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Tectonic analysis of Mare Humorum on the lunar surface

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TECTONIC ANALYSIS OF MARE HUMORUM ON THE LUNAR SURFACE

BY

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THESIS

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ABSTRACT

Morphology and internal structures of surface features of the Mare Humorum area were interpreted from photographs and topographic maps. The postulated origin of certain features is based on analog comparisons with known terrestrial features. The laws of cratering and a newly developed computer program were applied to two representative classes of craters to determine the possibility of a meteoritic impact origin. Some of the craters formed by meteoritic impact and others, including those with a radius larger than 10 Km, probably resulted from volcanic activity.

Mare Humorum formed from centripetal subsidence followed by extensive lava eruptions. Spacially related rilles and gravity faults on the east and west of the Mare are tension fractures resulting from directed radial forces produced by the subsidence. Bending and monoclinal centripetal warping on the north and south of the Mare resulted in inward tilted older craters. Wrinkle ridges of sub-parallel marginal pattern are lava filled fissures and surface highs of lava showing a rough anticlinal form. These and similar fractures were the channelways for the extensive lava eruptions which covered the Mare.

An interpretive geologic and tectonic map demonstrated the important structural features of the Mare Humorum area.

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Chapter I

INTRODUCTION

One of the most significant events in human history occurred when man through his inventiveness and carefully planned efforts showed that he no longer need be earth bound. Within his reach is travel in space and the ability to leave the Earth. The Moon, naturally, is his first target, because it is Earth's nearest celestial body. From the first photos of the Moon's backside in 7 October 1959, and the impact of a satellite on the lunar surface by the Russians 13 September 1959, to the latest soft landing of cameras and other instruments by the Russians in 3 February 1966, our body of information has been rapidly expanding.

The Moon is of primary interest to geologists for the challenge it offers and the many answers it will provide for some basic scientific questions. Can it yield answers to the origin and history of the Earth? Has the absence of an atmosphere and presumed lack of erosion by water, ice and wind, resulted in the preservation of features on the Moon's surface very much the same as they were after their formation billions of years ago? What was the thermal history of the Moon and how did it compare to that of the Earth? Is the Moon a layered body or is it heterogeneous in make-up? Are surface features the result of exogenous or endogenous forces? What basically are the maria and the highlands? What differences do they have? These and many other questions await specific answers as surface lunar exploration faces reality in the predictable future.

A. Purpose and Scope of Investigation

The purpose of this investigation was to study in detail, and as quantitatively as possible, the surface features of a selected Mare of somewhat different characteristics than others on the Moon's surface. Mare Humorum was chosen and its geomorphic* and structural characteristics investigated from available photographs and topographic maps of this portion of the lunar sphere. Computer analysis of data was also determined for specific features. These results were used to theorize on the origin and tectonic history of the lunar features.

Specific reasons for the choice of Mare Humorum (Latin: Sea of Moisture) are: a) the Mare is a tectonic unit, is sub-circular and surrounded by highlands, and could be studied as a single body; b) unique features not recognized in other places on the Moon, such as the conspicuous faults along its western side and large craters partially buried beneath the surface of the Mare; c) lack of conspicuous scarps around the Mare; d) downwarping characteristics versus scarp features of other Maria (Imbrium, Serenitatis, Crisium); e) conspicuous rille development on west and east sides, and f) occurrence of other common features of the Moon in Mare Humorum. Some of these features are defined below:

Wrinkle Ridges: Long, relatively narrow ridges that occur both singly and in complex en echelon systems. These may exceed

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*Geo - while commonly referred to Earth, ground, is here used to express Earth-like forms on the Moon's surface. Use of well established geologic terminology for Moon analogs will permit ease of reading the voluminous literature now available and which will continue to develop.

300 km in length. Individual ridges are typically 15 to 30 km long and may be more than 100 m high (p. 299, Shoemaker, et. al., 1962).

Rilles: Long narrow depressions in the lunar crust. They may exceed 250 km in length, and be less than 5 km in width and 1 km in depth (p. 209, Fielder, 1961).

Craters: This term is applied to all the circular depressions on the lunar or terrestrial surface irrespective of their origin. For a complete crater nomenclature see Figure 5.

Terrae: "Relatively bright, relatively high surfaces or island-like single areas, usually with distinct relief." (p. 3, Bulow, et al., 1961).

Maria: "Relatively dark, relatively low level surfaces, with more or less smooth surfaces and little relief surrounded by Terrae." (p.4, Bulow, et al., 1961).

In addition to the descriptive and interpretive portion of this report, a tectonic and geologic map of the Mare is presented which summarizes the results of this investigation.

B. Location, Size and Shape of Area

Mare Humorum is in the southwestern part of the Moon's visible surface (Figure 1). It extends from latitude 15° S to 32° S and from longitude 28° W to 50° W. This coordinate system is the same as that followed by the U.S.G.S., U.S.A.F., N.A.S.A. and others.

> "The coordinate origin is the point that would be the center of the Moon's visible disk if all librations* were simultaneously at their zero values". (p. 19, Alter, 1963)

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*Libration is the irregularity in the Moon's movements around the Earth which results in its not keeping exactly the same face towards the Earth.

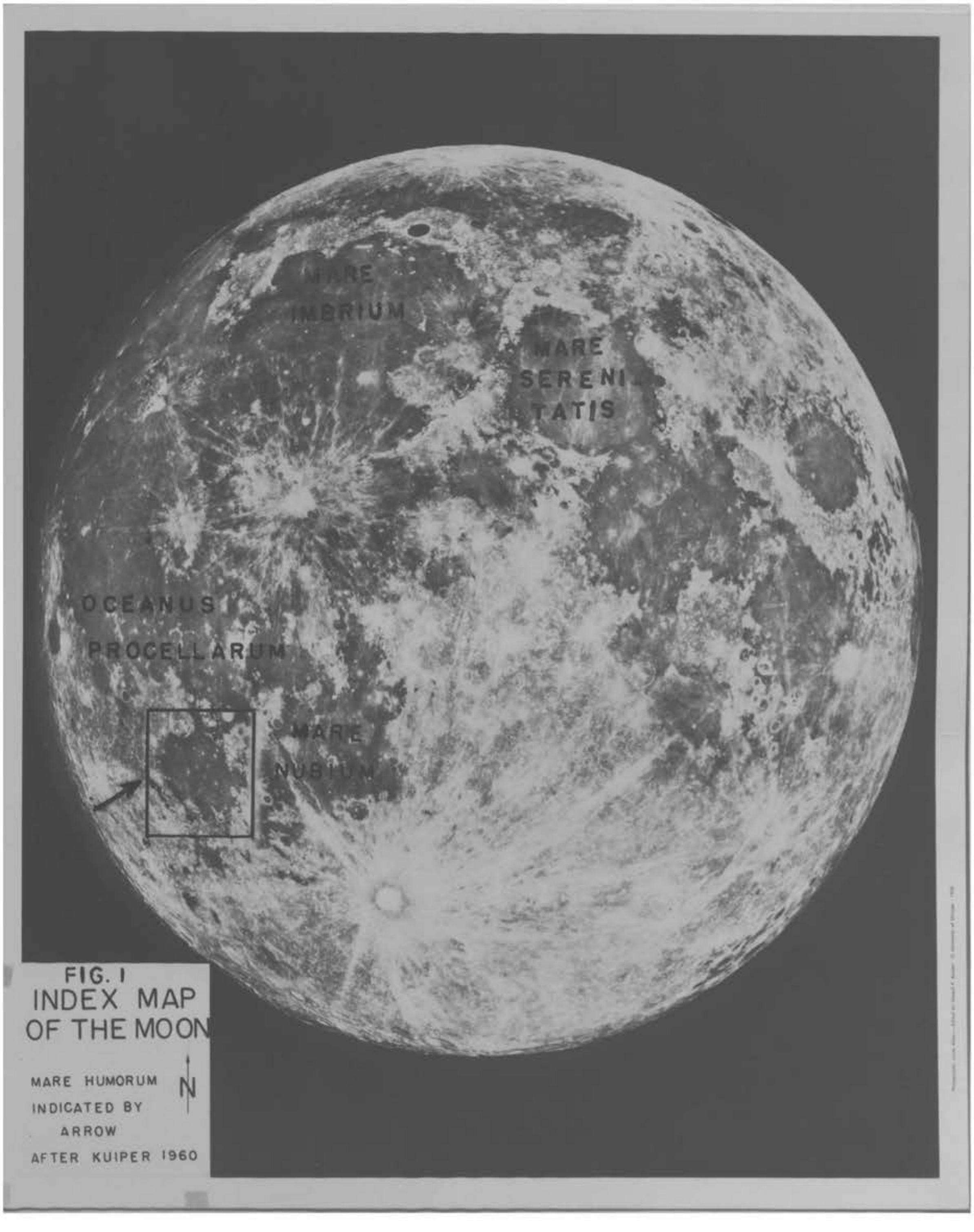

FIG. I
INDEX MAP
OF THE MOON

MARE HUMORUM
INDICATED BY
ARROW
AFTER KUIPER 1960

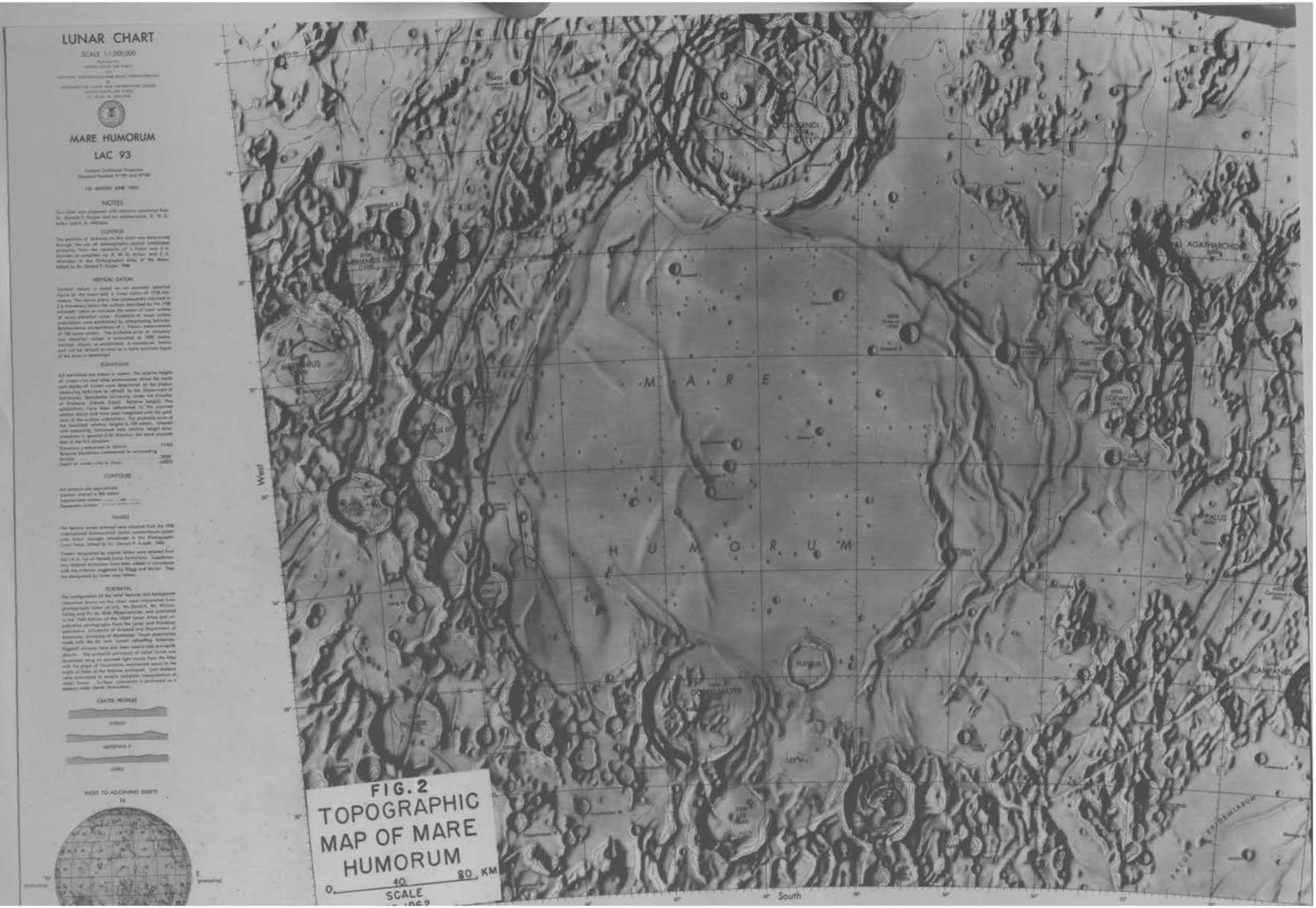

FIG. 2
TOPOGRAPHIC MAP OF MARE HUMORUM

0 40 80 KM
SCALE

Longitude is measured 360° around the equator from this point, clockwise for an observer at the Moon's north pole. Latitude is measured along meridians and reaches 90° at each of the poles. "These coordinates are selenographic longitude and latitude" (p. 19, Alter, 1963).

The area investigated includes Mare Humorum and the Terrae surrounding it to approximately 100 km from the margins of the Mare. Oceanus Procellanum bounds Mare Humorum on the North, Mare Nubium on the East and Terrae on the West and South (Figure 1).

The area studied extends 500 km north-south and 600 km east-west and includes 250,000 square kilometers (about 100,000 square miles). Half of this area is occupied by Mare Humorum.

Gassendi, a large crater, lies on the northern margin of the Mare and occupies 9,000 square kilometers. Doppelmayer on the southern margin is next largest and occupies 3,000 square kilometers. Craters of smaller size are irregularly distributed outside and inside the Mare (Figure 2). The Terrae occupy the rest of the area.

Maps of the Moon are compiled according to the following resolution by the International Astronomical Union at its triennial meeting at Berkeley in August, 1961 (p. 20, Alter, 1963).

> "Resolution Number 1.
> For compiling new maps of the Moon, the following conventions are recommended: Astronomical maps for purposes of telescopic observations are oriented according to the astronomical practice, the south being up. To remove confusion the terms east and west are deleted. Astronomical maps for direct exploration purposes, are printed in agreement with ordinary terrestrial mapping, north being up, east at right and west at left. Altitudes and distances are given in the Metric System."

Astrogeologic studies ordinarily utilize conventional maps with north at the top. This system is followed in this study.

Because Mare Humorum is some distance from the center of the visible lunar surface, its shape is somewhat distorted on photographs. The distortion varies from a minimum in a direction concentric to this center to a maximum of about 30% shortening of distances in a direction radial to it. The area appears therefore, as an ellipse with its major axis in a NW direction and its minor axis in a NE direction. If the photographs studied are not projected on a sphere to eliminate this distortion care should be taken to make the necessary corrections when measuring distances and directions. Some of the photographs used in this study were not corrected for distortion. Corrections were applied, however, to measurements obtained from them. The topographic map has been corrected to true dimensions.

C. Method of Investigation

The Photographic Lunar Atlas (Kuiper, 1960) and its two supplements were used for this study. Photographs included in the Atlas were taken at five observatories. Twelve photographs of Mare Humorum area were studied. The best resolution obtained in the photographs is 0.8 km. This matches the optical resolving power of an 11 inch visual telescope used under perfect conditions. Photographs are of non-stereoscopic type. This is a definite disadvantage because three-dimensional analysis of lunar terrain would permit much more critical analysis of the various surface features. The scale of the photographs utilized is 1:1,370,000.

The A.C.I.C. (Aeronautical Chart and Information Center, hereafter referred to as A.C.I.C.) topographic map of Mare Humorum was used in conjunction with the photographs. It has a scale of 1:1,000,000 and a contour interval of 300 meters. This served as the final base map. Horizontal and vertical measurements were made on the topographic map as well as the photographs to increase the accuracy of the results. This method was especially useful in shadow-length measurements to obtain relative elevations of certain points above the surrounding plain. This procedure is described below:

A point of known relative elevation on the topographic map was selected, located on the specific photograph and its shadow measured. This procedure was repeated with other points and a local relation established between the shadow length and the elevation of any elevated point on the photograph. The factor derived was then applied to other selected points on the photograph whose elevation was desired. These were needed for prominences whose relief was less than the contour interval. Results obtained by this method are accurate within the range of plus or minus 30 meters.

Comparisons were also made between certain lunar and terrestrial features of like shape and origin. Differences that might exist between the Earth and the Moon, such as gravity and essential absence of atmospheric pressure, where considered in this analog study.

Finally, a computer program, originally developed by Mr. W. J. Karwoski (personal communication, 1966) to determine the volume of material ejected from nuclear explosive craters, was modified to determine the volume of material ejected in a meteoritic impact and explosion. Results obtained were compared with the geometric properties of the craters on the Moon to determine whether or not they could have formed by meteoritic impact.

D. Previous Work

Very little detailed work has been published on the structure of Mare Humorum although it is mentioned occasionally in a number of publications. An abstract of a study was published by Proctor, et al., (1961) on work done on the structural features of the Moon with reference to Mare Humorum. Linear elements on Mare Humorum and their origin were analyzed by Salisbury (Salisbury, et al., 1965). Dr. Salisbury (personal communication, 1965) indicates that work is underway at the present time on the structural geology of Mare Humorum. Earlier workers include Baldwin (1949), Spurr (1944) and others.

A complete list of literature on the subject of the Moon used in this study is included in the bibliography.

E. Acknowledgements

The author is greatly indebted to Dr. Paul D. Proctor without whose supervision and guidance this work would have been impossible. My deepest appreciation goes to Dr. George B. Clark for his illuminating discussions. I thank Dr. William J. Karwoski for his permission and help to use and modify the computer program related to crater size and ejecta volume. I also thank Mr. Hasan El-Etr for his helpful comments and technical assistance.

Chapter II

MORPHOLOGY AND STRUCTURE OF MARE HUMORUM AREA

A particular description of the features of Mare Humorum, the surrounding Terrae, the craters, the faults, the wrinkle ridges, the rilles, the rays and the domes is presented. A detailed analysis of crater dimensions, volume of ejecta, and their possible origin based on energy relationships, strength of material and gravity is also considered in this section.

A. The Circular Plain

The Mare Humorum can be considered as a circular plain with irregular boundaries whose surface is for the most part smooth and flat and has a dark photographic tone.

Relief irregularities in the Mare include craters, wrinkle ridges, rilles and domes. Their combined area is less than 20% of the area of the Mare. In Figure 3, the 3,600 m contour line* roughly bounds the Mare and separates it from the surrounding Terrae. Note that some wrinkle areas actually extend above the plain in the eastern portion and the contour encompasses these. A low portion is present in the southwest part where the 3,600 m contour line curves west and north and south and southeast respectively. From this contour line the surface slopes very gently towards the central portion of the Mare with minor modification by wrinkle ridges. The amount of slope does not exceed 0.1% or one meter per thousand meters. The lowest point on the Mare's

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*Vertical datum is based on an assumed spherical figure of the Moon and a lunar radius of 1,738 km. The datum plane was subsequently adjusted to 2.6 km below the surface described by the 1,738 km radius to minimize the extent of lunar surface of minus elevation value (A.C.I.C., 1962).

surface (excluding crater floors) lies close to the crater Doppelmayer K near the center of the Mare and about 100 meters below the 3,600 m contour line. The crater itself is 300 meters deep and its floor elevation is therefore 3,200 meters, making it one of the lowest points on the surface of the Mare. The lowest point, however, is surprisingly the floor of the crater Gassendi O. It lies in the middle of a wrinkle ridge and its floor has an elevation of only 2,600 m. The floor of Gassendi J is at 2,700 m. Each of these deep craters is associated with wrinkle ridges.

Over 80% of Mare Humorum's surface can be considered as a level plain. The two topographic profiles across the Mare (Figure 4), with a vertical exaggeration of 50 times, show the relative elevation of each feature on the Mare's surface. The 3,600 m contour line is used as a reference plane (vertical datum) for its convenience only.

Tone and Texture - Photographic tones that characterize the Mare's surface are: very dark grey, dark grey and light grey. The light grey tone is associated with some of the small craters and will be discussed later. The dark grey tone covers most of the surface. The very dark grey tone exists over local separate areas distributed around the margins of the Mare. Some of these tone areas have well defined boundaries (Figure 2) such as around the crater Leibig G in the south-western part, in the vicinity of the craters Doppelmayer and Puiseux in the south and northwest of the crater Loewy in the east. Other tone areas do not have well defined boundaries but merge gradually into the dark grey tone area such as around the southern rim of the crater Gassendi (Figure 2).

At the photographic scale used the surface of the Mare has a smooth texture in both the dark and very dark grey tone areas. Some irregularities exist, however. These are low irregular ridges in the dark grey tone area, low hummocks and shallow depressions in the very dark grey tone areas, and small craters in both areas.

The tone and texture of the surface of Mare Humorum are characteristic of the formations described by the U.S.G.S. as the Procellarum Group (Shoemaker, 1960) named because of its extensive exposures in the Oceanus Procellarum area (Figure 1). The latter is the largest exposure of this material on the lunar surface. Note that (Table I) the Procellarum Group is part of the Archimedean Epoch of the Imbrian Period.

The tone and texture of the rocks of the Procellarum Group will be used as the major criterion in identifying exposures of this material throughout the Mare Humorum area.

Boundaries - The 3,600 m contour line which has been used to separate Mare Humorum from the surrounding Terrae is a rather logical boundary. The extent of the Procellarum Group material exposed to the surface was determined using its photographic characteristics for its identification. The results of this photogeologic study are shown in Figure 3, an index map for the area. The Mare Humorum surface material extends above the 3,600 m contour line. The maximum height at which this material is exposed is uniform and is about 250 meters above the 3,600 m contour. Its lateral extent beyond the 3,600 m contour is dependent on the slope of the land, extending further on the more gentle slopes.

TABLE I

Lunar Time Periods

PERIOD*	EPOCH	EVENTS
Copernican		Formation of ray craters.
Eratosthenian		Formation of craters whose rays are no longer visible.
Imbrian	Archimedian	Extensive deposition of Mare material of the Procellarum Group. Formation of Post-Apenninian craters, older than at least part of the Procellarum Group.
	Apenninian	Events related to the formation of the Mare Imbrium basin.
Pre-Imbrian		Not yet formally divided.

*Lunar time periods are shown according to the system established by the U.S.G.S. The chart shows the periods chronologically, with the earliest at the bottom (p. 41, Shoemaker, 1964).

In the southwestern part of the Mare the 3,600 m contour line is not closed but expresses an outlet leading from the Mare to a lower lying area to the southwest, which is some parts has an elevation of only 3,000 meters. This area includes the crater Palmieri (Figure 3) and is covered by the darker toned material of the Procellarum Group.

A profile of the probable original surface of Mare Humorum is shown in Figure 4, by the green line. The current surface is indicated by the black line. The suggested original surface has an elevation of 3,850 meters.

B. The Terrae

The Terrae are elevated areas of the lunar crust which surround the Maria on all sides. For the visible lunar surface these occupy 65%.

In the studied area, the Terrae surround Mare Humorum except for the local depressions on the north which connect this Mare with Oceanus Procellarum (Figure 1), and in the southwestern portion already noted. The Terrae are composed of isolated high areas with irregular shapes. The entire area is dotted with craters. Many of the higher areas are actually remnants of pre-existing crater rims.

The Terrae are distinguished by color tone, morphological features and elevation. The tone varies from very light grey on the slopes facing the sun to light grey elsewhere. Craters, consisting of old appearing somewhat subdued craters, to sharply defined and even rayed craters, pock the surface of the Terrae. The maximum elevation is 8,200 meters at a point in the northeastern part of the area west of

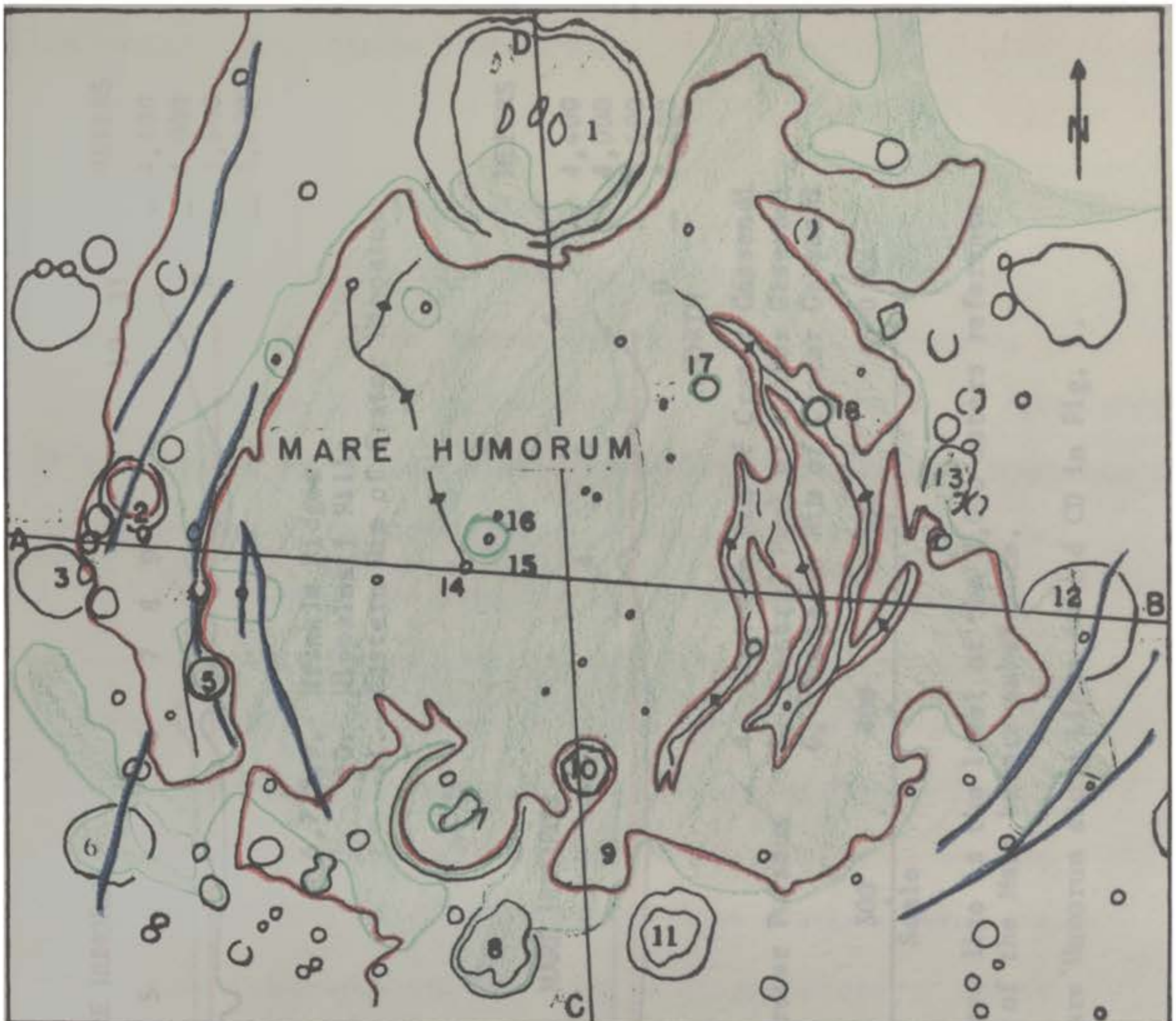


Fig. 3. Map of Mare Humorum Showing the Area Covered By Material of the Procellarum Group.

Material of the Procellarum Group

3600 Meters Contour Line

Wrinkle Ridges

Rilles

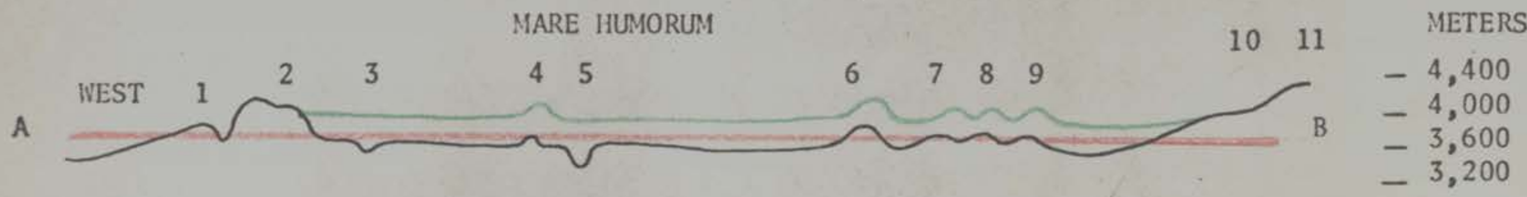
Craters

LIST OF CRATERS

1.	Gassendi	10.	Puiseux
2.	Mersenius D	11.	Vitello
3.	Liebig	12.	Hippalus
4.	Liebig F	13.	Loewy
5.	Liebig G	14.	Doppelmayer J
6.	Palmieri	15.	Doppelmayer K
7.	Doppelmayer	16.	Doppelmayer L
8.	Lee	17.	Gassendi J
9.	Lee M	18.	Gassendi O

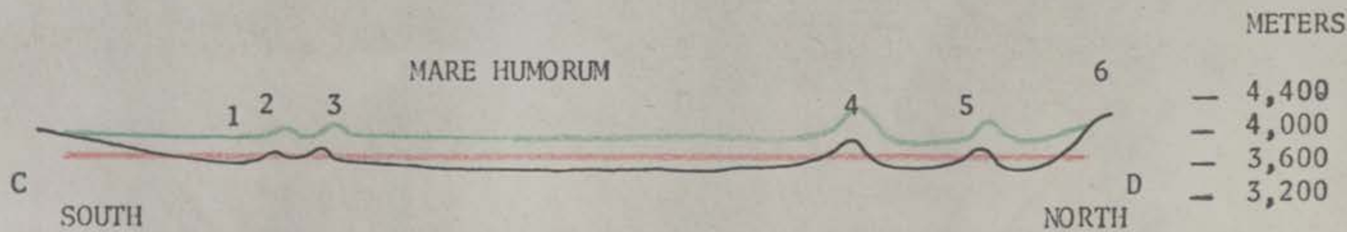
0 100 200 300 400 Km

Scale



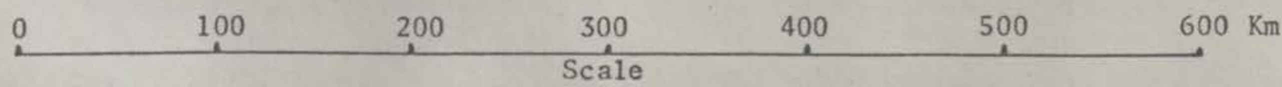
1. Mersenuis III Rille
2. Liebig I Rille (Fault)
3. Rille Inside Mare Humorum
5. Crater Coppelmayer J

4,6,7,8,9. Wrinkle Ridges
10. Hippalus I Rille
11. Eastern Rim of Crater Hippalus



1. Crater Lee M
2,3. Southern and Northern Rims of Crater Puiseus

4. Southern Rim of Crater Gassendi
5. Central Peak of Crater Gassendi
6. Northern Rim of Crater Gassendi



Vertical exaggeration 50 times. The red line is the level of the 3,600 meters reference plane. The green line is the surface of the Mare before subsidence.

Fig. 4. Topographic Section Across Mare Humorum along Lines A-B and CD in Fig. 1.

the crater Agatharchides (Figure 2).

C. The Craters

1. Lunar Crater Study History

No standard classification of lunar craters has been accepted to date. Major reasons for this are: a) difference in opinion as to the origin of the craters; b) difficulties of measurement of true crater depth and volume (Figure 5); c) uncertainty regarding the nature and characteristics of the lunar surface material and d) irregularities in the size and distribution of the craters.

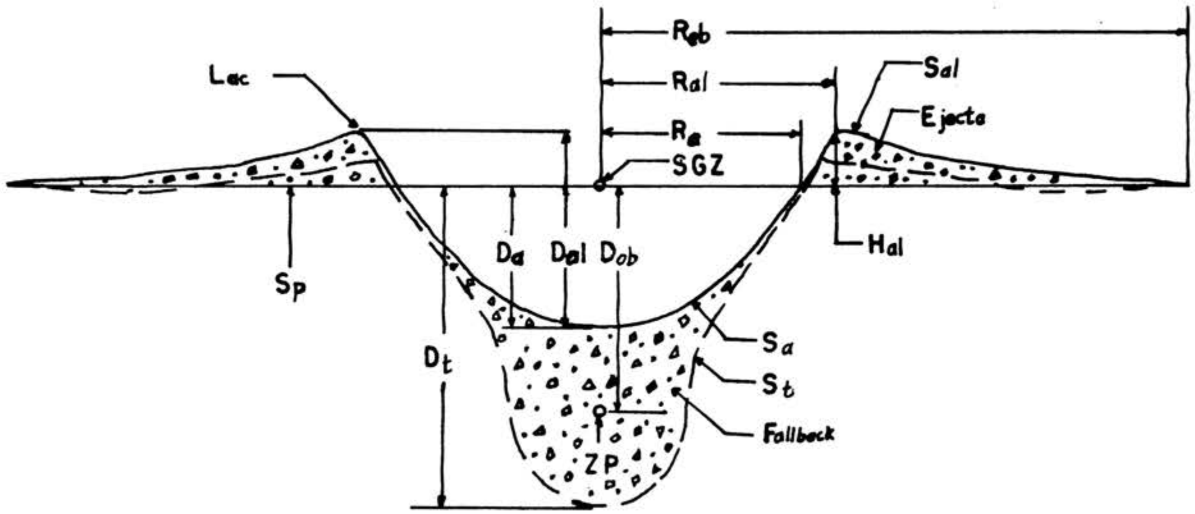
Crater nomenclature used throughout this study follows that of Hansen (1964) and is shown in Figure 5. A crater cross section and the various crater parts are labelled and defined by him.

Two major theories, the Volcanic Theory and the Meteoritic Impact Theory, have been suggested for lunar crater origin. One suggests an endogenous and the other an exogenous energy source. Supporting evidence for both schools of thoughts has been offered.

In this study of lunar craters, without respect to genetic connotations, four methods were considered in the analysis of the craters in the Mare Humorum area: 1) Analogy of lunar craters and terrestrial volcanoes in shape and size; 2) Correlation of depth and radius of craters, and 3) Simulation of lunar craters by laboratory experiments.

2. Analogy of Lunar Craters and Terrestrial Calderas

A caldera is defined as a large, approximately circular,



D_a . . . Maximum depth of apparent crater below preshot ground surface measured normal to the preshot ground surface.*

D_{al} . . . Depth of apparent crater below average apparent crater lip crest elevation.

Dob . . Normal depth of burst (measured normal to preshot ground surface).

Dt . . . Maximum depth of true crater below preshot ground surface.

Ejecta . Material above and or beyond the true crater and includes: (1) fallback; (2) breccia—ballastic trajectory; (3) dust—aerosol transport; etc.

Fallback. Material fallen inside the true crater and includes: (1) slide blocks; (2) breccia and stratified fallback—ballastic trajectory; (3) dust—aerosol transport; (4) talus; etc.

H_{al} . . . Apparent crater lip crest height above preshot ground surface.

L_{ac} . . . Apparent crater lip crest.

R_a . . . Radius of apparent crater measured on the preshot ground surface.

R_{al} . . . Radius of apparent lip crest to center.

R_{eb} . . . Radius of outer boundary of continuous ejecta.

S_a . . . Apparent crater surface, e.g. rock-air or rubble-air interface.

S_{al} . . . Apparent lip surface.

SGZ . . Surface ground zero.

S_p . . . Preshot ground surface.

S_t . . . . True crater surface, e.g. rock-air or rock rubble interface.

V_a . . . Volume of apparent crater below preshot ground surface.

V_{al} . . . Volume of apparent crater below apparent lip crest.

V_t . . . Volume of true crater below preshot ground surface.

ZP . . . Zero Point—effective center of explosion energy.

*All distances, unless specified otherwise, are measured parallel or perpendicular to preshot ground surface.

Fig. 5. Crater Terminology (After Hansen, et.al., 1964).

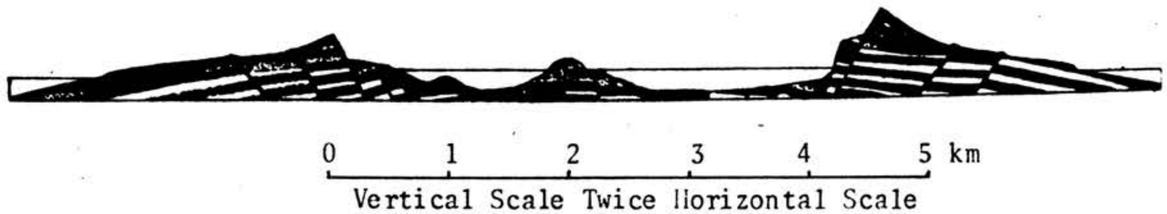
volcanic depression, which may be more than 5 km in diameter and 1,200 m in depth. Within the depression, considered to be a major collapse feature, one or more volcanic craters may occur, the largest of which is many times smaller than the caldera itself.

Three examples of calderas that are similar to some lunar craters are shown in Figure 6. The first one is Niuafo'ou (Figure 6A) which is "a caldera on ... a basalt dome the summit of which emerges from the ocean as the volcanic island Niuafo'ou, near Tonga, in the South Pacific" (p. 37, Cotton, 1944). It is similar in shape to the lunar crater Vitello (Figure 7) but is much smaller. The diameter and maximum depth of Niuafo'ou are 4.5 km and 1,200 m respectively, while those of Vitello are 40 km and 1,400 m.

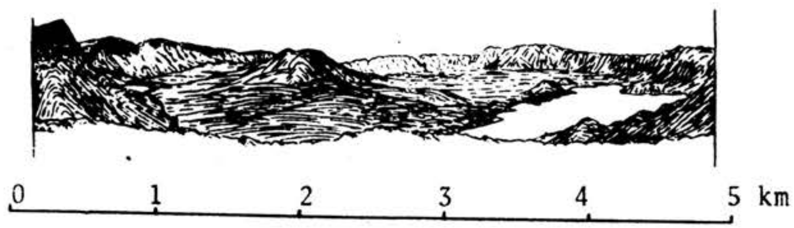
Another caldera which is similar to Vitello is Aniakchak in Alaska (Figure 6B). It ranges in depth from 360 to 900 m and is 5 km in diameter.

The last example is the active volcano Fogo in the Cape Verde Islands which has a summit higher than the surrounding caldera wall (Figure 6C). It is similar to the lunar crater Doppelmayer whose central peak is higher than its rim (Figure 7).

The difference in size between lunar craters and terrestrial calderas can be explained partly by the lesser gravity of the Moon. It can be shown by the laws of motion of a projectile that particles leaving the surface of the Earth and the Moon with the same initial velocity and angle will travel a horizontal distance on the Moon equal to six times that on the Earth, neglecting the effect of the atmosphere. The absence of an atmosphere on the Moon's surface will allow the particles to travel farther than on Earth where they encounter air



A. Cross section of the Pacific Island, Niuafo'ou (modified from Jaggar, 1931).



B. Aniakchak Caldera, Alaska, viewed from the eastern rim (modified from Cotton, 1944).

C. The active volcano Fogo, Cape Verde Islands (modified from Cotton, 1944).

Figure 6. Three terrestrial volcanoes.

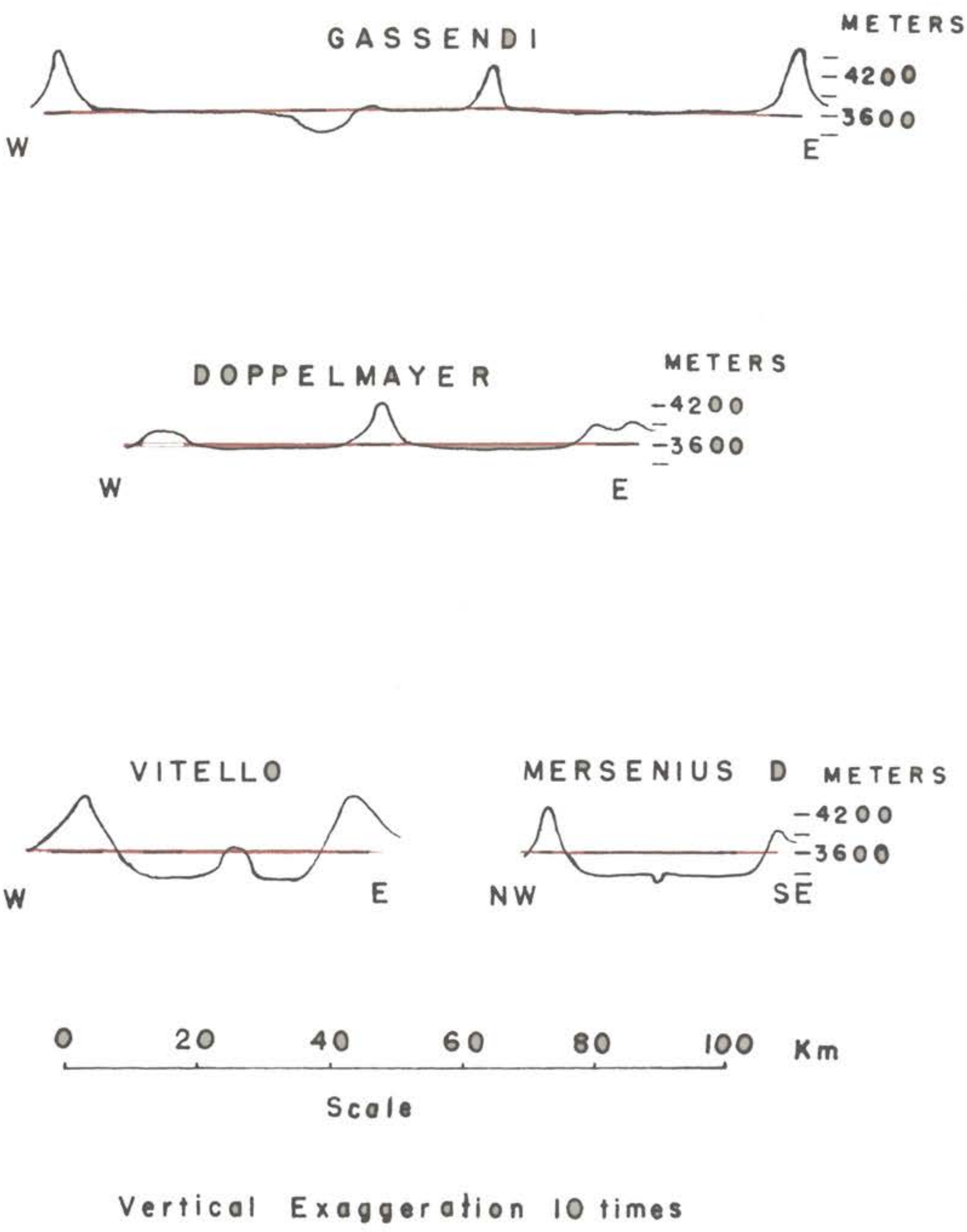


Fig. 7. Profile of Four Craters in Mare Humorum Area.

resistance. Other factors which could account for the difference in size are strength of the rock material and differences in available energy (i.e., vapor pressure and/or impact explosive energy).

3. Correlation of Depth and Radius of Craters

As a result of cratering experience a relation is known to exist between the dimensions (R and D) of different explosion craters whether it be a chemical, nuclear or impact explosion (Nordyke, 1961). Terrestrial volcanic craters, on the other hand, have a poor correlation of these dimensions (Baldwin, 1949). To determine whether lunar craters were formed by impact explosions or volcanism one must determine the radius to depth ratio of each crater.

Thirty-four well developed craters in the Mare Humorum area were studied. The radii of these craters were measured directly from the photographs and the topographic map. The depths of most of them were compiled from former studies. The depths of those not studied previously were measured by the method described above. Data on the 34 craters, arranged in order of decreasing radius, are listed in Table II. The ratio of radius to depth of the individual craters is also shown. It should be noted that the radius and depth measured for each crater are the radius from apparent lip crest to center (Ral) and depth of apparent crater below average lip crest elevation (Dal) (Figure 5).

Three distinct groups of Ral/Dal ratios are apparent and are distributed as follows:

(1) Ral/Dal = 4.2 - 5.8 for 14 craters

(2) Ral/Dal = 9.0 - 13.3 for 14 craters

(3) Ral/Dal > 13.3 for 6 craters

The last group includes the largest six craters in the area (Gassendi, Mersenius, Doppelmayer, Hippalus, Vitello and Palmieri). Note that these latter Ral/Dal ratios are widely scattered, actually ranging from 15.2 to 75.

For visual representation, the depths and radii of the three groups are plotted in Figure 8. Curves (a) and (b) are plots of groups (1) and (2) respectively. Curve (c) is a continuation of (b) but is plotted on a different scale.

The slope of each curve is the mean of the Ral/Dal ratios of the corresponding group. The slope of curve (a) is about 5 and that of (b) about 11. Curve (c) is dashed because of the lack of enough points. It is possible that the continuation of (c) should be a curve rather than a straight line relationship.

4. Simulation of Lunar Craters by Laboratory Experiments

Laboratory experimentation by simulation studies of crater development is another approach which might prove helpful to our understanding of lunar craters. Successful simulation of crater formation in the laboratory can be achieved when there is a dynamic similarity* between the model and the original.

Following the procedure of Hubbert (p. 1505, Hubbert, 1937) it was calculated that to simulate a spherical meteorite with a diameter of 100 meters, a velocity of 20 km/sec, impacting a surface having a shearing strength of 100 kg/cm^2, the following model is required: a

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*Dynamic similarity exists between a model and the original when all corresponding physical properties of, and the forces acting on the two bodies are proportional.

TABLE II

Depth and Radius of Craters

in the Mare Humorum Area*

NAME	RADIUS (Ral) (Kilometers)	DEPTH (Dal) (Kilometers)	Ral / Dal
Gassendi	55.0	2.0	27.5
Mersenius	35.0	2.3	15.2
Doppelmayer	30.0	0.4	75.0
Hippalus	28.0	0.9	31.1
Vitello	22.0	1.4	15.7
Palmieri	20.0	1.2	16.7
Lee	20.0	1.8	11.1
Liebig	17.0	1.5	11.3
Mersenius D	16.0	1.2	13.3
Liebig G	10.0	0.9	11.1
Mersenius S	8.0	1.6	5.0
Dunthorne	7.5	1.5	5.0
Doppelmayer G	7.5	0.7	10.7
Mersenius C	7.0	1.5	4.7
Palmieri E	6.5	1.3	5.0
Gassendi O	6.0	1.2	5.0
Agatharchides C	6.0	1.1	5.4
Agatharchides Ca	6.0	0.5	12.0
Vitello B	5.5	1.1	5.0
Gassendi J	5.0	0.9	5.6
Mersenius E	5.0	1.1	4.5
Vitello P	4.0	0.4	10.0
Hippalus A	4.0	0.8	5.0
Gassendi G	3.8	0.9	4.2
Gassendi E	3.7	0.8	4.6
Liebig F	3.5	0.6	5.8
Agatharchides B	3.4	0.3	11.3
Puiseux D	3.3	0.7	4.7
Vitello E	3.6	0.4	9.0
Doppelmayer K	3.0	0.3	10.0
Gassendi L **	2.9	0.27	10.7
Gassendi Y **	2.7	0.25	10.8
Doppelmayer J **	2.7	0.25	10.8
Doppelmayer L **	2.5	0.2	12.5

*Data on depths were obtained from former studies and data on radii were measured directly.

** Measured by the author.

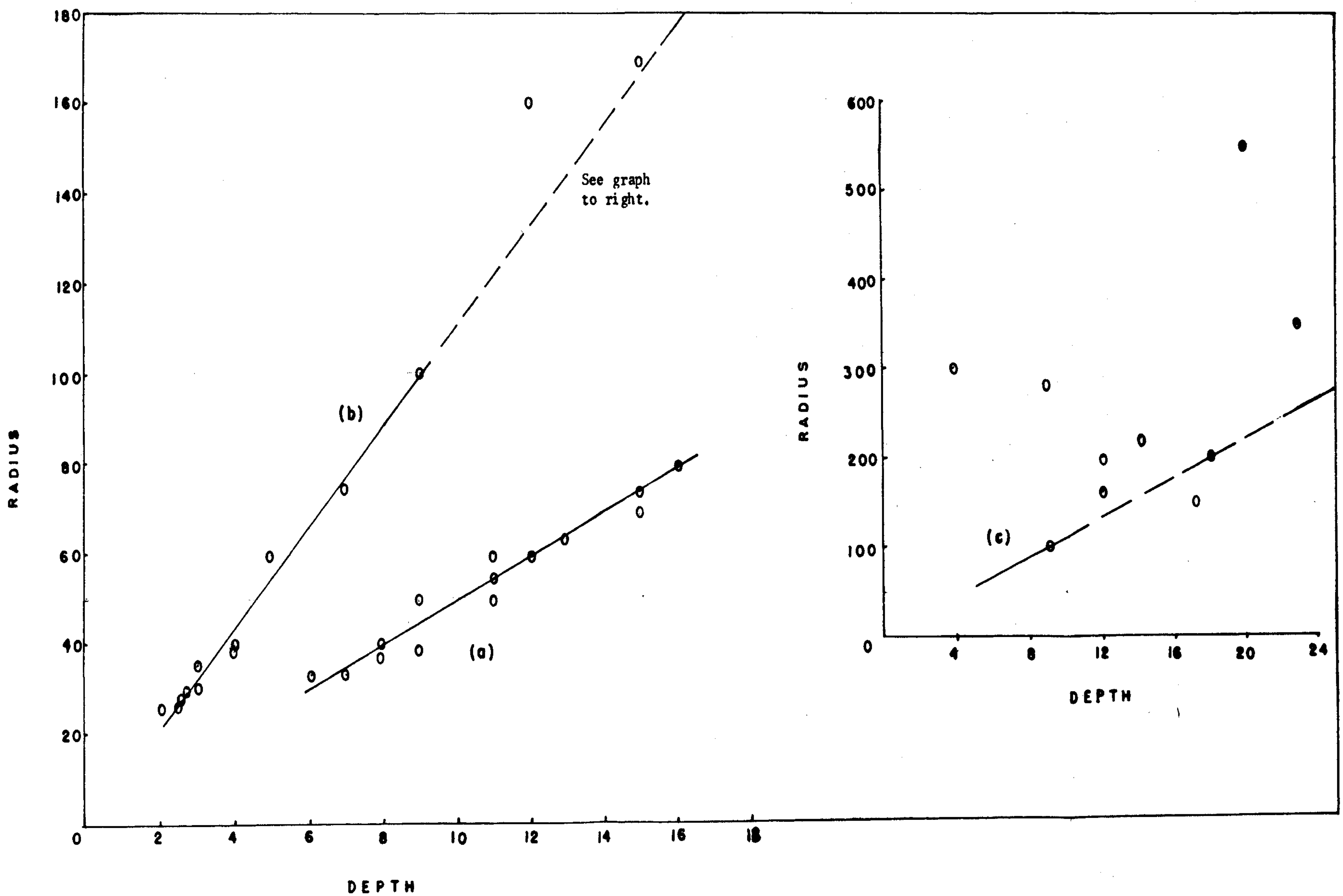

Fig. 8. Radius versus Depth of Apparent Craters in the Mare Humorum Area. (All figures are in hundreds of meters).

ball of lead 1 cm in diameter and a velocity of 0.5 km/sec impacting a surface of clay having a shearing strength of 10 g/cm^2. These models, however, do not account for the fact that high velocity meteors explode on impact.

Results of experiments performed by Sabaneyev and others (p. 423, Sabneyev, 1960) showed that the greatest similarity between models and lunar features was attained by dropping matter that possesses a spherical shape and negligible cohesion of its particles. For symmetrical craters the angle of incidence with respect to the horizon should be strictly perpendicular. Powders constituting perfectly loose material cannot be used as the ground material.

> "The models having a satisfactory similarity with lunar objects can be obtained only in a ground endowed with properties of the solid" (p. 425, Sabaneyev, 1960).

Several others: Benevolensky, Charters and Wegener (p. 416, Stanyukovich, *et al.*, 1960) performed similar experiments. These researchers confirm the results made by Sabaneyev and offer supporting evidence for a possible meteorite impact origin for some of the lunar craters.

5. Quantitative Analysis of Lunar Craters

A quantitative cratering approach is considered in an attempt to recognize lunar craters formed by meteoritic impact in the Mare Humorum area. This section utilizes recent developments and experience in cratering and applies them to two lunar craters representative of two classes in the Mare Humorum area. A similar procedure can be followed for other lunar craters. For this study the craters Hippalus A and Vitello P (Figure 2) were chosen for the following reasons:

a) each of them is representative of one of the two classes of craters shown in Figures 8 and 9. Thus the Ral/Dal ratio is 5 for Hippalus A and 10 for Vitello P; b) the two craters have equal radii which permits correlation between them and their respective classes; c) their size is small compared with other lunar craters (Table II). This makes them much easier to correlate with terrestrial craters.

The laws of cratering were developed by many researchers (Eichelberger, Nordyke, Cook and others) from experiments conducted on Earth (Cook, 1958). It is recognized that application of the data for lunar craters is very difficult because of the differences between the Earth and the Moon in surface gravity (9.8 m/sec^2 vs. 1.62 m/sec^2), atmosphere and the unknown nature and characteristics of the surface material.

Certain basic assumptions are made to simplify the problem of crater analysis and make a reasonable approach possible. These assumptions are: 1) When a meteorite impacts a surface, an explosion will result which is similar to a chemical or nuclear explosion that takes place at the surface or at a shallow depth (Clark, personal communication, 1966). After a meteorite impacts a target its velocity will be slowed until, after penetrating a certain distance, it reaches the shock wave velocity of the target. Then the meteorite's kinetic energy will be suddenly released and an explosion will occur (Baldwin, 1949); 2) The true crater radius is equal to the apparent crater radius (Figure 5); 3) The true crater dimensions are independent of gravity and particle velocity. Apparent crater dimensions are dependent on gravity and particle velocity (Clark, personal communication, 1966 and Karwoski, 1966); 4) The true crater dimensions obey the Cube-Root Scaling Law (p. 6, Nordyke, 1961). This law relates two craters in the following manner:

$$\frac{R_1}{R_2} = \frac{W_1^{1/3}}{W_2^{1/3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

and

$$\frac{V_1}{V_2} = \frac{W_1}{W_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where R_1, V_1, and W_1 are the radius, volume and charge weight (in tons* of TNT) of the first crater respectively, and R_2, V_2 and W_2 are the corresponding values for the second crater; 5) The effect of or absence of an atmosphere is ignored; 6) The craters are axially symmetrical with respect to the Y-axis; 7) The apparent crater volume is equal to the volume of an inverted cone whose diameter and height are equal to the diameter and depth of the apparent crater respectively.

Apparent Crater Volume: In the analysis of the apparent crater volume of the crater Hippalus A: R_a = 3.8 km and Da = 720 m.

$$V_a = 1/3\pi r^2 h = 1/3\,\pi (Ra)^2 (Da) = 1.09 \times 10^{16} cm^3$$

and that of Vitello P is: $5.45 \times 10^{15} cm^3$.

True Crater Volume: Because of the fallback material that partly covers the true crater (Figure 5), the true crater volume cannot be measured directly from a photograph or a topographic map. It can be calculated, however, in the following manner:

Equation (1) can be written in the form:

$$R = R_o A^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

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*Only metric tons are used in this study. The weight of the explosive is in tons of TNT.

where A is the energy of the explosion, R is the radius of the resulting crater, and R_o is the crater radius obtained with an explosive of unit maximum available energy (p. 263, Cook, 1958). For shallow depth of burst one gram of TNT produces 0.5 Kcal and R_o was computed to be 3.0 cm/Kcal$^{1/3}$ (p. 263, Cook, 1958).

Using this value of R_o in equation (3) and solving for A, the energy needed to form the crater Hippalus A can be found as:

$$A = \left(\frac{3.8}{3} \times 10^5\right)^3 = 2.03 \times 10^{15} \text{ Kcal}$$

The relation between the true crater volume and the energy of the explosion can be expressed in the general form:

$$V_t = KA \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

where K is a constant. K can be found from the Arizona meteoritic crater* in the following manner:

The energy used in producing the Arizona crater (R = 633m) is from equation (3).

$$A = \left(\frac{6.33}{3} \times 10^4\right)^3$$
$$= 9.4 \times 10^{12} \text{ Kcal}$$

The apparent volume for the Arizona crater is:

$$V_a = 1/3\,\pi(633)^2(213) = 8.9 \times 10^{13} \text{ cm}^3$$

The true crater volume is:

$$V_t = 1/3\,\pi(633)^2(403) = 16.9 \times 10^{13} \text{ cm}^3$$

Substituting the values of V_t and A in equation (4):

$$K = \frac{V_t}{A} = 18 \text{ cm}^3/\text{Kcal}$$

Using the value of K and A for the crater Hippalus A in equation

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*Geometric data on depth and radius of apparent and true crater of the Arizona meteoritic crater were taken from p. 70, Baldwin, 1949.

(4) we find:

$$V_t = (18)(2.35 \times 10^{15})$$
$$= 3.65 \times 10^{16} \text{ cm}^3$$

as the true crater volume of Hippalus A.

As a result of experiments performed on the impact of a projectile on a target, the value of K was found to be related to the density of the projectile and to the density and compressive strength of the target material (p. 256, Cook, 1958). Equation 4 is then:

$$V_t = \frac{P_p^{1/2} P_t^{1/2}}{(P_p^{1/2} + P_t^{1/2})^2} \quad \frac{m_p V^2}{2\sigma} \; . \; . \; . \; . \; . \; . \quad (5)$$

where V_t is the hole volume produced in the target material which is equal to the true crater volume, P_p, m_p and V are the density, mass and velocity of the projectile respectively, P_t and σ are the density and compressive strength of the target material.

The explosive energy A is equal to the kinetic energy of the projectile (1/2 mV_2); substituting this in equation (5) gives the value of K as:

$$K = \frac{P_p^{1/2} \; P_t^{1/2}}{(P_p^{1/2} + P_t^{1/2})^2} \quad \frac{1}{\sigma} \; . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

The value of K is inversely proportional to σ and since the term $\frac{P_p^{1/2} P_t^{1/2}}{(P_p^{1/2} + P_t^{1/2})^2}$ does not vary greatly with variations in P_p and P_t it follows that K is primarily dependent on σ .

In the solution for the true crater volume the value of σ was that of the material in which the Arizona Meteorite Crater was formed which is sandstone. The compressive strength of this sandstone can be found as follows:

$$\sigma = \frac{P_p^{1/2} P_t^{1/2}}{(P_p^{1/2} + P_t^{1/2})^2} \frac{1}{K} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

$K = 18\ cm^3/Kcal = 4.3 \times 10^{-10}\ cm^3/erg$. for extreme values of P_p and P_t, the value of σ varies from 4 to 5×10^8 dynes/cm^2 or 400 to 500 Kg/cm^2.

Now, for the crater Hippalus A:

$$\frac{\text{Actual } V_t}{\text{Calculated } V_t} = \frac{\sigma_{HA}}{\sigma} \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

where:

Actual V_t = correct value for the true crater volume of Hippalus A.

Calculated $V_t = 3.65 \times 10^{16}\ cm^3$

σ_{HA} = the compressive strength in Kg/cm^2 of the material in which the crater Hippalus A was formed.

σ = 400 to 500 Kg/cm^2.

The ratio of the true to apparent volume of the Arizona crater is:

$$\frac{V_t}{V_a} = \frac{16.9 \times 10^{13}}{8.9 \times 10^{13}} = 1.90$$

The ratio for Hippalus A is:

$$\frac{V_t}{V_a} = \frac{3.65 \times 10^{16}}{1.09 \times 10^{16}} = 3.35$$

A smaller percentage of the ejecta will be able to cross the rim of Hippalus A than the Arizona crater because the radius of the first is 6 times that of the second. On the other hand, a larger percentage will cross the rim of Hippalus A because the gravity is

6 times smaller. These factors tend to cancel each other. The ratios ($\frac{V_t}{V_a}$) of the two craters should approach each other. How much depends on the velocity of the ejecta, the difference in the nature and characteristics of the surface material, the difference in atmospheric pressure and other minor factors.

However, it is reasonable to say that the ratio of $\frac{V_t}{V_a}$ for Hippalus should be less than 3.35. The correct value of V_t is, therefore, less than 3.65×10^{16} cm^3. From equation (8) we find, then, that the compressive strength of the material in the vicinity of Hippalus A on the Moon is less than 400 Kg/cm^2 but not much less than 200 Kg/cm^2 because then the ratio of $\frac{V_t}{V_a}$ of Hippalus A would be less than that of the Arizona crater. The average compressive strength of basalt is 2,750 Kg/cm^2 and pumice is 142 Kg/cm^2 (p. 8, Strom, 1963).

The Computer Program: A computer program was set up to determine the volume of material (ejecta) thrown out of a crater following impact and explosion of a meteorite as well as the range of deposition of this ejecta around the crater.

Input data: a) the energy of the explosion in terms of equivalent tons of TNT: for surface or shallow depth of burst:

$$W = \frac{A(\text{Kcal})}{\text{Kcal/ton}} = 4.7 \times 10^9 \text{ tons}$$

b) the depth of burst was varied from 0 to 100 meters; c) the velocity range of the ejecta with assumed values from 80 m/sec up to the escape velocity of the Moon (2.38 Km/sec).

Results of various trials showed that the largest possible volume of ejecta (5.5×10^{15} cm^3) was obtained for a surface explosion with as assumed constant velocity field of 90 to 100 m/sec. As the velocity of the ejecta increased (from 90 m/sec), the volume decreased and the material was thrown a larger distance from the crater. Inspection of the area around Hippalus A on one of the photographs revealed that the maximum distance of ejecta deposition measured from the rim of the crater is approximately equal to one crater radius. This corresponds to a velocity field of 110 to 120 m/sec and to an ejecta volume of 3.3×10^9 cm^3.

The percentage of the calculated to the measured apparent crater volume is for Hippalus A:

$$\frac{3.3 \times 10^{15}}{1.09 \times 10^{16}} (100\%) = 30\%$$

for Vitello P:

$$\frac{3.3 \times 10^{15}}{5.45 \times 10^{15}} (100\%) = 60\%$$

The volume of the ejecta from the crater Hippalus A can be found by using the rim height and the range of deposition of ejecta measured from the photographs:

$$\text{Rim Volume, } V_r = 2.36 \times 10^{15} \text{ cm}^3$$

Difference in the volume of the ejecta before and after deposition is equal to the volume of the ejecta, V_e as calculated by the computer minus the volume of the rim.

$$\text{Volume lost} = V_e - V_r = (3.3-2.36) \times 10^{15}$$
$$= 0.94 \times 10^{15} \text{ cm}^3$$

Expressed as a percentage of V_e:

$$\frac{0.94 \times 10^{15}}{3.3 \times 10^{15}} (100\%) = 28.5\%$$

If the effect of erosion and isostasy is neglected, then this represents the difference in porosity between the ejecta before impact and after deposition or

$$N_e = N_r + 28.5\% \quad \ldots\ldots\ldots\ldots \quad (9)$$

where N_e is the porosity of the ejecta before impact and N_r is its porosity after impact and deposition.

Equation (9) also applies to the fallback material. It states that the volume of the fallback material will be 28.5% less than the original volume before impact. The apparent crater volume will increase by an equal amount.

D. The Faults

A fault is here defined as a fracture in the Moon's surface which shows visible displacement in photographs and/or on lunar topographic maps. The most pronounced fault in the Mare Humorum area lies along the western margin of the Mare (PLATE I). The northern end of the fault is just inside the crater Gassendi. It crosses the western wall of this crater and its vertical displacement decreases until it disappears 50 Km southwest of Gassendi under a later cover of the Mare's surface material. A rille appears on strike a short distance southward in this covering material. This separates into two branches, unites again and merges into the fault which reappears at a point east of the crater Mersenius E (PLATE I). The vertical displacement appears to increase gradually southward. The fault extends to 260 m above the surface of the Mare south of the crater Leibig G. The southern end of the fault disappears again under a cover of the Mare's surface material.

The fault is a normal fault with mainly dip slip movement and the downthrown side on the eastern block.

Another fault of less conspicuous appearance and N 40 E strike extends along the southeastern margin of the Mare (PLATE I). The length excluding the concealed part is 80 Km.

A small fault cuts across the western rim of the crater Hippalus. A number of faults cut the rim of Gassendi at various locations, especially the southern portion whcih adjoins the Mare (PLATE I). These do not show the continuity of the faults described above.

E. The Wrinkle Ridges

The wrinkle ridges occur within Mare Humorum (PLATE I). A largernumber occur in the eastern portion than in the western part. Few are present near the center. The general form is an elongate, relatively narrow rise above the Mare surface. In cross view they appear as anticlinal folds with plunge often shown on the terminal portions. Many of the wrinkle ridges show an en echelon pattern along the eastern part of the Mare. All of the ridges are less than 200 m in height and their slopes are less than 5°. The color tone suggest a rock composition the same as that which covers the Mare.

Most of the individual ridges are less than 20 Km long but two of them north of Doppelmayer are more than 60 Km and one ridge southwest of Gassendi is more than 100 Km long (PLATE I).

> "By telescopic examination Kuiper has found protrusions and fissure-like depressions on their crests" (p. 295, Shoemaker, *et al.*, 1960).

Similarities have been suggested between lunar Mare ridges and terrestrial oceanic ridges (p. 473, Fielder, 1963).

F. The Rilles

Rilles in the Mare Humorum area are continuous gently curved to straight line segments. They vary in length from 10 Km to more than 250 Km. Generally the longer rilles are the widest. Based on topographic and photographic evidence they appear to maintain the same width through their entire length. Small rilles are generally less than half a kilometer in width while the longer rilles are 3-4 km in width. Depths are unknown.

Rilles may branch, merge, cross each other or other surface features as well. Some craters (Mersenius D, Palmieri, Hippalus and others) are crossed by the rilles and are thought to be older (PLATE I). Some craters such as Mersenius C and Gassendi G, cover the rilles and are younger.

The preferred directions for the rilles are NE-SW, N-S and NW-SE. In this they resemble the wrinkle ridges.

The rilles are present both inside and outside of Mare Humorum. They are also visible within some of the large craters (PLATE I). They are concentrated northwest, east and southeast of the Mare and inside Gassendi.

G. The Rays

The rays are generally narrow bright areas on the lunar surface. They may be locally concentrated as relatively small irregular elongate covering of the Maria. Wrinkle ridges may affect the local distribution of the ray forms. Rays cast no shadow suggesting absence of relief. They are usually associated with some of the large young appearing craters.

Rays in the Mare Humorum area occur within the Mare. They appear to be associated with craters younger than Mare material (PLATE I). No general trend or pattern is noticeable for the Mare Humorum rays. They do not appear to radiate from any particular crater area.

H. The Domes

Domes are rounded structures rising above the lunar surface which resemble terrestrial domes and shield volcanoes in form. These structures occur both within and without Mare Humorum.

A typical dome occurs in the southwestern part of the Mare (PLATE I). The dome is circular in shape, about 50 Km across and rises to 150 m above the Mare surface.

> "An obvious feature of the lunar Maria is the presence of domes - some with summit pits. Moreover in the basaltic provinces on Earth, basaltic domes are common and often have a summit pit". (p. 182, Green, 1960).

Domes resemble also terrestrial shield volcanoes. However, "the surfaces of many domes are, unlike most shield volcanoes distinctly convex" upward (p. 295, Shoemaker, 1960).

Eight domes are visible inside Mare Humorum with a concentration of six in the east and southeast (PLATE I). Domes are difficult to recognize in the Terrae and are not readily distinguishable from individual hills. No definite pattern of distribution is recognized for the domes.

Chapter III

DEVELOPMENT OF MARE HUMORUM AREA

The observations and measurements made in this study will be interpreted here. On the basis of this interpretation, the geological history of Mare Humorum area will be constructed and discussed. The events will be presented in the order in which they occurred.

A. The Mare Humorum Basin

The position of Mare Humorum in the central part of the investigated area, its circular to subcircular boundary, its lower elevation relative to the surrounding Terrae, the concentric pattern of the linears of probable tensional origin around the Mare, and the centripetal tilting of the craters on its margin indicate that the formation of Mare Humorum basin was preceeded only by the formation of the Terrae and the oldest craters (Figure 11).

Meteorite impact has been suggested as a process responsible for the Mare formation. Proposed principally by Urey and Baldwin, they noted "the generally circular outline, dark color, and smooth appearance of the Maria" (p. 45, Weil, 1965). They suggested that the size of the impacting body must have been very large, possibly of the order of small planets called planetesimals. The resulting crater was then filled by molten rock.

The explosion energy required to form Mare Humorum was calculated using equation (1) to be 1.35×10^{30} ergs. This is the minimum kinetic energy that the meteorite should have ($1/2\ mV_2$). The mass of the meteorite for various assumed velocities is shown in Table III.

The difference in color tone between the Mare and Terrae suggest a difference in density, based on the Earth analog that the heavier

TABLE III

Velocity and Mass of the Meteorite that might

have formed Mare Humorum

Velocity Km/sec	Mass* grams	Remarks
1	2.7×10^{20}	Low velocity for meteorites.
2.4	4.7×10^{19}	Escape velocity of the Moon is 2.38 Km/sec.
10	2.7×10^{18}	Low velocity range for terrestrial meteorites (p. 48, Weil, 1965). Escape velocity of Earth is 11.2 Km/sec.
15	1.2×10^{18}	Average velocity for terrestrial meteorites, close to escape velocity of Earth-Moon system.
20	6.75×10^{17}	High velocity range for terrestrial meteorites (p. 48, Weil, 1965).
72	5.2×10^{16}	Escape velocity from the solar system, close to highest observed velocity for meteorites

*Mass of Moon = 7.35×10^{25} g
Mass of Earth = 5.98×10^{27} g

iron oxides are darker than the lighter silicates in igneous rocks. The lighter toned rocks of the Terrae stand higher than the darker toned more dense rocks of the Mare. This is analogous to the continents of the Earth which rise above the darker and more dense rocks of the ocean basins.

B. Subsidence

The tilting of the larger craters on the margins of Mare Humorum toward the Mare is strong evidence for subsidence of the basin. The tilt is sufficient that the rim facing the Mare is covered by its surface material. This indicates that subsidence was initiated before the surface material reached the craters or was somewhat contemporaneous with it. By projecting a line from the top of the northern rim to the top of the southern rim of Gassendi and another line of similar construction from the southern to the northern rim of Doppelmayer, these two lines intersect in the vicinity of the crater Doppelmayer K within the Mare. Assuming the craters rims were once horizontal, this intersection suggests that the amount of subsidence approximated 1,100 - 1,200 m. The effect of the curvature of the Moon's surface tends to decrease this value but only by a small amount because the total distance involved is less than 430 km.

It has already been noted that the Mare's surface material reached a level on the Mare's margin higher than its surface. This, and the gravity faults along west margin with the east block down are evidences for continuation of subsidence after the deposition of the surface material. The amount of this subsidence was found from Figure 4 to be more than 400 m in the vicinity of the crater Doppelmayer K. The total amount of subsidence near the center of Mare Humorum basin, therefore approximates 1,600 m.

Subsidence of the basin resulted in radial forces acting on the margins of the Mare towards its center. These forces acted in tension and could well have produced the rilles strongly developed in the east and southeast and to the northwest. The tensional stresses appear to have been greater from the west, where faulting occurs, towards the Mare. In the north and south directions the rocks behaved plastically by downwarping rather than fracturing. The warping is exemplified inside the crater Hippalus where a monocline resulted from centripetal subsidence. This and other examples suggest that the amount and rate of subsidence was not uniform throughout the basin.

From a stress-strain relationship the forces that formed the Mare Humorum basin are shown in Figure 9. The absence of the typical upturned rim, the lack of radial fractures demonstrating former tensional stresses, all suggest an endogenous force for the origin of the Mare. If this be so the material filling the Mare must have been internally generated in the Moon and hence a heat source is needed. This in turn leads to a heat source somewhat late in the Moon's history and suggests a continuous radioactive source.

An experiment on subsidence and fault patterns was performed by Proctor (personal communication, 1966) to attempt to duplicate the conditions of withdrawal of large amounts of magma from a chamber. His description follows:

> "A frozen pond of 27.4 x 19.8 m size and up to 240 cm deep (Figure 10) was drained of its still fluid water. Collapse of the overlying rock (ice) cover into the developing cavity was recorded by the centripetal tilting of the ice sheet, the development of tension fractures and gravity faults. Some folds were formed, but the significance of these is

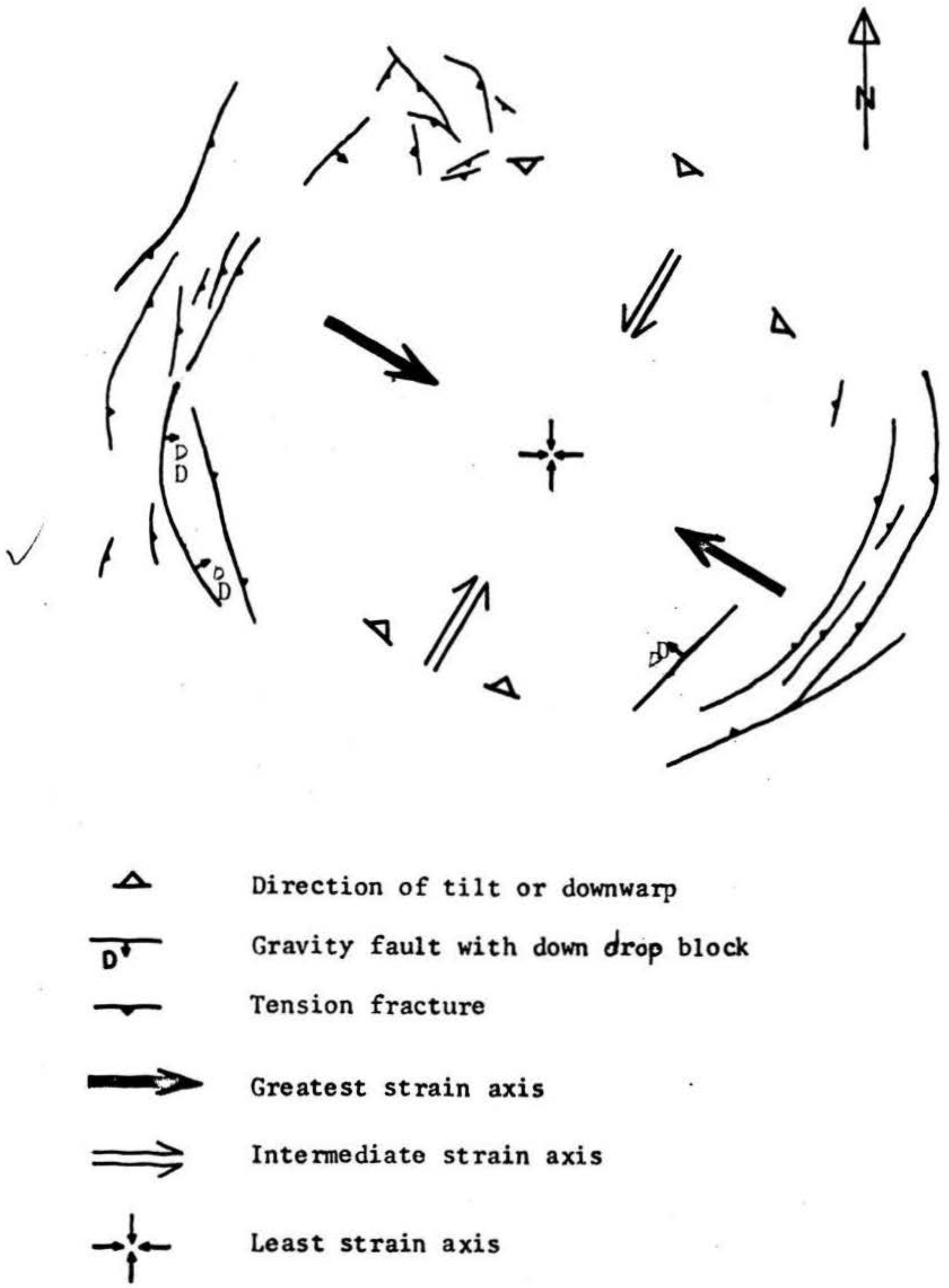

Fig. 9. Possible stress patterns of Mare Humorum.

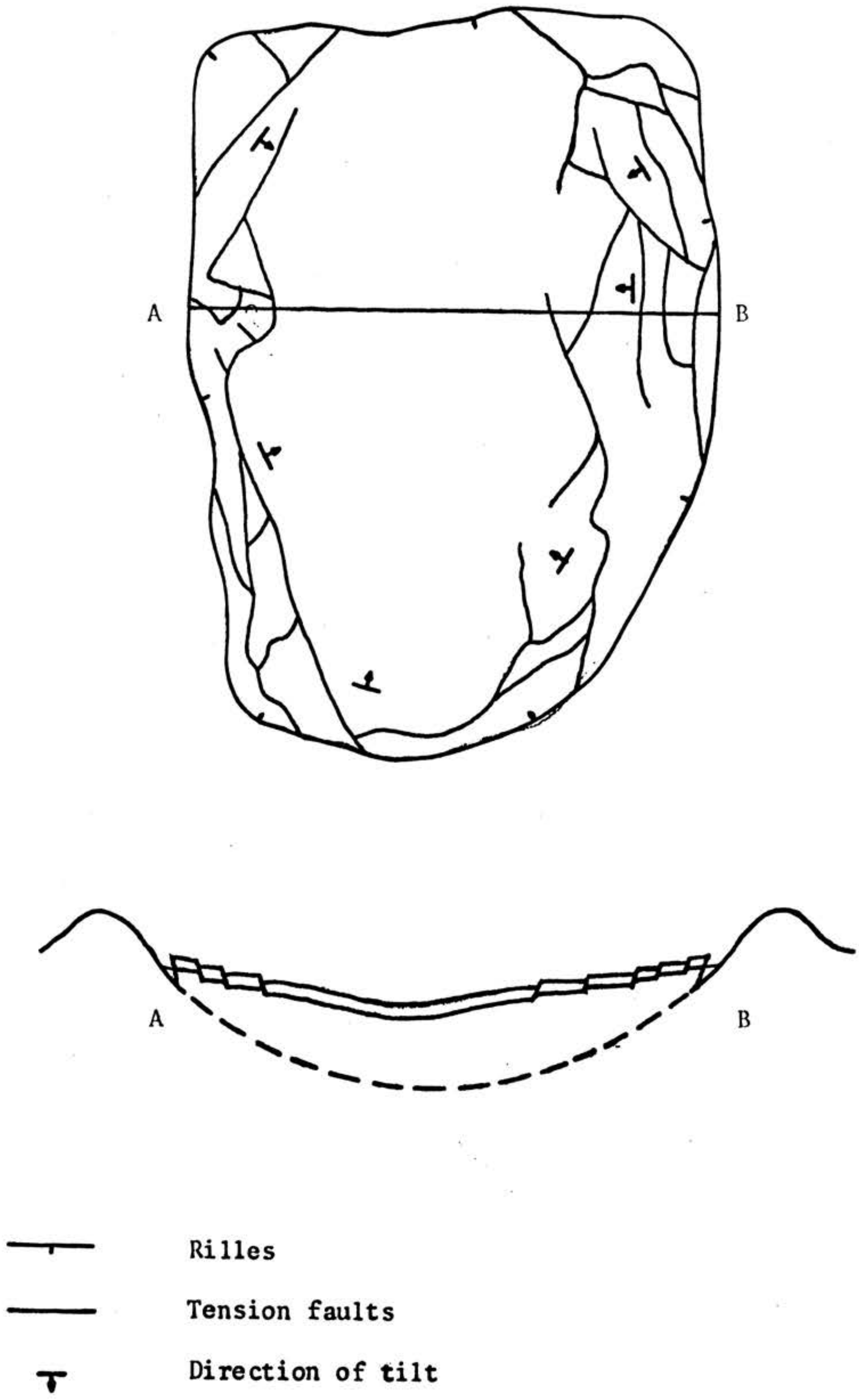

Fig. 10. Tension fractures and rilles developed in a frozen pond after withdrawing the water from below. (After Proctor, 1966).

unknown since the underlying topography of the pond's bottom may have influenced the fold form.

In actuality a series of accurate tension cracks and faults developed concave to the central part of the pond. Rille-like features developed along the edges where the ice slid away from the walls of the pond.

From an analog viewpoint, the tension cracks, gravity faults, and rille-like forms at the margin bear striking resemblance to the patterns of Mare Humorum (PLATE I). Going one step further, if water were to have issued forth along the fractures and filled over the ice, a 'lava' cover resembling the Mare Humorum would have developed. The channelways, if finally frozen, could have shown the characteristics of wrinkle ridges." (Proctor, personal communication, 1966).

C. Mare Cover Material

The general smoothness of the surface of Mare Humorum and its dark tone, the covering of the marginal inward tilted craters and adjacent low lying areas by a dark rock cover, the endogenous force that formed the Mare and consequently the internal generation of the Mare's cover material, and the resemblance of the patterns in the frozen pond experiment to the patterns of Mare Humorum, all suggest an original surface material of considerable mobility and post-Mare depression age. These characteristics are best met by a fluid lava flow of basic composition.

Another indirect proof for the existence of lava on the lunar surface came from the Russian unmanned space-craft Luna 9 which landed in Oceanus Procellarum (Figure 1) on the lunar surface, about 900km NW of Mare Humorum, in February 1966. This is covered by material similar in color tone and texture to the material covering Mare Humorum.

"The Russians confirmed that Luna 9 ... hit a surface that consisted of hard porous, volcanic soil formed from lava that had crumbled during billions of years of drastic temperature changes and bombardment by meteors and solar particles". (p. 52, Time, 1966).

The presence of wrinkle ridges of subparallel pattern and somewhat arcuate form inside the Mare, the fissures along their crests and the similarity in tone between these and the Mare's cover material suggests underlying fractures up along which lava welled and flowed outward at right angles to the feeding channels. The lava rising forth along these zones built up the wrinkle ridges by successive stages of eruption and solidification.

Concurrent with these eruptions, the fluid and very mobile lava gradually filled the basin of Mare Humorum to a certain horizontal level just as a liquid would fill the container in which it is placed. The areal extent of the dark tone and smooth texture of the Mare's surface rocks to a level of 3,800-3,900 m suggests that this was the maximum level the lava reached. The volume of the lava based on the estimated depression of the basin and the height of the floor assuming the basin to resemble an inverted cone was calculated and compared to the volume of lava in the Columbia Plateau on Earth. The results are shown in Table IV.

TABLE IV

Amount of Lava in the Mare Humorum Basin on the Moon and the Columbia Plateau on Earth

	Area Km^2	Depth Km	Volume Km^3
Mare Humorum	125,000	1.2	50,000
Columbia Plateau	500,000	1.0	500,000

Lava filled the older craters that formerly pocked the Mare Humorum basin, and except along the inward tilted margins, completely covered most of them. Some craters along the margins of the basin were partially covered. Good examples include: Gassendi, Doppelmayer, Hippalus, Loewy, Puieseux and many others. These craters are older than the Mare basin, because they are tilted into the Mare. One of them (Puiseux) lies completely inside the basin but is surrounded by the lava cover material.

The mobile lava moved out of the basin through the outlet on the southwest where it filled low lying areas to a level reached prior to the lava solidification. The amount of lava discharged through the outlet depended on the level of the lava inside the Mare, its viscosity, the time it took to solidify, and the cross section of the outlet. At least three of these variables can be measured or approximated and the others can be calculated.

The very dark grey tone in certain areas within the Mare suggests lava flows of different composition. The western marginal fault cuts across this darker lava cover while the lava cover of lighter tone covers the fault. There seems to be, therefore, at least three series of lava eruptions: (a) the lava of the dark grey tone which is older than the fault, (b) the lava of the very dark grey tone which is also older than the fault but younger than (a), and (c) medium dark grey lava which is younger than, and covers the fault (Figure 11).

D. Crater Considerations

Much distorted craters of subdued character, larger craters tilted toward the Mare, and craters of distinct rim-depression morphology imposed upon the other two and on the Mare comprise the three major groups of craters in the Mare area.

The craters with rims greatly distorted by smaller and younger craters and with subdued rims and escarpments are exemplified by Agatharchides and Mersenius (PLATE I). These are considered to be the oldest craters in the Mare Humorum area.

A much larger group of craters marginal to the Mare with distinct rims, some rilles and their floors partly lava covered include Gassendi, Doppelmayer and Hippalus. These are not as much disturbed by younger craters, even though they are much larger than the first group. They are, therefore, younger than the first group but they are older than the lava eruptions of Mare Humorum.

A group of craters formed on or over the rims of other craters or in their floors and also on the cover of Mare Humorum. These are considered to be the youngest craters in the area. Hippalus A and Vitello P belong to this group. All the craters of this group have a radius of less than 8 Km while all the craters of the first two groups have a radius of more than 6 Km.

The craters Hippalus A and Vitello P have the same radius but the depth of the first is twice that of the second. This is true for other craters in Classes 1 and 2 (Figure 8). Both classes could have been formed as a result of impact only if one of the following conditions is satisfied:

(1) The meteorites that formed the Class 1 craters impacted the surface in a pre-existing topographic depression (G.B. Clark, personal communication, 1966).

(2) The two crater classes are formed in two different types of surface material.

(3) Floors of Class 2 craters are covered by later material such as the Mare's surface material.

It is possible that meteorites may have impacted in preexisting depressions. These depressions, however, should have had nearly equal depths in order to account for the linear relationship between the Class 1 craters (Figure 8). The visible depressions on the lunar surface do not have equal depths, and there is no reason to believe that in the lunar past they did. This suggests that condition (1) is highly unlikely.

For condition (2) to be true one would expect all the craters of one class to exist only in Mare material and those of the other class to be in Terra material. This is not the case because we find craters of both classes present in the same material. For example; the craters Gassendi J of Class 1 and Doppelmayer K of Class 2 occur in Mare material while Dunthorne of Class 1 and Vitello of Class 2 are present in Terra material (Figure 2).

Some of the Class 2 craters have their floors covered with the Mare material. The depth of this material is greater in craters near the Mare. Only the crater Leibig G has its floor completely covered. The other craters are only partially covered and their measured depths are very close to their real values. Condition (3) therefore, does not explain the difference between the two classes.

In conclusion, meteoritic impacts based on the facts above cannot account for all craters in the Mare Humorum area. From the evidence presented in this study, crater Hippalus A and other craters in Class 1 formed as a result of meteoritic impact. This explains the close relationship between these craters (Figure 8). Some craters of Class 2 may also have the same origin, especially the very small craters since the two curves in Figure 8 will intersect each other if extended.

If one may interpolate from this it appears that the very small craters which are beyond the resolving power of the telescope will have similar radius to depth ratios irrespective of their origin.

For most of the craters of Class 2, however, another crater forming mechanism is needed. This is discussed in the following section.

E. Lunar Volcanism

Indirect evidence presented for volcanism on the lunar surface includes:

(a) the lava eruptions which covered Mare Humorum and adjacent areas, (b) the fissure-like fractures on the crests of the wrinkle ridges from which lava erupted, (c) the relationship between the radius to depth ratios of the craters in Class 2, especially the larger craters (Figure 8), (d) the domes with small craters on their summits which resemble terrestrial shield volcanoes, and (e) the fact that the ejecta that surround some of the smaller craters, such as Doppelmayer K (PLATE I), extend a distance which may be many times greater than the crater radius and finally, the volume of this ejecta appears to be greater than the apparent crater volume although direct measurement of the ejecta volume is extremely difficult because the size of the craters is so small.

According to the radius to depth ratio of curve (c) in Figure 8, the depth of Gassendi, for example, should be 5,000 meters or two and a half times its present depth of 2,000 meters.

The probable eruption in 1958 of the crater Alphonsus which lies northeast of Mare Nubium (Figure 1) is another indirect evidence in support of volcanic origin of the large craters in Mare Humorum area. The size of Alphonsus is about the same as that of Gassendi. Spectrograms of the central peak of Alphonsus taken by Kozyrev in 3 November 1958 indicated that gases of high temperature were being emitted (p. 267, Kozyrev, 1960). Several observations of this phenomenon were confirmed by other astronomers.

The central peaks of lunar craters may be similar to terrestrial volcanoes and the "outer craters themselves may be similar to calderas of terrestrial volcanoes formed by subsidence due to the depletion of the magmatic source (p. 267, Kozyrev, 1960).

In conclusion, while the only direct evidence for some type of thermal activity on the lunar surface is that of the crater Alphonsus, yet the other indirect evidences presented do lend strong support to a volcanic origin for many of the Class 2 craters in the Mare Humorum area.

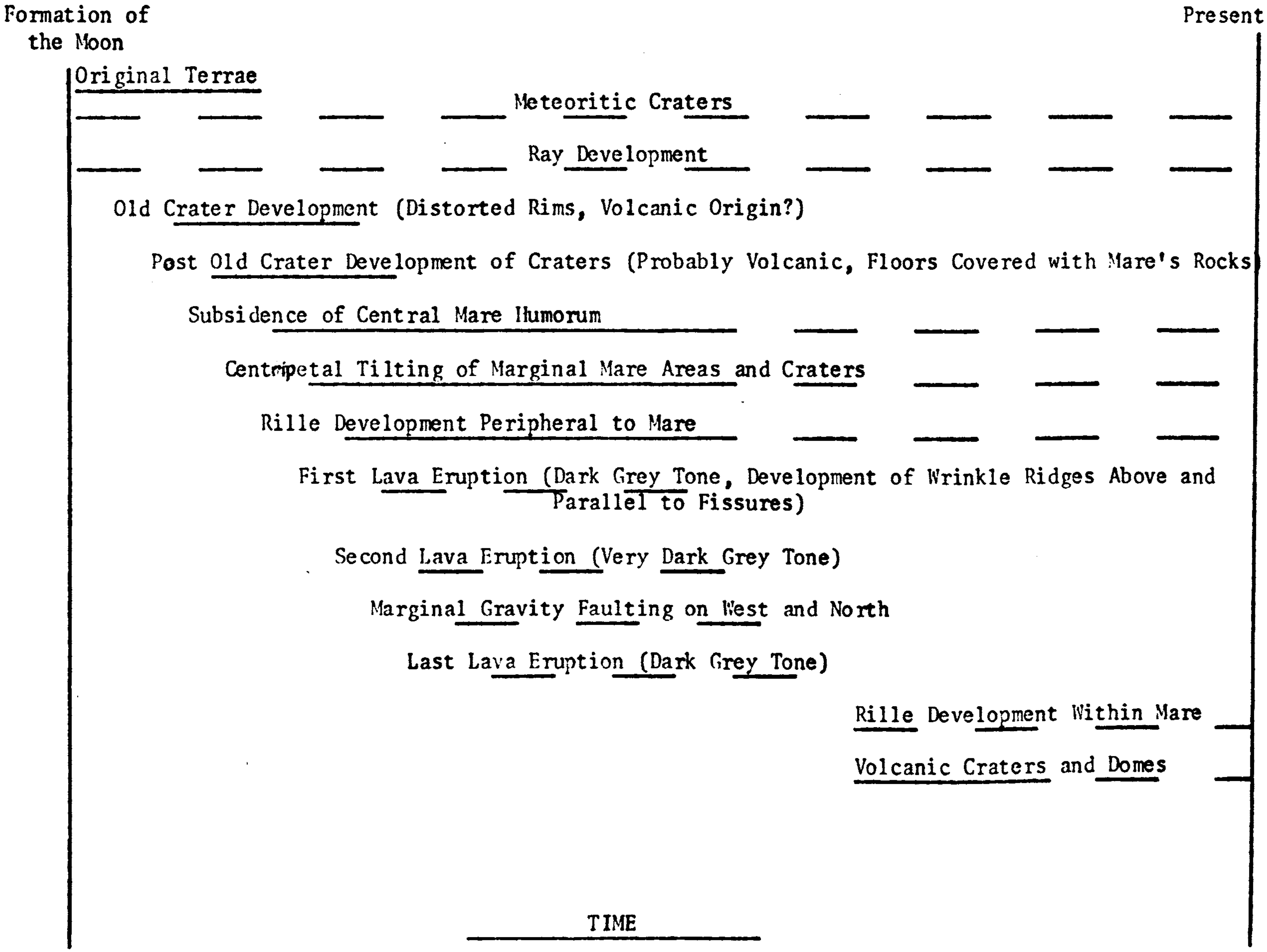

Fig. 11. Chart of the Geologic and Tectonic History of Mare Humorum Area.

Chapter IV

CONCLUSIONS

The first event in geological history of the Mare Humorum area was the formation of the original Terrae. This was followed by the formation of the first craters such as Agatharchides and Mersenius. They are probably of volcanic origin. Their rims are distorted and they appear to have a subdued form. This group of craters was followed by a second group of volcanic origin. This includes the largest craters in the area such as Gassendi and Doppelmayer. The floors of many of these craters are covered by the Mare's rocks, probably volcanic.

The central portion of the area started to subside forming the Mare Humorum basin and causing prominent and extensive tension fractures (rilles), gravity faults, monoclines, and inward centripetal tilting of the craters on the basin's margins.

A series of extensive lava eruptions covered the Mare. At least three such eruptions are recognized by their color tone and age relationship with the gravity faults on the western margin of Mare Humorum. Wrinkle ridges formed along the fissures where lava welled upward and solidified. The mobile lava issuing from the feeding channelways flowed over large areas and covered portions of the marginal craters and adjacent low lying areas.

After, and possibly concomitant with the lava eruptions, craters of volcanic and meteoritic origin formed. These were distributed over the surface of the Mare and the Terrae. They are smaller than the previous craters and their rims are distinctly defined.

The latest events appear to be continued impact of small meteorites, and development of some ray structures. Subsidence of the basin appears to have stopped sometime in the past. The lack of continued subsidence features suggests that the former energy source responsible for the basin origin and lava eruptions has completely disappeared and current features are only indicative of past events. The Moon in this area is essentially dead.

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