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THE GEOLOGIC EVOLUTION OF THE MOON

PAUL D. LOWMAN, JR.

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ABSTRACT

This paper synthesizes pre- and post-Apollo 11 studies to produce an outline of the geologic evolution of the moon from three lines of evidence: (1) relative ages of major lunar landforms and rock types, (2) absolute ages of returned lunar samples, and (3) petrography of lunar rocks and soils. It is assumed that the ray craters, circular mare basins, and most intermediate circular landforms are primarily of impact origin, but that many other features are volcanic.

The moon's geologic evolution can be divided into four main states, each including several distinct but overlapping events or processes: Stage I (4.7 billion years ago): Origin of moon by unknown means, followed immediately by heating to temperatures of at least 1200°C. Old highland craters formed in last stages of origin. Stage II (4.6 to 3.7 billion years before present): First differentiation to form highland crust, of anorthositic, basaltic, or granitic composition; formation of circular mare basins by infall of large circumterrestrial bodies; formation of Archimedes-type craters; vulcanism in highlands. Stage III (3.8 to 3.4 billion years before present): Second differentiation of moon — basaltic magma generation and eruption to form maria. Stage IV (3.4 billion years ago to present time): Sporadic impacts by asteroid belt meteoroids and comet nuclei to form ray craters, local vulcanism, tension faulting, and continual landscape degradation by small meteorite impacts and other agents. The moon now appears to be relatively inactive compared to the earth, cold and rigid to depths of at least 300 kilometers, but hot enough below that to produce minor sporadic vulcanism evidenced by lunar transient phenomena and relatively young volcanic features. Major questions still unanswered about the moon's geology include the composition and origin of the highlands, the reality of the apparent depletion in volatile elements compared to the earth, the origin of ray craters, and the relation of the moon to the earth.

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CONTENTS

Note: All NASA lunar photographs can be purchased from the National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, Maryland 20771.

*Since the illustrations are an integral part of the paper, they are placed in the beginning for easy reference; it is suggested that the reader glance through them before reading the main part of the paper.

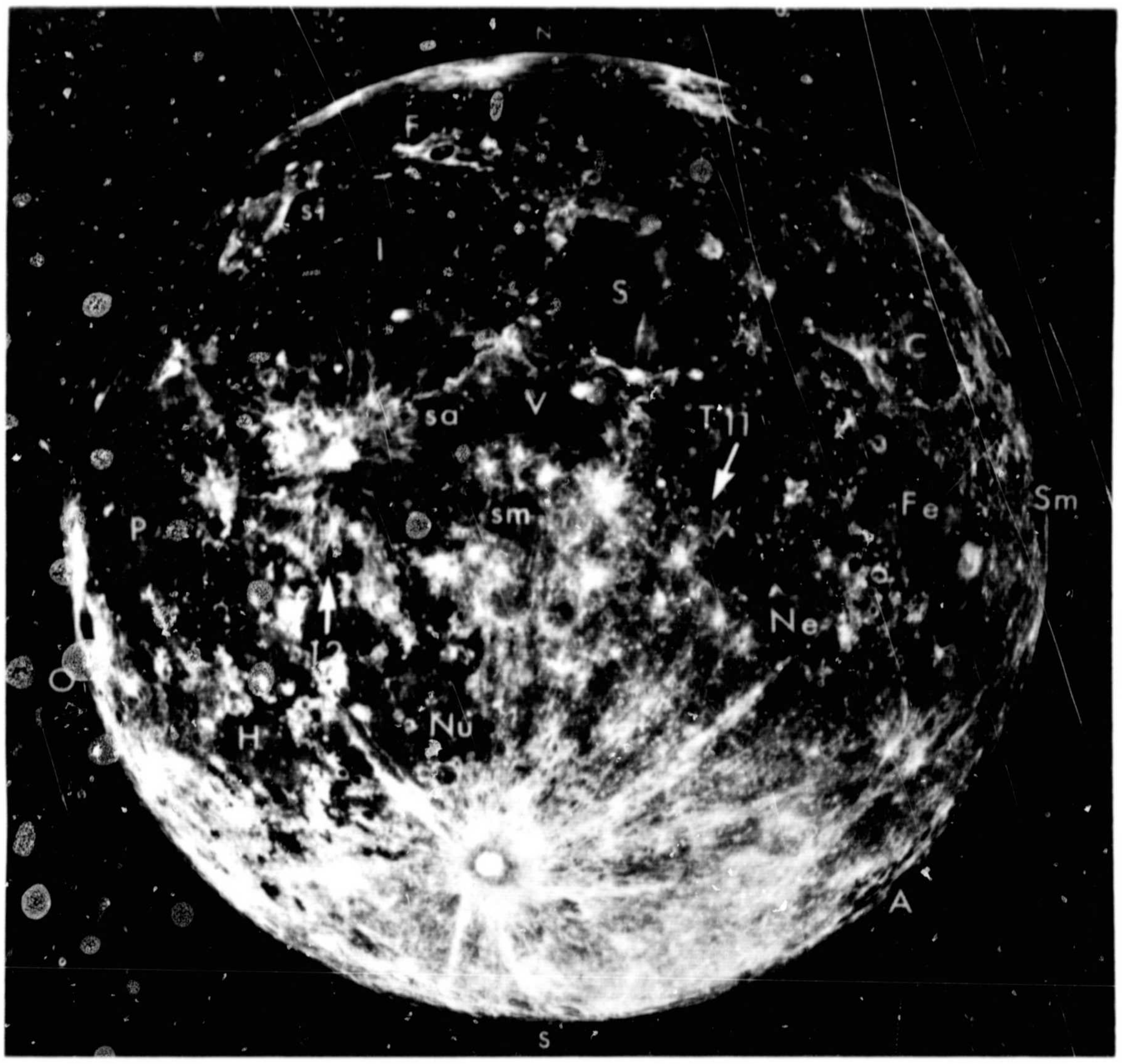

Figure 1. Full moon photograph with 36-inch Lick Observatory refractor, made by J. H. Moore and J. F. Chappel Jan. 17, 1946. High sun angle emphasizes albedo differences, hence photograph is used to illustrate distribution of mare material as seen from earth. Main areas are labeled as follows.

I	– Mare Imbrium	S	– Mare Serenitatis
F	– Mare Frigoris	T	– Mare Tranquillitatis; "11" is Apollo 11 landing site.
P	– Oceanus Procellarum (extends from M. Figoris to M. Nubium; "12" is Apollo 12 landing site)	Ne	– Mare Nectaris
		Fe	– Mare Fecunditatis
H	– Mare Humorum	C	– Mare Crisium
Nu	– Mare Nubium	A	– Mare Australe
O	– Mare Orientale (not visible on photo; beyond west limb; see Figure 12)	Sm	– Mare Smythii
V	– Mare Vaporum; dark areas in southeast part of mare are Sulpicius Gallus formation (see text).	si	– Sinus Iridum
		sm	– Sinus Medii
		sa	– Sinus Aestuum

Maria Imbrium, Orientale, Humorum, Serenitatis, and Crisium are generally recognized as "circular" maria: occupying roughly equidimensional basins ringed with apparent ejecta deposits, and generally characterized by positive Bouger anomalies (O'Keefe, 1968) discovered by Muller and Sjogren (1968) and labeled by them "mascons." Other maria are irregular or composite. Nature of Nectaris and Smythii not clear.

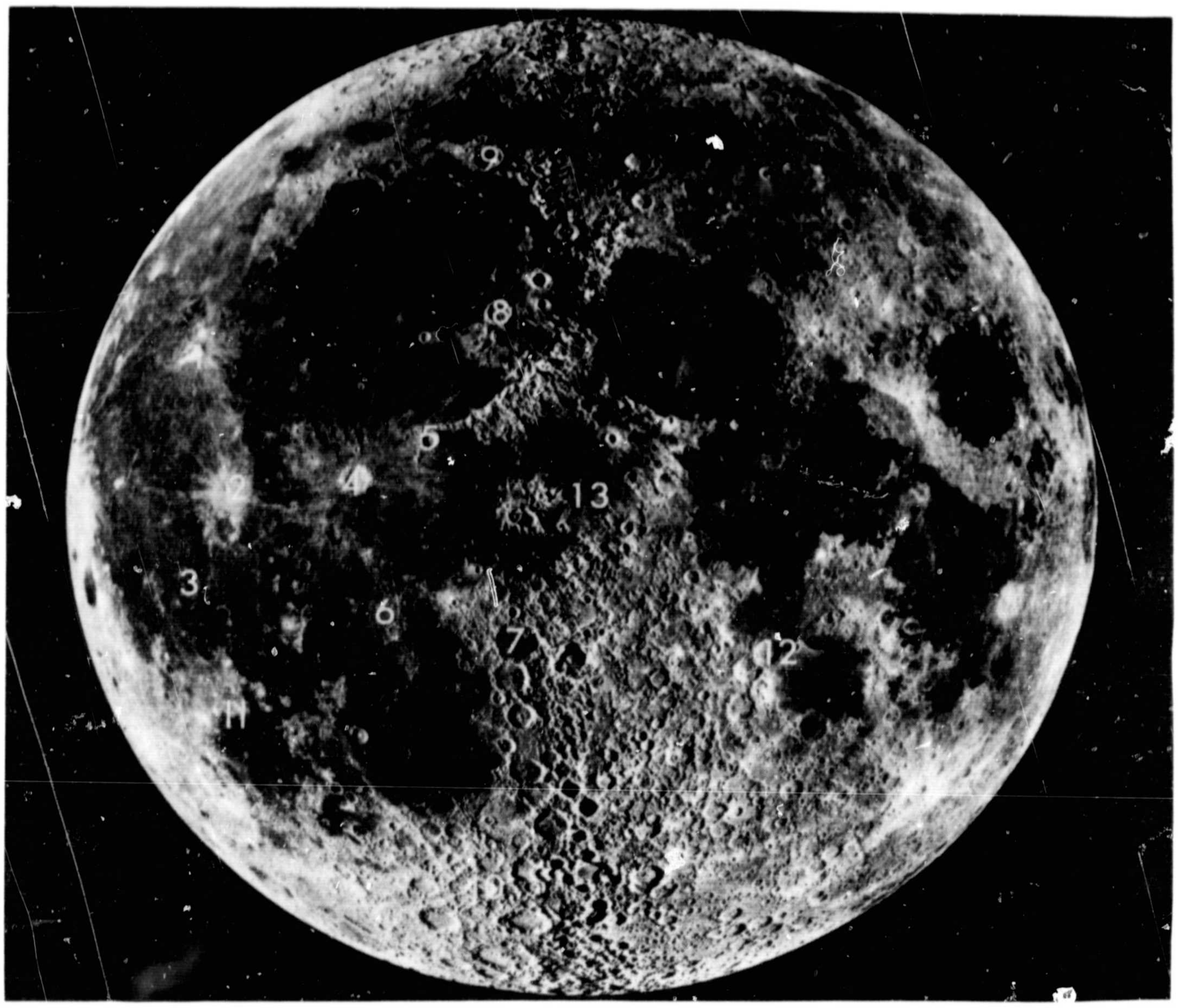

Figure 2. Composite of first-quarter (right) and last-quarter (left) moon photographs taken by Moore and Chappell with 36-inch Lick refractor in 1937. Low sun angle along terminator, bisecting the image, emphasizes topography, hence photograph is used to index main craters referred to in text.

1 – Aristarchus
2 – Kepler
3 – Flamsteed Ring
4 – Copernicus
5 – (note that this crater, having no rays, is Eratosthenes invisible on the previous, full-moon, photo)
6 – Fra Mauro (type locality of the Fra Mauro formation)
7 – Ptolomaeus; Alphonsus immediately below
8 – Archimedes
9 – Plato
10 – Tycho; note that prominent ray system seen in Figure 1 is nearly invisible here.
11 – Gassendi
12 – Theophilus
13 – Hyginus and Hyginus Rille

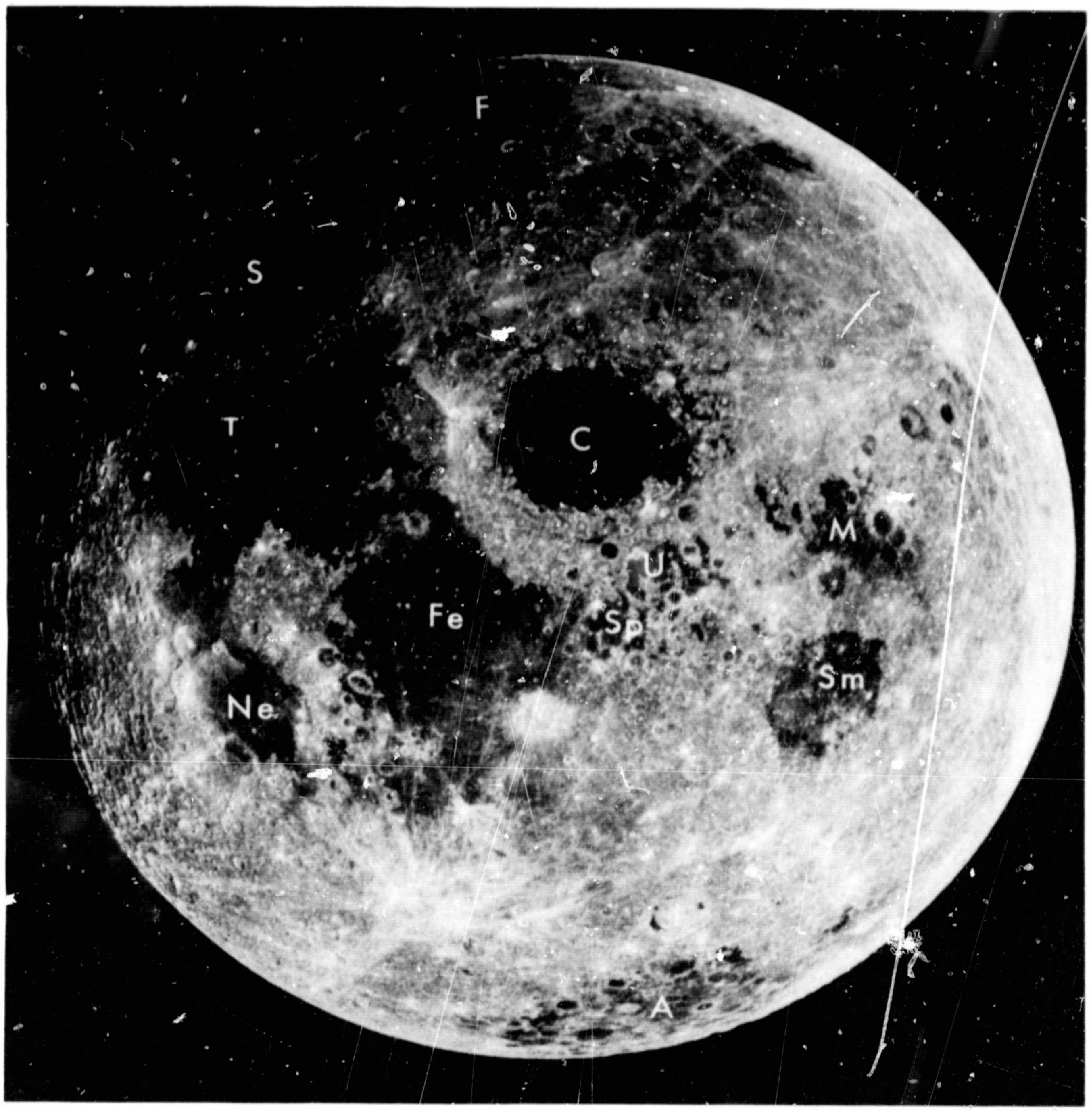

Figure 3. East limb of the moon, taken by Apollo 11 astronauts after trans-earth injection about 10,000 nautical miles from the moon (NASA photograph AS 11-44-6667). High sun angle emphasizes areas of mare material, labeled as follows.

F	– Mare Frigoris	Sp	– Mare Spumans
S	– Mare Serenitatis	U	– Mare Undarum
T	– Mare Tranquillitatis	M	-- Mare Marginis
Ne	– Mare Nectaris	Sm	– Mare Smythii
Fe	– Mare Fecunditatis	A	– Mare Australe
C	– Mare Crisium		

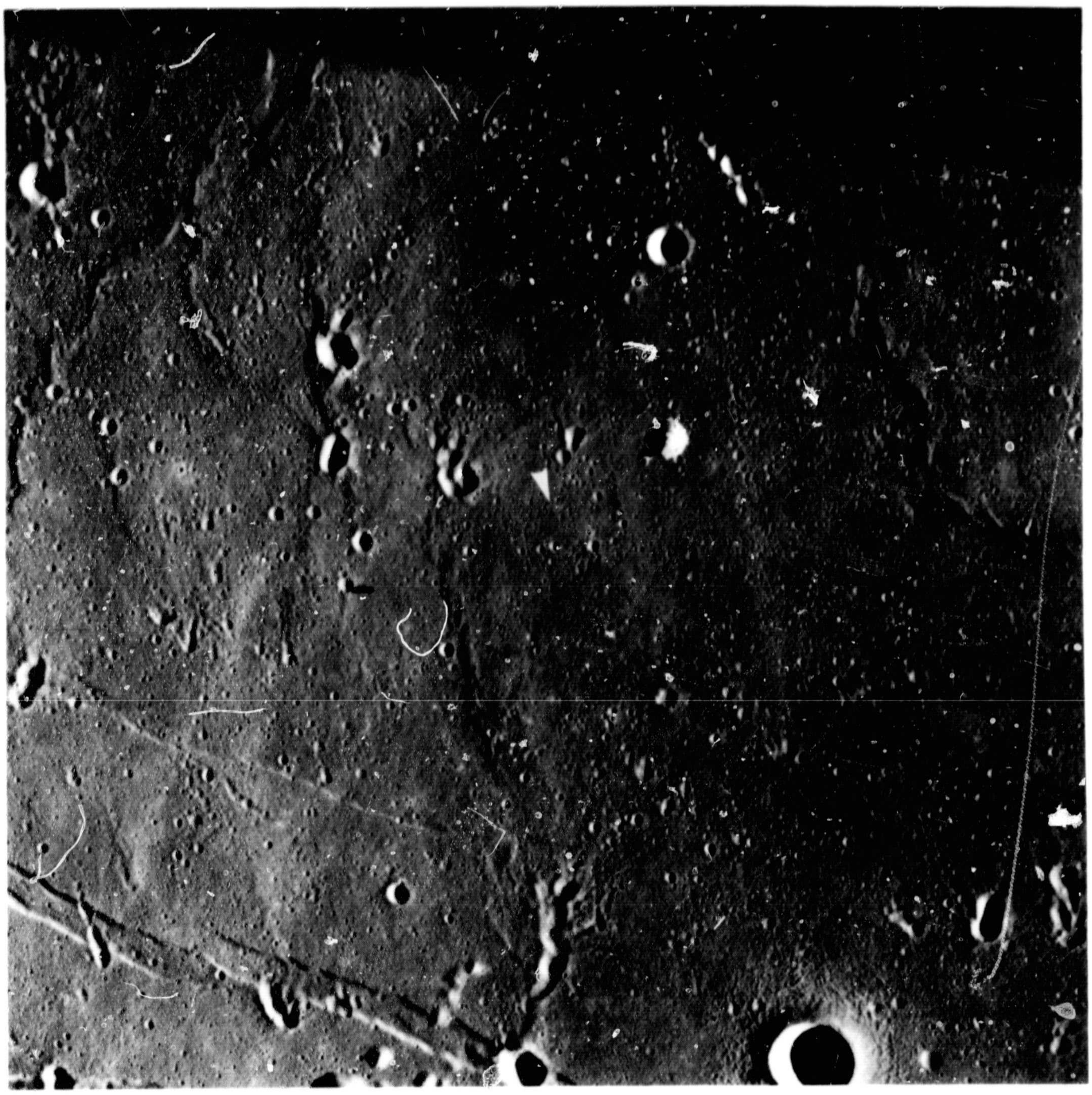

Figure 4. Vertical view of Apollo 11 landing site (arrow), taken from LM Eagle at 147 km altitude shortly after separation from CSM Columbia (right of arrow) (NASA photograph AS 11-37-5447). North at top, sun coming from right. Large crater at lower right is Moltke, about 45 km SE of the landing site; diameter is about 7 km. Hypatia Rille is at lower left. Elongate craters are probably secondaries from Theophilus. Rays from Theophilus cross the area covered by photo (see Figure 1), but actual landing site is not on a ray.

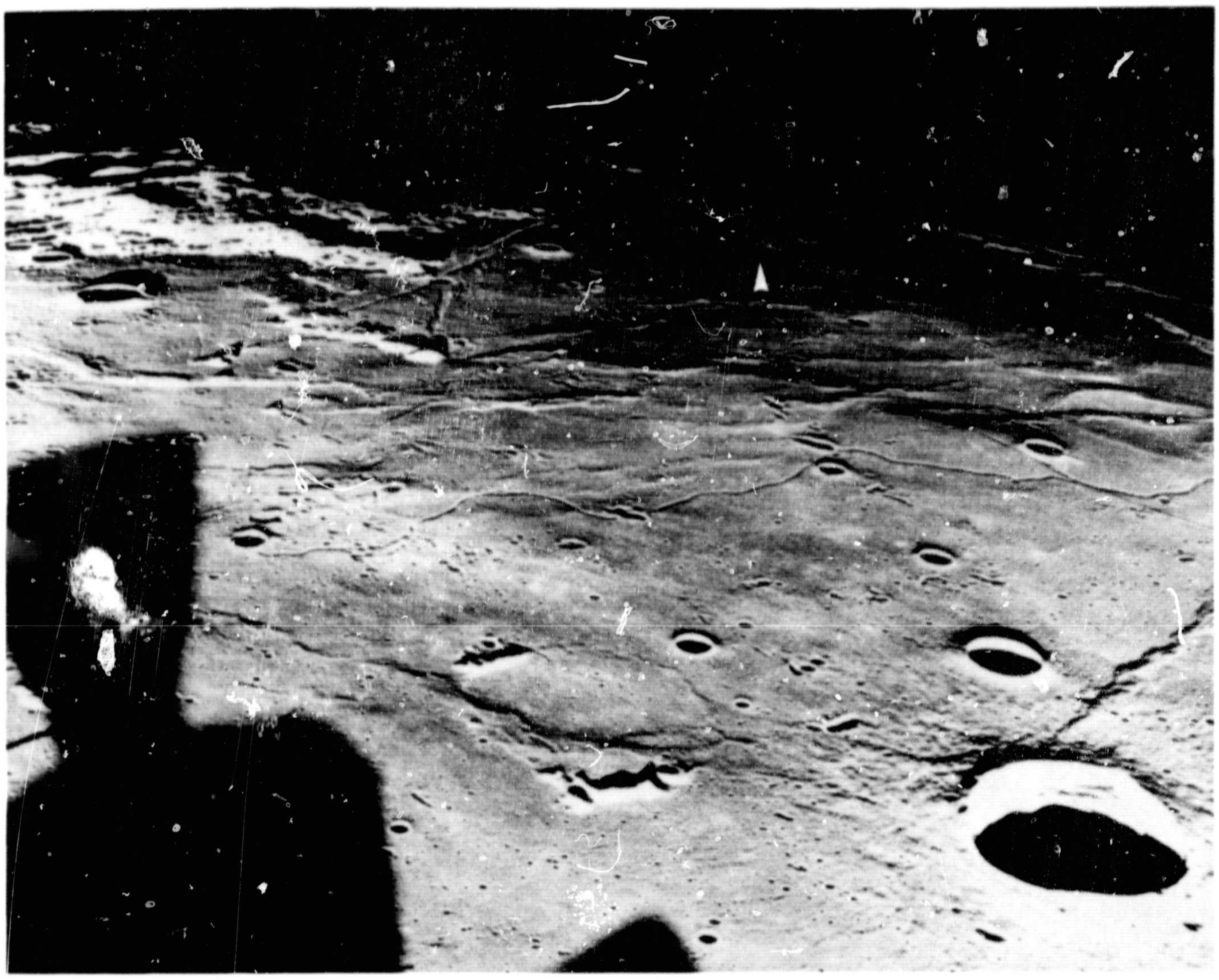

Figure 5. Oblique view to west of Apollo 11 landing site (arrow), taken from LM Eagle at about 95 km altitude (NASA photograph AS 11-37-5437). Hypatia Rille at top center. Low sun angle accentuates ridges in Mare Tranquillitatis. Highlands (terrae) at upper left are about 50 km from Apollo 11 site at closest point. Large crater at lower right is Maskelyne.

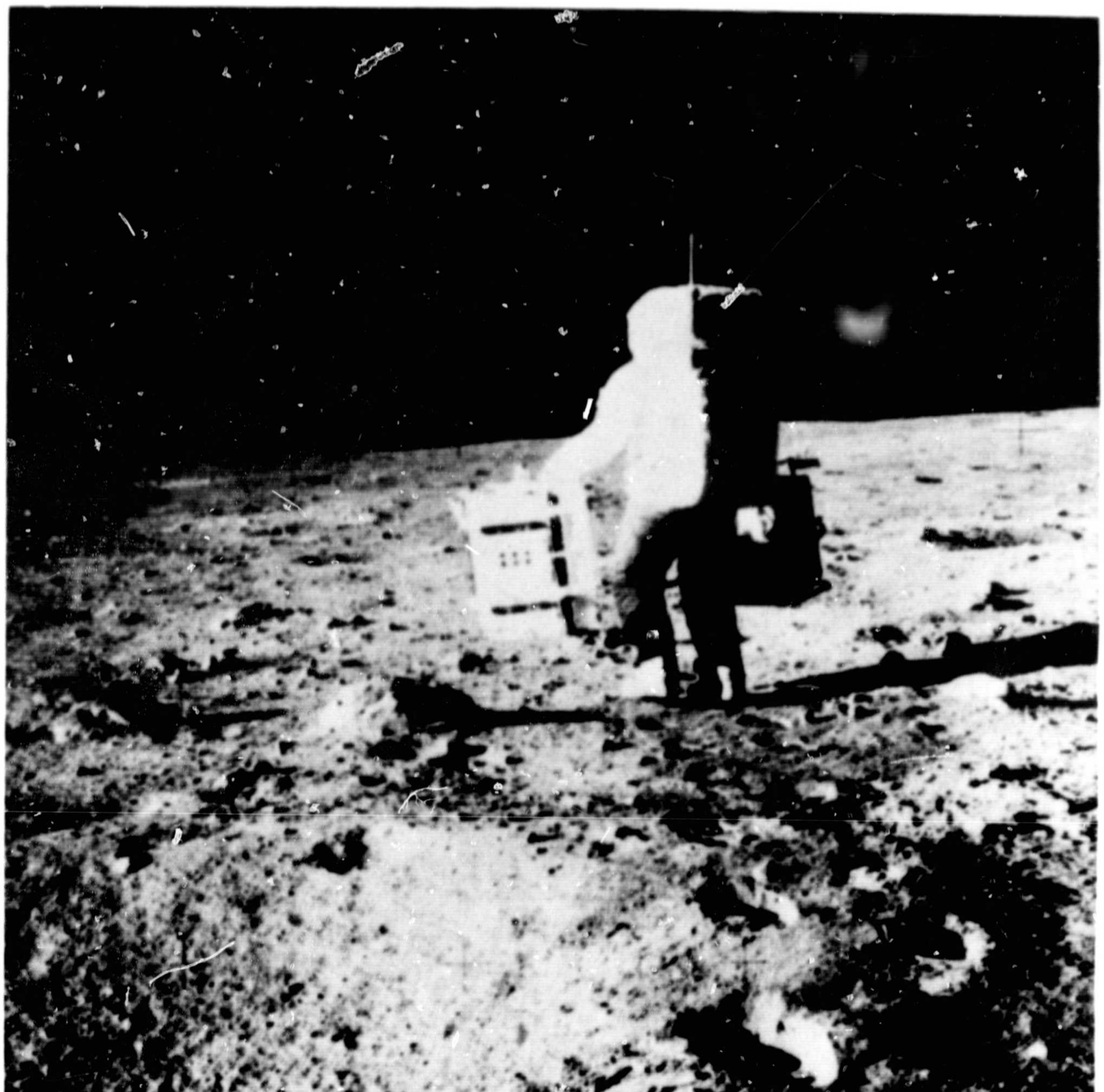

Figure 6. EVA photograph by N. A. Armstrong showing E. E. Aldrin carrying seismograph and laser reflector experiments (NASA photograph AS 11-40-5943). Photo shows typical mare structure at close range. Note deep footprint on rim of shallow crater, illustrating soil zone described by Aldrin, et al. (in Apollo 11 Preliminary Science Report) as 2-6 inches thick, soft, and noticeably thicker on crater rims. Probably ejecta from crater formed entirely in regolith. Note also fillets of soil around rocks, probably formed by disintegration of rocks in place.

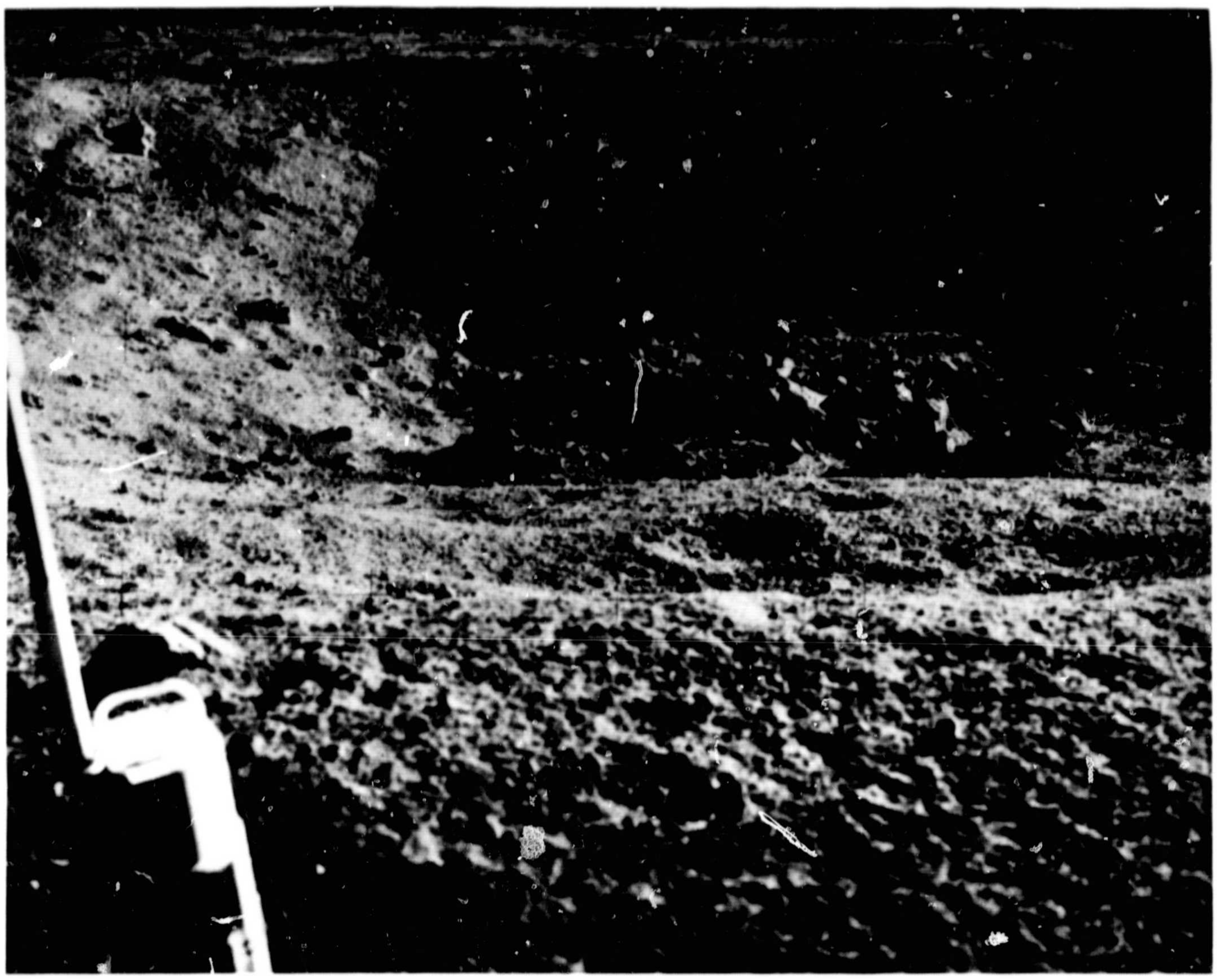

Figure 7. EVA photograph by N. A. Armstrong taken about 54 meters east of LM (NASA photograph AS 11-40-5956). Lunar surface closeup camera at lower left. Photo shows part of crater 33 meters wide and about 4 meters deep probably penetrating through regolith to bedrock, now exposed at center. Note relative scarcity of rocks on rim, as reported by Aldrin, et al., further suggesting crater formation in previously fragmented material (regolith) rather than solid rock.

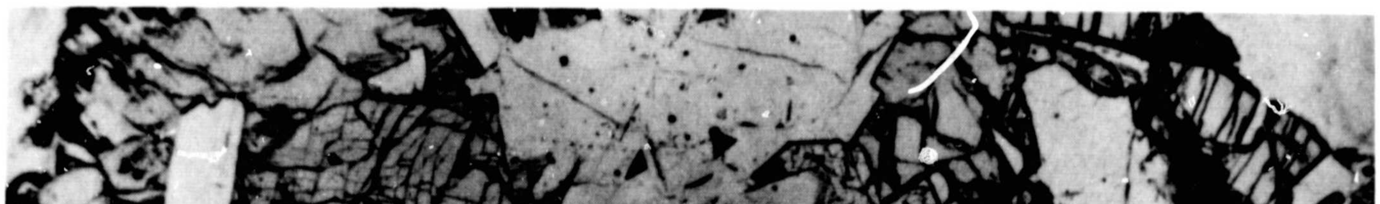

Figure 8. Photomicrograph, plane-polarized light, of Apollo 11 crystalline rock sample #10047 (NASA photograph 70-H-227). Dark gray mineral is "pyroxene," white plagioclase, black ilmenite. Note complete absence of alteration in plagioclase. Pyroxenes complexly zoned; zoning not evident in photograph.

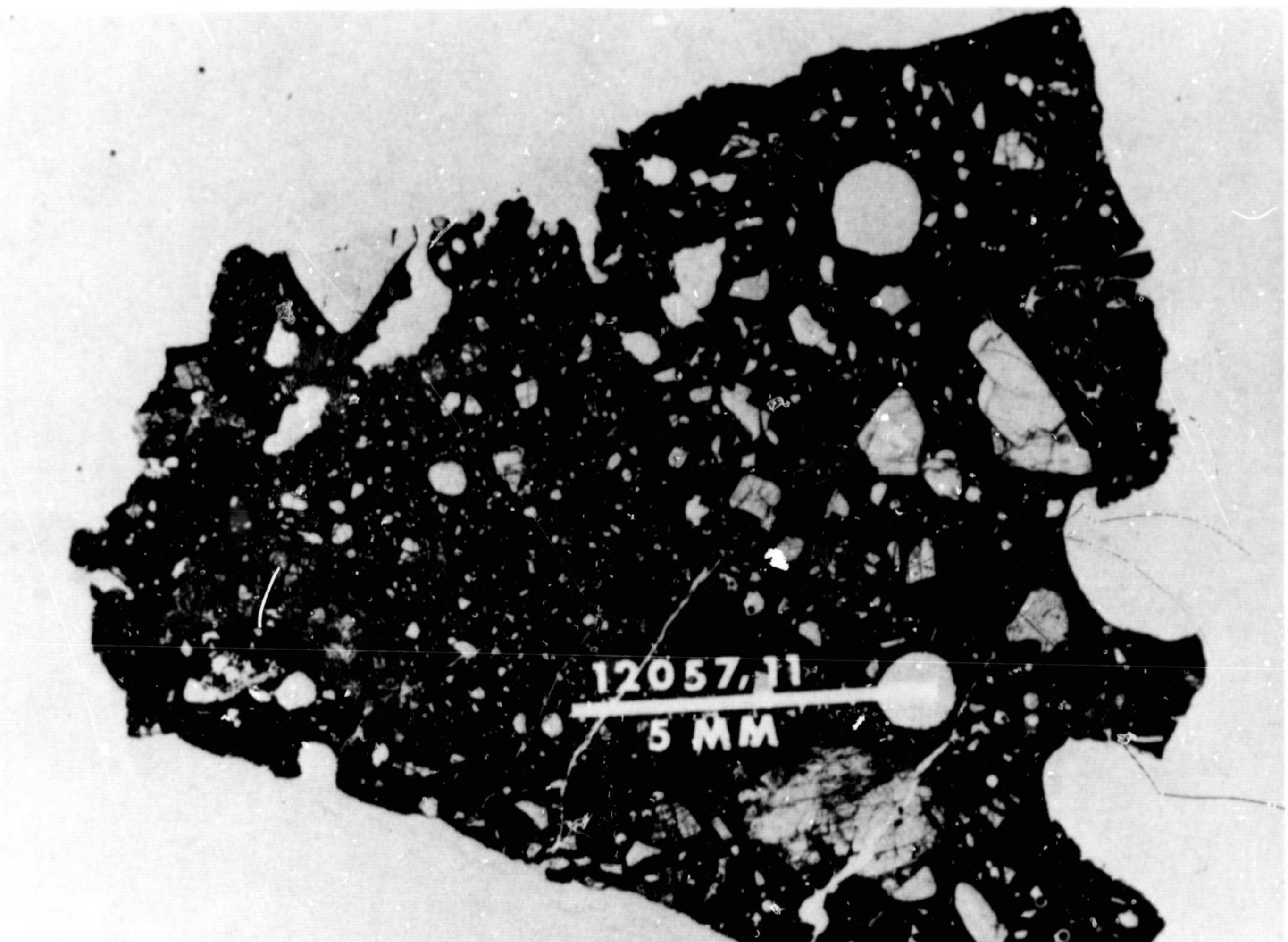

Figure 9. Photomicrograph, plane-polarized light, of Apollo 12 breccia sample #12057,11 (NASA photograph S-69-63407). Breccia consists of rock and mineral fragments and glass spherules in fine-grained opaque matrix. Breccia is generally thought to have been formed by shock lithification of soil, during production of many small mare impact craters (e.g., Short, 1970).

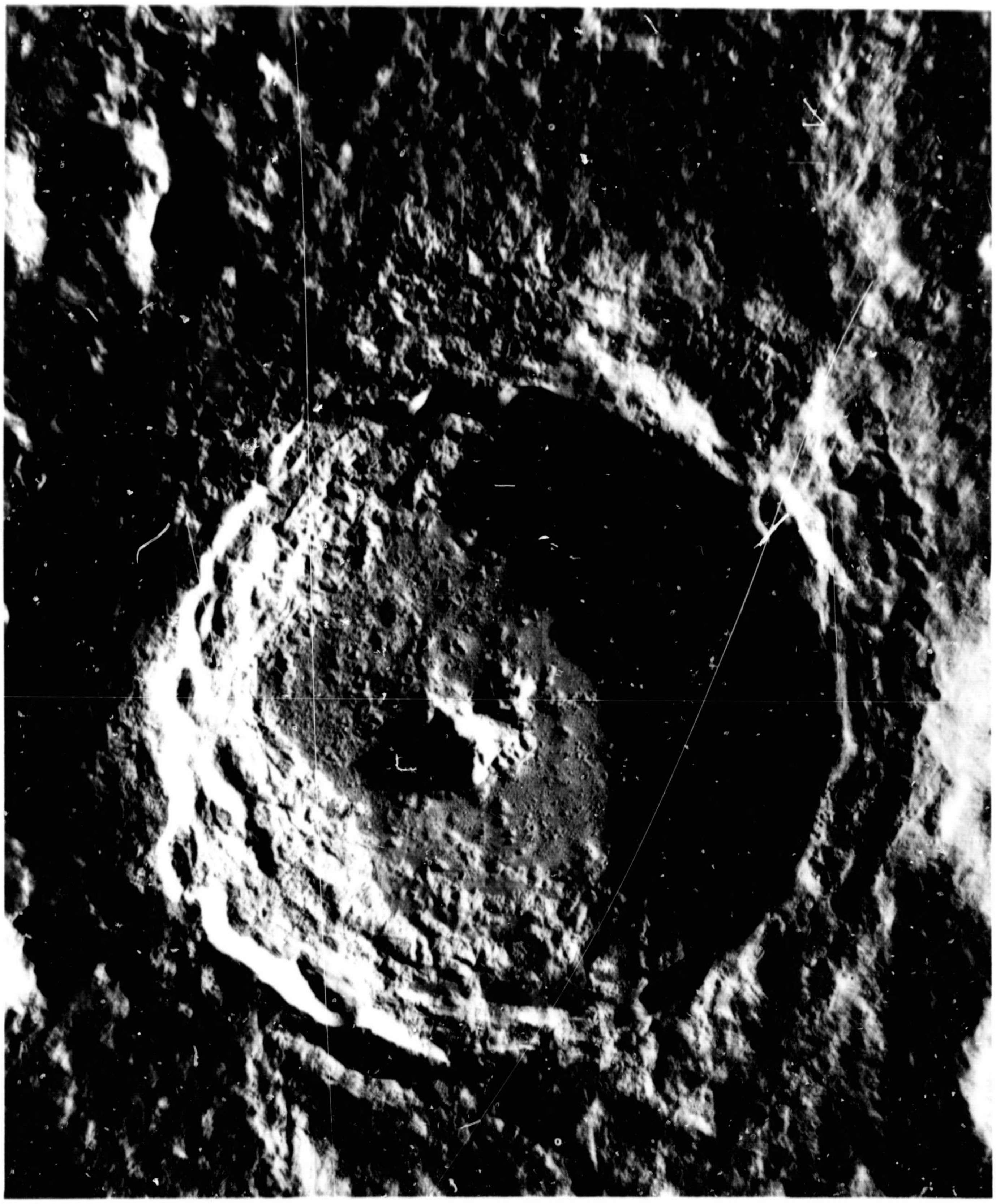

Figure 10. Lunar Orbiter photograph V-125M of crater Tycho, diameter 85 km and depth 4½ km. North at top, sun from right. Tycho is considered the freshest of large ray craters. Note rough structure in floor, considered primary impact melt or possibly impact-induced lava. Flows on flank have similar possible explanations.

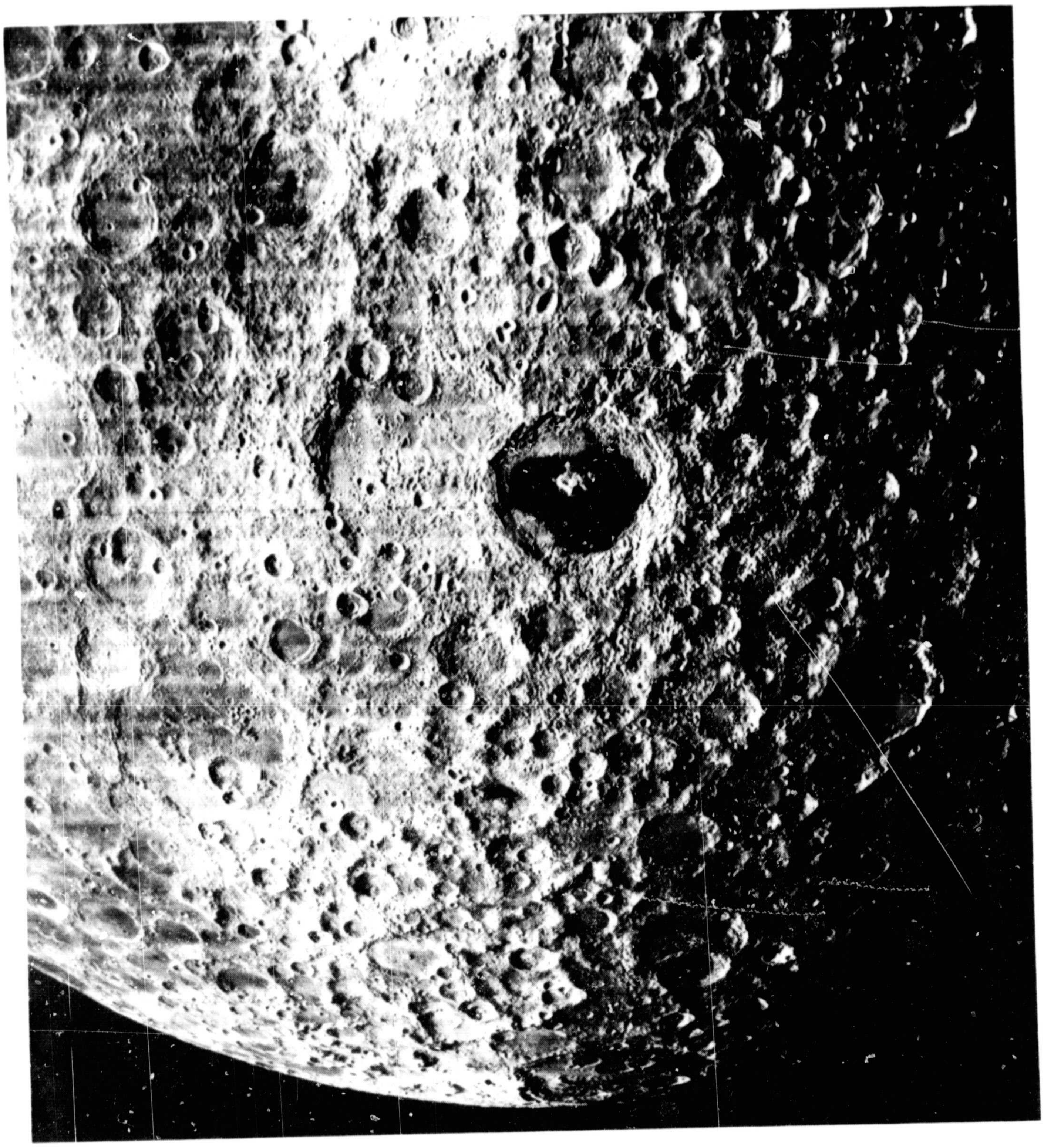

Figure 11. Lunar Orbiter photograph III-121M of far side crater Tsiolkovsky, 240 km wide. North at top, sun from left. Tsiolkovsky forms link between Tycho-like craters and circular mare basins. Note that mare material filling crater apparently overlies rough, higher albedo terrain resembling impact melt? in floor of Tycho. Relative freshness with absence of rays suggests Eratosthenian age for Tsiolkovsky.

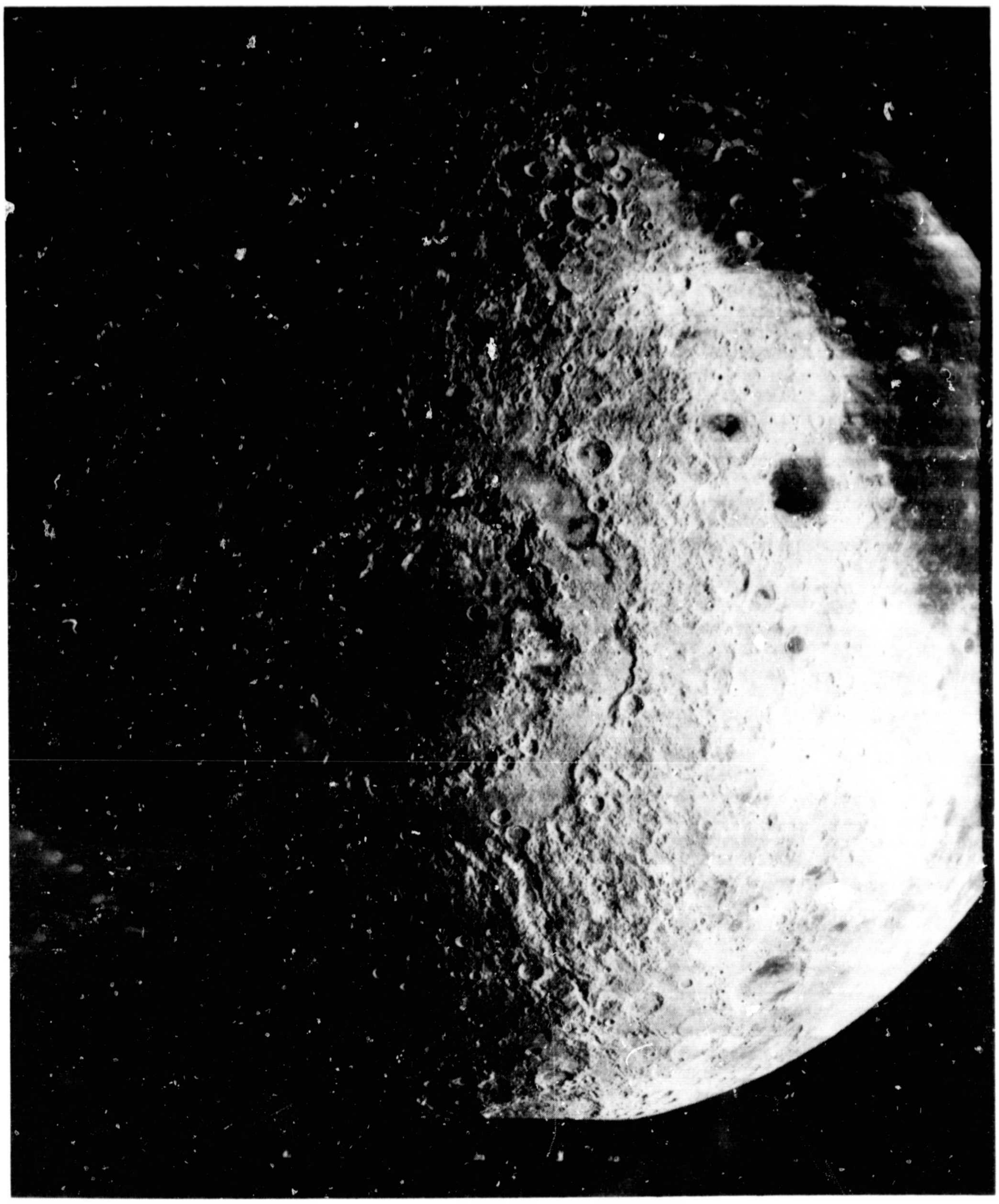

Figure 12. Lunar Orbiter photograph IV-187M of Orientale Basin, with Mare Orientale at center. Outer rim (Cordillera Mts.) has diameter of about 1000 km. North at top, sun from right. Orientale is considered the youngest of circular mare basins, but apparent ejecta does not overlie O. Procellarum at right, hence basin is pre-mare. Mare material in basin and between rings shown by Gault (1970) to be much less cratered than terra in basin, demonstrating time gap between basin formation and mare eruptions.

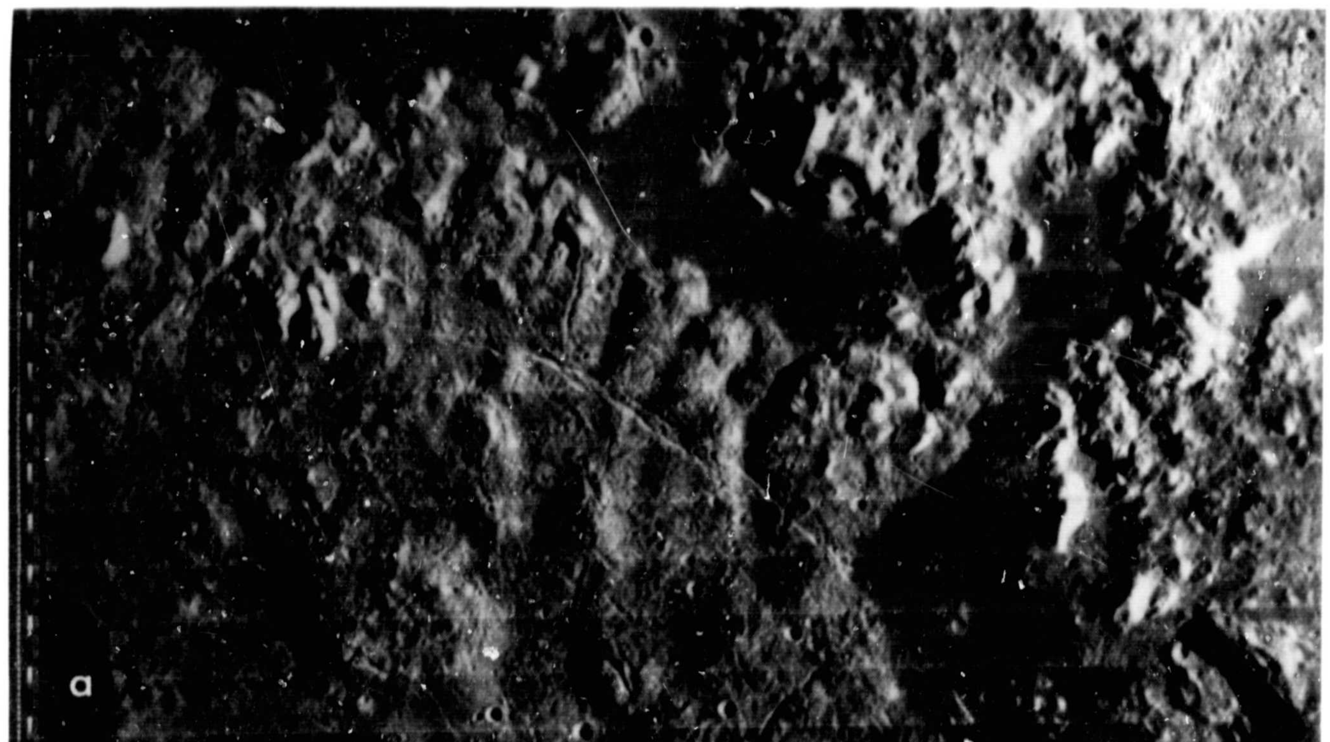

Figure 13. Lunar Orbiter photograph IV-187H_2 showing northeast part of Orientale Basin. Craters "a" and "b" are suggested by McCauley to represent impact (a) and volcanic (b) types. "a" has terrain resembling Tycho and Copernicus, while "b" has no central peak or secondary craters. Since both are post-basin, differences can not be attributed to age. Diameter of "a" is 55 km and "b" 35 km.

Figure 14. Lunar Orbiter photograph V-102M showing Alpine Valley and northeast rim of Imbrium Basin (Alps Mts.). Oblique view to southwest, sun from behind camera. Alps considered Imbrium ejecta, mapped as Fra Mauro formation by USGS. Alpine Valley formerly considered impact gouge, but now thought to be of essentially tectonic origin related to basin-forming impact. Note sinuous rilles at upper right.

Figure 15. Lunar Orbiter photograph V-95M showing Hyginus Rille. North at top, sun from right. Crater Hyginus at center of chain has diameter of 6.5 km. Rille generally interpreted as tectonically-controlled subsidence feature, with craters as volcanic vents (maars?) localized by fractures.

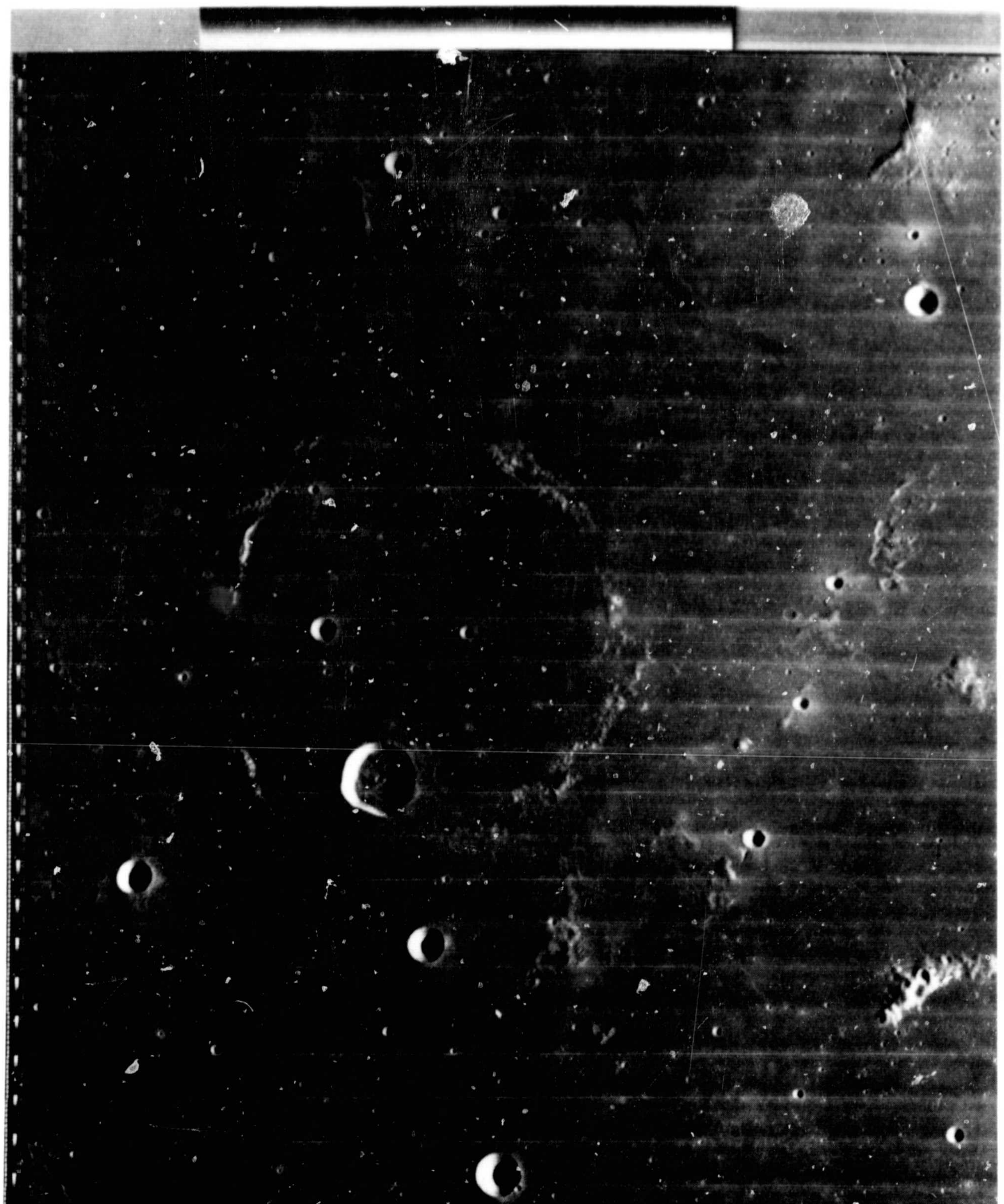

Figure 16. Lunar Orbiter photograph IV-143H_3 showing crater Flamsteed (center) with diameter of 24 km and "Flamsteed Ring," circular line of hills about 100 km across. Ring interpreted variously as pre-mare impact crater now much-modified and as post-mare series of siliceous extrusions. Note gradation in north from Ring material into mare ridges trending north across Oceanus Procellarum.

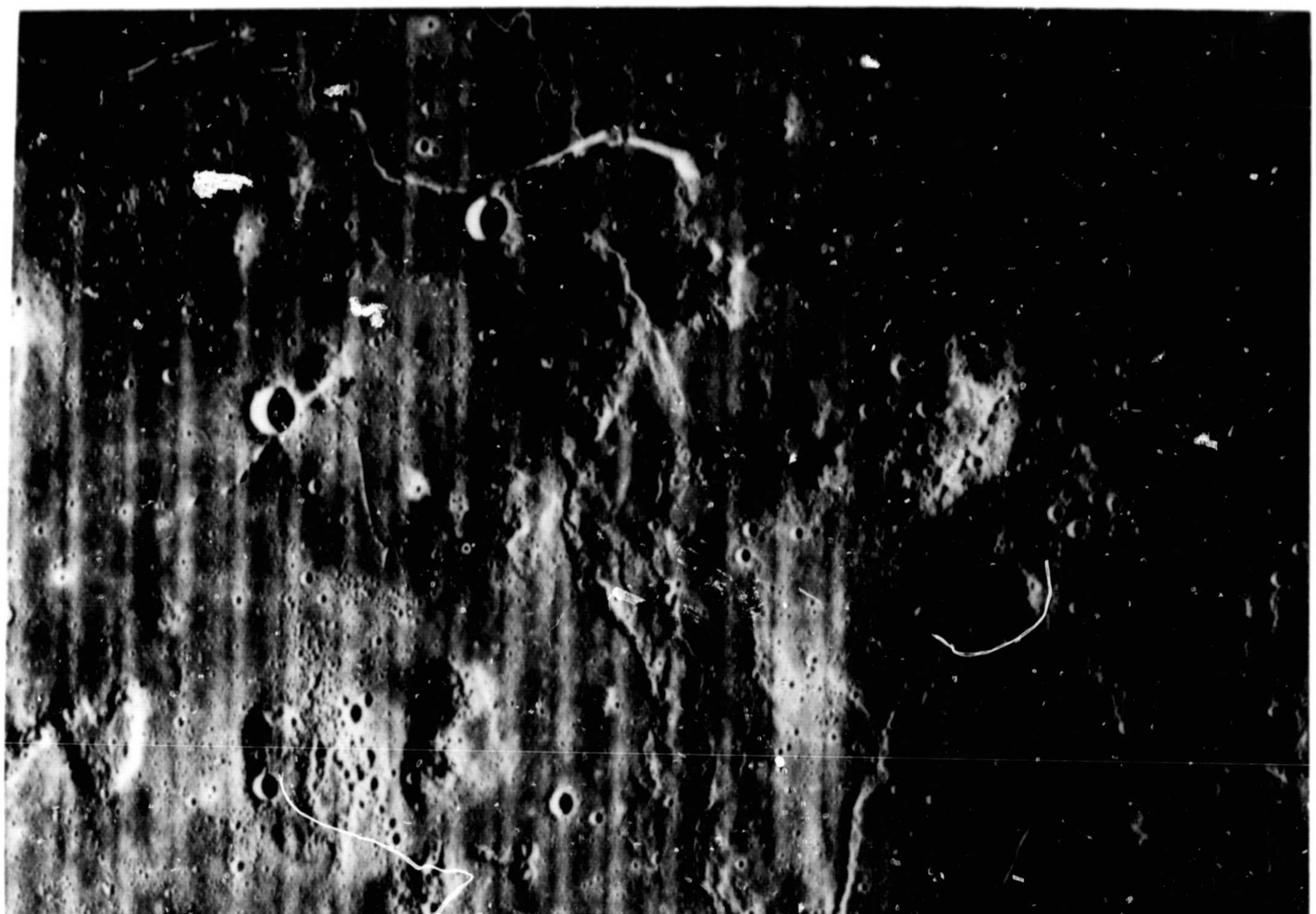

Figure 17. Lunar Orbiter photograph V-213M, showing Marius Hills. Area covered is about 94 by 77 km, centered on 56.0 °W, 13.5 °N in O. Procellarum. North at top, sun from right. Hills considered to be post-mare volcanoes, possibly laccoliths. Note prominent sinuous rille at top.

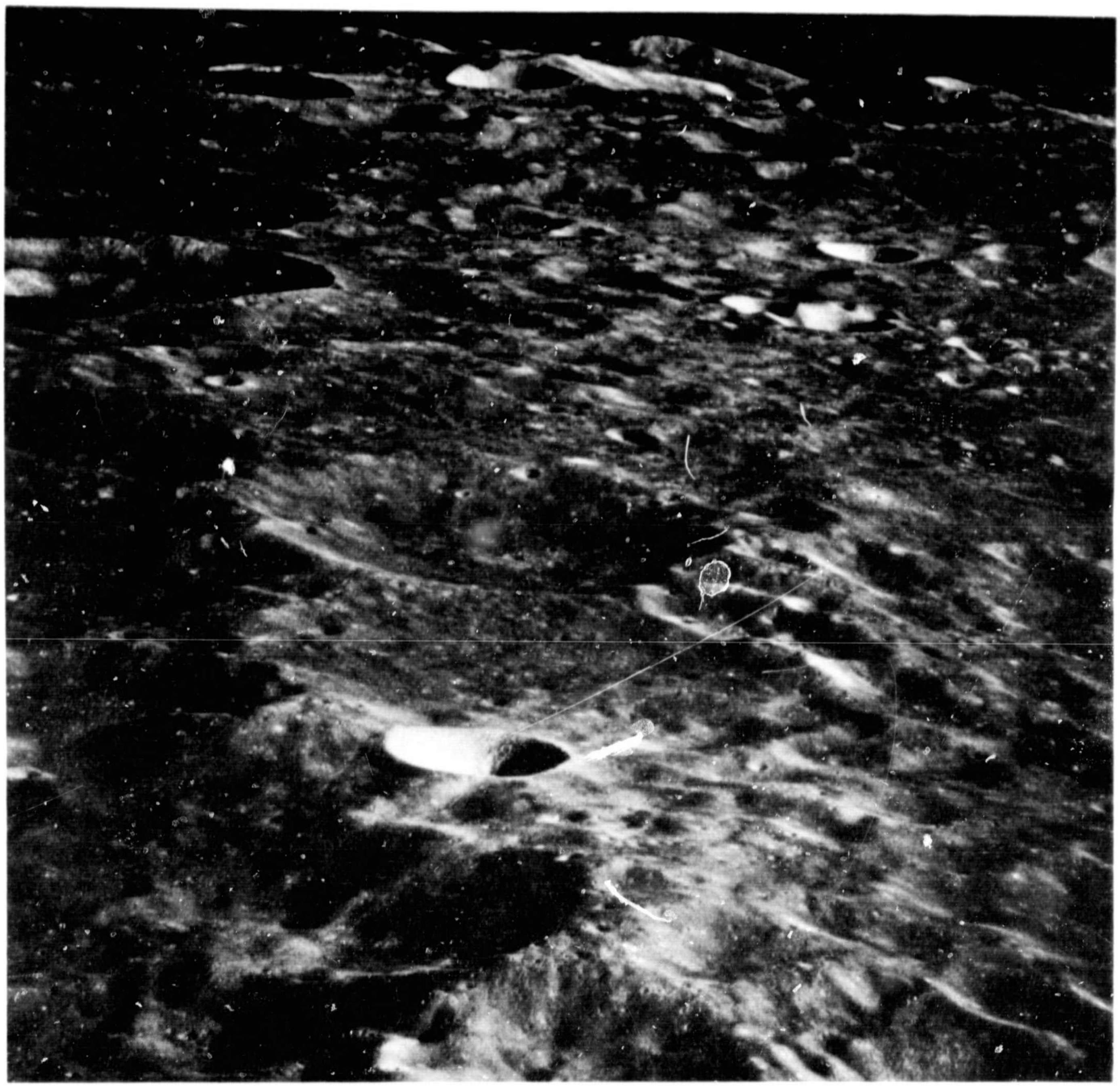

Figure 18. Apollo 10 far side photograph taken from about 15 km altitude showing typical highland terrain. Density of craters and subdued topography suggest that crust consists of layer of poorly consolidated rubble several kilometers deep (Blodget, et al., 1970; Short, in press).

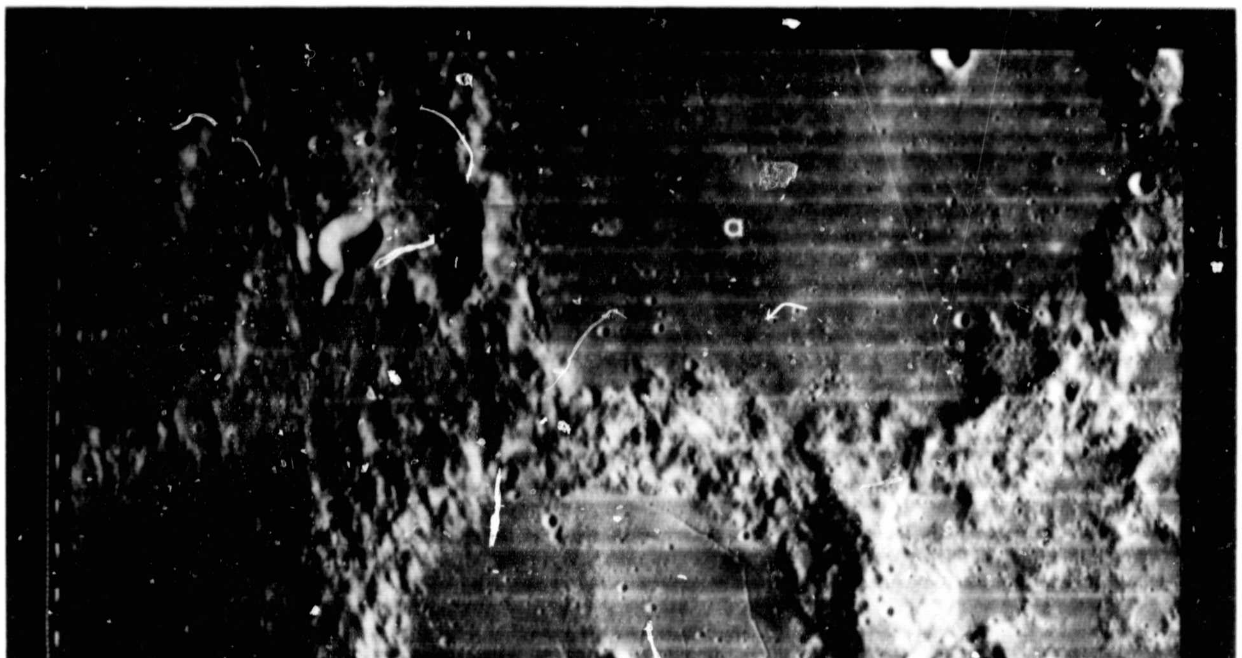

Figure 19. Lunar Orbiter photograph IV-108H_2 showing craters Ptolomaeus ("a"), Alphonsus ("b"), and Arzachel ("c"). North at top, sun from right. Ptolomaeus and Alphonsus are filled with mare-like material mapped by USGS as Cayley formation. Surrounding terrain mapped as Fra Mauro formation. Note that Fra Mauro does not fill craters, hence latter are post-Imbrium basin. Dark halo craters in Alphonsus interpreted by McGetchin as diatremes. Transient activity observed on Alphonsus central peak by Kozyrev in 1958, interpreted by him as volcanic activity. Linear valleys southeast of Alphonsus part of Imbrium sculpture, generally interpreted as graben formed with Imbrium basin.

Figure 20. Apollo 12 EVA photograph showing Surveyor 3 footpad 2 (NASA photograph AS 12-48-7110). This is the original footprint made by Surveyor on landing 2½ years earlier. Extreme freshness indicates slow rate of landscape modification and freedom from major seismic activity during this period.

THE GEOLOGIC EVOLUTION OF THE MOON

INTRODUCTION

The landings of the spacecraft Eagle (Apollo 11) and Intrepid (Apollo 12) on the moon in 1969 were only the beginning of manned exploration of our companion planet. But they were the culmination of several decades' study of the moon's geology from earth, in that analysis of the returned samples has begun to fill two major gaps in our knowledge: the absolute ages of the lunar geologic time scale, and definite knowledge of the composition and origin of the main lunar rock types. It is now possible to combine these early analytical results with data from earth-based studies to produce a surprisingly specific outline of the moon's geologic evolution. The purpose of this paper is to present such an outline, based on three main lines of evidence:

(1) relative ages of major landforms and rock types

(2) absolute ages of returned samples

(3) petrography of lunar crystalline rocks, breccias, and soil.

This outline is but one of many such analyses, only a few of which can be mentioned here. From a geological viewpoint, the work of Shoemaker and Hackman (1962) is the most important; they constructed a usable lunar stratigraphic time scale from fundamental principles such as superposition. This time scale and the methods used to develop it have been the foundation for the USGS/NASA 1:1,000,000 scale lunar geologic mapping program which was started with Hackman's (1962) Kepler quadrangle map. A comprehensive reconstruction of the moon's evolution as a whole, presented by Baldwin (1963), has been verified in many respects by the recent manned missions. Khabakov (in Markov, 1962) presented a similar though more general reconstruction, although he, unlike Baldwin, assumed most of the lunar craters and mare basins to be of internal origin. Fielder (1965) likewise favored an internal (volcanic) origin for most lunar landforms, and proposed a lunar time scale in which the maria were on the order of 100 million years old — an age now known to be far too low. Hartmann (1964) produced a simplified scheme of the moon's history whose main features, including the time scale, appear consistent with recent discoveries from returned samples.

EVIDENCE BEARING ON THE MOON'S EVOLUTION

This reconstruction of the moon's geologic evolution rests on three main bases. The first of these is the relative ages of the main lunar landforms and rock types. The relative ages of the main physiographic provinces — highlands, mare basins, and maria — are evident from gross morphology and crater populations. The highlands, heavily cratered, are oldest; the mare basins, cutting the highlands, are younger; and the maria, filling the mare basins and flooding much additional area, are youngest. Superposition relations then permit fitting the less prominent features into a chronologic sequence. Craters excavated (by whatever process) in the maria are clearly post-mare. The youngest of the post-mare craters are those with rays, since the rays overlie almost all other features. Superposition can be supplemented, as explained by Mutch (1970), by crater counts and albedo measurements to deduce the relative ages of various features. Though subject to resolution limits (especially for earth-based observations) and to some extent the assumption that most small craters are of impact origin, this system is objective and the maps based on it are of permanent value, especially now that they can be supplemented by study of returned samples.

The second line of evidence is the determination of absolute ages in the lunar geologic time scale by radiometric methods. At present, the most unambiguous radiometric ages obtained are those of the crystalline rocks from Mare Tranquillitatis and Oceanus Procellarum. Several independent methods, described at the Apollo 11 Lunar Science Conference (Science, Jan. 30, 1970), give crystallization ages of 3.7 billion years for the Apollo 11 samples from Mare Tranquillitatis. Preliminary analyses of Apollo 12 samples from Oceanus Procellarum give ages of about 3.4 billion years (Apollo 12 Preliminary Science Report, Manned Spacecraft Center, 1970). These closely similar ages are consistent with the generally similar crater populations and albedoes of different maria indicating similar ages. If the maria were in fact all formed within a few hundred million years, the importance of even these first radiometric dates is magnified because most features on the earthward hemisphere can be dated relative to the maria.

The absolute ages of the regolith samples, although just as important, are more difficult to interpret. Soil and breccia samples from Apollo 11 gave ages of about 4.6 to 4.7 billion years, which have been generally interpreted as an average for the lunar crust as a whole. However, Silver (1970) suggested that a very old component, with an age of 4.9 billion years, might be partly responsible for this figure. Discovery of allocthonous fragments with ages of 4.0 and 4.4 billion years implies the existence of substantial amounts of such old rock somewhere on the moon, and tends to support the crustal average interpretation of regolith ages.

The third line of evidence for this outline, petrographic and chemical analyses (Table 1) of the returned mare samples, has shown that the maria are chiefly basic and ultrabasic igneous rock (Figure 8) overlain by several meters of debris (Figures 6, 7, 9) largely formed by innumerable impacts (Shoemaker, et al, 1970), both of meteorites and secondary ejecta fragments. Minor amounts of meteoritic iron have been found in the regolith, as well as rare fragments of anorthosite that have been generally interpreted as impact ejecta from the highlands. The source and origin of the complex siliceous breccia #12013 (60% SiO_2) are not known, since it was not found in place, but it too may be a highland sample.

A detailed discussion of lunar petrology is beyond the scope of this paper, but the broad outlines of mare rock-forming processes can be summarized and some of the major problems noted.

To begin, it is perfectly clear that the liquids which solidified to form the maria were not melts produced by the impacts thought to have formed the mare basins. This is demonstrated by several lines of evidence. First, there is abundant mare material outside the circular mare basins, both in small patches (Figure 3) and in large irregular maria (of which Mare Tranquillitatis is one); impact melts would at most fill the circular maria, since their ejecta, as we shall see, can be accounted for already. Second, the mare material will be shown to have erupted long after formation of the circular mare basins, whereas impact melts form instantly. Third, probable impact melts can be identified in some lunar craters, especially Tycho (Figure 10). Similar material is visible in Tsiolkovsky (Figure 11), but is obviously older and easily distinguished from the mare material filling the crater. Fourth, the mare rocks should have the same bulk composition and density as much of the moon if they were simple impact melts, but Ringwood and Essene (1970) have shown that this is not possible because the moon's density is too low. Finally, the microscopic textures of crystalline rocks from both the Apollo 11 and 12 missions are totally distinct from terrestrial impact melts such as those in the Tenoumer crater (French, et al., 1970), and are largely free of shock effects (Short, 1970).

On the other hand, the major impacts thought to have formed the circular mare basins probably produced deep fractures which localized the mare eruptions in some areas; French (1967) showed that this probably happened in the Sudbury irruptive, and later (1969) suggested Tsiolkovsky (Figure 10) as a lunar analogue. Furthermore, there have been countless minor impacts on the maria, producing small beads of glass (Figure 9) and abundant shock effects. But the mare liquids in general were produced by internal processes, not directly by impact.

The general nature of the mare magmas is now reasonably clear. They were unusually fluid and dry, and somewhat hotter than many comparable terrestrial

Table 1

Lunar and Terrestrial Rock Compositions[5] (wt. %, water free)

	Apollo 11[1]	Apollo 12[2]	198 Basalts[3]	182 Ultramafic Rocks[4]
SiO_2	40.2	39.7	49.9	44.0
TiO_2	11.4	3.7	1.4	1.7
Al_2O_3	9.9	11.3	16.0	6.1
Fe_2O_3	0.0	—	5.4	4.5
FeO	18.7	21.3	6.5	8.8
MnO	0.3	0.3	0.3	0.2
MgO	7.3	11.7	6.3	22.7
CaO	11.1	10.7	9.1	10.2
Na_2O	0.6	0.5	3.2	0.8
K_2O	0.2	0.7	1.5	0.7

1. Average of 13 basaltic (Type A or B) crystalline rocks, ranging from 37.8 to 42.0% SiO_2, from the Apollo 11 landing site, reported in Science (The Moon Issue), V. 167, No. 3918, 30 Jan. 1970. Specific samples included, with authors of the report, are: 10044 (Engel and Engel), 10057 (Engel and Engel), 10017-29 (Maxwell, et al.), 10020-30 (Maxwell, et al.), 10072 (Wiik and Ojanpera), 10003, 10022, 10024, 10047, 10049, 10050, 10058, and 10062 (Rose, et al.). None of the analysts reported significant combined water.

2. Average of 9 crystalline rocks, ranging from 35 to 49% SiO_2, from the Apollo 12 landing site, reported by the Lunar Sample Preliminary Examination Team in Science, V. 167, No. 3923, p. 1325-1339, 6 March 1970. Specific samples included are: 12012, 12004, 12015, 12022, 12009, 12065, 12052, 12064, and 12038. The rocks were described by the LSPET as pyroxene-rich peridotites, olivine gabbros, gabbros, troctolites, and similar types.

3. Terrestrial basalts, compiled by R. A. Daly, Igneous Rocks and the Depths of the Earth, Table 1, Column 58, McGraw-Hill Book Company, 1933, 598 pages. Rocks included 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites.

4. Terrestrial ultramafic rocks, compiled by S. R. Nockolds, Average chemical composition of some igneous rocks, Geol. Soc. America Bulletin, V. 65, p. 1007-1032. Rocks included peridotites, perknites, and dunites.

5. Samples from Mare Tranquillitatis (Apollo 11) may not be very representative of regional compositions because of time and distance restrictions on the crew; the limited range of compositions in the analyses suggests that they may have sampled only one or two flows. The Apollo 12 samples, collected on two long traverses, show much more variation in modal composition, and are undoubtedly more representative of that landing site.

lavas. These magmas originated under extremely reducing, water-free conditions, as shown by the many analyses of crystalline rocks (Table 1): there is no appreciable combined water, all the iron is ferrous, and metallic iron occurs as an accessory mineral. The absence of water was probably an inherent property of the magma, rather than the result of loss on eruption into vacuum, since there is no obvious difference in water content or oxidation state between the coarse-grained (i.e., interior) and fine-grained (i.e., exterior) lunar rocks. Furthermore, there is no evidence (Figure 8) at all of hydrothermal alteration, such as iddingsite or sericite, which would be expected even in a rapidly degassing magma. Comparable evidence suggests that the magmas were also inherently low in alkalis, contrary to the suggestion of several investigators that this was caused by volatilization from the magma at the surface.

The origin of the mare magmas is not yet agreed upon; in particular, it is not clear whether they were primary (i.e., formed by partial or complete melting of solid rock) or secondary (i.e., formed by magmatic differentiation). Evidence for a primary nature is found in the Apollo 11 mineralogy, which suggests an early rather than a late stage of magmatic evolution. The plagioclase is calcic; Stewart, et al. (1970) report 79% anorthite by weight, although this may result from alkali deficiency in the magma. The few olivine compositions reported so far are magnesian, thought not extremely so, with most values for Apollo 11 samples around Fo_{70} [Anderson, et al., (1970); Brown, et al., (1970), and Haggerty, et al., (1970)]. These contrast sharply with the olivines of the Skaergaard and Bushveld intrusions, which according to Wager and Brown (1967) range from Fo_{88} to pure fayalite, Fo_0. Evidence from the pyroxenes is not so clear-cut; they have proven extremely complex and strongly zoned in the Apollo 11 samples, showing extreme iron enrichment (e.g., French, et al., 1970). However, the weight of evidence, such as the equigranular texture of Apollo 11 rocks, suggests that this zoning was formed rapidly during the solidification of the magma. Hargraves, et al., (1970) state specifically that the pyroxenes grew from a melt of the same composition as that in which they occur, i.e., they formed essentially in place rather than in a large magma chamber somewhere else.

Opposed to this evidence for an early stage of evolution, however, is the TiO_2 content of all the Apollo 11 rocks, which is one of their most striking characteristics. Smith, et al. (1970), suggest that this and the Fe/Mg ratio in the mesostasis indicate differentiation along a Skaergaard-like trend, and that the magma from which these rocks formed had already undergone extensive fractional crystallization. The Lunar Sample Preliminary Examination Team (1969) had earlier reached a similar conclusion.

At this time, the most reasonable view appears to be that the mare magmas in bulk were primary, as are terrestrial basaltic magmas, but that they did undergo considerable near-surface fractionation during or after emplacement. The long time lag between formation of the mare basins and eruption of the mare lavas argues against fractionation in the deep interior of the moon then constituting, as Wood, et al., put it, "one vast magma chamber" (1970b, p. 64).

ORIGIN OF LUNAR LANDFORMS

Before going on to the main outline of lunar geologic history, it will be helpful to discuss the origin of the most common lunar landforms. Of these, the craters are of course most important, because most lunar topographic features (except for the mare lava flows) are craters, parts of craters, or crater-related features such as rays. If allowance is made for different degrees of erosion, burial under ejecta, and lava filling, it is apparent that there is a continuum from ray craters like Tycho to the circular mare basins such as that occupied by Mare Imbrium. The crater Tsiolkovsky is extremely interesting in this respect (French, 1970) because it provides a link between the ray craters and the mare basins (Figures 2, 10, 11, 12). If the existence of this continuum is granted, it is clear that proof of a particular origin for the ray craters has major implications for the evolution of most lunar topography.

An impact origin for the ray craters is indicated by several lines of evidence (see also Lowman, 1968). First, large bodies (the Apollo asteroids) are seen to cross the earth-moon solar orbit, and some of these have undoubtedly have hit the earth. A target as large as the moon exposed for 4.7 billion years must have been struck several times, and the ray craters (or degraded ray craters) are the only possible results from such encounters. A related argument is the existence of several dozen structures on earth (not all recognizable as craters) up to 65 kilometers wide for which there is strong geologic evidence of impact origin (Short and Bunch, 1968). Similar structures must have been formed on the moon, and many more would be preserved there in the absence of destructive processes such as orogeny, ocean floor spreading, and sub-aerial erosion. Finally, there are many morphologic features in common among known terrestrial impact craters, artificial impact and explosion craters, and young lunar craters like Copernicus, although similarities can also be found between calderas and lunar craters (Green, 1965). A full discussion of the crater problem is beyond the scope of this paper, but because of the strength of evidence for an impact origin, it will be assumed here that most large lunar craters and the circular mare basins were formed initially by impact. (In mare-filled craters like Plato and Tsiolkovsky, the assumed impact was apparently followed by major vulcanism (French, 1970); there is also some evidence for post-impact vulcanism in non-mare-filled craters such as Aristarchus (Lowman, 1969b).)

Not all lunar craters, of course, belong to the Copernicus-Imbrium Basin class. The chain craters, such as those of the Hyginus Rill (Figure 15), are undoubtedly of internal origin; Gilbert (1896), Shoemaker (1962), and others have compared them to maars. Other large crater-like structures are difficult to classify. The "Flamsteed Ring" (Figure 17), for example, has been interpreted both as an old, pre-mare crater remnant (Marshall, 1963) and by O'Keefe, et al., (1967) as a post-mare ring of acidic extrusives. Still others may be tuff-rings (Figure 13).

EVOLUTION OF THE MOON

With the objective evidence of relative ages, absolute ages, and returned sample analyses, and assuming an impact origin for most lunar craters and mare basins, the following outline of the moon's geologic evolution has been constructed.

Although presumably continuous, it can be conveniently divided into several major stages (Table 2):

Stage I — Formation and rapid heating of moon;

Stage II — First differentiation, formation of mare basins and Archimedian craters, and highland vulcanism;

Stage III — Second differentiation (mare eruptions);

Stage IV — Development of post-mare physiography (sporadic impact, minor vulcanism, landscape degradation).

These stages are summarized, with supporting evidence, in Table 2; discussion follows.

Stage I (4.7 b.y. before present): Formation of the Moon

All the modern theories of the moon's origin — independent origin, capture, and several variants of the fission theory — are currently viable to the extent that each is still supported by competent workers. Evidence from the Apollo samples, in particular the depletion in nickel and the well-known iron deficiency of the moon, supports some form of fission from the earth after the earth's core had formed. It should be noted that the fission concept has in effect been enlarged from Darwin's original tidal resonance mechanism to include processes as diverse as Ringwood's (1966, 1970) secondary accretion from a circumterrestrial sediment ring.

Table 2

Tabular Summary: Geologic Evolution of the Moon

Stage (time, in billion years before present)	Events (sub-events in chronological order)	Evidence
I (4.7-4.6)	a) Formation of moon; last stages were production of old highland craters. Process of formation took about 10 million years, very possibly as little as 1000 years or less. b) Rapid heating to temperatures over 1200 °C, from energy of accretion or fission, tidal interaction with earth, short-lived isotopes, and compression.	1) Radiogenic gas (Ar, He) retention in meteorites began 4.6 b.y. before present. 2) Interval between last stage of nucleosynthesis and radiogenic xenon retention est. at 176-179 million years in meteorites by Hohenburg (1969), suggesting rapid formation of planetesimals. 3) Age of lunar soil 4.4-4.6 b.y. interpreted as highland age sets lower limit to time of moon's origin. 4) Comparative Sr isotope ratios of lunar rocks and meteorites indicate separation of moon from solar nebula in less than 10 million years at 4.6 b.y. before present (Papanastassiou, et al., 1970a). Age of moon supported by Pb-U-Th studies (e.g., Tatsumoto and Rosholt, 1970).
II (4.6-3.7)	a) First differentiation of moon by partial melting, fractional crystallization, or unknown process to form highland crust (anorthositic, basaltic, or granitic?), concurrent with intense but decreasing cratering. Deep layer of rubble and ejecta in highlands formed. Differentiation peaked early, around 4.4-4.6 b.y. age, diminishing rapidly.	1) Age of highland crust estimated at 4.0-4.6 b.y. from soil samples and exotic rock fragments (12013, LR-1 from 10085). 2) Low density of highland crust, indicated by isostasy, implies chemical differentiation (O'Keefe, 1968; Kaula, 1969). 3) Anorthosite fragments in lunar soil considered highland-derived by Wood, et al. (1970), Short (1970), and others. 4) 4.4 b.y. time of melting in meteorite parent bodies (Wood, 1969) suggests comparable melting in moon. 5) Pre-mare age of highlands shown by high crater density. 6) High pre-mare cratering rates shown by abnormally high highland ages derived from highland crater counts (10 to 100 billion years (Gault, 1970); est. at 200 times post mare cratering rate by Hartmann (1965).
	b) Infall of proto-moons or fragments from fission to form circular mare basins, in order: Nectaris — Serenitatis Humorum — Crisium — Imbrium — S. Iridum -- Orientale. (Other smaller basins also formed by impact; exclusion arbitrary.)	1) Continuity of Copernican craters and mare basins implies similar origin; evidence for impact formation summarized in text. 2) Superposition of mare ejecta on highland craters indicates lower relative age of mare basins. 3) Ejecta from youngest mare basin (Orientale) not superimposed on O. Procullarum, suggesting pre-mare ages for mare basins.
	c) Formation of Archimedian generation craters (after mare basins, before mare filling).	1) Archimedes ejecta overlies M. Imbrium, but crater is filled with mare material, demonstrating relative age (Hackman, 1966). 2) Existence of post-Fra Mauro, pre-Plato craters (e.g., Lowman, 1969b, Figure 50) indicates significant interval between mare basins and Archimedian craters.
	d) Eruption of highland volcanics such as Cayley formation.	1) Evidence for possible volcanic nature of Cayley formation summarized by Howard and Masursky (1968). 2) Cayley formation shown to be post-mare basin by superposition on Fra Mauro formation (Imbrian ejecta), and pre-mare by crater population and albedo (Howard and Masursky, 1968).
III (3.7-3.4)	Second differentiation of moon by partial melting of interior to produce basaltic magma, then erupted to form maria. Main eruptions occurred in interval of few hundred million years, with minor mare eruptions considerably later. Tsiolkovsky mare material probably much younger, possibly Eratosthenian in age.	1) Igneous nature and internal derivation of mare lavas shown by petrography of Apollo 11 and 12 crystalline rocks. 2) Absolute ages from radiometric studies of Apollo 11 and 12 crystalline studies of Apollo 11 and 12 crystalline rocks. 3) General similarity of crater densities and albedo in various mare area indicate similar ages; unusually dark, smooth patches (e.g., M. Serenitatis) indicate minor relatively later eruptions.
IV 3.4 to present	a) Localized mare and highland vulcanism, forming Marius Hills, Flamsteed Ring, chain craters, sinuous rills, Sulpicius Gallus formation, Gambart-type craters, and possibly other features. Tension faulting, sometime localizing chain craters as along the Hyginus Rille.	1) Evidence for volcanic origin of specific features summarized by Lowman (1969b). 2) Evidence for age and origin of named units given on USGS maps cited in text.
	b) Sporadic impact of meteoroids from asteroid belt and cometary nuclei to form ray craters (including Eratosthenian) such as Copernicus.	1) Evidence for impact origin of ray craters summarized in text. 2) Relative age of craters deduced from superposition and albedo.
	c) Continual slow landscape degradation by meteoritic and secondary impacts and ejecta deposition, thermal shock, radiation, tectonic events, possibly other conditions.	1) Evidence for and nature of minor impact crater production discussed by Gault (1970). 2) Evidence for mass wasting presented in Surveyor photographs. 3) Slow rate of erosion deduced from cosmogenic isotopes in returned samples and studies of Surveyor III landing site from Apollo 12 photographs and samples.
Present condition of moon:	Cold and rigid to depths of 400 km or greater, but with potential P,T conditions for magma generation at greater depths. Occasional minor vulcanism, perhaps largely gaseous, indicated by transient events at Aristarchus and other sites. Moon tectonically quiet compared to earth, with only minor seismicity triggered by earth's attraction.	

Whatever the process, the time at which the moon formed can now be fixed by radiometric dates from the Apollo samples and other evidence at about 4.7 billion years ago. This value is the time at which radiogenic gas retention began in meteorites (Hohenberg, 1969) and the Pb^{207}/Pb^{208} age of several meteorites (many more falling around 4.4 billion years by Rb^{87}/Sr^{87} methods). It is also close to the 4.5 billion year age currently accepted as a lower limit for the earth's origin, and which probably represents the time of core separation (Hurley, 1959). The most direct evidence for the age of the moon is the 4.6 billion year figure for the lunar soil at Tranquillity Base, determined by Rb-Sr (Papanastassiou, et al., 1970) and Pb-U-Th (Tatsumoto and Rosholt, 1970; Silver, 1970) methods. As mentioned earlier, this figure is generally interpreted as an average for the lunar crust resulting from the mixing of older and more radiogenic (highland) material with the younger mare material at the Apollo 11 site.

Several lines of evidence indicate that the moon formed in a time surprisingly short by geologic standards. A suggestive figure is Hohenberg's (1970) estimate of 176-179 million years for the interval between the last nucleosynthetic event and the beginning of Xe^{129} retention in meteorites, which he interprets as the time of formation of the solar system. A specific figure of less than 10 million years for separation of the moon from the solar nebula was inferred by Papanastassiou, et al., (1970a) from the limited range of Sr^{87}/Sr^{86} ratios in the lunar samples and achondrites. An even shorter formation period, on the order of 1000 years, was suggested by Cameron (1970), and Opik (1967) had previously estimated 350 years.

Such a rapid process may strike the geologist as unlikely, compared to the times involved in evolution of the earth's crust. But the moon's origin was primarily astrophysical rather than geological in nature; and astrophysical processes, involving turbulent plasmas, gas, and dust rather than large solid bodies, are generally fast by geological standards (Cameron, 1968). Herbig in 1954 photographed the Orion Nebula and found two star-like objects that had not been there only 8 years earlier (Cameron, 1968, p. 910). Variable stars (to say nothing of pulsars) frequently have periods of hours, and there is a suspicion that variations in the periods of variable stars over a few decades may actually mark evolutionary processes within individual stars (as opposed to the continuum of evolutionary stages simultaneously visible among different stars). From a cosmological viewpoint, then, there seems no inherent reason to doubt that the moon was born rapidly. It should also be noted that the earth is thought to have formed in a short period; Hanks and Anderson (1969) concluded from calculations on the earth's thermal history that it must have accreted in less than 500,000 years.

The question of how hot the moon was during its evolution is a fundamental and much-debated one, which can not be adequately treated here. Since about 1950, planetary origin has generally been considered a low-temperature process (Urey. 1952). However, it now appears that the moon became very hot during its formation or shortly afterward, regardless of just what the process of formation was. Direct evidence for a high-temperature origin is found in the production of mare-filling magmas about 3.7 billion years ago, implying temperatures over 1200°C at some level in the moon at that time. Evidence for earlier differentiation, to be discussed, also implies high temperatures at origin for the moon. Furthermore, several recent theoretical studies point to a high-temperature early stage. The work of Hanks and Anderson (1969), though not treating the moon directly, have application to it, indicating that rapid accretion would generate heat more rapidly than it could be lost by radiation. O'Keefe's (1969) study suggests that if the moon formed by fission of the earth, both the proto-earth and proto-moon would be extremely hot; and his prediction that the moon would be systematically depleted in volatiles, such as water and alkalies, has so far been borne out by the Apollo samples. An additional source that must now be considered in view of the moon's age of 4.7 billion years (shortly after the end of nucleosynthesis) is the heat from short-lived isotopes such as Al^{26}. Adiabatic compression would also raise the temperature, but only slightly; Fricker, et al., (1967) estimated a temperature rise of some 20°C at the center of the moon.

Taken together, the cumulative evidence indicates that even if the moon formed from relatively cool material, it heated up immediately. This raises the possibility of partial or even complete melting in the first billion years of lunar geologic history, as suggested by Kuiper (1954).

Stage II (4.6 to 3.7 b.y. before present): Pre-mare Events

Four major events, overlapping in time and space, can be distinguished in this stage. The first of these ("a" in Table 2) was formation of the highland crust, which can be placed very approximately at between 4.6 and 4.0 billion years ago from the radiometric ages of soil samples and the few allocthonous rock fragments so far dated, such as LR-1 (4.4 b.y.) (Papanastassiou, et al., 1970a) and 12013 (4.0 b.y.). The lower limit cited, 4.0 billion years, is both uncertain and arbitrary, since highland crustal evolution in the form of localized vulcanism (Mutch, 1970) has probably occurred throughout the moon's history. This age does, however, emphasize the probability that highland crust formation peaked early.

The highlands constitute most of the moon's surface; statistically, the far side is the normal side. They have major implications for the origin of terrestrial continents (Lowman, 1969a), the origin of the moon, and its relation to the earth. Therefore, the origin and nature of the highlands must be discussed in some detail despite the present scarcity of reliable information on their composition.

The moon's isostasy (O'Keefe and Cameron, 1962; O'Keefe, 1968) indicates that the highland crust is less dense and, by implication, chemically different from the body of the moon. This difference may have arisen in several ways. Mueller (1969) points out that the moon's bulk composition could have resulted from "differentiation" in the solar nebula before accretion, or during the process of condensation and agglomeration. Following this argument, it seems possible that the highlands might represent a subsidiary pre-formation chemical differentiation. However, there is no specific geologic or experimental evidence of this. The other possibility for formation of the highland crust is by internal petrologic processes which would represent a "first differentiation" on a global scale.

Present thinking on highland petrology centers on anorthosite or gabbroic anorthosite since the unexpected discovery by Wood, et al., (1970) and others of anorthosite fragments in the Apollo 11 soil samples. Wood, et al., and Smith, et al. (1970) have proposed that these fragments are highland samples (Figures 3 and 4), and that the highland crust is anorthosite formed by plagioclase crystal flotation. In addition to the petrologic arguments, showing that anorthosites could form from these magmas, there is independent evidence for anorthositic highlands. Short (1970) points out that the Surveyor VII analyses from Tycho are normatively close to gabbroic anorthosite, and that the degree of shock damage in some fragments is consistent with an impact origin from the heavily-cratered highlands. The systematic europium deficiency of the Apollo 11 basalts (Philpotts and Schnetzler, 1970; Gast and Hubbard, 1970) can be explained by its depletion by previous plagioclase crystallization. However, the plagioclase thus formed could be in the maria; this argument does not by itself point to anorthositic highlands. And other possibilities exist; Gast and Hubbard point out that if the interior of the moon from which the mare magmas came contained feldspar, it might have remained in the residue left by partial melting, thus accounting for the europium deficiency.

Against these arguments must be set the fact that, as will be demonstrated shortly, the mare basalts were erupted long after the highlands were formed; enough time elapsed for formation of the circular mare basins, the many post-basin, pre-mare craters, and the Cayley formation (highland volcanics?). This argues against simple release of the mare magmas by crust-penetrating impacts, and more indirectly, against the theory that the supposed anorthositic highlands are a differentiation product of these magmas. Furthermore, other compositions for the highlands are possible; discovery of a siliceous mesostasis in the Apollo 11 rocks (Adler, et al., 1970; French, et al., 1970), inclusions evidently formed by liquid immiscibility (Roedder and Weiblen, 1970), and nonanorthositic rock fragments such as sample 12013 suggest some as yet unknown acidic rock. It should also be pointed out that the maria have only been sampled at two sites; in view of the convincing evidence that anorthosite could form from magmas of this or similar composition, it appears very possible that the anorthosite fragments may have come, by impact, from plagioclase-rich layers in the maria rather than from the highlands. In view of these complications, it seems best to suspend judgement on the composition and origin of the highlands until more samples can be returned.

While it was forming, by whatever means, the highland crust was being heavily cratered (presumably by impact, for reasons given before). The pre-mare cratering rate has for some time been recognized as abnormally high; Hartmann (1965) estimated it at about 200 times the post-mare rate. More recent studies by Gault (1970) substantiate this view, by showing that highland ages based on crater counts and the post-mare rate range from 10 to 100 billion years. This "early intense bombardment", to use Hartmann's term, has been considered to be, by authorities such as Kuiper and Baldwin, the last stage of the moon's formation. The layer of rubble and ejecta thus formed is probably several kilometers thick in places, averaging 1.5 to 2.0 kilometers on the near side, according to Short and Forman (1970).

The next event in Stage II, occurring after most of the highland crust had formed, was the excavation of the circular mare basins, presumably by the impact of large bodies. Regardless of their actual mode of origin, the superposition of basin-related deposits (ejecta blankets in impact terminology) such as the Fra Mauro formation (Figure 14) on highland crust demonstrates the largely post-highland age of the mare basins. The approximate sequence of the largest circular basins can be deduced from superposition of their individual ejecta blankets and the degree of post-basin cratering (oldest first): Nectaris, Serenitatis, Humorum, Crisium, Imbrium, S. Iridum, and Orientale. Other circular basins (especially on the far side) were also probably formed at about this time, but are not currently recognized as maria. An important point here is that the ejecta from the youngest large mare basin, Orientale, is <u>not</u> superimposed on mare material of Oceanus Procellarum, indicating that the mare basins as here defined <u>all</u> predate the main mare eruptions.

It must be recognized that formation of the mare basins (by impact, as assumed here) represents something of a discontinuity in the moon's early evolution. The cratering rate was, as mentioned previously, evidently decreasing at this time, when the moon was hit by several very large bodies in a relatively short period; Baldwin (1963) estimates the Imbrium projectile to have had a diameter of between 64 and 190 kilometers, depending on the impact velocity. At least two sources for these late-coming bodies can be suggested. They might have been small proto-moons forming around the earth in the same way as did the moon proper, and their infall would have been a process of sweeping up by the biggest proto-moon (MacDonald, 1964). An alternative possibility is that they were fragments detached from the earth when the moon was formed by tidal fission.

The third class of events in Stage II was the formation of large craters like Archimedes and Plato (Figure 2). These craters are in or on the borders of circular mare basins and are at least partly filled with mare material. They are surprisingly common, and can be found in all the circular maria; even Sinus Iridum (Figure 2) can be included. These post-basin, pre-mare craters have important implications for the origin of the mare magmas, and will therefore be discussed at some length (see also Baldwin, 1963, pp. 305-309). Their relative age is unambiguous; they must be younger than the mare basins, since they would have been destroyed when the basins were formed. But they must be older than the mare lavas, which flood or partially flood them. Thus they demonstrate that a significant time elapsed between formation of the mare basins and at least the later eruptions of lava. Furthermore, still another generation of craters can be distinguished around Plato which are post-Fra Mauro (i.e., post-Imbrium-basin) but pre-Plato. It seems clear, then, that the mare basins were not filled for some time after they were formed. This proves that the mare magmas were formed internally, rather than directly as impact melts by the infall of the presumed basin-forming bodies. Furthermore, it tends to weaken the theory that the magmas were simply released by these impacts, as suggested by Anderson, et al. (1970) and Wood (1970) to account for formation of anorthositic highlands by crystal flotation from the same magmas; under that theory, the eruptions should have immediately followed basin formation. The basin/lava time interval does, however, seem consistent with generation of the mare magmas by partial melting of the interior.

The fourth class of events in Stage II provides further support for the existence of a substantial time gap between mare basin formation and filling. These events include the production of mare-like high-albedo terrain in the highlands and the floors of old pre-mare craters such as Ptolemaeus and Alphonsus (Figure 19). This terrain has been named the Cayley formation by Howard and Masursky (1968), and interpreted by them as possibly volcanic material. Regardless of its actual origin, the Cayley formation is younger than the Imbrium Basin (since the Fra Mauro formation does not overlie it) but older than the mare material (as shown by its greater crater density and higher albedo). The Cayley formation thus constitutes still another event which took place after the mare basins were formed, but before they were filled with mare material.

Stage III (3.8 to 3.4 b.y. before present):
Second Differentiation and Mare Formation

We come now to the event in the moon's evolution about which we know the most: the generation and eruption of mafic magmas to form the maria. For a variety of reasons, as previously explained, it is clear that the moon must have a bulk composition considerably different from that of the mare rocks. Therefore, the generation of these magmas must represent differentiation in a broad sense – the second differentiation, in light of the evidence for a previously-formed highland crust.

The petrology of the mare rocks returned by the Apollo 11 and 12 missions has already been discussed and need not be repeated here, except to stress again that several lines of evidence now indicate strongly that these are true igneous rocks which crystallized from a magma produced by partial melting of a solid interior.

The present estimates for the age of Mare Tranquillitatis and Oceanus Procellarum rest of course on the radiometric age determinations done on the crystalline rock samples. There is evidence, however, that most of the maria are composite, having been formed by repeated eruptions and possibly by associated intrusions. Carr (1966) found evidence for this in Mare Serenitatis (Figure 1), in which several mare units with different albedo, implying different ages, are apparent. Mapping at larger scales reveals comparable mare units elsewhere (Mutch, 1970, p. 214). From a broad viewpoint, however, it seems likely that the major maria formed in one period of the moon's history (Shoemaker and Hackman, 1962). A possible exception is the mare material filling the crater Tsiolkovsky (Figure 11); the sharp external topography of this crater indicates a relatively low age, comparable to the post-mare front side crater Eratosthenes. Crater counts on high resolution photographs should settle this question.

Stage IV (4 b.y. before present to now): Post Mare Events

By the end of Stage III, around 3 billion years ago, the moon had developed much of its present physiography. (One of the most intriguing geological aspects of the Apollo 11 mission is the fact that Astronauts Armstrong and Aldrin were walking on a landscape essentially older than any known rocks on earth.) There remain, however, several types of post-mare topography to account for. The following features are not listed in chronologic order, but their relative ages can frequently be determined by examination of the USGS 1:1,000,000 geologic maps.

Most students of the moon now recognize the existence of many landforms produced by volcanic activity. The chain craters have long been considered of internal origin, although careful examination with high-resolution photography is necessary to distinguish between undoubtedly internally-caused chains and those produced by strings of ejecta fragments from large craters. Chain craters like those of the Hyginus Rille are frequently located on rilles that appear to be the result of tension faulting. Much of this faulting is clearly post-mare, and is suggestive of the association of terrestrial basaltic vulcanism and crustal extension such as that discussed by Lipman et al., (1970) in the southwest United States. The Marius Hills (Figure 16), a large dome field in Oceanus Procellarum, are almost certainly volcanoes (McCauley, 1967), possibly of siliceous composition in places; they thus represent localized late-stage mare vulcanism. Several other rather large crater-like features, such as that in Mare Orientale, are now thought to be some sort of volcanic landform, because the morphologic differences between them and ray craters can not be realistically attributed to age (Mutch, 1970). The sinuous rilles (Figures 14, 16), frequently proposed as water-eroded valleys before Apollo 11, are almost certainly internally-caused. Although the suggestion of Lingenfelter, et al., (1968), that the water might have been released from deep layers by impact, is still a possibility, volcanic mechanisms seem more promising (see, for example, Cameron, 1964).

The problem of whether the moon is still volcanically active, either now or recently, is still debated. Of considerable interest are the dark terrain-mantling deposits mapped by Carr (1966) as the Sulpicius Gallus formation (Figure 2). They are interpreted as volcanic material, but their low albedo and fresh appearance indicate that the material is relatively young; Wilhelms (1968) in fact mapped one such area as Eratosthenian or Copernican mare material, implying relatively late volcanic activity. To this morphologic evidence must be added the well-confirmed observations since 1958 of transient phenomena such as the "red spots" seen by Greenacre and Barr around the crater Aristarchus in 1963. Taken together, the evidence from all sources seems to indicate that there has been localized volcanic activity on the moon throughout the post-mare period, very possibly continuing at present. This conflicts with the interpretation of Explorer 35 data (Ness, 1968) that the moon is currently not hotter than 1000°C throughout. To resolve this conflict remains for future investigations, especially for the heat-flow and magnetic field measurements planned for later Apollo missions.

Ray craters (including those like Eratosthenes which once had rays) have been formed on the moon sporadically since eruption of the mare lavas, probably by the impact of large bodies. A point not brought out in the previous discussion of impact craters is that the post-mare craters were probably produced for the most part by bodies from the asteroid belt or by comets, in contrast to the old pre-mare craters, which are generally thought to have been formed by a swarm of circum-terrestrial bodies in the last stages of the moon's growth.

A slow but steady process of landscape degradation and soil formation (Figures 6, 7) has clearly gone on throughout the post-mare period, to the point that there are few areas of exposed solid bedrock on the moon (chiefly in the floors of the youngest ray craters). Small meteorite and secondary ejecta impacts are probably responsible for most of this degradation, which includes both erosion (crater formation) and deposition (blanketing by crater ejecta). Radiation, thermal shock, and possibly tectonic events may have contributed to this process, but their importance is not yet fully known. A striking example of how slow erosion is on the moon was provided by the Apollo 12 photograph (Figure 20) of a Surveyor III footprint; although exposed to space for over 2-1/2 years, the impression appeared to the astronauts as fresh as if it had just been made.

THE MOON TODAY

Geologically, the major aspect of the moon's present condition is its lack of tectonic activity. As we have seen, landscape evolution on the moon is incredibly slow by terrestrial standards, but this observation is consistent with the almost total absence of true seismic activity indicated so far on the Apollo 11 and 12 seismographs (Latham, et al., 1970). The picture now emerging is of a body compared to which the earth is a bubbling cauldron of geologic activity.

Evidence for minor internal activity does exist, however, especially the now well-confirmed existence of transient events (just mentioned) around Aristarchus and other areas (Cameron, in press; Burley and Middlehurst, 1966). These events cannot reasonably be attributed to luminescence, because the luminescent efficiency of returned samples is far too low to account for them (see, for example, Edgington and Blair, 1970). The only plausible alternative is some sort of degassing, implying at least the potential for deep-seated volcanic activity at the present time.

These two lines of evidence may be reconciled if the moon is indeed cold and rigid to a depth of several hundred kilometers. Such a possibility was suggested by earlier studies of the moon's thermal history (MacDonald, 1959) which indicated that magma generation at this time could take place below 300 kilometers (Lowman, 1963) even if the moon had started out with a temperature around 600°C.

SUMMARY

The most general conclusion about the moon's geologic evolution is that most of it happened before formation of the oldest known rocks on earth. The collective evidence indicates that the moon must have originated, grown to its present size, developed a solid differentiated crust, captured a number of large circumterrestrial bodies, and begun a second period of differentiation all in the first billion years or so of its history. Uniformitarianism must obviously be applied with caution to the moon, since most of the present major landforms are the result of long-finished processes.

A second conclusion is that the moon's origin was a high-temperature process, whatever its nature. In addition to the evidence already cited, it seems clear that formation of the highland crust and the mare magmas occurred too early in the moon's history for the conventionally-treated heat sources (uranium, thorium, and potassium 40) to have produced enough heat in an initially cold moon.

Finally, the pre-Apollo concept of the moon as a body whose physiography is the result of both igneous and impact processes, in roughly equal measure, appears to be confirmed by studies of returned lunar samples and spacecraft photography.

It is hardly necessary to point out that several major problems and controversies remain; this paper has necessarily concentrated on areas of agreement rather than disagreement. Prominent among these problems are the nature and origin of the highlands, which will have implications for the origin of terrestrial continents regardless of what the highland composition turns out to be. The reason for the moon's apparent depletion in volatile elements, such as potassium, sodium, lead, and hydrogen (as water), is still to be confirmed and explained if true. It seems possible, for example, that these and related elements are low in mare rocks because they had already been driven out of the moon's interior during the first differentiation to form the highland crust. The impact origin of ray craters has not yet been proven to the satisfaction of all; a specific related question is the origin of the obviously once-fluid materials found in and around young craters such as Tycho. Perhaps the most general question is the relation of the moon to the earth; to use Firsoff's (1962) phrase: Is it "Earth's fair child or a foundling"? Or something else?

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