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Evolution of the Moon: Apollo model

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ABSTRACT

The major stages of lunar evolution as derived from information obtained from the Apollo and Luna missions can be defined as follows:

1. Beginning—4.55 eons. The moon formed contemporaneously with the Earth. Geophysical data and parentless Pb and volatiles in pyroclastic glasses of Imbrium age derived from deep source regions indicate that initially undifferentiated material accreted below about 480 km.

2. Magma Ocean—4.5–4.4(?) eons. Accretionary melting, volatile depletion, and crystal settling and floating differentiated the outer 400–500 km of the moon into an anorthositic crust 50–70 km thick and an ultramafic upper mantle containing urKREEP residual liquids.

3. Cratered Highlands—4.4(?)–4.2(?) eons. Impacts capable of forming craters at least 50 km in diameter saturated the Pre-Nectarian lunar crust, producing intense crustal brecciation and increased thermal insulation of the interior.

4. Old Large Basins and Crustal Strengthening—4.2(?)–3.9 eons. Pre-Nectarian large basins formed with rapid isostatic adjustment of the crust. Residual urKREEP liquids apparently moved upward into the pervasively fractured crust. The removal of underlying liquid combined with interlocking intrusions strengthened the crust.

5. Young Large Basins—3.9–3.8 eons. Large impact basins of Nectarian and Imbrium age formed in a crust strong enough to support mascons and mass deficiencies. Materials related to this stage of large basin formation, including ejecta blankets, debris flows, and shock melted lava, covered most of the near side, if not most of the Moon. A lunar cataclysm of this age does not appear to be required to explain the rarity of older, datable breccia samples.

6. Basaltic Maria—3.8–3.0(?) eons. Mare basalt, produced by downwardly progressing partial melting of the mantle, erupted at the lunar surface and intruded the subsurface. The sequence of near-side surface eruptions proceeded roughly radially from northern Tranquillitatis, the region of minimum gravitational potential. Early volatile-driven eruptions of crustal debris contributed to light plains deposits. Late mafic pyroclastic materials appear to be a mixture of differentiated mantle and undifferentiated volatiles derived from below 400 km.

7. Mature Surface—3.0(?) eons to present. Formation of rayed craters occurred in all regions. Maturation of the lunar regolith continued, including implantation of solar wind gases. Bright swirls formed over large areas.

INTRODUCTION

The Apollo Program gave us a first order understanding of the sequence of events and the processes by which the Moon evolved over 4.55 eons. This conclusion, so far, relates only to events and processes after the Moon's formation near the Earth. Speculation about what happened during formation has intensified in recent years with broad, but not unanimous, support for fission of the already differentiated Earth after collision of a "Mars-sized asteroid" (Hartmann, 1986).

Information about the Moon was accessible even to our distant ancestors as they planned monthly hunting and gathering around ancient African lakes. Had they looked closely at the full Moon, as they may well have done, they would have seen light regions interrupted in some places by sharply defined circular areas. These circular areas and other more irregular patches would have appeared relatively dark. If our ancestors had good eyes and squinted, they would have seen, even then, several very bright spots on both the light and the dark surfaces.

In the 16th century, the observations and logic of Copernicus, following in the footsteps of Aristarchus and probably others before who remain unrecorded, demonstrated that the Moon orbited the Earth while both bodies orbited the sun. Then, in the 17th century, Galileo invented the telescope. Through this remarkable example

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Table 1. Pre-Apollo model of lunar evolution

1. Formation of an old highly cratered crust, rich in Ca and Al, on a generally chondritic interior.
2. Excavation of large circular impact basins, the younger ones with underlying mass concentrations.
3. Floors of many highland basins covered by light colored smooth plains.
4. Most large basins on the near side partially filled by basaltic lava flows (mare).
5. Postmare lunar surfaces slightly modified by formation of constructional volcanic deposits, dark mantling materials, faults, rilles, and light-colored swirls.
6. Pulverized rock debris, or regolith, formed on all surfaces in response to meteoritic bombardment and radiation.

of human ingenuity and technology, Galileo soon discovered that the light areas were cratered terra, or highlands; the dark areas were less heavily cratered basins, or lowlands, at first mistaken for seas and called maria; and the bright spots were craters with vast systems of bright radial patterns, or rays.

Kepler, Newton, and others, also in the 17th century, provided the mathematical means of calculating the Moon's shape (roughly a sphere), size (radius about 1738 km), mean density (3.34 g/cm^3), and the moments of inertia (about 0.400 for the principal moment). These facts, although slightly inaccurate, placed limits on composition, that is, the overall Moon resembles stony meteorites that fall on the Earth and had significantly less Fe relative to the Earth and the sun. The same facts, however, also limited the possible distribution of mass, that is, the Moon must be a roughly uniform solid sphere. With any logical bent, these same observers may have realized that the Moon had no clouds or other apparent protection from the ravages of space and the sun.

Gilbert's (1893) studies in the 19th century marked the beginning of modern considerations about the Moon. During the mid-20th century, indirect analyses by Baldwin (1949), Urey (1952), and Kuiper (1959) contributed new insights about composition, age, shape, motions, and surface properties. In the years just preceding human footsteps on the Moon's surface, and as it became apparent that humans might soon go there, knowledge of this small planet's past expanded rapidly through specialized investigations. Shoemaker (1962), Hackman (1962), and many others (see Wilhelms, 1987) used telescopic photographs and observations, photographs from space probes, and extensions of Steno's law of superposition to add refinements to the more ancient text about the Moon.

The highlands were seen to be saturated with large meteorite impact craters at least 50 km in diameter and clearly constituted the oldest visible crust of the Moon. Many highland basins appeared to contain relatively smooth, light-colored plains. The analyses by the Surveyor VII spacecraft demonstrated that this light crust contains significantly more Ca and Al than the mare (Turkevich et al., 1969, p. 336). The large circular basins not only penetrated the upper crust but cut across large irregular basins as well. Tracking of Lunar Orbiter spacecraft disclosed that at least some of the youngest large basins

Table 2. Apollo model for the evolution of the Moon

Stage	Age (eons)
Pre-Nectarian	
Beginning	4.55
Contemporaneous with Earth	
Early cold accretion below about 480 km	
Magma ocean	4.55–4.4(?)
Accretionary melting above about 480 km	
Volatile depletion	
Differentiation of 60 km thick crust	
Separation of urKREEP liquid	
Separation of iron-sulfur liquid	
Cratered highlands	4.4(?)–4.2(?)
Crater saturation to >50 km diameter	
Crustal brecciation to >25 km	
Old large basins/crustal strengthening	4.2(?)–3.9
Formation of >29 basins	
Crustal thinning and thickening	
Impact materials broadly distributed	
Isostatic adjustment	
UrKREEP liquids moved into lower crust	
Strengthening of the crust	
Nectarian and Lower Imbrium	
Young large basins	3.9–3.8
Formation of 14 basins	
Mascons and mass deficiencies sustained	
Impact materials broadly distributed	
Upper Imbrium	
Basaltic maria	3.8–3.0(?)
Downwardly phased mantle partial melting	
Early eruptions of crustal debris	
Basaltic intrusions and extrusions	
Basin related extensional faulting	
Late mafic pyroclastic eruptions	
Eratosthenian and Copernican	
Mature surface	3.0(?)–
Rayed crater formation	
Surface regolith formation	
Bright swirl alteration of large areas	
Declining meteor impact frequency	

overlay significant mass concentrations (Muller and Sjogren, 1968).

Early in this modern but still remote study, observations at low sun angles disclosed that the dark maria were vast plains of remarkably fluid volcanic flows, visually similar to flood basalts on Earth. Surveyor V and VI analyses confirmed these conclusions (Gault et al., 1968). The flows partially filled many of the large circular and irregular basins on the Moon's near side and covered some of the light plains. Soviet photography of the lunar far side (Whitaker, 1963), as well as later Lunar Orbiter coverage (Kosofsky and El Baz, 1970), showed that the far side of the Moon consisted of an almost continuous expanse of cratered highlands with significantly fewer dark maria than the near side.

It soon became clear that little major internally generated activity had occurred at the Moon's surface after the last major episode of mare formation. As studies became more detailed, an overprint of subtle features became apparent. A lengthy ridge and volcanic island system existed in the Moon's largest western mare region, Procellarum (see, for example, McCauley, 1967); strange sinuous rilles and light-colored swirls were found; and extensive, relatively young fault systems, in particular, grabens, cut large regions of the surface (see Wilhelms,

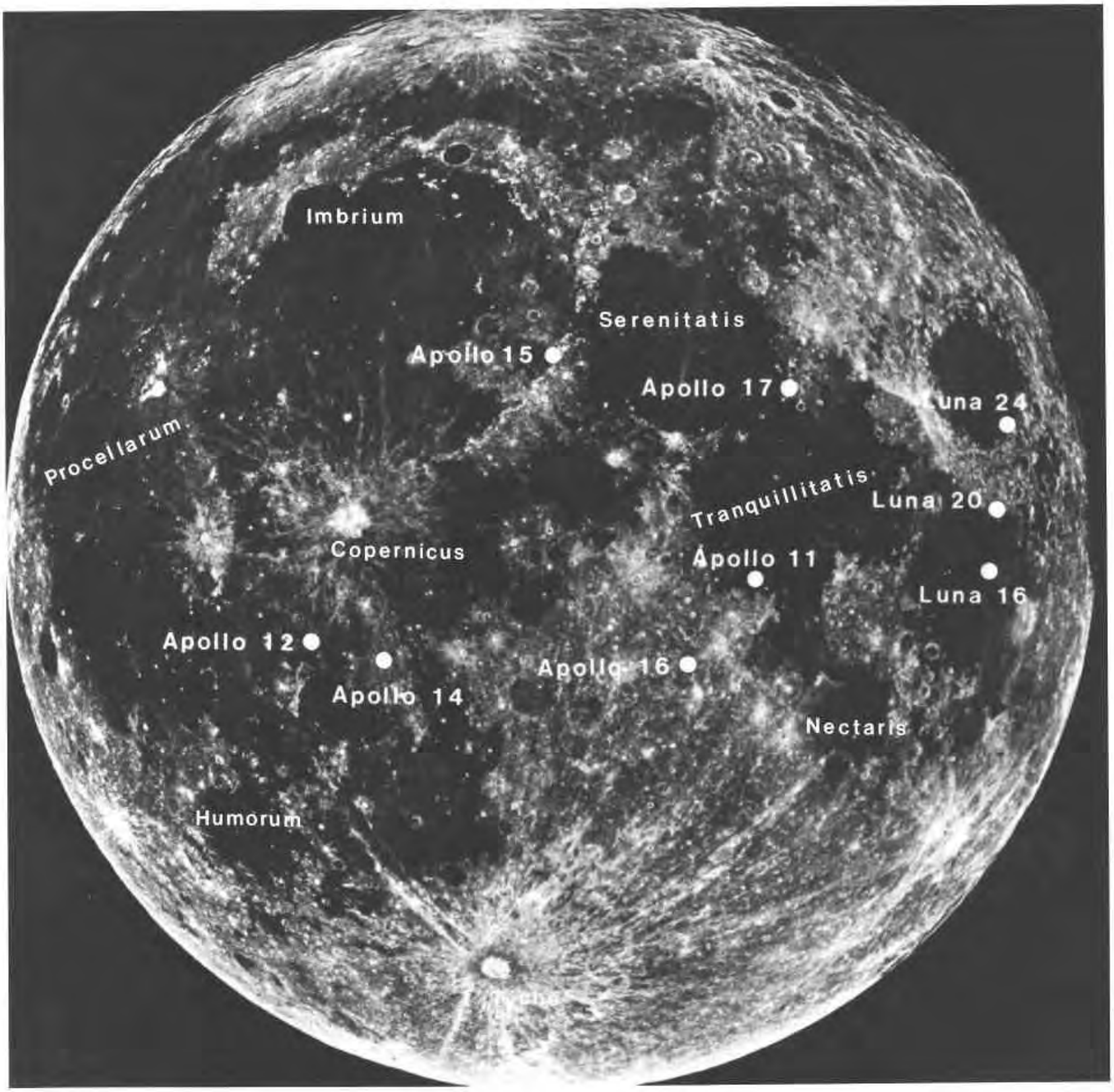

Fig. 1. The location of the six Apollo and three Luna landing sites relative to major features on the near side of the Moon. (NASA Photo S84-31673).

1987, chapter 6, p. 244, 256). Overall, a pulverized rock layer, defined as "regolith" (Shoemaker et al., 1967), covered essentially all of the surface, attesting to extensive and probably continuous meteoritic bombardment and radiation from space.

Table 1 outlines the relative sequence of events that formed a plausible model of lunar evolution before any pieces of rock or scoops of soil arrived from the lunar surface.

Apollo model

An early post-Apollo model for the evolution of the Moon proposed by Schmitt (1975a) attempted to provide a consistent framework for the interpretation of Apollo and Luna exploration data (see Fig. 1) then available. Revision and expansion of this model may help to focus the scientific planning of future exploration. Table 2 summarizes the broad characteristics of the updated model.

Beginning: 4.55 eons

The one largely undisputed conclusion about the origin of the Moon since the acquisition of Apollo samples places its formation at about 4.55 eons (Tatsumoto et al., 1977), apparently contemporaneously with the Earth. The process of formation remains unclear; however, that process probably could not have produced a fully or largely molten moon. Subsequent differentiation of a molten moon would have eliminated relatively undifferentiated material rich in volatiles (summarized by Delano, 1986) and parentless Pb (Tera and Wasserburg, 1976) required as components in the source materials for orange, black, and green pyroclastic (picritic) volcanic deposits. This constraint suggests a lunar beginning through accretion of initially relatively cold material. Catastrophic separation of the Moon from a preexisting and differentiated Earth, as suggested recently by Hartmann (1986) and many others, may not be able to satisfy such a constraint.

Magma ocean: 4.55-4.4(?) eons

As lunar accretion accelerated, melting (Smith et al., 1970; Wood, 1970) and volatile depletion of the outer several hundred kilometers of the Moon occurred, creating a melted shell (Schmitt, 1975a) or magma ocean (Walker, 1975; Wood, 1975; Warren, 1985). The more commonly used term, magma ocean, designates this first major stage of lunar evolution. Differentiation of the magma ocean (see review by Taylor, 1982, chapter 8) resulted in a roughly 50–70 km thick crust of ferroan (Dowty et al., 1974) anorthosite and olivine norite in roughly equal proportions (Korotev et al., 1980) and an ultramafic upper mantle several hundred kilometers thick, possibly with its base at 400–480 km (Goins et al., 1979). The residual liquid in the differentiating magma gradually took on the chemical characteristics attributed to urKREEP (Warren and Wasson, 1979; Warren, 1988), the proposed parent of rocks rich in K, REE, and P described initially by Hubbard et al. (1971). Left undisturbed, this liquid would probably remain largely uncrystallized owing to concentration of radioisotopes and the insulating nature of the increasingly brecciated crust.

Prior to the development of a physically coherent crust, large accretionary impacts would have mixed the still-differentiating melt into the protocrust, adding both an overall gabbroic contaminant, the olivine norite of Korotev et al. (1980) and many impact-forced intrusions and extrusions. Once the crust could maintain its overall coherency in the face of continued high but decreasing impact frequency, strong evidence exists that intrusions from the differentiating mantle magma were emplaced (Warren and Wasson, 1980; James, 1980). The local differentiation of these intrusions appears to be the source of the Mg-rich suite of pristine clasts found in highland breccias such as those reviewed by Prinz and Keil (1977).

Crystallization ages greater than 4.4 eons (see Wilhelms, 1987, Table 8.4) measured for many of the examples of pristine mafic and ultramafic clasts strongly suggest that these may constitute remnants of differentiated intrusions from this period. As might be expected from this process of late accretionary mixing of differentiating magma, Pieters's (1987) spectroscopic studies of the central peaks and ejecta blankets of Copernican and Eratosthenian craters indicate the presence of large bodies of Mg-rich rocks below the upper 10 or so km of the crust. The lower age limit of 4.4(?) eons assigned to the magma ocean stage corresponds to the minimum crystallization ages measured for clear-cut samples of the Mg-rich suite of highland breccia clasts.

Late in the magma ocean stage, uncrystallized and relatively low density urKREEP would have concentrated near the base of the still forming and continuously brecciated crust. (See Schmitt, 1975a; Ryder and Wood, 1977; Warren and Wasson, 1979; however, Ryder, 1990, now advocates cataclysmic brecciation at 3.9 eons, discussed subsequently.) In response to particularly large impacts, some urKREEP also may have been separated from the mantle and incorporated in the crust either as disseminated ejecta or as coherent intrusions. KREEP model ages of 4.4–4.3 b.y. (Lugmair and Carlson, 1978; summarized by Taylor, 1982) support this conclusion and support an overlap between the magma ocean stage and the following cratered highlands stage.

During accretion and melting, any immiscible iron-sulfur liquid could be expected to settle quickly to the base of the magma ocean. Ultimately, as radioisotopic heating permitted solid state flow, this liquid would have moved toward the center of the Moon. Except for some purging of chalcophile and siderophile elements, the downwardly migrating iron-sulfur liquid probably did not affect the composition of undifferentiated and still relatively cool lower mantle material. The formation of a lunar core has not been conclusively proved (see Wiskerchen and Sonett, 1977; Goins et al., 1979; summarized by Taylor, 1982, p. 358–359); however, the weight of evidence suggests the presence of a fluid core with an upper limit of about 500 km in radius.

Table 3 summarizes the major lunar features present at the completion of the magma ocean stage of lunar evolution.

Cratered highlands: 4.4(?)-4.2(?) eons

The cratered highlands stage of lunar evolution (early Pre-Nectarian) represents a time between about 4.4(?) and 4.2(?) eons when impacts on the lunar surface produced a saturation of craters as large as 60–70 km, that is, curves of crater size vs. frequency approach a slope of −1 at these diameters (Wilhelms, 1987, p. 145). The lower age limit for this stage has been selected as that suggested by Taylor (1982, p. 238–240) for the resetting of most radioisotopic Ar clocks of possible Pre-Nectarian age; however, a final selection of a lower limit requires samples that clearly record Pre-Nectarian events. As discussed below, the possibility remains that no such samples have yet been recognized or collected.

Significant regional homogenization (Pieters, 1987) of the upper crust and intense brecciation of the lower crust to at least a 25-km depth (Toksoz, 1974) occurred during this stage. Any extremely large impact events, such as those proposed for Procellarum and South Pole–Aitken (see Wilhelms, 1987, p. 145), would have disrupted and thinned the upper crust and potentially triggered surface eruptions of KREEP-related lavas (Wilhelms, 1987, p. 143–144). The increasingly insulating character of the

Table 3. Major lunar features: end of the magma ocean stage

1. Surface to 50–70 km: ferroan anorthosite and olivine norite crust.
   a. Upper 25 km: impact brecciated material seismically similar to present outer crust, containing remnants of impact-forced intrusions and extrusions.
   b. Lower 40–60 km: numerous, relatively coherent intrusions of Mg-rich material.
2. 60 to 400–480 km: upper mantle, consisting largely of pyroxene and olivine.
   a. Residual urKREEP liquids concentrated near the mantle-crust interface.
   b. Iron-sulfur liquid concentrated near the base of the upper mantle.
3. 400–480 km to center: lower mantle, consisting mostly of largely undifferentiated primordial accretionary material.
   a. Depending on temperature, masses of iron-sulfur liquid may have been migrating downward with depletion of chalcophile and siderophile elements.

Table 4. Changes to major lunar features: end of the cratered highlands stage

1. Upper 25 km of crust: intensely brecciated and regionally homogenized by large impacts with significant enhancement of thermal insulation properties.
   a. A few extremely large impacts excavated significant thicknesses of the brecciated upper crust.

progressively more intensely brecciated upper crust allowed the gradual accumulation of radiogenic heat necessary to eventually partially remelt source regions in the upper mantle that produced Imbrium and younger basaltic lavas.

The cratered highlands stage merged with the next stage as the overall frequency of impacts declined. Table 4 summarizes this stage's modification of features present at the end of the magma ocean stage.

Old large basins and crustal strengthening: 4.2(?)-3.9 eons

All but the largest of the 29 clearly recognizable Pre-Nectarian large basins (Wilhelms, 1987, chapter 8) formed after the period of intense overall cratering had waned. Otherwise most surface expression of basin structure would have been obscured. Qualitative comparison of the Pre-Nectarian large basins with younger large basins (see Wilhelms, 1987, Fig. 5.22, Plates 5 and 6) indicates that major strengthening of the lunar crust occurred during this stage. The younger basins (Nectarian and Lower Imbrium systems) are sharply defined and circular. Central mass concentrations or mascons (Muller and Sjogren, 1968) surrounded by mass deficiencies under mountain rims several thousand meters high underlie the young basins. The Pre-Nectarian older basins are only irregularly circular with relatively low rims and are largely compensated isostatically.

The absence of significant central mascons and rim-mass deficiencies associated with Pre-Nectarian basins demonstrates that just prior to Nectarian time, the lunar crust had little strength to resist isostatic adjustment. Although the selection of the Nectaris impact event as the beginning of this time unit evolved from the lunar mapping program of the 1960s and 1970s (Stuart-Alexander and Wilhelms, 1975), the usefulness of its selection is reinforced by the Nectaris Basin being the oldest of the mascon basins. The old large basins and crustal strengthening stage of lunar evolution therefore encompasses major crustal changes as well as the formation of all the still recognizable nonmascon large basins. The age limit on the end of the stage coincides with the formation of Nectaris, concluded by Wilhelms (1987, p. 168–170) to be about 3.92 eons.

The formation of Pre-Nectarian basins in the now coherent crust had three major effects: (1) redistribution of upper crustal material as ejecta, ejecta blankets, debris flows, and impact melt flows, (2) regional thinning and thickening of the crust (see Bills and Ferrari, 1977, Fig. 3), and (3) fracturing of the lower crust beneath each basin. After each large basin formed, the relatively low density urKREEP liquid would move upward into the deeply and closely fractured crust (Schmitt, 1988). Following the excavation of the deepest of the older large basins formed about 4.2 Ga, KREEP-related lavas may have locally reached the floor of such basins (see Wilhelms, 1987, p. 143–144).

Becoming cooler and significantly contaminated with unconsolidated and largely anorthositic crustal debris, the KREEP-related liquids could be expected to crystallize into networks of compositionally varied intrusions. Removal of underlying urKREEP liquid, combined with an interlocking boxwork of solidified intrusions, would have strengthened the crust. Crystallization ages of 4.2 eons for a few KREEP-related materials (Nyquist et al., 1977) may support this hypothesis of Pre-Nectarian solidification of KREEP-related intrusions.

Finally, the downward migration of iron-sulfur liquid, which began in the melted shell stage, may have been completed in this stage. This would be suggested if the activation of a dynamo-related dipole magnetic field created the measured remnant magnetic fields (see Taylor, 1982, p. 364–370).

Table 5 summarizes changes in major lunar features produced by the old large basin and crustal strengthening stage of lunar evolution.

Young large basins: 3.9-3.8 eons

Between 3.9 and 3.8 eons, 14 large impact basins of Nectarian and Lower Imbrium age (Wilhelms, 1987, chapters 9 and 10) formed in a crust strong enough to support significant mascons and mass deficiencies. The

Table 5. Changes to major lunar features: old large basin and crustal strengthening stage

1. Redistribution of upper crustal material as ejecta, ejecta blankets, debris flows, and impact melt flows.
2. Regional thinning and thickening of the crust.
3. Pervasive fracturing of the crust beneath each basin.
4. Upward migration of urKREEP residual liquid from the upper mantle.
   a. Formation of an interlocking boxwork of KREEP-related intrusions with corresponding enhancement of crustal strength.

Fig. 2. The author begins the investigation of the large boulders at Station 6 in the Valley of Taurus-Littrow on the Moon. This boulder contained a contact between blue-gray breccia and an intrusive vesicular tan-gray breccia, both of impact origin. (NASA Photo AS17 140-21496).

initial crustal penetration of the Imbrium event apparently excavated particularly large quantities of KREEP-related intrusions or flow material and distributed it to where Apollo 14 sampling (see Swann et al., 1977) and geochemical remote sensing (Metzger et al., 1977) found it concentrated. The work of the Consortium Indomitabile (1974) on a layered breccia boulder examined and sampled at the base of mountains bordering Serenitatis strongly suggests that other basin-forming events also excavated significant quantities of now buried KREEP-related material (see Schmitt, 1975b).

Tera et al. (1974) suggested that a lunar cataclysm, including the events of the cratered highlands stage and the formation of all large basins, occurred between 3.9 and 3.8 eons. This suggestion recently has been revived in detail by Ryder (1990). A cataclysmic compression of all the events associated with the formation of old and young large basins as well as the crater saturation in the highlands does not appear to be supported by the analysis leading to the model of lunar evolution presented here.

First, it seems unlikely that there would be a hiatus of half a billion years in significant impact activity after such a remarkably violent accretionary beginning. Second, the cataclysm hypothesis requires that within 100 m.y., there must occur both a much compressed cratered highlands stage and the formation of two groups of large basins with markedly different relative ages and physical characteristics. Third, within the same 100 m.y. and between the formation of the two groups of large basins, the crust must strengthen significantly. Fourth, the ages of impact melts sampled by Apollo 16 in the highlands show ages that range from 3.7 to 4.2 eons (James, 1981), indicating that at least some pre–3.9 eon impact melts exist where one might expect to find them.

Finally, in the context of the cataclysm hypothesis, it should be noted that the sampling of impact breccias and melts during Apollo and Luna missions took place well within the portion of the Moon most affected by Nectarian-age cratering and basin formation, which may account for a major part of the 3.9–3.8 eon bias in impact melt ages. In addition, as suggested by Wilhelms (1987, p. 190–191), a significant concentration of radiometric ages can be expected statistically from the natural consequences of a declining cratering rate. A final resolution of this controversy, however, may have to await a broader and more geologically selective collection of samples from other regions of the Moon.

The formation of large basins makes major modifications to the crust many crater diameters beyond the initial point of excavation. Lithostatic resistance at depth appears to divert the force of the impact radially both in the effects of crustal deformation and in the movement of ballistic and flowing ejecta. Lunar photogeologic mapping of Orientale (McCauley, 1987) and investigations of large breccia boulders by Apollo 17 (Schmitt and Cernan, 1972) at the Valley of Taurus-Littrow traverse Stations 2, 6 (Fig. 2), and 7 (in the mountain ring surrounding the Serenitatis Basin) illustrate at different scales the complexity of processes that characterized the formation and interaction of large basins. A definitive study has been made (Consortium Indomitabile, 1974) of Boulder 1 at Station 2 at the base of the South Massif. The geological model for the formation of this complexly layered breccia presented by Schmitt (1975b) spans most of the first one-half billion years of lunar evolution. At least three major dynamic events that modified and deposited impact ejecta contributed to Boulder 1's present structure, geochemistry, and petrology.

An additional view into the processes of large basin formation comes from the very large breccia boulder described and sampled at Station 6 near the base of the North Massif of the Valley of Taurus-Littrow (Schmitt and Cernan, 1972; Schmitt, 1973; Apollo Field Geology Investigation Team, 1973). The Station 6 boulder had rolled down the side of the North Massif from a point about 1200 m below the top of the massif. The boulder (Fig. 2) included a contact between blue-gray and tan-gray breccias, both containing numerous clasts of the anorthositic and Mg-rich suites of rocks. The blue-gray breccia contains small vesicles within about 1 m of its contact with the coarsely vesicular tan-gray breccia. This evidence of high-temperature contact metamorphism indicates that the tan-gray breccia intruded the blue-gray breccia as a partially molten mass with sufficient heat to melt portions of its host.

After the completion of the two stages of large basin formation defined here, regional deposits of crustal ejecta and shock-melted lava covered many regions of the Moon. Except for the shock-melted lava exposed inside the outer

Rook Mountain ring of the Orientale Basin, the Maunder Formation (McCauley, 1987, p. 76–77), younger mare units cover most of such material inside the basins themselves. Impact events into shock-melted lavas, however, would have distributed samples of this type over most of the Moon, a fact that should be considered in the interpretation of fragments of Al-rich rock types in the lunar regolith.

Lunar-wide debris deposits in closed basins, now recognized as light plains, terra plains, and Cayley plains (Wilhelms, 1987, p. 216–220) probably have several origins. Many clearly are deposits of fine gas-charged debris ejected during large impact events and transported across the lunar surface as regional debris flows. Such flows would have settled preferentially in basins, leaving relatively smooth plains. Orbital observations of the lunar far side (Schmitt, unpublished data, 1972) included views of large, markedly smooth floored craters without visible central peaks, suggesting that the central peaks as well as any irregular floor and slump material has been covered by later deposits. The absence of younger maria except in craters excavated in the deepest of these smooth floored craters, has left these relationships exposed.

Although relatively short-lived, the young large basins stage resulted in major modifications to the model of lunar evolution presented here. Table 6 summarizes these changes.

TABLE 6. Changes to major lunar features: Young large basin stage

1. Additional redistribution of upper crustal material as ejecta and debris flows.
   a. Impact melt and debris flow units constituted significant surface units in and around all large basins.
2. Additional regional thinning and thickening, as well as unloading and loading, of the crust.
3. Additional fracturing of the lower crust beneath each basin; however, such fracturing apparently did not significantly affect the strength of the crust, established during the preceding stage.
4. Creation of uncompensated positive gravity anomalies under young impact basins and negative anomalies under their rims.

Mare basalt: 3.8-3.0(?) eons

Surface eruption and subsurface intrusion of mare basalt magmas (see reviews in Basaltic Volcanism Study Project, 1981; Wilhelms, 1987, chapter 5) became a significant crustal phenomena about 3.8 eons (Wilhelms, 1987, chapter 10). Surface eruptions probably appeared first at a selenopotential low in the vicinity of northern Tranquillitatis and southern Serenitatis with subsequent eruptions appearing in roughly concentric zones (Schmitt, 1974, 1975a, p. 266) around this low. The offset of the center of mass of the Moon from its center of figure toward the Earth (Kaula et al., 1974), caused by asymmetrical thinning of the crust during the large basin stages, would have created this selenopotential low and the resulting asymmetrical distribution of surface mare basalts (Taylor, 1982, p. 344–345). Progressively younger upward migrations of mare basalt magmas from the mantle would encounter a largely sealed surface near preceding eruptive regions and be forced concentrically away from the selenopotential low. Basin and highland distributions would produce the observed perturbations to idealized concentric zoning.

Exact upper and lower age limits for the mare basalt stage will remain uncertain (see Basaltic Volcanism Study Project, 1981; Taylor et al., 1983; Schultz and Spudis, 1983; Wilhelms, 1987) until field studies take place in the major unvisited mare regions of the Moon, including Mare Procellarum, Mare Orientale, and the mare and highlands of the lunar far side. The Apollo 14 breccia clast with mare-related chemistry, a cumulate texture, and an age of 4.2 eons (Taylor, 1982) deserves particular emphasis in this regard. Clearly, however, the span of 3.8 to 3.0 eons encompasses the major identified portion of eruptive as well as intrusive activity involving mare basalt magma (see Taylor, 1982, p. 319; Wilhelms, 1987, chapters 10–13).

Early precursors of the mare basalt stage also may have contributed to light plains deposits. The surface character of light plains in some far-side basins observed by the author (unpublished data, 1972) suggests pyroclastic eruptions dominated by crustal debris. Relevant surface characteristics include irregular rimless depressions suggestive of terrestrial pyroclastic vents and collapse features.

Although volatile depletion of the magma ocean appears to have been extensive, some residual volatiles remained as indicated by the vesicular nature of many mare basalts. Evolved with low melting point components before the first true mare basalt magmas in each mantle source zone, such residual volatiles would be expected to entrain crustal debris as they move upward to erupt at various times prior to basaltic magma extrusion or intrusion into any given province. With this scenario, the earliest coherent magmas also would have been charged with volatiles, as found for certain highly fractionated kimberlite-minette eruptive sequences on Earth (Schmitt and Swann, 1968). Upon assimilating variable quantities of anorthositic crustal debris, possibly including some KREEP components, early precursor magmas may account for some of the pre-Imbrium (older than 3.8 eons) basalts that are highly fractionated and Al rich.

Late-stage debris eruptions producing similar morphological characteristics, as seen on light plains deposits, also may have occurred in various provinces as subsurface mare basalt intrusions cooled and released volatiles, particularly beneath the lunar highlands. Vesicle assemblages in many mare basalts (Schmitt et al., 1970) further suggest a largely unreactive volatile phase that might drive late eruptions from cooling intrusives. Such eruptions may help explain some of the age relationships of dark halo and dark mantling deposits not associated directly with extrusive mare basalt (Schmitt et al., 1967; Head and McCord, 1978; Head and Wilson, 1979; Wilhelms, 1987, p. 89).

The lowest melting components of the lunar mantle

TABLE 7. Geologic model for emplacement of Apollo 17 orange and black beads

1. Eruption of the mare basalt flows that partially filled the Valley of Taurus-Littrow—3.8–3.7 eons (Wilhelms, 1987, Table 11.3).
2. Eruption of orange glass beads and compositionally identical but more slowly cooled black devitrified glass beads as part of a pattern of basin edge pyroclastic eruptions in the Serenitatis Basin—3.7–3.6 eons (Wilhelms, 1987, Table 11.3).
3. Immediate covering of the pyroclastic deposits by a basalt flow of sufficient thickness to protect the orange and black bead deposits from significant contamination by regolith related processes—3.7–3.6 eons (Wilhelms, 1987, Table 11.3).*
4. Avalanche from the north side of the South Massif to form the light mantle—109 m.y. (Drozd et al., 1977).
5. Meteor impact that created Shorty Crater and penetrated below the Light Mantle and into or through the basalt flow overlying the pyroclastic deposits—19 m.y. (Eugster, 1977).
6. Instantaneous shock stimulated release and pressurization of adsorbed gases and the fluidization of pyroclastic deposits immediately beneath the protecting basalt flow.
7. Eruption of gas–bead mixtures along conduits in the radial and circumferential fractures around Shorty Crater.
8. Continuous sorting of the orange glass beads from their more dense black crystallized equivalent toward the top of the gas column to give the sharp separation of orange and black beads observed on and in the core tube (Schmitt and Cernan, 1972, and Heiken et al., 1974).**
9. Development of 1–2 cm of regolith on the exposed top of the orange bead deposit.

* Small areas of mare basalts younger than the orange pyroclastic deposits in the Sulpicius Gallus region of southwestern Serenitatis have been mapped by Carr (1966).

** Preservation of primary layering remains an alternative explanation for the sharp physical separation of orange and black beads. The purity of the separation as well as the evidence that the bead deposit was emplaced in the rim rather than ejected from the crater argues against this possibility, however.

probably were approaching their melting points by 3.8 eons because of the accumulation of radiogenic heat trapped by the highly insulating crust. Unloading of the mantle by the formation of young large basins, however, possibly controlled the specific timing of some early mare basalt eruptions (Schmitt, 1975a). As discussed by Taylor (1975), large scale impact melting does not appear to be a viable source for the mare basalts.

Strong evidence exists that individual mare basalt flows underwent considerable differentiation in place (Schmitt et al., 1970; Schmitt and Sutton, 1971; Basaltic Volcanism Study Project, 1981). Both the settling of dense crystals and iron-sulfide liquid and the flotation of plagioclase and vesicle assemblages constitute demonstrated processes for significant differentiation in mare basalt magma, the chemical evidence for which has been well documented (James and Wright, 1972; Rhodes et al., 1977). As suggested by Schmitt (1975a), during periods of rapid mare basalt eruption, the thickness of cooling units may be as much as hundreds of meters or more (see Wilhelms, 1987, p. 99–101), leading to the possibility of layered complexes comparable to large stratified and resource-rich igneous bodies on Earth.

Schmitt's (1975a, p. 267) analysis of the significance of REE distributions among mare basalts of various ages suggests that the remelting of the lunar mantle proceeded inward from zones near the base of the insulating crust. Such a process also would be suggested by pressure considerations and the probable locations of concentrations of radiogenic heat after differentiation of the melted shell. A definitive determination of the sequence of melting depths for the mare basalts, however, has not been accomplished (see Wilhelms, 1987, p. 102).

The discovery of the orange and black pyroclastic materials in the rim of Shorty Crater during the Apollo 17 mission to the Valley of Taurus-Littrow (Schmitt and Cernan, 1972; Schmitt, 1973) and subsequent recognition of orange materials as a major component of dark mantling deposits at the southwestern edge of Mare Serenitatis (Schmitt and Evans, 1972; Lucchitta and Schmitt, 1974) added excitement, puzzles, and critical new information to our studies of the Moon. The excitement came from the discovery of what, at the time, appeared to be volcanic material the Apollo 17 science team had speculated might be found at a dark halo crater named Shorty. The puzzles emerged when, after the so-called orange soil had been examined carefully on Earth, the conclusion had to be that orange glass beads of pyroclastic origin, 3.6 eons old and underlain by their black devitrified equivalent, somehow had been emplaced in the rim and ejecta blanket of an impact crater 80 m in diameter with only minor contamination by other material (Wilhelms, 1987, Table 11.3; Apollo Field Geology Investigation Team, 1973; Heiken et al., 1974). The critical new information was that the source region for the magma that formed these materials, and others like them at other sites, must be the deep interior of the Moon, possibly below the region included in the original melted shell (Schmitt, 1975a, p. 267; Delano, 1980).

The initial observation of the orange soil came as the result of a serendipitous interaction of mission planning, field observation, and the power of suggestion. The dark halo crater, Shorty, had been thought to be either an impact crater or a volcanic crater that penetrated the light-colored materials of a probable avalanche. If Shorty were a volcanic vent, local effluents might have altered surrounding material in some recognizable way. Even though visual inspection of Shorty disclosed that it was clearly an impact crater that had penetrated the avalanche and ejected underlying dark material as well as mare basalt fragments, thought processes that tested hypotheses on the origin of Shorty Crater played a key role in calling attention to the very light orange coloration in the thin regolith covering the main orange glass deposit.

A geologic model for the emplacement of the orange and black beads (Schmitt, 1989) comes from personal observations of the effects of the explosion of 500 tons of ammonium nitrate (1971 Dial Pack event) near Medicine Hat, Alberta. This explosion caused the pressurization of underlying H_2O-saturated sand and the eruption of the H_2O-sand mixture along conduits in radial and circumferential fractures cutting the rim and ejecta blanket of the explosion crater. Table 7 summarizes the sequence of analogous events that may have taken place in the vicinity of Shorty Crater.

Experimental data related to lunar pyroclastic glasses (see Delano, 1980) suggest that their magma source region lies 400–500 km below the surface. Further, the geochemistry of the glasses suggests that their magmas came from differentiated material at these depths (see Hughes et al., 1989). On the other hand, the noncrustal and primitive nature of the volatiles adsorbed on the surfaces of the orange and black beads (Meyer et al., 1975; Tera and Wasserburg, 1976; Tatsumoto et al., 1976) indicate a source region for these volatiles below the zones affected by the loss of volatiles during the magma ocean stage. These seemingly conflicting constraints can be reconciled by postulating the upward migration of volatiles from the primitive lower mantle into the magma source regions and possibly assisting both the partial melting and the upward movement of the integrated magma. Alternatively, Delano (1980) has suggested that the source region may straddle the boundary between differentiated and primordial materials.

The presence of volatiles below 400–500 km also would suggest that their deep source materials remained relatively cool during the processes that formed the Moon and had not been subject to significant earlier differentiation. The possible existence of a density reversal below 400–480 km, a reasonable depth of differentiated crust and mantle, supports this possibility. These potential constraints on lunar composition and structure limit possible mechanisms for the formation of the Moon. In fact, they suggest formation of the moon as an initially cool contemporaneous partner of the Earth rather than derivation from the already differentiated Earth as suggested by others (Hartmann, 1986).

Structural adjustments related to the large basins continued well into the mare basalt stage. For example, in the Valley of Taurus-Littrow, the original southeast-northwest bounding faults between the valley and the massifs are high angle normal faults formed during dilation of the crust immediately after impact (Apollo Field Geology Investigation Team, 1973; Wolfe et al., 1981); that is, the valley began as graben roughly radial to the center of Serenitatis. A lack of talus and the presence of moatlike depressions at the base of the South Massif (Scott et al., 1972; Schmitt, 1973) may indicate postmare isostatic adjustment by reversal of movement with the massif moving relatively downward and separating from the valley's mare basalt fill. This reversal also can be viewed as progressive southwest-northeast extension along the South Massif's bounding fault (Schmitt, 1975a, p. 276) after the major episode of basin filling by mare basalt. Extension with this orientation also would be consistent with eastward thrusting having produced the north-south trending Lee-Lincoln scarp.

Late graben structures spatially associated with pyroclastic deposits near the southwestern rim of Serenitatis in the Sulpicius Gallus region (Carr, 1966) appear to be a more definitive indication of extensional adjustment. Arkani-Hamed (1989) has suggested that extensional faults related to these basin-edge stresses could propagate to great depth. This particularly might be true in a postmare basalt upper mantle made increasingly brittle by cooling and magma withdrawal. If so, such faults could act as conduits for pyroclastic glasses from deep source regions.

The mare basalt stage completed the major changes during lunar evolution. Table 8 summarizes the additional changes that had occurred at its conclusion.

Table 8. Changes to major lunar features: Mare basalt stage

1. Partial melting of the upper mantle, probably from the base of the crust downward, sequentially produced mare basalts and enhanced the ultramafic character of the upper mantle as a whole.
   a. Early pyroclastic eruptions dominated by crustal debris and driven by precursor volatile release from the mantle added deposits of light plains material in many basins.
2. Basaltic maria partially filled most near-side basins, adding to the gravitational anomalies in Nectaris and younger large basins. Basaltic magma also permeated much of the lunar crust, further contributing to crustal strength.
   a. Late pyroclastic eruptions of crustal debris mixed with basaltic ash, driven by volatiles released from solidifying basaltic intrusives under the highlands, added dark halo and dark mantling deposits in some highland areas.
3. Late-stage pyroclastic eruption of magmas derived from deep-source materials took place in regions under extensional stress, particularly near the edges of young large basins with significant mare basalt fill.

Mature surface: 3.0(?) eons to present

The end of major eruptions of mare basalt in Eratosthenian time at about 3.0 eons (Wilhelms, 1987, p. 258–262) ushered in a stage of lunar evolution when only minor changes to the surface occurred (see Wilhelms, 1987, Plates 10–11) and completed the major evolutionary sequence on the Moon. Although impact events continued and declined to approximately present frequency levels early in this stage (Wilhelms, 1987, Fig. 7.16), they did little to change the face of the Moon as seen for the last 3 b.y. except for the excavation of the relatively young rayed craters and the deepening, mixing, and maturation of surface regolith. The type example for the few major events of this stage has been that which created the crater Copernicus (see Shoemaker, 1962; Schmitt et al., 1967) about 0.85 eon ago (Silver, 1971).

The bright swirls that appear to have altered all older materials (Schmitt and Evans, 1972; Wilhelms, 1987, Figs. 4.7, 10.32, and 12.10) and to correlate with high amplitude magnetic anomalies (Hood et al., 1981) constitute one significant puzzle remaining to be solved that may relate to the mature stage of lunar evolution. Some bright swirls appear also to correlate with potential stress induced at the antipodes of large impacts, such as Imbrium and Orientale. Bright swirls in other regions, particularly on Mare Procellarum and throughout the highlands east of Smythii, appear to have no obvious correlations.

Many bright swirls in the highlands east of Smythii have interior zones with darker albedos than the surrounding highlands (Schmitt, unpublished mission notes). These and other bright swirls may be evidence of volatiles released as the lower mantle of the Moon reached its maximum general temperature as a result of radiogenic heat accumulation in relatively undifferentiated material. This same thermal event may in some way correlate

Table 9. Changes to major lunar features: Mature surface stage

1. Scattered impact events produced relatively young, rayed craters.
2. Local impact events, implanation of solar wind gasses, and related processes, including the development of mature regolith, reached present day intensities.
3. Late, thermally induced evolution of volatiles from the deep lunar interior may have altered surface materials to create the bright swirls.

with the disappearance of the lunar magnetic field (see Taylor, 1982, p. 368–370) if that field originally related to some manifestation of a permanent magnet.

Perhaps the most significant processes of the mature surface stage are related to the local effects of continued primary and secondary impact cratering (see Wilhelms, 1987, Chapters 12 and 13). For example, in addition to many sizes and types of impact craters related to this stage, Apollo 17 (Schmitt and Cernan, 1972) investigated the effects of an avalanche off the side of the South Massif, probably induced by the impact of secondary material from Tycho (Apollo Field Geology Investigation Team, 1973; Wolfe et al., 1981).

Informal pre-mission photographic and analytical interpretation (H. H. Schmitt and R. Shreve, unpublished discussions, 1972) of the plumelike deposit of light colored material extending 6 km away from the base of the South Massif produced a plausible working hypothesis for this "light mantle's" origin. Formation as a gas-lubricated and suspended avalanche of debris off the side of the 2200-m high mountain appeared most likely. Energy considerations led Shreve to conclude that simple landslide mechanics could not have moved debris as far as observed. Thus, it seemed likely that solar wind gases, particularly H, had been released by particle abrasion as the flow of talus debris began to move down the side of the South Massif.

This hypothesis in turn led to a search for supporting evidence while exploring its surface (Schmitt and Cernan, 1972). In situ size screening of both talus and light mantle surface debris showed a distinctly lower frequency of rock fragments larger than about 2 cm in diameter on the light mantle. Consistent with this, visual observations from the Lunar Rover disclosed that the size of boulders excavated by impacts into the avalanche material correlated roughly to the diameter, and therefore the depth of penetration, of the impact crater. These relationships suggest that the deposit was sorted vertically by size as would be expected in debris suspended by gas during transport.

Table 9 summarizes the changes by which the mature surface stage completes this model of lunar evolution.

Conclusion

The Apollo era began the modern process of understanding the evolution of the Moon. Through that remarkable effort on the part of national leaders, managers, engineers, workers, industry, a worldwide community of scientists, and the American people, we also have looked with new insight at our own planet and the other terrestrial planets. The Apollo exploration of the Moon stimulated investigations that now reach toward real understanding of the early differentiation of the planets, the nature of their internal structure, the environmental dynamics at the origin of life more than 3.5 eons ago, the geochemical and biological influence of very large impact events, and the effects of early partial melting in protomantles.

Further, the Apollo explorations were of incalculable value in adding the reality of known materials and processes to the interpretation of subsequent automated exploration of the solar system.

It has been recently noted (Wittenberg et al., 1986; Kulcinski and Schmitt, 1987) that, early in the third millennium, Apollo's discovery of concentrations of ^{3}He and other solar wind gases in the Moon's regolith may lead to vast and environmentally benign energy resources required by Earth and to consumables required for Martian settlement.

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