^{235}U$ (*18*). This common "concordant" age can be read from the scale marked along concordia. Figure 4 shows that samples of soil and breccia (essentially compacted soil) from Apollo 11 fall on concordia at an age of 4.6×10^9 to 4.7×10^9 years. Thus the Apollo 11 soil appears to represent a closed system which was enriched in U and Th relative to Pb about 4.65×10^9 years ago, and has not experienced a major U-Pb fractionation since that time. Remarkably, this same result was obtained for the ^{232}Th-^{208}Pb age. This age of 4.65×10^9 years obtained from these data has been interpreted as the age of the moon (*15, 16*). This is a plausible inference, because more detailed discussions show that this result is unlikely on a body significantly less than 4.65×10^9 years old, whereas a moon significantly older would be in conflict with the age of the solar system, as calculated from meteoritic data.

At the time this result was first reported, there was considerable discussion both in the press and within the scientific community as to how it was possible for the soil samples to be older than the rocks (3.6×10^9 years by Rb-Sr dating) from which they presumably were derived. In many of these discussions, there was at least an implicit assumption that some kind of logical paradox was thereby involved. This is not the case. For example, if lunar basalts were formed 3.6×10^9 years ago, and if, at least on the average, there were no U-Pb or Th-Pb fractionations at the time of their formation, then this is exactly the result which would be found. Therefore, the paradox, if any, is a geochemical one, and not a logical one.

Apollo 12 soils and breccia differ from those at Apollo 11 in that they do not give concordant U-Pb and Th-Pb ages (*12, 19, 20*). When plotted on a concordia diagram, they fall along a line approximately joining the concordant Apollo 11 points and a point on the concordia corresponding to about 1.5×10^9 years. As was the case for Rb, the

Apollo 12 soil is greatly enriched in U and Th relative to the Apollo 12 rocks; this enrichment is apparently associated with the presence in the soil of at least one component rich in K, Rb, Ba, U, Th, P, and rare earth elements, and this component has been shown (Fig. 3C) to have a Rb-Sr age of 4.5×10^9 years. The U-Pb data may be interpreted as indicating an age of 4.5×10^9 years for the source of this component; however this component has lost Pb relative to U and Th at some much more recent time. A simple two-stage model for this loss implies that the loss took place $\sim 1.5 \times 10^9$ years ago. This model is by no means unique. However, all plausible models imply that at least some Pb loss took place this recently. A highly speculative interpretation of these data would be that this component was ejected from a deeper layer in the moon at the time of formation of a large nearby crater—for example, Copernicus—that the loss of Pb resulted from vaporization of Pb from the hot ejecta, and that consequently the crater formation took place $\sim 1.5 \times 10^9$ years ago. This is a very interesting possibility, but it is not free from difficulties.

Time of Filling of the Lunar Maria

A key question in any discussion of lunar chronology is that of the time at which the dark mare regions were filled with the basaltic rock now present in these regions, and the related question as to whether mare filling was a single event, or took place at various times in lunar history. Data obtained from Apollo 11 and Apollo 12 samples have given some clear answers relevant to these questions.

The Apollo 11 basalts fall into two discrete groups, one characterized by Rb concentrations of about 6 micrograms per gram of sample, the other by Rb concentrations of about 1 microgram per gram of sample; corresponding differences are found for many other minor elements (*21*). It is possible that these two groups merely represent two different lava flows underlying the soil at this site. Measurements of Rb and Sr have been carried out on rock from both of these groups, in order to determine the time since the rock was crystallized (*10, 15, 21*). Although the enrichment in radiogenic Sr is very low, definitive ages have been obtained.

Both the high (Fig. 5A) and the low Rb groups were formed 3.61×10^9 years ago. Although both of these groups were formed at nearly the same time, they cannot be interpreted as representing differentiation from a common source at the time of extrusion, because their initial $^{87}Sr/^{86}Sr$ ratios are distinctly different. In addition, the initial $^{87}Sr/^{86}Sr$ ratios of the high Rb group rocks is lower than that predicted for a 3.6×10^9 year magma source with the Rb/Sr ratio of these rocks. The initial ratio is consistent with an approximately threefold enrichment in Rb relative to Sr at the time the rocks were formed. On the other hand, the initial $^{87}Sr/^{86}Sr$ ratio of the low Rb rocks does not require this enrichment.

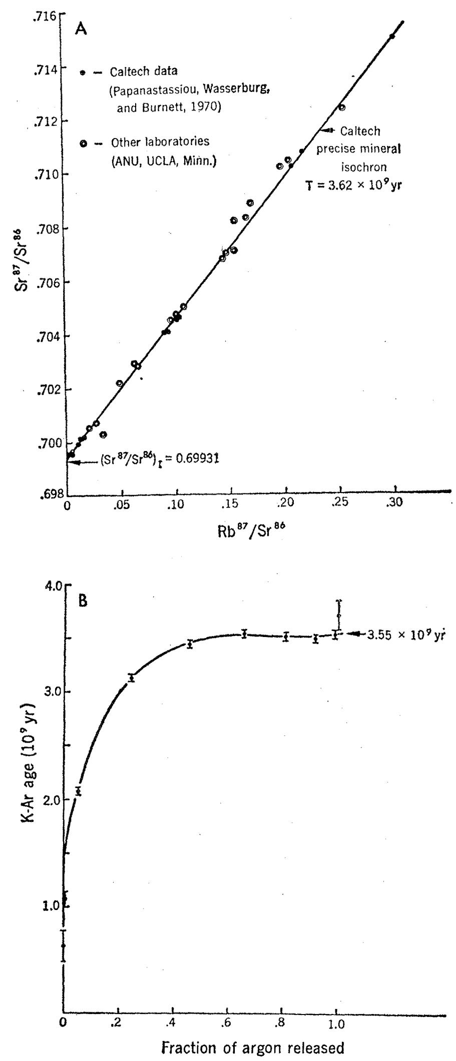


Fig. 5. (A) Rubidium-strontium data for high Rb group of Apollo 11 basalts. Both groups of Apollo 11 basalts have been dated by this method at 3.6×10^9 years. (B) Potassium-argon data of Turner (*23*) obtained by neutron irradiation and stepwise heating of the sample. The "plateau" at 3.55×10^9 years is interpreted as the age of the rock.

Similar Rb-Sr data for the Apollo 12 rocks indicate a distinctly younger age of $\sim 3.25 \times 10^9$ years (*11, 12, 22*); possibly younger rocks with an age of $\sim 2.9 \times 10^9$ years are also present (*22*), but this result requires further confirmation. Like the low Rb group from Apollo 11, the initial ratios found for the Apollo 12 basalts require no major Rb-Sr fractionation between the rocks and their source.

Preliminary K-Ar data indicated that the Apollo 11 and Apollo 12 basalts are considerably younger than these Rb-Sr ages (*4*), but more refined K-Ar measurements have been reported by Turner (*23*) which are in generally good agreement with the Rb-Sr data. These more accurate data have been obtained by the step-heating method of Merrihue and Turner (*24*), and involve irradiation of the sample with energetic neutrons converting ^{39}K to ^{39}Ar by an (n, p) reaction. The sample is then heated in vacuum to successively higher temperatures, and an age calculated from the $^{39}Ar/^{40}Ar$ ratio measured on the gas released following each heating step. In most cases (Fig. 5B), a plateau is reached; at higher temperatures a nearly uniform age is found. This high temperature data is interpreted to represent sites in which radiogenic ^{40}Ar is quantitatively retained, and hence these plateau ages represent the true age of the rock. Ages are found by this method to be from 3.5×10^9 to 3.8×10^9 years for the Apollo 11 rocks, and from 3.2×10^9 to 3.3×10^9 years for the Apollo 12 rocks. These are similar to ages obtained by the Rb-Sr method, although in some cases the K-Ar ages are apparently 200 million years older; this slight discrepancy remains to be explained.

The interpretation of the U-Pb and Th-Pb ages for these basaltic rocks is less straightforward. In principle, one should be able to separate minerals from each of these rocks, and obtain ^{238}U-^{206}Pb, ^{235}U-^{207}Pb, and ^{232}Th-^{208}Pb isochrons analogous to those found by the Rb-Sr method. This has been attempted by Tatsumoto (*16*), but the data have considerable scatter and are only roughly in agreement with the Rb-Sr results. The cause of the scatter has not been definitely established; however, it may be caused by terrestrial Pb contamination, in spite of the fact that Tatsumoto has achieved lower contamination levels than anyone else working on this problem. Analytical errors, possibly associated with equilibration of the isotopic tracers used in the isotope dilution analysis, may also play a role. Furthermore, in contrast to the case of Rb-Sr, for which a large number of internal mineral isochrons have been obtained there is no backlog of analogous U-Pb and Th-Pb age data for terrestrial rocks. It may be that U and Th and their Pb daughters are not sufficiently tightly bound to sites in their host minerals in basaltic rocks to fulfill the closed system requirement essential to interpretation of these data as an age. A corollary of this failure to obtain internal isochrons for lunar rocks is that we have no idea what isotopic composition should be assumed in calculating whole rock U-Pb and Th-Pb ages for these rocks. We have seen that lunar Pb is extremely radiogenic because the ratio of $^{238}U/^{204}Pb$ in lunar rocks is ~ 1000, in contrast to the average terrestrial ratio of 9. These lunar rocks were almost certainly derived from a source which also had a very high ratio of $^{238}U/^{204}Pb$ and consequently it would be grossly incorrect to use terrestrial Pb data to estimate the initial isotopic composition of lead in a lunar basalt.

Thus, it is not possible at the present time to calculate meaningful U-Pb and Th-Pb ages for lunar rocks. It is possible, however, to discuss the extent to which those measurements which have been made on lunar rocks are consistent with the Rb-Sr and K-Ar data which have already resolved the question of the age of these mare basalts.

The lunar basaltic magmas probably undergo U-Pb fractionation similar to that of terrestrial basalts at the time of their formation. Tatsumoto (*25*) has published data for modern terrestrial basalts, which are plotted on a concordia diagram in Fig. 6A. In calculating the radiogenic $^{206}Pb/^{238}U$ ratios for this figure, the Pb isotopic composition has been corrected by subtraction of the primordial Pb present at the time the earth was formed, as indicated by meteoritic data (*17*). It may be seen from Fig. 6A that the resulting data points from these new basalts with an age of zero do not lie at the origin of the concordia diagram, but are spread out, with some scatter, along a line extending from the origin through a point on concordia corresponding to $\sim 4.55 \times 10^9$ years. This indicates that basalts invariably contain some radiogenic Pb at the time of their formation; those points lying above the concordia curve in Fig. 6A correspond to basaltic magmas for which the $^{238}U/^{204}Pb$ ratio was fractionated so as to decrease this ratio in the magma relative to the average mantle ratio of 9; those points lying below concordia correspond to basaltic magmas which were enriched in ^{238}U relative to the value in their source. Both types of fractionation are common, and on the average the $^{238}U/^{204}Pb$ ratio of basalts may be about the same as that of their source.

Data of this kind exist only for modern terrestrial basalts, that is, those of zero age. If it is assumed that similar processes occurred during the first billion years of earth and lunar history, these results can be used to "predict" what 3.6×10^9 year lunar basalts should look like when data from them is plotted in this way (Fig. 6B). The points are spread out along a line extending from 3.6×10^9 years on the concordia curve through 4.6×10^9 years on the curve. This line passes through Tatsumoto's Apollo 11 data (Fig. 4), within their experimental errors. Tatsumoto's data appears to be less affected by terrestrial contamination than that obtained in other laboratories, and consequently it is the best data to use for this comparison. Therefore, the U-Pb data do not conflict with the Rb-Sr and K-Ar data on these rocks. A

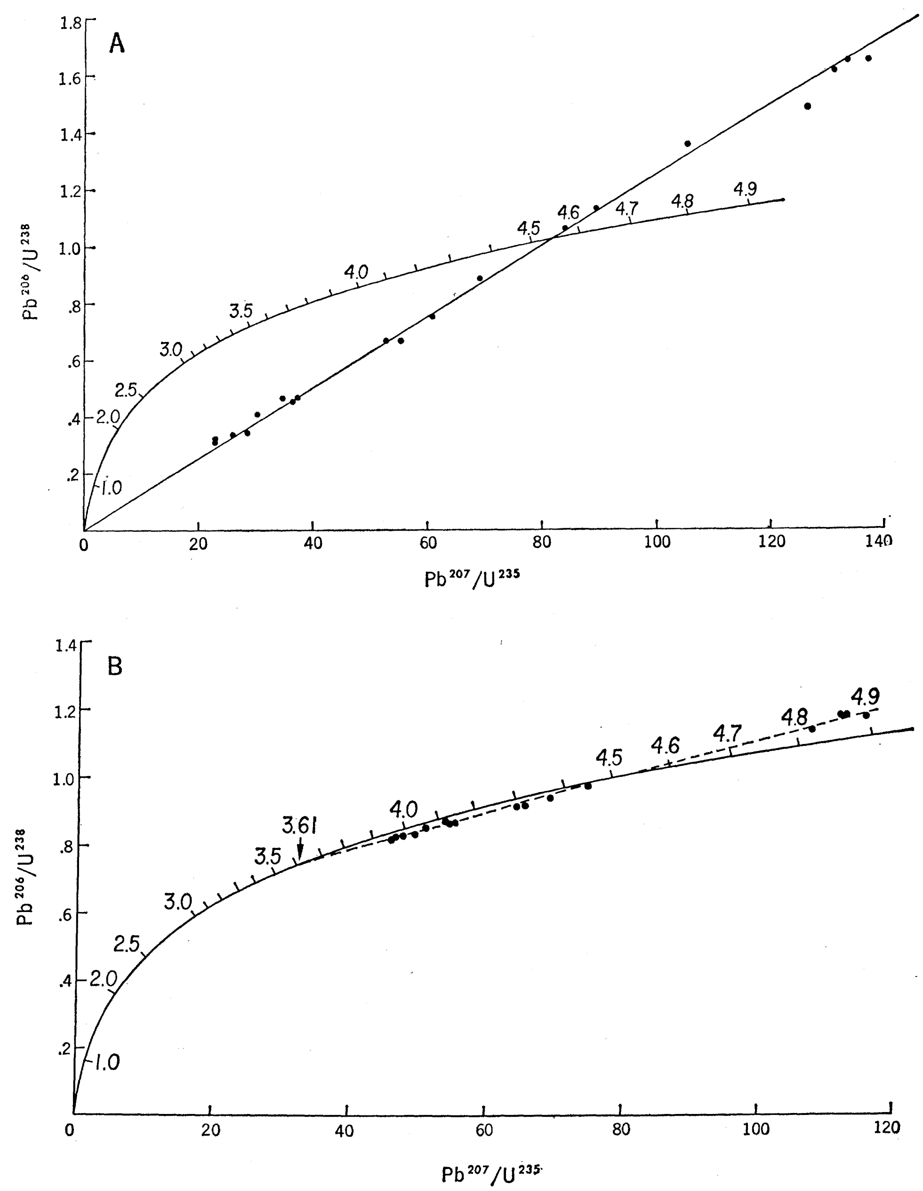


Fig. 6. (A) Data of Tatsumoto (*25*) for terrestrial basalts plotted on a concordia diagram after subtraction of the primordial Pb present at the time the earth was formed. The points scatter about a line passing through the origin and the point on concordia representing the age of the earth. (B) "Predicted" distribution of points representing 3.6×10^9 year old basalts, based on data of (A).

similar comparison for Apollo 12 basalts leads to the same conclusion.

It may be asked why all of the lunar data occupy a relatively limited portion of the line. This would imply a similar U/Pb fractionation factor relative to their source for all these rocks. It is quite likely that the Apollo 11 data represent but two lava flows. Terrestrial data do not exist for multiple samples from an identical lava flow. However, data obtained on subsequent flows from the same source give $^{238}U/^{204}Pb$ ratios similar to one another (*26*). Because of the limited number of flows sampled, no explanation may be required for the clustering of the lunar data nor for the fact that all the lunar data plot below the concordia curve, while the terrestrial data fall both above and below the curve. On the other hand, this latter fact could represent a systematic difference between lunar and terrestrial basalts, a systematic Pb volatilization occurring when a thin lava flow is exposed to the lunar vacuum. In considering this possibility it must be recognized that the Rb-Sr data for soil (Fig. 3C) gives no evidence that Rb was lost from the Rb-rich component of the soil, in spite of the fact that a considerable fraction of this Rb-rich component is contained in glassy material which was almost certainly exposed to the lunar vacuum in the form of liquid droplets. Significant Rb loss would increase the scatter in these points and cause at least some of them to fall well to the left of the 4.6×10^9 year isochron. Laboratory data on the volatilization of Pb relative to Rb is not definitive (*12, 27*), but it is quite likely that significant Pb loss must be accompanied by similar loss of Rb and K.

The above discussion suggests several possibilities about the concordant 4.6×10^9 year ages found for the Apollo 11 soil. First, if lunar basalts, like terrestrial basalts, undergo both U/Pb enrichment and depletion relative to their source, points both above and below concordia on the dashed line in Fig. 6B should occur, and these could average to give concordant ages. This would require that there be nearby basalts which would lie above concordia; the sampling at the Apollo 11 site was certainly not complete enough to eliminate this possibility. This would be particularly likely if there were a major component in the Apollo 11 soil derived from an $\sim 4.4 \times 10^9$ to 4.6×10^9 year old source, because the spread along the line will become less as the age approaches 4.65×10^9 years. It is also possible, in spite of the reservation mentioned in the previous paragraph, that Pb is volatilized from the magma when it flows onto the lunar surface. If this volatilized Pb is mixed into the lunar soil together with Pb derived from the basaltic rocks, the result will be that the soil is effectively a closed U-Pb and Th-Pb system (*21*). This volatilized Pb may be related to the component of old radiogenic Pb which Silver (*14*) has separated from Apollo 11 soil. Because of these possibilities, the coexistence of a 4.6×10^9 year old soil with 3.6×10^9 year old basalts does not necessarily represent a geochemical paradox, and certainly not a logical paradox.

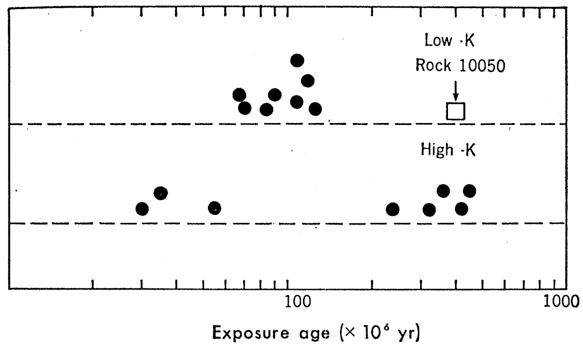


Fig. 7. Data of Eberhardt *et al.* (*29*) shows that the high and low K (or Rb) groups of Apollo 11 basalts can be distinguished by their cosmic-ray exposure ages.

Solar and Cosmic-Ray Bombardment

Another aspect of lunar chronology of considerable importance concerns more recent surface processes resulting from extralunar bombardment by meteoritic bodies. Information bearing on the time scale for these processes can be obtained by techniques which measure the length of time lunar material has been near the lunar surface. These techniques make use of the fact that the lunar surface is bombarded by particles of various energies such as solar wind (1000 electron volts per nucleon), solar flare particles (10 to 100 million electron volts), and galactic cosmic rays (1 to 10 billion electron volts per nucleon). These particles implant in the lunar surface material, cause nuclear reactions in this material which result in the production of both stable and radioactive nuclei, and leave particle tracks as a result of radiation damage produced as the particles traverse lunar minerals. The depths to which these effects extend vary according to the energy of the bombarding particle; the solar wind penetrates only to a depth of 0.1 micrometer, solar flare particles to a depth of several centimeters, and galactic cosmic rays to a depth of several meters. This makes possible the measurement of various "bombardment ages," which, depending on the type of particle studied, permit determination of such quantities as the time since a rock now lying on the surface was ejected from a nearby crater, the rate of turnover of the lunar soil to a given depth ("gardening"), and the time since a sample of lunar material, once on the surface, was buried. A complete review of the experimental data obtained by these techniques, and their theoretical basis, is beyond the scope of this article. However, there is room to outline the principal discoveries that have been made.

It has been determined that the energy spectrum and intensity of solar flare particles has been essentially constant over the last several million years, and some rocks have been within ~ 1 centimeter of the lunar surface for times of the order of 10 million years (*28*). Rocks and soil have been within ~ 1 meter of the lunar surface for times of approximately 450 million years (*29*). The rate at which rocks are eroded by micrometeorite bombardment has been found to be very low (10^{-7} to 10^{-8} centimeter per year) (*30*) and the solar flare bombardment record of a lunar surface rock is more likely to be terminated by burial with ejecta from nearby craters, or by total destruction by bombardment by meteoritic bodies of the order of 1/40 the dimension of the rock itself (*31*), rather than by micrometeorite erosion.

Both the experimental and the theoretical problems associated with obtaining and interpreting these data are complex, and it will probably be some time before many of the details are understood. However, progress to date

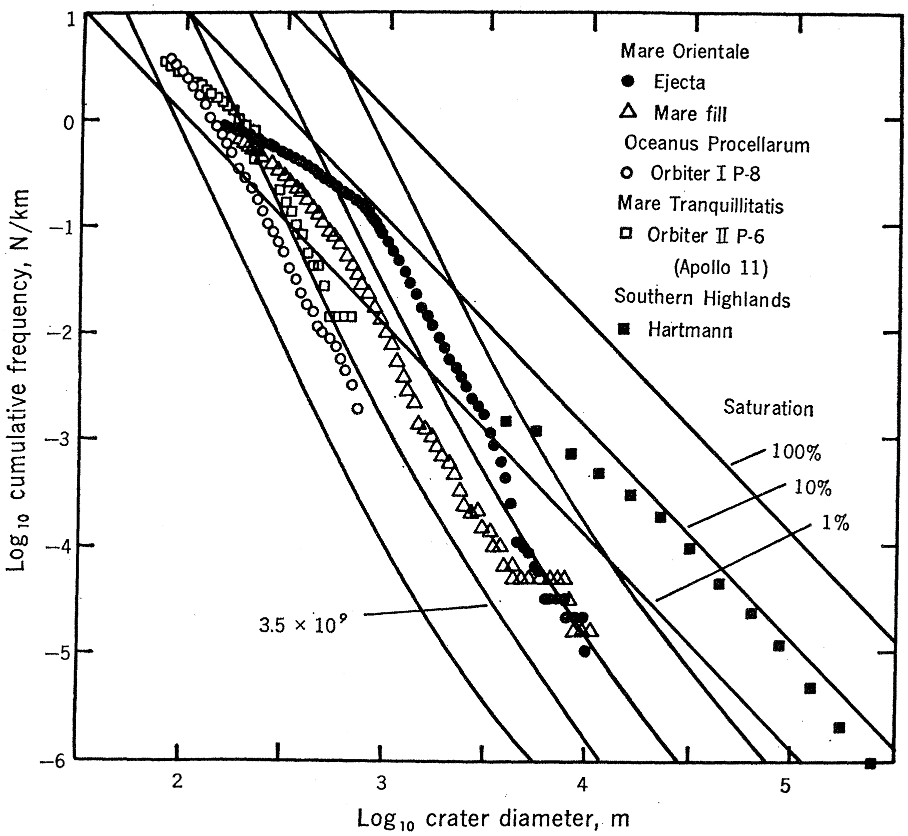


Fig. 8. Data of Gault (*32*) for the density of craters of a given size for several regions of the moon. The curve marked "3.5×10^{9}" fits the Mare Tranquillitatis data which have been dated at this age by the Rb-Sr and K-Ar methods. This curve and the three curves parallel to it represent integral fluxes differing by a factor of 10. The curves labeled "Saturation, 100%, 10%, 1%" are theoretical curves for steady-state crater frequency distributions.

is encouraging. One very interesting example of the potential application of data obtained by these techniques is that reported by Eberhardt *et al.* (*29*) in which they were able to resolve the high and low Rb group of Apollo 11 basalts on the basis of their galactic cosmic-ray bombardment ages. These results are shown in Fig. 7 and indicate that all but one of the low Rb group rocks were exposed for 100 million years, while the high Rb group rocks were exposed for either a shorter or longer period of time. One possible interpretation of the data on the high Rb group is that some of these rocks were formed sufficiently near the surface to allow "prebombardment" prior to their more recent ejection to very near the surface.

Cratering Chronology

Prior to the availability of lunar materials, lunar chronology was entirely based on photogeology, first making use of earth-based telescopic photographs, and later, those obtained from Ranger and Orbiter spacecraft. Photogeology provided chronological data based on the principle of superposition and also by counting the density of craters as a function of diameter in various regions of the moon. On the basis of these techniques, a relative lunar stratigraphy was established. The oldest lunar terranes were in the densely cratered highland regions, which in part have been covered with ejecta blankets from the circular maria. These ejecta blankets are considerably more densely cratered than the material filling the maria, and hence are significantly older. The relatively lightly cratered mare regions are in turn older than the mare craters, such as Copernicus, and also older than some highlands craters such as Tycho. In addition, some younger volcanic regions, such as the Marius Hills, have been distinguished.

Attempts were made to place this cratering chronology on an absolute basis, using observed values for the flux of the crater-forming impacting bodies. A rather complete account of this work has been given by Gault (*32*). The principal conclusions were that the youngest craters were about 10^{7} years old, the mare regions about 10^{8} years old, and the mare ejecta blankets about 10^{9} years old, whereas the heavily cratered highlands required an increased flux early in lunar history to account for their crater density. An important consideration in this work is the concept of saturation and equilibrium. The crater density on an initially crater-free surface will at first increase in proportion to the integrated flux of impacting bodies. However, this linear increase cannot continue indefinitely, even if one ignores the effects of material ejected from the craters; after a time the surface will become saturated for purely geometrical reasons; new craters will overlap and obscure older ones. Experimental work by Gault (*32*) has shown that before this condition of geometrical saturation is reached, an equilibrium, or steady-state condition is reached, whereby older small craters are filled by the ejecta of later craters. The experimental data shows that this effect limits the crater density to about 5 to 10 percent of the saturation value for craters of a given size. Cumulative crater count data as a function of crater diameter (Fig. 8) exhibit a characteristic break in the cumulative crater density, below which diameter the steady-state condition exists.

The curve in Fig. 8 labeled "3.5×10^{9}" and the three other solid curves nearly parallel to it are calculated cumulative crater frequency distribution curves representing integral fluxes which differ by a factor of 10. Prior to the dating of lunar samples, the curve marked "3.5×10^{9}" was called "10^{8} years," based on the assumed present-day flux. We now know that the time of filling of Mare Tranquillitatis was more like 3.5×10^{9} years ago, so this curve which approximately fits the Mare Tranquillitatis crater counts can be relabeled to represent 3.5×10^{9} years. A uniform flux of bombarding particles would imply that the next curve should be labeled "3.5×10^{10} years," older than the age of the moon, the solar system, and even the universe. The cratering data for the ejecta blanket for Mare Orientale fall to the right of even this curve. Clearly, it is not possible to assume a uniform rate of bombardment prior to 3.5×10^{9} years ago. In actuality, the southern highlands points must represent no more than 4.6×10^{9} years of integrated flux, and the flux must have dropped by about three orders of magnitude during the the first billion years of lunar history.

There remains the problem of reconciling the presently observed flux at the earth with that required by lunar crater counting, the observed flux being a factor of about 35 higher than the mean lunar flux over the last 3.5×10^9 years. At the velocity of these impacting bodies, the differences in the gravitational fields and heliocentric velocities of the earth and moon will have a negligible effect. It has been suggested that the flux of meteoritic bodies on the earth and moon has gone through a minimum and has now increased to the present value. This seems unlikely, based on our present knowledge of the orbits and sources of these bodies, which appear to be primarily associated with remnants of short-period comets (*33*), and there is no known reason why the rate at which comets are captured by Jupiter into short-period orbits should be increasing at the present time. This discrepancy remains an unsolved problem; it appears worthwhile to critically examine the evidence for the present flux of objects over 10^6 kilograms in mass.

Future Problems

Surprisingly much has been learned about lunar history from the Apollo 11 and Apollo 12 samples. In addition, some heretofore unknown problems have come to attention, and hypotheses have been made regarding the solution to these problems.

The principal need in future work will be to provide samples from a sufficiently wide variety of lunar terranes to avoid misconceptions arising from limited sampling, and to understand the relationship of the processes occurring in these other regions of the moon to one another and to the mare regions already sampled. The number of regions which may be studied is severely constrained by the small number of remaining Apollo missions; the original number of planned Apollo landings would have permitted a far more adequate study, and any further curtailment in the Apollo program would represent a lost opportunity which would be increasingly regretted as its consequences became generally realized.

Hopefully, future missions will extend our time scale so as to include the time (or times) at which igneous rocks

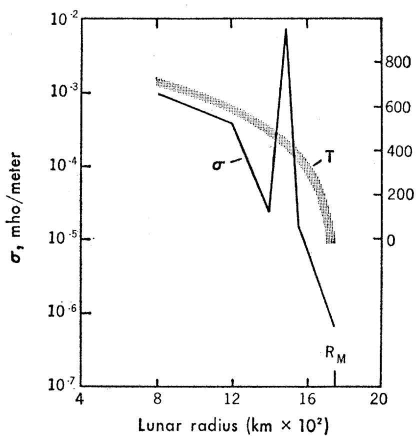


Fig. 9. Data of Sonett *et al.* (*37*) for electrical conductivity (σ) and temperature (T) for the interior of the moon. R_m is the lunar radius.

were formed in the lunar highlands, the relationship of this age to the age of rocks underlying the mare basalts, the time of mare formation, and the extent to which lunar volcanism has persisted since the time of mare filling dated by the samples from Apollo 11 and Apollo 12.

The answers to geochronological questions have major implications with regard to many other lunar problems. For example, the association of mascons with circular maria (*34*) indicates that the origin of the mascons must be in some way, perhaps indirectly, associated with the impacts which produced the maria. These impacts are generally thought to have occurred very early in lunar history ($\sim 4.5 \times 10^9$ years ago), and future geochronological work may confirm this inference. Some theories for the origin of mascons have invoked filling of the mare basins with volcanic rocks at some later time, but an objection has been that subsequent mare volcanism would not be consistent with the preservation of the departures from isostatic equilibrium indicated by the mascons. While this may be hard to understand, the geochronological data clearly indicate that relatively late mare volcanism did in fact occur, and the invocation of such volcanism cannot be considered a fault of any lunar theory.

One of the central problems is that of the thermal history of the moon. We now know that lunar igneous activity was not confined to a single epoch in lunar history, such as might be associated with a close approach to the earth at the time of capture. An adequate thermal history must explain the presence of an internal regime sufficient to provide igneous differentiation over a period of time at least as long as 1.3×10^9 years. This heat source cannot be entirely surficial, since seismic data (*35*) indicates that the mare basalts extend to a depth of at least 20 kilometers. The great enrichment of these basalts in certain elements (U and Th) implies a much deeper chemically differentiated region, extending to a depth of several hundred kilometers, which would include about half of the volume of the moon. Measurements of remanent magnetism of lunar rocks indicate that they crystallized in a magnetic field of about one tenth the strength of the present field of the earth (*36*). Again, the geochronological data precludes an explanation in terms of a close approach to the earth, and these data may therefore imply that the moon has a small core and, therefore, extensive chemical differentiation. This evidence for deep chemical differentiation must be reconciled with measurements of the moon's electrical conductivity and present internal temperature as a function of depth reported by Sonett *et al.* (*37*), and shown in Fig. 9. The present internal temperature is far below the melting point of iron or basaltic rocks, and the deeper regions of the moon should not have cooled this much in the time available, if they had melted. Severe constraints are being placed on the thermal history of the moon, and further geochronological data, particularly on young igneous rocks, will further limit the range of possibilities.

It may be expected that future geochronological work will rely heavily on small rock fragments, separated from the lunar soil, which have been ejected from distant craters, as only in this way will it be possible to sample the many areas of the moon which cannot be landing sites. Measurements of these fragments should permit an understanding of the continuity or episodicity of lunar igneous activity, the extent to which it has diminished with time, and the changes in chemical and mineralogical composition of lunar rocks as a function of time. In addition to the usual quantity of rocks of about 1 kilogram mass and soil particles of less than 1 millimeter which are returned from the moon, it would be very valuable to return a similar mass of 1-millimeter to 2-centimeter fragments obtained by sieving, on the moon, the lunar soil. In this way, many thousands of samples, sufficiently large for considerable geochronological work, as well as other studies, would be available.

Future geochronological work may also emphasize measurements of the products of extinct natural radioactivities, such as ^{129}I, and ^{244}Pu. In contrast to the importance of these radioisotopes in studies of meteorites, they have not yet played a major role in lunar work. If, as anticipated, rocks approaching the age of the moon are found in the highlands and in the mare ejecta, the high inherent resolution of these techniques may prove useful in interpreting the history of these very ancient rocks.

Summary

Considerable information concerning lunar chronology has been obtained by the study of rocks and soil returned by the Apollo 11 and Apollo 12 missions. It has been shown that at the time the moon, earth, and solar system were formed, $\sim 4.6 \times 10^9$ years ago, a severe chemical fractionation took place, resulting in depletion of relatively volatile elements such as Rb and Pb from the sources of the lunar rocks studied. It is very likely that much of this material was lost to interplanetary space, although some of the loss may be associated with internal chemical differentiation of the moon.

It has also been shown that igneous processes have enriched some regions of the moon in lithophile elements such as Rb, U, and Ba, very early in lunar history, within 100 million years of its formation. Subsequent igneous and metamorphic activity occurred over a long period of time; mare volcanism of the Apollo 11 and Apollo 12 sites occurred at distinctly different times, 3.6×10^9 and 3.3×10^9 years ago, respectively. Consequently, lunar magmatism and remanent magnetism cannot be explained in terms of a unique event, such as a close approach to the earth at a time of lunar capture. It is likely that these phenomena will require explanation in terms of internal lunar processes, operative to a considerable depth in the moon, over a long period of time. These data, together with the low present internal temperatures of the moon, inferred from measurements of lunar electrical conductivity, impose severe constraints on acceptable thermal histories of the moon.

Progress is being made toward understanding lunar surface properties by use of the effects of particle bombardment of the lunar surface (solar wind, solar flare particles, galactic cosmic rays). It has been shown that the rate of micrometeorite erosion is very low (angstroms per year) and that lunar rocks and soil have been within approximately a meter of the lunar surface for hundreds of millions of years.

Future work will require sampling distinctly different regions of the moon in order to provide data concerning other important lunar events, such as the time of formation of the highland regions and of the mare basins, and of the extent to which lunar volcanism has persisted subsequent to the first third of lunar history. This work will require a sufficient number of Apollo landings, and any further cancellation of Apollo missions will jeopardize this unique opportunity to study the development of a planetary body from its beginning. Such a study is fundamental to our understanding of the earth and other planets.

References and Notes

1. D. A. Papanastassiou, thesis, California Institute of Technology (1970); D. A. Papanastassiou and G. J. Wasserburg, *Earth Planet. Sci. Lett.* **5**, 361 (1969).
2. G. J. Wasserburg, D. A. Papanastassiou, H. G. Sanz, *Earth Planet. Sci. Lett.* **7**, 33 (1969).
3. J. H. Reynolds, *J. Geophys. Res.* **68**, 2939 (1963); C. N. Hohenberg, *Science* **166**, 212 (1969); G. J. Wasserburg, D. N. Schramm, J. Huneke, *Astrophys. J.* **157**, L91 (1969).
4. Lunar Sample Preliminary Examination Team, *Science* **167**, 1325 (1970).
5. L. Asylum, *Earth Planet. Sci. Lett.* **9**, 137 (1970).
6. L. O. Nicolaysen, *Ann. N.Y. Acad. Sci.* **91**, 198 (1961); M. A. Lanphere, G. J. Wasserburg, A. L. Albee, G. R. Tilton, in *Isotopic and Cosmic Chemistry*, H. Craig *et al.*, Eds. (North-Holland, Amsterdam, 1964), p. 269.
7. K. Gopalan and G. W. Wetherill, *J. Geophys. Res.* **75**, 3457 (1970).
8. P. W. Gast, *Geochim. Cosmochim. Acta* **26**, 927 (1962); W. H. Pinson, Jr., C. C. Schnetzler, E. Beiser, H. W. Fairbairn, P. M. Hurley, *ibid.* **29**, 455 (1965); K. Gopalan and G. W. Wetherill, *J. Geophys. Res.* **73**, 7133 (1968), *ibid.* **74**, 1439 (1969); S. K. Kaushal and G. W. Wetherill, *ibid.*, p. 2717; *ibid.* **75** 463 (1970).
9. G. Turner, *Earth Planet. Sci. Lett.* **9**, 177 (1977).
10. D. A. Papanastassiou, G. J. Wasserburg, D. S. Burnett, *ibid.* **8**, 1 (1970).
11. D. A. Papanastassiou and G. J. Wasserburg, *ibid.*, p. 269.
12. R. A. Cliff, C. Lee-Hu, G. W. Wetherill, Apollo 12 Conference, Houston (1971), unpublished data; *Geochim. Cosmochim. Acta* Suppl. 2, in press.
13. N. Hubbard, C. Meyer, P. Gast, H. Wiesman, *Earth Planet. Sci. Lett.*, in press.
14. L. T. Silver, *Geochim. Cosmochim. Acta*, Suppl. 1, **2**, 1533 (1970).
15. K. Gopalan, S. Kaushal, C. Lee-Hu, G. W. Wetherill, *ibid.*, p. 1195.
16. M. Tatsumoto, *ibid.*, p. 1595.
17. C. C. Patterson, *Geochim. Cosmochim. Acta* **7**, 151 (1955).
18. G. W. Wetherill, *Trans. Amer. Geophys. Union* **37**, 320 (1956).
19. M. Tatsumoto, Apollo 12 Conference, Houston (1971), unpublished data.
20. L. T. Silver, Apollo 12 Conference, Houston (1971), unpublished data.
21. W. Compston, B. W. Chapell, P. A. Arriens, M. J. Vernon, *Geochim. Cosmochim. Acta* Suppl. 1, **2** 1007 (1970).
22. W. Compston, H. Berry, M. J. Vernon, Apollo 12 Conference, Houston (1971), unpublished data; V. R. Murthy, N. Evenson, Bor-Ming Jahn, M. Coscio, Jr., Apollo 12 Conference, Houston (1971), unpublished data.
23. G. Turner, Apollo 12 Conference, Houston (1971), unpublished data; *Geochim. Cosmochim. Acta* Suppl. 1, **2** 1665 (1970).
24. C. M. Merrihue and G. Turner, *J. Geophys. Res.* **71**, 2852 (1966).
25. M. Tatsumoto, *ibid.*, p. 1721.
26. H. Kurosawa, *Geochem. J.* **2**, 11 (1968); M. Tatsumoto and R. J. Knight, *ibid.* **3**, 53 (1969); M. Tatsumoto and P. D. Snavely, *J. Geophys. Res.* **74**, 1087 (1969).
27. D. R. Chapman and L. C. Scheiber, *J. Geophys. Res.* **74**, 6737 (1969).
28. R. L. Fleischer, E. L. Haynes, H. R. Hart, Jr., R. T. Woods, G. M. Comstock, *Geochim. Cosmochim. Acta* Suppl. 1, **3**, 2103 (1970); P. B. Price and D. O'Sullivan, *ibid.*, p. 2351; G. Crozaz, U. Haack, M. Hair, M. Maurette, R. Walker, D. Woolum, *ibid.*, p. 2051; R. C. Finkel, J. R. Arnold, R. C. Reedy, J. S. Fruchter, H. H. Loosli, J. C. Evans, J. P. Shedlovsky, M. Imamura, A. C. Delany, Apollo 12 Conference, Houston (1971), unpublished data.
29. P. Eberhardt, J. Geiss, H. Graf, N. Grögler, U. Krähenbühl, H. Schwaller, J. Schwarzmüller, A. Stetler, *Earth Planet. Sci. Lett.* **10**, 67 (1970), and references therein.
30. G. M. Comstock, A. D. Evwaraye, R. L. Fleischer, H. R. Hart, Jr., Apollo 12 Conference, Houston (1971), unpublished data; G. Crozaz, R. Walker, D. Woolum, Apollo 12 Conference, Houston (1971), unpublished data.
31. E. M. Shoemaker, M. H. Hait, G. A. Swann, D. L. Schleicher, G. G. Schaber, R. L. Sutton, D. H. Dahlem, E. N. Goddard, A. C. Waters, *Geochim. Cosmochim. Acta* Suppl. 1, **3**, 2399 (1970); E. M. Shoemaker and M. H. Hait, Apollo 12 Conference, Houston (1971), unpublished data.
32. D. E. Gault, *Radio Sci.* **5**, 237 (1970).
33. G. W. Wetherill, in *Vinogradov 75th Anniversary Volume* (Moscow, in press); *EOS* **50**, 224 (1969).
34. P. M. Muller and W. L. Sjogren, *Science* **161**, 680 (1968).
35. G. Latham, E. Ewing, F. Press, G. Sutton, J. Dorman, V. Nakamura, R. Meissner, N. Toksoz, F. Duennebier, R. Kovach, D. Lammlein, Apollo 12 Conference, Houston (1971), unpublished data.
36. C. E. Helsley, *Geochim. Cosmochim. Acta* Suppl. 1 3, 2213 (1970); S. K. Runcorn, D. W. Collinson, W. O'Reilly, M. H. Battey, A. Stephenson, J. M. Jones, A. J. Manson, P. W. Readman, *ibid.*, p. 2369.
37. C. P. Sonett, B. F. Smith, D. S. Colburn, G. Schubert, K. Schwartz, P. Dyal, C. W. Parkin, Apollo 12 Conference, Houston (1971), unpublished data.

38. I thank M. Duke and J. Strand for photographs of lunar rocks.