Evolution of the Moon: The 1974 Model [1]

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The geology of the decade of Apollo and Luna probably will become one of the fundamental turning points in the history of all science. For the first time, the scientists of the Earth have been presented with the opportunity to interpret their home planet through the direct investigations of another. Mankind can be proud and take heart in this fact.

The interpretive evolution of the Moon can be divided now into seven major stages beginning sometime near the end of the formation of the solar system. These stages and their approximate durations in time are as follows:

1. The Beginning: 4.6 billion years ago
2. The Melted Shell: 4.6 to 4.4 billion years ago
3. The Cratered Highlands: 4.4 to 4.1 billion years ago
4. The Large Basins: 4.1 to 3.9 billion years ago
5. The Light-colored Plains: 3.9 to 3.8 billion years ago
6. The Basaltic Maria: 3.8 to 3.0 (?) billion years ago
7. The Quiet Crust: 3.0 (?) billion years ago to the present

The Apollo and Luna explorations that permit us to study these stages of evolution each have contributed in progressive and significant ways. Through them we now can look with new insight into the early differentiation of the Earth, the nature of the Earth's protocrust, the influence of the formation of large impact basins in that crust, the effects of early partial melting of the protomantle, and possibly the earliest stages of the breakup of the protocrust into continents and ocean basins.

The probability is very great that the synthesis of the geological discoveries of Apollo and Luna will become one of the fundamental turning points in the history of all science. For the first time, men have been presented with the opportunity to interpret their own Earth through an understanding of a second planet. This second planet, the Moon, is now a pitted and dusty window into the Earth's own origins and evolution.

The view through this window is new and at present incomplete. On the other hand, at the close of the decade of Apollo and Luna, we can speak with considerable confidence about the internal structure of the Moon, the composition of its crust, the past processes that formed that crust, and the evolutionary sequence through which major portions of that small planet have passed. This paper will review the new limits on our interpretive understanding of the Moon and the sequence of events by which we gained this understanding. It also will suggest some of the new directions we can follow in search for understanding of the Earth as we attempt to apply our new vision of the Moon.

The summary of lunar science contained in this paper draws upon a broad spectrum of ideas and investigations performed by what has become known internationally as "The Lunar Science Team." One of the major difficulties inherent in such a large joint

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effort and in the intimate verbal contact among those involved is the nearly impossible task of properly acknowledging all contributors to a given idea or area of discussion. This is manifestly more difficult in a review paper such as this. For the present work, I hope that it will suffice to include some general references and to say that what the reader finds he can agree with should be credited to the lunar science team as a whole; what he finds he cannot agree with should be blamed on the author.

The Moon and Its Evolution

THE BEGINNING

Mysterious events were taking place around our youthful Sun about 4.6 billion years ago. The materials left over from the birth of that Sun were combining in systematic ways, but by largely unknown processes, to form the planets and their satellites. The specific beginning of the Moon remains unclear, as is the case for all the planets and satellites in the solar system; however, there appears to be no reason to doubt that the beginning occurred about 4.6 billion years ago. On the other hand, the rate at which new information is being provided by the space investigations of the Soviet Union and the United States makes it almost certain that an internally consistent model for the origin of the solar system will appear in the not too distant future. It is this very rate by which we are learning, plus the vast detail that now constrains the possible models, that has presently saturated our collective ability to find a satisfactory model. A return to fundamental principles, extrapolated under the new constraints, has begun. However, the first new, generally accepted model for the evolution of the solar system has not appeared.

THE MELTED SHELL

Sunset on the farside of the Moon was not always so starkly tranquil as it is now. About 4.6 billion years ago, when the growing Moon was approximately its present size, the Sun probably set on a glowing, splashing sea of molten rock. Storms of debris still swept this sea, mixing, quenching, outgassing, and remelting a primitive melted shell. This outer shell, and possibly the entire Moon, appear to have been melted by the great thermal energy released by the last violent stages of the formation of terrestrial planets. The actual processes by which this energy was released and, in fact, the processes by which the seemingly closely related materials of the Moon and Earth came together in space remain subjects of heated debate.

Inside the melted shell the crust and upper mantle of the Moon were gradually taking form through processes associated with the fractional separation of phases on a planetary scale. At the base of the melted shell or possibly in the center of the completely melted Moon, an immiscible, dense liquid of iron and sulfur probably accumulated as the melting took place. The initial separation of silicate minerals in the outer melted shell then produced a combined crust and upper mantle a few hundred kilometers thick; the crust rich in calcium and aluminum (anorthitic plagioclase), the upper mantle rich in magnesium and iron (pyroxene and olivine).

Our lunar samples indicate that, in addition to calcium-feldspar, about 30 percent of the volume of material of the outer 25 kilometers of the crust is made up of minerals rich in magnesium and iron. Seismic information from beneath the area of our nearside net of seismometers indicates that the lower crust, that is, a zone between depths of about 25 and 65 kilometers, is similar in mineralogical composition to the outer crust; however, it appears to be of a much more coherent and more uniform structure. Below 65 kilometers and at least to about 200 kilometers beneath the Moon's surface, our seismic evidence indicates that the upper lunar mantle is probably composed largely of pyroxene and olivine. Both the upper mantle and crust, however, have been greatly modified by later events and materials.

Most of the major chemical differentiation we have observed on the Moon may have been established with the formation and cooling of the outer melted shell. This differentiation included the fractionation of siderophile and chalcophile elements into the immiscible iron-sulfur liquid; the fractionation of many major, minor, and trace elements between the crust and upper mantle during the fractional crystallization of silicate minerals; and the loss of volatile elements from the crust and upper mantle as the continued rain of primordial debris mixed and splashed the outer melted shell in the vacuum of space.

The distributions of rare earth elements presently form one of the major tests of the validity of arguments for the existence of an early melted shell as well as other events during the evolution of the Moon. We can assume that differences and similarities in the valence state and ionic radii of the rare earth elements, as compared with themselves and other elements, would exercise the major controls over the effect of various lunar processes on specific element distribution. The now obvious reduced oxidation state of the Moon and the systematic decrease in ionic radius with increasing atomic number of the rare earth elements offer some simplifications to problems of interpretation. However, the uncertainties in the nature of lunar evolutionary processes and in critical distribution coefficients for these elements leave much room for alternative explanations of the observed distributions.

An additional uncertainty is the average or beginning abundances of the rare earth elements in the Moon. In the absence of these data, the abundances in chondrites are used as a standard for comparison; however, it is clear that the initial abundances and variations in those initial abundances can affect some interpretations.

The period of crystallization of the melted shell appears to have been dominated by the simultaneous formation of calcium-feldspar and one or more magnesium- and iron-rich minerals. The dense magesium- and iron-rich minerals would sink in response to gravity to form a cumulate at the base of the melted shell. It is probable that the less dense calcium-feldspar floated upward in the shell, for there has occurred a great enrichment of that mineral in the upper 60 km of the Moon. The dominant effects of these crystallization processes on the rare earth elements of the Moon were the gradual enrichment of rare earths in the residual liquid and the relative depletion of europium in that liquid as it was extracted preferentially by the calcium-feldspar.

As our confidence grows in the "melted shell" interpretation of the second phase of lunar evolution, we must emphasize the concept of early crustal melting and differentiation in our thinking about the early history of the Earth. In addition to the creation of the protoforms ("proto" means "first") of a crust, mantle, and possibly a core at this time, the earth probably also had accumulated a fluidsphere by virtue of a gravitational field strong enough to hold volatile components that would have been lost from the less massive Moon. The extreme depletion of the Moon's crust in components more volatile than sodium relative to the Earth seems to reflect this difference in mass. On Earth as on the Moon, it is probable that the major radial controls on the distribution of the elements were established at the very start of the planet's evolution.

It may be of interest to note at this point that in the oldest complexes on Earth there are rocks called anorthosites, which are rich in calcium and aluminum, as are the very old crustal rocks on the moon. The early differentiation of a plagioclase-rich crust on earth may account for at least the initial concentration of elements composing these mysterious rocks. Understanding their origin and evolution is not a trivial problem, as most of our known titanium resources are found in such rocks.

The early fluidsphere of the Earth is also of great interest. It can be assumed to have contained nitrogen, water, and carbon because of the present great abundance of these components in the atmosphere and hydrosphere. They are also abundant in meteorites of the carbonaceous chondrite variety. The analysis of lunar volatile components that are indigenous (in contrast to solar-wind-derived components) indicates that the early fluidsphere of the earth probably also contained significant sulfur and chlorine. The exact chemical and physical nature of this fluidsphere would be greatly dependent on temperatures that are presently unknown.

The formation of a core is one of the most important planetary phenomena that may have occurred at or soon after the time of the melted shell. There is geochemical, magnetic, and seismic evidence suggesting that a core of a liquid solution of sulfur and iron accumulated in the Moon at or prior to 3.9 billion years ago. This would have occurred early in lunar history if the entire Moon was once molten, or somewhat later if there was a gradual gravitational migration of the immiscible liquid from the melted shell period through an always solid mantle.

Whenever the core formed, a remarkable and still little understood phenomenon apparently occurred: an electric dynamo probably came into existence, began to perpetuate itself, and produced a magnetic field about 1/25th the strength of that presently associated with the Earth. Other alternatives for the creation of this field presently exist; however, its previous presence is unquestioned. Although the field is not presently active, regional magnetic anomalies left in crustal rocks persist. The anomalies have dimensions on the order of 100 kilometers and the strongest known is, appropriately, near the crater Van de Graaff. The presence of hard remanent magnetism in soil breccias formed only a few tens of millions of years ago suggests the possibility that the lunar magnetic field is only temporarily inactive.

If the creation of a lunar magnetic field was dependent on the formation of a conducting core, as seems most likely, then such a core was present at least 3.9 billion years ago, the age of the oldest rock that has been examined for remanent magnetic evidence of an ancient field. It also seems likely that a protective magnetic field existed around the Earth at least as far into the past as that of the Moon. The nature of the influence of this field on ancient climatic and biological processes on Earth is not yet known, but there are many reasons to believe that this influence would have been considerable. Further delineations of the history and origin of the magnetic fields of the Moon and other planets will bear heavily on our understanding of these terrestrial processes and their significance.

THE CRATERED HIGHLANDS

By about 4.4 billion years ago the surface of the Moon's outer crust was solid and must have looked not unlike the cratered highland areas we see today. As the debris storms continued their declining but still violent ways, this cratered and broken outer crust was saturated by craters 50 to 100 kilometers in diameter. It is now composed largely of impact-pulverized, shock-melted, and reaggregated plagioclase feldspar, a silicate mineral rich in calcium and aluminum. The intensity and depth of the disturbance of the outer crust cannot be overemphasized. By about 4.1 billion years ago, a debris zone formed that was at least 10 kilometers thick. The size of the craters with which the surface is saturated and the seismic data we have accumulated, indicate that the total disturbance extended to about 25 kilometers below the surface. It is not yet certain that the infall of debris declined in a continuous way or that this decline may have occurred in pulses of varying intensity.

The four- to five-hundred million years during which the cratered highlands were being profoundly modified by impacting debris may have resulted in changes in the characteristics of the rare earth element distributions established during the melted shell stage. Such changes would have been most extensive in the upper 10 kilometers of the cratered highlands. The first obvious possibility is that new material with different rare earth characteristics from those in the early crust may have been added either from deep or extralunar sources. In addition, selective volatilization and redeposition of the light rare earth elements may have occurred. Possibly most important, however, was the regional homogenization of the outer crust over areas on the scale of a few hundred kilometers in diameter. Presently observed geochemical heterogeneities on scales less than this must be the result of late additions of new material. In particular, the most obvious geochemical anomalies appear to be the result of the additions of material derived from depth through excavation or magmatic activity.

It is highly probable that the protocrust of the Earth underwent disturbance comparable to that of the Moon. There is no clear evidence of this yet recognized on Earth; however, we should begin to consider the implications of the occurrence of such intense cratering. For example, the rates of mechanical and chemical weathering of the protocrust in the environments of the fluidsphere probably were greatly accelerated, with a resulting increase in the rates and degree of geochemical differentiation at the Earth's surface. The rates of early biological evolution also may have been greatly enhanced by the availability of nutrients and thermal energy and by the continuous mixing caused by impacting debris. That debris also may have continuously supplied the early organic building blocks of life which are present even now in some meteorites and in the interstellar medium.

THE LARGE BASINS

As the residue of creation was consumed by Earth and Moon alike, the debris storms decreased in frequency, although not without occasional unusually massive reminders of the past. Some time prior to about 4.1 billion years ago, large basins began to be formed by major impact events at a time when they could not be obliterated by smaller collisions or by a subsequent period of large collisions. Most of these basins are now partially filled by younger materials such as the basaltic maria; however, certain generalizations can be made.

The relatively young large basins, such as Serenitatis, are circular in shape and have deep original floors. Variations in gravitational accelerations measured from lunar orbit show that these young basins overlie large concentrations of mass (mascons) and have roughly concentric deficiencies of mass just inside their rims. The older large basins, such as Tranquillitatis, are irregular in shape, have shallow original floors, and contain no large concentrations or deficiencies of mass within them. Although all of the great basins appear to have been formed by major impact events, the general differences between them suggest a major change in the mechanical properties of the crust about 4.0 billion years ago. The final upward migration and crystallization of the highly fractionated residual liquids of the melted shell may have occurred at this time.

The mechanics of the formation of the large basins and the detailed physical and chemical processes associated with their formation are poorly understood. Most of our terrestrial experience with impact and explosion cratering has been on a scale where local shock effects, hemispherical excavation, ballistic ejection, and limited movement of shock-melted material have been dominant. We must now try to understand events that occur on scales ten to a hundred times more energetic, and which will interact with large portions of an entire planet. Regional or global shock waves, large-scale lateral excavation, fluidized ejection and transport of pulverized debris, and regional movement and deep crustal injection of shock-melted material are phenomena that may need to dominate our thinking about the formation and effects of the large basins.

Samples from the lunar surface and data from orbital sensors indicate that rocks possibly formed from the residual liquids of the melted shell, and rich in alkalies, radioactive isotopes, rare earth elements, and phosphorus, are now present in varying amounts in the debris on the Moon's surface. They have been referred to as the "KREEP" basalts. Their major known distribution limits are between longitudes 5° E and about 60° W.

They appear to be spatially associated with the southern portion of the Imbrium Basin and its ejecta blanket to the south and southwest.

The separation of large volumes of calcium-feldspar and magnesium- and iron-rich minerals from the residual liquid of the melted shell appears to be the most likely origin for at least the parent materials of the KREEP basalts. In addition to the great enrichment of all the rare earth elements and the greatly accented depletion of europium in these materials, we find the expected relative enrichment of the light over the heavy elements, imposed by differences in ionic radii.

With the completion of the formation of the large basins and prior to their partial filling by younger materials, a major lunar surface formation existed that is now largely covered by light-colored plains materials and basaltic maria. This formation is now extensively exposed only inside the outer mountain ring of the Orientale Basin where it consists of a hummocky, cracked, and locally draped layer that appears to have been shock-melted lava that flowed within the basin just after the impact event that created it. Although now largely covered elsewhere on the Moon, impacts into this surface may have contributed significant amounts of its material to the debris that was forming on the surrounding highland regions.

There are many good reasons to believe that the early crust of the Earth suffered the same violent indignities of large basin formation as did the Moon's crust. Although the subsequent 4 billion years of dynamic Earth history have masked the effects of this violence, there are now many new things to look for and many new lines of interpretation to pursue. For example, the distribution of the early ocean basins may have been determined by the distribution of large impact basins and groups of basins. Also, throughout the Earth's crust there have long been recognized regional provinces that are rich in certain elements and which are the loci of ore deposits of those elements. For example, the southwestern United States is one such geochemical province rich in copper. Our present understanding of the origin and structure of these provinces is very limited even though much time, effort, and money have been spent in endeavoring to understand. Locked in the mechanics of the formation of the very large lunar basins, and their penetration into the crust, and in the distribution of ejecta around such basins, may be much of the understanding we seek.

THE LIGHT-COLORED PLAINS

The first event possibly generated by the Moon's interior processes about 3.9 billion years ago was the surface deposition of light-colored, plains-forming materials. Visual and geochemical studies conducted from lunar orbit indicate that these light-colored materials are composed largely of the pulverized, but possibly annealed, remnants of the ancient feldspar-rich crust. The surface features of the plains that fill large basins on the farside of the Moon suggest that the materials underlying the plains are eruptive and have partially filled all the great basins that then existed. These surface features include irregular, nearly rimless maar-like craters and low, finely hummocky terrain overlain locally by smooth, ponded material. The eruption of such light-colored plains materials may have been driven by the first internal melting of the lunar mantle. These early melts probably were rich in gaseous components. Through additional partial melting of the mantle, less gaseous and more magnesium- and iron-rich basaltic melts would later concentrate in much larger volumes to form the maria.

There are other light-colored plains in old, irregular depressions on the Moon's surface. Many of these, particularly those that are roughly circumferential to the large basins near the limits of their ejecta blankets, may have formed from the ponding of fine debris ejected or remobilized by the impacts that formed the basins. Still other plains as yet have no obvious origins. It is probable that both eruptive and impact processes created light-colored plains during this period of time.

THE BASALTIC MARIA

Just after the last of the large basins were created about 3.9 billion years ago, the final major internally generated episode of evolution took place. This chapter of lunar history consists of the flooding of all the great basins on the frontside of the Moon by vast, now frozen "oceans" of dark basalt. Only the very deepest of basins on the farside, such as Tsiolkovsky, were affected by the formation of the maria. To some degree, however, all portions of the broken outer crust must have been permeated up to a general mare "sea-level."

The tremendous upwellings and extrusions of the basaltic maria were perpetuated by heat from radioisotopic decay, and, in this case, geochemical and petrogenetic arguments suggest that portions of the Moon's upper mantle or even deeper inner mantle probably melted. The radioisotopic heat accumulation was probably accentuated by at least one of four factors: (1) the insulative properties of the outer crustal regolith produced during the cratered highland period, (2) the additional insulative properties of regional blankets of hot ejecta from large basins, (3) the possible heat contribution from the less differentiated inner mantle, and (4) in some cases of the earliest maria eruptions, the local release of pressure caused by the formation of the large basins.

The extrusions of the products of the melting appear to have been in pulses each of which is now represented by the basaltic filling of many of the large basins and of other topographically low areas. The distribution of different chemical varieties appears to be roughly concentric to the Tranquillitatis region. This suggests that successive surface eruptions of the maria may have been controlled by the interaction of the equipotential surfaces of the lunar gravitational field with an offset lunar figure and the borders of impermeable crust beneath older mare eruptive areas. The limits of the large basins would be the dominant lateral modifier of this idealized pattern of eruption.

The early extrusion of each major pulse of mare basalt may have been very rapid through the intensely and deeply broken outer crust of the preceding cratered highland stage. If this was true, then each local basalt-filled basin may be a single cooling unit and similar in internal structure to our own planet's basaltic and ultramafic stratiform sheets. Most of the upper visible portions of these basins, however, are now composed of extensive lava flows, 10 to 100 meters thick, and, in some cases, several hundred kilometers long. These flows, along with some pyroclastic debris, appear to have erupted from late-stage, localized centers and then spread over vast areas in and around the large basins.

Variations in the internal composition of the Moon or in temperatures as a function of depth caused the period of mare basin flooding to span at least the time from 3.8 to 3.0 billion years ago. Such variations in composition or depth of origin also caused major differences in the contents of titanium and certain minor and trace elements in the basalts that were produced as this time passed. Finally, near the end of each of several periods of mare flooding, mantles of chemically distinct, orange, black, red, and green basaltic material were deposited as pyroclastic debris over large areas. This debris is unusually rich in magnesium, iron, some volatiles, and primitive lead isotopes, and may have been derived from the very deep, less differentiated interior of the Moon.

The details of the rare earth element distribution after the crystallization of the melted shell may offer some clues to the depths of origin of the mare basalts. As the magnesium- and iron-rich cumulate formed at the base of the shell, the lunar mantle was gradually formed. In an extremely simplistic model, the cumulate as it formed would trap and isolate an intercumulate liquid. Because of the progressive concentration of the rare earth elements in the residual liquids, the intercumulate liquid would tend to have progressively higher concentrations of these elements with decreasing depth and age of accumulation in the mantle. In addition, the separation of calcium-feldspar from the residual liquid would cause the intercumulate liquid to have a progressively greater depletion of europium relative to other rare earths with decreasing depth in the mantle.

A large number of the characteristics of the basaltic maria indicate that they originated by the partial melting of selected portions of the lunar mantle. In particular, the nearly complete remelting of localized intercumulate material is suggested by the model ages (approximately 4.5 billion years) of many mare basalts. The characteristics of the rare earth abundances in the various mare basalts suggest a depth-dependent sequence of remelting of the mantle to produce the magmas from which they crystallized. This sequence is based on the expected increases with decreasing depth in (1) the total rare earth abundances, and (2) the relative depletion of europium relative to other rare earths. The probable sequence of maria sampled to date in order of decreasing depth of origin is Apollo 15 (3.2 b.y.), Apollo 12 (3.1 b.y.), possibly Luna 16 (3.4 b.y.), Apollo 17 (3.8 b.y.), and Apollo 11 (3.7 b.y.). As is indicated by the apparent ages of the maria, the remelting of the mantle was generally from the outside in, as has been suggested by many workers based on geophysical arguments.

There is a further suggestion in this sequence that the titanium-rich portions of the original mantle, from which came the Apollo 17 and 11 basalts, were formed relatively late (shallow mantle depths) in the crystallization of the melted shell. The remelting of titanium- and iron-rich oxides in addition to the intercumulate material may account for the enrichment of the heavy rare earths relative to the light rare earths in the Apollo 17 and Apollo 11 titanium-rich basalts.

With the completion of the eruptions of the maria, a relative quiet settled forever on the surface of the Moon. When the waves and currents in the surface flows of the maria had finally been arrested, the Moon's appearance differed only slightly from that of today.

We perhaps should note at this point that the oldest rock terrains on Earth also contain vast layered rock sheets which in aggregate are basaltic or ultramafic in composition. Their resemblance to the lunar maria may be more than coincidental. The possibly higher rate of radioisotopic heat accumulation in the Earth due to its larger volume to surface area ratio would have accelerated and prolonged any internal melting that might have produced mare-like materials. Again, as with the anorthosites, the question of the existence of terrestrial maria is not of trivial interest because large portions of the nickel, chromium, and platinum-group metal resources of our planet are located within these sheets of rock. In addition, the eruption and weathering of terrestrial basaltic maria may have produced a "geochemical pulse" at the Earth's surface, of presently undefined significance.

THE QUIET CRUST

About 3 billion years ago, except for faint rumblings and occasional sharp ringings we hear now as seismic reminders of the past, the storied Moon apparently completed the visible record of its tale. There are indications of a brief period of later internal activity, possibly a convective overturn of the mantle, but nothing like the continuing activity of Earth and, apparently, of Mars. The stratigraphically young ridge and volcanic system in Mare Procellarum, the great regional graben systems across the southeast quadrant of the frontside of the Moon, and the light-colored swirls of apparent alteration scattered around the whole Moon may reflect the embryonic stresses of aborted evolution.

Thus, we bring ourselves to the Moon as it is at present. In many respects, the Moon is as chemically and structurally differentiated as the Earth, lacking only the continued refinements of mantle melting and convection and crustal weathering and metamorphism. In other respects, the Moon moves through space as an ancient text, related to the history of the Earth only through the interpretations of our minds, and as the modern archive of our Sun, recording in its soils much of immediate importance to man's future well-being. Our only means of reading the text and using the archive is to study what we now have and, most importantly, to continue to go there.

The History of Apollo's and Luna's Science

TRANQUILLITY BASE—APOLLO 11

(July 20, 1969)

What was the history of events of Apollo and Luna that have led us to this first-order interpretation of the evolution of another planet? The most important of those events occurred in the southern region of Mare Tranquillitatis. That region holds a unique place in the annals of science and of mankind. The event which history will remember as having changed forever the course of that same history was the landing of Apollo 11 by Armstrong, Aldrin, and Collins.

Science for its part finally had real and factual insight into the temporal dimensions, if not all of the actualities, of the evolution of our sister planet. The ages of at least major portions of the rocks in the lunar crust were found to be very old relative to known terrestrial rocks and to most previous estimates of the probable ages of lunar rocks. Support for the arrested evolution of the Moon was also illustrated by the lack of significant internal seismic activity. The fact that the relatively young-appearing Tranquillitatis mare was 3.7 *billion* years old seemed to confirm that we would be studying our own past along with that of the Moon. As a consequence of comparing the very highly cratered highlands of the Moon with the relatively uncratered but nonetheless very old maria, it was necessary to conclude that a major change in the frequency of large impact events occurred prior to 3.7 billion years ago. This conclusion caused major revisions in our stratigraphic interpretations related to the time scale of lunar and, therefore, terrestrial evolution.

The rocks of the maria were found to be basaltic, as predicted; however, they were not only unusually rich in iron and titanium and poor in sodium, carbon, and water by terrestrial standards, but were highly differentiated chemically, relative to solar and meteoritic elemental abundances. Because of this and other new factors, the isotope and trace element chemistry of the Moon was obviously not to be a straightforward application of fact and prejudice gained from studies of the Earth and meteorites. Within the basalts as a whole, we began to see that the crust of the Moon was much richer in uranium and thorium than would be expected from accepted solar abundances. The basalts also appeared to make up several flow units that in turn appeared to be locally differentiated through fractional crystallization. Related to this crystallization is a still incompletely identified, immiscible sulphur-rich gas phase that produced spherical holes and vugs in most of the basalt samples. The detailed nature of this gas phase in these and many other rocks from all other landing sites remains a mystery.

Tranquillity Base gave us our first direct exposure to the complexities and puzzles of the lunar soils, or what became known as the "lunar regolith." As had been supposed from previous investigations, including Ranger, Surveyor, and early Luna missions, most of the material in these soils appeared to have been derived by the pulverization, shock metamorphism, shock melting, and local reaggregation of the underlying basalts. The reaggreation process produced dark matrix breccias that are chemically and texturally nearly equivalent to the soils. Within the soils and soil breccias there were found to be small amounts of exotic materials including not only basaltic material from distant or now covered maria, but also anorthositic and granitic non-mare debris apparently derived from the cratered highlands to the south. Meteoritic debris, migrant volatiles from other regions, gases derived from the solar wind, and the effects of galactic cosmic rays were also identified. The debris that may have come from the cratered highlands seemed to confirm the Surveyor VII results at Tycho that the southern lunar highlands, and, therefore, the lunar crust, were rich in calcium and aluminum silicates.

Possibly most important to science, Apollo 11 confirmed that much of our intellectual experience in geoscience was applicable to our studies of the Moon; however, it also confirmed that our intellectual insight was in great need of expansion.

MARE COGNITUM—APOLLO 12

(November 19, 1969)

Conrad, Bean, and Gordon on Apollo 12 landed within a few hundred meters of a previously landed Surveyor III automated spacecraft in Mare Cognitum southwest of Imbrium. Their mission returned obvious complexity to lunar science after the emotional early simplifications following the results from Apollo 11. The structure of the gardened upper few meters of the lunar surface became a complex history book not only recording solar and cosmic events, but showing that the relative mobility of volatile elements in high vacuum would be of great significance in interpreting geochemical measurements. Representatives were uncovered of heretofore unsuspected rocks rich in potassium, rare earth elements, and phosphorus (KREEP basalts) apparently recording a fractionation event that occurred about 4.5 billion years ago in the melted shell. The range of ages of the basaltic maria was extended downward to about 3.2 billion years; that is, the formation of the mare basalts covered at least half a billion years. It also was found that the major chemical variability in basaltic maria extended to varieties with relatively low quantities of titanium. The surface units of the maria were confirmed to be differentiated flows on the order of several tens of meters thick.

Of considerable importance to lunar stratigraphy was the fact that the landing site was located on a ray of debris from the crater Copernicus. Rays were thus seen to consist of large masses of material and not just disruptions of the surface by relatively small amounts of ejecta. Material from this ray was used to determine that the event that formed Copernicus probably occurred 0.9 billion years ago. This date now provides an anchor to much of the stratigraphic correlation of events that occurred after the formation of the basaltic maria.

The geophysical data from Apollo 12, taken in concert with the strange findings from Apollo 11, began to establish their own special surprises. The seismometer showed us that the upper crust of the Moon rings like a bell when hit. It has the unusual and unexpected combined properties of very low attenuation (high Q) and very intense wave scattering. Such properties probably are the result of a dry, pervasively fractured crust in which individual blocks have well-seated contact points against one another.

Magnetometers onboard automated orbital spacecraft had previously shown that the Moon presently has essentially no global magnetic field (less than 1 gamma). In contrast, the Apollo 12 surface magnetometer showed that local, low-intensity fields (around 100 gammas) were present. This, combined with the presence of hard remanent magnetism in the rocks, indicated that there had been a strong ancient global magnetic field (2000–3000 gammas).

MARE FECUNDITATIS—LUNA 16

(September 20, 1970)

The sample return from the northwestern part of Mare Fecunditatis by Luna 16 demonstrated an important new dimension to the previous Luna and Surveyor automated study of the Moon's surface. The data from the materials of the upper surface of this great eastern plain permitted further generalizations to be made concerning the character of the basaltic maria previously sampled by Apollo 11 and Apollo 12 in Mare Tranquillitatis and Mare Cognitum. Although each mission had sampled only a very small part of the vast region contained in these three, widely separated maria, the internal consistency of the results of various investigations on the samples increased the confidence that many of the data from an individual mission were representative of broad regions.

The crystallization age of a fragment of the local Fecunditatis basalt was determined to be about 3.4 billion years, intermediate to the 3.7- and 3.2-billion-year crystallization ages measured for Tranquillitatis and Cognitum mare basalts, respectively. Some other characteristics of the Fecunditatis basaltic material also are intermediate relative to Tranquillitatis and Cognitum, including the titanium and silicon contents. On the other hand, new ranges in the variability of basaltic compositions were established by the Luna 16 analyses; rare earth element concentrations are lower than found for earlier missions, and the depletion of europium relative to chondrites is less.

The investigation of the regolith characteristics at the Luna 16 site indicates broad similarities with those of Tranquillity Base; however, the non-mare components of the regolith show many distinctive features relative to both the Apollo 11 and 12 sites. In particular, the chemistry of the non-mare components indicates that the cratered highlands (surrounding Fecunditatis) that have contributed to the regolith, have retained their own distinctive provincial character, as has been seen at all Apollo and Luna landing sites.

FRA MAURO—APOLLOS 13 AND 14

(February 5, 1971)

To the east of the Mare Cognitum landing site of Apollo 12, and in the highlands south of the crater Copernicus, we planned the landing of the Apollo 13 mission. We were anticipating that through study of the Imbrium Basin ejecta blanket, we would receive insight into the intensity and timing of the event that formed the basin. Instead, we received new insight into ourselves. The courage of Lovell, Haise, and Swigert, as well as the resourcefulness of the ground controllers of their mission following the explosive destruction of the Service Module, provided one of history's most graphic examples of man's potential in the face of extreme adversity.

Apollo 14 and Shepard, Mitchell, and Roosa inherited Apollo 13's exploration plan for Fra Mauro. The mission told us that not only did the Imbrium event occur barely 100 million years before the oldest mare basalt extrusions, but that such massive collisions cause much more geologic disruption and transfer much more heat energy into a planet's surface than we had ever before imagined. In fact, it now appears that much of the pulverized crustal material ejected from the large basins moved many hundreds of kilometers across the Moon's surface and had many of the mechanical, dynamic, and metamorphic characteristics of volcanic ash flows.

The Apollo 14 mission also confirmed the extreme chemical differences between the highlands and the maria detected on previous missions. On the other hand, the abundance of rocks richer in alkalies, radioactive isotopes, rare earth elements, and phosphorus than were other known highland rocks suggested a well-defined provincial nature to the distribution of at least some lunar materials other than the maria.

With Apollo 14 we finally established the baseline of a net of seismometers. In conjunction with the Apollo 12 seismometer, it became possible to look at the structure and physical properties of the lunar crust through the analysis of data from natural and manmade seismic (impact) events. Most importantly, evidence appeared that at least the outer portions of the Moon are layered. Also, the first evidence of moonquakes began to accumulate, indicating that, although very quiet, the Moon was not yet completely dead internally.

HADLEY-APENNINES—APOLLO 15

(July 30, 1971)

The Apollo 15 mission to Hadley Rille at the foot of the lunar Apennine Mountains introduced a new scale to lunar exploration. First, Scott, Irwin, and Worden began to look at the whole planet through the eyes of precision cameras and electronics as well as the eyes of man. Then, on the Moon's surface they reached beyond our earlier hopes and were the first to use a powered surface vehicle to rove and observe the wide variety of features available for investigation.

The varied samples and observations from the vicinity of Hadley Rille and the mountain ring of Imbrium pushed our knowledge of lunar time and processes back past the 3.9-billion-year barrier we had seemed to see on previous missions. We discovered, however, that our interpretations of lunar history behind this barrier would have to come through the mask of multiple cycles of impact brecciation. Nevertheless, through the clasts in the breccias we began to vaguely see into the first half-billion years of lunar evolution and into some of the details of the melted shell period. In addition, we expanded our delineation of the complex volcanic processes that created the present surfaces of the maria. These processes now were seen to include not only internally differentiated lava flows but possible processes of volcanic erosion that could create the lunar sinuous rilles. We also saw once again how pervasive are the effects of contamination of surface materials by the rays of distant impact events.

With Apollo 15, we finally established a geophysical net, particularly a seismic net, by which we began to see into the inside of a second planet; the structure of that planet as partly described earlier had begun to be deciphered. This net and correlations of its information with other facts have shown that the general structure of at least major portions of the Moon's interior is as follows: an upper, broken, calcium- and aluminum-rich silicate crust extending from 0 to 25 kilometers; a lower, coherent, calcium- and aluminum-rich silicate crust from 25 to 65 kilometers; an upper, magnesium- and iron-rich silicate mantle from 65 to about 200 or 300 kilometers; an inner, probably chondritic and volatile-bearing silicate mantle from about 300 to about 600 kilometers; a lower, also probably chondritic and volatile-bearing, seismically active, locally melted mantle from about 600 to about 1100 kilometers; and an at least partially fluid, possibly iron-sulfur core from about 1100 kilometers to the Moon's center at 1735 kilometers.

Our geophysical station at Hadley-Appennines also told us that the flow of heat from the Moon was possibly two times that expected for a Moon of the approximate radioisotopic composition of the Earth's mantle. If true, this tended to confirm earlier suggestions that much of the radioisotopic materials in the Moon were concentrated in its crust. Otherwise, the interior of the Moon would be more fluid and active than the record of the seismometers indicates.

We began to be able to correlate our landing areas around the whole Moon by virtue of geochemical X-ray and gamma-ray mapping from orbit. These remote sensing investigations disclosed the provincial nature of lunar chemistry, particularly by highlighting differences in the ratios of aluminum to silicon and of magnesium to silicon within the maria and the highlands. By outlining anomalies in the distribution of uranium, thorium, and potassium, the gamma-ray information suggested that large basin-forming events were capable of creating surface geochemical provinces through the ejection of deep-seated material.

From our orbital investigations, we also greatly expanded our knowledge of the distribution and geological correlation of gravitational and magnetic anomalies in the Moon's crust. This was accomplished by use of a small satellite ejected by Apollo 15 prior to leaving lunar orbit for the return to Earth.

Possibly of equal importance with all these discoveries by Apollo 15 was the realization, by ourselves and through television by millions of people around the world, that there yet existed beauty and majesty in views of nature previously outside human experience.

APOLLONIUS REGION—LUNA 20

(February 21, 1972)

The second automated sample return mission from the Moon, Luna 20, landed in the Apollonius region south of the large basin Crisium and 120 kilometers north of the Mare Fecunditatis landing site of Luna 16. As with Luna 16's data on the basaltic maria, the most important aspect of the Luna 20 sample was the increased global perspective it gave us with respect to the character of lunar highlands. When compared with the investigation of cratered highland material sampled on Apollos 14 and 15 and later on Apollos 16 and 17, the Luna 20 materials emphasize the homogenization effects of the half-billion years of cratering that formed the highland regions we now see. It is in the remaining traces of heterogeneity which reflect ancient highland provinces that we see the extent of the homogenization.

The materials of the Apollonius region appear to be similar to the materials returned slightly later by Apollo 16 from the Descartes region. The major exceptions to this similarity are the significantly lower aluminum contents of debris probably representative of the Apollonius region, and the abundance of fragments representing a distinctive suite of crystalline rocks known as the anorthosite-norite-troctolite suite. This suite first became recognized after Apollo 15 as possibly being the much reworked remnants of at least portions of the ancient lunar crust. Luna 20 confirmed its importance. In addition to these major distinctions, the Luna 20 material show differences in their trace element concentrations relative to other highland areas. In particular, the rare earth elements are present in clearly lower abundances than in materials from Apollos 14, 15, and 16.

The last crystallization age of some of the Luna 20 rocks appears to be about 3.9 billion years, and continued to point up this age as reflecting a major age limit in lunar history. The same general age for the cooling of highland or highlandlike materials had been determined for the ejecta blanket of the Imbrium Basin at Fra Mauro and for the rocks of the Apennines, and soon would be determined for the highland rocks at Descartes. This age limit was now seen to represent one of the following occurrences: (1) a major thermal event associated with the formation of several of the large basins over a relatively short time period, (2) a major thermal event associated with the formation of the light-colored plains, or (3) the rapid cessation of the period of major cratering that had continually reworked the cratered highlands until most vestiges of original ages had disappeared and only the last local impact event was recorded. As we attempt to explain the absence of very old rocks on Earth, we also should not forget these possibilities.

DESCARTES—APOLLO 16

(April 21, 1972)

Apollo 16 found that we were not yet ready to understand the earliest chapters of lunar history exposed in the southern highlands. In the samples returned by Young, Duke, and Mattingly from the Descartes area, we seem to see that the major central events of that history were compressed in time far more than we had guessed. There are indications that the formation of the youngest major lunar basins, the eruption of light-colored plains materials, and the earliest extrusions of basaltic maria took place over about 100 million years of time around 3.9 billion years ago. In addition, indications are present at Descartes that the light-colored plains may be the loci of many of the observed regional magnetic anomalies, suggesting that the plains formed as single cooling units that were initially above the Curie point.

The extreme complexity of the problem of interpreting the lunar highland rocks and processes became clearly evident even as the Apollo 16 mission progressed. Rather than revealing materials of clearly volcanic origin as had been expected, most information suggests that the samples from the Descartes regolith had been subjected to an interlocking sequence of igneous and impact processes. Some of these samples may have been derived from the distant, now covered surface layer of shock-melted lava in the large basins, as well as from bedrock beneath the Descartes highland region. A new chemical rock group known as "very high aluminum basalts" could be defined although their ancestry relative to other lunar materials has been obscured by the final events that gave the cratered highlands their present form. The results of Apollo 16 have within them an integrated look at almost all previously and subsequently identified highland rock types. With this complexity comes a unique opportunity to understand the formation and modification of the Moon's, and potentially the Earth's, early crust.

Apollo 16 continued the broad-scale geological, geochemical, and geophysical mapping of the Moon's crust from orbit. This mapping greatly expanded our knowledge of geochemical provinces and geophysical anomalies, and has helped to lead to many of the generalizations it is now possible to make about the evolution of the crust.

TAURUS-LITTROW—APOLLO 17

(December 11, 1972)

Near the coast of the great frozen sea of Serenitatis, Apollo 17 carried Cernan, Evans, and me to visit the valley of Taurus-Littrow. The unique scientific character of this valley helps to mitigate the sadness that with our visit the Apollo explorations ended. If this end had to be, it would have been difficult to find a better locality to synthesize and expand our ideas on the evolution of the Moon.

At Taurus-Littrow we have looked at and sampled the ancient lunar record ranging back from the extrusion of the oldest known basaltic maria, through the formation of the breccias of the Serenitatis mountain ring, and thence back into clasts in these breccias that may reflect the very origins of the lunar crust itself. Also, we have found and are studying volcanic materials and debris-forming processes that range forward from the formation of the earliest basaltic maria surface and through 3.8 billion years of modification of that surface.

The pre-mare events in the Taurus-Littrow region that culminated in the formation of the Serenitatis Basin produced at least three major and distinctive units of multilithic breccias. The oldest of these breccia units contains distinctive clasts of crystalline mafic and ultramafic rocks that appear to be the remains of the fractional crystallization of portions of the melted shell. This conclusion is supported by one of these distinctive clasts, a crushed rock of magnesium olivine, which has an apparent crystallization age of 4.6 billion years. The old breccia unit containing these clasts has been intruded and locally metamorphosed by another breccia unit which was partially molten at the time of intrusion. This intrusive event appears to have occurred about 3.9 billion years ago. Such intrusive breccias are probably the direct result of the massive impact event that formed the nearby large basin of Serenitatis; however, an internal eruptive origin cannot yet be ruled out. The third unit appears to partially cap the tops of the mountains and it may be another old ejecta unit from one of the several large basins within range of the valley. This breccia contains a wide variety of clasts of mafic crystalline material plus other, previously unrecognized material that includes barium-rich granitic rock.

The valley of Taurus-Littrow and other nearby low areas appear to be a coincidental structural window that exposes some of the oldest, if not the oldest, basaltic maria extrusives on the Moon. With an age of 3.8 billion years, they are 50 to 100 million years older than the basalts at Tranquillity Base. Like the Tranquillity Base basalts, the Taurus-Littrow rocks are titanium-rich with up to 13 weight percent TiO_2. Except for near-surface, fine-grained varieties, the texture and composition of the Taurus-Littrow basalt appears to be essentially uniform to depths of at least 120 meters. This suggests that the valley may be the top of a very thick cooling unit of basaltic material. Geophysical evidence indicates that this unit of basaltic material may be as thick as two kilometers indicating also that, when taken with the present height of the surrounding massifs, the valley may have had an original depth of over four kilometers.

One of the many major remaining puzzles of potentially great significance is that of the tectonic history of the valley and the massifs surrounding it. Several facts suggest that the structural boundary between the valley and the massifs has been active throughout most of its existence. A young scarp strongly resembling that of a fault suggests recent activity. Also, there are no debris accumulations at the bases of the steep (20°–25°) slopes of the massifs; in fact, there tends to be a continuous shallow moat instead. In addition, the soils and rocks that are present at the bases of the massifs are all tens to hundreds of millions of years old rather than having the imprint of the presumed 3.9-billion-year age of the massifs. All of these considerations suggest that blocks of the lunar crust may be in continuous, but episodic motion in spite of the obvious general strength and quiescence of that crust. Recently identified, but rare near-surface moonquakes may also relate to this phenomenon.

Relatively recent modifications of the lunar surface as a result of internal processes also are indicated by the visual and photographic data on the mysterious light-colored swirls that were obtained by Apollo 17 from orbit. The swirls, of which Riner Gamma in Oceanus Procellarum is the most well-known example, are much more widely distributed than previously thought, particularly in broad regions to the north and east of Mare Smythii. In all known instances, the swirls have no discernable topographic relief and are superimposed on all associated features. In addition, many swirls are zoned, with light-colored zones bordering an inner dark-colored zone that is darker than the surrounding, unaffected surface. These characteristics suggest that fluidized alteration processes have formed the swirls. The fluids in turn may have their origin in the continued, gradual degassing of the lunar interior.

The modifications of the surface of the valley basalt included the addition of mantles of beads of chemically distinctive orange glass and black devitrified glass. These glasses may have been formed as the result of processes once active within the deep interior of the Moon. The titanium-rich, basaltic to ultramafic glasses surprised us once again; their 10- to 30-million-year exposure age is young and was expected for the dark mantling deposits seen in photographs; but their 3.5- to 3.7-*billion*-year cooling age was not expected. The explanation for this difference is complex and not yet completely understood. The glasses also have an unusual complement of trace elements, including lead, zinc, sulfur, chlorine, and others. Some of the more volatile trace components are present as relatively low-temperature absorbed material. The volatile lead in the orange glasses is extremely enriched in primitive lead isotopes and has other isotopic characteristics that indicate early isolation from the rock systems that produced other lunar materials examined to date. Green glass beads found at Hadley-Apennines on Apollo 15 have similar but less definitive characteristics. The characteristics of the glass beads strongly suggest a volcanic source and a parent material in or below the mantle of the Moon and different in major respects from the parent of the mare basalts.

As a followup to the recognition of orange and black pyroclastic materials on the lunar surface at Taurus-Littrow, Apollo 17 also provided visual and photographic data from orbit that have permitted the identification and interpretation of broad areas of similar materials around the southwestern, southern, and southeastern borders of the Serenitatis Basin. It is now clear that the previously identified and mapped "dark-mantle materials" in these areas (and most probably elsewhere on the Moon) are indeed volcanic deposits made up of various combinations of layers of orange, black, red, and green glass and devitrified glass.

THE FUTURE

For all of our Apollo missions we left the Moon before the lunar sunrise had progressed into the vast regions of the lunar west: Mare Procellarum, where the young mysterious features of that region's central ridge system still await the crew of a mission diverted after Apollo 13; Mare Orientale, whose stark Alpine rings have been viewed closely by man only in the subdued blue light of the Earth. The promise of the story in these regions has not diminished, but seemingly watches for the progression of the sunrises and the landing craft of another generation of explorers. When that time comes and we merge the scientific revolution brought about by Apollo and Luna on the Moon with the simultaneous revolution brought about by new insight into the origins of ocean basins and continents on the Earth, we may begin to understand the great stresses and strains within our planet's crust as ocean floors grow and continents move. Within future understanding of features like the basalts of Mare Procellarum and its vast ridge and volcanic system may lie further inspiration for all of us.

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