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INTERAGENCY REPORT: ASTROGEOLOGY 6

CHARACTER AND GEOLOGIC HABITAT OF POTENTIAL DEPOSITS OF WATER, CARBON, AND RARE GASES ON THE MOON

By

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May 1968

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

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Introduction

A partly self-sustaining lunar base would facilitate extended manned exploration of space. It could serve as a center for geological and geophysical investigations of the moon, for moon-based astronomical and geophysical studies of space, and as a refueling station and point of departure for manned flights to other planets. Of importance to the establishment and maintenance of such a base would be the availability of materials in which the light elements--hydrogen, oxygen, carbon, and perhaps even nitrogen--are relatively abundant and fairly easily extractable. Compounds of these could be used to support life (perhaps even locally terrestrialize a small part of the lunar environment) and to provide fuel for the lunar base, lunar exploration vehicles, and interplanetary rockets.

In the context of present knowledge of the nature of meteorites and lunar crater materials, this paper briefly reviews circumstantial evidence that the rim deposits of certain lunar craters may be breccias that contain water, carbon, and inert gases. If the model proposed here is valid, the water would be largely recoverable by heating the brecciated rock to a few hundred degrees Centigrade. Reserves may be very large. Although most deposits of water-bearing rocks would probably be low grade (about 1-2 weight percent H_2O), high-grade deposits (perhaps 5 weight percent or more H_2O) may occur locally. Finally, a rather special type of permafrost also may be present in some deposits.

Compositional Characteristics and Inferred Sources of Extraterrestrial Materials

Assumptions fundamental to the model proposed in this paper are: (1) meteorites fairly well represent the composition of extraterrestrial materials and have been derived from more than one source; (2) the sources may include the comets, the asteroids, and the moon; a suggested correlation of meteorites and sources, shown in a proposed genetic classification of the meteorites (table 1), is adopted as a working model; and, (3) polymict meteorite breccias, which display mixtures of materials of different meteorite classes, may have formed during collisions or impacts, and thus may be physical records of comet-asteroid collisions, interasteroidal collisions, and impact of the moon by cometary and asteroidal materials. Some of the polymict breccias are water bearing and contain more than 1 weight percent H_2O. It is these breccias that we shall be concerned with in this paper.

The compositions of several meteorite classes are summarized in table 2. In the carbonaceous meteorites (chondrites and achondrites), water is apparently indigenous to fine-grained hydrated magnesium silicates that form the matrix of the rock. In the carbonaceous chondrites, the hydrated silicates are commonly referred to as layer lattice silicates (for example, see Fredriksson and Keil, 1964) and include material that has been identified as the chrysotile variety of serpentine (Mason, 1962). In the Orgueil carbonaceous achondrite, the material has been referred to as bituminous clay and described as an iron-rich, aluminum-poor septechlorite (Boström and Fredriksson, 1966), which Mason (1967a) suggests is possibly best described as a ferric chamosite. Most of the water in the carbonaceous meteorites is released above 110°C (see Wiik, 1956). Water in the liquid state appears to have once been present in some carbonaceous achondrite material. This is inferred from the presence of a vein of magnesium sulfate in the Orgueil meteorite (DuFresne and Anders, 1963, pl. 1).

As in the volatile-rich carbonaceous meteorites, water in the pigeonite chondrites also appears to be intrinsic to the rock, and is apparently associated with carbonaceous material in the chondrite matrix that accumulated at the time of accretion. These meteorites, which contain up to about 1.75 percent H_2O, are poorer

Table 1.--Proposed genetic classification of the meteorites

Distinguishing chemical characteristics	Volatile-rich meteorites ($\lesssim$8 percent H_2O)	Volatile - poor meteorites ($\lesssim$2 percent H_2O)							
	Calcium - poor (< 5 percent CaO)					Calcium - rich (>5 percent CaO)			
Textural-structural groups	Mineralogical or compositional class								
Chondrite	Carbonaceous (Type II)[1/]	Pigeonite[2, 3/]	Hypersthene[2/]	Bronzite[2/]	Enstatite	-----	-----		
Achondrite[4/]	[a/] Carbonaceous (Type I)[1/]	[b/] Olivine (Chassigny)[5/] Pigeonite	Hypersthene	Bronzite[6/]	Enstatite	[c/] Diopside-olivine (Nakhla, Lafayette)	Pyroxene-plagioclase: Hypersthene-anorthite (Howardite)[7/]	Pyroxene-plagioclase: Pigeonite-anorthite (Eucrite)	Augite (Angra)
Stony-iron---	-----	?[8/]	Siderophyre[9/]	Pallasite[10/] (Ga-Ge III) Lodranite[11/]	?[12/]	-----	-----		-----
Iron - - -	-----	?[13/]	Ga-Ge II[14/]	Ga-Ge III[14/] Ga-Ge IV (?)	Ga-Ge I[14/]	-----	-----		-----
Inferred source - - -	Comets	Asteroids				Mars ?	Moon		?

1/. Classification of Wiik (1956).
2/. Olivine is an essential mineral, but for the purpose of classification, only the name of the characteristic mineral is used.
3/. Includes Type III carbonaceous chondrites of Wiik (1956), and C-3 chondrites of Van Schmus and Wood (1967).
4/. Achondritic materials may be assigned to one of three groups:
   a. Relatively low temperature silicates that may be serpentinized or chloritized carbonaceous chondrite material;
   b. High temperature silicates that may have been recrystallized from mineralogically similar parent chondrite materials;
   c. High temperature silicates that may have been differentiated from unsampled and perhaps now non-existent parent chondrite materials.
5/. Olivine containing "nascent chondrules" (Jérémine and others, 1962).
6/. Not recognized as a discrete class, but may be represented by bronzite achondrite fragments in Breitscheid polymict(?) bronzite chondrite, described by Wlotzka (1963).
7/. One howardite, Frankfort, contains less than 5 percent CaO (Mason, 1967b).
8/. Could possibly be represented by one or more pallasites.
9/. Correlated with hypersthene chondrite and achondrite material on the basis of the iron content of the pyroxene.
10/. Eight pallasites analyzed for Ga and Ge fall in Ga-Ge group III (Lovering and others, 1957). Seven belong to the low fayalite group and one belongs to the high fayalite group of pallasites (see Mason 1963 , p. 10).
11/. Correlated with bronzite chondrite and achondrite material on basis of the iron contents of the olivine and pyroxene.
12/. None recognized. Structurally disrupted materials that may have been derived from an environment containing both iron-free pyroxene and metal may be preserved in the $MgSiO_3$ mesosiderites.
13/. Could possibly be represented by irons in Ga-Ge groups I and II, and by anomalous irons that lie between or outside these groups.
14/. The Ga and Ge contents of group I, II and III irons (Lovering and others, 1957) correlate with published bulk values of Ga and Ge in the enstatite, hypersthene and bronzite chondrites, respectively, if it is assumed that the metal phase of the chondrites has preferentially incorporated Ga and Ge from the chondrite silicate matrix during thermal metamorphism of the chondrite prior to and during fractionation of the metal. It is proposed that the lower boundary of group III be extended to slightly less than 1 ppm Ge to include a low Ge pallasite (Goldstein and Short, 1967, table 1), and a group of 10 "anomalous" irons reported by Wasson (1967). This would leave, at most, a narrow compositional gap between Ga-Ge groups III and IV, which may be, in the broad sense, a single group.

Foldout Frame 1

Foldout Frame 2

Table 2.--Chemical composition, in weight percent, of selected meteoritic materials

FAMILY	VOLATILE-RICH METEORITES		VOLATILE-POOR METEORITES					
	CALCIUM-POOR					CALCIUM-RICH		
Class--------	Carbonaceous meteorite		Olivine-pigeonite		Olivine hypersthene	Pyroxene-plagioclase		
Texture------	Chondrite	Achondrite	Chondrite	Achondrite	Chondrite	Achondrite		
Type, or common name--	Type II[1]	Type I[1]	Type III[1]	Ureilite		Hyper-sthene anorthite (howardite)		Pigeonite-anorthite (eucrite)
Number of meteorites averaged---	8[2]	3[2]	5[2]	2[3]	68[4]	8[5]	1[6] (Bununu)	13[5]
Oxides								
SiO_2---------	27.31	23.08	33.75	38.90	39.87	49.27	48.67	47.60
MgO----------	19.00	15.56	23.86	35.73	25.16	11.76	14.20	8.46
FeO----------	20.06	10.32	24.32	12.73	14.66	15.58	16.04	15.58
Fe_2O_3--------	---	---	---	---	---	1.56	---	.98
Al_2O_3--------	2.31	1.77	2.65	.38	2.51	9.95	8.87	13.01
CaO----------	2.03	1.51	2.32	.79	1.89	7.71	6.77	10.18
Na_2O---------	.54	.76	.55	.43	.95	1.06	.34	.43
K_2O----------	.05	.07	.05	---	.15	.36	.04	.06
Cr_2O_3--------	.39	.28	.51	.43	.45	.53	.56	.36
MnO----------	.17	.19	.20	.35	.29	.66	.53	.47
TiO_2---------	.10	.08	.12	.09	.15	.10	.11	.43
P_2O_5---------	.27	.27	.32	.07	.27	.08	---	.09
H_2O----------	13.23	20.54	1.00	1.13	---	.33	1.53(H_2O+) .12(H_2O-)	.61
NiO----------	1.56	1.17	.33	---	---	---	---	---
Total------	87.02	75.60	89.98	91.03	86.35	98.74	97.78	98.27
Metals								
Fe-----------	0.00	0.11	2.34	8.13	6.28	0.35	1.01	1.18
Ni-----------	.16	.02	1.08	.15	1.10	.10	.06	---
Co-----------	.00	.00	.06	---	.059	---	---	---
P------------	---	---	---	---	---	---	---	---
Cu-----------	---	---	---	---	---	---	---	---
Total------	0.16	0.13	3.48	8.28	7.44	0.45	1.07	1.18
FeS----------	8.58[7]	16.88[7]	6.08	---	6.07	0.60	0.96	0.56
C------------	2.44	3.62	0.46	0.69	---	---	---	---
Other--------	1.80[8]	3.77[8]	---	---	---	---	---	---

[1] Classification of Wiik (1956).
[2] Wiik (1956).
[3] From compilation of Wood (1963, table 10).
[4] Mason (1965).
[5] Urey and Craig (1953).
[6] Mason (1967b).

[7] Wiik (1956) reports all sulfur as FeS. Carbonaceous meteorites, however, are not characterized by troilite. Rather the sulfur is present as soluble sulfates and elemental S (DuFresne and Anders, 1962), and as pentlandite (Fredriksson and Keil, 1964). Some of the iron reported as FeS, thus, properly should be reported as FeO.
[8] Loss on ignition. Wiik (1956) considers this loss approximately equal to the content of complex organic matter.

in hydrated magnesium silicates and are richer in anhydrous magnesium silicates than the carbonaceous chondrites. The carbonaceous meteorites and the pigeonite chondrites, in addition to containing water, also are characteristically rich in rare gases (for example, see Signer and Suess, 1963). In contrast, most stony meteorites are essentially anhydrous, are not characterized by abundant rare gases, and lack carbonaceous matter. Examples include the hypersthene chondrites and most of the pyroxene-plagioclase achondrites (table 2).

Some meteorites that consist principally of anhydrous silicates are water bearing. These meteorites are brecciated and commonly display a light-dark structure. The dark parts contain carbon and rare gases, and it is assumed that the water released during analysis is associated with the carbonaceous matter. An example of such water-bearing breccias are the pigeonite achondrites or ureilites (table 2), in which carbonaceous matter (and diamond) occurs in fractured olivine and clinopyroxene (see Carter and Kenndey, 1964, fig. 7). These meteorites are rich in fractionated rare gases (see Anders, 1964, table 8), and the source of the water-bearing carbonaceous material may have been unmetamorphosed pigeonite chondrite materials.

A few pyroxene-plagioclase (basaltic) achondrites contain carbonaceous matter; in these, unfractionated rare gases characteristically occur in the dark parts of highly brecciated materials that show a light-dark structure. Light-dark structure is a compositional feature that is peculiar only to brecciated meteorites. The light parts consist of typical pyroxene-plagioclase meteorite material; the fairly light gray aspect is attributable to a milkiness that was developed in the feldspar as the result of brecciation. The dark parts are diffusely grayer. They display irregular, extremely sharp contacts with the light gray material. The light-dark contacts are not characterized by obvious changes in texture. Rather, the darkened material is breccia that appears to have been pervasively darkened by the addition of some fairly easily diffusible foreign material. Light-dark structure is visible in photographs of the Kapoeta howardite (Signer and Suess, 1963) and the Jodzie howardite (Duke and Silver, 1967, fig. 12).

The dark parts of the Kapoeta and Jodzie howardites are rare-gas bearing, whereas the light parts are not (Signer and Suess, 1963; Mazor and Anders, 1967). The rare gases in Kapoeta are unfractionated (are nearly in solar proportions), whereas rare gases in unbrecciated meteorites such as the carbonaceous and pigeonite chondrites are fractionated (see Anders, 1964, table 8, fig. 25, and discussion). P. Ramdohr (cited in Müller and Zähringer, 1966) has reported the presence of chondrules and carbonaceous layer lattice material in Kapoeta. Müller and Zähringer (1966) have suggested that the rare gases in Kapoeta were emplaced by carbonaceous meteorite material. Mazor and Anders (1967) proposed that Jodzie was invaded by a "carrier" of carbonaceous meteorite composition as the result of impact. They suggested that the "carrier" contained a generous quota of solar gases, acquired during exposure to the solar wind. More probably, the source of the gases and lattice silicates was icy carbonaceous meteorite (cometary) material in which solar proportions of the rare gases had been preserved from the time of accretion.

Water has not been reported for Kapoeta and Jodzie, but it may be present. Water has been reported for the brecciated howardite, Bununu (table 2), but light-dark structure was not mentioned and the analysis does not record the presence of carbon (Mason, 1967b). By analogy with other meteorites, Bununu may contain carbon and rare gases. A fourth howardite that may have been invaded by carbonaceous meteorite materials is Frankfort. It is reported to contain 0.24 weight percent carbon (Mason and Wiik, 1966, table 3). Lastly, one brecciated eucrite, Haraiya, contains 0.25 weight percent carbon (Carleton B. Moore, 1968, personal commun.). The rare gas and water contents of Frankfort and Haraiya are unknown. Haraiya does not display obvious light-dark structure, but it is grayer than other brecciated eucrites that are carbon-free. The presence of associated carbon, rare gases, and water in brecciated rocks that are normally anhydrous is interpreted to be the result of mechanical mixing during brecciation, and to be evidence of invasion by hydrated carbonaceous meteorite materials.

The foregoing data and relations indicate that: (1) water exists in extraterrestrial materials apparently in two forms--as original water (in carbonaceous meteorites and in the carbonaceous matrix of relatively little metamorphosed chondrites), and in association with carbonaceous material that was introduced at the time of brecciation of anhydrous silicates; (2) certain extraterrestrial silicates (the layer lattice silicates) retain water during brecciation and mild heating but release it when heated to a few hundred degrees Centigrade; and, (3) water-bearing breccias contain associated carbon and rare gases.

Some Geologic Characteristics of the Moon

General Composition

Dark plains-forming material of Mare Tranquillitatis and Sinus Medii, and higher albedo rim material of the crater Tycho in the southern highlands, are generally similar in composition, as shown by alpha-scattering analyses performed during Surveyor Missions V, VI, and VII (Turkevich and others, 1967; Surveyor VII press conf. at NASA Hdqrs., Turkevich, 1968). Their composition is similar to that of basalt and also to that of the pyroxene-plagioclase achondrites (Gault and others, 1967), which Duke (1964) suggested are representative of lunar materials. On the basis of relative iron contents and degree of brecciation, Duke and Silver (1967) suggest that the howardites may represent uplands materials, and the eucrites--mare material.

There is some indirect evidence that the pyroxene-plagioclase achondrites are lunar materials. The moon's average density, 3.34 g/cm^3, is less than that of the volatile-poor chondritic meteorites (see Wood, 1963, table 3). This appears to preclude a general chondritic composition for the moon, or the existence of a significant metallic core. The pyroxene-plagioclase achondrites are the one relatively abundant class of volatile-poor meteorites whose densities are appreciably lower than the average density of the moon.

Support for the lunar origin of the pyroxene-plagioclase achondrites also exists in the natural remanent magnetic moments. The pyroxene-plagioclase achondrites display very low remanent moments compared with the volatile-poor chondrites and the irons (DuBois and Elston, 1967); preliminary thermal demagnetization studies have shown that these achondrites acquire a stronger remanence on cooling in the earth's field and thus could have acquired a stronger moment when cooling in the magnetic field of their parent body (DuBois and Elston, unpub. data). This suggests that the parent body of the pyroxene-plagioclase achondrites possessed a relatively weak magnetic field, perhaps because it lacked a fluid-conducting core.

Lastly, the reflectance of pyroxene-plagioclase achondrites is markedly increased by brecciation because of a milky whiteness that develops in the contained plagioclase feldspar (Elston and Holt, 1967; and unpub. data). Only these meteorites contain appreciable plagioclase; thus only they exhibit increased reflectance analogous to that of freshly exposed presumably brecciated materials at the lunar surface. For example, lunar mare material is intrinsically dark, but where it is exposed in crater walls and in fresh rim and ray materials of probable impact craters, it generally displays a much higher reflectance. The ray, rim, and wall materials are inferred to be highly brecciated, and the change in reflectance may be the result of the development of milkiness in feldspar. Disaggregation of the brecciated pyroxene-plagioclase rock results in a lowered reflectance (Elston and Holt, unpub. data), which can partly explain the apparent loss of reflectance that occurs in older rim and ray materials. Stony meteorites that are made up dominantly of pyroxene and olivine do not show substantial increases in reflectance unless they are very finely comminuted.

In summary, direct and indirect evidence suggests that the composition of lunar materials is closer to that of the pyroxene-plagioclase achondrites than to that of the other classes of meteorites.

Lunar Geologic Processes

Detailed geologic mapping of the Colombo quadrangle (fig. 1), first from earth-based data and later from Lunar Orbiter photographs (Elston, 1965; and unpub. map), has led to a three-fold division of surface materials: (1) materials modified or emplaced as the result of exogenetic processes (materials associated with craters of probable impact origin); (2) materials formed and emplaced by endogenetic processes (plains materials of probable volcanic origin, and associated maar craters and cratered cones); and, 3) products of mass-wasting, including material transported by impact-induced seismicity.

The processes resulting in the first two classes of material are the dominant ones. Although they are defined as exogenetic and endogenetic, cause and effect relationships may exist between them. On a moon-wide basis, there appears to be a spatial relationship between the distribution of plains-forming mare materials and the location of major basins. However, materials at the surface of the maria are considerably younger than the basins and thus cannot be directly related to basin formation; they appear, instead, to result from heating within the moon at some later time. Nonetheless, although dark mare material and older plains-forming materials of intermediate albedo are classed as endogenetic in origin, their origin may in some way be related to the process of formation and evolution of the lunar basins.

On a local scale, plains-forming materials occur in the floors and rim materials of a number of craters. Where observed in detail in very young craters of probable impact origin, the plains-forming materials appear to have formed either immediately following or at some relatively short time after crater formation. Such deposits, particularly in the crater floors, may be the result of volcanic activity, perhaps induced and sustained by impact. Irregularly scattered relatively small deposits of plains materials that occupy local depressions in crater rim materials appear, from spatial considerations, to be related to the rim materials rather than to regional lunar fracture systems. If this is the case, these deposits may be the result of devolatilization of rim materials and possibly may be a peculiar form of "cold volcanism" related to the cratering event.

Exogenetic processes.--Cratering phenomenology has been described in detail for the earth and moon by Shoemaker (1962, 1963). The type example for a young, large lunar impact crater is Copernicus and it serves as the type crater for the Copernican System (Shoemaker and Hackman, 1962). Such craters characteristically have steep terraced walls, floors that are at least partly occupied by plains-forming materials, and crater rim deposits that are more hummocky in their inner than in their outer parts. The crater rim materials grade outward into radial rim facies, which in turn can be traced into ray and satellitic (secondary) crater facies. The detailed distribution of the crater materials of Copernicus is shown in a recently published geologic map (Schmitt and others, 1967).

The ejecta of young craters of probable impact origin commonly exhibits a relatively high albedo and is inferred to be highly brecciated. At low resolution, the high-albedo rim and ray materials of small craters are seen as bright halos. With the passage of time the reflectance of the brecciated materials in deposits of low relief appears to decrease until the materials no longer can be resolved from background materials. In contrast, crater wall materials exposed in steep slopes retain much of their relatively high reflectance, presumably because fresh bedrock continues to be exposed as disaggregated materials are transported to

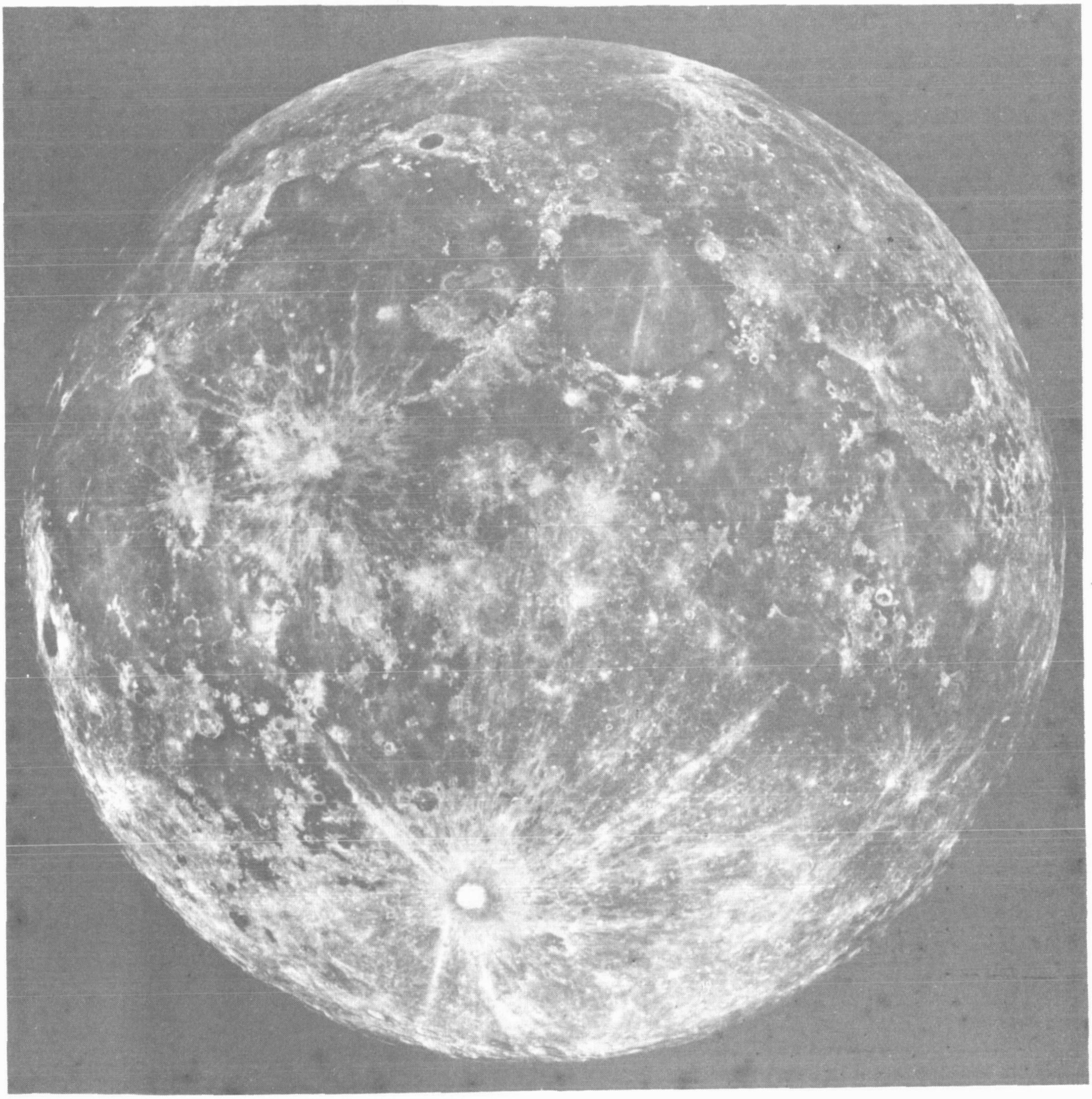


Figure 1a.--Full-moon photograph taken at the 100-inch reflector, Mt. Wilson Observatory.

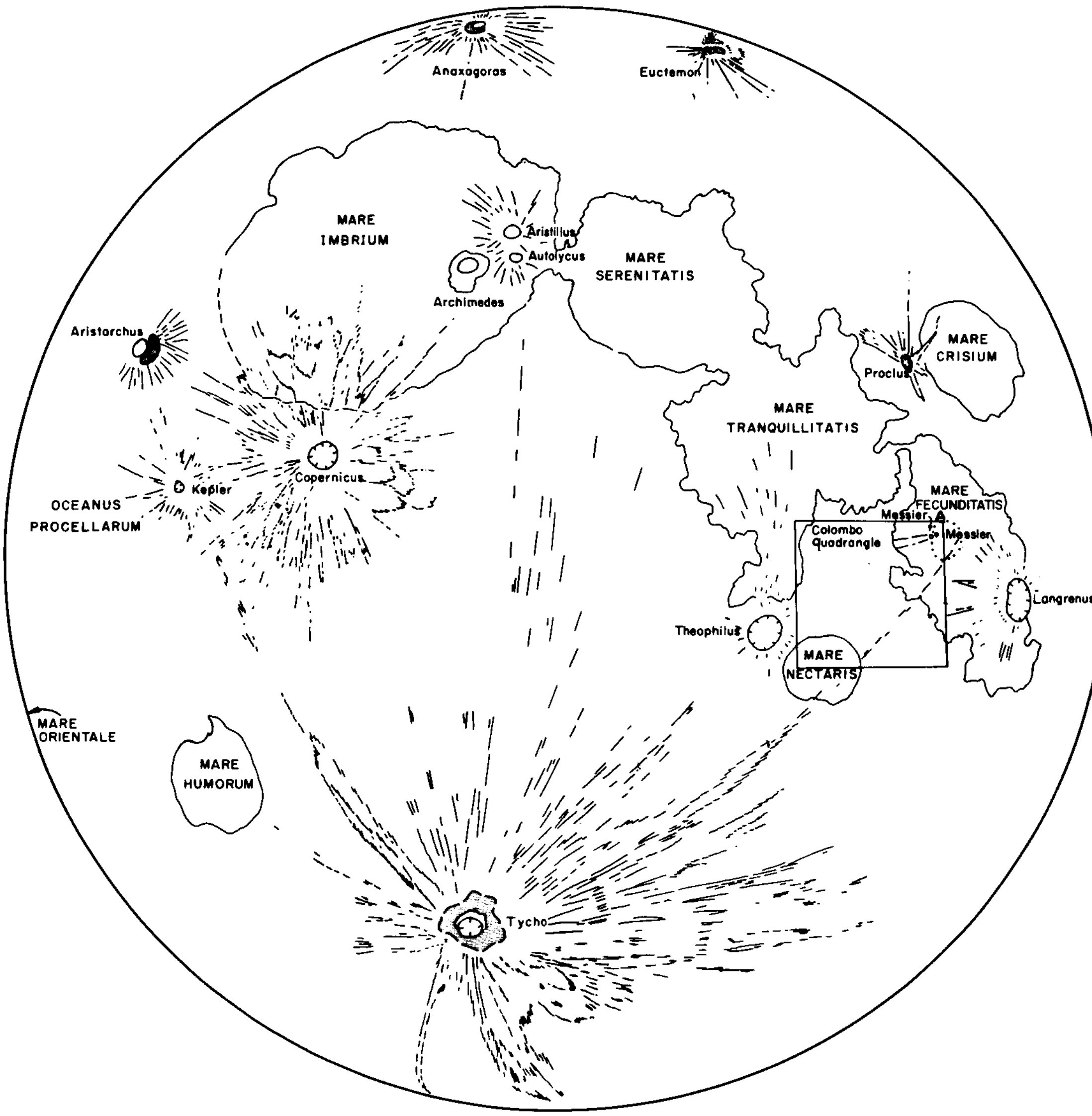
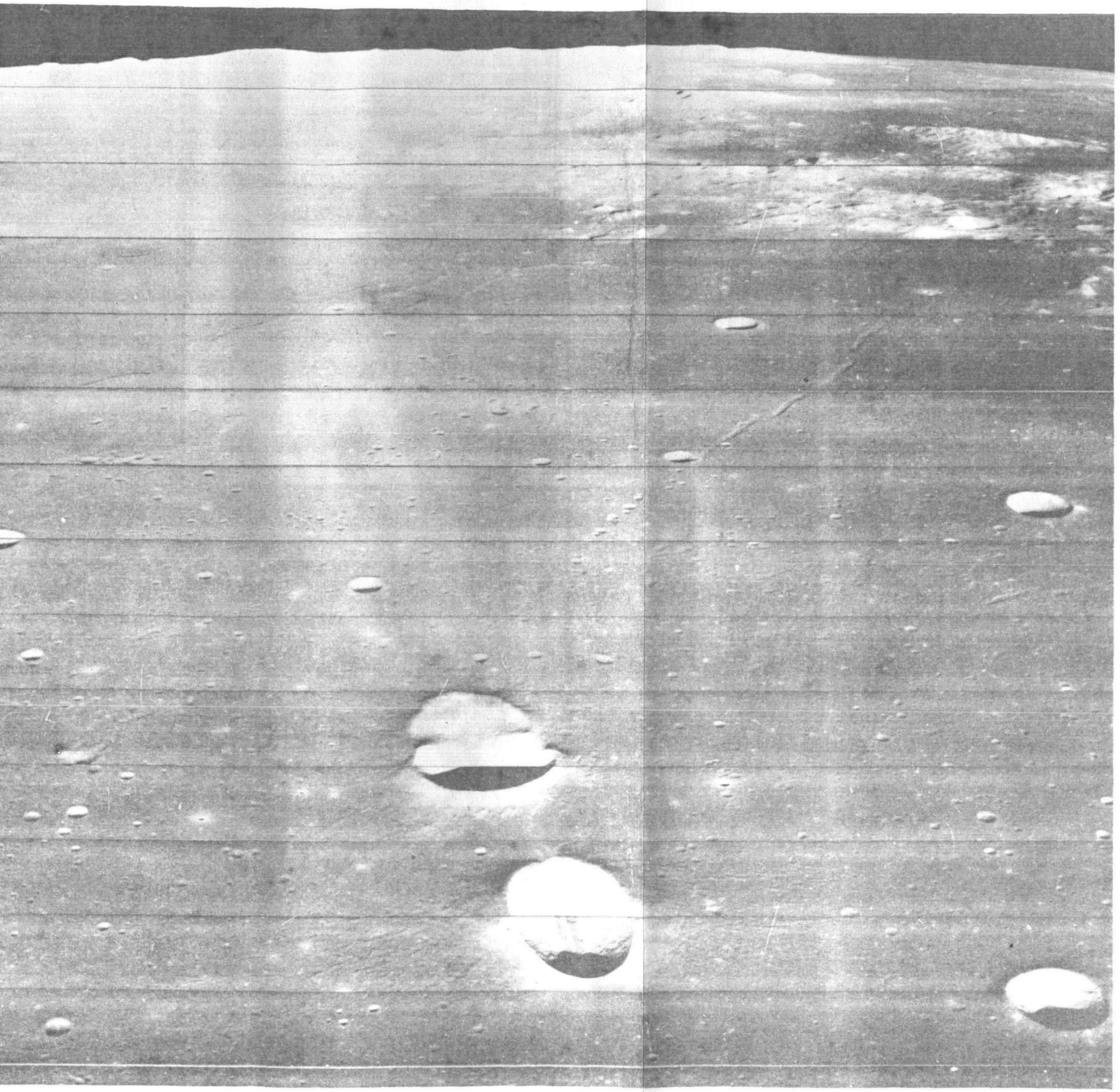


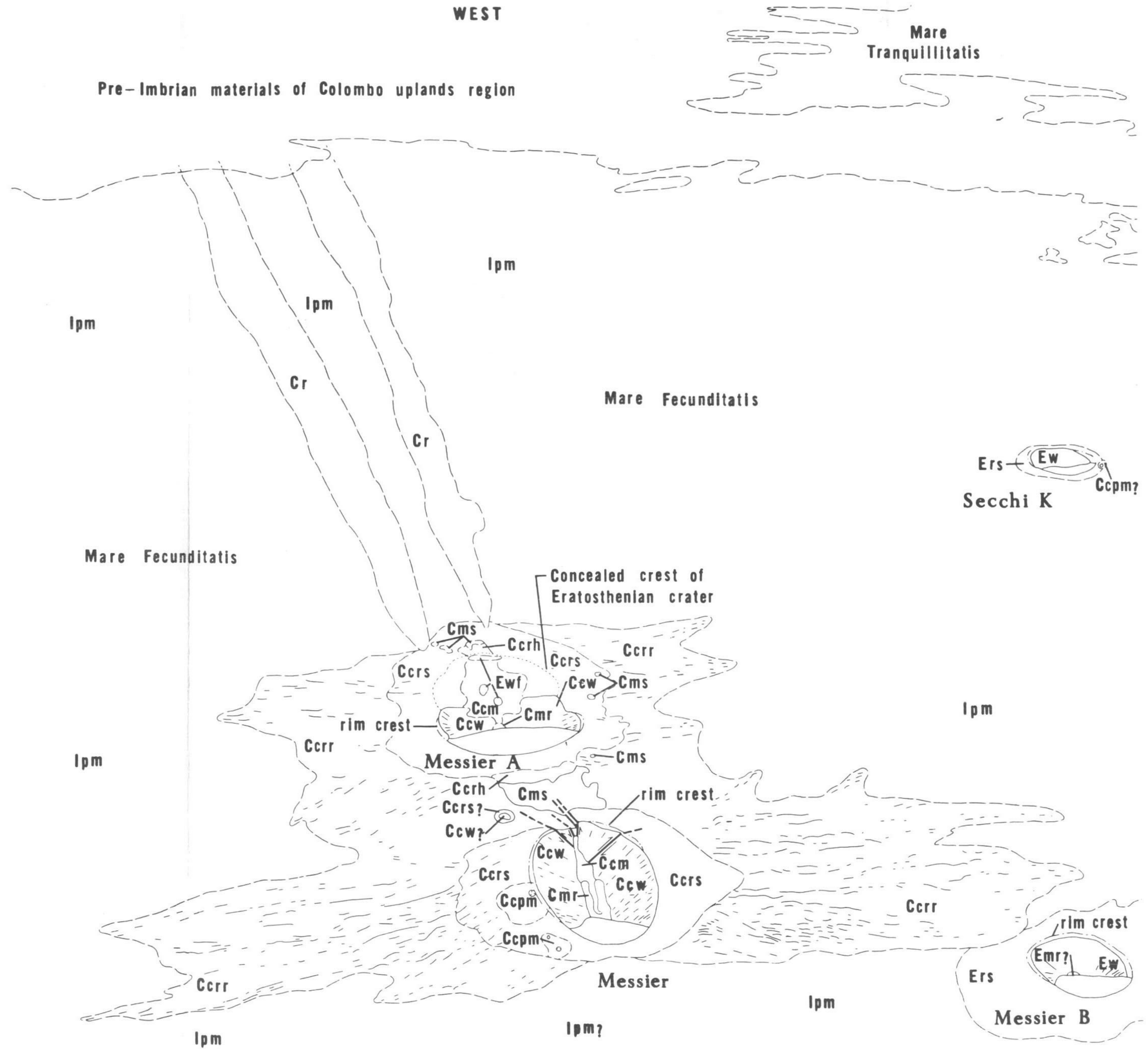
Figure 1b.--Index map of the moon. Prominent rays are sketched approximately. Diffuse dark halo around Tycho and possibly similar halos around Anaxagoras, Aristarchus, Euctemon and Proclus are stippled. Outline of concealed basin "deep" of Mare Fecunditatis is shown in dotted line.

the crater floors by mass wasting. The rim and ray materials of the bright halo craters commonly are blocky, and the inner parts of the rim deposits are hummocky. However, some young craters of probable impact origin do not conform to the foregoing generalizations. Although the wall materials of these craters are bright, the rim materials are wholly or partly dark. Where dark, the rim materials lack prominent blocks and appear to be anomalously smooth. In high-resolution photographs these materials commonly display a peculiar, diffusely darkened appearance, almost as if the photographs were out of focus. It is these craters and crater materials with which this paper is concerned, and it is suggested that they may have formed by the impact of cometary materials.

Cratering by Possible Cometary Materials

Formation of Messier and Messier A.--Messier and Messier A are a pair of dark-halo craters excavated in Mare Fecunditatis (fig. 1). High-resolution Orbiter V photographs reveal that they are enclosed by fairly fresh radial rim materials (fig. 2), the ropy to braided topographic character of which is analogous to radial rim materials of bright halo craters of probable impact origin. The radial rim materials are asymmetrically disposed in a north-south direction, normal to the long dimension of highly elliptical (9 x 17 km) Messier, and the slightly elliptical younger part of Messier A (see topographic map of Colombo quadrangle, LAC 79, USAF Aeronautical Chart and Information Center; and the Lunar Orbiter IV photograph taken almost directly above these craters). The crater rim materials are smooth and dark, and they crop out as a thin dark layer in the uppermost part of the crater walls (fig. 2b). The dark layer is penetrated in Messier rim material by two younger bright halo craters, which shows that mare material here is typical of that elsewhere in that it displays high reflectance where ejected from the crater as well as high reflectance in crater walls.





FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 2a.--Geologic sketch map and Orbiter V photograph (moderate resolution) of the Messier and Messier A area of Mare Fecunditatis. Messier is approximately 9 km across north-south. View faces west.

EXPLANATION

Copernican System

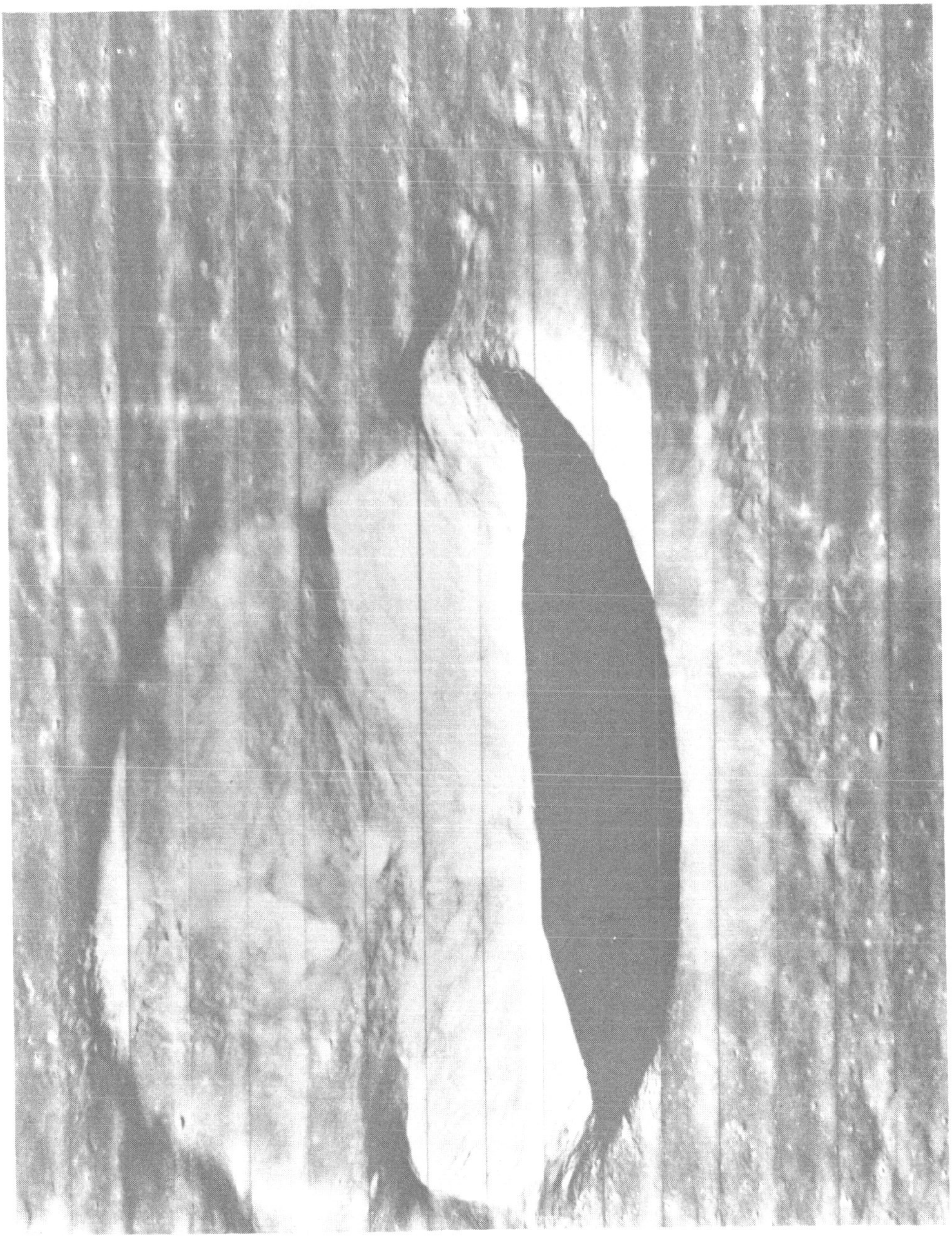
	Ccpm	Crater wall, rim and radial materials of small bright halo, impact(?) craters of post-Messier age. High albedo.
	Cms, Cmr	Smooth (s) and rough (r) mare-like materials of post-Messier age. Low albedo. Smooth materials are developed in topographically low areas in Messier crater rim materials. Rough materials are in floors of Messier craters.
Materials of Messier and Messier A (younger part)	Cr	Ray material apparently derived from previously brecciated wall materials of partly destroyed crater of Eratosthenian age. High albedo.
	Ccrr	Radial crater rim materials. Discontinuous low ropy ridges and sharp furrows that lie radial to sub-radial to the craters and are preferentially distributed in a north-south direction, normal to the long axes of the craters. Low to intermediate albedo.
	Ccrs	Crater rim material. Mostly smooth but locally finely blocky and topographically irregular in small scale relief. Low to intermediate albedo. Locally appears to be diffusely darkened.
	Ccrh	Gently hummocky to locally smooth rim materials. Low to intermediate albedo. Appears diffusely darkened.
	Ccm	Hummocky to locally smooth material that mantles the wall and floor of the partly destroyed Eratosthenian crater in Messier A, and the west wall and floor of Messier. Low to intermediate albedo. Appears diffusely darkened. Analogous to Ccrh, but lies within the craters.
	Ccw	Crater wall material showing blast(?) pattern. Probably brecciated. High albedo.

Eratosthenian System

Ewf	Wall and floor (?) material of partly destroyed Eratosthenian crater of Messier A. High albedo.
Emr(?)	Rough(?) mare-like material in floor of Messier B. Low albedo.
Ers	Smooth rim material of Messier B and Secchi K. Low albedo. Materials crop out as prominent dark layers in upper part of crater walls.
Ew	Wall materials of Messier B and Secchi K. Intermediate to moderately high albedo.

Imbrian System

Ipm	Mare material of Procellarum Group. Low albedo.



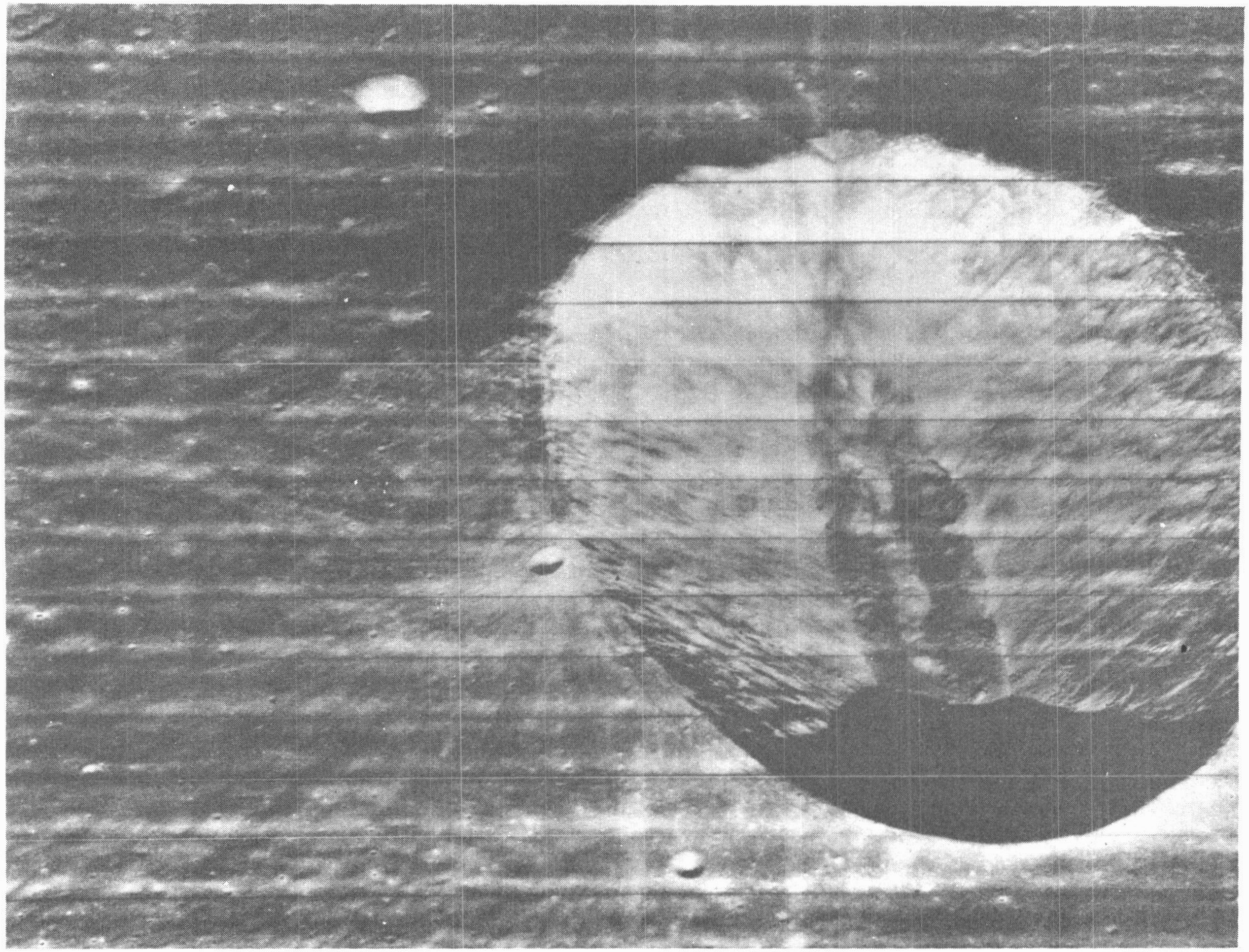


Figure 2b.--High resolution Orbiter V photographs of Messier (lower) and Messier A (upper).

Note the smoothness of the crater rim materials; the existence of a dark layer, which is exposed in the upper parts of the crater walls; the upward and outward radiating texture in the crater walls that may be attributable to blast; the diffusely grayish appearance of Ccwf, Ccrh, and Ccrm materials; the rough hummocky dark mare-like materials in the floor of Messier and the smooth dark mare-like material of post-Messier age; and the north-south asymmetry in the distribution of the radial rim materials. Note the flow-like character of rim materials in the upper left hand part of the photograph of Messier A. The flows appear to emanate from Ccrh materials.

Messier A is a doublet crater (fig. 2). On the east it consists of a younger, slightly elliptical crater that is enclosed by dark rim materials; on the west it consists of a partly circular older crater, the eastern part of which is missing. Small patches of high-albedo wall and floor(?) material are exposed in the older crater where dark material associated with the younger crater has failed to completely mantle steep slopes. A pair of bright rays extend more than 120 km westward across Mare Fecunditatis to the Colombo uplands. The rays converge slightly toward Messier A, and if extended to the crater, intersect a part of the crater formerly occupied by now missing wall materials of the older crater. The force of the younger cratering event was apparently considerable, and the cratering event seems to have been essentially instantaneous. The east wall of the older crater was breached and its wall material was ejected westward as two jets of bright ray material. The hiatus in ray material that gives rise to the doublet appearance is probably due to a lack of ejecta. This may be explained if, in the process of excavation of the pre-existing crater wall material, part of the explosion broke through into the older crater and the crater wall materials on either side of the breach were detached as separate flaps of ejecta. This ejecta, already brecciated and of relatively high albedo, retained its albedo and was not darkened, as were rim, radial rim, and fallback(?) materials. It thus was not involved in the diffuse darkening and apparent comminution of materials which were excavated from the Messier and Messier A (younger part) craters and deposited as rim materials. The Messier ejecta is dark, although materials of the crater walls display moderately high albedo under full-moon illumination (fig. 1). Field relations suggest that brecciated high-albedo lunar material, in the process of becoming ejecta, was diffusely darkened by the invasion of some foreign material. Bright material in the doublet rays probably escaped invasion because it lacked confinement where it resided in the wall of the older crater, which allowed it to be blown out along a low trajectory before invasion of foreign materials could occur.

The smoothness and the darkness of crater rim and mantling materials of the Messier craters may be attributable to compositional and physical characteristics of the impacting material. Energies are inferred to have been high relative to the depth of burst because even material on the crater rim crest appears thoroughly comminuted. This is in marked contrast to the rubbly and blocky character of crater rim materials of bright halo craters, for example, Censorinus in the Colombo uplands; materials in such bright halo craters have undergone little apparent darkening during brecciation and ejection. In Messier and Messier A (younger part), the strength of the impacting material is inferred to have been low, and the material must have been easily diffusible for it to have thoroughly invaded the brecciated bedrock that was excavated from the sites of the craters. The type of impacting material that seems to best meet these general requirements is low-density volatile-rich cometary material.

Field relations suggest that Messier and Messier A (younger part) are of the same origin and, because of the apparent lack of overlap relations, are the same age. If this is true, the impacting material may have originated from a parent body that had split before impact. The extremely elliptical outline of Messier and the slightly elliptical outline of Messier A (younger part) then might be explained as the result of a grazing or low-angle impact. The bolides could have approached either from the east or the west, which would suggest a cometary nucleus in a short-period orbit.

Other dark and intermediate halo craters.--In the Colombo quadrangle, other youthful craters are recognized that are enclosed by halos of low to intermediate albedo material. One of these, Messier B, lies a few tens of kilometers north of Messier. It has been classed as Eratosthenian in age on the basis of its topographically subdued crater rim materials. Orbiter photographs of Mare Fecunditatis reveal that several subdued craters, comparable in size to the Messier craters, exhibit dark layers in the uppermost parts of their walls. At this time, these have been classed simply as Eratosthenian craters of uncertain origin, but the dark layers and the smoothness of their crater rim materials suggest that they are similar in origin to the Messier craters; thus, dark halo craters of possible cometary origin may form an important part of the crater population. Analogous craters also appear to be present in the Colombo uplands (Elston, unpub. map). Mapping has revealed at least three youthful craters, comparable in size or slightly larger than the Messier craters, that are enclosed by halos of intermediate albedo material. The grayish halos and locally grayish rim material are discernible because uplands materials that border the halos are intrinsically higher in albedo.

A number of young large craters outside the Colombo quadrangle exhibit diffusely darkened halos in their rim materials, or anomalously dark ray materials. Dark halos appear, for example, in rim materials of Tycho, Aristarchus, Anaxagoras, Euctemon, and possibly Proclus (fig. 1). Near the western margin of Mare Tranquillitatis, light and dark ray materials extend from the crater Dionysius (Morris and Wilhelms, 1967).

A diffusely darkened halo in the rim materials of the crater Tycho (fig. 1) only locally extends to the crater rim. The darkened material thus does not form a unit that crops out in the crater wall, as would a displaced inverted stratigraphic unit. Rather, the halo, which appears fairly smooth, diffusely darkened, and out of focus in fine surface detail in Lunar Orbiter IV and V photographs, irregularly encircles the crater rim, commonly at some variable distance from the rim crest. The inner and outer margins of the halo grade unevenly into more typical uplands materials of higher albedo. In the original preexcavation position, ejecta of the dark halo would have been in or near the path of penetration of the impacting bolide and thus would have been in the region of mixing during impact. Field relations thus suggest that excavation of Tycho extended beyond the region of intense mixing of bolide and country rock.

<u>Potential reserves around Tycho</u>.--If material of the diffusely darkened halo of Tycho is analogous to water- and rare gas-bearing polymict meteorite breccias that are inferred to have been

invaded by carbonaceous meteorite material, a large potential deposit of water-bearing rock may exist around Tycho. The materials would be highly crushed and brecciated and would be ready for strip mining, beneficiation, and extraction of volatiles by mechanized and largely automated methods. The distribution of the diffusely darkened halo material can be outlined on rectified lunar atlas plate 24-C (Whitaker and others, 1963). If, conservatively, the diffusely darkened rock in the halo contains 1 weight percent H_2O in a layer 2 meters thick, reserves of water-bearing material would amount to about 40 km^3, containing about 0.8 km^3 (or 0.8 x 10^{12} liters) of water. The thickness of the diffusely darkened material undoubtedly is much greater than 2 meters throughout much of the ejecta blanket; thus, reserves could very well be much greater. Also, it may not be unreasonable to expect carbon-rich, high-grade lodes of water-bearing breccias, which could contain on the order of 5 to perhaps 10 weight percent H_2O where hydrated parent material (carbonaceous layer lattice silicate material) is abundant.

The development of an ejecta blanket containing hydrated silicates derived from a cometary bolide also might be accompanied by the development of a permafrost layer. This is suggested because it is unlikely that the free volatiles of a comet could be entirely dissipated during cratering or be lost from the brecciated ejecta before the ejecta came to rest as crater rim materials. A permafrost layer could conceivably form more readily if impact occurred during the lunar night. The uppermost parts of a permafrost layer would probably be lost during succeeding lunar days as the upper surface was turned over by small-scale particle bombardment of the surface. The deeper parts might remain for some time, sublimating mainly where the ejecta blanket was penetrated and turned over by relatively large-sized impacts.

Empirical studies of the behavior of water in a vacuum, alone and mixed with basaltic sand, have shown that water, when introduced into a vacuum, cools rapidly until it freezes, and that for each gram of liquid evaporated approximately 7 grams freeze (J. R. Bruman, personal commun., 1968). Thus, volatiles driven into brecciated ejecta as liquids and gas at the time of an impact may very well freeze into a rather special type of permafrost, which from the inferred composition of comets, might consist of water, ammonia, and methane. Bruman reports that in a vacuum, ice covered by a layer of basalt sand 75 mm thick sublimated at depth when the surface of the capping basalt sand was heated. This resulted in the formation of frost at the surface, although the surface temperature was 65°C. After about 80 minutes the ice was completely melted and a void developed between the liquid and the overlying cap of basalt sand. This was shortly followed by a violent explosion. All that was left were 20-30 mm high bulbous columns of frozen mud in the bottom of the container. Small eruptions occurred through 1-2 mm fumarole-like openings in the columns.

"Cold volcanism" may occur on the moon. The "ponds" of smooth, dark mare-like material in the rim materials of the Messier craters, and the plains-like materials that occupy depressions in the rim materials of Tycho, may be the result of degassing of ejecta rather than a product of endogenetic hot volcanism. Also, the syrupy, flowlike structure in the Tycho ejecta may have been partly due to fluids in the breccia at the time of its emplacement. That flowage and flows need not be the result of endogenetic volcanism is suggested by the flowlike character of deposits that appear to emanate from diffusely darkened ejecta in the rim materials of Messier A (fig. 2c).

If exploitable permafrost deposits of cometary origin do exist, they should be found in and near diffusely darkened rim materials of young, large dark halo craters. The existence of permafrost deposits might even make the extraction of water from layer-lattice silicate materials unnecessary.

Summary

Circumstantial evidence deduced from the meteorites and extrapolated to field relations on the lunar surface leads to a model for cratering of the lunar surface by cometary materials, and to the inference that volatiles derived from such impacting material may occur in diffusely darkened, smooth ejecta around such craters. The ejecta around Tycho may constitute a potentially large source of water, and field evidence in the Colombo quadrangle suggests that many other potential deposits of water-bearing breccia exist on the lunar surface.

Planning for extended exploration of space should include the possibility of establishing a lunar base that could utilize a source of cometary-introduced volatiles at the lunar surface. Exploration for sites suitable for a major base falls into two categories: (1) earth-based studies which would include geologic mapping on medium- and high-resolution Orbiter photographs of craters that may be analogous to the Messier and Tycho craters, and a moonwide compilation of such craters; crater-modeling studies on the preservation of water in layer lattice silicates in breccias, and investigations on the possible development of permafrost in ejecta blankets; development of models anticipating the composition of volatiles entrapped in breccias, derived from compositional data on meteorites and comets; and, (2) lunar field exploration, which would entail direct geologic examination and sampling; such exploration may well have use for a drill to test for permafrost.

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