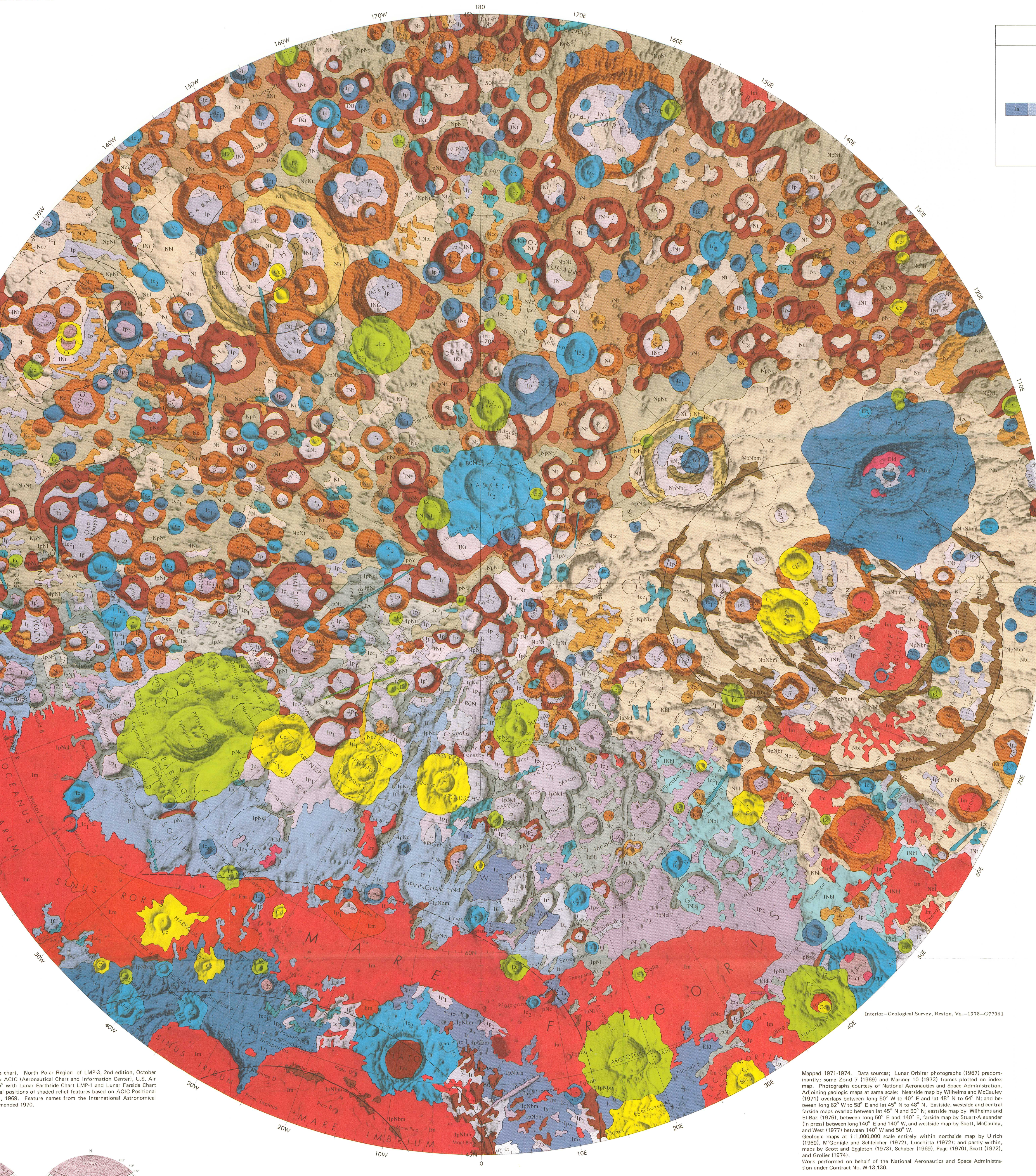
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AND IN COOPERATION WITH THE
DEFENSE MAPPING AGENCY, AEROSPACE CENTER

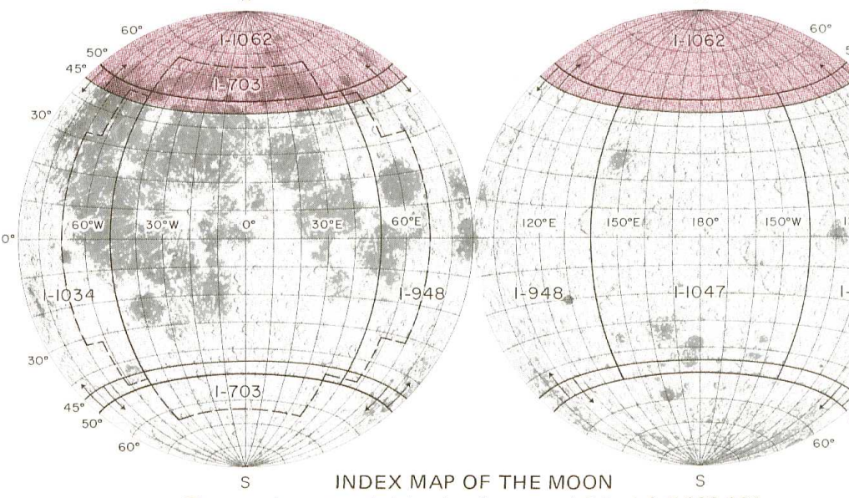
GEOLOGIC ATLAS OF THE MOON
NORTH SIDE OF THE MOON
I-1062



Interior—Geological Survey, Reston, Va.—1978—G77061

KILOMETERS
300 200 100 75 50 25 0 25 50 75 100 200 300
POLAR STEREOGRAPHIC PROJECTION
Scale 1:5 000 000 at the Pole

Shaded relief base chart, North Polar Region of LMP-3, 2nd edition, October 1970, prepared by ACIC (Aeronautical Chart and Information Center), U.S. Air Force. Overlaps 5° with Lunar Earthside Chart LMP-1 and Lunar Farside Chart LMP-2. Horizontal positions of shaded relief features based on ACIC Positional Reference System, 1969. Feature names from the International Astronomical Union catalogue emended 1970.



INDEX MAP OF THE MOON
The number preceded by I refers to published 1:5,000,000 geologic map

I-703 Geologic map of the Near Side of the Moon (dashed line)
I-948 Geologic map of the East Side of the Moon
I-1034 Geologic map of the West Side of the Moon
I-1047 Geologic map of the Central Far Side of the Moon
I-1062 Geologic map of the North Side of the Moon

Mapped 1971-1974. Data sources; Lunar Orbiter photographs (1967) predominantly; some Zond 7 (1969) and Mariner 10 (1973) frames plotted on index map. Photographs courtesy of National Aeronautics and Space Administration. Adjoining geologic maps at same scale: Nearside map by Wilhelms and McCauley (1971) overlaps between long 50° W to 40° E and lat 48° N to 64° N; and between long 62° W to 58° E and lat 45° N to 48° N. Eastside, westside and central farside maps overlap between lat 45° N and 50° N; eastside map by Wilhelms and El-Baz (1976), between long 50° E and 140° E, farside map by Stuart-Alexander (in press) between long 140° E and 140° W, and westside map by Scott, McCauley, and West (1977) between 140° W and 50° W.

Geologic maps at 1:1,000,000 scale entirely within northside map by Ulrich (1969), M'Gonigle and Schleicher (1972), Lucchitta (1972); and partly within, maps by Scott and Eggleton (1973), Schaber (1969), Page (1970), Scott (1972), and Grolier (1974).

Work performed on behalf of the National Aeronautics and Space Administration under Contract No. W-13,130.

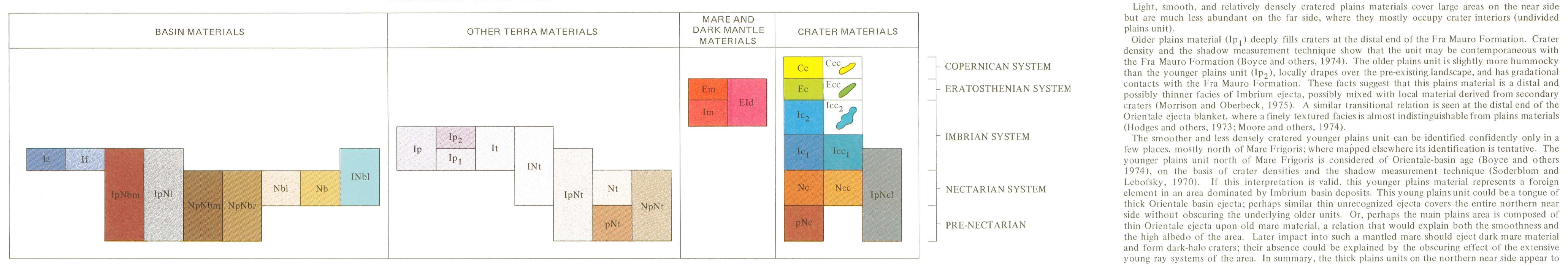
GEOLOGIC MAP OF THE NORTH SIDE OF THE MOON

By

Baerbel K. Lucchitta

1978

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

BASIN MATERIALS

Ia ALPES FORMATION—Angular or rounded, closely spaced hills and irregular hummocks

If FRA MAURO FORMATION—Sinuous, curvilinear, and straight ridges draping over underlying landscape. Surface texture locally hummocky

IpNbm MATERIAL OF IMBRIUM BASIN MASSIFS—(Imbrian, Nectarian, and pre-Nectarian) Bright, high, steep-sided mountain blocks and ridges

IpNl IMBRIUM LINEATED BASIN MATERIAL—(Imbrian, Nectarian, and pre-Nectarian) Linear subparallel arrays of scalloped troughs and ridges radial to Imbrium basin

NpNbm MATERIAL OF HUMBOLDTIANUM BASIN MASSIFS—(Nectarian and pre-Nectarian) High, rugged mountain blocks and chains forming basin rings

NpNbr MATERIAL OF RUGGED BASIN TERRAIN—(Nectarian and pre-Nectarian) Irregular mountain blocks and rugged hills, forming inner rings of Birkhoff and Schwarzschild basins, and Bel'kovich central peaks

Nbl LINEATED BASIN MATERIAL—Irregular hilly material and broadly undulating ridges and troughs radial to Humboldtianum and Birkhoff basins

Nb UNDIVIDED BASIN MATERIAL—Craterlike rims and terraced walls of Birkhoff and Schwarzschild basins

INbl UNDIVIDED LINEATED BASIN MATERIAL—(Imbrian and Nectarian) Intersecting ridges, troughs, and vaguely lineated material radial to Imbrium and Humboldtianum basins

OTHER TERRA MATERIALS

Ip UNDIVIDED PLAINS MATERIAL—Light, smooth, flat surface in low areas. Higher density of craters than mare

Ip_2 YOUNGER PLAINS MATERIAL—Light, smooth, flat surface. Lower density of craters than Ip_1. Contacts mostly sharp

Ip_1 OLDER PLAINS MATERIAL—Light, fairly smooth, flat to locally undulatory surface. Crater density like that on Fra Mauro Formation. Contacts locally diffuse

It TERRA MATERIAL—Light, slightly hummocky surface. Smooth and level on medium-resolution pictures

INt TERRA MATERIAL—(Imbrian and Nectarian) On high-resolution pictures, hummocky plain with some subdued hills (kilometers in size), mostly in low areas. On medium-resolution pictures light, fairly smooth and level plains. Surface more undulating and contacts more diffuse than those of plains units. Mixture of hilly material and plains material in areas too small to map separately. Includes unit INp of some adjacent maps

IpNt TERRA MATERIAL—(Imbrian, Nectarian, and pre-Nectarian) on high-resolution pictures, smooth to undulating, pitted, and grooved surface on topographically high areas. On medium-resolution pictures, resembles unit Nt

Nt TERRA MATERIAL—Irregular hills and depressions, a few kilometers to tens of kilometers in size. On medium-resolution pictures, somewhat subdued highlands. On high and low areas

pNt TERRA MATERIAL—Rugged mountains, irregular depressions, and clusters of old craters and crater rim remnants

NpNt TERRA MATERIAL—(Nectarian and pre-Nectarian) Irregular hills, ridges, depressions, furrows, and crater remnants

MARE AND DARK MANTLE MATERIALS

Em YOUNGER MARE MATERIAL—Dark, smooth, flat surface of bluish color. Lower albedo and lower density of craters than Imbrian mare

Im OLDER MARE MATERIAL—Dark, smooth, flat surface in Mare Frigoris, Oceanus Procellarum and Imbrium and Humboldtianum basins. Mostly on lunar near side

Eld DARK MATERIAL—(Eratosthenian or Imbrian) Dark, smooth, or hummocky material draping over underlying landscape. Locally associated with rimless depressions or grooves

CRATER MATERIALS

Cc MATERIAL OF RAYED CRATERS—Sharp topographic detail at all photographic scales, sharp continuous rimcrest. On high-resolution pictures, deep rugged interior, terraced walls, radially ribbed rim materials, and secondary crater clusters and chains. Rays visible on near side images. Small craters are sharp-rimmed with deep bowls

Ccc MATERIAL OF CRATER CHAIN—Linear chain of sharp-rimmed, overlapping irregular craters radial to Philolaus

Ec MATERIAL OF FRESH CRATERS—Fairly sharp topographic detail, sharp continuous rimcrest. On high-resolution pictures, deep, somewhat subdued interior, terraced walls, radially ribbed rim materials, and secondary crater clusters and chains. Small craters have deep bowls

Ecc MATERIAL OF CRATER CHAIN—Linear crater chain radial to Pythagoras

Ic_2 MATERIAL OF MODERATELY FRESH CRATERS—Subdued but distinct topographic detail, fairly continuous rimcrest. On high-resolution pictures and around large craters (Plato, Plaskett), terraced walls, radially ribbed rim facies, and secondary craters. On medium-resolution pictures, outer rim facies indistinct or smooth. Small craters have deep bowls, rim more subdued than those in unit Ec

Icc_2 MATERIAL OF CRATER CLUSTERS AND CHAINS—Round to irregular overlapping craters and chains, somewhat subdued rims and fairly deep interiors

Ic_1 MATERIAL OF MODERATELY SUBDUED CRATERS—Subdued topographic detail, fairly continuous rimcrest. Terraced walls, radial rim facies and secondary craters on very large craters (Iridum, Compton); on other craters outer rim facies indistinct or smooth. Small craters have shallow bowls with rubdued rims, irregular shadows

Icc_1 MATERIAL OF CRATER CLUSTERS AND CHAINS—Round to irregular overlapping craters, subdued rims, shallow interiors, irregular shadows

Nc MATERIAL OF SUBDUED CRATERS—Continuous to interrupted subdued rimcrest. Only large craters show terrace remnants; outer rim facies only on d'Alembert. Small craters have smooth walls, mostly flat floors

Ncc MATERIAL OF CRATER CLUSTERS AND CHAINS—Round to irregular, overlapping craters, rounded rims; irregular, shallow interiors or flat floors

pNc MATERIAL OF HIGHLY SUBDUED CRATERS—Discontinuous, subdued rimcrests and rounded, curved or straight rim remnants

IpNcl MATERIAL OF LINEATED CRATERS—(Imbrian, Nectarian, and pre-Nectarian) Linear subparallel arrays of troughs and ridges radial to Imbrium basin; on crater rims

——— Approximate contact

- - -——- - - Crest of buried crater rim

———— — — Crest of basin ring structure (generalized). Dashed where poorly defined or inferred

cf Fractured crater floor, occurs in craters of Nectarian, Imbrian, and Copernican age.

INTRODUCTION

Geologic mapping of the north side of the Moon follows the practices established by Shoemaker and Hackman (1962) and Wilhelms (1970). Most units and map conventions conform to those of the near-side geologic map by Wilhelms and McCauley (1971), except for a larger size cutoff (20 km) for craters and patches of other units. A significant departure is division of pre-Imbrian materials into a Nectarian System and pre-Nectarian materials. The base of the Nectarian System is defined as the base of the Janssen Formation, the lineated ejecta blanket in the Nectaris basin (Stuart-Alexander and Wilhelms, 1975). On the present map, units are assigned to the Nectarian by comparison of crater morphologies. The base of the informally designated upper Imbrian series is defined by materials of the Orientale basin.

Identification of geologic units is based mostly on Orbiter photographs, supplemented in places by Zond 7 and Mariner 10 images. The coverage for the front side is excellent (Orbiter IV high-resolution pictures) and identification of units is made fairly confidently. The coverage of most of the far side is less good (Orbiter IV and V medium-resolution photographs, locally with highly oblique viewing angles). Thus identification of geologic units on the far side is tentative, and location of contacts approximate. The low sun illumination angle on all pictures near the pole also complicates recognition of units.

The mapping of the lower latitudes of the near side in this map area closely follows that of the detailed maps at a scale of 1:1,000,000 listed in the credit note. This map is slightly modified in view of the different scale and scope of the present rendition.

GENERAL FEATURES

The north side of the Moon reflects the Moon's general dichotomy: the near side is imprinted by the Imbrium impact and flooded by mare material; the far side is characterized by cratered highlands mantled to various degrees. A third major element, on the east limb, is the Humboldtianum basin and its ejecta blanket. This general setting is displayed on the province map (Fig. 1).

The Imbrium basin units include basin massifs that partially define Imbrium basin rings, and the Alpes and Fra Mauro Formations. In addition, Imbrian lineated material trends northeast, radial to the basin. Thick plains material fills many craters in a belt beyond the Fra Mauro Formation, and smooth terra material covers highland surfaces beyond it. Mare Frigoris on the east and Oceanus Procellarum on the west occupy a broad depression across the near side in the map area.

On the far side, craters and basins dominate the surface: the old basin here named Coulomb-Sarton and the two small younger basins, Birkhoff and Schwarzschild, are recognized. The intervening areas are mantled by hilly terra units whose roughness increases with age; the oldest and roughest unit consists mostly of ancient crater rims.

Radial ejecta deposits and secondary craters of the Humboltianum basin are pronounced and extensive. The basin rings encircle the basin and the superimposed crater Bel'kovich.

Among post-Imbrium craters the early Imbrian craters Iridum and Compton are most prominent; their ejecta blankets obscure sizable areas on the near and far sides. Several large Eratosthenian and Copernican craters on the near side give rise to a dense secondary crater population and to the bright appearance of the north pole area on full Moon photographs.

GEOLOGIC UNITS

BASIN MATERIALS

Multiringed basins produced by impact have long been recognized on the Moon (Hartmann and Kuiper, 1962; Baldwin, 1963; Stuart-Alexander and Howard, 1970; Wilhelms, 1970; Hartmann and Wood, 1971). Younger basins typically consist of one or more mountainous rings with rugged intervening terrain and a radial ejecta blanket beyond the outermost ring. Older basins display traces of ring structures composed of mountains or uplifted crater rim segments. Mantled terra material near the older basins attests to the presence of degraded ejecta blankets.

Basin ring structures are assigned a pre-basin and basin age on the assumption that pre-basin rocks are structurally displaced to form the basin rings (Wilhelms and McCauley, 1971). Recent investigators, however, concur that the outer basin rings may be predominantly composed of ejecta (Head, 1974; Howard and others, 1974; Moore and others, 1974; Reed and Wolfe, 1975; Scott and others, 1977). The ejecta are assigned a basin age because included pre-basin rocks are thought to have been thoroughly modified by the impact. Not included here in the definition of basins are craters that display both ring structures and central peaks.

Imbrium basin materials

The northern part of the Imbrium basin extends into the map area. The inner and second basin rings follow the massifs, which form "islands" in Mare Imbrium and blocky mountains near Vallis Alpes. The second ring becomes indistinguishable underneath the ejecta blankets of craters Plato and Iridum. The outer ring, represented by Montes Apenninus farther south, diverges outward in the map area and can be traced through mountain massifs near crater Aristoteles, through "islands" in Mare Frigoris, and possibly through the north "shore" of the mare. The basin rings are inferred to result from structural adjustment upon impact, either as frozen tsunamilike waves (Baldwin, 1972, 1974) or by rebound and collapse (Head, 1974, Howard and others, 1974).

The Alpes Formation occurs on both sides of the outer Imbrium basin ring. It was previously interpreted as Imbrium basin ejecta and structurally modified older rock (Page, 1970; M'Gonigle and Schleicher, 1972; Lucchitta, 1972). The present study suggests different origins in different places: near the basin ring, where its texture is coarse, the Alpes may be fractured fallback ejecta, as suggested for similar material near the main ring of the Orientale basin (McCauley, 1968; Head, 1974) or a fall-back ejecta facies of deep-seated origin (Scott and others, 1977); farther outward from the Imbrium basin rings, where its texture is fine, the Alpes may be a hummocky facies of Imbrium ejecta (Scott, 1972; Lucchitta, 1972). Some of the hummocky appearance may result from dense cratering by small secondary projectiles.

The Fra Mauro Formation is a thick deposit of Imbrium ejecta (Eggleton, 1964; Wilhelms, 1970) that buries cratered highlands north of Mare Frigoris and extends to about 700 km from the inner basin ring with tongues over 1000 km. These distances are comparable to those of ejecta deposits on the south side of the basin (Wilhelms and McCauley, 1971). The Fra Mauro also occurs west of the Imbrium basin, where it is locally deposited against the far walls of craters, but it is not present northeast and east of the basin, where lineated material and the Alpes Formation take its place. The Fra Mauro may have been deposited from a dense, rapidly moving cloud of debris, in the manner envisioned for the Orientale ejecta (McCauley and Masursky, 1968; McCauley, 1968; Masursky, 1968), or as collision products from primary and secondary ejecta debris (Oberbeck and others, 1974, 1975; Morrison and Oberbeck, 1975). Analysis of samples returned from the Fra Mauro Formation south of the Imbrium basin suggest that the formation consists of breccia in various stages of thermal metamorphism (Sutton and others, 1972; Wilshire and Jackson, 1972; Warner, 1972; Chao and others, 1972).

Lineated basin material occurs mainly northeast of the Imbrium basin but is also present to the northwest and west. The grooves forming the lineations traverse highland terrain and gouge old crater rims; they are similar to grooves of "Imbrium sculpture" southeast of the basin (Wilhelms and McCauley, 1971), and the unit in the map area was likewise interpreted to consist of radially faulted bedrock (Lucchitta, 1972). Although some faulting may have taken place, the lineated material extending to the northeast is now thought to be linear chains of secondary craters produced by concentrated projectiles traveling in low trajectories (Moore and others, 1974; Wilhelms, 1976). There is less primary ejecta and more locally excavated material than in the Fra Mauro Formation, and the lineated material obscures the underlying landscape much less than does the Fra Mauro. The asymmetrical distribution of the lineated material (mainly northeast of the basin) and the Fra Mauro (north and northwest) may result from an oblique approach of the basin-forming bolide.

Older plains material and the terra material, even though probably associated with the Imbrium event, are discussed below under "terra material".

Humboldtianum basin materials

The Humboldtianum basin near the east limb of the Moon is believed to be of middle Nectarian age, as Nectarian craters are both superposed on it and partly obliterated by it, and because its well-developed rings and ejecta blanket appear morphologically sharper than those of the Nectaris basin. Its interior is partly flooded by mare material. The two basin rings form massifs. The large crater Bel'kovich is superimposed on the inner basin ring. This ring, which resembles the rim of Bel'kovich, may nearly delineate the original impact cavity of the basin. The outer ring is similar to though more degraded than the Cordilleran scarp around the Orientale basin and likewise probably originated by faulting (McCauley, 1968; Howard and others, 1974; Head, 1974). On the east side, the outer ring forms a scarp that is partly buried by ejecta from crater Compton. The outer ring is elliptical and surrounds both the inner basin and Bel'kovich. These relations and the similar degradation of their rims suggest that Humboldtianum and Bel'kovich were emplaced nearly simultaneously. Even though Bel'kovich caused the northern deflection of the Humboldtianum ring structure, it is mapped as a crater because it has central peaks and not peak rings.

Between the Humboldtianum basin rings, hummocky material grades into lineated material, and there are mountains (unit NpNbr) along grooves radial to both the inner ring of Humboldtianum and Bel'kovich. These grooves and massifs may have been produced by secondary impacts from Humboldtianum and Bel'kovich. Lineated material interpreted to be ejecta locally occurs inside the outer basin ring on the south side; the occurrence confirms that the outer ring was formed outside the original impact cavity. Humboldtianum ejecta includes sinuous, hummocky, and radially grooved deposits; they are not mapped separately like the Imbrium ejecta, mostly because of the poor picture quality around part of the basin. The sinuous, grooved facies is predominant south of the basin, whereas a hummocky and hilly facies extends to the northwest, where it partly buries older craters near the blanket margin. West of the basin a grid is formed where Humboldtianum basin radial ejecta is transected by Imbrium basin linear chains (unit INbl).

Birkhoff and Schwarzschild basin materials

The small basins Birkhoff and Schwarzschild on the far side are transitional to craters: they have well-defined continuous terraced rims resembling those of impact craters, but have inner rings of mountains rather than central peaks (unit NpNbr), and thus are similar to basins. Their rims are assigned a basin age because they are thought to consist predominantly of ejected debris. Both basins are considered of Nectarian age on the basis of morphologic sharpness and the Nectarian and younger age of superimposed craters; both basins are older than the Humboldtianum basin. Birkhoff, on the western far side, is heavily cratered, suggesting an old age; however, traces of a radially grooved ejecta blanket on its southeast side and radially arranged secondary chains and clusters suggest that it is young. The crater Stebbins, which is superimposed on the basin rim, is filled with plains material that has a wrinkle ridge along the projected trend of the former basin rim, indicating the presence of a former structural zone of weakness (Hartmann and Wood, 1971). Schwarzschild, on the eastern far side, appears to be partially buried by Humboldtianum ejecta. Mantled hilly highlands (unit Nt) near these basins are probably a degraded or smooth facies of basin ejecta.

Other basin materials

An old basin centered near the west limb on the far side (about lat 51° N long 122° W) (Hartmann and Wood, 1971), here named Coulomb-Sarton basin for two unrelated superimposed craters, is composed of alternating concentric rings of highly cratered terrain and smoother terrain mantled by plains or other terra material. The basin is ancient, and only its outline remains expressed topographically; basin-related deposits are degraded beyond recognition.

OTHER TERRA MATERIALS

Light, smooth, and relatively densely cratered plains materials cover large areas on the near side but are much less abundant on the far side, where they mostly occupy crater interiors (undivided plains unit).

Older plains material (Ip_1) deeply fills craters at the distal end of the Fra Mauro Formation. Crater density and the shadow measurement technique show that the unit may be contemporaneous with the Fra Mauro Formation (Boyce and others, 1974). The older plains unit is slightly more hummocky than the younger plains unit (Ip_2), locally drapes over the pre-existing landscape, and has gradational contacts with the Fra Mauro Formation. These facts suggest that this plains material is a distal and possibly thinner facies of Imbrium ejecta, possibly mixed with local material derived from secondary craters (Morrison and Oberbeck, 1975). A similar transitional relation is seen at the distal end of the Orientale ejecta blanket, where a finely textured facies is almost indistinguishable from plains materials (Hodges and others, 1973; Moore and others, 1974).

The smoother and less densely cratered younger plains unit can be identified confidently only in a few places, mostly north of Mare Frigoris; where mapped elsewhere its identification is tentative. The younger plains unit north of Mare Frigoris is considered of Orientale-basin age (Boyce and others 1974), on the basis of crater densities and the shadow measurement technique (Soderblom and Lebofsky, 1970). If this interpretation is valid, this younger plains material represents a foreign element in an area dominated by Imbrium basin deposits. This young plains unit could be a tongue of thick Orientale basin ejecta; perhaps similar thin unrecognized ejecta covers the entire northern near side without obscuring the underlying older units. Or, perhaps the main plains area is composed of thin Orientale ejecta upon old mare material, a relation that would explain both the smoothness and the high albedo of the area. Later impact into such a mantled mare should eject dark mare material and form dark-halo craters; their absence could be explained by the obscuring effect of the extensive young ray systems of the area. In summary, the thick plains units on the northern near side appear to be primary and secondary ejecta from the Imbrium basin and probably contain a substantial contribution from local highland materials, redistributed by secondary impact (Oberbeck and others, 1975). The plains may possibly be underlain by ejecta from Humboldtianum and overlain by a thin veneer of ejecta from Orientale.

Most of the hummocky Imbrian terra material probably is similar in origin to the older plains material but represents a facies transitional between plains material and the Alpes Formation.

Older, relatively smooth mantling material (INt) occurs mostly inside Nectarian and older craters and basins on the far side of the Moon. It looks like plains material on medium-resolution pictures but is distinctly more hilly than plains material on high-resolution frames. It consists of older hilly material and intervening Imbrian plains on a scale too fine to map separately or of an older plains unit degraded to a more hummocky surface by cratering and mass wasting.

A mantle (IpNt) with diffuse contacts locally smooths and levels highland areas north of and beyond the belt of older plains material. It differs from the Fra Mauro Formation in not displaying sinuous ridges or completely burying craters. It probably represents a transitional facies at the distal end of the Imbrium ejecta blanket, where Imbrium ejecta mixed with local materials thinly covers the pre-existing highlands. North of the Humboldtianum basin, the unit may include much Humboldtianum ejecta.

A hummocky terra unit (Nt) fills craters and mantles highlands. Its roughness suggests that it is older than more planar surfaces, and its smoothing of highland terrain indicates that it buries the older landscape and probably consists of ejecta blankets from numerous older craters and basins. In the Humboldtianum basin some of this material may be remnants of impact melt, but even there it more likely is ejecta from Bel'kovich.

Nectarian and pre-Nectarian terra material covers large areas on the far side of the Moon. It has a rough surface composed of hilly material that appears to mantle the landscape, interspersed with rugged terrain that is mostly composed of remnants of ancient craters. The hilly morphology is thought to be the result of primary roughness of old overlapping ejecta blankets, partially degraded by later impacts and concomitant secondary gouging, structural adjustments, seismic shaking, and mass wasting.

Pre-Nectarian terra material consists almost entirely of old craters, crater segments, or crater clusters. Because of the absence of obvious mantling deposits, the material is envisioned to consist mostly of ancient crater debris.

MARE AND DARK MANTLE MATERIALS

In the map area mare material is restricted mostly to the near side, where it forms Mare Imbrium, Mare Frigoris, Oceanus Procellarum, Mare Humboldtianum, and patches near the Humboldtianum basin. On the far side only one small patch was observed, in crater Campbell. The albedo of Mare Frigoris is relatively high for maria (Pohn and Wildey, 1970) and appears not to be intrinsic to the mare surface but caused by superposed ray material from the young craters farther north. The color of Mare Frigoris is reddish, much like the surrounding highlands, but bluish mare surfaces having lower albedo than Mare Frigoris elsewhere (Pohn and Wildey, 1970) occur in Sinus Roris and the northwest margin of Oceanus Procellarum (Whitaker, 1972).

The dark bluish mare unit at the northwest margin of Oceanus Procellarum is old (Boyce, 1976) and here assigned an Imbrian age. By contrast, dark bluish mare material in Sinus Roris floods secondary craters of the Eratosthenian crater Pythagoras and coincides approximately with Boyce's (1976) two youngest mare units. It is assigned an Eratosthenian age on this map.

All mare materials are assumed to be basalts in accordance with the findings from the Apollo missions. The bluish maria probably are basalts with a higher titanium content than the reddish maria (McCord and Adams, 1972).

Dark mantling material covers Imbrium basin ejecta in the crater J. Herschel, and ejecta and mare materials along the southeastern margin of Mare Frigoris. It also occurs on the floor of the crater Compton. In all places the material is associated with rimless craters and fissures or with grabens. It is best interpreted as a pyroclastic deposit (McGetchin and Head, 1973; Lucchitta, 1973), possibly caused by fire fountains (Heiken and others, 1974). Its age is considered Imbrian on the basis of evidence elsewhere (Howard and others, 1973; Lucchitta and Schmitt, 1974); however, the freshness of associated depressions suggests that it may be younger.

CRATER MATERIALS

A sequence of large Eratosthenian and Copernican impact craters extends across the western highlands of the northern near side. Their age decreases from west to east; Pythagoras is oldest, Anaxagoras is youngest. Pythagoras has faint rays, and some of its secondary craters are flooded by mare material. Anaxagoras is believed to be as young as Aristarchus on the basis of its morphologic sharpness. Anaxagoras and the 35-km crater Thales on the eastern north side are the sources of the extensive ray system that brightens the northern highlands. The crater Hayn on the east limb has sent rays southward across Mare Humboldtianum, and some of these link with others and contribute to some of the very long rays on the eastern near side of the Moon. Secondary craters are well developed around all of these young craters, but most are too small to map. Chains of secondaries from Philolaus extending to the northwest are parallel to each other and to the direction radial to Imbrium and possibly reflect a pre-existing Imbrium-radial fracture system that influenced the direction of ejection. On the far side of the Moon, more Copernican craters may be present than have been identified because the lack of photographs displaying albedo variations prevents the detection of rays.

Two prominent late Imbrian craters are Plato on the Imbrium basin margin and Plaskett on the far side near the north pole. Plato formed early in the epoch, as its secondary craters are flooded by Imbrian mare material. It differs from other craters in having an unusually reddish ejecta blanket (Whitaker, 1972). Plaskett's secondary craters trend across the pole towards the near side and contribute to the dense swarm of secondary craters in that area. Near the west limb many small relatively sharp Imbrian craters and clusters may be secondaries of the Orientale basin. At this distance from the basin the individual craters were probably excavated by projectiles with high trajectories that produce circular craters similar to primary ones.

Iridum and Compton are large and conspicuous early Imbrian craters. Both predate mare emplacement. Secondary craters from Iridum can be recognized on the map by their orientation radial to Iridum and their smaller size than Imbrium secondary crater clusters. Secondaries from Iridum are mapped as far away as the crater Meton, where they overlie older plains material. Compton is distinguished from other craters by an inner ring and a central peak, thus being transitional between craters and basins (Hartmann and Wood, 1971; Howard and others, 1974). The floor of Compton has the grooved and cracked appearance of the floor of the Orientale basin and may consist of shock-melted material (Saunders, 1968; McCauley, 1968; Howard and others, 1974). The central peak may have formed by rebound (Wilshire and Howard, 1968; Howard and others, 1972), and the ring by faulting and slumping of the crater walls, which were displaced inward and upward along curved fault planes (Howard and others, 1974).

Crater clusters of early Imbrian age and clusters of craters larger than the secondary craters from Iridum are especially numerous northeast of the Imbrium basin near the margin of the Imbrium ejecta blanket; some of these form linear chains approximately radial to the Imbrium basin. These clusters and chains are interpreted to be secondary craters from Imbrium. Many of the linear chains are straight and narrow and could be grabens; however, traces of raised rims and scalloped walls suggest an origin as chains of overlapping secondary craters. The linear chains typically are more degraded than the clusters, possibly owing to the successive impact erosion of earlier arrivals by later ones or to the low trajectory of the impacting body. Many of the early Imbrian crater clusters on the far side of the Moon may be secondary to the Imbrium basin, but the association is not certain.

Nectarian craters are equivalent to those previously mapped by Wilhelms and McCauley (1971) as late pre-Imbrian and include relatively fresh-looking middle pre-Imbrian craters. Nectarian craters are identified by morphologic comparison with craters superposed on the Nectaris ejecta blanket. On the northern front side, a relative dearth of Nectarian craters can be attributed to the proximity to the Imbrium basin: the impact buried and destroyed many older craters. These craters now morphologically appear and are mapped as pre-Nectarian even though their real age may be Nectarian. On the far side large Nectarian craters show traces of radial ejecta (d'Alembert) or smooth highland mantles nearby which may be their degraded ejecta blankets. Large Nectarian craters (d'Alembert, Rowland, Sommerfield) appear more degraded than smaller ones of the same age. This degradation may have occurred early in the history of the crater, and, as for basins, may result from destructive rebound and isostatic adjustment; alternatively, it may be a later effect due to the erosion caused by the many superimposed craters.

On the far side of the Moon, where photographs are poor, early Imbrian and late Nectarian craters are difficult to distinguish. Both may show moderately dissected rims, terrace remnants on the walls, and central peaks; age assignment is therefore tentative, and in fact, the unusually large number of early Imbrian craters mapped suggests that many late Nectarian ones may be included.

Fields of subdued but nearly uniformly degraded clusters of Nectarian craters of similar size surround the Humboldtianum basin near the margin of the ejecta blanket and are inferred to be secondary craters of Humboldtianum. Remnants of probable Nectarian clusters of secondaries also exist in the area of Imbrium lineated material north of eastern Mare Frigoris, where the crater rims are pervasively cut by "Imbrium sculpture." Fields of crater clusters southeast of Birkhoff on the west limb may be secondary craters of Birkhoff, but the craters appear somewhat larger than expected from this small basin; it cannot be ruled out entirely that some of these craters and some of the clusters of subdued craters northeast of the Imbrium ejecta blanket and northwest of Humboldtianum are early arrivals from Imbrium rather than secondary craters of Birkhoff and Humboldtianum. Other Nectarian crater clusters occur throughout the north side and where not near and radial to known basins are inferred to be secondary crater clusters from unknown sources.

Pre-Nectarian craters include all old degraded craters previously mapped as early pre-Imbrian, and most of those mapped as middle pre-Imbrian (Wilhelms and McCauley, 1971). Many of them consist of rim remnants. They locally occur in overlapping clusters, resulting in a rough crater-rim topography. These craters and their ejecta occupy the oldest known surfaces on the Moon.

Lineated crater material occurs mostly northeast, north, and west of the Imbrium basin. It is the crater equivalent of the terra unit "basin lineated material" and is inferred to have originated similarly through gouging of older materials by dense secondary bombardment from Imbrium. The lineated basin material north of the basin differs from that in other areas, forming massive linear mountain chains radial to the Imbrium basin. The mountains may be remnants of ancient crater rims that were faulted, or they may be the rim remnants of large and irregular secondary craters from Imbrium. Also attributed to secondary impact may be a northeast-trending valley system east of crater Epigenes that resembles the Vallis Bouvard structure of the Orientale Basin.

GEOLOGIC HISTORY

The first surface record in lunar history is that of the formation of numerous craters and basins by impacts, which must have followed early differentiation and formation of a feldspathic crust (Toksöz, 1974). The pre-Nectarian cratering and basin formation may have preceded or been part of the terminal cratering event around 3.9 b.y. ago detected by Tera, Papanastassiou, and Wasserburg (1974a, b), whereas the Nectarian Period may have coincided with most of this cratering.

On the north side of the Moon, basins and craters were formed during pre-Nectarian time, but most of them were destroyed by subsequent impacts. Only one ancient basin remains preserved as topographically high ring structures. Similarly, most ejecta from pre-Nectarian craters was destroyed, but ejecta from those emplaced during late pre-Nectarian time may have contributed to the present-day terra mantles.

The Nectaris basin impact farther south initiated the Nectarian Period, and relatively soon afterward the Birkhoff and Schwarzschild basins were excavated. Later, almost simultaneous impacts created the Humboldtianum basin and the crater Bel'kovich and produced ring structures around both impact sites. Ejecta formed a blanket of lineated and hummocky debris and clusters of secondary craters. Deposits from other basins and craters mantled highland surfaces and filled craters during the Nectarian Period.

The Imbrium impact initiated the Imbrian Period and profoundly altered the topography of the northern front side. It broke the surface near the impact site into fault-block massifs and threw the terrain farther from the impact into nearly concentric highs and lows, the latter now being occupied by Sinus Roris and part of Mare Frigoris. Simultaneously, vast amounts of ejecta were thrown around the basin and partly buried the older landscape, forming the Alpes and Fra Mauro Formations and much plains material. Secondary low-angle projectiles gouged older crater rims and created the lineated terrain to the northeast. Secondary projectiles were also thrown to great distances on the far side of the Moon, forming crater chains and clusters. Older craters near the Imbrium basin were severely modified by structural disturbance, secondary impact, and burial.

The Orientale basin impact created secondary craters mostly near the west limb and possibly spread a thin sheet of ejecta across most of the north side. Locally, tongues of ejecta may have been thick enough to bury low areas and to form the younger plains unit. Alternatively, mare basalt may have been erupted in northeastern Mare Frigoris before the Orientale impact and been buried by thin, light-colored Orientale ejecta to form the younger plains units. The main eruptions of mare basalt, however, postdate the Orientale impact, and the basalts flooded depressions, including the Imbrium basin, Mare Frigoris, Oceanus Procellarum, and part of the Humboldtianum basin. Lava fountaining may have spread dark mantles over highlands and mare during this time. A younger basalt, possibly with a higher titanium content than the earlier north-side lavas, later buried flows in part of Sinus Roris.

Cratering had decreased markedly by the beginning of the Imbrian Period around 3.9 b.y. ago (Tera and others, 1974a,b). Subsequently, only a few large craters were emplaced on the north side of the Moon. Among these are the large craters Compton, Iridum, and Plato, which impacted before mare flooding, and a series of large craters on the northern nearside highlands, which impacted after most flooding, during the Eratosthenian and Copernican Periods. Of these Pythagoras is the oldest, Anaxagoras the youngest. The most recent event is the emplacement of ray material over the northern highlands, originating from craters Anaxagoras and Thales.

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EXPLANATION

🟫 Ancient pre-Nectarian cratered terrain; dense clustering of craters; includes units pNt and pNc.

▨ Ancient Nectarian and pre-Nectarian cratered terrain; partly subdued by mantling deposits; includes units NpNt, Nc, and parts of pNc, Nt, INt, and Ip.

🟨 Nectarian basin terrain; includes units Nb, NpNbm, NpNbr, Nbl, Ncc, and parts of Nt, INt, INbl, and Ip.

🟦 Imbrium basin terrain; includes units IpNbm, If, It, Ia, IpNl, IpNcl, IpNt, and part of INbl.

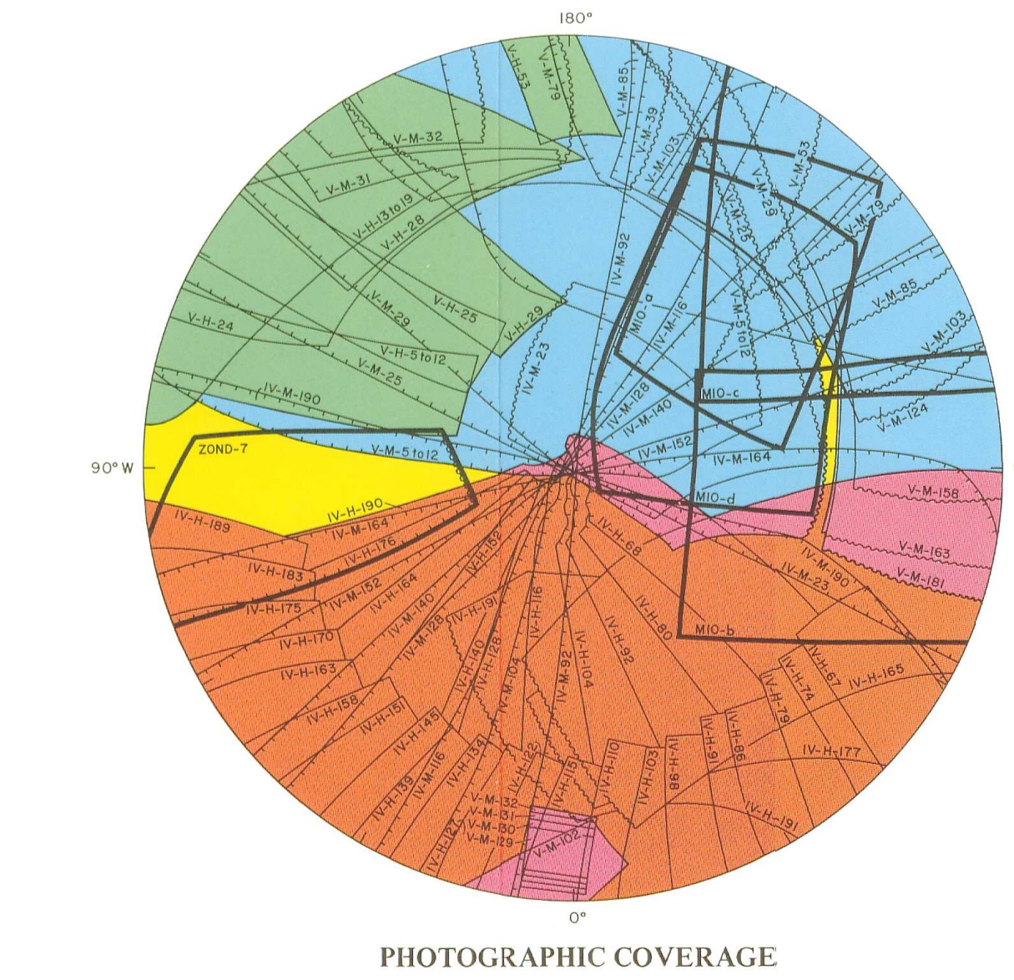
⬜ Imbrium basin plains; plains inferred to be composed partly of Imbrium ejecta (Ip_1).

🟪 Undivided Imbrian plains; may be composed of material younger than Imbrium ejecta; includes units Ip_2 and Ip where patches are large.

🟥 Imbrian terrain underlain by mare basalts, includes small patches of unit Em.

PROVINCE MAP

Figure 1.—Generalized geologic map showing major geologic units grouped stratigraphically and genetically. Craters of Imbrian and younger age are omitted.



PHOTOGRAPHIC COVERAGE

EXPLANATION

Footprints of useful frames. Overlapping areas not delineated for Lunar Orbiter IV pictures; on all others, entire outline of useful part of picture shown. H refers to high resolution, M to moderate resolution.

Lunar Orbiter IV-H

Lunar Orbiter IV-M, where it is the only Lunar Orbiter coverage. For other areas, only terminator trace of each picture delineated, but useful coverage extends to more than 500 km eastward. Center of pictures near lat 75° N

Lunar Orbiter V-H and V-M

Lunar Orbiter V-M

Overlap of Lunar Orbiter IV-H and V-M

Zond 7 and Mariner 10

M10A+FDS 2269, M10B+FDS 2277, M10C+FDS 2278, M10D+FDS 2288

Terminator, hachures on illuminated part of picture

Limit of useful coverage of obliquely viewed part near limb

Not shown are:

1. Lunar Orbiter IV-M frames except for those of the northernmost sequence and IV-23M.
2. IV-165M, 177M, and 191M, and frames V-13M to 19M, 24M, 28M, all of which have very small scale.
3. Mariner 10 photographs that duplicate areas well covered by Lunar Orbiter.

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