

EVOLUTION OF THE MOON: THE 1974 MODEL

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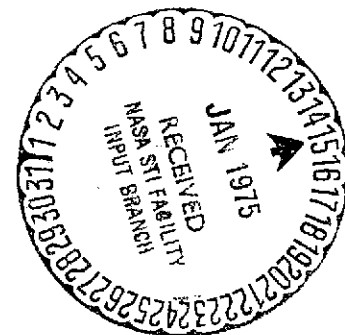
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EVOLUTION OF THE MOON: THE 1974 MODEL^{1/}

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Soviet-American Conference on Cosmochemistry
of the Moon and Planets

The probability is very great that the synthesis of the geology 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 which we call 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 this 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 directions we can follow in search for understanding of the earth as we attempt to apply our new vision of the moon.

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The summary of lunar science contained in this paper draws upon a broad spectrum of ideas and investigations performed by what has become known as "The Lunar Science Team". One of the major difficulties inherent in such a large 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. It is appropriate to add, however, that the model for lunar evolution as presented here grew out of detailed discussions within a group informally known as "Everyman". Everyman consisted of many of the geologists, geochemists and geophysicists working at the Johnson Space Center in 1972 and occasional other investigators who visited this Center during that year. The model became known as "Everyman's Moon" and was the hypothetical testing ground for my personal examination of the geology of the Valley of Taurus-Littrow during the Apollo 17 mission. I am thus deeply in debt to the men of Everyman.

THE MOON AND ITS EVOLUTION

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 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 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) and the upper mantle rich in magnesium and iron (pyroxene and olivine).

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.

As our confidence grows in this interpretation of the first 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" equals "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. Thus, on earth as on the moon, it is probable that the major radial controls on the distribution of the elements was established at the very start of the planet's evolution.

It may be of interest to note at this point that in the oldest rock 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 comprising 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, methane, chlorine and other compounds and elements. The exact chemical and physical nature of this fluidsphere would be greatly dependent on temperature.

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 or possibly even ten times larger. 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 over-emphasized. The size of the craters with which it is saturated and the seismic data we have accumulated, indicate that the disturbance extended to at least 25 kilometers below the surface.

It is highly probable that the protocrust of the earth underwent comparable disturbance as that of the moon. There is no clear evidence of this yet recognized on earth; however, we should begin to consider the implications of it having occurred. 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 the continuous mixing caused by impacting debris. This debris also may have continuously supplied the early organic building blocks of life which we know to be present even now in some meteorites and in the interstellar medium.

About 30 percent of the volume of material of the outer crust is made up of minerals rich in magnesium and iron. Seismic information from beneath

the area of our net of seismometers indicates that the lower crust, that is, a zone between about 25 and 65 kilometers, is similar in mineralogical composition to the outer crust; however, it appears to be of 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 there is an upper lunar mantle and that it is probably composed largely of pyroxene and olivine, silicate minerals rich in magnesium and iron. Both the upper mantle and the crust, however, have been greatly modified by later events and materials.

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 form by major impact events at a time when they could not be obliterated by smaller collisions. Most of these basins are now partially filled by younger materials; however, certain generalizations can be made.

The young basins, such as Serenitatis, are circular in shape and have deep original floors. Gravitational accelerations measured from lunar orbit show that these young basins overlie large concentrations of mass and have roughly concentric deficiencies of mass just inside their rims. The older 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.

Samples from the surface and data from orbital sensors indicate that rocks possibly formed from the residual liquids of the melted shell and rich in alkalis, radioactive isotopes, rare earth elements and phosphorus, are now present in varying amounts in the debris on the moon's surface. 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 the ejecta blanket to the south and southwest of Imbrium.

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 are the locus of ore deposits of those elements. My home country of 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 weak even though much time, effort, and money has 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 the answers.

Near the conclusion of the period of large basin formation about 3.9 billion years ago, the moon's interior, through the accumulation of the heat

of radioisotopic decay, again reached temperatures by which it could begin to influence the character of the surface regions. First, there is geochemical, magnetic and seismic evidence suggesting that a core of a liquid solution of sulfur and iron accumulated prior to this time. This may have occurred early in lunar history if the entire moon was once molten, or somewhat later by the gradual gravitational migration through the solid mantle of the immiscible liquid from the melted shell period.

Whenever the core formed, a remarkable and still little understood phenomena 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 Graff. The presence of hard remanent magnetism in breccias formed at most only a few hundred million 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 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 such a core. It seems likely that a protective magnetic field also existed around the earth at least as far into the past as that of the moon's. 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 influence was considerable. The further delineations of the history and origin of the lunar magnetic field will bear heavily on our understanding of these terrestrial processes and their significance.

THE LIGHT-COLORED PLAINS

The second 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 filling large basins on the farside of the moon indicate 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 melts would later concentrate in much larger volumes to form the maria.

There are other light-colored plains in old, low 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 coincidental eruptive and impact processes created most of the light-colored plains.

THE MARE BASALTS

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 tells 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 upwelling and extrusion of molten rock was probably 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 extrusion of the products of this melting appears 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 and ages of mare may have been controlled by the interaction of the equipotential surfaces of the lunar gravitational field with the borders of older mare eruptive areas and the limits of topographic basins.

The early extrusion of each major pulse of mare basalt may have been very rapid through the intensely and deeply broken outer crust. If this was true, then each basalt-filled basin may be a single cooling unit and similar in internal structure to our own planet's basaltic and ultramafic stratiform sheets. The upper visible portions of these basins, however, are now comprised of extensive lava flows, 10 to 100 meters thick, and, in some cases, several hundred kilometers long.

Variations in the internal composition of the moon or in temperatures as a function of depth caused the period of mare flooding to span at least the time from 3.8 to 3.0 billion years ago. Such variations in composition or depth or 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 dark-colored, chemically distinct, 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 very deep within the moon.

Then a relative quiet settled forever on the surface of the moon. When the waves and currents on the maria had finally been arrested, the moon's appearance differed only slightly from that of today.

We should note 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 any internal melting that might have produced mare-like materials. Again, as with the anorthosites, the question of the existence of terrestrial mare is not of trivial interest because much of the nickel, chromium, and platinum-group metal resources of our planet are located within these sheets of rock. In addition, the eruption of terrestrial mare 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 some 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 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 as 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 in 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 on the far horizon of Mare Tranquillitatis. That horizon 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 of 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 cosmic 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 reaggregation 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 anorthositic and granitic non-mare debris apparently derived from the highlands to the south. Meteoritic debris, migrant volatiles from other regions, gases derives from the solar wind and the effects of galactic cosmic rays were also identified. The debris that may have come from the highlands seemed to confirm the Surveyor VII results at Tycho that the southern lunar highlands 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, but 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 apparently recording one of the fractionation events in the melted shell that occurred about 4.5 billion years ago. The range of ages of the mare basalts 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 mare basalts extended to relatively low titanium varieties. The surface units of the mare 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 date the event that formed Copernicus as having 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 mare basalts.

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 spacecraft had previously showed that the moon has essentially no global magnetic field (less than 1γ). In contrast, the Apollo 12 magnetometer showed that local, low-intensity fields (around 100γ) were present. This combined with the presence of hard magnetism in the rocks indicated that there had been an ancient global magnetic field ($2000 - 3000\gamma$).

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 generalization to be made concerning the character of the basaltic mare previously sampled by Apollo 11 and 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 much of the data from an individual mission were representative of broad mare 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 3.1 billion year crystallization ages measured for Tranquillitatis and Cognitum mare basalt, 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, new ranges in the variability of basaltic composition 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 investigating of the regolith characteristics at the Luna 16 site indicate broad similarities with those of Tranquillity Base; however, the non-mare components of the regolith shows many distinctive features relative to both the Apollo 11 and 12 sites. In particular, the chemistry of the non-mare components indicate 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 of the crater Copernicus, we planned the landing of the Apollo 13 mission. We were anticipating insight into the intensity and timing of the event that formed the Imbrium Basin through the study of its ejecta blanket. Instead, we received new insight into ourselves. The courage of Lovell, Haise, and Swigert, and the resourcefulness of the ground controllers of their mission following the explosive destruction of the service module gave 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 appeared 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 ash flows.

The Apollo 14 mission also confirmed the extreme chemical differences between the highlands and the mare detected on previous missions. On the other hand, the abundance of rocks richer in alkalis, 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 man-made 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 wheeled 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 4 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 masque 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 mare surfaces. 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 kilometers; an inner, probably chondritic and volatile-bearing silicate mantle from about 300 to 600 kilometers; a lower, also probably chondritic and volatile-bearing, seismically active, locally melted mantle from 600 to about 1,000 kilometers; and an at least partially fluid, possibly iron-sulfur core from 1,000 kilometers to the moon's center.

Our geophysical station at Hadley-Apennines 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 is recorded by the seismometers. We began to be able to correlate our landing areas around the whole moon by virtue of geochemical X-ray and γ -ray mapping from orbit. These remote sensing investigations disclosed the provincial nature of lunar chemistry, particularly by highlighting differences in aluminum to silicon and magnesium to silicon ratios within the mare and the highlands. By outlining anomalies in the distribution of uranium, thorium, and potassium, the γ -ray information suggested that large basin-forming events are capable of creating surface geochemical provinces through the ejection of deep-seated material.

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 was

Luna 16 with respect to the basaltic mare, the most important aspect of the Luna 20 sample is the increased global perspective it gives 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 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 as possibly being the much reworked remnants of at least portions of the ancient lunar crust after Apollo 15. Luna 20 confirmed its importance. In addition to these major distinctions, the Luna 20 materials 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 highland-like materials had been found for the ejecta blanket of the Imbrium Basin at Fra Mauro, for the rocks of the Apennines and soon 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 continually reworked the cratered highlands until most vestiges of original ages had disappeared and only the last 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 mare basalts took place over about 100 million years of time around 3.9 billion years ago. Also, indications are present at Descartes that the light-colored plains may be the loci of many of the observed regional magnetic anomalies, suggesting that they 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 discovering materials of clearly volcanic origin as had been expected, most information suggests that the samples had been subjected to an interlocking sequence of igneous and impact processes. 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 myself to visit the valley of Taurus-Littrow. The unique visual character and beauty of this valley was, I hope, seen by most readers in December of 1972. 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 hard 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 mare basalts, 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 mare basalt 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 which appear to be the remains of the fractional crystallization of the melted shell. This conclusion is supported by one of these distinctive clasts, a crushed, rock of magnesium olivine has an apparent crystallization age of 4.7 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; however, an internal eruptive origin cannot yet be ruled out. The third and youngest breccia unit appears to cap the tops of the mountains and it may be the ejecta from one of the several large basins within range of the valley. This breccia contains a wide variety of clasts of the material of the two older breccias plus other, new 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, mare basalt extrusives on the moon. At about 3.8 billion years in age 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 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.

The modification 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. These titanium-rich, basaltic to ultramafic glasses surprised us once again; their 10 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 not yet obvious. 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. These characteristics 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.

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 awaits 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 had 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 crust as ocean floors grow and continents move. These stresses and strains profoundly affect the everyday lives of people living within belts of present earthquakes and volcanic activity and have affected the distribution and control of the ore deposits upon which our civilization is based. Within future understanding features like the frozen ocean of basalt of Mare Procellarum, and the vast ridge and volcanic system that splits it, may lie further inspiration for all of us.

Many of the present attempts to correlate our new understanding of the moon with our old understanding of the earth still lie in the realm of imagination. Our new knowledge from the moon, however, will never become a resource until it is married to imagination. It is thus and only thus that the scientific legacy of Apollo and Luna will be realized.

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