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Fourth Lunar Science Conference

Relocation of crustal materials by cataclysmic impacts dominated the first 700 million years of lunar history.

Lunar Sample Analysis Planning Team

On 30 January 1973, the last sample containment bag from the last Apollo mission to the moon was logged into the processing cabinets of the Lunar Receiving Laboratory in Houston, Texas. The Apollo program, an undertaking that began as a demonstration of technological prowess and evolved into one of the greatest voyages of scientific exploration in our century, had drawn to a close.

On 5 to 8 March, scientists of the Apollo program gathered at the Lyndon B. Johnson Space Center in Houston for a fourth Lunar Science Conference. By this time the preliminary examination of the Apollo 17 samples had been completed and a limited number of specimens had been distributed for study in laboratories around the world. From the reports of this and earlier lunar science conferences (*1*, *2*), it is now possible to make a first-order assessment of the character of the material that comprises the surface of the moon (*3*) and its potential as a source of information about the early solar system.

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Of primary importance is the fact that all lunar rocks encountered to date are differentiates: they have the specialized chemical compositions that are characteristically produced by magmatic fractionation processes. No primitive, undifferentiated lunar material has been found. Evidently the part of the moon we have access to has been completely melted at one time or another. From one point of view, this is a disappointment. Studies of primitive lunar material, if any had survived, could have told us a great deal about the origin of the moon, and more generally about the early condensation of planetary material in the inner solar system. The special value of lunar science lies more in its reading of the earliest stages of planetary evolution than of creation. Continuing geologic activity on the earth has long since erased the record of its first billion years. The moon, a smaller and less active planet than the earth, contains an older and simpler array of rock types; in principle it should be possible to reconstruct the early geologic history of the moon, although in practice our view is obstructed by the randomizing effects of impact cratering on lunar stratigraphy.

This early record is written in the rocks of the lunar terrae or highlands, the oldest terrain units preserved. The one Apollo mission to an interior highland region, Apollo 16 (21 to 24 April 1972), occurred somewhat less than a year before the Fourth Lunar Science Conference. As a consequence of this timing, most of the discussions at the conference centered on the analysis of Apollo 16 samples and geophysical data, although studies relating to all the other Apollo and Luna missions were also reported.

Terra Rocks

The great majority of rocks collected in the lunar highlands are feldspathic breccias. The brecciated character of highland rocks should come as no surprise, considering the pattern of overlapping impact craters that comprises the highland landscape. Petrographers recognize a half-dozen categories of highland breccia rock, differing chiefly in the compositional variability of the clasts (fragments) they contain, the size distribution of clasts, the content of glass, and the degree of thermal sintering or recrystallization that has occurred since aggregation. Some were derived straightforwardly from parent crystalline rock, others reflect a complex history of mixing of rock types from many sources. A number of truly igneous rocks have also been collected in the highlands, but it is uncertain whether any of these were melted in the interior of the moon: some are undoubtedly the products of impact melting, and all of them may be.

It is generally agreed that the moon's crust (a discrete layer, tens of kilometers thick, similar in specific gravity and seismic properties to the feldspathic rocks collected in the highlands) must have been produced by magmatic fractionation, operating at a time when extensive melting occurred in the outermost layers of the moon (hundreds of kilometers deep). The source of heat for such an event is poorly understood: accretional heating during rapid assembly of the moon, electrical heating by an early intense solar wind, or tidal heating when the moon was very close to the earth, are traditionally invoked. The large-scale primary fractionation of the moon is thought to have occurred during or immediately after the formation of that body, chiefly because of the difficulty of accounting for extensive near-surface melting at a later time.

Table 1. Selected oxide and elemental abundance in three chemical classes of terra rocks (4); ppm, parts per million.

	Anorthositic rocks	KREEP-poor norites and troctolites	KREEP-rich norites
Al_2O_3 (%)	> 25	20–25	15–20
FeO (%)	0–5	4–9	8–10
MgO (%)	2–8	8–16	7–13
P_2O_5 (%)	0–0.06	0.1 –0.3	0.3–2
K_2O (%)	0.01–0.2	0.05–0.1	0.2–2.0
U (ppm)	< 0.4	0.4 –1.0	2–6
La (ppm)	0.1–4.5	10–30	40–80
Eu (ppm)	0.6–1.2	1–2	2–3
Eu anomaly	Positive	Negative	Negative
Hf (ppm)	< 0.01–1.5	4–10	10–30
Examples from Apollo 16	60025 67075 67455 68415 68416	60335 61016 61156 62295 64455 66095	60315 62235 65015

The basic pattern of primary differentiation may have been relatively simple, but the picture has been greatly confused by the tendency of large cratering events and lava eruptions to transport (both vertically and laterally) and mingle chemical entities during and after the act of differentiation. One of the principal goals of lunar science must be to filter this "noise" out of the scene, and clearly perceive the first large-scale act of differentiation that reordered the structure of the moon.

The secondary processing a rock has received commonly affects its petrographic properties and radiometric age more profoundly than its chemical composition. Our hope of understanding the primary differentiation of the moon rests chiefly on comparisons of elemental abundance patterns. On the basis of chemistry, three broad classes of terra rocks have been recognized (Table 1) (4). It must be stressed that members of these categories do not form well-separated clusters in elemental abundance plots, but tend to grade into one another. The division into three classes could be regarded as arbitrary, depending on artifacts such as the terrestrial definition of the term "anorthositic" (more than 65 percent normative plagioclase). There is no simple correlation of chemical class with petrographic texture.

The KREEP-rich norites, however, have an important property that legitimately sets them apart from the other classes: their compositions occupy a special position in the phase diagram that describes the melting behavior of rocks of this general type. They plot along the plagioclase-olivine or plagioclase-pyroxene cotectic lines on the liquidus surface of the olivine-anorthite-silica pseudoternary phase diagram. The KREEP-rich norites therefore represent the low-melting fraction of some larger system. Anorthositic rock types plot in the anorthite field of such a diagram, but the KREEP-poor norites and troctolites appear in several fields.

Considerations of phase equilibria and trace element partitioning make it seem most likely that the moon first separated a plagioclase-rich crust, presumably by upward flotation of plagioclase as it crystallized from an early surface magma system of monumental proportions, and that subsequently the KREEP-rich and KREEP-poor noritic rock types were formed by partial melting of a feldspar-rich parent material (presumably the roots of the anorthositic crust) and erupted onto the surface as lavas.

This solution of the chemical problem creates a difficulty in the area of heat generation, however. Calculations of planetary thermal histories show that once the surface layers of the moon had solidified and their content of heat-generating radionuclides had been immobilized, this part of the system would cool monotonically. Temperatures would not rise again in a subcrustal layer or zone unless some external source of energy was involved. If the hypothetical subcrustal material had been radioactive enough to remelt itself at a later time, it would simply not solidify in the first place. To cause remelting at the base of the lunar crust, additional mechanical energy from major surface impacts must be invoked, or the arrival at the subcrust of additional radionuclide-rich magmas generated by partial melting at greater depths in the moon.

Radiometric dating of terra rock samples has yielded a surprising result. Ages derived from Rb-Sr internal isochrons and the ^{40}Ar-^{39}Ar technique almost invariably fall in the range 3.85 to 4.05×10^9 years. The rocks are neither as old nor as scattered in age as was expected. We are confident that the moon is as old as the rest of the solar system, 4.6×10^9 years, and we anticipated that terra rocks, most of which have suffered a series of shock brecciations and reheatings, would display a spectrum of apparent ages extending back to that time. The affinity of terra rocks for ages of 3.9 to 4.0×10^9 years is so pronounced that it appears some major cataclysm affected the moon at that time, or had affected it continuously until about 3.9×10^9 years ago, resetting the clocks of rocks throughout the part of the crust we have access to. The cataclysm is thought to have taken the form of a particularly intense and violent epoch of meteoroid bombardment, culminating in the giant impacts that excavated the Imbrium and Orientale basins.

The Orientale basin (Fig. 1) may, in fact, have been the source of much of the highland material collected at the Apollo 16 and other landing sites. It has always been apparent that debris from Orientale, the youngest major ringed basin, would have been projected over the whole surface of the moon; but one assumed that no more than a trifling veneer of Orientale material would have been deposited as far away from the basin (3000 km) as the Descartes landing site of Apollo 16. In fact the debris-moving capability of giant impacts has not been calibrated, and it is possible that such a thickness of Orientale ejecta was deposited at Descartes as to preclude substantial dilution by indigenous materials up to the present day. Depositions elsewhere on this scale would account for the remarkable similarity of terra rock types recovered from one site to the next.

This interpretation is based on the observation that crater densities in the close-in ejecta blanket of Mare Orientale (the Hevelius Formation) and in occurrences of the Cayley Formation, a light-colored plains-forming deposit that is widely distributed over the lunar nearside, are indistinguishable. Therefore the Cayley Formation was laid down at approximately, perhaps exactly, the same time Mare Orientale was excavated. Before the Apollo 16 mission it had been thought most probable that the Cayley Formation consisted of premare volcanic flows; but this mission, which landed on and sampled the Cayley, brought back an assortment of feldspathic breccias, not volcanic rocks. The Cayley Formation had to be reconsidered, and there is a strong possibility that these are deposits of Orientale debris that "ponded" in topographic depressions.

The Cayley Plain at the Apollo 16 site is bounded on the north and south by rugged mountainous terrain (the Smoky Mountains and Stone Mountain, respectively), and dominated by two relatively recent major craters (North Ray and South Ray). Cosmic-ray exposure ages of rocks and boulders ejected from the craters show that North Ray was excavated 50×10^6 years ago, while the South Ray impact appears to have occurred 2×10^6 years ago. The materials apparently excavated from South Ray Crater do not differ systematically from those collected at many sites on the Cayley Plain and the lower slope of Stone Mountain: feldspathic breccias of the types summarized in Table 1 were collected at all the stations sampled.

The only conspicuously different distribution of materials was collected at the northernmost station visited, on the rim of North Ray Crater. Here the soil contains a substantially higher component of light-matrix breccia fragments than do the soil samples taken at other stations. These particular breccias are porous, friable, and have a very high (> 70 percent) content of plagioclase; they are poor in large-ion lithophile elements. A fragment of this material less than 4 millimeters in diameter, from a soil sample, yielded the greatest age yet found for a lunar sample, 4.2×10^9 years (^{40}Ar-^{39}Ar dating). Thus at least some of the light-matrix breccia predates the cataclysm 3.9×10^9 years ago.

North Ray Crater lies at the break of slope between the Cayley Plain and the Smoky Mountains. It is likely that the 230-meter-deep crater penetrated the Cayley deposit and brought samples of the substance of Smoky Mountains to the surface. Possibly the light-matrix breccias are these samples. They may be the only materials collected that are indigenous to the central highlands: everything else may be a mantling of Orientale debris. Going one step further, it is probably not realistic to expect to find indigenous central highlands material at all. A sample taken from beneath the hypothetical Orientale deposit would have to be Imbrium ejecta; and if not this, then debris from the Nectaris or Serenitatis basins.

Mare Basalts

The lunar maria are broad depressions filled with dark volcanic basalts rich in iron and titanium. By now the maria have been sampled at five sites, and the range of basalt compositions and ages has been explored. Basalt ages fall in a surprisingly narrow time range 3.15 to 3.85×10^9 years. Apparently, the mare basalts were generated by radioactive heating and partial melting in an iron-rich, plagioclase-poor region in the interior of the moon, and were not a product of the primary differentiation that gave rise to the lunar crust.

High-resolution photographs of the lunar surface taken from orbit have provided information on the mode of emplacement of basaltic lavas in the mare basins. Numerous overlapping flow fronts on the mare surfaces show that basins were filled by a succession of flows, with intervals between them during which cooling and solidification occurred. At least five different basalt units, representing dissimilar petrology or time of emplacement or both, can be distinguished at the surface of Mare Serenitatis from remote observations of color differences, radar backscatter, and infrared emissivity. Where the mare basalts lap against highland masses, especially on the western nearside, small dark steps or ledges are sometimes visible at the base of the highlands. These appear to be "bathtub rings," relicts of the highest level attained by the lava as it was emplaced. The most recent flows emanated from sources at the margins of the maria; they followed definite but subdued axial channels, which may be collapsed lava tubes. Some of the flow units are at least 350 km long; older flows may have extended as much as 1200 km north across the center of the basin. Slopes were less than 1 degree. The prominent wrinkle ridges that occur in

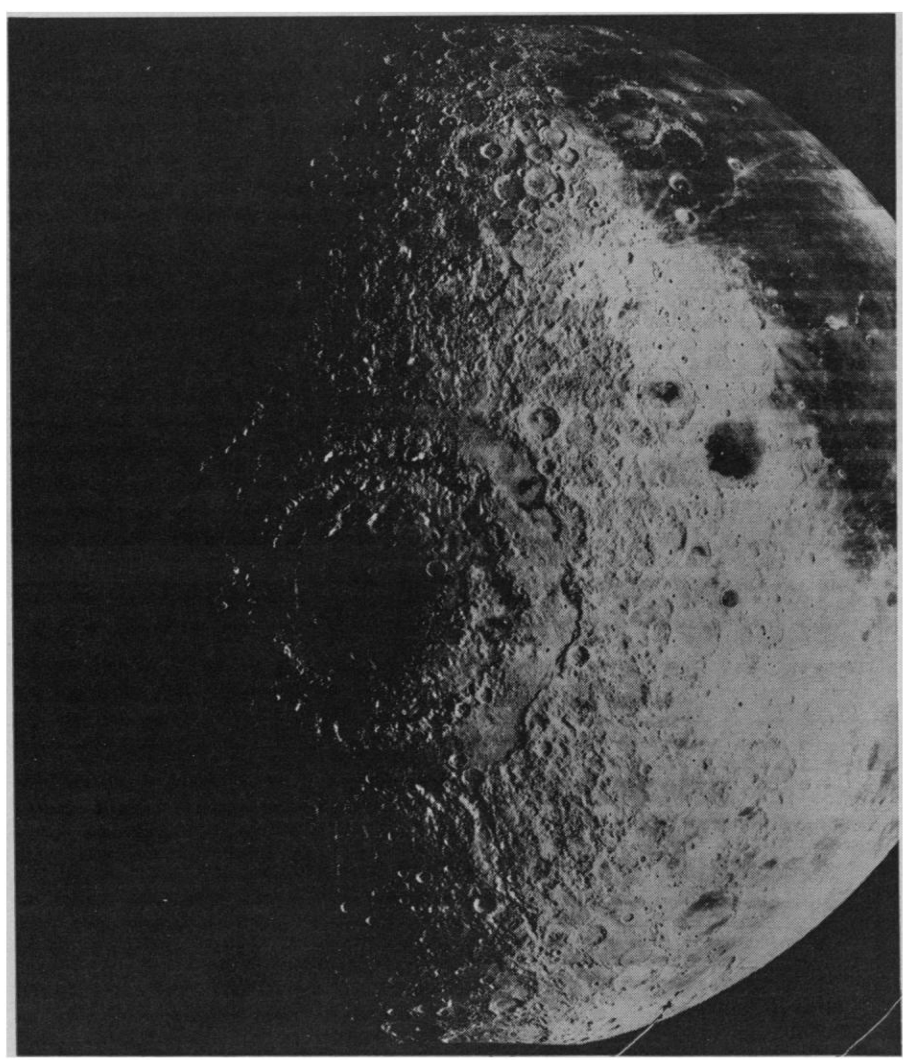

Fig. 1. Mare Orientale, a great ringed basin centered at latitude 20°S, longitude 93°W. The diameter of the outer ring is 900 km. Unlike Mare Imbrium, Orientale was not flooded with lava. The dark plain at the upper right is Oceanus Procellarum. [Lunar Orbiter IV photograph IV-187M]

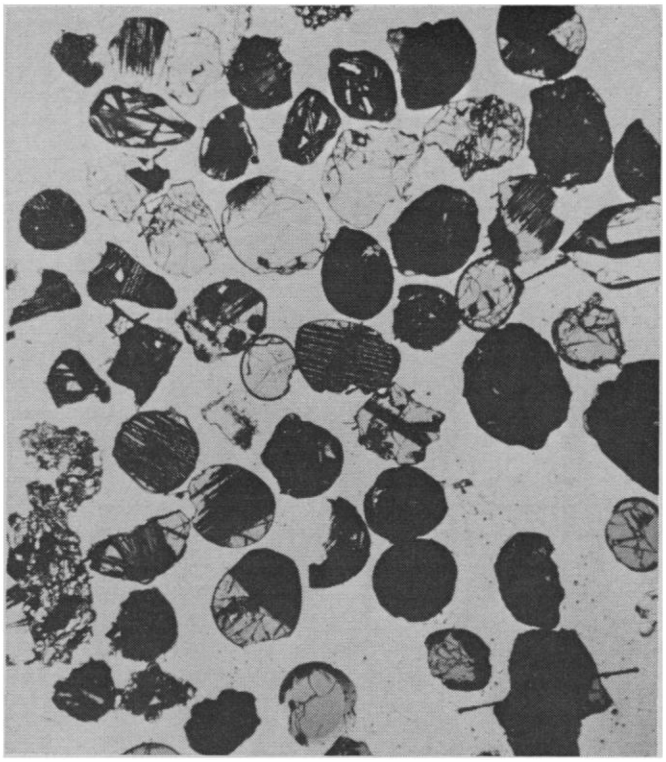

Fig. 2. Thin section of spherules and more irregular bodies sieved from the orange soil (sample 74220). The height of the field (long dimension) is 2.5 mm. Some particles consist largely of orange glass (which appears gray here): others have precipitated plates of olivine (parallel lines) or ilmenite (black).

the southern Imbrium region are interpreted as compressional structures superimposed before complete solidification of the lavas.

Basalt thicknesses appear to be greatest in the centers of maria, tapering toward the margins; this may be attributable to load-induced subsidence. Models of mare structure in which the basalt layer is approximately 20 km thick, and has not subsided all the way to a position of isostatic equilibrium, reproduce in detail the mascons (positive gravity anomalies) earlier revealed by orbital gravity measurements. Seismic velocity profiles indicate that the depth of mare basalt in Oceanus Procellarum, in the vicinity of the Apollo 12 and Apollo 14 sites, is about 20 km.

In a number of small areas on the lunar nearside, typically at the margins of maria, some very dark material appears to have blanketed craters and other structures. These areas are so much darker than the rest of the moon that they are apparent, even to the untrained eye, in a high-quality photograph of the full moon. Because the dark material mantles other structures it has been most often interpreted as a layer of volcanic ash, and because few craters seem to postdate the dark mantling material it has been thought to constitute evidence of relatively recent volcanism on the moon. Most of the occurrences of dark mantling are arrayed on the perimeter of an ellipse, centered at approximately latitude 4°N and longitude 23°E. It is an interesting coincidence that the center of mass of the moon is offset from the center of figure, by about 2.5 km, in a direction very nearly toward the center of this ellipse. The offset of centers can be interpreted most simply as meaning that the moon's low-density crust is substantially thinner on the face that contains the deposits of dark mantling material than elsewhere. Volcanic eruptions might be expected to occur most readily where the crust is thinnest.

The Apollo 17 landing site at Taurus-Littrow, near the southeast margin of Mare Serenitatis, was chosen partly because it included a prominent deposit of dark mantling material. The valley floor on which the *Challenger* landed is, in fact, completely blanketed with this dark substance. Surprisingly, no prominent component of ash-like material was found in the soil samples. The soils are similar to those collected at other sites, and were undoubtedly produced primarily by the same regolith-forming processes that are understood to operate everywhere on the lunar surface: comminution and local vitrification of the underlying bedrock by meteoroid impacts, and a minor degree of ballistic dispersion and mixing of soil fragments.

The blackness of the Taurus-Littrow soils stems from the high titanium and iron content of the underlying bedrock, which is a mare-type basalt similar in chemical composition and in other respects to that collected by Apollo 11 in Mare Tranquillitatis. These elements cause the bedrock, and soil derived from it by comminution, to have a high content of the black mineral ilmenite ($FeTiO_3$), and they deeply color glasses generated by impacts in the local soil. The local basalts crystallized 3.8×10^9 years ago (Rb-Sr internal isochrons and ^{40}Ar-^{39}Ar dating); thus the dark mantling material at the one place where it has been sampled is attributable to early volcanic activity—eruptions that occurred at the very beginning of the epoch of basin-filling volcanism—not late volcanism as was anticipated.

However, deposits of a special kind of soil, which appeared distinctly orange in the brilliant unfiltered sunlight, were found on the rim of one crater. Primed to look for evidence of recent volcanism, the astronauts and their scientific advisers in Houston tentatively attributed the orange coloration to the presence of ferric iron (normally rare or absent in the highly reduced lunar rock systems), and speculated that steamy volcanic fumaroles might have oxidized the ferrous iron present in the soil. This turned out not to be the case. The orange soil is not colored by ferric iron, and was not simply derived from a more normal type of soil. It consists largely of orange glass in the form of microscopic spherules, ellipsoids, and shards (Fig. 2). The smallest size fraction of particles (< 100 micrometers) imparts the orange color to the soil. Larger particles are so deeply colored that they transmit little light, and as they cooled more slowly than the finer particles, a larger proportion of them have crystallized.

The major element composition of the orange glass is similar (although not identical) to the compositions of the local mare basalts that were analyzed. It is almost identical to the compositions of some of the golden glass spherules (those with the highest titanium content) that characterized Apollo 11 soils and breccias. Glasses of this type have, in fact, been found in soils from every site visited on the moon. These glasses always occurred dispersed in lunar soil of the more prosaic sort, however; no concentrated deposit of orange glass particles was found before Apollo 17.

The orange soil has some peculiar chemical properties: it contains exceptionally high levels of some volatile elements (lead, copper, zinc, chlorine) but not others (sodium, potassium), and low levels of uranium and rare-earth elements (which display an unusual abundance pattern).

The Taurus-Littrow orange soil has a ^{40}Ar-^{39}Ar age of 3.7×10^9 years, equal to the age of the local mare basalts, within the uncertainty of the technique. On the other hand its cosmic-ray exposure age is less than 30×10^6 years, and it is deficient in elements implanted by the solar wind (such as helium, hydrogen, carbon, nitrogen, and sulfur). Evidently the formation of the orange soil was associated with that of the mare basalt, but the soil was covered over shortly thereafter. It was not exhumed until relatively recently (less than 30×10^6 years ago), probably by the excavation of Shorty Crater. Masses of orange soil dumped on the crater rim at that time have retained their integrity to the present day.

The ultimate origin of the orange soil is still unknown. Almost instantaneous dispersal of large amounts of melted rock in the form of tiny droplets is called for. Volcanic fire fountains may have been the mechanism; perhaps these are, after all, the long-sought lunar pyroclastics. The presence of large olivine phenocrysts in some glass particles points to a volcanic origin. Or, the concentration of glassy droplets may be a bizarre and hitherto unencountered effect of impact cratering.

The dark-mantled plain at Taurus-Littrow is bounded on the north and south by major highland masses. Geophysical measurements (the active seismic, traverse gravimeter, and electrical properties experiments) indicate that the valley filling consists of about 10 m of soil, 300 m of more coarsely broken rock, and 1 to 2 km of basalt; beneath this, presumably, lies a basement of feldspathic terra rock. A landslide from the South Massif has blanketed part of the valley floor.

The terra rock samples collected at the North and South massifs are broadly similar to those returned by previous missions to the highlands. The KREEP content of South Massif rocks appears to be higher than that of North Massif rocks, as judged from soil samples collected at both localities. One rock, sample 76055, has been dated; its age (time of last thermal metamorphism) is 3.84×10^9 years. Most of the terra samples were taken from a series of large, complex boulders lying at the feet of the North and South massifs; these were studied and methodically chipped by the astronauts. The boulders undoubtedly rolled down to their present positions from high up on the slopes of the massifs: the tracks along which they rolled can still be traced on the North Massif, to an original height of some 700 m above the valley floor. The content of ^{26}Al produced by solar flares in a soil taken from under one of the boulders is similar to that measured in a nearby reference soil. Because the boulder effectively shields the underlying soil from solar particles, the fact that the ^{26}Al has not decayed probably indicates that this boulder rolled down from the North Massif within the last 10^6 years. (It is also possible, however, that a recent local impact scattered irradiated soil under the overhang.)

Structure and Evolution

Compressional seismic waves from meteoroid impacts and internal moonquakes on all sides of the moon have been detected by the Apollo seismometer network. Shear waves, however, have been received only from the nearside events. The deep lunar interior attenuates shear waves, which shows that it is probably hot and weak; a small fraction of the rock may be melted. The lunar lithosphere (the relatively rigid layer, which transmits shear waves) is approximately 1000 km thick. All internally generated moonquakes for which focal depths can be determined occur at depths of 700 to 1000 km, near the boundary between the lithosphere and the asthenosphere (deep attenuating zone). These moonquakes could result from stresses applied by convection in the asthenosphere, but they are clearly triggered by tidal forces; the frequency of moonquakes increases at lunar apogee and perigee, and also responds to a 207-day cycle of solar tides.

These and other observations have all but extinguished the idea, once widely held, that the moon might still have a relatively "cold" interior. Preliminary results from the Apollo 17 heat flow experiment give a value of 28 ergs per square centimeter per second, essentially the same as the Apollo 15 value (30 erg cm^{-2} sec^{-1}). This is a very substantial rate of heat flow; calculated thermal history models that reproduce this heat flow and other properties of the moon (seismic velocity profile, electrical conductivity, magmatic history) require initial temperatures near the surface that would have been sufficient to melt the outermost several hundred kilometers of that body, and an average present-day uranium concentration for the whole moon of 60×10^{-9} gram per gram.

The moon's magnetic properties (as determined by orbiting satellites, station magnetometers, portable magnetometers, and laboratory measurements on returned samples) are consistent with a model in which the outermost 300 to 400 km of the moon contains 3 to 4 percent metallic iron, is below the Curie temperature of that mineral, and is randomly magnetized. The strength of the local field tends to correlate with the abundance of breccias, which contain more free metal than igneous rocks. Thus the maximum field intensity is 313 gammas (*5*) at the Apollo 16 site, where breccias are abundant; and 4 gammas at the Apollo 15 site, most of which is underlain by mare basalt. Satellite magnetometers record similar differences between the lunar nearside, with its abundance of igneous maria, and the farside, composed largely of brecciated terra rocks.

How the lunar rocks came to be magnetized, however, is not easily explained. The rocks studied were heated above their Curie temperatures, either by volcanism or by cataclysm 3 to 4×10^9 years ago; this was long after the departure of any transient magnetic field that might have been associated with the origin of the solar system. Presumably the lunar crust in general was similarly affected. But a substantial magnetic field, which no longer exists, must have been present at that time in order to impress the observed degree of thermal remanent magnetization on the rocks as they cooled. It is very hard to rationalize the existence of this field. One remote possibility is that the moon had a small, fluid, metallic core which acted as a self-exciting dynamo at that time; another is that a primeval solar system field magnetized the cool interior of the moon while its surface layers were molten, after which the field of the lunar interior in turn magnetized the outer layers as they cooled; finally radioactive heating eliminated the interior magnetization.

Laser altimeter measurements from the orbiting Command and Service Module have shown that the lunar center of mass is displaced about 2 km earthward, 1 km north, and 1 km east of the center of figure. As already noted, the most plausible explanation is that the mean thickness of the low-density lunar crust is about a factor of

2 greater on the lunar farside than on the nearside. Crustal heterogeneities on this scale, even if isostatically equilibrated, can probably also account for the differences in principal moments of inertia of the moon, which had been known before the Apollo missions from observations of the lunar librations. These moment differences had previously been interpreted in terms of a distorted, nonequilibrium form for the moon; to maintain such a form requires internal rigidity, which is difficult to reconcile with the evidence of interior warmth and softness cited earlier. The latest value for the moment of inertia factor for the moon (*6*), $C/MR^2 = 0.395 + 0.005$ or $- 0.010$, is somewhat less restrictive than earlier values, and makes it easier to construct a lunar model without density reversals or a hollow center.

The overall composition of the moon is still uncertain, although it has always been clear that there is an enhancement of refractory lithophile (but not siderophile) elements, and a depletion of volatiles, relative to chondritic meteorites. A particular type of inclusion that occurs in the Allende carbonaceous chondrite is widely favored as an ingredient of the moon when it formed. The Allende inclusions are heavily enriched in refractory elements (especially aluminum, calcium, and titanium), and may be surviving samples of an early, high-temperature condensate from the cooling solar nebula. An enrichment in this component, especially near the surface of the early moon, makes it easier to understand how magmatic fractionation could produce large amounts of anorthosite and KREEP-rich norite. Various concentrations of the Allende ingredient have been proposed for the moon, up to 100 percent, although the model with this concentration has difficulty accounting for the FeO content of mare basalts.

Lunar Surface

Meteoroid bombardment. The meteoroid bombardment of the lunar surface, the major geologic agent for regolith formation, has been studied over a wide range of impacting masses by both direct and indirect methods. Signals detected by the seismic network from impacts of meteoroids of mass 10^2 to 10^6 g yield an average present-day flux

$$\log N = -1.62 - 1.16 \log m$$

where N is the number of bodies with mass greater than m (in grams) which strike the lunar surface per year per square kilometer. This estimated flux is one to three orders of magnitude lower than previous estimates based on observations from the earth.

The flux and effects of smaller meteoritic debris have continued to be studied by using the returned lunar samples (particularly glass surfaces) as micrometeoroid recorders. It is now clear that the population of microcraters extends downward in size, in increasing numbers, to diameters of about 0.1 μm; this corresponds to impacts by masses of the order of 10^{-15} g. Thus, a cutoff in particle size due to a tendency of solar light pressure to sweep very small particles from the solar system does not appear to exist.

Rusty rocks. Measurements of oxygen fugacity on Apollo 14 and Apollo 15 materials continue to show the dry, reducing nature of the lunar environment. The logarithm of the oxygen fugacity is about -15.5 at 1000°C and -11 to -12.5 at 1200°C. Experimental studies of the effects of oxygen fugacity on the concentration ratio of Eu^{2+} to Eu^{3+} have been made on minerals. The results were consistent with the measured values for oxygen fugacity and the extent of partial reduction of europium inferred from analyses of that element in a wide variety of lunar rocks and minerals.

The above notwithstanding, the Apollo 16 samples were found to include a large number of rocks with rust-colored patches in them. The rust consists largely of the mineral goethite, $Fe_2O_3 \cdot H_2O$, and occurs in association with minerals that are common to meteorites: nickel-iron metal, lawrencite ($FeCl_2$), schreibersite [$(Fe,Ni)_3P$], and cohenite (Fe_3C). The "rusty" rock, 66095, which has been widely studied, shows enrichments of Cl, Br, Tl, Pb, Bi, Cd, Zn, Au, and the Pt metals. The meaning of the rust is still not clear. Some investigators argue that the rust formed on the moon and that the water was derived either from a cometary impact or from genuinely lunar hydrothermal activity. Others believe that the rust formed in the samples after they were brought to the earth. Lawrencite is a powerful corrosive agent: it absorbs water from the atmosphere and the iron in it oxidizes to the ferric state, creating a hydrochloric acid solution as it does so; this attacks and rusts any metallic iron at hand. The process has been known for years, from observations of the progressive deterioration of meteorites in museum storage. It is possible that meteorites were the ultimate source of lawrencite in the rusty rocks, as well as the other meteoritic minerals noted and the trace element enrichments.

Solar and galactic particles. Particle track measurements on target materials carried to the lunar surface on Apollo 16 and Apollo 17 have provided new data on heavy ions from solar and galactic cosmic rays in the low-energy range where satellite measurements are not possible. Previously unknown "quiet time" fluxes of ions from carbon to iron in the energy range 0.05 to 1 million electron volts per nucleon were observed. At roughly 10 Mev per nucleon, the energy (E) spectra of carbon, nitrogen, and oxygen nuclei deviated from the usual E^{-2} dependence; the deviations appear to be due to very low energy galactic particles not previously observed. The galactic fluxes are much higher than would have been predicted from satellite data on ^4He in this energy region. The fluxes were observed to increase by about 10^3 during the small solar flare that occurred during the Apollo 16 mission. An enhancement of iron relative to helium in low-energy solar flare particles was first discovered from particle tracks in the Surveyor camera lens returned by Apollo 12. The same enhancement was found in particles from the Apollo 16 flare and, surprisingly, in the quiet-time particles, which suggests similar acceleration mechanisms for the quiet-time and flare particles. However, the enhancement decreases with increasing energy, and the energy at which the iron enhancement disappears is variable and increases with the intensity of the flare. Studies of the abundance ratio of long to short solar particle tracks in lunar soil grains are interpreted as showing an enhancement of particles in the atomic mass range 80 to 100 relative to iron (mass 56). This would indicate that the heavy element enhancement was a property of ancient as well as modern solar flares.

The large solar flares of August 1972 produced relatively large amounts of induced radioactivity in the samples collected by Apollo 17. These flares were shown to have a larger average particle energy and greater intensity than any flare in the past 15 years.

Light elements and surface effects.

The distribution of carbon and nitrogen among types of Apollo 16 samples is similar to that observed in earlier missions: the highest concentrations occur in fines [88 to 206 parts per million (ppm) of C; 60 to 124 ppm of N] and the lowest in crystalline rocks (< 10 to 50 ppm of C; < 20 ppm of N). Breccias contain intermediate amounts of carbon, the values for anorthositic breccias being comparable to those found for rocks (< 20 ppm).

In experiments where methane and carbide-like substances have been measured in particles of fines separated according to size, magnetic susceptibility, and density, the abundances of these compounds were found to vary with inverse grain diameter, metallic iron content, and degree of agglutination of particles. This relationship is attributed to the history of the surface exposure of the particles: implantation of solar wind ions and reaction with vapor clouds caused by meteorite impacts are thought to have been involved in the synthesis of methane and carbide-like substances in the surface layers of the particles.

Metallic iron may be produced on surfaces heated and melted by micrometeoroid impacts, when the surfaces are saturated with solar wind hydrogen. Water molecules are formed in the reaction and presumably escape. As a consequence, a source of metal completely independent of meteorite contributions or of magmatic processes exists.

Carbon isotope ratios [$\delta^{13}C_{PDB}$ (*7*)] for typical Apollo 16 fines range from 9.4 to 16.1 per mil, showing the strong enrichment of ^{13}C relative to ^{12}C in rocks. Nitrogen, which occurs almost entirely in chemically bound form in the fines, is also very enriched in ^{15}N, the isotope ratios ($\delta^{15}N_{air}$) ranging from 12.6 to 63.4 per mil. The sulfur isotope ratios ($\delta^{34}S_{CD}$), which range from 6.4 to 18.9 per mil, show the heaviest ^{34}S enrichments observed thus far in lunar material.

The carbon abundance and isotopic data for lunar fines can be rationalized by assuming a two-component mixing model based on lunar basaltic carbon ($\delta^{13}C_{PDB} \sim -20$ per mil) and solar wind carbon (presumed to have $\delta^{13}C_{PDB}$ values of 10 to 25 per mil). One exception is sample 61221 from the rim of Plum Crater, which has a carbon content of 100 ppm and a $\delta^{13}C_{PDB}$ value of -13.9 per mil. This isotopic composition and the presence of (volatile) organic compounds released at low temperatures (<400°C) suggest the presence of a carbonaceous chondritic or cometary component in 61221.

Amino acid precursors were detected at the parts per billion level in Apollo 16 fines, but no other complex organic compounds were identified.

Lunar Atmosphere

The Apollo 17 ALSEP station included a mass spectrometer for measuring the density and chemical composition of the lunar atmosphere. Helium-4, argon-40, and probably also neon have been detected in the lunar atmosphere during the initial 2.5-month observation period. The daytime and nighttime ^4He concentrations at the lunar surface are 3×10^3 and 6×10^4 atoms per cubic centimeter. The factor of 20 variation between the daytime and nighttime concentrations is in good agreement with the predicted behavior of a noncondensable gas in the lunar atmosphere. The ^{40}Ar concentration in the lunar atmosphere behaved unexpectedly. During the night it dropped below 100 atoms per cubic centimeter, but it rose by orders of magnitudes a few hours before the sunrise terminator reached the ALSEP site. Evidently lunar ^{40}Ar is adsorbed at the lunar surface during the night and released again at sunrise; from the sunrise terminator it diffuses to the ALSEP station while it is still in the shade.

A record of present and past lunar atmospheres is preserved in the lunar fines and breccias. Atmospheric atoms are ionized by solar ultraviolet radiation and by charge exchange with the solar wind, and subsequently accelerated by interaction with the solar wind. A fraction of these accelerated ions are trapped in the fine-grained lunar surface material, together with solar wind ions. It has been recognized since Apollo 11 that lunar soil particles contain a component of ^{40}Ar whose abundance is proportional to the surface area of the particles, and that this must be retrapped gas from the lunar atmosphere. The amount of ^{40}Ar present in the lunar atmosphere is thus reflected by the $^{40}Ar/^{36}Ar$ ratio of the trapped gas. The ratios observed vary in such a way as to suggest that ^{40}Ar was more abundant in the ancient lunar atmosphere than it is now. Fission xenon from the decay of ^{244}Pu has now been recognized as an additional lunar atmospheric constituent retrapped in lunar breccias.

The orbital alpha particle spectrometer on Apollo 15 and Apollo 16 detected small amounts of ^{222}Rn and its daughter ^{210}Po. Higher levels near the craters Aristarchus and Grimaldi are close to sites of transient lunar events observed from the earth during the last few centuries.

The fourth Lunar Science Conference marked the end of a period of mission-oriented research, when most scientists in the program had all they could do to provide basic descriptions of the lunar samples as fast as they were collected, and the beginning of a new, problem-oriented approach to lunar science. Many Apollo scientists, thinking of the problems left unsolved and the opportunities not yet exploited, wondered how long the National Aeronautics and Space Administration's interest in lunar research would last beyond the end of the Apollo program. The formal position of the space agency, as set forth in an address by Deputy Administrator George M. Low, turned out to be reassuring. He announced, among other things, a firm commitment by NASA "first, to preserve and protect the resources we already have at hand and, second, to set aside substantial funding to support the scientific effort of lunar analysis, and this is a continuing effort. . . . I think Apollo continues to be a challenge into the future."

In response to Low's address, the assembled Apollo lunar science community unanimously adopted a formal statement of gratitude for the opportunity to participate in the Apollo program, and of congratulations to the space agency on its success: "The conception, design and implementation of lunar exploration represents an extraordinary human and technological achievement—the first exploration of another planet by men."

References and Notes

1. Previous Lunar Science Conferences have been summarized by the Lunar Sample Analysis Planning Team in "The Moon Issue," *Science* **167** (No. 3918) (1970) and in *ibid.* **176**, 975 (1972). The research summarized in this article is reported in more detail in a compendium of extended abstracts, *Lunar Science IV* (*2*). It will also appear in three volumes as *Proceedings of the Fourth Lunar Science Conference* (in preparation).
2. J. W. Chamberlain and C. Watkins, Eds., *Lunar Science IV* (Lunar Science Institute, Houston, Texas, 1973).
3. The six Apollo and two Soviet Luna round-trip missions performed a very respectable sampling of the nearside of the moon. The moon's surface is not as heterogeneous in

lithology as the earth's, where an eight-point sampling grid would be grossly inadequate. The lunar farside and poles remain to be sampled, but the magnesium, aluminum, and silicon concentrations on the farside, determined from orbit by x-ray fluorescence measurements, indicate that soils there are similar to the materials directly sampled in terra regions on the nearside.
4. The use of the terrestrial rock names anorthosite, norite, and troctolite is a reference to chemical similarities, and does not imply an origin in deep-seated igneous bodies as do the terrestrial names. Anorthositic rocks contain more than 65 percent plagioclase; norites and troctolites contain roughly equal amounts of plagioclase and a mafic mineral. The latter is chiefly orthopyroxene in the case of norites, olivine in the case of troctolites. The acronym KREEP refers to potassium, rare-earth elements, and phosphorus. Our category of KREEP-poor norites and troctolites corresponds to the very-high-Al_2O_3 basalts described by P. W. Gast (in *2*, p. 275).
5. One gamma equals 10^{-5} gauss.
6. With respect to the axis of rotation *C* is the moment of inertia, *M* is the mass of the moon, and *R* is the moon's radius.
7. The per mil notation is customarily used in studies of stable isotopes to express small differences between isotopic abundances in the sample studied and in a standard sample. Thus

$$\delta^{13}C_{PDB} = \left[\frac{(^{13}C/^{12}C)_{sample}}{(^{13}C/^{12}C)_{standard}} - 1 \right] \times 1000$$

where PDB refers to the Peedee belemnite limestone standard. Similarly, $\delta^{15}N_{air}$ expresses the isotope ratio $^{15}N/^{14}N$ relative to that in air; $\delta^{34}S_{CD}$ compares the isotope ratio $^{34}S/^{32}S$ to that in troilite (FeS) from the Canyon Diablo meteorite.

Membrane Structure: Some General Principles

Membranes are asymmetric lipid bilayers in which cytoplasmically synthesized proteins are dissolved.

Mark S. Bretscher

My purpose in writing this article is to indicate how the constituent parts of cellular membranes are organized and to suggest what this may tell us about their function and assembly. There are many excellent reviews that consider membrane proteins, carbohydrates, and lipids, but these usually cover only one of these components (*1*). In a sense that is unfortunate because each plays an important role in the function of the membrane. Much of what I have to say centers around the erythrocyte membrane. It is sometimes argued that the erythrocyte is dead and that therefore its membrane may be somewhat atypical. This may be true; but once it was alive, and there is much to be gained by studying fossils.

The principal components of membranes are lipids and proteins. The amount of carbohydrate is usually small, from none to less than 10 percent of the mass of the membrane. Lipids usually account for around 40 percent by weight, the balance being protein. I shall assume that the matrix of the membrane is composed of lipid molecules arranged in a bimolecular leaflet as originally proposed by Gorter and Grendel (*2*) and later emphasized by Danielli and Davson (*3*); this assumption may not be acceptable to everyone, but the weight of firm evidence seems to be strongly in favor of this structure.

I first summarize what is known of three of the major protein components of the erythrocyte membrane, for each is a good example of a different class of membrane protein. This summary is followed by a consideration of asymmetry of lipid and carbohydrate distribution in membranes, and some general comments on membrane structure. As a guide to background reading, a few of the many models produced over the last 10 years is depicted in Fig. 1.

Proteins

The introduction of sodium dodecyl sulfate (SDS) as a solubilizing agent for insoluble molecules has revolutionized the study of membrane proteins. The great advantages of this detergent are that (i) polypeptides exist free from one another and from lipid molecules, presumably as micelles, and (ii) these polypeptides can be separated on a semimicro scale on SDS-polyacrylamide gels (*4*) where they migrate according to their molecular weights (*5*). The fractionated polypeptides are readily visualized by a variety of stains. The simplicity and resolution of this system make it a most powerful technique.

When applied to erythrocyte membranes, the result is remarkably simple (*6–11*). About a third of all the protein resides in a pair of close bands (molecular weights in excess of 200,000); roughly another quarter is found in a band characterized often by being rather diffuse (molecular weight, about 100,000; hereafter referred to as component *a*); the remaining weaker bands vary in size (some nine components, including residual globin, with molecular weights between 90,000 and 15,000) and intensity. Scrutiny of the gels reveals many more bands, and there must be very many which, by their paucity, are not seen at all. This would include, for example, the Na^+, K^+-activated adenosine triphosphatase present only in a few hundred copies per cell. Those proteins visualized are present in at least hundredfold greater amounts. The proteins that I shall discuss are therefore the major components.

Even simpler is the picture seen if the gels are stained for carbohydrate instead of protein. Here just one major and several minor components are seen. These are all glycoproteins. Their molecular weights cannot be ascertained from the gels because of the large proportion of carbohydrate they carry (*12*). Attempts to make such calculations (*13*) have no theoretical basis and as such should be mistrusted.

Several proteins, then, are present in the erythrocyte membrane. How is each located with respect to the lipid bilayer? There are two distinct methods for determining which of them may be exposed on the outer surface

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