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79. I am deeply indebted to Richard Dugdale and James Kelley, who have contributed a great deal to this article. In a gestalt approach to oceanography it is hard sometimes to sort out individual ideas, but I will claim responsibility for the bad ones. This research was supported by NSF grants GB-8648 and GB-18568 and is Contribution No. 633, Department of Oceanography, University of Washington, Seattle 98105.

Third Lunar Science Conference

Primal igneous activity in the outer layers of the moon generated a feldspathic crust 40 kilometers thick.

Lunar Sample Analysis Planning Team

Two years ago the first scientific investigations of returned lunar samples were reported at the Apollo 11 Lunar Science Conference (*1*). Samples from the first mission to the moon had been in the hands of investigators for 3 months or less, and the picture of the moon that emerged at that time was necessarily restricted in scope. We learned that Tranquillity Base is underlain by basaltic rock that erupted onto the mare surface 3.7×10^9 years ago, rock that is generally similar to terrestrial basalts but with important differences: titanium and other refractory elements are enhanced in abundance, sodium and other volatile elements are depleted, and the water content and oxidation potential of the lunar basalt lava are orders of magnitude lower than those of analogous terrestrial lavas. The existence of other types of rock on the moon was only glimpsed, and the structure and evolution of the moon remained a mystery.

By now five round-trip missions to the moon (including the Soviet Luna 16) have returned some 176 kilograms of samples. Hundreds of man-years of scientific effort and thousands of pages of journal space have been devoted to investigation of the samples and to other aspects of the lunar problem. Our understanding of the moon has increased proportionately. The Third Lunar Science Conference, held at the National Aeronautics and Space Administration Manned Spacecraft Center in Houston from 10 to 13 January 1972, provided an opportunity to take stock of the advances made and problems outstanding (*2*).

Crust of the Moon

Unquestionably the most important gain made is that we now know there is a lunar crust: We know the principal types of rock that comprise it and, broadly speaking, their distribution over the surface of the moon. We know the thickness of the crust in one region.

There are three principal classes of crustal rock. One is mare basalt, rich in iron and sometimes titanium; the Tranquillity Base rocks are examples. Another is noritic rock (KREEP), rich in radioactive elements and refractory trace elements. The third is aluminum-rich anorthositic rocks (*3*). The most abundant lunar material of this class appears to be anorthositic gabbro, containing 70 percent plagioclase, although rocks with greater plagioclase content are also present.

All three rock types are represented among the large rock specimens collected by Apollo astronauts, but our confidence that these are the principal crustal rock types is based on the analysis and classification of thousands of glass and rock fragments in soil samples from the various landing sites. The soils, being mixtures of particles excavated, pulverized, and dispersed over the lunar surface by meteoroid impacts, are the best random samples of crustal material available. Minor numbers of particles having other compositions are also present in the soils: granitic and ultrabasic rock fragments, and glasses compositionally similar to howarditic meteorites.

We are informed of the surface distribution of basalt, norite, and anorthositic rock by two remote sensing instruments that the orbiting Apollo 15 Command and Service Module (CSM) trained on the moon. An x-ray spectrometer detected fluorescent magnesium, aluminum, and silicon x-rays generated on the lunar surface by impinging shortwave solar radiation, and reported variations in the x-ray intensity ratios Al/Si and Mg/Si along the ground track of the CSM. A gamma-ray spectrometer sensed the natural decay of potassium, uranium, and thorium in the lunar soil and reported the abundances of these elements (Fig. 1). The ground resolution in both experiments was about 150 kilometers in diameter. Generation of x-rays was confined to the upper millimeter of the soil layer; gamma rays from as deep as 10 to 20 centimeters in the soil were detected.

The Al/Si x-ray intensity profile

This article was prepared by the Lunar Sample Analysis Planning Team. Participating were A. Burlingame. University of California, Berkeley; D. Burnett, California Institute of Technology, Pasadena; B. Doe, U.S. Geological Survey, Denver; D. Gault, NASA Ames Research Center, Moffett Field, California; L. Haskin and H. Schnoes, University of Wisconsin, Madison; D. Heymann, Rice University, Houston, Texas; W. Melson, Smithsonian Institution, Washington, D.C.; J. Papike, State University of New York, Stony Brook; R. Tilling, U.S. Geological Survey and NASA headquarters, Washington, D.C.; N. Toksoz, Massachusetts Institute of Technology, Cambridge; and J. Wood, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts. The manuscript was compiled by J. Wood.

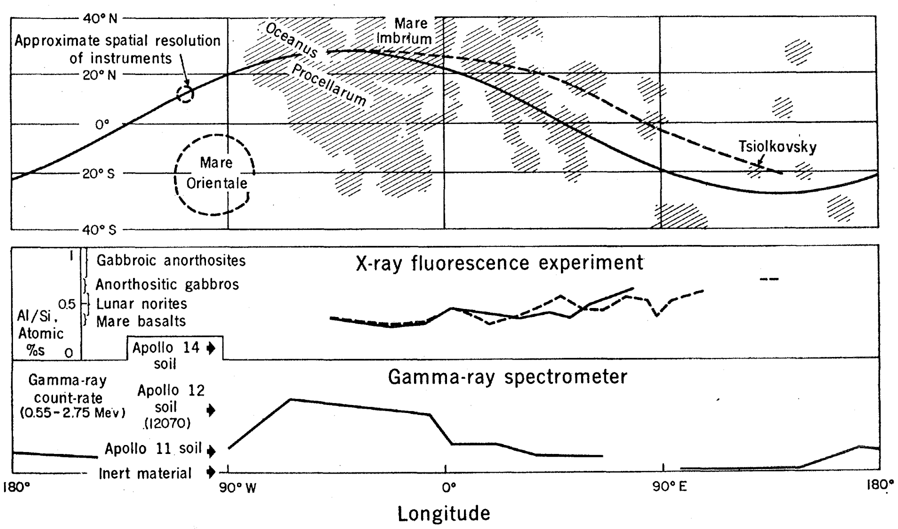

Fig. 1. Large-scale compositional variability on the moon, discovered by Apollo 15 orbital experiments [preliminary data reductions (5)]. The solid and dashed lines in the graphs of Al/Si ratios and gamma-ray count rates refer to data taken along the solid and dashed orbital tracks shown in the lunar map. The gamma-ray measurements have not yet been reduced in terms of the contributions of individual radioactive elements; total count rates appropriate to known lunar soil types are shown relative to the orbital data. Apollo 11 soils contain 1200 ppm of potassium, 2 ppm of thorium, and 0.5 ppm of uranium; Apollo 12 soil 12070 contains 2000 ppm of potassium, 6 ppm of thorium, and 1.5 ppm of uranium; Apollo 14 soils contain 4500 ppm of potassium, 12 ppm of thorium, and 3.3 ppm of uranium.

shows structure on a scale comparable to the units on photogeologic maps of the moon. The Al/Si x-ray intensity ratio ranges from low values appropriate to lunar basalts over the maria to higher values corresponding to anorthositic gabbro over some highland terrains (especially on the lunar backside). Intermediate Al/Si values usually correlate with geologic mixed terrains.

The gamma-ray profile is quite different from this. A broad gamma-ray high is present in the northwest quadrant of the moon (southern Mare Imbrium, northern Oceanus Procellarum). Radioactivity levels decrease gradually and monotonically on both sides of the high, essentially independently of apparent geologic structures, reaching very low values over the lunar highlands. A lesser radioactivity high is present on the back of the moon, near the antipode of the frontside high. The frontside high occurs over mare surfaces, presumably composed of the mare basalts we are familiar with, but the levels of radioactivity detected are about twice those appropriate for pure mare basalt. Evidently the mare regolith in this region contains, in addition to basalt, a component of some rock type rich in potassium, uranium, and thorium. The most likely interpretation is that a laterally extensive substrate of norite underlies the mare basalt in this region (see "Fra Mauro Formation," below), and major cratering impacts, such as the Copernican event, have penetrated the basalt and spread rays of noritic ejecta over the mare surfaces.

Crustal structure in the Fra Mauro region (Apollo 14 site) has been determined by monitoring seismic signals generated by deliberate impacts of spent spacecraft on the moon. A 25-kilometer layer of basaltic material overlies a 40-kilometer layer of anorthositic or noritic rock (or both). Beneath this, in what could be a finite layer of pressure-inverted crustal rock or the beginning of the lunar mantle, the apparent seismic velocity is very high (9 kilometers per second). The thickness of anorthositic or noritic material (40 kilometers) in this area is consistent with the average amount of low-density crustal material needed to reconcile the observed gravity differences between the mascon maria and the rest of the moon, if it is assumed that the mascon maria are underlain by material having the mean lunar density (3.5 grams per cubic centimeter).

Fra Mauro Formation

Mare Imbrium, the vast circular lava plain that dominates the northwest quadrant of the full moon, fills a basin that was excavated by an impacting planetesimal in early times. Deposits of basin ejecta concentric about Imbrium are termed the Fra Mauro Formation by photogeologists. The Apollo 14 mission landed on the most prominent such deposit, with the expectation of obtaining samples of early subsurface crustal material. Studies of cratering mechanics show that debris excavated from the greatest depths tends to be deposited closest in to the crater. The Apollo 14 site is relatively far from the Imbrium basin, so crustal samples from shallow depths (0 to 10 kilometers) were anticipated. The active seismic experiment (thumper and geophones) conducted by the astronauts revealed that the soil layer (regolith) at the Apollo 14 site is 8.5 meters deep. Beneath is 20 to 70 meters of broken rubble and soil; presumably this is the local extent of the Fra Mauro Formation debris layer, and solid pre-Imbrian crustal rock lies at greater depths.

Most of the discussion at the conference centered on the properties of the Apollo 14 samples, which had been under investigation for 8 months. The samples consist almost entirely of complex rock breccias, displaying shock and thermal effects that are consistent with their supposed origin as debris from a large-scale cratering event. The breccias are noritic in overall composition, although a few of the clasts in them are anorthositic or granitic. The Fra Mauro norites are relatively radioactive (4); 20 percent of this material mixed into a mare basalt regolith would account for the levels of radioactivity measured by the orbital gamma-ray spectrometer over Mare Imbrium, the basin from which the Fra Mauro Formation was presumably derived.

Some of the Apollo 14 samples are soil breccias similar to those returned by previous missions. These are created by shock induration of the local regolith whenever meteoroids impact the surface. Many Fra Mauro breccia samples, however, display the effects of long-term thermal processing not attributable to small local impacts: recrystallization, mineral reactions, and incipient fusion. Some specimens contain veins and pools of glass rich in potassium and silicon, which were presumably "sweated out" of the host rock at elevated temperatures. It appears that the Imbrium ejecta blanket was hot when it was deposited and that high temperatures (up to 900°C) were maintained in the blanket for protracted periods. The debris was not tightly compacted, and voids in the material as deposited are still preserved as vugs in which beautifully developed crystals of feldspar, pyroxene, and apatite have been deposited from hot vapors.

The Fra Mauro breccias contain fragments (clasts) of igneous rock of noritic and other compositions, reflecting igneous activity in the pre-Imbrian lunar crust, but they also contain clasts of earlier breccias. These are similar in all respects (including thermal alteration) to the Fra Mauro breccias themselves and must have been generated earlier by analogous means. Evidently the lunar crust in what is now Mare Imbrium had been blanketed by hot debris layers from the Serenitatis impact and other early basin-forming events before the Imbrium planetesimal struck.

Only two of the major rock samples returned by Apollo 14 are unbrecciated, crystalline, igneous rocks. Sample 14310 is an intersertal plagioclase-rich basalt. Its chemical composition is dissimilar to that of all three principal classes of lunar rock but resembles the composition of breccias and bulk soils (which are mechanical mixtures of rock types) at the Apollo 14 site. Its content of volatile and siderophile trace elements is much higher than that of lunar igneous rocks but corresponds to levels found in soils (where abundances of these elements are enhanced by meteorite infall). For these and other reasons, it appears likely that 14310 is a remelted pre-Imbrian soil or breccia, not a primary igneous rock. Sample 14053 is a typical lunar basalt similar to Apollo 11 and Apollo 12 mare basalts in most respects, although it is older than any of them (3.95×10^9 years compared with 3.7×10^9 years for the oldest Apollo 11 basalt).

Radiometric ages obtained for the Apollo 14 samples, including 14310, cluster around a value of 3.9×10^9 years (Fig. 2). In view of the violence of the event that delivered the rocks to Fra Mauro, and the clear evidence in them of drastic thermal alterations, it seems unlikely that they could preserve a consistent radiometric record extending to pre-Imbrian times. The clustering of ages is taken to mean that most of or all the rocks had their radioactive clocks reset by the Imbrium event and that this occurred 3.9×10^9 years ago. The age difference between samples 14310 (3.89×10^9 years) and 14053 (3.95×10^9 years) is small but real; evidently 14053 is a pre-Imbrian mare-type basalt.

The Apollo 14 soils and breccias are three times richer in siderophile elements (iridium, rhenium, gold, nickel) than are soils from other missions. These elements are depleted in indigenous lunar rocks, and their abundance in Apollo 14 soils cannot be attributed to meteorite infall over the past 3.5×10^9 years, since this would have affected the Apollo 11 and Apollo 12 soils as well. Apparently they derive from early planetesimals that impacted the moon: the Imbrium projectile itself, or bodies that excavated the Serenitatis and other pre-Imbrian basins, or all of these. The pattern of excess abundances of siderophile elements is not identifiable with any known class of meteorites; the match is closest to one of the subclasses of iron meteorites (group IVA).

Lunar Chronology

Eruption of lavas into the mare basins is still the phase of lunar activity for which we have the best time record (Fig. 2). Ages obtained by the Rb-Sr, ^{40}Ar-^{39}Ar, and U-Th-Pb internal isochron methods are in good agreement. The oldest mare basalt is rock 14053 (3.95×10^9 years). Basalts from the mare surfaces designated Imbrian in age by photogeologists, sampled by the Apollo 11 and Luna 16 missions, are of intermediate age (3.4 to 3.7×10^9 years). Youngest of all are the Apollo 12 and Apollo 15 basalts (3.15 to 3.36×10^9 years), taken from Eratosthenian mare surfaces that had been thought to be somewhat younger than Imbrian in age on the basis of crater densities. As yet no younger crystallization ages have been found for lunar rocks.

Earlier than 3.95×10^9 years ago the record grows dim, although we are confident that extensive igneous activity occurred in the lunar crust during the earliest period of its history. Perhaps early chronology in lunar rocks has been systematically erased by later brecciation and reheating; perhaps we have not yet collected and investigated the right rocks. Our knowledge of early rock-forming events has been limited to the age of 4.1×10^9 years of the "Genesis rock," anorthosite 15415; the the last major event that affected rock 12013, 4.0×10^9 years ago; and the

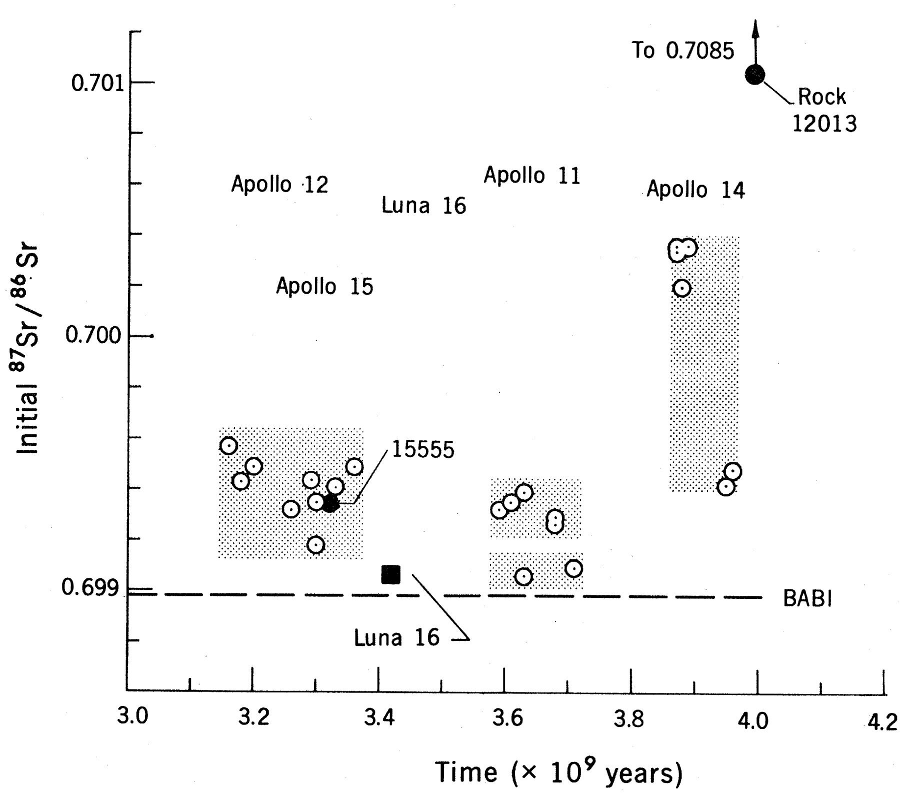

Fig. 2. Summary of internal isochron ages of lunar rocks, plotted against the isotopic composition of strontium in the rocks when they were formed (*6*). Apollo 14 rocks fall into two discrete groups: the younger group, high in ^{87}Sr, includes 14310 and noritic breccias; two older points represent 14053 and a basaltic clast from a breccia. The dashed line labeled *BABI* (for "basaltic achondrite best initial") stands for the most primitive strontium isotopic composition found in meteorites (*7*).

model age of 4.6×10^9 years of a component with a high Rb/Sr ratio present in all soil samples.

A recent addition to this record has come from the study of fission-derived xenon isotopes in Apollo 14 breccias. A detailed mass spectral analysis of xenon from one breccia (14301) revealed an isotope abundance pattern that matches the fission yield of the now extinct nuclide ^{244}Pu (half-life 82×10^6 years) and is quite distinct from the pattern produced by spontaneous fission of ^{238}U. The absolute amounts of fission xenon are also much larger than can be explained by in situ spontaneous fission. If the ratio of uranium to fission xenon has not been altered during brecciation, then the parent rocks of the breccia must have formed at least 4.4×10^9 years ago.

In addition to rock ages, the times of formation of lunar craters have been determined radiometrically. Mare Imbrium was excavated 3.9×10^9 years ago, and the crater Copernicus, on the south rim of Imbrium, 0.85×10^9 years ago (if we interpret the noritic glass component of Apollo 12 soils correctly as Copernican ray material). Cosmic-ray exposure ages of rocky debris from Cone Crater, the dominant geologic landmark at the Apollo 14 site, show that it was excavated 25×10^6 years ago.

Interior of the Moon

It is clear by now that the moon was extensively differentiated by igneous processes early in its history. The requirements for source regions and processes to account for known lunar rock types appear to be as follows (Fig. 3): (i) A near-surface layer rich in calcium, aluminum, and rare-earth elements was extensively, perhaps completely, melted to produce a liquid from which the observed highlands surface layer of anorthositic gabbro separated by crystal flotation. Surface melting requires an external energy source, such as the energy of accretion of the moon itself. (ii) Noritic liquids appeared soon after the formation of the moon, according to Rb-Sr model ages. It appears that they were generated at shallow depths by small degrees of partial melting of a plagioclase-rich source rock, in which uranium, thorium, barium, strontium, and rare-earth elements were at least five times more abundant than in chondritic meteorites. (iii) Mare basalts were generated later by more extensive (3 to 30 percent) partial melting in pyroxene-rich source regions.

The general picture developed seems to require that the moon was chemically heterogeneous from the outset, with an outer layer enriched in refractory elements (notably calcium and aluminum) and a more ferromagnesian interior. The implication is that material of the lunar interior was a lower-temperature condensate from preplanetary solar-system gases, and possibly richer in volatiles and more similar to chondrites, than was the surface layer of the moon. The history of magma generation in the moon appears to require that melting first occurred near the surface; then, with time and the accumulation of heat from internal radioactivity, the zone of high temperatures and the partial melting moved to progressively greater depths, affecting layers with dissimilar chemical compositions.

Calculations of thermal history performed for layered lunar models showed that a high-temperature pulse can be made to move downward on the right time scale. There can be no doubt that the outer layers of the moon contain abundant radioactivity and that igneous fractionation has concentrated much of it near the surface: this is required to account for the exceptionally high rate of surface heat flow (33 ergs per square centimeter per second) detected by the thermal-probe experiment at Hadley Base. It is less likely that the lunar interior is as radioactive or that it has reached melting temperatures. Evidence from lunar electrical conductivity and seismicity indicates that the present-day interior is relatively cool.

Internal conductivity is inferred from the rate of passage of transients in the solar-wind magnetic field through the moon, as monitored by surface (ALSEP) and satellite magnetometers. The observations require an electrical conductivity profile that is consistent with a deep interior temperature of 1000° to 1200°C.

The Apollo 14 seismic station records 1800 internally generated moonquakes per year, but the total seismic-energy release in the moon is 10^{-9} that of the earth. Two types of moonquakes are observed: those with fixed source locations, which repeat monthly when the moon is near perigee, and moonquake swarms, which repeat at short intervals for a period of several days.

Swarm patterns of this type are observed during terrestrial volcanic eruptions. The moonquakes that repeat monthly emanate from at least ten small focal zones, but 80 percent of the seismic energy is released at a single source: a small (less than 10 kilometers) zone 800 kilometers beneath the surface of the Mare Humorum–Mare Nubium region. The moon could not be

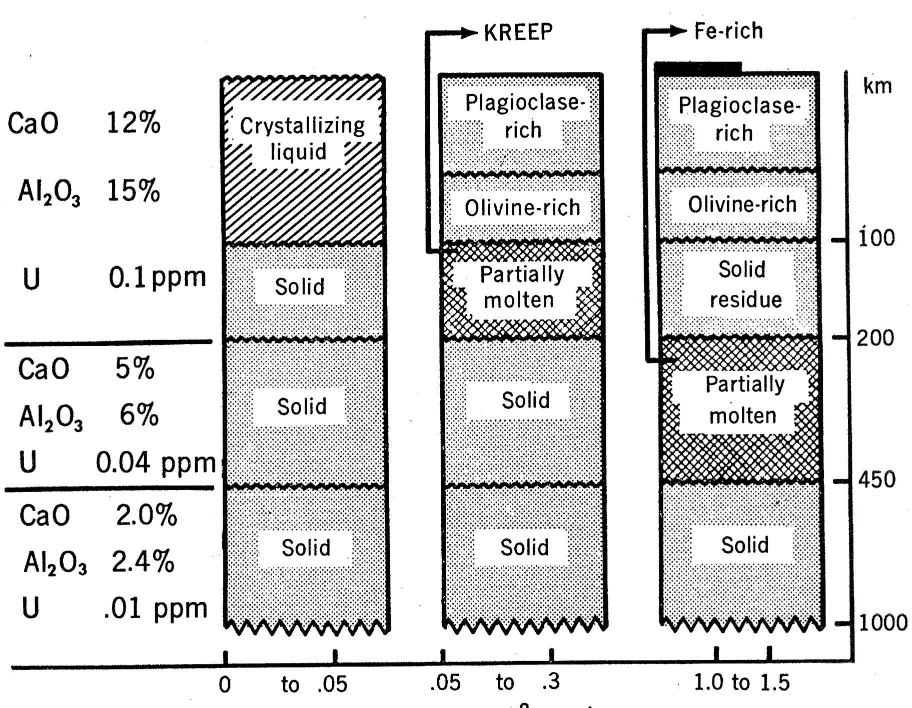

Fig. 3. Model of lunar crustal evolution, developed by R. K. McConnell, Jr., and P. W. Gast (*8*), showing the initial heterogeneity of moon (left), downward progression with time of the zone of melting (three columns), and generation and eruption of lavas (arrows).

rigid enough at this depth to store and release mechanical strain energy in the form of moonquakes, nor would its general level of seismic activity at shallow depths be as low as is observed, if interior temperatures were very high.

The question of whether the moon had a core and a magnetic field in its early history remains open. Most lunar rocks have some remanent magnetization. It is widely accepted that the igneous rocks contain a component of stable thermoremanent magnetization, but the mode of magnetization cannot be defined uniquely. In addition to an internal magnetic field, possibilities include shock magnetization and external fields. At present, the dipole component of the moon's magnetic field is about 2 gammas. A uniformly magnetized crust and mantle (below the Curie temperature) produce a value of about 6 gammas at the surface. Surface magnetometers have detected fields of 36 gammas (at the Apollo 12 site), 100 and 40 gammas (two measurements at the Apollo 14 site), and nearly zero (at the Apollo 15 site). These demonstrate that random magnetization has occurred at different points on the moon. Some interesting magnetic anomalies have been mapped by the Apollo 15 subsatellite. The anomalies that correlate with sharp craters (Gagarin, Van de Graaff) on the backside may have been produced either by shock demagnetization of the areas of the crust that are cratered or by remagnetization of these areas by fields in impact-generated plasma clouds.

Surface Processes

Impact cratering is the dominant surface process on the moon. The population of large craters (more than 1 kilometer in diameter) in the vicinity of the Apollo 12 site can be accounted for by assuming that the estimated present-day flux of large meteoroids at 1 astronomical unit has remained essentially constant since the time of formation of the mare surface visited by Apollo 12—3.2×10^9 years ago. However, this does not hold for the Apollo 11 and Apollo 14 sites. On these older surfaces the crater densities are so high as to require greatly enhanced meteoroid fluxes earlier than 3.2×10^9 years ago. Crater densities at the three sites cannot be fitted to a simple exponential decay of the interplanetary meteoroid population.

The most plausible bombardment model assumes two discrete meteoroid populations, one with a nearly constant flux rate continuing to the present day and another, an exponentially diminishing family of bodies that bombarded the early moon. Constraints can be placed on the half-life of the latter population. It could not have been more than 10^8 years if it is to account for crater densities at the Apollo 11 and Apollo 14 sites, and it could not have been less than 5×10^7 years, or the total amount of accreted meteoroids, extrapolated to 4.6×10^9 years ago, would exceed the mass of the moon. These limits on half-life dictate that the early impacting objects were not in orbit around the earth but in eccentric, earth-crossing, heliocentric orbits that reached aphelion beyond the present asteroid belt. If the moon accreted entirely from objects having these orbits and half-lives, it would have taken several hundred million years, which is hard to reconcile with the very early chemical fractionation of the lunar crust indicated by geochemical investigations.

The scale of hypervelocity impact craters on the moon extends down to submillimeter and submicron micrometeoroidal pits on rock surfaces. Most rock surfaces are saturated with pits, in that additional pits could not be recorded without destroying an equal number of old ones; the total number of impacts experienced cannot be determined. More interesting are relatively fresh, unsaturated surfaces, on which the total number of pits can be counted. When the age of such a surface is determined from data on particle tracks or cosmogenic radionuclides, the mean micrometeoroid flux over the age of the surface can be calculated. Comparison of pit-count flux rates with each other and with impact rates on satellites allows the constancy of the micrometeoroid flux over the past 10^6 years to be tested. A tentative conclusion is that the current flux is somewhat higher than the average value over the past 10^3 to 10^4 years.

Cratering activity generates heat, which is capable of vaporizing and redistributing volatile elements (mercury, lead, potassium, rubidium) in lunar soils. The extent to which soil compositions have been altered by volatile transfer is still unknown, but some insight is gained from a consideration of U-Th-Pb systematics. Soils and breccias from previous missions have shown evidence of lead loss long ago, relative to the amounts of parent uranium and thorium present. Now the Apollo 14 soils have been found to be enriched in lead. In the case of soil 14259, it appears that lead was gained at the time of the Imbrium impact (3.9×10^9 years ago), and then an undefined later event (2×10^9 years ago) caused loss of lead.

The suprathermal ion detector experiment (SIDE) on the Apollo 14 ALSEP geophysical station detected an intense, prolonged pulse of ions of mass 18 on 7 March 1971. This is of great potential interest because the observed ions may be water vapor originating from a lunar volcanic event, an unexpected result in view of the exceptional dryness of the moon dictated by lunar mineral compositions. The experimenters argue that the intensity and duration of the event are not consistent with a nonlunar origin (for example, waste dumped from the CSM a month earlier, before it left lunar orbit). The interpretation remains controversial.

Earth-Moon Environment

The moon is an ideal place to study extraterrestrial particle fluxes, both by direct surface measurements and by examination of the time-accumulated record of irradiation of lunar samples. Solar cosmic-ray effects are confined to the outermost few centimeters of samples; at depth, the nuclear transformations observed were caused by galactic cosmic rays. Information on the depth dependence of galactic cosmic-ray nuclear reaction rates was gained by the study of samples from trenches, under boulders, and from the interior of the "football-sized rock," 14321. The absence of major solar flares just before the Apollo 15 mission permitted the galactic cosmic-ray production rates of several radioactive nuclei to be measured independently of solar-flare contributions for the first time.

The cosmogenic radionuclides ^{237}Np (half-life 2×10^6 years) and ^{236}U (half-life 24×10^6 years) were found in lunar samples. The latter nuclide can be employed to test the constancy of the galactic cosmic-ray flux over a time period ten times longer than was previously possible. Several nuclei produced by neutron capture have been discovered: ^{150}Sm, ^{80}Kr, ^{82}Kr, ^{39}Ar, and ^{187}Re. It now appears that the large amounts of ^{131}Xe previously observed in lunar samples are due to capture of neutrons in the energy range 20 to 200 electron volts by ^{130}Ba. These data help define the neutron energy spectrum at the moon, a key quantity in understanding the irradiation history of lunar samples.

The intensities and energy spectra of solar flares have been determined from concentration gradients of short-lived radionuclides in lunar samples. These are in reasonable agreement with the results from direct measurements of flare activity made by satellites. A solar-flare spectrum proportional to $E^{-2.5}$ in the energy range 0.5 to 10 million electron volts and an overabundance of iron-group nuclei relative to helium among flare particles have been inferred from measurements of particle tracks in glass from the Surveyor 3 spacecraft, which was returned by the Apollo 12 mission. These results are now supported by satellite observations.

The aluminum foil solar-wind catchers deployed by all four Apollo missions accumulated neon with a $^{20}Ne/^{22}Ne$ ratio of 13.6. This is much higher than the terrestrial ratio (9.8), which supports the idea that extensive mass fractionation accompanied formation of the terrestrial atmosphere. Solar-wind hydrogen trapped in lunar soil samples is not accompanied by deuterium (D/H is one-tenth of the terrestrial ratio, or less), showing that early in the history of the solar system the sun "burned" all its deuterium to ^{3}He. However, the ratio $^{3}He/^{4}He$ for solar-wind helium trapped in the aluminum foil experiment (4.5×10^{-4}) is four times less than it would be if the solar D/H ratio had ever been as high as the present terrestrial ratio. It appears that D/H was enhanced in the earth and meteorites by undefined early solar-system processes. High densities of particle tracks (10^{11} per square centimeter) in micron-sized lunar soil grains, detected by high-voltage electron microscopy, may demonstrate the existence of a solar "superthermal" ion flux in the energy range 10^4 to 10^5 electron volts per nucleon.

Some of the small amount of carbon and nitrogen in lunar samples is implanted from the solar wind. The carbon content of lunar materials ranges from 15 parts per million (basalts) to 200 parts per million (soils). Carbon is extracted for analysis by dissolution of samples in deuterated acids, and by pyrolysis. During dissolution, methane (which apparently existed as such in the lunar material) and deuteromethane (presumably derived from carbide-like compounds) are evolved. A series of experiments has demonstrated that this carbon is chiefly derived from the solar wind. However, only a fraction of the total carbon in the samples is obtained by dissolution. Pyrolysis extracts all the carbon, chiefly as carbon monoxide. The prepyrolysis form of this carbon, and the fraction of it indigenous to the lunar rocks, are not known. Carbon isotope studies of a rock (14321) with low total carbon (27 parts per million) yield a value of $\delta^{13}C$ of -17.3 per mil, supporting the presence of an "igneous," presumably indigenous, component of the total carbon. Nitrogen, which also appears to be solar-wind derived, is probably present in the lunar samples as nitride or ammonium species.

Amino acids are the only complex organic compounds that have been detected in lunar surface fines. The most careful analysis of a lunar sample to date (14240, by three laboratories) has yielded evidence that 3 to 4 nanograms of glycine per gram of fines are present, and possibly smaller quantities (less than 1 nanogram per gram) of alanine, glutamic and aspartic acids, and serine. These have been characterized only by ion exchange or gas chromatography. It appears possible that all amino acids reported to date were formed during the analysis procedure.

Results of the search for viable organisms in Apollo 14 materials were negative, as was the case with previous sample returns.

Apollo 15

The mission to the Hadley-Apennine region provided the first opportunity to observe lunar geologic structure close at hand, and the opportunity was not wasted on Apollo 15 astronauts Scott, Worden, and Irwin, as was made clear by their presentations to the conference. A sequence of flat-lying lava flow units, typically 10 meters thick, outcrop along the wall of Hadley Rille. Although additional evidence that the rille is a collapsed lava tube was presented, its origin still cannot be termed well understood. Prominent layering was also observed on slopes of the mountains surrounding the landing site. The layers are plane and parallel but tilted; they are not shadow artifacts attributable to the low sun angle. At this juncture they seem most likely to be lava flow bedding in a pre-Imbrian crust that was shattered and heaved up in tilted blocks by the Imbrium impact. The samples collected on the Apennine front will contain talus that has rolled down from exposures of this type, and impact debris from the Imbrium basin, in as yet unknown proportions. Since the Apollo 15 site is closer in to the Imbrium basin than is the Apollo 14 site, basin ejecta at Hadley should derive from deeper in the pre-Imbrian crust (20 to 30 kilometers) than does the Fra Mauro Formation.

Some reports were made on the nature of the Apollo 15 samples, which were distributed to investigators during the fall of last year. The mare basalt under the plain at Hadley is similar in petrography and age (3.3×10^9 years) to that sampled by Apollo 12. The Genesis rock collected by astronauts Scott and Irwin on the Apennine front is a true anorthosite (97 percent plagioclase), with a ^{40}Ar-^{39}Ar age of 4.1×10^9 years. This must be taken as a lower limit to the real age, as it is clear from petrographic relationships that the Genesis rock has experienced a complex history of brecciation and thermal recrystallization.

Samples from the core of a deep (2.5-meter) hole drilled in the regolith by astronauts Scott and Irwin are under examination. Large numbers of soil grains from all levels in the drill hole contain high particle-track densities (more than 10^8 particles per square centimeter), showing that material at all levels has resided within a few centimeters of the lunar surface at some time. However, measurements of $^{157}Gd/^{158}Gd$ in the deep drill samples show that a gradient in some cosmic-ray product exists and allow a tentative conclusion that soil in the lower half of the core has been stratified for 0.5×10^9 years.

This is our view of the moon 30 months after the Eagle landed at Tranquillity Base. Many fundamental questions have been answered, but it is in the nature of science that each answer raises new questions. Several important old and new questions can be singled out. What are the nature and chronology of rock types in the lunar highlands? Answers to date have been indirect or broadbrush. The most interesting epoch of lunar history, the first half-billion years, is recorded in highland rocks if it is preserved anywhere. Why is the occurrence of lunar norite or KREEP so sharply restricted to the northwest quandrant of the moon's nearside? Is an exceptionally mighty impact (Imbrium) required to raise noritic rock to the surface? This would be inconsistent with the supposedly shallow depth of origin of the Fra

Mauro Formation cratering debris. Does it mean that the moon has been sectorally as well as radially heterogeneous since the time of its formation? Has volcanism occurred anywhere on the moon substantially later than 3.15×10^9 years ago (the age of the youngest mare basalt samples)? The last two Apollo missions are targeted to regions that offer the prospect of answering these questions. The most profound question of all is the origin of the moon, or more properly the earth-moon system. Apollo science has eliminated the once-popular hypothesis that the moon was captured recently (1 to 2×10^9 years ago), but beyond this the question remains unanswered. If the nature of compositional heterogeneities in the moon at the time of its accretion can be inferred correctly from chemical and petrologic studies of the present magmatically differentiated moon, this information will go far toward answering the question.

Our goal of understanding the moon, like other objectives of space research, is bound to be furthered by cooperation between the nations engaged in exploration of space. The Third Lunar Science Conference was a minor landmark in international collaboration, in that for the first time Soviet scientists reported results of their research on Apollo samples and Americans described their work with Luna 16 material, the fruits of a sample-exchange agreement concluded by the National Aeronautics and Space Administration and the Soviet Academy of Sciences last spring. We can hope this small but tangible cooperative arrangement presages an era in which joint United States–Soviet space ventures become commonplace.

References and Notes

1. "The Moon Issue," *Science* **167** (No. 3918) (1970).
2. The research summarized in this article is reported in more detail in *Revised Abstracts of the Third Lunar Science Conference* (Lunar Science Institute, Houston, 1972). It will also appear in three volumes as *Proceedings of the Third Lunar Science Conference* (M.I.T. Press, Cambridge, Mass., in press).
3. Lunar anorthositic rocks contain more than 65 percent calcic plagioclase, the remainder being calcium-poor pyroxene or olivine; lunar norite contains approximately equal amounts of calcic plagioclase and calcium-poor pyroxene. Lunar anorthosites and norites are rarely coarse-grained igneous rocks, as are their terrestrial namesakes: most examples described to date are fine-grained recrystallized breccias or igneous rocks. Lunar anorthosites are poor in radioactivity (sample 15415; 120 ppm of potassium, 0.01 ppm of thorium, 0.002 ppm of uranium); norites are highly radioactive (typically 5000 ppm of potassium, 12 ppm of thorium, and 4 ppm of uranium); basalts occupy an intermediate position (500 to 2500 ppm of potassium, 1 to 3 ppm of thorium, and 0.2 to 0.8 ppm of uranium).
4. Noritic breccias at Fra Mauro contain 4000 to 6000 ppm of potassium, 11 to 15 ppm of thorium, and 3 to 4.5 ppm of uranium.
5. For x-ray fluorescence data, see I. Adler, J. Trombka, J. Gerard, R. Schmadebeck, P. Lowman, H. Blodgett, L. Yin, E. Eller, R. Lamothe, P. Gorenstein, P. Bjorkholm, in *Apollo 15 Preliminary Science Report* (National Aeronautics and Space Administration, Washington, D.C., in press). For gamma-ray spectrometer data, see J. R. Arnold, L. E. Peterson, A. E. Metzger, J. I. Trombka, *ibid.*, in press.
6. G. J. Wasserburg, G. Turner, F. Tera, F. A. Podosek, D. A. Papanastassiou, J. C. Hunecke, in *Revised Abstracts of the Third Lunar Science Conference* (Lunar Science Institute, Houston, 1972), p. 788.
7. D. A. Papanastassiou and G. J. Wasserburg, *Earth Planet. Sci. Lett.* **5**, 361, 376 (1969).
8. R. K. McConnell, Jr., and P. W. Gast, in a paper delivered at the Conference on Lunar Geophysics held at the Lunar Science Institute, Houston, Texas, 18 to 21 October 1971.

The Nature of the Darwinian Revolution

Acceptance of evolution by natural selection required the rejection of many previously held concepts.

Ernst Mayr

The road on which science advances is not a smoothly rising ramp; there are periods of stagnation, and periods of accelerated progress. Some historians of science have recently emphasized that there are occasional breakthroughs, scientific revolutions (*1*), consisting of rather drastic revisions of previously maintained assumptions and concepts. The actual nature of these revolutions, however, has remained highly controversial (*2*). When we look at those of the so-called scientific revolutions that are most frequently mentioned, we find that they are identified with the names Copernicus, Newton, Lavoisier, Darwin, Planck, Einstein, and Heisenberg; in other words, with one exception, all of them are revolutions in the physical sciences.

Does this focus on the physical sciences affect the interpretation of the concept "scientific revolution"? I am taking a new look at the Darwinian revolution of 1859, perhaps the most fundamental of all intellectual revolutions in the history of mankind. It not only eliminated man's anthropocentrism, but affected every metaphysical and ethical concept, if consistently applied. The earlier prevailing concept of a created, and subsequently static, world was miles apart from Darwin's picture of a steadily evolving world. Kuhn (*1*) maintains that scientific revolutions are characterized by the replacement of an outworn paradigm by a new one. But a paradigm is, so to speak, a bundle of separate concepts, and not all of these are changed at the same time. In this analysis of the Darwinian revolution, I am attempting to dissect the total change of thinking involved in the Darwinian revolution into the major changing concepts, to determine the relative chronology of these changes, and to test the resistance to these changes among Darwin's contemporaries.

The idea of evolution had been widespread for more than 100 years before 1859. Evolutionary interpretations were advanced increasingly often in the second half of the 18th and the first half of the 19th centuries, only to be ignored, ridiculed, or maligned. What were the reasons for this determined resistance?

The history of evolutionism has long been a favorite subject among historians

Dr. E. Mayr is Alexander Agassiz Professor of Zoology at the Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts. This article is the text of the George Sarton Memorial Lecture delivered at the annual meeting of the AAAS in Philadelphia, Pennsylvania, 28 December 1971.