

N69-14858

NASA-CR-14858 (Revised)

NASA-CR-98742

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

FACILITY FORM 602	<u>N69-14858</u>	_____
	(ACCESSION NUMBER)	(THRU)
	<u>64</u>	<u>1</u>
	(PAGES)	(CODE)
<u>NASA CR-98742</u>	<u>30</u>	_____
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)	

INTERAGENCY REPORT: ASTROGEOLOGY 7
 ADVANCED SYSTEMS TRAVERSE RESEARCH PROJECT REPORT
 By G. E. Ulrich

With a Section on Problems for Geologic
 Investigations of the Orientale Region of
 the Moon
 By R. S. Saunders

July 1968

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

Prepared by the Geological Survey for the National Aeronautics and Space Administration

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ADVANCED SYSTEMS TRAVERSE RESEARCH PROJECT REPORT

by

G. E. Ulrich

ABSTRACT

This report presents the results of the Advanced Systems Traverse Research Project for fiscal year 1968.

The Orientale region on the west limb of the Moon was selected for preliminary traverse research because of its variety of physiographic features and its potential for solving many of the broader lunar problems. The region is dominated by a large, young, multi-ring structure--the Orientale basin--about 900 km in diameter. The origin and geologic history of the basin have been variously attributed to volcanism, tectonism, and to impact by an asteroid-sized body.

The movement of lunar surface vehicles and the landing of flying units will be affected by crater density and geometry, small-scale surface roughness, and the mechanical properties of surficial materials. Topographic definition is a first step in estimating these properties; it is also essential, on a different scale, for geologic analysis and for relating geophysical data to the subsurface structure and stratigraphy of the lunar crust.

A group of missions combining an intermediate-length manned traverse of approximately 400 km with automated vehicle missions at both ends is proposed for studying the Orientale basin. The value of open-ended traverses, a closed mobile laboratory, and auxiliary flying units is evident for missions aimed at exploring major planetary problems.

As a result of this study it is strongly recommended that new Orbiter photography, designed for high-quality photogrammetric reduction, be obtained of areas being seriously considered for extended lunar traverses.

INTRODUCTION

The Advanced Systems Traverse Research Project commenced in July 1967 as an outgrowth of discussions among National Aeronautics and Space Administration Headquarters, Manned Spacecraft Center, Marshall Space Flight Center, and the U.S. Geological Survey. It was originally conceived as a feasibility study of long-range geological and geophysical traverses on the Moon, with particular attention to the trafficability characteristics of different geologic terranes, the potential scientific value of such investigations, and the specific and unique capabilities that continuous surface exploration contributes to the solution of regional geologic problems. Surface mobility concepts to be considered range from a single-man open vehicle through a completely enclosed scientific laboratory for long-range exploration including the added potential of unmanned configurations where applicable.

The first half year's effort was spent primarily on investigating techniques of determining the terrain characteristics and other variables along hypothetical lunar traverse routes, so that regional trafficability characteristics in areas of scientific interest could be evaluated. The remainder of the fiscal year was devoted to planning traverses for specific areas of scientific interest with special emphasis on the Orientale region (see p. 30).

The technical contributions to traverse research presently include the application of shadow measurements, analytical parallax measurements, and photogrammetry. Many of the limitations on photogrammetric techniques imposed by equipment now in use should be reduced when the test trials on the AP/C analytical plotter are completed. Research in the Advanced Systems Project is coordinated with that in the Terrain Analysis, Trafficability, and Lunar Mapping Projects and fully utilizes the results of those studies.

The Orientale region on the west limb of the Moon (fig. 1) has been chosen for preliminary comparative studies of post-Apollo missions. This is a logical place to apply long-range traverse studies and to extend the base of scientific information that will have developed from localized studies on earlier missions. Preliminary mission profiles will incorporate long-base geophysical measurements, visual observations, sample collection and analysis, navigation data, and other scientific requirements as established by currently available documents.

The need for various types of topographic information in traverse research and other aspects of mission planning has been examined in detail. The present capability of the U.S. Geological Survey and other agencies for producing the necessary information from existing lunar photography has been evaluated. Rudimentary slope and obstacle data for a straight-line traverse in the Orientale region have been obtained by extrapolating shadow measurements and crater-size frequency distribution.

Proposed directions for continuation of the Advanced Systems Project include more sophisticated methods of traverse evaluation with presently available photography. Study of engineering properties of lunar soils and terrestrial analogs is recommended. In addition, recommendations are made for new photographic coverage of selected mission sites by systems better suited to photogrammetric reduction techniques.

PHYSIOGRAPHIC SUBDIVISION OF THE LUNAR SURFACE

Classification of the lunar surface has undergone numerous revisions since Galileo first described it as "rough, replete with cavities, and packed with protruding eminences." Table 1 compares recent classifications that are based on visible morphologic features and albedo variations. Classifications in the first four columns are the result of Earth-based telescopic observation; those in the fifth column are derived from studies of Lunar Orbiter and Ranger photography.



Figure 1A.--Generalized map of Orientale basin region. (Drawn by Pat Bridges, U.S. Air Force, Aeronautical Chart and Information Center.) Scale approximately 1:7,000,000.

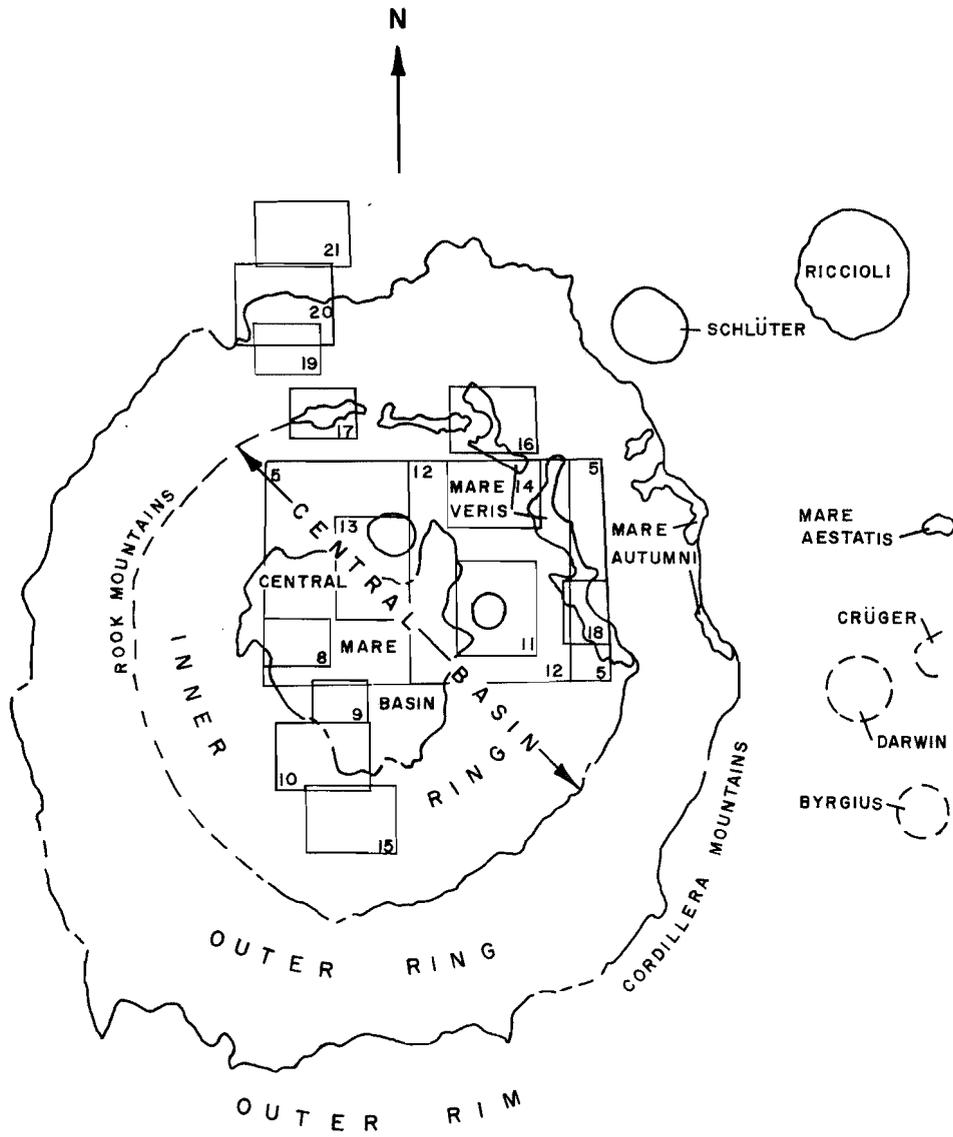


Figure 1B.--Index map of Orientale basin region. Numbered rectangles indicate areas shown by photographs in text.

Table 1.--Classifications of lunar terrain

Hackman and Mason (1961)	McCauley (1964a)	Holm, Rowan, and McCauley ^{1/} Rowan and McCauley (1966)	Slope reversal (percent)	El-Baz (1968)	Trask (1968, unpub. rept.) H. A. Pohn and T. W. Offield (1968, unpub. rept.) Wilshire (1968)	
Lowlands Mare provinces	Maria I. Dark mare 1° II. Ray-covered mare 1° III. Mare ridges, rilles and domes 1.5°	I. Mare A. Undifferentiated -smooth -rough B. Dark	Arithmetic mean slope 1.00° 1°-1.78°	21.0 21-26.5	Maria Light Dark Smooth Rough	Mare materials (Trask) Level mare (few craters and lineaments, younger) Rolling mare (more craters and lineaments, older) Mare ridges (younger, older)
Highlands Geographic provinces Cratered plain Crater Macro-crater Mountains	Uplands III. Smooth terra 1.5° VI. Overlapping craters and regional material 4.5°	II. Uplands A. Smooth plains B. Hummocky to subdued C. Moderate local relief D. Rough	1.78°- 2.28° 2.28° 2.28°	26.5- 29.5 29.5 29.5	Highland Even Pitted Rugged	Terra materials (Wilshire) Hilly terra Terrace Rolling terra Terra apron
Crater provinces as above	Craters IV. Floors of large craters 2° V. Individual craters and rim deposits 3°	III. Craters A. Sharp ("well-formed") 1. Wall 2. Floor 3. Rim B. Modified 1. Wall 2. Floor 3. Rim C. Crater fields and craters <2 km diameter	1°-1.20°	22-24.0	Craters Number Single Cluster Chain Shape Circular Elongate Polygonal Irregular Halo Bright Dark Rim Stepped Ejecta Floor structure Center peak Center ridge Hummocky Age Fresh Floor-filled Ghost	Large crater-size classes (Pohn- Offield) I. >45 km diameter (youngest→oldest) Tycho→Regiomontanus II. 20-45 km Kepler→Wilkins III. 8-20 km Diophantus→Nicolai Z IV. 3-8 km (degradation rate higher than I-III) Small crater-size classes (Trask) (freshest→most subdued) (youngest→oldest) 0.8-3 km Cc8→Cc1→Ec 400-800 m Cc8→Cc1→Ec 100-400 m Cc8→Cc1 (Ec's largely destroyed) 50-100 m Cc8→Cc2 (Cc1's largely destroyed)
		IV. Linear features A. Ridges B. Domes C. Rilles 1. Linear 2. Sinuous D. Plateaus E. Escarpments F. Depressions G. Chain craters Lineament Fault			Structural features Strata (bedding, contacts) Faults (scarp, slump) Rilles (linear, sinuous) Rays (bright, dark) Ridges (flow, wrinkle) Domes	Structural features (Wilshire) Fault Graben Lineament Ridge Scarp Trough Rimmed trough Mare ridge Irregular depression

^{1/}"Terrain atlas of the lunar equatorial belt"; being prepared for publication as U.S. Geol. Survey Prof. Paper.

The basic division into highlands and lowlands (terrae and maria, generally possessing high and low albedo, respectively) was established by the earliest telescopic work. Craters and linear features on these major terrain types became subjects of detailed studies with the advent of telescopic photography. Refinements in detailed morphologic description of features less than 1 meter in size were made possible by Ranger and Surveyor spacecraft, which photographed selected small areas. Larger sites near the equatorial belt are covered by 2-meter resolution photography from Lunar Orbiters I, II, and III. Further coverage of Apollo sites and some areas of post-Apollo scientific interest was obtained with 5-meter resolution photography from Orbiter V; 60-100 meter resolution photographic coverage of most of the earthside hemisphere was provided by Orbiter IV.

This spectrum of resolution has spawned elaborate subdivisions of crater types such as those shown in table 1, based generally on differences in surface texture and freshness of crater rims and on apparent modification of rims, walls, and floors. The modification of fresh impact craters depends primarily on two factors: age and original crater size (N. J. Trask, 1967, unpub. rept.). The morphologic features of a small crater are subdued more rapidly than those of a large one. This "aging" is interpreted to be the result of meteoritic bombardment and seismic activity. The size dependence of crater aging is particularly noticeable in craters up to 8 km in diameter (Pohn and Offield, 1967, unpub. rept.). Characteristics of larger craters, from 8 km to several hundred kilometers, are grossly similar in any given age class, although in certain details there are diagnostic morphologic differences between classes. The differences include rim-crest outline, nature and extent of terraces on crater walls, and presence or absence of rays--factors that appear to be a function of crater size and cannot at this time be evaluated in terms of rock strength, layered structure, or possible volcanic processes (Pohn and Offield, 1967, unpub. rept.).

SITE SELECTION AND PRELIMINARY TRAVERSE RESEARCH

In planning vehicular traverses, the variety of crater types and sizes deserves careful consideration because: (1) the origin and evolution of craters and the information they furnish of the lunar subsurface are subjects of scientific interest, and (2) craters are the primary obstacles which a vehicle must avoid in order to complete a mission. The linear or structural features listed in table 1 are of interest for similar reasons. On a regional basis, the general properties of maria and terrae will have been established in several locations by missions preceding vehicular traverses. Results from the Surveyor missions suggest that long-range unmanned traverses may enable exploration of large mare areas such as Imbrium and Tranquillitatis with routine, repetitive experiments that can be automated. More sophisticated scientific experiments and manned-mission concepts are applicable in terrain that is geologically and morphologically more complex. Such areas will probably provide more important evidence concerning the basic questions about the Moon than will the broad expanses of maria.

Early lunar missions will conduct local geological and geophysical investigations of near-surface features, and automated geophysical observatories may provide important data on the Moon's deepest regions. However, a gap in our projected knowledge occurs in the zone between the Moon's surficial materials and its inner depths. The regional information needed to fill the gap can perhaps be gathered in multi-ring basins which penetrate this zone.

The Orientale basin on the west limb of the Moon (fig. 1) has been selected as the logical place for preliminary traverse research. It is the best exposed large multi-ring lunar basin and contains nearly all the features noted in table 1. A large variety of these are of scientific interest individually for later lunar investigations; some are described in the last section of this report. The entire basin is uniquely suitable for comparative

studies of both local and regional geologic problems and for planning missions aimed at their solution.

The regional subdivision of the Orientale basin into natural terrain units (fig. 1) coincides generally with the division into photogeologic units (fig. 6, p. 32); both are delineated chiefly on the basis of morphologic characteristics. These units in turn are listed by relative degrees of roughness (table 2) at the 70-meter scale of Lunar Orbiter IV photography. The smoother units are evaluated in terms of crater density because craters are the major observable obstacles in the areas where these units are exposed.

Preliminary traverse routes may be evaluated by extrapolating resolvable terrain features such as crater density down to scales that would affect a surface vehicle. The method is a tenuous one based on empirical data from 2-5 meter-resolution Lunar Orbiter photography of comparable terrain.

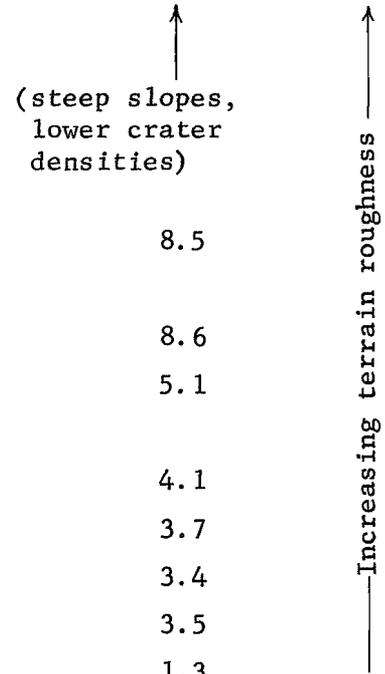
Crater-size frequency distribution curves are another roughness indicator prepared from crater-density data. Figure 2 shows these curves for the Orientale basin units. A drawback to this method of comparison is the fact that a slight displacement between curves represents a sizeable difference in crater-based roughness. (Compare, for instance, the difference between Montes Rook Formation and central basin mare in table 2 and fig. 2.)

The rougher terrain units, including the Cordillera Formation, the scarps of the Cordillera and Rook Mountains, and parts of the Montes Rook Formation and central basin plains units, are characterized by large slope values and high percentages of slope reversals. Craters within these units constitute secondary obstacles and, as a rule, are less abundant than on level areas, possibly because surficial material on slopes is less stable than material on level terrain and tends to bury or otherwise destroy craters more rapidly.

Two preliminary traverses across Orientale were selected (fig. 3) for experimentation with photogrammetric, photometric, analytical

Table 2.--Roughness of photogeologic and terrain units of the Orientale basin (see figs. 1, 3, and 6 for distribution of units)

	<u>Percent saturation by craters</u> <u>>100 meters in diameter</u>	
Escarpments:		
Cordillera Mountains		
Rook Mountains		
Terra plains units:	(steep slopes, lower crater densities)	
Cordillera Formation		
Montes Rook Formation	8.5	
Central basin plains material		
Fractured rolling hills	8.6	
Smooth light plains	5.1	
Mare plains units:		
Central basin mare	4.1	
Mare Veris	3.7	
Mare Autumni	3.4	
Crüger mare	3.5	
Grimaldi mare	1.3	



parallax, and shadow-measuring techniques. Photogrammetric reduction is awaiting operational checkout of the analytical plotter. Attempts to obtain photometric data in the Orientale region have been discontinued, pending receipt of better photography, for two reasons: (1) heavy shadowing and 70-meter resolution preclude the use of photoclinometry in the rougher terra where it is most needed, and (2) the handling of densitometer data from second- and third-generation photography remains in an experimental stage; highly variable results are obtained with the present computer program.

An analytical method for computing relative elevations using a stereoscopic parallax difference equation is being developed by

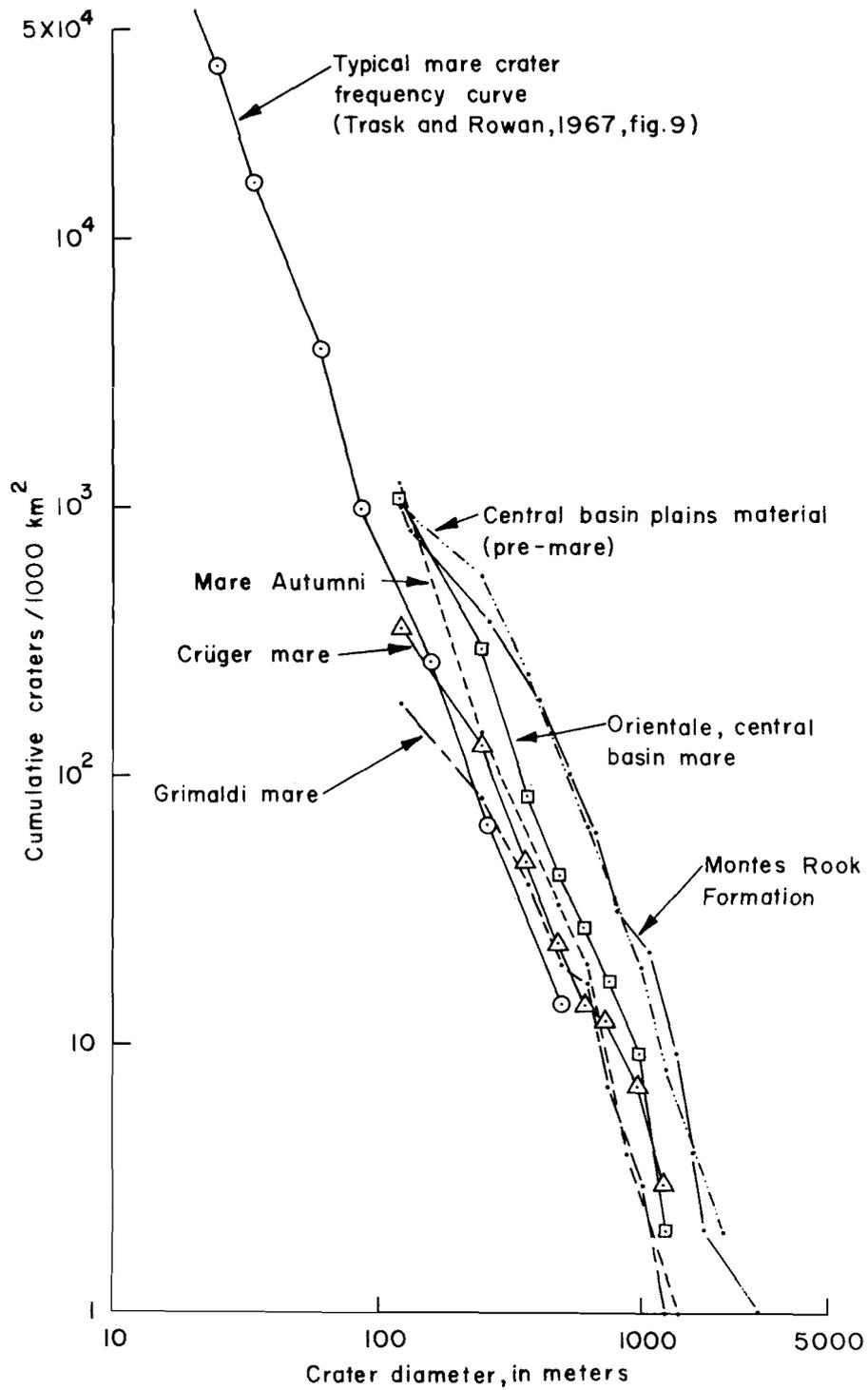


Figure 2.--Crater-size frequency distributions of Orientale basin terrain units. (Crater counts by R. E. Hoffman.)

F. Schafer of the U.S. Geological Survey. Preliminary results show good correlation with 5-meter resolution photography of Aris-tarchus (where photogrammetric reduction has also been successful), but the application to the Orientale region is currently limited by (1) the lower resolution, (2) very low base-to-height ratio (0.074 compared with values of 0.18 to 0.3 from other Orbiter photography), and (3) difficulty in calculating magnification values to produce reasonable elevation differences.

The fourth technique, utilizing shadow measurements, gives useful approximations of regional slopes and local relief based on a knowledge of the Sun's azimuth and vertical angle. Table 3 lists the results of measurements and deductions compiled for the traverses shown in figure 3. These values represent straight-line paths nearly perpendicular to the concentric structure of the basin, and, as such, serve to characterize the regional terrain rather than follow the smoothest path. The effect of photographic exposure on the measurements is shown in figure 4. The histogram illustrates that accurate definition of the smooth and rough terra units depends on proper exposure. These same units are the most difficult to treat photometrically, but both methods have the advantage of not requiring stereoscopic coverage.

Preliminary estimates of trafficability based on Lunar Orbiter IV photography are very tentative because obstacles of the size (1-3 meters) which will affect a vehicle directly are not photographically resolvable. Nevertheless, generalizations can be made concerning regional terrain, and when quantitative trafficability data for areas of high-resolution coverage elsewhere on the Moon become available, these can perhaps be extrapolated to the Orientale region.

If it is assumed that regional slopes of less than 15° are negotiable, then 60 and 70 percent, respectively, of the two traverses in figure 3 and table 3 are trafficable along a straight path. Two-meter resolution photography will permit much more accurate estimates and can be expected to increase terrain roughness

Table 3.--Preliminary shadow measurements in the Orientale basin region

	<u>Traverse 1</u>		<u>Traverse 2</u>	
	<u>Length (km)</u>	<u>Percent</u>	<u>Length (km)</u>	<u>Percent</u>
Smooth mare surface, 0°-2°	31	3	149	20
Rough terra, >15°	330	34	232	24
Walls of fresh craters, >0.5 km diam., 30°-40°	46	5	34	3
Inward-facing scarps, >40°	10	1	18	2
Smooth terra, 0°-15°	<u>545</u>	<u>57</u>	<u>542</u>	<u>51</u>
Total	962	100	975	100

- Notes: 1. Location of traverses is shown in figure 3.
2. Measurements made on 1:500,000 enlarged segments of Lunar Orbiter IV photographs H-168, 173, 181, 187, and 195.
3. Smallest interval of measurement, 0.5 km.

values (McCauley, 1964a, p. 39). If obstacles to vehicular movement can be measured or determined statistically and extrapolated to the scale of the vehicle, then the minimum distance between two points that must be traveled to avoid the obstacles can be estimated. If the obstacles are equidimensional and uniformly distributed, the maximum length of detour required can be calculated simply as half of the circumferences of the cumulative obstacles. Such calculations on the above traverses indicate that the length of a given vehicular route in the Orientale region, not including the mare areas, will be one-third to one-half larger than the straight-line distance. Obstacles that are approached at less than their maximum diameter or are not equidimensional, uniformly distributed, or resolvable on available photography will vary these estimates considerably.

Surveyor photographs suggest that craters are likely to be the primary obstacles to movement of vehicles in mare areas.

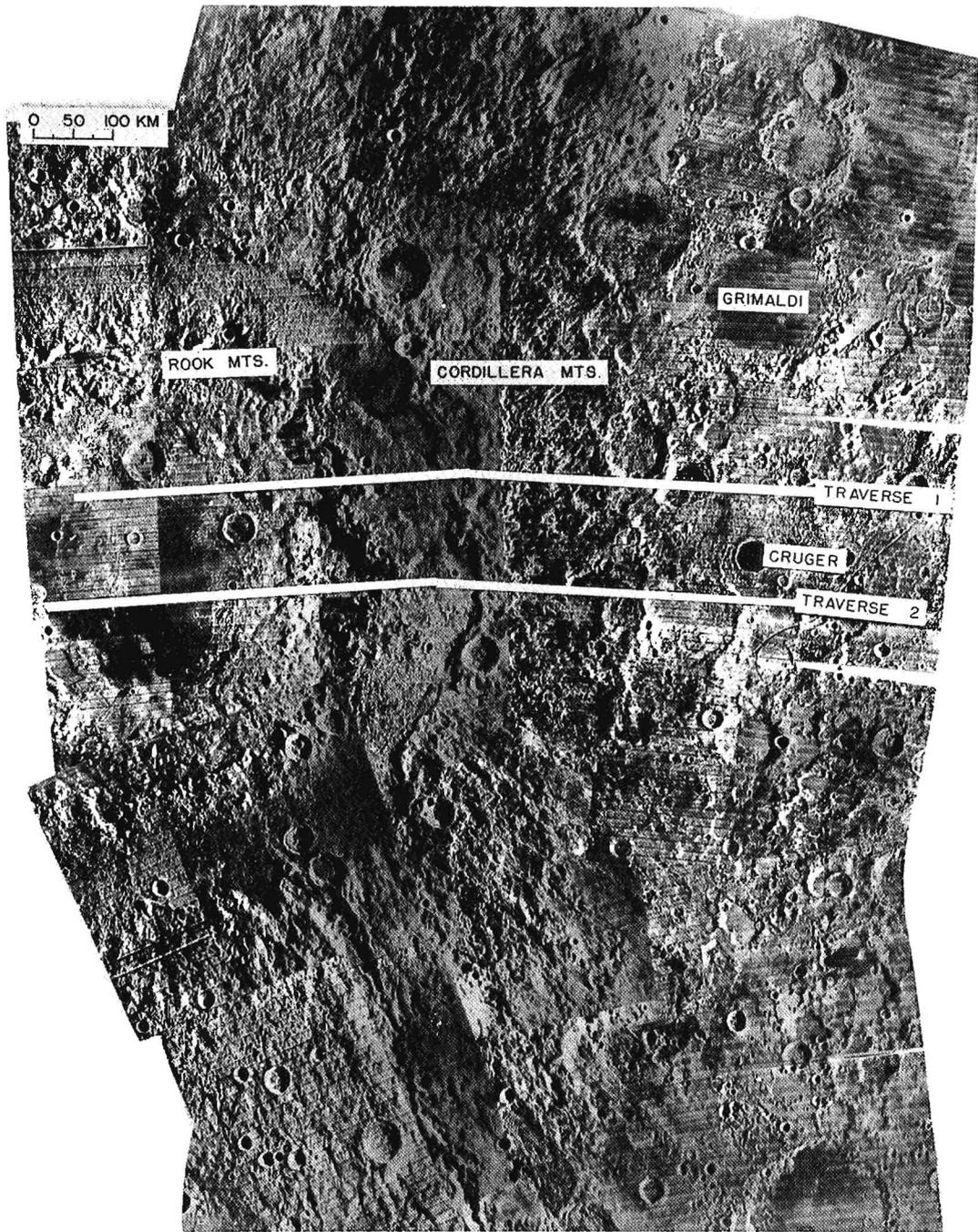


Figure 3.--Orientale basin region. (Uncontrolled mosaic of Lunar Orbiter IV high-resolution photography prepared by U.S. Geol. Survey Surveyor team.)

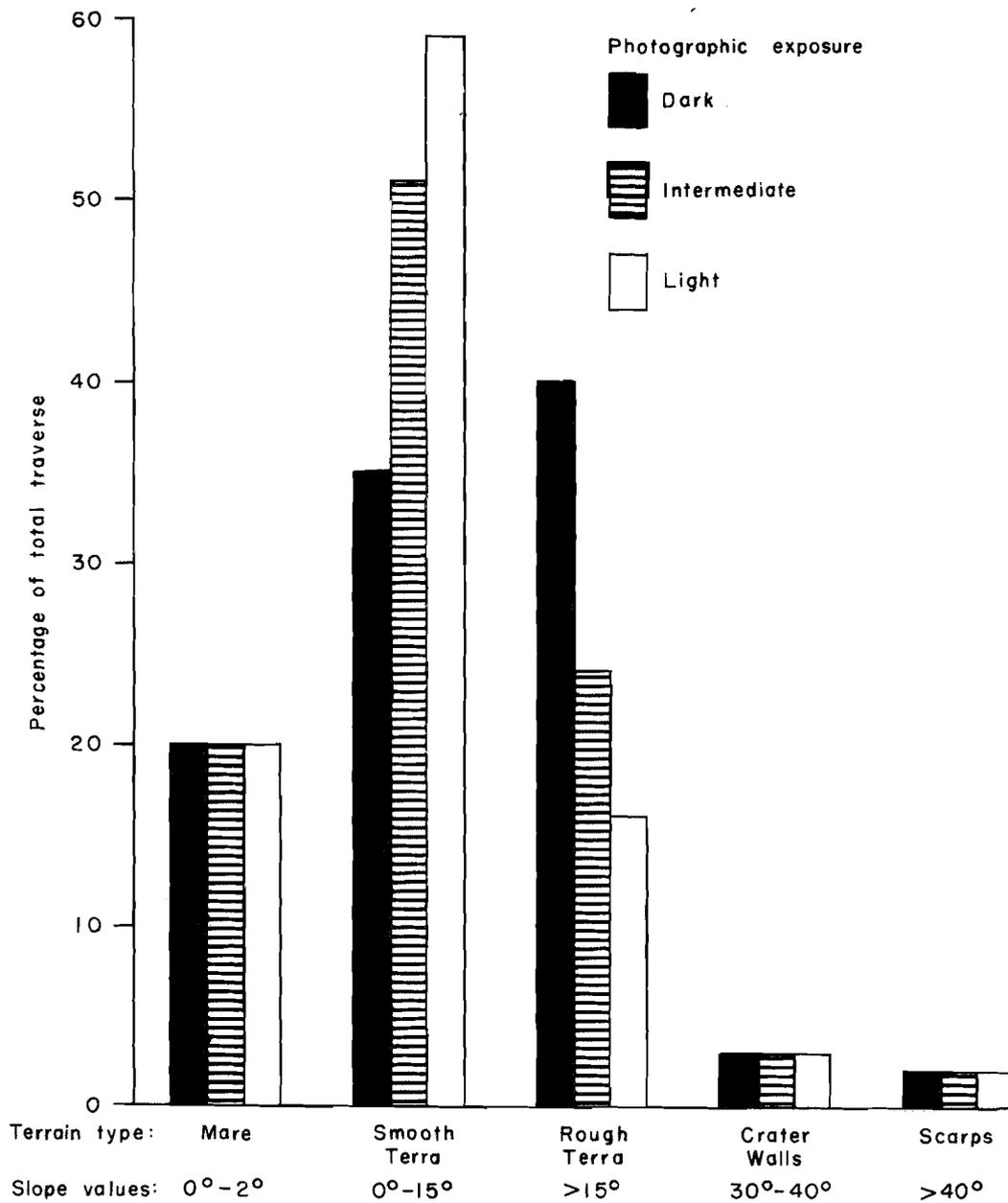


Figure 4.--Effect of photographic exposure on shadow measurements of terrain types along approximate line of traverse 2 in figure 3, eastern Orientale region.

Extrapolation of the crater-size frequency curves (fig. 2) for mare areas to the 2 meter crater diameter permits a "worst-case" calculation of the frequency distribution of all craters larger than 2 meters. For typical mare areas illustrated by Trask and Rowan (1967, fig. 9), about 24 percent of an average straight-line traverse would cross craters large enough to obstruct the movement of a vehicle.

A formula for calculating the additional travel distance necessary to circumvent circular obstacles having a known areal density has been derived by Brooks (1958, p. 7-8). His formula was modified as follows by W. Rozema of the U.S. Geological Survey, who used revised probability functions and revised paths around the crater rims:

$$L' = 0.169 ND^2 \quad \text{where}$$

L' = average additional distance per unit length (e.g. 1 km) of traverse required to detour around craters

D = diameter of crater rim crests

N = number of craters of diameter D per unit area (e.g. 1 km²)

It is more realistic to consider the outer diameter of crater rim deposits rather than rim-crest diameter in calculating the statistical increase in traverse length. This value is approximately 1.4 D for most lunar craters (Pike, 1967, p. 2102). The increased effective diameter revises Rozema's formula to nearly double the rim-crest detour or:

$$L' = 0.331 ND^2$$

L' calculated for Trask and Rowan's average mare for all fresh craters larger than 2 meters equals approximately 0.10 km per 1 km traverse or a 10 percent increase in traverse distance required to detour around crater rim deposits.

The increase in traverse distance due to terrain slopes can be simplified as proportional to the secant of the angle of slope above horizontal (ignoring slope curvature). For 5°, 10°, and 15° slopes, the map distance will be increased by 0.4, 1.5, and 3.5 percent, respectively, assuming that the slopes are traversed along a straight line.

Although these estimates are rough, they are the best available with present photography and can serve as a basis for preliminary evaluation of the feasibility of traverses designed for solving specific scientific problems. Higher degrees of confidence can be attained with further study, particularly with an analytical plotter. However, accurate determinations cannot be made without higher resolution photography.

LUNAR TOPOGRAPHIC DATA

Information on lunar topography is very useful for compilation and interpretation of geological and geophysical data and, even more so, for engineering analysis of terrain, trafficability, and properties of surface materials. The accuracy and contour resolution required depend on the anticipated use of the data. For vehicular design and precise determination of traverse routes, 1-meter contour intervals are probably adequate; the resolution should be three to five times greater than the size of topographic features that are potential obstacles to vehicle movement (Hess, 1967, p. 308). Such precision is unattainable with available Orbiter photography. Surveyor data indicate that small contour intervals are probably unnecessary for trafficability analysis in at least four mare sites and on one rough crater rim.

The two current sources of lunar topographic maps are the U.S. Air Force Aeronautical Chart and Information Center and the U.S. Army Map Service. Shaded-relief maps of Apollo landing sites at scales of 1:100,000 and 1:25,000 were prepared from Lunar Orbiter I and II medium-resolution stereophotography. They show topographic contours at 25-, 50-, or 100-meter intervals with relative accuracies of ± 25 meters. These maps do not meet the accuracy standards usually required at these scales (Hess, 1967, p. 312). A recent topographic map of a small area in Mare Tranquillitatis, prepared from Lunar Orbiter II photography (U.S. Air Force, 1968), appears to meet the standards of 3-meter accuracy on a scale of 1:2,000 by combining photoclinometric profiles with

sparse photogrammetric control. The map text states that the capability now exists "to produce large quantities of reliable topographic data from Orbiter photographs" (ibid., p. 30).

Topographic profiles for use in individual research have been prepared by the U.S. Geological Survey from overlapping Orbiter I-III and V medium-resolution single framelets. G. Nakata has drawn topographic contours across framelet boundaries on one experimental model of Aristarchus on 5-meter resolution photography. The errors introduced by the mosaic format and the nonlinearity of the spacecraft scanning process were minimal and were successfully corrected in this instance. Lunar Orbiter photography was not intended for conventional geodetic or photogrammetric reduction (Hess, 1967, p. 310). Future photography should be designed to correct this deficiency, particularly for exploration sites, where topographic hazards will critically affect the efficiency of planned traverse routes and surface activities.

An experimental photogrammetric model of the Orientale region was prepared by J. Alderman and G. Nakata (U.S. Geol. Survey) using stereoscopic framelets from two medium-resolution Orbiter IV photographs. The spacecraft altitude was 2,720 km, and the model scale was 1:3,250,000. The small base-to-height ratio (approximately 0.08) required modification of the stereoplotter. The best vertical resolution obtainable even then was ± 6.5 km.

The analytical parallax method being developed by F. Schafer (p. 10) has been used to produce topographic profiles in the Orientale region; however, like the profiles produced by the photogrammetric model, they reflect unreasonable elevation differences (two to three times the values obtained by shadow measurements). These errors result from one or more of the following: resolution of Lunar Orbiter IV photography, extremely low base-to-height ratio, inaccuracy of marking common images on stereo pairs, and inaccuracy of calculated magnification (scale) factors, which may reflect possible errors inherent in the mission readout data.

The AP/C analytical plotter will enable greater versatility in handling unconventional photography. This instrument is currently in a status of operational checkout and should be ready for lunar topographic investigation at about the date of this report. Although it may not completely solve the problems of mosaic discontinuities and nonlinear scanning rates, it should be a significant improvement over presently available stereoplotters.

The techniques of photoclinometry were originally developed for obtaining lunar topographic data from Earth-based monoscopic photographs. The method uses photometry to derive slope information from the brightness variation on lunar images (Rowan and McCauley, 1966, p. 90). It must be applied to uniform albedo units, is restricted to measurements within the Sun's phase plane, and is generally more applicable to smooth terrain. It has been performed by the U.S. Geological Survey on Lunar Orbiter photography along individual framelets using multiple adjacent scans on high- or medium-resolution photographs. The largest single difficulty with the method has been the data reduction and correlation by computer.

An alternative approach to photometric data is direct use of the GRE tape readouts, eliminating the degrading effects of later generation photographic copies. A disadvantage to this is that different albedo units cannot be discriminated; thus, the technique is probably unsuitable in areas other than simple mare sites having uniform geologic characteristics.

The U.S. Geological Survey Trafficability Project (R. Pike and W. Rozema) is engaged in investigating the use of the power spectral density function and the amplitude probability distribution function in determining the roughness characteristics of mare areas. Topographic maps of Surveyor sites and profiles of a variety of terrestrial areas are providing the initial data. Reduction of photoclinometric profiles from one Ranger and one Orbiter site has also been attempted. The application to vehicle design and trafficability for traverse research is currently being

explored. The technique appears very promising for terrain evaluation in terms of the relative effect of varying wavelengths or frequencies of roughness on the overall roughness of a given profile. It also allows easy comparison of different areas on a spectrum of roughness scales. The major requirement currently is for more abundant and accurate topographic data on lunar terrain.

The shadow measurement technique is presently the simplest way of obtaining topographic data. Measurements in rough terrain give an approximation of regional slopes and local relief if the scale of the photography and the Sun's azimuth and vertical angle are known. The regional slope of an area in dark shadow, whose width is measured parallel to the phase plane of the Sun, is greater than the vertical angle of the Sun. Irregularities hidden by the shadow are not measurable. If the topographic features are roughly equidimensional, the percentage of a traverse in shadow along the phase plane is assumed to be half of the total distance having slopes greater than the Sun's vertical angle. This angle for the traverses shown in figure 3 is 13° to 15° ; thus the terrain along these routes can be divided into slopes that exceed, or are less than, approximately 15° . Fresh crater walls have average slopes of 30° - 40° ; these and prominent scarps are treated individually. Flat-lying mare areas generally have regional slopes of less than 2° .

OBJECTIVES AND EVALUATION OF TRAVERSE CONCEPTS

Generalized sample exploration plans for specific lunar sites evolved from the NASA 1967 Summer Conference at Santa Cruz, Calif. (Hess, 1967). More detailed plans resulted from the studies of nine mission sites selected by the Group for Lunar Exploration Planning, including the Marius Hills region (Karlstrom, McCauley, and Swann, 1968), and from a resume of the sites (El-Baz, 1968). These studies were based on a maximum operating radius of 5 km using a lunar roving vehicle (LRV) and two lunar flying units

(LFU) on a mission of 3 days' duration. El Baz concluded that the LFU is generally preferable to the LRV. However, whereas the LFU concept is better suited for rapid access to important local areas of high relief that are inaccessible to a surface vehicle, the roving vehicle concept provides the continuous ground coverage necessary for comprehensive scientific investigations (Karlstrom, McCauley, and Swann, 1968). The LRV has the additional important advantages of permitting changes in route and operational technique as a traverse progresses and of carrying a larger payload. Results of the Marius Hills mission planning exercise strongly suggest that detailed planning for exploration in most of the other selected lunar sites will indicate a similar scientific and operational requirement for both LRV and LFU. El Baz noted that a roving vehicle (manned or unmanned) also has the advantage of providing a mission with more stops along its route, the capability for extensive geophysical traverses, and the potential, in automated mode, for evaluating a site prior to manned landing, thus reducing the need for high resolution photography in some scientifically interesting sites. Most of the working groups at the Santa Cruz meetings (Hess, 1967, p. 10) concluded that for the post-Apollo lunar missions, a dual-mode vehicle (automated/manned) with the probable addition of one or two LFU's during manned operation is the optimum mobility system.

A wide variety of mission types and mobility concepts have been studied to determine how well each can achieve specific scientific objectives in the Orientale basin region. These objectives are as follows:

1. Comprehensive geologic analysis of the lunar crust on the west limb of the Moon and evaluation of the origin of multi-ring lunar basins based on the following:
 - a. Analysis of surface materials which make up major photo-geologic units. Do they reflect impact, volcanic, intrusive, or tectonic origins of the individual units, or are they some combination of these factors?

- b. Determination of the stratigraphic section; relationships of the major units visible on Lunar Orbiter photography and correlation with more detailed observations from the exposed sequences in the high scarps of the Cordillera and Rook Mountains. Rocks from deep in the lunar crust may be present in these scarps, in the central peaks of crater A (figs. 5 and 12), and in the rim deposits of the maar-like crater B (figs. 5 and 11), but are probably not completely exposed in any single area.
 - c. Examination of pronounced radial and concentric fracture systems to permit analysis of local structural events and their reflection of the regional stress-strain relationships in the upper crust.
2. Age dating of returned samples whose stratigraphic positions are accurately determined.
 3. Long geophysical traverses incorporating seismic, magnetic, gravitational, and heat-flow data into the geologic framework as an extended traverse proceeds. The proper combination of these data will greatly facilitate interpretation of the Orientale basin's subsurface characteristics.
 4. Local investigations of interesting features such as the low domes in Mare Veris (site 1 in fig. 5 and fig. 18), the dark-halo crater and the braided secondary crater features radial to crater A (site 2 in fig. 5), an irregular forked rille (site 3 in fig. 5), and the mare ridge and fresh crater in the western part of the central mare basin (site 4 in fig. 5).

In addition to achieving the objectives described immediately above (4), short local missions could profitably be assigned to each of the major photogeologic units illustrated in figure 6. A 5-km radius mobility limitation would restrict these missions to slightly less than the width of one of the photograph framelets. Five or six such missions would probably permit observation and sampling of each of the photogeologic units. Samples obtained on such

missions could not be expected to represent the variety of lithologies likely to exist in any single regional unit. This approach to solving the major questions about the Orientale region has the obvious disadvantage of requiring extrapolation of interpretations over large areas between sites.

Long-distance open-ended traverses conceptually overcome many of the scientific handicaps of local closed-loop type missions. However, traverses as long as those shown in figure 3 (1,000 km straight line), apart from the high cost of new systems development, require crossing of very rough-appearing terrain such as the outer rim of the Orientale basin. It does not seem practical to attempt this kind of crossing very early in the extended mobility program. The same distance capability could be utilized to cover a greater variety of areas critical to the interpretation of the entire basin, with the important proviso that a continuum of information be developed between the critical sites. In terrestrial geologic fieldwork, a common result of hopscotching between distant outcrops is that backtracking to intervening areas is required to fill in vital gaps in the information.

Figure 5 illustrates a compromise traverse of intermediate length (415 km in the manned mode) designed to fulfill all the objectives listed above except for surface coverage of the outer ring and rim areas of the basin. If such information becomes critical to the overall picture, as seems likely on the basis of present interpretations, a subsequent traverse based in Mare Autumni would be a logical recommendation. The roughest terrain that requires surface traversing in figure 5 is in the "smooth terra" category ($<15^\circ$ slopes at 0.5 km resolution).

Traverses of this range would be most productive if they were open ended and conducted in a self-contained mobile laboratory by three or more astronauts. LFU's would be needed to visit the rims, walls, and floors of craters A and B (fig. 5), as well as the scarps of the Rook Mountains, and for investigating the accessibility and geology of the concentric and radial rilles between

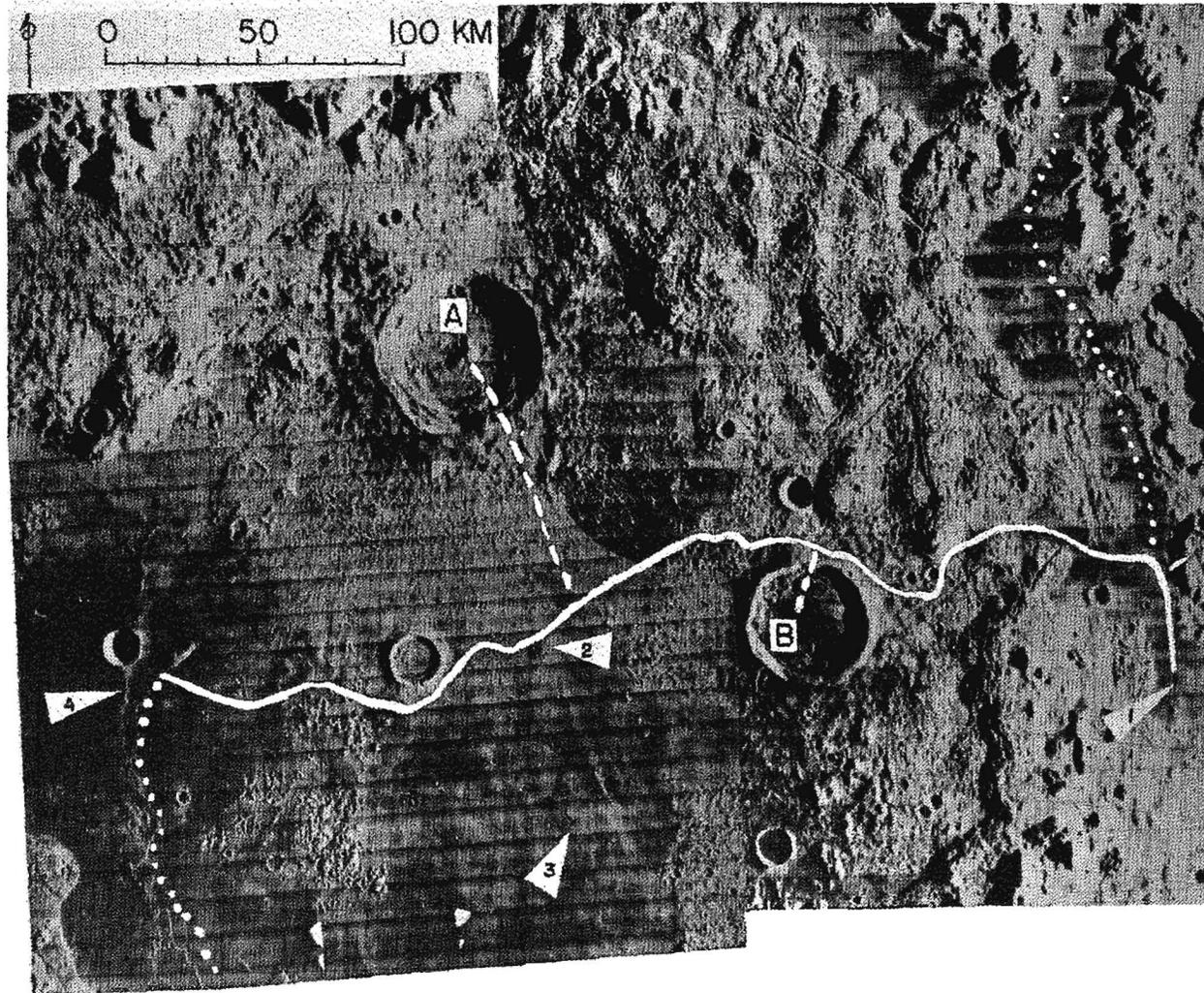


Figure 5.--Alternate traverse areas for short and intermediate duration missions. Northeastern sector of central Orientale basin. (Solid line, manned LRV; dotted line, unmanned LRV; dashed line, LFU traverse.)

Mare Veris and crater B. Open vehicles with one- or two-man crews would be a tenuous proposal for a mission of this scope; with any further reduction in scope, however, the mission would soon approach a superficial investigation of individual features that could hardly solve the major problems of this region. In the automated mode, either vehicle could very profitably precede or follow the manned mission to obtain more extensive visual and possibly geophysical coverage of the smooth terrain in Mare Veris or the central mare basin.

If all attempts to study the Orientale basin by surface exploration in the near future were judged as too ambitious, an alternative traverse directed toward the understanding of multi-ring lunar basins could be designed across the concentric structure (375 km diameter) enclosing the crater Grimaldi northeast of Orientale (fig. 3). The terrain of this area has not been analyzed in detail; however, the dark mare has a very low crater density and thus may be the youngest mare in the region. Although the Grimaldi structure is more degraded and appears older than Orientale, its outer ring and two concentric scarps may provide answers to some of the same problems posed by the larger basin. The terrain appears passable in most areas and is amenable to the same mobility concepts discussed above.

Craters with concentric ring structures such as these on the west limb of the Moon differ from craters of similar size elsewhere, which generally lack multiple rims. This type of evidence suggests that such concentric structures may reflect crustal or subcrustal discontinuities which may be lacking in other areas and is additional justification for study of such large-scale features elsewhere on the Moon. In the last section of this report, current geologic interpretations and areas requiring surface investigation to resolve scientific problems are discussed in detail.

RECOMMENDATIONS FOR CONTINUED
TRAVERSE RESEARCH

It is the author's belief that the scope of planetary exploration will be extended beyond the present limited goals of the lunar program. Orderly and timely planning for such efforts is essential. In the field of traverse research, the lead-times required to analyze the scientific and engineering basis for long-range vehicular exploration are measured in years, even with the benefit of studies that commenced several years ago.

Among the 10 fundamental scientific disciplines listed by the Summer Conference on Lunar Exploration and Science at Falmouth. (Natl. Aeronautics and Space Adm. , 1965; Lockheed Missiles and Space Co. , 1967), four are included within the geosciences. These are geodesy/cartography, geology, geochemistry, and geophysics. Success in interpreting the Moon's origin and history, as well as the Earth's, will require the integration of all these disciplines which must be incorporated into a unified program of investigation. A vehicular traverse profile for geologic exploration should include the following basic activities:

1. Visual and photographic observation of the lunar surface
2. Sampling of lunar surface and subsurface materials
3. Textural, mineralogical, and chemical analyses of lunar samples
4. Active seismic refraction/reflection measurements
5. Measurement of remanent and total field magnetism
6. Gravity measurements
7. Heat flow measurements
8. Distribution of remote geophysical monitoring stations
9. Measurement of basic engineering properties of surface materials
10. Determination of vehicle position continually along traverse in both geographic and elevation coordinates.

Cartographic base maps and topographic profiles are the primary formats for the compilation and comparison of the geologic and geophysical data that will be gathered. Ground control for these maps will be obtained by geodetic techniques during the missions. However, accurate photographic and topographic maps must be available for mission planning from an engineering aspect as well as for attaining maximum scientific results.

Selected parts of the Orientale basin should be rephotographed with optimum Sun angle and exposure values for photogrammetric reduction so that high-quality base maps can be prepared. These photographs and maps should provide the engineering data necessary for quantitative analysis of the terrain and its potential trafficability. A resolution of 1 or 2 meters is required to produce data meaningful at the scale of a vehicular traverse. For example, in determinations of the power spectral density function of terrain units, analysis of terrain frequencies with 2-meter wavelengths requires 1-meter resolution.

The following alternative recommendations for new Orbiter photography of the Orientale region are based on discussions with several U.S. Geological Survey geologists and photogrammetrists who have been concerned with lunar photography since the beginning of modern lunar investigations:

1. A metric camera of conventional 6-inch focal length should be adapted to future orbital flights, manned or unmanned, and film return should be made a primary requirement of the mission in accordance with the report of the Geodesy/Cartography working group (Hess, 1967, p. 302). Twelve- and 24-inch systems also have desirable characteristics. The 24-inch fixed-lens camera has simpler data-reduction requirements than the panoramic system.
2. An electro-mechanical scanning system similar in principle to that developed for Ranger by Philco's Aeronutronics Division should be adapted for use on Lunar Orbiter missions as soon as possible. Although this system has not been flight tested, it

can provide imagery in any or several parts of the ultraviolet through near-infrared spectrum. Theoretically it has better resolution qualities than metric cameras, and, in contrast to film cameras, the number of pictures it can produce is nearly unlimited. J.D. Alderman of the U.S. Geological Survey is presently investigating this facsimile system and its applications.

3. If neither of the above recommendations is feasible at this time, another Lunar Orbiter should be flown with the same camera system used on earlier missions, but with the primary objective of getting selected photographic coverage of the Orientale basin region at 2-meter resolution.

In the event that improved Orientale photography is not feasible in the foreseeable future, the U.S. Air Force Aeronautical Chart and Information Center's techniques for producing topographic maps from available Lunar Orbiter II photography (U.S. Air Force, 1968) should be followed up by further research in photometric-photogrammetric reduction of Lunar Orbiter IV photography, particularly in the Orientale region.

For the next fiscal year, the following activities are proposed for the Advanced Systems Project:

1. Continue a comparative study of specific traverse routes including appropriate scientific experiments for missions 200 to 2,000 km in length, designed to construct a complete geologic cross section of the eastern half of the Orientale region and alternately the Grimaldi structure in order to interpret the stratigraphy and structure of a large multi-ring lunar basin and to apply such knowledge in recommending traverses for older buried basins such as Mare Imbrium.
2. Develop application of the analytical plotter to nonconventional photography. Continue using photogrammetric techniques to obtain the topographic data needed for geologic evaluation of specific traverse routes in the Orientale basin. Results of the Trafficability Project will be incorporated as they become available.

3. Relate engineering properties of lunar soils to mobility characteristics of proposed lunar vehicles. The study will combine results from Surveyor and Lunar Orbiter investigations with measurements in analogous terrains on Earth. Preliminary investigations have commenced in the Cinder Lake crater field near Flagstaff, Arizona, with the assistance of T. L. Youd, a U.S. Geological Survey soils engineer. The initial effort will attempt to define what basic soils properties may be reflected in the measurable upper slopes of small craters. In effect, the fresh crater morphology, precisely known, may permit predictions regarding trafficability that are also related to geological interpretations of the surface and near-surface materials.

The Advanced Systems Traverse Research Project, together with related investigations (lunar geologic mapping, terrain analysis, trafficability, and mission planning) will define specific problems in applying photo-interpretation and terrain studies (utilizing techniques of photogrammetry, analytical parallax, and shadow measurements) to geology and to trafficability. The program may be augmented by suitable terrestrial experiments. These experiments can be incorporated into the Advanced Systems Traverse Research Project by use of (1) high-altitude photography and other remote-sensing data, if they can be obtained, with and without available topographic base maps, and (2) the U.S. Geological Survey's Mobile Geological Laboratory or possibly one of the Mobility Test Article vehicles from Marshall Space Flight Center. The eastern and northern parts of the San Francisco volcanic field in Arizona provide good analogs of lunar topographic features and would be appropriate for this type of experiment. Remote-sensing data are already available or are scheduled to be obtained for most of that area, and geologic control is well established in several places.

PROBLEMS FOR GEOLOGIC INVESTIGATIONS OF THE
ORIENTALE REGION OF THE MOON

By R. S. Saunders

Introduction

When Lunar Orbiter IV transmitted photographs of the Moon's southwest limb to the Jet Propulsion Laboratory in Pasadena, Calif., one of the most spectacular features photographed during the Unmanned Exploration Program was revealed. Earlier photographs of the Orientale basin, taken from Earth, were tantalizingly obscure. The new photographs show that it is a distinct, symmetric bull's-eye some 500-900 km across. One scientist was moved to remark that were this feature visible from Earth, a whole mythology would have developed about a "great eye." Geologists now have the opportunity to study a large young multi-ring basin: here is a model for a young Nectaris, Humorum, or Imbrium. Orientale still bears many of the birthmarks which have been obliterated or obscured in the older basins. By studying a youthful counterpart to the Appennine Mountains or the Fra Mauro Formation, much more can be learned about the origin of large basins, and the effects of various surface-shaping processes can be seen in detail.

The purpose of this section is to review various theories of the origin of the Orientale basin and to recommend areas where surface exploration might solve local and regional geologic problems. There are two hypotheses: (1) the basin is endogenetic; i.e., it has been produced by volcanic and tectonic processes, and (2) the basin and related features were produced in response to the disequilibrium caused by impact of a body of asteroidal dimensions. Although volcanism and tectonism may also be involved in the second hypothesis, the initiating force is external.

Physiography

Mare Orientale is a large young multi-ring basin on the extreme southwest limb of the Moon. About one-half of the basin is visible from Earth, and only at times of maximum libration. The

name Orientale was first used by Franz (1913). Wilkins, however, made the first detailed drawings of the feature (Wilkins and Moore, 1961).

For this discussion, the Orientale basin has been divided into four physiographic divisions: (1) the central mare basin and (2) the inner ring between the central mare and the Rook Mountains; (1) and (2) together form the central basin; (3) the outer ring between the Rook Mountains and the Cordillera Mountains, and (4) the outer rim (figs. 1, 6). McCauley (1967a) has identified five rings surrounding the dark mare of the central basin. The inner two, 360 km and 480 km in diameter, are rings of blocks between the central mare and the Rook Mountains. The Rook Mountains comprise the third, and the Cordillera scarp the fourth. The fifth ring is indistinct and consists of elevated pre-Orientale crater walls.

The most striking of the annular features are two nearly continuous inward-facing scarps. The outermost scarp marks the front of the Cordillera Mountains. These have a local relief of about 3,000 meters. The Cordillera ring has a diameter of about 930 km. It encloses the Rook Mountains, which make up a second slightly less continuous concentric scarp. These mountains form a ring 700 km in diameter with local relief matching that of the Cordillera.

Also contributing to the striking annularity of the basin are a number of distinctive units that lie in and around the basin (refer to fig. 6). Dark mare occupies a subcircular central basin 325 km in diameter. Within the inner ring between the central mare and the Rook Mountains are four terrain types, distributed in a crude circumferential pattern. The first consists of plains of higher albedo than the mare and elevated a few meters above it. The boundary between the two is marked by a low irregular scarp. These plains are not present in the northern and eastern parts of the basin. The second terrain type consists of broad, rolling hills typically about 10 km across and generally longer in the in the direction radial to the basin. The unit is best developed

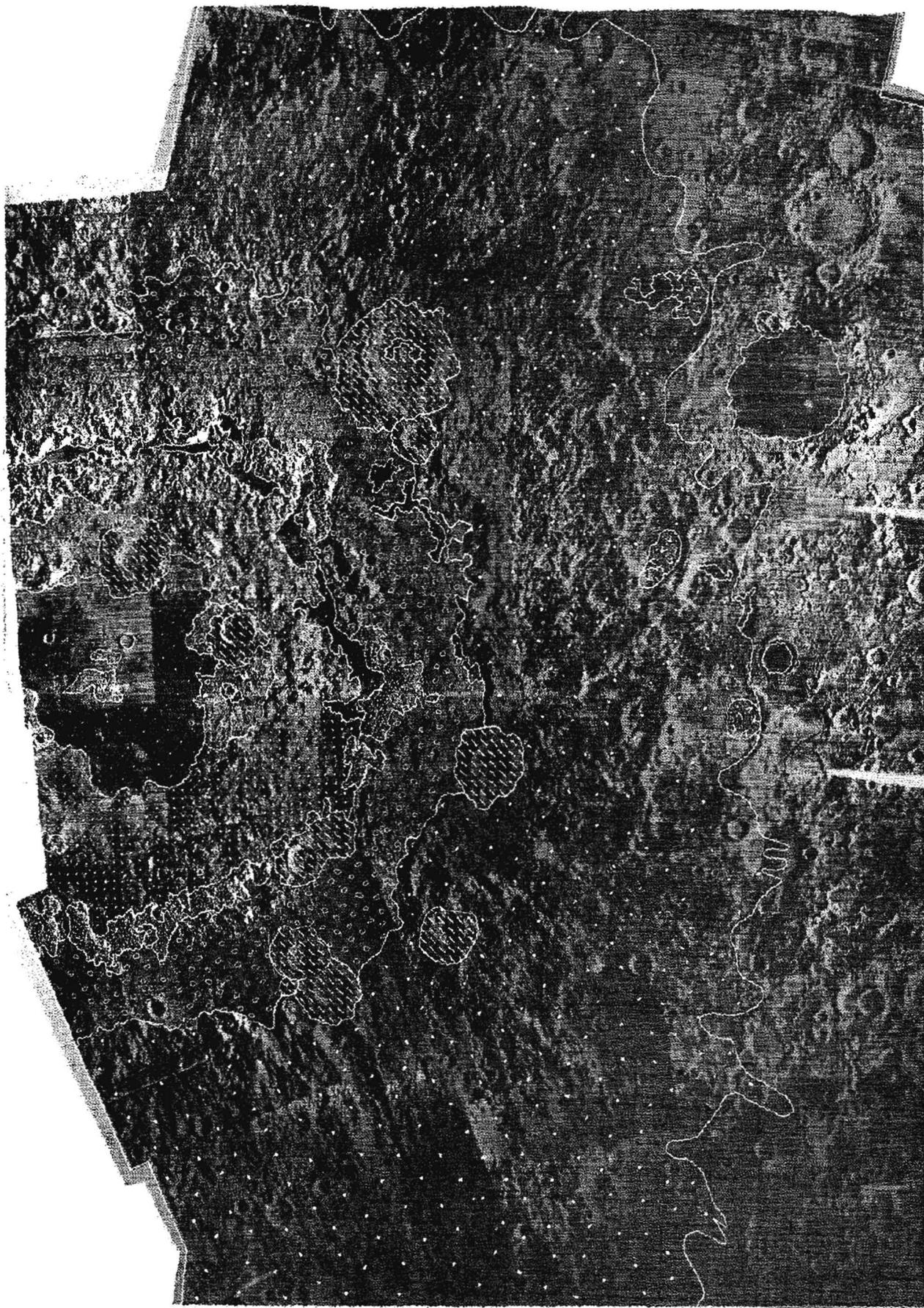


Figure 6.--Preliminary photogeologic map of the Orientale basin region (by J. F. McCauley).



Crater materials, undivided



Mare material

Dark plains material, which fills local depressions in center of basin, in Mare Veris at the base of the Rook scarp, in Mare Autumni at the base of the Cordillera scarp, in Mare Aestatis, and in the central parts of Grimaldi, Crüger, Schlüter, and Riccioli.



Central basin plains material

Includes smooth light plains material and material of closely spaced rolling, highly fractured hills. Appears to mantle pre-Orientele terra material. Is restricted to Orientele basin within Rook Mountain scarp. Contains several large collapse depressions. Surface texture is grossly similar to that on floors of young craters such as Tycho and Aristarchus. May consist of impact-melted materials or volcanic materials which filled the lowest part of the basin shortly after its formation.



Montes Rook Formation

Forms small closely spaced smooth hills. Weakly to moderately lineated but not coarsely braided like the Cordillera Formation. Contains local patches of moderately smooth terrain. Contact with Cordillera Formation is locally gradational. Occurs mostly between Cordillera and Rook Mountain scarps but northwest of Schlüter occurs outside depressed part of Cordillera scarp. Also occurs in patches in center of basin. Origin uncertain. May consist mostly of fallback from the base surge column. Alternatively, may consist of intensely fractured rim material which was originally similar to the Cordillera Formation but slumped inward during crater filling and scarp formation, thereby modifying the primary surface texture.



Radially braided material

Cordillera Formation

Radially braided material. Characterized by coarse to fine subradial ridges and grooves with a swirly to braided texture. Occurs mostly outside Cordillera scarp and completely surrounds Orientele basin. Extends farthest from basin towards the north and south. Overlies complexly cratered older terra surface. Braided texture becomes progressively less distinct with increasing distance from the basin, as thickness apparently decreases. Becomes indistinguishable from cratered terra materials in vicinity of Grimaldi, Darwin, and Byrgius.



Transverse ridge material

Transverse ridge material. Characterized by fine dunelike structures oriented circumferentially to the basin and at right angles to the lineation of the radially braided material. Occurs on distal walls of pre-Orientele craters. This unit is not present within 300 km of the Cordillera scarp. Composed of base-surge materials whose radial momentum was dissipated at the base of obstacles such as crater walls.

Consists of ballistically deposited ejecta overlain by base-surge deposits of unknown thickness; both materials produced by the impact of an asteroidal body near the center of Orientele.



Pre-Orientele terra material

Mapped only within Orientele basin. Forms smooth-textured large blocks often with rectilinear outlines. Occurs mostly in Rook Mountains but also present in the inner ring. Probably consists of highly fractured pre-Orientele bedrock of diverse origin. Present surface expression suggests that these blocks have been structurally depressed less than the materials of the adjacent crudely concentric troughs. Fallback and rim deposits thin to absent at surface.

south of the central mare. The hills are irregular on a 1 km scale and are highly dissected by fractures up to 1 km across. The third terrain unit of the inner ring is transitional with the rolling topography. It consists of isolated massifs or areas of steep hilly topography on the outer fringe of the rolling hills as in the southeast. This terrain is very similar to that of the Rook Mountains. The fourth terrain type at the foot of the Rook Mountains nearest the central basin is an incompletely developed ring of dark smooth mare (Mare Veris) which is similar to that of the central mare basin.

The outer ring between the Rook and Cordillera Mountains contains three distinct terrain types. First, the Rook Mountains comprise a ring of rugged, blocky topography up to 75 km wide. The relief is most pronounced on the central basin side. Opposite the basin, individual blocks tend to merge into the second type of outer-ring terrain, which is hummocky on a 1-km scale, somewhat like the rolling topography inside the Rook Mountains. The surface, although rough at a 1-km scale, is level on a 10-km scale. This area is more homogeneous than the other units. The belt ranges from 80 to 115 km in width. The third terrain type of the outer ring is an area of dark smooth mare (Mare Autumni) similar to the fourth terrain type in the inner ring. This occurs at the foot of the Cordillera scarp. This mare is only developed in a few places, all on the east side of the basin.

The outer rim of the Orientale basin can be recognized for at least 300 km beyond the Cordillera Mountains. It has a coarsely braided texture making it the most distinctive terrain type. In some areas it resembles a series of interlocking chevrons which open away from the basin. There are a number of radial grooves, the largest of which is on the southeastern rim. Beyond 300 km from the Cordillera scarp the texture becomes less apparent until it is indistinguishable from the surrounding highlands or mare surfaces.

Pre-Orbiter Observations and Interpretations

Geologic interpretations of the Orientale basin from Earth-based telescopic observations were made by Hartmann and Kuiper (1962), Hartmann (1964), and McCauley (1964b). These interpretations were based in part on the excellent limb drawings produced by Alike Herring (1962).

This early work is of interest because it demonstrates what can be done even with incomplete telescopic data (fig. 7). Hartmann and Kuiper (1962) discussed the similarity between Mare Orientale and other multi-ringed basins such as Mare Nectaris and Mare Imbrium. They noted the patches of smooth mare material which occupy valley floors adjacent to the inner faces of the steep arcuate scarps. They interpreted these as pools of lava which had welled up along faults associated with the scarps. Hartmann (1964) described the basin in considerable detail with particular attention to the radial structures. In his interpretation, dark mare material came up from a depth which was reached only by fractures in the center and along the concentric scarps. The larger radial valleys and associated craters were interpreted as genetically related structural features. The asymmetrical north-south distribution of the radial structure system was noted and attributed to a nonvertical impact.

McCauley (1964b) took the stratigraphic approach to the geology of Mare Orientale and described for the first time a blanket of materials surrounding the basin and resting on an older cratered surface. At telescopic resolution the materials appear to be hummocky and to partly fill older craters. The two largest craters within the blanket, Riccioli and Grimaldi, are partly filled but their floors are, in turn, flooded by later mare material. The thickness of the blanket decreases out from the basin center, as suggested by the fact that the depth of fill of older craters is progressively less away from the basin. McCauley informally named this blanket the Cordillera Group and interpreted it to consist of a mixture of crushed debris derived from the center

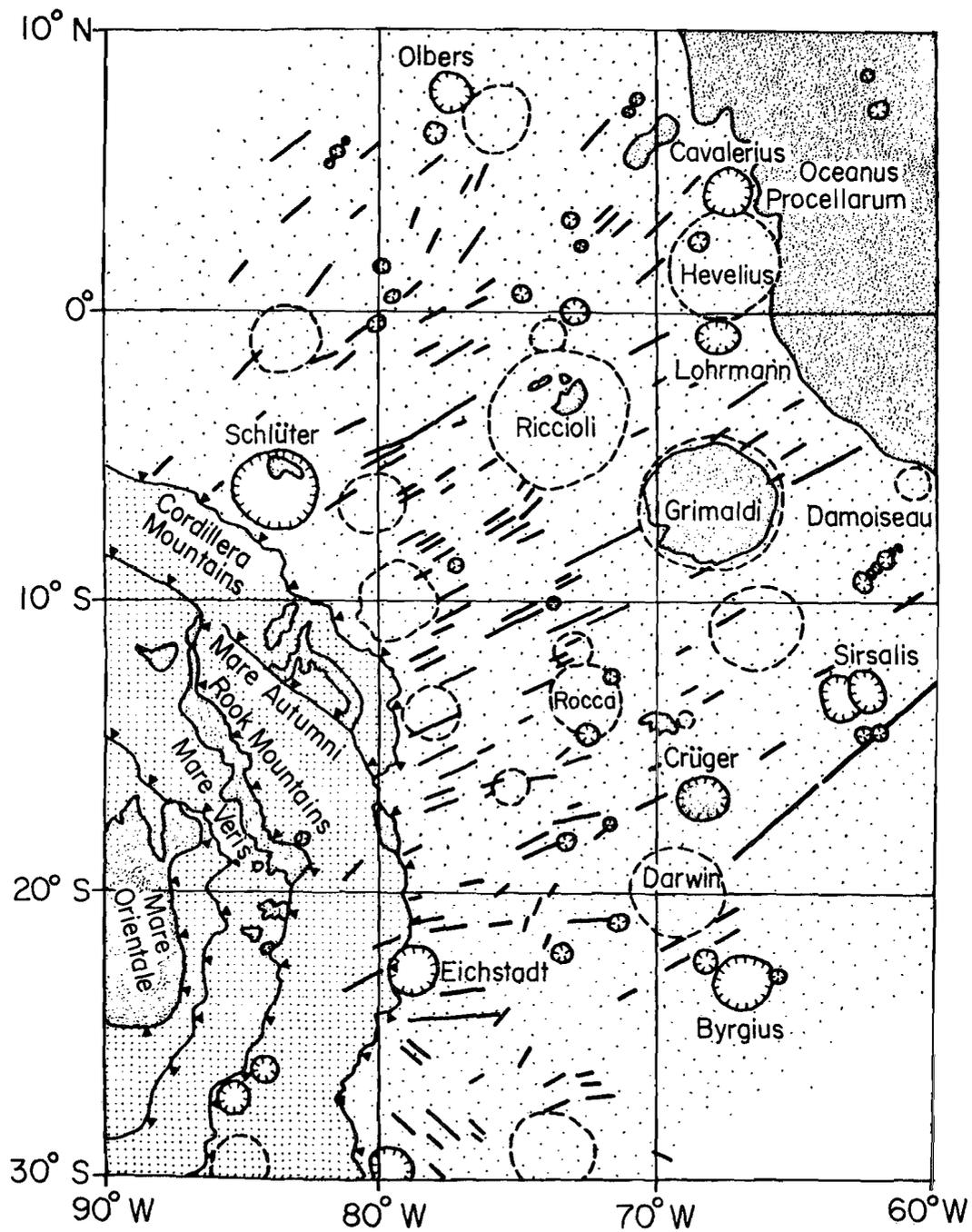


Figure 7.--Sketch map of Mare Orientale region prepared from Earth-based telescopic photography. (From McCauley, 1964, 1967b.) Scale approximately 1:7,000,000.

Explanation



Craters superposed on hummocky material from Mare Orientale.



Dark mare material filling craters and large basins.



Material without prominent radial structure on benches between concentric scarps.



Hummocky to smooth material on rim of Mare Orientale. Combination of radial and concentric structure gives a pronounced "blocky" texture within several hundred kilometers of the Cordillera scarp.



Pre-Oriental craters partly or completely mantled with hummocky to blocky material from Mare Orientale.



Scarps concentric with Mare Orientale. Barbs point toward the foot of the scarp.



Linear structures (mostly faults) radial to Mare Orientale.

of the basin. Two subunits were recognized but not formally defined pending the acquisition of better photographs. These were: (1) the material between the Cordillera and Rook Mountains which has no buried craters and appears much smoother than the rim material at telescopic resolution, and (2) the more coarsely textured rim material.

McCauley concluded that the major features were formed by a combination of impact and volcanic processes. The basin itself was excavated by a large meteorite which threw out debris and blanketed an area 1,000 km in radius. The concentric scarps and radial fractures formed contemporaneously with the blanket. Extensive volcanism occurred during Imbrian time and flooded the central basin of Orientale and many of the nearby craters.

Geologic Interpretations Based on Orbiter Photography

Several hypotheses of the origin and history of the Orientale basin may be set up from photogeologic interpretation of Orbiter photography using stratigraphic principles similar to those adopted by McCauley (1964b) and drawing from studies of terrestrial analogs. The preliminary tests for these hypotheses lie in whether or not they are consistent with the presently available photographic data.

In contrast to the impact origin previously proposed by Hartmann, Kuiper, and McCauley, Green proposed a volcanic origin for the basin (Oriti and Green, 1967). He interpreted the concentric features as ring dikes and cone sheets. The origin of such features has been described and discussed in some detail by Anderson (1936). Green's model calls for regional doming and development of subradial and concentric fractures. Collapse of the dome caused the formation of inward-facing tangential scarps. These tangential fractures filled with volcanic material to form ring dikes. Later doming or explosive phases may have formed cone sheets. Chain craters developed along radial fractures.

Green's analysis is incomplete, however, because he did not discuss the obvious braided rim facies or the secondary craters

which may be identified out to at least 1,500 km. The secondary craters closely resemble those that form as a result of major impacts. However, Green's central argument that the major scarps appear to have formed as a result of collapse is also consistent with an impact origin as developed by McCauley (1967a, b). In McCauley's interpretation, the initial event was the impact of an asteroid at the center of the present inner basin. The shock wave that was propagated outward caused large crustal segments to be thrust up and outward. The subsequent shock-wave rarefaction resulted in crater excavation. Although much of the high-angle ejecta probably reached escape velocity, the low-angle ejecta impacted the lunar surface and formed secondary craters. A base surge produced by the collapse of a dense column of ejecta over the basin formed the braided rim deposit. The concentric scarps formed shortly after crater excavation by gravitational collapse along circumferential fractures. Subsequent volcanic activity produced the mare and plains materials which occupy the central basin and low areas adjacent to the scarps.

Although the interpretations by McCauley and Green are very different, they agree on a history involving volcanic activity for the region. There is also agreement on the formation of the scarps by collapse.

That volcanism occurred during Orientale's later history is by no means certain. Mass-wasting processes may have modified an initial impact crater to produce the present physiographic features. This situation is one member of a series of possibilities: volcanism only, impact and volcanism, impact and primarily mass wasting. Mass wasting is probably an element of all members of the series.

The idea that large mare areas may form solely by mass wasting has been proposed by Gold (1955). The argument has been weakened by evidence from the large-scale photographs by Ranger, Orbiter, and Surveyor missions. Mass wasting as the origin of mare and plains areas implies total homogenization of the materials.

However, lateral variations in mare stratigraphy are visible in Orbiter photographs. Vertical variation (i.e., horizontal layering) is implied by the blocks and terraces associated with fresh craters larger than a certain limiting size (Eggleton, 1967a). This size varies from region to region. Fragmental material may overlies dense cohesive material which provides blocks and forms terraces in the larger craters. If these blocks are all "instant rock" produced by compaction of fragmental material, then it is difficult to explain why the lower size limit of fresh craters with block fields varies from one mare area to another. Field studies of fresh craters produced by missile impacts at White Sands, N. Mex. (H. J. Moore, personal commun.) indicate that the total amount of "instant rock" in the ejecta blanket is a relatively small proportion of the total ejecta--most blocks are quarried from shallow layers of weakly cohesive material and are not shock lithified.

In the remaining discussion, a number of features from the Orientale basin are described in the context of various geologic interpretations. It is pointed out how these or similar features may support or detract from particular arguments and how manned surface investigations may provide the necessary answers. The resolution of the present photography (approximately 70 meters) limits the consideration to large features.

The photogeologic map (fig. 6) and index (fig. 1) will aid in the location of these examples with respect to major basin features.

The central basin mare resembles typical mare elsewhere on the Moon. Before exploration of Orientale becomes a reality, much will be known about mare materials and detailed comparisons will be possible.

One of the mare structures in Orientale is an irregular ridge in the western part of the central basin (fig. 8). It resembles wrinkle ridges seen in other mare regions. Baldwin (1963) stated that wrinkles in the mare surfaces imply a compression effect.

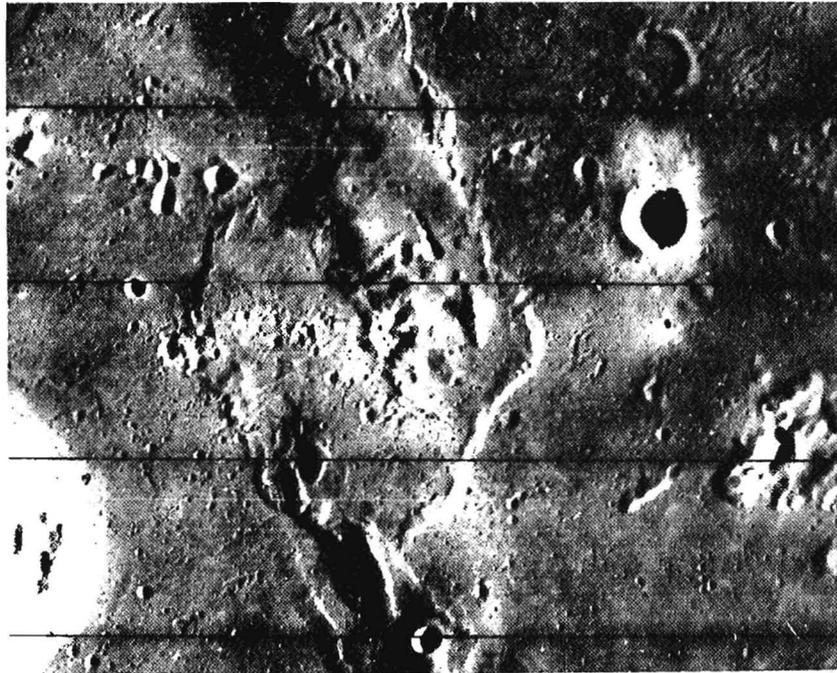


Figure 8.--Part of wrinkle ridge. Scale 1:500,000.

The mechanism for this compression may be isostatic readjustment to the weight of the mare flows or withdrawal of molten magma back into the Moon's interior before a thick surface crust has formed. Wrinkle ridges should tend to form over subsurface obstructions in shallow areas where the adjustment to the compressional stress is inhibited.

The central basin of Orientale is barely large enough to provide enough shortening by evacuation of material in the manner postulated by Baldwin. However, there is an association of the wrinkle ridge with an underlying ridge of floor material. Rough portions of floor material appear to be exposed in places along the ridge. Evacuation of molten material from below the thin crust may have caused the ridge to form where the crust had become welded to underlying floor material. Another ridge farther eastward extending from the south edge of the central mare shows the same relationship.

The wrinkle ridges in Orientale would be structural features by this interpretation. The margins are indeed bounded by low scarps; the more rugged material seen in the central part of the ridges should be composed of brecciated floor material. The scarps at the margins of the ridges should provide a vertical section of mare material and may provide clues to the crystallization history of this mare.

Evacuation of magma from the central part of a volcanic flow may cause scarps to form on the margin of the flow or around protruding older rocks (steptoes). These scarps are called slump scarps (Finch, 1933) or lava subsidence scarps (Sharpe, 1938). Owing to shrinkage and loss of gas, the height of these scarps may be 20 percent of the thickness of the flow (Macdonald, 1954, p. 133-134). Evacuation of magma and shrinking are processes which commonly produce slump scarps in Hawaii. The decrease in volume of fill in Halemaumau in 1954 was about 52 percent, suggesting that as well as shrinking, the lava drained back into its vents (Macdonald and Eaton, 1957).

Several mare structures provide evidence in support of the interpretation of collapse around protruding blocks on the floor after the evacuation or shrinkage of magma. In figures 9 and 10, the blocks that rise above the general surface appear to be supported by steptoes where molten material became frozen around blocks of floor material and remained elevated when the surrounding area subsided. The west-facing scarp of the block in figure 9 rises 425 meters above the mare surface. The subcircular depression at the south end of this block is a subsidence feature with a low rim on the west side. This rim rises about 140 meters above the mare outside the depression. The rim could be composed of volcanic materials and the depression itself may be a pit crater which has subsided along fractures produced during the initial shrinkage or draining of the mare material. This region should be studied during ground traverses. Cross sections of mare material may be displayed on the sides of the elevated blocks. The calderalike depression should be studied to determine whether there are associated volcanic materials.

The low scarp between the light plains and the mare of the central basin is probably a slump scarp (fig. 10). The higher albedo material appears to be slightly older mare-like filling. After withdrawal or shrinkage of material in the central mare basin, the darker mare flooded the area up to the slump scarp. The depressed block in figure 10 is probably bounded by fractures in the light plains and not related to deep-seated fractures.

A calderalike crater about 35 km in diameter occurs at the eastern rim of the central mare basin. The most enigmatic feature of this crater is a rim deposit which subdues adjacent topography (figs. 11, 12) and is thus clearly younger (Eggleton, 1967b; McCauley, 1967a). If this were ejecta from an impact crater, one would expect to find secondary craters on the surrounding terrain (see fig. 13, an impact crater 150 km northwest of this crater). None have been identified. The crater could have formed by impact before the dark mare was emplaced, and the dark mare could have



Figure 9.--Slump scarp around step toe and collapse depression. Scale 1:500,000.

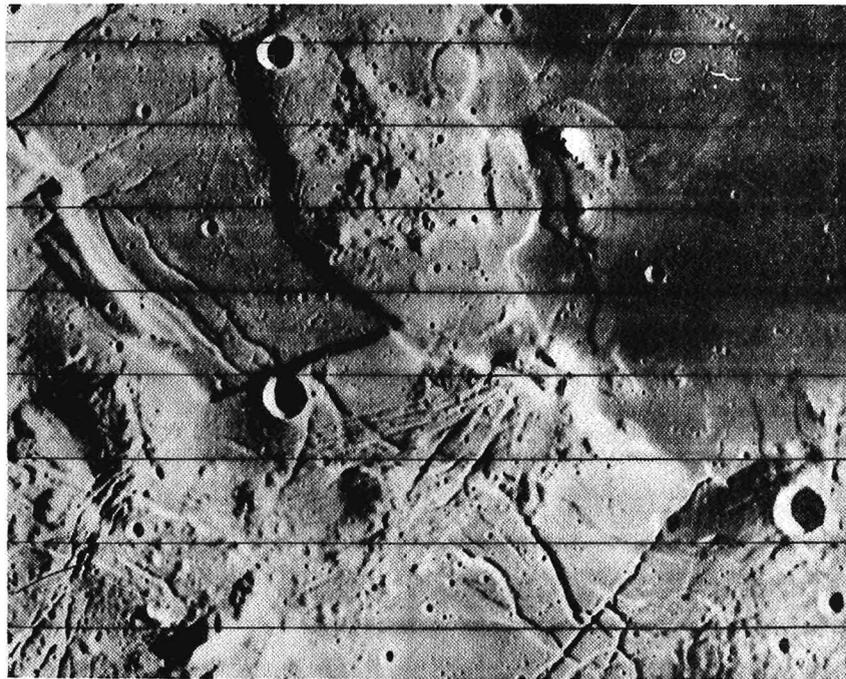


Figure 10.--Slump scarps along margin of central mare basin outlining collapse depression. Scale 1:1,000,000.

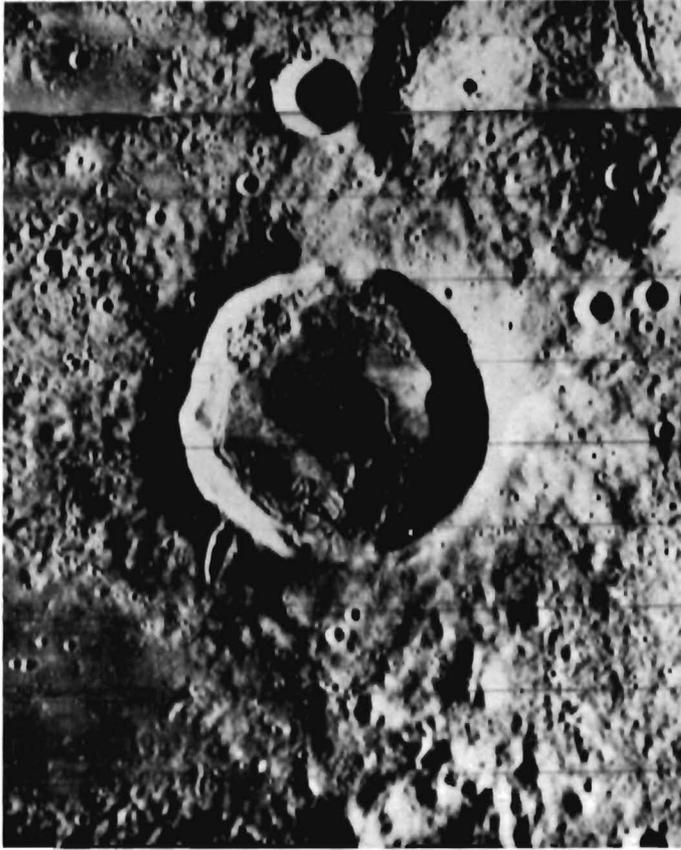


Figure 11.--Possible caldera. Note how texture is slightly subdued for a distance of several kilometers out from the rim. Scale 1:1,000,000.

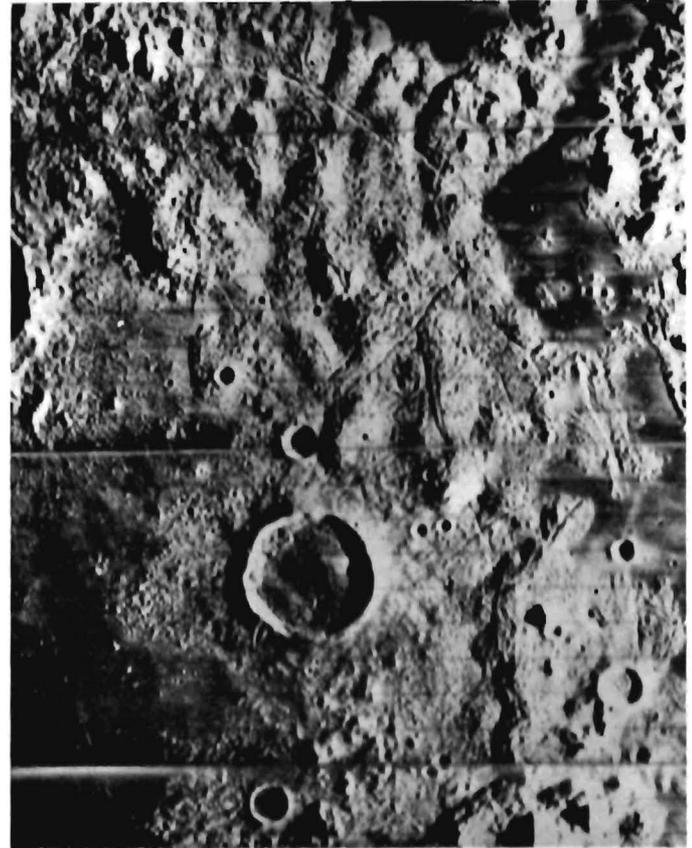


Figure 12.--Northeast quadrant of inner ring showing central basin material and mare units. Scale 1:2,500,000.

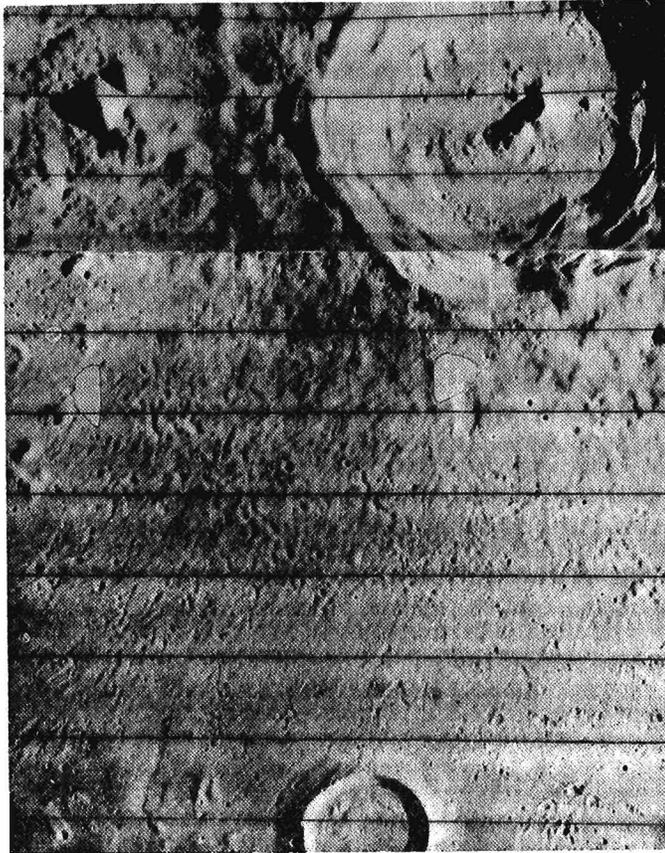


Figure 13.--Impact crater and secondary craters. Scale
1:1,000,000.

later obliterated the secondaries. The original rim may, therefore, be modified by recent volcanism along fractures formed by the impact, thereby obliterating the original topography. McCauley (1967a), however, pointed out that large rim troughs and terraces are produced around impact craters. These features have not been found in volcanic craters. The crater in question is too young and too large to have lost these diagnostic features by any combination of mass wasting and volcanism. On the basis of detailed comparison of the form and stratigraphic relations of this crater and the impact crater 150 km to the northwest, McCauley concluded that two primary crater types are present on the Moon. Those with the exterior troughs and terraces are impact craters; those with smooth exterior rims are volcanic in origin. Detailed study of

both these features during manned exploration may resolve finally the problem of lunar crater genesis. If McCauley's thesis is correct, both impact and volcanic craters are present and they can be distinguished by objective photographic criteria if the craters are not severely modified and if the quality of the photographs is sufficient to show the fine details of rim morphology. A ground traverse could establish whether the rim is purely of a constructional volcanic nature, and thus the crater is a caldera, or is composed of impact breccia mantled by a few meters of volcanic material.

The surface texture of the material adjacent to the central mare in the southern, eastern, and northeastern parts of the inner ring is unlike that of the light plains material. It is rough on a 1-km scale and is characterized by broad domical hills on a 10-km scale. This hilly facies of the central basin plains material may have been emplaced as lava flows at the same time as the light plains. When the draining or shrinkage of the plains material occurred, this material would have draped down over large blocks of floor material to form the broad rolling hills (figs. 14, 15).

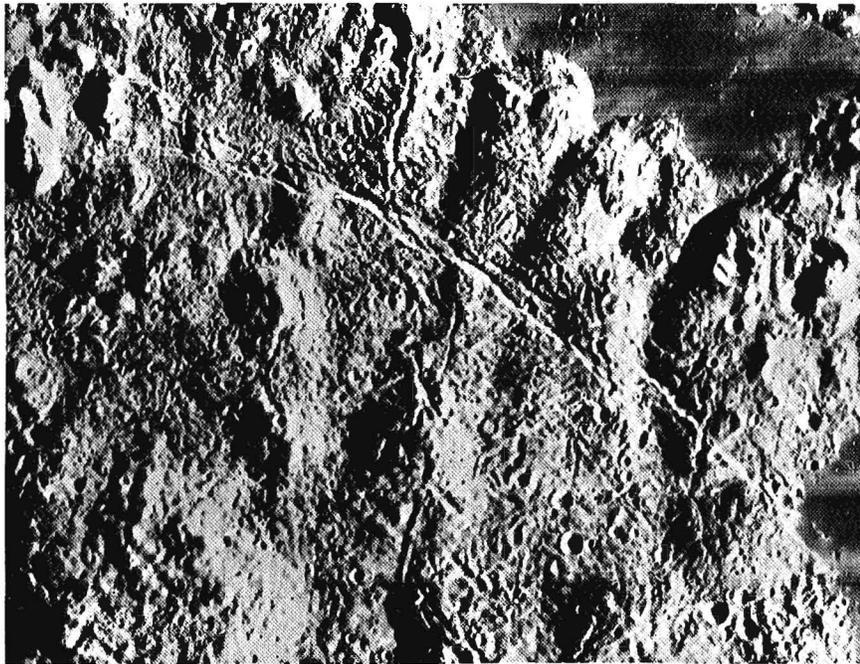


Figure 14.--Lobate hills in central basin plains material.
Scale 1:1,000,000.

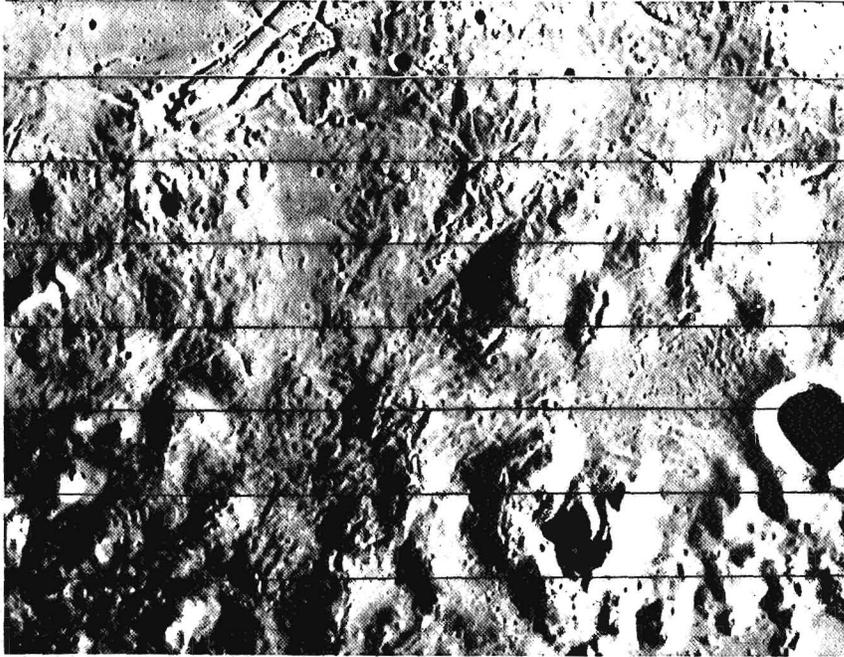


Figure 15.--Southern part of inner ring showing hilly central basin plains material. Scale 1:1,000,000.

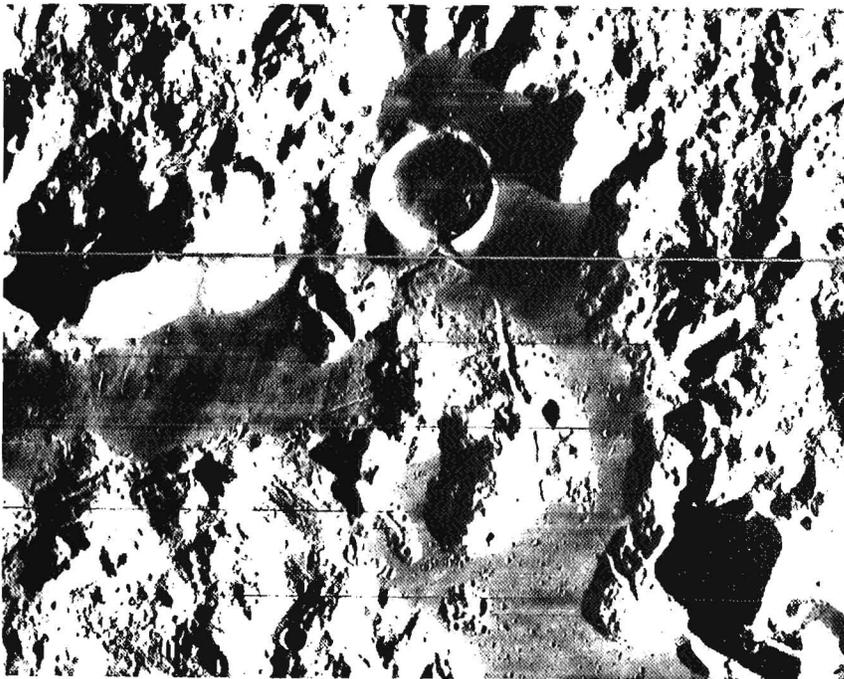


Figure 16.--Breached crater in Mare Veris, at base of northern Rook Mountains. Two periods of flow activity indicated by rille breaching southern wall which is itself covered by more recent material. Scale 1:1,000,000.

Large blocks similar to those which may underlie these domical hills occur in many places as a ring just inside the dark plains material (Mare Veris) of the inner ring (figs. 1, 6).

An alternative interpretation is that this material is impact-melted breccia (suevite). Such material might have been in a semi-molten state and would have flowed back into the central mare basin. Blocks and other irregularities in the floor would be draped by it and would impede its flow. This may explain the roughly radial disposition of the domical hills. The surface of the suevite would be covered with blocky ejecta which fell back into the basin. A third possibility is that ash flows in a very low-density gas-filled state, welled up in the central basin and then settled down over blocks on the floor (McCauley, personal commun.). These possibilities could be checked by ground traverse. Welded volcanic ash may closely resemble lava flows. Suevite would contain evidence of shock effects either as lamellae, selective vitrification, or other petrographic features (Chao and Littler, 1963). Laboratory analyses of samples and thin section study could resolve this problem.

Mare plains occur adjacent to the hilly facies, at the foot of the Rook Mountains. These plains, which resemble the central mare both in albedo and crater frequency, have several features of geologic interest associated with them. One such feature, a breached crater about 15 km across (fig. 16), is occupied and surrounded by plains material. Several sinuous rilles partly filled by mare plains material extend from the breached part of the crater wall. The association of this crater with mare material and sinuous rilles suggests volcanism. Surface observations and sample analysis should relate the crater, rilles, and mare materials. The rilles predate the uppermost mare material and cut the hilly facies of the light plains material. Possibly the crater is a volcanic feature consisting of material of the same composition as the light plains material and was associated with the deposition of that material.

A 3-km dark-halo crater occurs in the northern part of the inner ring (fig. 17). If the difference between the dark rim ejecta of this crater and the surrounding mare plains were determined, the origin of the crater could probably be established.

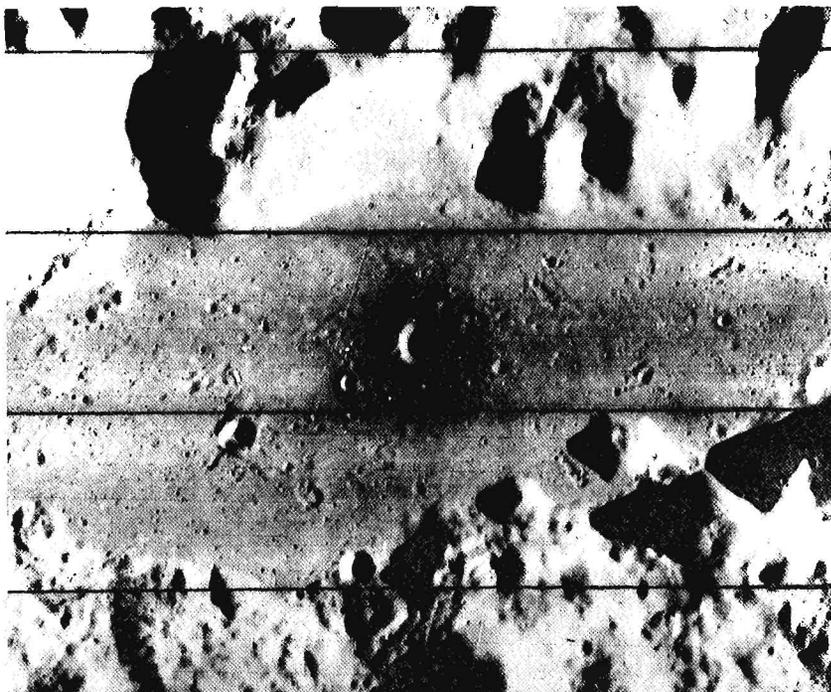


Figure 17.--Dark-halo crater. Scale 1:500,000.

Several low domes occur in Mare Veris, the easternmost of the inner ring mare plains (fig. 18). They appear to be constructional volcanic features; however, they are locally bounded by fairly distinct scarps. Three of them have central protrusions of light and irregular blocks similar in appearance to the blocks of the Rook Mountains. These may be steptoes. This association suggests a structural origin by withdrawal of magma, as with similar features on the central mare. These features should be studied by ground traverse. There is a suggestion of overlap of two of the domes, thus supporting an extrusive origin. The composition of the dome material may be slightly different from that of the surrounding dark plains material, indicating a differentiation trend. If the scarps are structural, they may retain some evidence of the type of deformation which occurred.

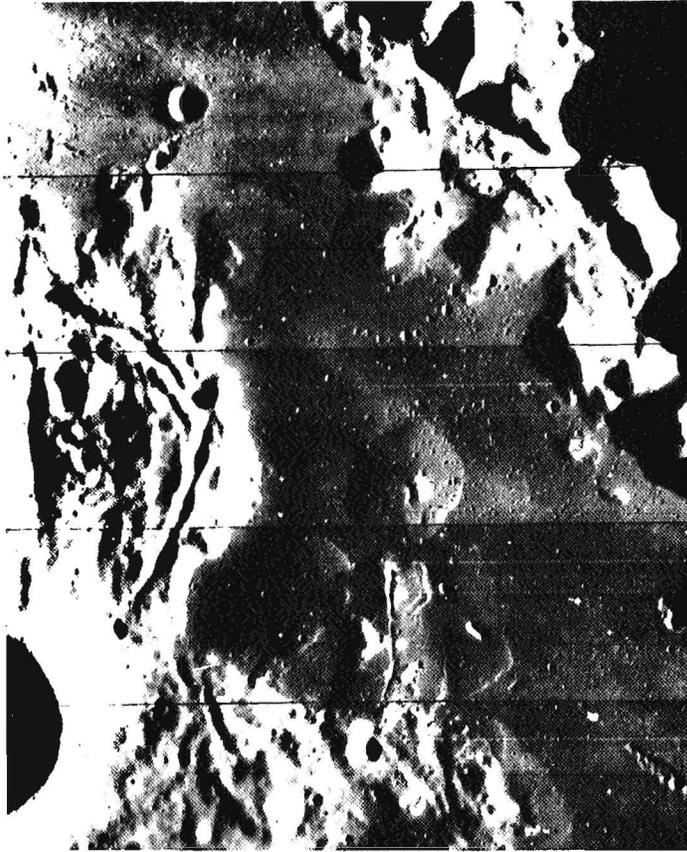


Figure 18.--Domes on mare material. Scale 1:500,000.

The Montes Rook Formation (informal name) of the outer ring is rough at a 1-km scale but level at a scale of 10 to 100 km (fig. 19). McCauley (1967a, b) tentatively interpreted this formation as ejecta and crustal material brecciated by impact. Brecciation could also have been induced by subsidence of the ring, as in a large caldera. If some of the surface material is shock metamorphosed and can be recognized by different composition or by the presence of meteoritic material, this may help resolve the problem of impact versus caldera origin of the basin.

The Cordillera Mountains are bounded on the interior by a scarp of considerable local relief (fig. 20). Owing to either impact or caldera subsidence, this scarp exposes great sections of crustal material. If the basin formed by impact, the scarp may be mantled by the ejecta blanket, which should exhibit enough

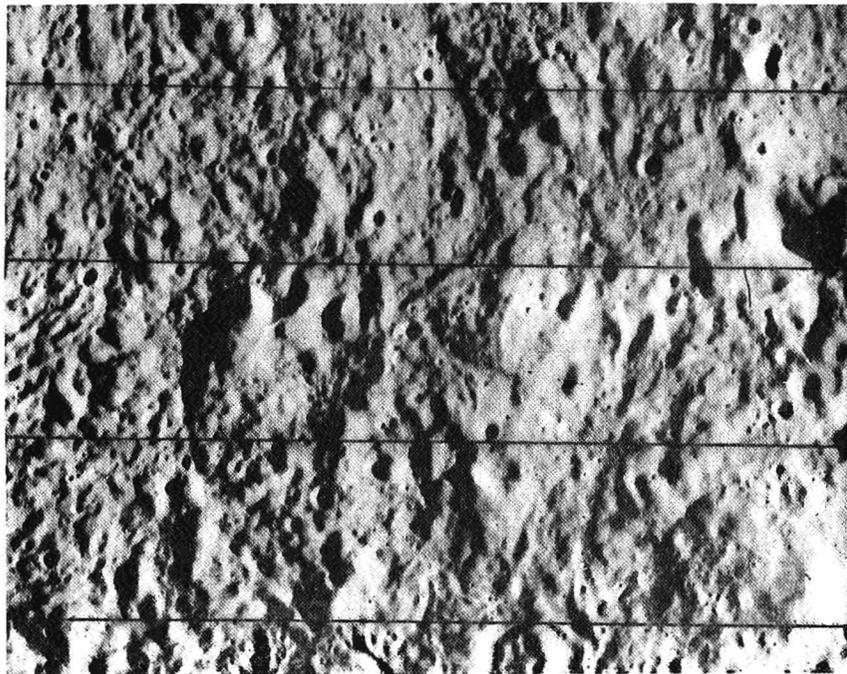


Figure 19.--Montes Rook Formation in northern part of outer ring. Scale 1:500,000.

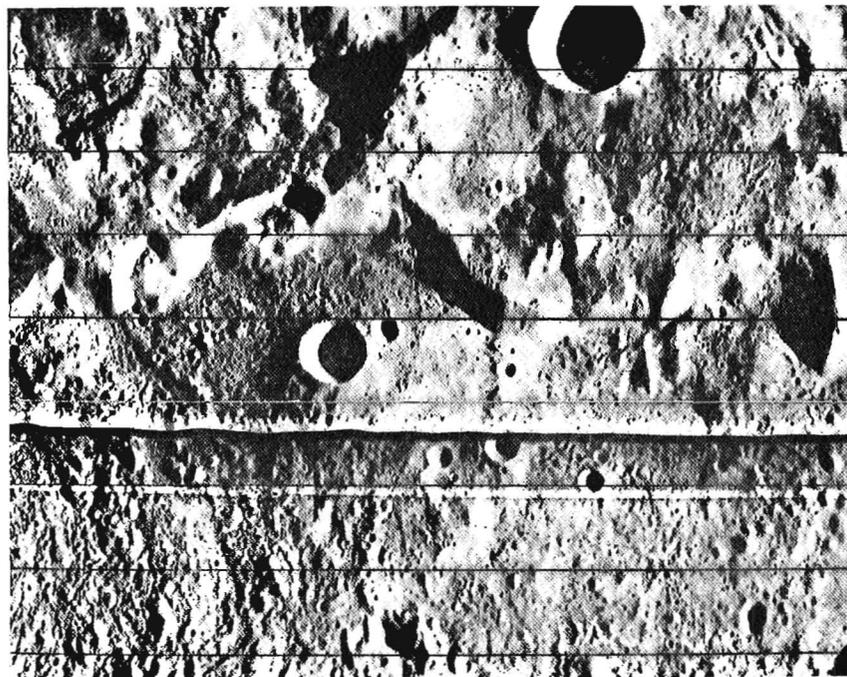


Figure 20.--Cordillera scarp (contact between Montes Rook Formation and Cordillera Formation). Scale 1:1,000,000.

compositional and textural characteristics to enable its identification. The radially braided facies or outer rim blanket is shown in figure 21. Locally generated volcanic material should be readily distinguishable from impact ejecta. The Cordillera scarp will display an extensive section of crustal material in areas where scree does not completely mantle the slope. In the upper part of this section the blanketing material which forms the radially braided facies of the Cordillera Formation should also be exposed.

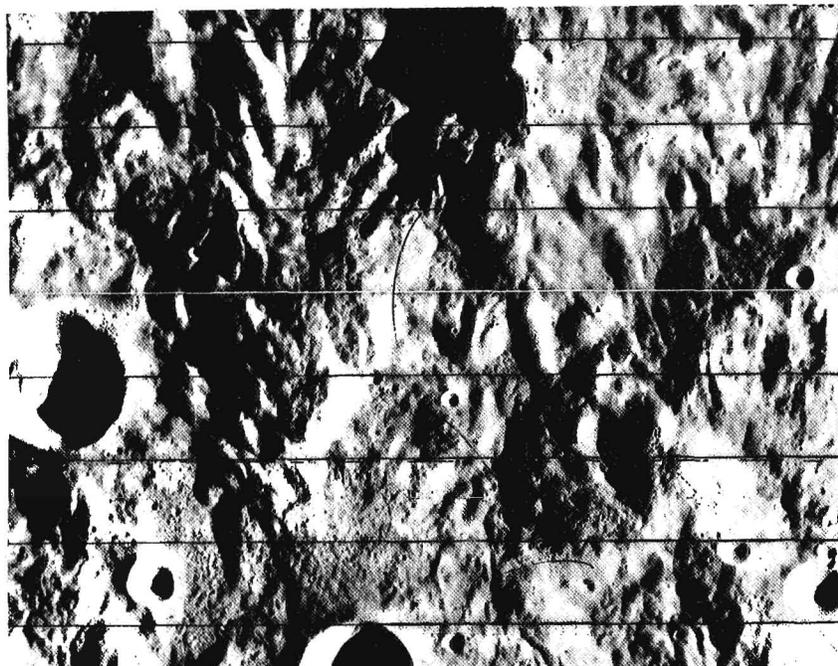


Figure 21.--Radially braided facies of Cordillera Formation. Scale 1:1,000,000.

The Cordillera Formation appears to overlie some Orientale secondary craters (McCauley, personal commun.). Secondary craters related to Orientale are well preserved immediately beyond the blanket but are indistinguishable on the blanket; suggesting that most of the secondaries formed before deposition of the uppermost part of the Cordillera blanket. Since the bulk of the material ejected at a high angle at less than escape velocity will return to the surface within several hours, the blanket was probably still form-

ing after that time. A possible mechanism for the blanket deposition is a base surge produced by the initial wave of material (Young, 1965) or by the subsidence of a column of ejecta over the basin. Most of the ballistic material which produced secondaries apparently impacted before the base surge had subsided. This surge of material completely overwhelmed the secondary craters which preceded it.

Conclusions

Impact of an asteroidal body followed by a history of volcanism and gravity tectonics appears, at the present time, to be the origin which satisfies most of the observations. The asymmetry of the radial fractures and of the Cordillera blanket may have been produced by an inclined impact as suggested by Hartmann (1964). The impact produced radial and circumferential fractures. The target rock near the center was highly brecciated and shock metamorphosed. Farther from the basin center the rock was less brecciated. No brecciation occurred from the Cordillera scarp outward, but the rock was fractured into large blocks.

At the time of impact, large quantities of material were excavated and ejected in ballistic trajectories, producing secondary impact craters out to at least 1,000 km. Much of the material ejected may have reached escape velocity. Some of the late-stage ejecta was partially melted. This material (suevite) was thrown out to the area of the Montes Rook Formation. The partially melted ejecta tended to flow back into the central basin. As the ejecta fell back, material tended to move outward covering the surface out to nearly 300 km. This entire sequence of events probably took place in a few hours.

The mare filling took place soon after the formation of the basin. Fractures may have reached molten material or the energy of the impact may have raised the temperature of already hot subsurface rock to the melting point. Materials of the central basin, Mare Veris, and Mare Autumni are probably identical in composition and age. Crater densities suggest that mare filling of craters on

the rim of the basin is younger than the central basin mare (see table 2).

Even with limited mobility, a mission to the Orientale basin could yield much scientific information. Additional high-resolution photographic coverage would be needed, however, as early as possible. Perhaps a camera in the command module could provide the additional coverage. A possible landing site might be in the eastern part of the central mare basin to the southwest of the 35 km calderalike crater (fig. 11). Within a few kilometers of such a site samples could be obtained of mare material, crater rim material from the calderalike crater, pre-mare basin material, and perhaps secondary crater material from the impact crater to the northwest. Thus, within a few kilometers much could be learned of the sequence of events in the formation of the Orientale basin and by analogy something of the early history of the other large multi-ring basins.

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