

RARE BOOK

R. S. Mason

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Having enjoyed a week's sojourn and
study in the magnificent volcanic landscapes of Oregon, ---

August 28, 65

TRANSACTIONS

OF THE

LUNAR GEOLOGICAL FIELD CONFERENCE

BEND, OREGON

AUGUST 1965

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THESE TRANSACTIONS are the outcome of the Lunar Geological Field Conference held in Bend, Oregon, August 22 to 29, 1965, the official publication for which was the State of Oregon Department of Geology and Mineral Industries Bulletin 57, "Lunar Geological Field Conference Guidebook." The Oregon Conference was a continuation of a symposium on lunar geology held in New York City May 16 to 19, 1964, the transactions for which were published as "Geological Problems in Lunar Research," in the Annals of the New York Academy of Sciences, Vol. 123, Art. 2, p. 367-1257, July 15, 1965.

SKETCH ON COVER is from a scroll prepared by B. B. Brock and signed by all members of the Conference.

TRANSACTIONS
LUNAR GEOLOGICAL FIELD CONFERENCE

Bend, Oregon
August 22 to August 29, 1965

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TRANSACTIONS OF THE LUNAR GEOLOGICAL FIELD CONFERENCE

Bend, Oregon - August 22 to 29, 1965

FOREWORD

This volume, containing a collection of papers on volcanic geology, lunar geology, and related subjects, is the outcome of the field conference held in Bend, Oregon, in August of 1965. The conference was sponsored by the University of Oregon Department of Geology and the New York Academy of Sciences. It followed a somewhat similar conference on Geological Problems in Lunar Research sponsored by the New York Academy of Sciences in New York City May 16 to 19, 1964.

Although primarily a field conference to take advantage of the remarkable display of volcanic features in the Bend area, opportunity was also provided for the presentation of scientific papers. This volume contains a list of the papers presented and either an abstract or the complete paper as submitted by the author. In addition, there are some reports which appear pertinent, written by invited participants but not actually presented at the sessions. There is also included a copy of a resolution passed by the conference on August 29, 1965.

A valuable contribution of the conference was the Lunar Geological Field Conference Guide Book, prepared by the State of Oregon Department of Geology and Mineral Industries.

The sponsors of the conference wish to acknowledge the assistance of the State of Oregon Division of Planning and Development in arranging the financing, the State of Oregon Department of Geology and Mineral Industries for undertaking the publication of this volume, and the work of the editorial staff headed by Dr. G. T. Benson of the Department of Geology, University of Oregon.

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COMPARATIVE MORPHOLOGY OF LUNAR CRATERS AND CIRQUES AND SOME VOLCANIC FORMATIONS IN KAMCHATKA

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ABSTRACT

Caldera morphology of the Kamchatka peninsula is similar to that of lunar craters. Intersection of craters producing loci for secondary rim craterlets is documented for Clavius on the moon and Ksudach caldera in southern Kamchatka. Photographs taken at low sun angle of the volcanics of the Mean ridge in Kamchatka are compared with near terminator photographs of lunar features. The association of maar cratering within the Uzon, Ksudach, and the Karymsky volcanic complex appears to have lunar analogs. Diameter-depth plots of many calderas fall on the curve defining meteorites, chemical and nuclear explosion craters. Diameter to depth crater plots cannot be genetically interpreted. Impact triggering of volcanism appears to explain the large size of lunar craters by the break-down and subsidence of the lunar crustal blocks into a molten interior. Normal volcanic processes such as the development of volcanoes and ridges within calderas followed the subsidence of these crustal plates. Lava flooding produced by impact mechanisms is considered improbable.

* * * * *

At present there are two basic hypotheses dealing with the origin of lunar surface features; these are the endogenic or volcanic and the meteorite or ballistic concept. Both hypotheses practically enjoy equal rights and the effect of both factors – the endogenic and the meteorite upon the formation of the lunar relief – is acknowledged by the adherents of both hypotheses. The basic problem of immediate importance is to determine which of the two factors appears to be dominant.

This report briefly compares the morphology of lunar craters and cirques, on one hand, and volcanoes and calderas in the Kurilo-Kamchatka volcano area, on the other.

Relative to the problem of the formation and the development of the lunar surface, the morphological comparison of lunar objects with volcanic structures of the earth has been carried out rather irregularly and in a number of instances has been based preferably on popular opinion rather than on systematic scientific investigations. As a result, obvious errors appear even in the most comprehensive studies covering the field of selenology and selenography. Moreover, notwithstanding the assumption expressed even in the 18th century on the possibility of volcanic activity on the moon, the study of the lunar surface has been almost entirely the domain of astronomers. Only recently have geologists joined the research team. One should bear in mind that volcanology is a very specialized branch of the geological sciences and, hence, studies of geologists engaged in the field of general geology but yet directed to the analysis of volcanic forms on the lunar surface frequently are in error.

Observations of the lunar surface, the study of lunar atlases (Kuiper, 1960 a, b), aerial photography and aerovisual observations carried out by the author during 1959 to 1964 in the Eastern volcanic belt area and in the Kljuchevsky volcano group reveal morphological similarities between lunar surface features and those of the Kamchatka volcanic area.

From this point of view, the Krashenninnikov volcano, situated in the eastern coastline area of Kamchatka south of the Kronotsky Lake and thus far inadequately studied, is certainly an object of special interest. The volcano is in a caldera 12 km in diameter. The circular scarp of the caldera is topographically distinct. On the exterior northern flank of the caldera along a fracture extending 5 kilometers, one observes a continuous chain of craters (figure 1). A similar object on the lunar surface is the Hyginus rille (figure 2) where a series of smaller craters is associated with the fracture. The same relationship exists in the rille area of Vendelinus, Silberschlag and Ariadaeus (Barabashov and others, 1963; Khabakov, 1949). According to Green (1963) there are more than 180 telescopically visible chain crater series on the moon (associated with fractures).



Figure 1. A chain of craters in the northern slope of the Krasheninnikov volcano caldera.

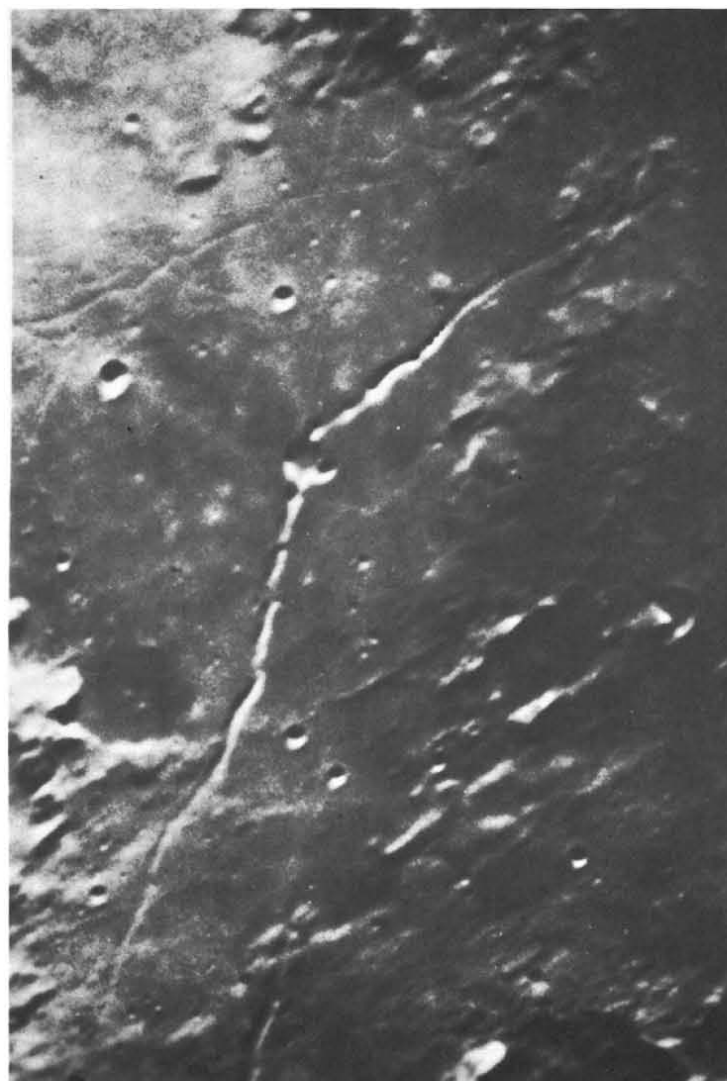


Figure 2. A crater chain along the Hyginus rille (after G. P. Kuiper).



Figure 3. The Krasheninnikov volcano crater.

A crater with a central cone and a smaller crater (figure 3) set concentrically within it is situated in the caldera of the Krasheninnikov's volcanic complex. The diameter of the caldera is 2 km. An analogous concentric arrangement is observed on the moon in a small crater named Birt (with a diameter of 6 km) situated along the shores of the Sea of Clouds. Its central hill with an apical crater is surrounded by two narrow concentric rims with a height up to 300 m. In addition to Birt, concentric rims are observed in the Taruntius and A. Pavlov craters. Traces of flooded rims are noted in Posidonius and in some others. It is practically impossible to interpret the origin of similar craters from the standpoint of the meteorite hypothesis. Most probably these craters resulted from volcanic activity.

In the southern part of Kamchatka within a volcanic plateau situated between the Khodutka and the Zheltovsky volcanoes, we also note the low circular ridge of the Ksudach caldera (figure 4). Its diameter is 7 km and its exterior flanks have gentle slopes of 5° to 9° ; the rim of the caldera is up to 600 m higher than the floor. The inner part of the caldera contains a crater flooded by a lake 1.5 km in diameter, which formed as a result of a severe explosive eruption in 1907 (figure 5). A comparative morphological study of the Ksudach caldera (figure 4) and the morphology of the craters situated along the rim of Clavius is recommended (figure 6). Note that of the six relatively large craters situated within the range occupied by Ksudach, four are located on the circular caldera rim and two of them are with central mountains.

Figure 7 illustrates one of the numerous volcanoes of the Mean ridge. The photograph has been



Figure 4. The Ksudach caldera.



Figure 5. An explosion crater in the Ksudach caldera.



Figure 6. Clavius (after G. P. Kuiper).

made at a low sun angle which is most convenient for the purpose of comparing it with the photographs of the lunar craters placed next to the terminator under analogous conditions of exposure (figure 8).

Figure 9 shows two intersecting circular structures: the remains of the old Dvor volcano and the caldera of the Karym volcano superimposed upon the latter. Similar interrelations can be observed in the moon in Cyrillus, Catharina, Theophilus, Maurolycus and Stofler craters (figure 10).

The morphology of Stofler crater deserves a somewhat more careful study. Stofler, in the southern hemisphere of the moon, is located on the extension of the major crater chain of Purbach and Regiomontanus and appears as a relatively ruined circular ridge. Two smaller craters of younger formation with still smaller (and younger) craters are disposed along the rims. This entire complex is superposed on the southern crest of the Stofler ridge. Observe that the craters are intimately associated with and defined by the loci of intersection of circular rims within the range of first and second generation craters, that is on the most structurally favorable sites from the point of view of the volcanic hypothesis. A similar picture relative to the small craters and their location on intersections of circular rims of various ages is observed in the area of the Barocius, Albategnius, Polybius, Catharina and others.

The ballistic hypothesis completely fails to explain the fact of the close adherence of small (parasitic) craters to the rims of large-sized craters and proves to be totally incapable of interpreting the frequently observed close association of the small craters to the loci of rim intersections. On the other hand, all these facts are in full agreement with the phenomena observed in terrestrial areas of recent volcanic activity.

Moreover, lunar craters often reveal features similar to explosive volcanic craters (maars). It is relevant to mention the explosion maar in the Galja (figure 11), the Uzon (figure 12), the Shtjibel maar in the Ksudach caldera (figure 5), and the Valentine explosion maar northeast of the Karymsky volcano (figure 13). The comparison of these craters and maars with numerous smaller lunar craters (figures 2, 6, 8, and 10) shows that their morphological features are similar. This conclusion is fully supported by a comparative study of topographic profiles. Maar floors (figure 13) are flat. The inclination of the inner slopes have an angle of repose of 20° to 35° , while the exterior ones are 3° to 15° . These values are quite analogous to what we observe on the moon (figure 14).

Hence, the qualitative congruity between lunar morphology and explosive volcanic craters can be regarded as an established fact. However, there is a radical quantitative difference. The diameters of the volcanic craters and maars fail to exceed 2-3 km, whereas the most frequently observed lunar diameters are from 20-40 km (Khabakov, 1949). The most massive volcanic objects which appear to show morphological likeness with lunar craters and cirques are the calderas. The calderas can be subdivided

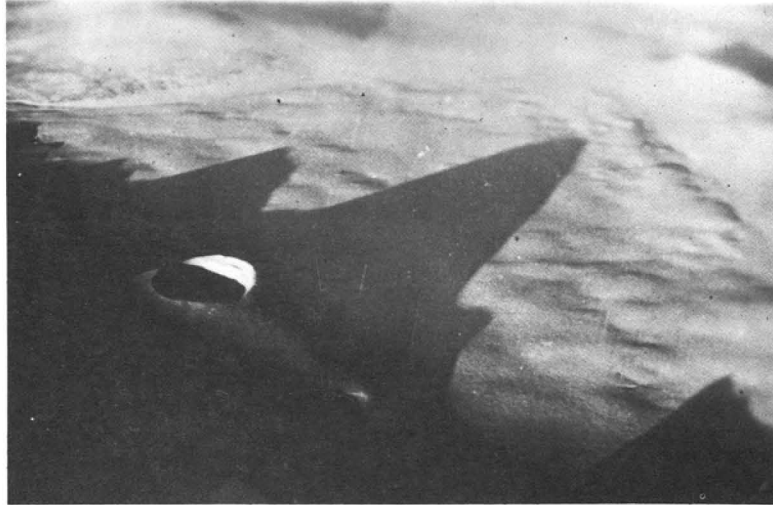


Figure 7. One of the numerous volcanoes of the Mean ridge.

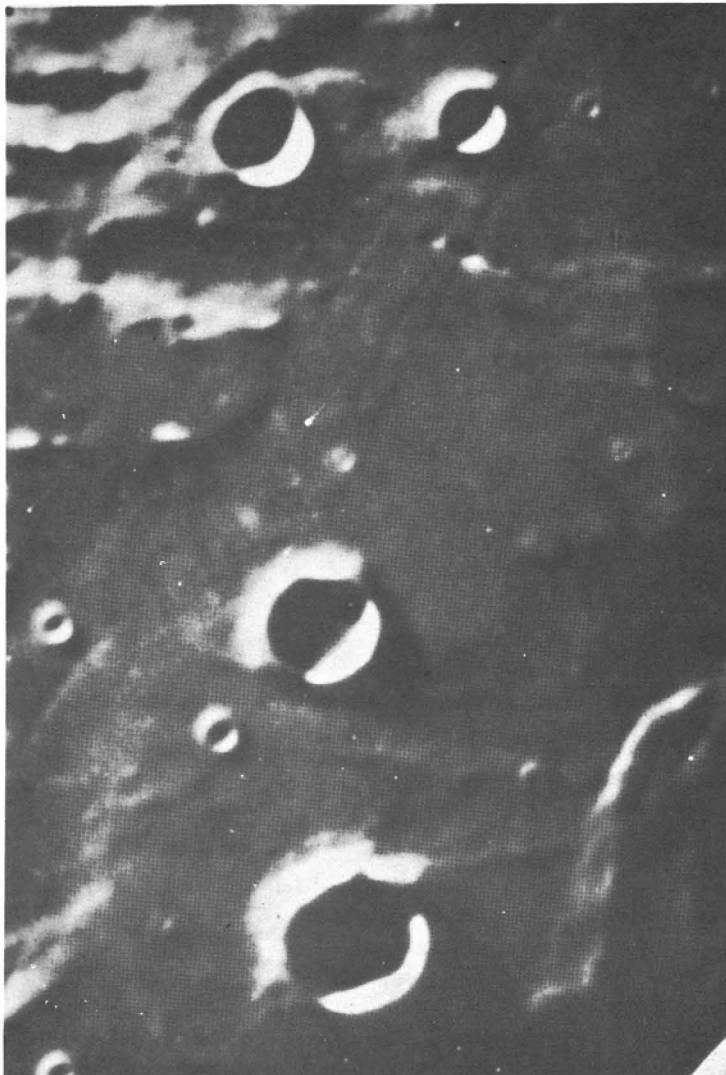


Figure 8. Craters in the area of the Sea of Vaporum (after G. P. Kuiper).

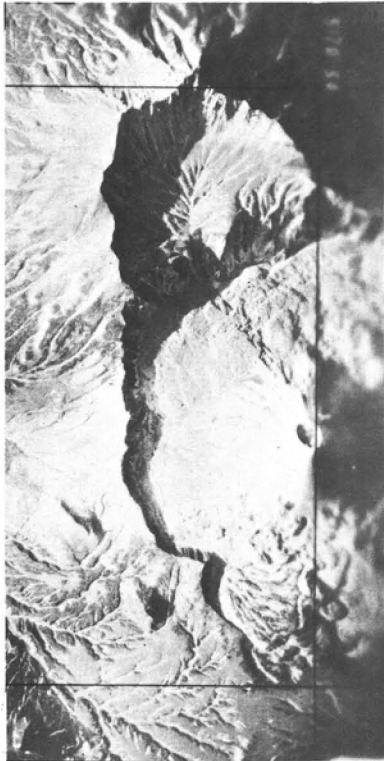


Figure 9. Caldera of the Karymsky volcano intersecting the remnants of the Dvor volcano.

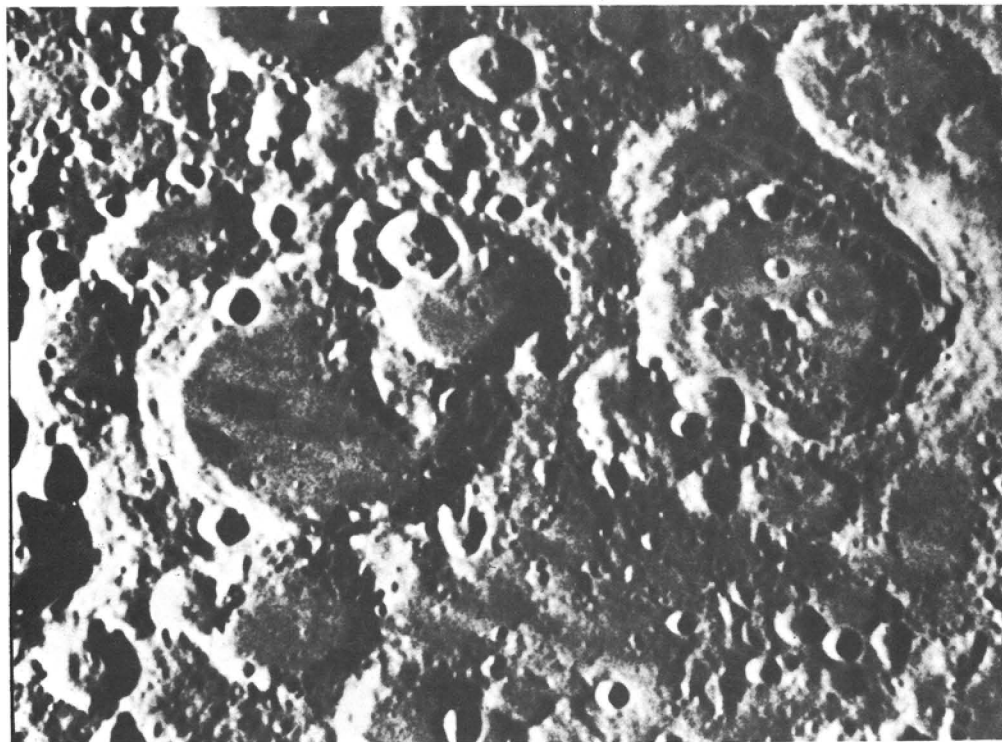


Figure 10. The Stofler cirque
(after G. P. Kuiper).

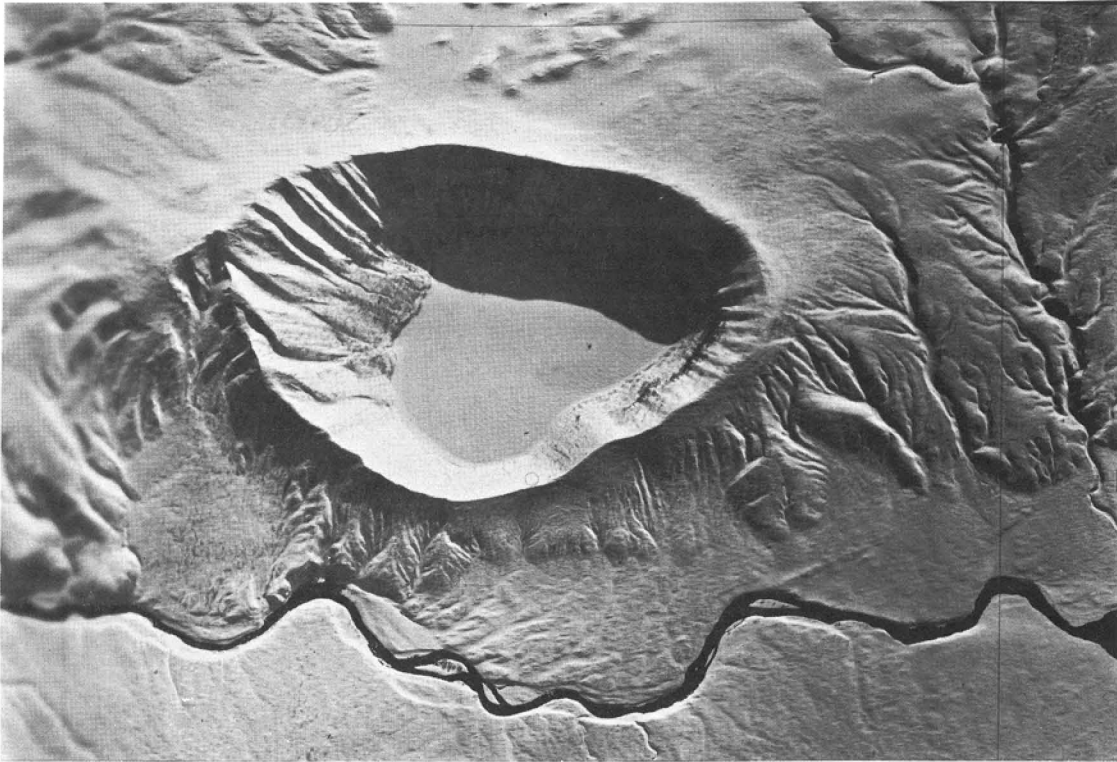


Figure 11. The Galja maar explosion in the area of the Krashennnikov-Kov volcano.

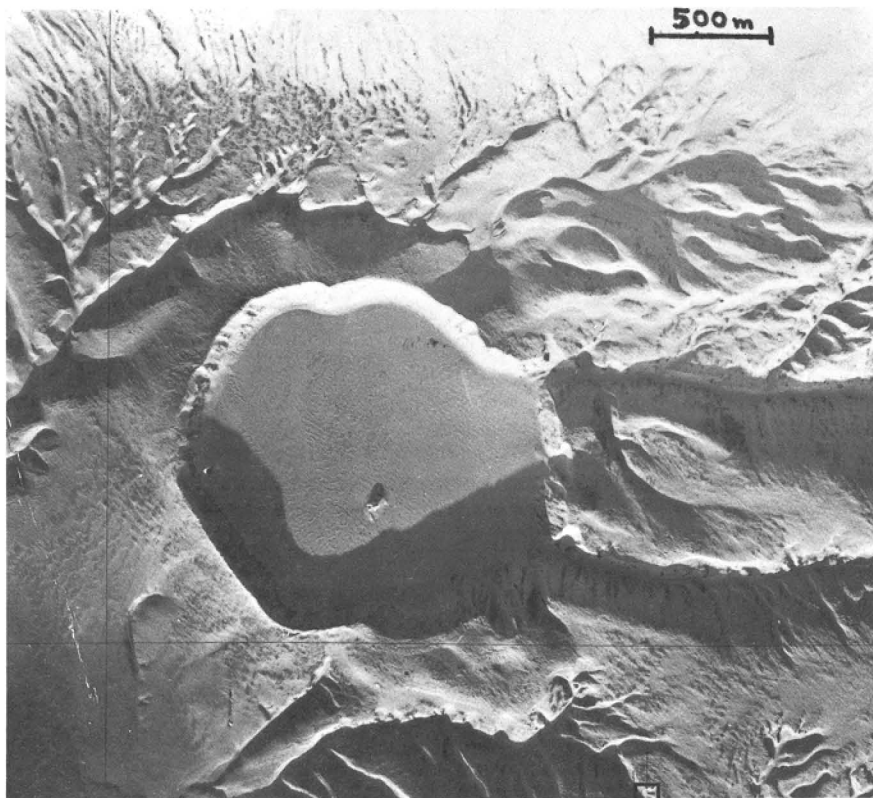


Figure 12. The maar explosion in the Uzon caldera.

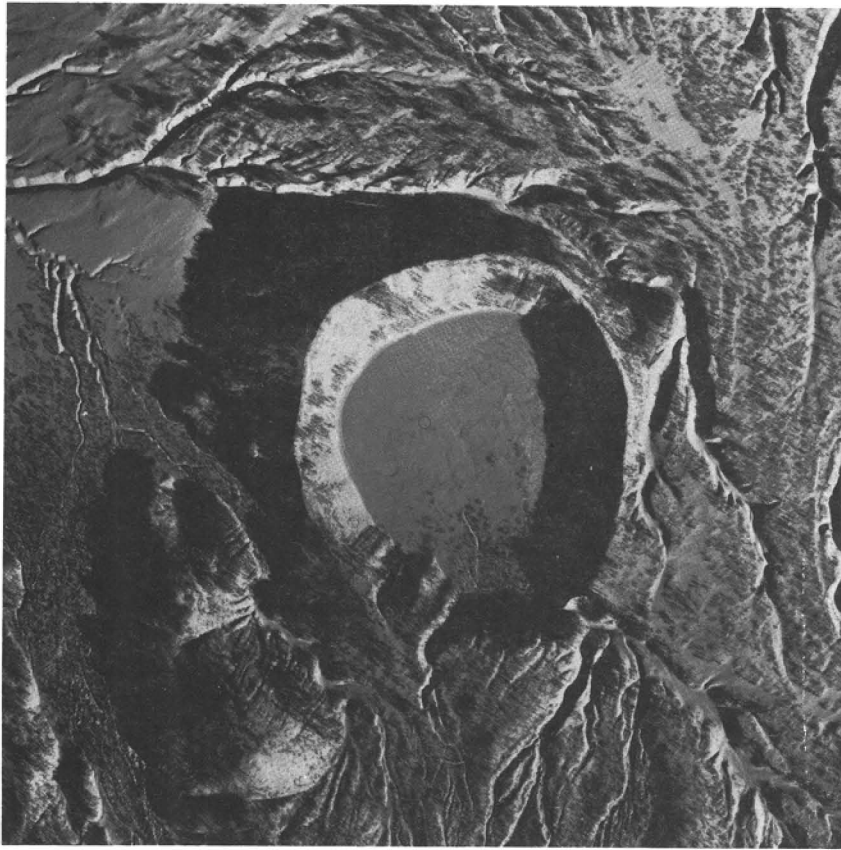


Figure 13. The Valentine maar explosion in the area of the Karmysky volcano.



Figure 14. A crater in the area of the Hipparchus (after G. P. Kuiper).

into two groups according to their mechanism of formation: calderas formed by stoping (the Glencoe type) and calderas formed by explosion (the Krakatau type). Calderas which in the course of their formation erupted huge amounts of pumice and ignimbrite are classified by most authors as having an explosive genesis. The problem involved with caldera genesis of lunar craters has been frequently discussed and, therefore, the author does not wish to go into the problem of calderas and lunar craters once again. Instead, we shall dwell upon some quantitative parameters characterizing calderas and compare them with analogous parameters established for explosion meteorite and lunar craters.

The adherents of the meteorite hypothesis have shown quite convincingly that most lunar craters have originated as a result of impact explosions. According to their viewpoint this very fact is an adequate basis for accepting the meteorite hypothesis. Apart from the problem concerning the genesis of the lunar craters, the author wishes to show that many volcanic objects of the earth (maars and calderas) are morphologically similar to craters which originated from explosions.

Baldwin (1949) has shown that craters produced by mines, bombs, shells, and meteorites reveal a uniform sequence in ratios between depth and diameter, energy and diameter. His plots include terrestrial and lunar craters (including the largest ones). According to Urey the relationships established by Baldwin are so convincing that there is no longer any sense in discussing the problem concerned with the causes responsible for the formation of lunar craters because the meteorite nature of their origin is beyond doubt.

On the basis of gravimetric studies, Yokoyama (1963) estimated the energy involved with the movement of volcanic material concurrent with eruptions and which lead to the formation of calderas. He established an empirical relation showing the dependence of the eruption energy upon the size of the caldera (Yokoyama, 1963). Figure 15 represents a combined graph showing the relation between energy and diameter compiled by the author in accordance with the data cited in the papers of Baldwin (1949) and Yokoyama (1963). As seen in the graph, the calderas fit into the curve developed by Baldwin in regard to shell craters, meteorite craters and lunar craters. The same conclusion appears to be justly applicable to the relationship of the depth of craters and calderas with their diameter (figure 16). The results fully conform with normal processes of terrestrial or lunar surface deformation. As a result of a near-surface explosion crater morphology depends merely upon the physico-mechanical properties of the environment and the energy of the explosion and does not depend upon the type of the explosion (chemical, nuclear, meteorite, or volcanic). Hence, the very fact that the lunar craters fall on the curve established for the explosive and meteorite pits does not mean that the lunar craters are of meteorite origin for this relation is applicable to volcanic objects as well. In order to incorporate craters into the meteorite or volcanic group we need other criteria.

However, apart from the similarity of details of all lunar craters and cirques with the volcanic formations of the earth, the gross morphology of the lunar surface radically differs from the morphology observed in the areas of active volcanoes. The remark made by A. Vegenra seems to be quite reasonable: "...that because of the small size of the Moon one becomes dubious from the very outset if the lunar crust has developed similar to that of the earth." Therefore, the approach to the study of the lunar surface with criteria similar to those applied to the earth's crust is an erroneous one. Conclusions about the block structure of the moon, the genetic development of its basic structural elements, differential movements along zones of deep fractures and stable and mobile sites (Khodak, 1963) have been made chiefly on the basis of terrestrial analogies and are in most cases premature. Possibly in the future some of these surmises will turn to be true. However, today they remain as guesses and hypotheses, especially in regard to the far side of the moon. Structural speculations for this area are probably incorrect, because photography of the moon's far side has been carried out in full moon when the visibility of details is determined by the difference of their brightness, that is, practically by the difference of their reflection coefficients (Levin and Ruskol, 1962). Those having studied the moon with astronomical instruments know too well that the detailed morphology of lunar objects (especially crater or fracture depths) is observable solely under conditions of oblique illumination at the terminator. The photographs of the moon's far side made in a full moon can be viewed as an early approximation which only permits an estimation of the number of craters, seas, and the correlation of areas covered by them. It would be rather careless to classify the structural elements, as stable or mobile, and assign them to different epochs (Khodak, 1963) on the basis of these photographs.

Before singling out the deep fractures or the mobile and stable sites on the basis of morphological data, one should solve the main problem involved with the causes which determine the morphology of the lunar surface and the origin of the lunar craters. It is a matter of major importance to establish criteria enabling classification of lunar forms into volcanic and meteorite groups.

We cannot ignore meteorites (Khodak, 1963) relative to the examination of the geology and the

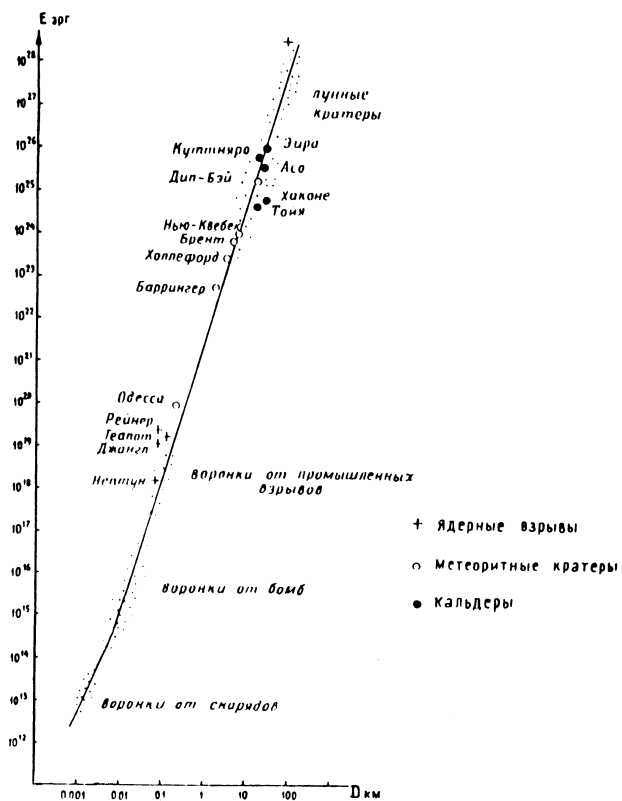


Figure 15. Relationship between the explosion energy and the diameter of the crater (compiled from Baldwin, 1949, and Yokoyama, 1963).

- o Meteorite craters
- + Nuclear craters
- Calderas

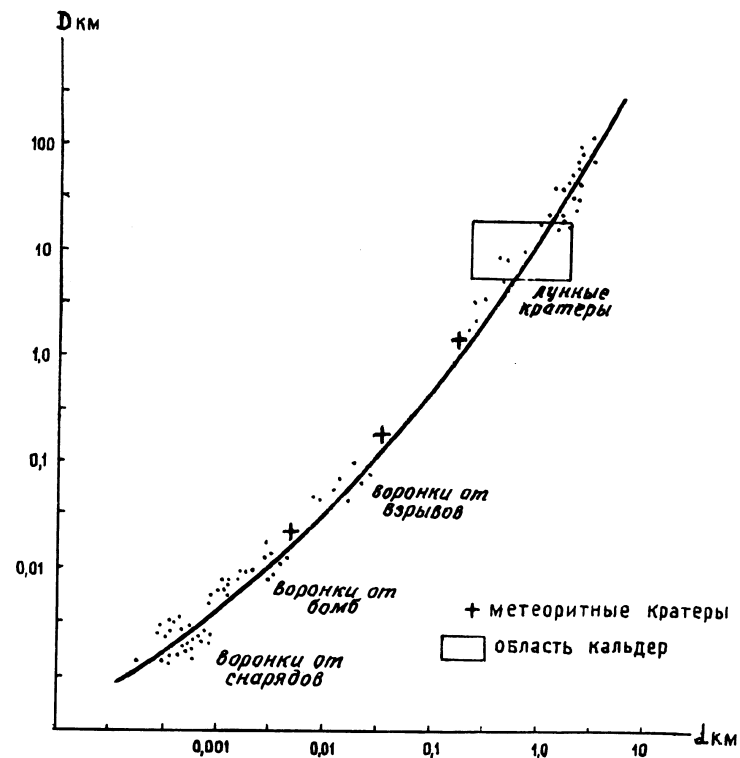


Figure 16. Diameter-depth relationships of craters (according to Baldwin, 1949).

- + Meteorite craters
- Calderas

morphology of the moon. Meteorite bombardment played a no less important role in the development of the moon's relief than exogenic processes and sedimentation in building up the relief of the earth. Levin (1964) has shown that during the moon's radiogenic heat-up, melting began practically at the same time from the depth of 200–300 km and reached the center. In the course of progressive heating and differentiation of the lunar interior the thickness of the exterior solid layer decreased and its instability increased. The bombardment of the moon triggered the break-down of the exterior layer into crustal plates which submerged and were inundated by lava extrusions. The heating, melting and formation of magma followed as a result of the moon's inner development. However, meteorite bombardment frequently (in most cases) acted as a trigger mechanism for surface volcanism responsible for the building up of gigantic circular structures.

Following the emplacement of these structures, subsequent development of circular zones in the areas of active volcanism was determined by inner (endogenic) factors. Particularly, subsidence along the circular fractures, to a certain extent analogous to the formation of ring-fracture stoping in calderas, occurred concurrent with intense volcanic activity along these fractures resulting in the formation of circular ridges and small craters localized on tension zones on crater rims. On our planet one rarely observes a coincidence of volcanic apparatuses with the circular fractures defining the calderas (the Opada and Iljinsky volcanoes in Kamchatka, Sakurazima and Usu in Japan, for example). The activity of these volcanoes is preceded by and accompanied with the subsidence of the inner central caldera block (Mogi, 1958).

In the process of volcanism under lunar conditions developing along the circular ridge and the subsidence of the central block, the latter develop fractures along which volcanic apparatuses may arise.

In a simplified model of stress distribution in a right vertical cylinder where the radius is greater than the height, the resultant of the force of gravity, applied to the center, is directed downwards, whereas the frictional forces are applied upward along the periphery. This leads to the conclusion that a similar system most easily develops stresses running through the center of the cylinder base, that is, along the diameters. Therefore, within a crustal block of this type, volcanic apparatuses ought to arise at the intersection of these disturbances, at the central area. Such a regularity is observed in the intimate association of the volcanic structures at the intersections of diversely orientated fractures in the Kurilo-Kamchatka zone. In individual cases, the fractures which control the arrangement of the volcanic apparatuses have formed off-center features. At times, a series of merged volcanoes have arisen along these fractures forming a linearly orientated ridge. Analogs of such ridges are observed on the moon in Alphonsus, Bullialdus, Arzachel, and so forth. Similar volcanic structures, namely, the Zhupanovsky, Goreliy, Krashennnikov, M. Semyachek, Shiveluch, Tolbachik, and Kichpinych are observed in the Kuril-Kamchatka zone.

Nevertheless, apart from the major role of the meteorite bombardment in the development of the lunar surface, certain concepts of some adherents of this hypothesis prove to be erroneous and have not been confirmed by calculations. Such concepts hold that the lunar seas and craters are flooded with lava which had formed as a result of melting following meteorite explosions.

Assuming that the relation between the diameter of the meteorite crater and the required energy necessary for its formation which was established by Baldwin (1949) is valid, the explosion energy to form craters and cirques with a diameter of 100–200 km is estimated to be 10^{29} – 10^{30} ergs. For underground nuclear explosions, 1 kiloton of an equivalent explosion from TNT forms 500 ± 150 tons of melted rock (Johnson, Higgins and Violet, 1959). Bearing in mind that the average specific gravity of rocks under the conditions of an underground nuclear explosion amounted to 2.0 g/cm^3 , the volumetric equivalent would be $250 \pm 75 \text{ m}^3$ per 1 kiloton.

Supposing as a first approximation that the volume of rocks transformed into a melt in the course of meteorite explosions is similar to the volume observed in underground nuclear explosions, it is possible to calculate for an explosion energy of 10^{30} ergs, the formation of $2.5 \cdot 10^3 \text{ km}^3$ of molten substance. And consequently, a crater 100–200 km in diameter would be flooded by a lava layer 80–300 m thick. These values of the lava volumes are undoubtedly excessive because in underground nuclear explosions, a decrease of the depth of explosion results in a decrease in heat irradiation up to a minimum for surface explosions. Accordingly, the volume of rocks converted into melted substance during surface explosions is less than in underground explosions (Vaile, 1961; Norduke, 1961).

Madler established that 60 percent of lunar mountains are 1–4 km high. On the basis that in numerous lunar craters and seas one can observe traces of flooded and semiflooded rims (ghost craters) and supposing that their initial height failed to differ from the average statistical level, it is probable that the lava flooding craters and seas cover an area of about one kilometer or only a few kilometers. As indicated above, a similar amount of melted substance could not have been formed in the course of meteorite

explosions; hence, lava flooding of lunar seas and craters has originated as a result of endogenic processes.

An alternative explanation of the problem involved with factors responsible for the formation of the lunar surface relief fail to produce a satisfactory answer.

The meteorite hypothesis provides the scientist with a convincing interpretation of such facts as: (1) the sizes of lunar craters noncomparable with those of the earth; (2) a single event formation process; (3) a regular circular shape of numerous craters; and (4) a random distribution of craters in separately selected areas.

The volcanic hypothesis explains:

1. The multiphase pattern of development for some craters.
2. The linear arrangement of craters and the coincidence of smaller craters with fractures.
3. The coincidence of smaller craters on large crater rims and at the loci of intersection of large crater rims.
4. The non-central arrangement of 'central' mountains and ridges with craters.
5. The apical craters observed in some central mountains.

The author believes it is time to break away from general (mainly hypothetical) constructions and to develop a detailed morphological analysis of lunar objects and to compare the latter with the meteorite and volcanic forms and, thus, adopt criteria for subdivision. The single event process for forming meteorite craters and the duration and multiphase features of volcanic activity are undoubtedly reflected in the morphology of craters. When astronomers and geologists possess detailed close-up photographs of the lunar surface as with Ranger 7, 8, and 9 such task may be fulfilled.

I wish to thank Professor V. V. Sharonov who kindly afforded me the possibility to work with telescopes and who instructed me in astronomical observations and also Dr. A. V. Khabakov for his valuable remarks, advice and support in carrying out this work.

References

- Arthur, D. U. G., 1963, Visual observations of the moon, *in* New data on lunar studies: USSR Acad. of Sci. Publishing House (in Russian).
- Baldwin, R. B., 1949, The face of the moon: Univ. of Chicago Press.
- Barabashev, N. P., and others, 1960, The moon: Publishing House for Phys. and Math. Sciences (in Russian).
- Green, J., 1963, The geosciences as applied to lunar research, *in* New data on lunar studies, USSR Acad. of Sci. Publishing House.
- Johnson, G. V., Higgins, G. X., and Voilet, K. I., 1959, Underground nuclear detonations: Jour. of Geophys. Research, Vol. 64, No. 10, p. 1457.
- Khabakov, A. V., 1949, On the basic problems of the moon's surface development: Publishing House for Geographical Lit. (in Russian).
- Khodak, Yu. A., 1963, Basic structural elements of the moon and the significance of geographical and geological methods for its study: Izvestia of the USSR Acad. of Sci., Geol. Series, No. 8 (in Russian).
- Kuiper, G. P., 1960a, Orthographic atlas of the moon: Tucson, Univ. of Arizona Press.
- _____, 1960b, The photographic lunar atlas: Univ. of Chicago Press.
- Levin, B. U., and Ruskol, E. L., 1962, A review of recent data on moon research: *in* Problems of Cosmogony, No. 8 (in Russian).
- Levin, B. U., 1964, The thermal history of the earth and the moon as a physical basis for differentiation of their mineral resources and volcanism at surface areas: *in* Problems of volcanism: Far East Publ. House (in Russian).
- Mogi, K., 1958, Relation between eruption of various volcanoes and the deformation of the ground surfaces around them: Tokyo Univ. Earth. Res. Inst. Bull., Vol. 36, 99 p.
- Norduke, M. D., 1961, Nuclear craters and preliminary theory of the mechanics of explosive crater formation: Jour. Geophys. Research, Vol. 66, no. 10, p. 3439.
- Vaile, R. B. Jr., 1961, Pacific craters and scaling laws: Jour. Geophys. Research, Vol. 66, no. 10, p. 3413.
- Yokoyama, J., 1963, Volcanic calderas and meteorite craters with the special relation to their gravity anomalies: Jour. of the Faculty of the Sci., Hokkaido Univ. ser. VII geophys.

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CALDERAS OF KYUSYU

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ABSTRACT

In Kyusyu, there are many large and small calderas, which are related to welded pyroclastic rocks. In all, eleven calderas are described, including one buried caldera and one cryptocaldera.

Along the rim of Aso caldera, various kinds of lavas are exposed. All of these are older than the pyroclastics, going back to the Neogene age. It was previously believed that all these lavas had erupted from a common vent in the present depression, and that the whole somma was a portion of the rim of a single huge volcano. More than a dozen older volcanoes, however, are now recognized along or near the caldera rim.

The walls of Aira and Ata calderas are made also of various kinds of rocks -- volcanic, sedimentary, and plutonic. At the sites of these and other calderas in Kyusyu no original high volcanoes have yet been found, which is quite different from the cases of Crater Lake, Krakatau, and Hakone.

In plan and in elevation too, in some areas, the contour of the caldera is not simple. The margins of Aso and Aira calderas are locally scalloped somewhat like that of Santorin caldera. The sea bottom of the head of Kagosima Bay, that is, the Aira atrio, is not flat throughout the area. One part averages 140 m deep, while another is much deeper, sounding 180 to 200 m.

The basin of Kusu caldera consists of four Neogene andesite and tuffite units, all of which are older than the Yabakei ignimbrite. The remaining area (younger than the ignimbrite) can be divided into four separate parts, which are related to the vents of Yabakei pyroclastics. These may represent an embryonic stage of a big caldera of Aso type. The name of 'semicaldera' or 'protocaldera' is proposed for these vents.

Introduction

In Japan pyroclastic flows, welded and nonwelded, are found abundantly. The majority of them are developed around and related to big calderas -- Kuttayaro, Akan, Sikotu, Toya in Hokkaido; Towada, Tazawa, Hakone in Honsyu; Aso, Aira, Ata, Kikai in Kyusyu; and so forth. Hakone and Aso are, so to speak, the twin star calderas of Japan and have been best known from the beginning of western sciences in Japan. As to Aso, many pioneer geologists made surveys of the volcano, among which Dr. T. Iki's in 1902 is the most comprehensive.

Aso Caldera

The caldera of Aso (see figure 1) is one of the biggest (17 by 25 km; 379 km²) and the immense quantity of pyroclastic flows erupted from there covers an area of about 3500 km², the farthestmost outcrop being 100 km from the centre. Three or four layers of the welded rock are enumerated and the whole quantity is estimated to be more than 175 km³. Along the rim of the caldera various kinds of lavas -- olivine-bearing pyroxene andesite, pyroxene andesite, pyroxene-hornblende andesite and biotite rhyolite -- are seen, all of which are a great deal older than the pyroclastic rock, most probably going back to the Neogene age.

Pioneer geologists of Japan supposed that all these lavas of various kinds erupted from a common vent in the present depression and the whole somma was nothing more than a single huge high -- even higher than Huzi -- volcano. The writer has shown, however, that the older andesites and rhyolite have issued from a lot of different vents, some situated within the confines of the caldera and others beyond the caldera rim. More than a dozen older volcanoes are recognized along or near the rim of the caldera.

In plan, the margin is locally, especially in the northern half, scalloped like that of the Santorin

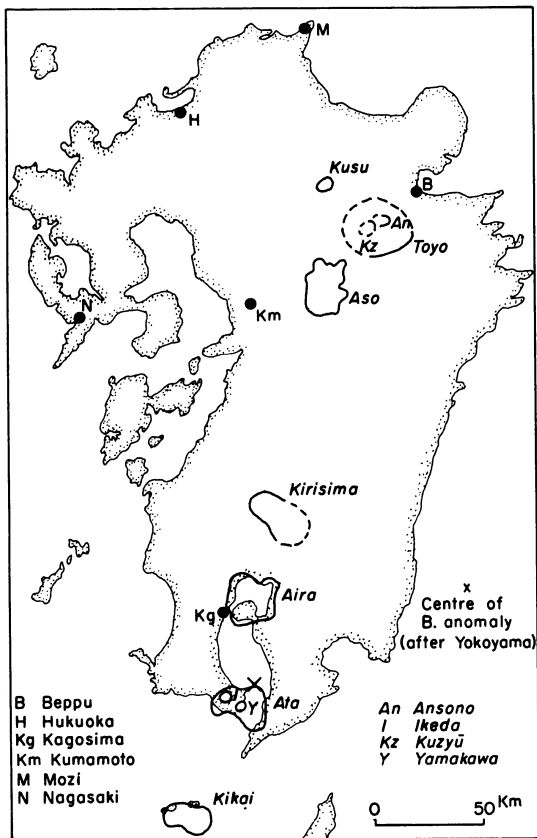


Figure 1. Index map showing location of calderas in Kyushu, Japan.

a core of granite about 15 m long was found under the andesites of the caldera wall. These facts seem to disfavour a little the collapse theory on the caldera formation.

Aira Caldera

Mount Aso is a world-renowned giant caldera volcano and has long been considered unique. Some 20 years ago the writer found three other gigantic caldera volcanoes of the same type lined up approximately in a north-south direction and christened them Aira, Ata, and Kikai. The Aira caldera occupies the blind head of the Bay of Kagosima, north of the cone of Sakura-zima. The Aira caldera (24 by 23 km; 429 km²) just rivals Aso in its size and in the extension (3870 km²) and volume (155 km³) of its extrusives.

The northern and western rims of the Aira caldera are made of various andesites and rhyolite, while the eastern wall is composed of the Mesozoic sedimentary group. The atrio, that is the sea bottom of the head of Kagosima Bay, is not flat throughout the whole area, a low ridge running south from four islets off the coast of Hayato. The western half averages 140 m deep, while the northeastern part is much deeper, sounding 180 to 200 m. This peculiar submarine morphological feature is worthy of note. Whether it is due to unequal sinking or to inequality of original activity will need further detailed study to answer. Aira may be a composite caldera.

After the great eruption of Sakura-zima of 1914, a conspicuous subsidence occurred in regions surrounding the volcano. Notwithstanding the vast outpouring of lava from the island, the mode of the subsidence agrees with the form of Aira caldera, Sakura-zima being only a subordinate centre of subsidence.

caldera. Formerly it was thought that the upper part of the original somma volcano collapsed after the tremendous quantity of pyroclastic flow extruded from the centre vent. Before the eruption of the so-called "Aso lava," there must have been a cluster of many older volcanoes standing side by side, rather than one single volcano. At the site of Crater Lake in Oregon, there stood the high Mount Mazama. It is believed that at both Krakatau and at Hakone, a high mountain towered up into the sky. At this point Aso is different from others in its history and its mode of formation. The writer holds the tentative view that the magma rose up in a cylindrical form and burst out simultaneously from a group of vents in a limited area. The scalloped outline of the caldera is probably due to the initial explosive eruption, and not to the later sinking. The caldera of Kusu, referred to later, is probably a somewhat incomplete protocaldera of the same type. It might be called a sort of areal eruption in a limited area or "cauldron eruption."

The atrio of Aso-dani is deeply covered by alluvial deposits and we have not had much information on the nature of the basal rock of the caldera. Recently a few hot-spring drillings were made. No definite cores of ignimbrite were found in the boring. On the contrary, the pyroxene andesite and pyroxene-hornblende andesite, which are common on the caldera wall, were seen. In one drilling at Utinomaki spa, which is some 160 m deep,

Ata Caldera

Ata caldera lies just at the entrance of Kagosima Bay. The caldera (25 by 12 km; 325 km²) has, as a whole, the shape of a violin with a centrally compressed ellipse. The western half has several cones and craters together with two nested calderas, Ikeda and Yamakawa. The eastern half has no volcanic centre, being entirely filled with sea water and partly surrounded by Tuzi-ga-take ridge of granite.

Recently Dr. I. Yokoyama made a gravity survey of the Ata caldera area and discovered a centre of negative anomaly at a northern point outside the rim and not within the confines of the caldera which the writer proposed in 1943. Dr. S. Aramaki and his colleague agree with Yokoyama's view for the reasons that (1) along the east and west sides of Kagosima Bay near the anomaly centre, the outcrops of the welded rock are thicker than elsewhere, and (2) the lithic fragments in the pyroclastic flow are mainly of older volcanic rocks and not of granite. By the way, both the east and west sides of the bay near the anomaly centre are made of Neogene volcanics, while the eastern side of Ata caldera proposed before is of granite.

Akamidu-dake and the upper half of Uomi-ga-take are made of thick pumice falls which are well bedded and considerably welded. They are of the later period than the main Ata. The vent is presumed to be somewhere between the above two, Akamidu-dake and Uomi-ga-take.

Lake Ikeda is one of the deepest lakes in Japan, reaching 224 m. Its topography is typical of a caldera both on land and water, though not so big (5 by 4 km). The western side of the caldera is bounded by the so-called Onkadobira fault scarp, while the other sides are surrounded by several cones mostly of pyroxene andesite with a few of tholoids of hornblende andesite, as Nabesima-dake. One of the hornblende andesite masses flowed into the lake and one central sublacustrine cone rises to a depth of 35 m.

The extrusives of Ikeda caldera are quite pumiceous, rather loose and slightly welded at a certain point, for example, near the northwestern coast of the lake. Pumice fall extends to a distance of about 5 km or a little more.

Yamakawa Bay is also a caldera lake, the eastern border of which is broken, opening to the sea. The lava cliff of basic pyroxene andesite around the bay is about 100 m above the sea, in addition to the depth of about 50 m in the bay. The entrance of the harbour is shallow, much shallower than the interior of the Yamakawa engulfment. Unose, together with the shallow zone just mentioned, is no other than the eastern wall of the caldera. The pyroclastic rock is a yellowish brown agglomerate with some lithic fragments. The rock is fairly hard, though not so welded. It is distributed to the south and to the southwestern side of the caldera.

Kikai Caldera

On September 20, 1934, a submarine eruption took place off the island of Iwo-zima to the south of Kyusyu, and a new islet, Syowa-Iwo-zima, rose up from the sea bottom, which is some 300 m deep. The writer went to observe the behavior of the activity and saw a new lava dome forming within a big caldera of the Aso type. Kikai is, in short, a submerged caldera (23 by 16 km; 233 km²). Examining the chart, besides the main conide of Iwo-dake a few submarine central cones rise up from the caldera floor, 400 to 500 m deep.

Kirisima Group

The Kirisima group consists of many beautiful cones such as Takatiho, Karakuni, Onami, Sinmoe Kosiki, and so forth, all of which have top craters, often filled with water. The whole group rises up roughly in the northwest-southeast line. They are surrounded by the Kakuto group of Neogene volcanoes and the Eocene sedimentary formation. The southern extremity of the Kakuto group comes to an end at the bank of Sendai-gawa River. Beyond the river, the rim of the caldera continues to the line of Kurino-dake, Sagari-yama and Ebosi-dake, all of Neogene age. This topography of the Kakuto ridge is quite conspicuous and leads one to think that the area may be a cryptocaldera, because no distinct pyroclastic extrusives related to the said caldera have yet been found. The gravity survey by Dr. I. Yokoyama proves that there exists a centre of Bouguer anomaly. The Kirisima cryptocaldera lies exactly on the line of four big calderas, precisely corresponding to the Kirisima Volcanic Zone.

After the writer found the three giant calderas of the Aso type in south Kyusyu, he tried for several years to find more calderas in the district from the Tokara Islands down to Okinawa. He surveyed in detail 13 island volcanoes in all without success. On the other hand, in central Kyusyu some calderas, big and small, old and young, were found.

Kuzyu Group

Central Kyusyu is one of the most extensive volcanic districts in Japan. The well-known caldera of Aso, the Kuzyu group including the two most prominent peaks in Kyusyu, the scenic spot of Yabakei, and countless other volcanoes are assembled in this area. Several calderas related to welded pyroclastic rocks are also found here in the same volcanic district, one of Miocene, two of Pliocene, and two of Pleistocene age.

Kuzyu is one of the most conspicuous volcanic groups in Kyusyu and includes the two highest peaks in Kyusyu Island. It consists of many tholoids of hornblende andesite with a few conides of pyroxene andesite. Surrounding the group of Kuzyu, slightly welded pyroclastic flows of hornblende andesite are found abundantly. The pumices are rather dense and light in colour. They contain much of the hornblende crystals.

The central part of Kuzyu is entirely covered by younger domes and so the real boundary of the caldera cannot be traced. It is a buried caldera. Chronologically, Kuzyu pyroclastics are about the same age as those at Aso, one flow being covered by Aso ignimbrite, as in the area between Kuzyu and Aso, while the other rests on Aso pyroclastics, as along the Kusu-gawa. It is worthy of note that quite different kinds of volcanic rocks extruded independently at the same time from the two points, Kuzyu and Aso, only 20 km distant from each other.

Kusu Caldera

The Yabakei pyroclastic flow (figure 2) shows the most extensive distribution in central Kyusyu, next to Aso, covering an area of more than 50 km in diameter. The rock is hornblende andesite and is somewhat similar to that of Aso in its field appearance, especially when weathered, and for a long time was mistaken for Aso ignimbrite. The northwestern part of the Kusu caldera shows a typical topography. The basin of the caldera is geologically made up of four kinds of Neogene andesites and Pliocene sediments of volcanic materials. All of these are older than the Yabakei welded rock, probably uppermost Pliocene in age. The remaining area of the basin, younger than the welded rock, can be divided into four separated parts. The writer is inclined to be of the opinion that these four separated parts are the vents of Yabakei pyroclastics. Considering these facts, then, the Kusu basin is not a typical sunken caldera caused by the general engulfment of the whole area. It might be considered an embryonic stage of the big caldera of Aso type and be called a "semicaldera" or "protocaldera."

Haneyama Lava

Biotite rhyolite, which the writer has called by the name of Haneyama lava, is widely distributed in many detached patches in central Kyusyu. The pyroclastic flow of the same rock is found between Aso and Beppu, which the writer has called the Syonai pyroclastic flow. The welding phenomenon is not so strong though the rock is often hard. The lowland of Asona is presumed to be the centre of extrusion. The wall of Asona caldera is made up mostly of pyroxene andesite with the subordinate cap lava of biotite rhyolite (Haneyama lava). The half-welded pyroclastic rock of the same rhyolite is seen between the above two. The western wall is broken and obliterated by younger volcanics. The central cones of the Hanamure group are composed of pyroxene andesite, some of which contains hornblende.

Ono Ignimbrites

To the south of the Oita-Kumamoto Line, the westernmost extension of the Median Line in southwestern Japan, Yoro-ga-take and Miyake-yama rise up, roughly forming a northeast-southwest ridge.

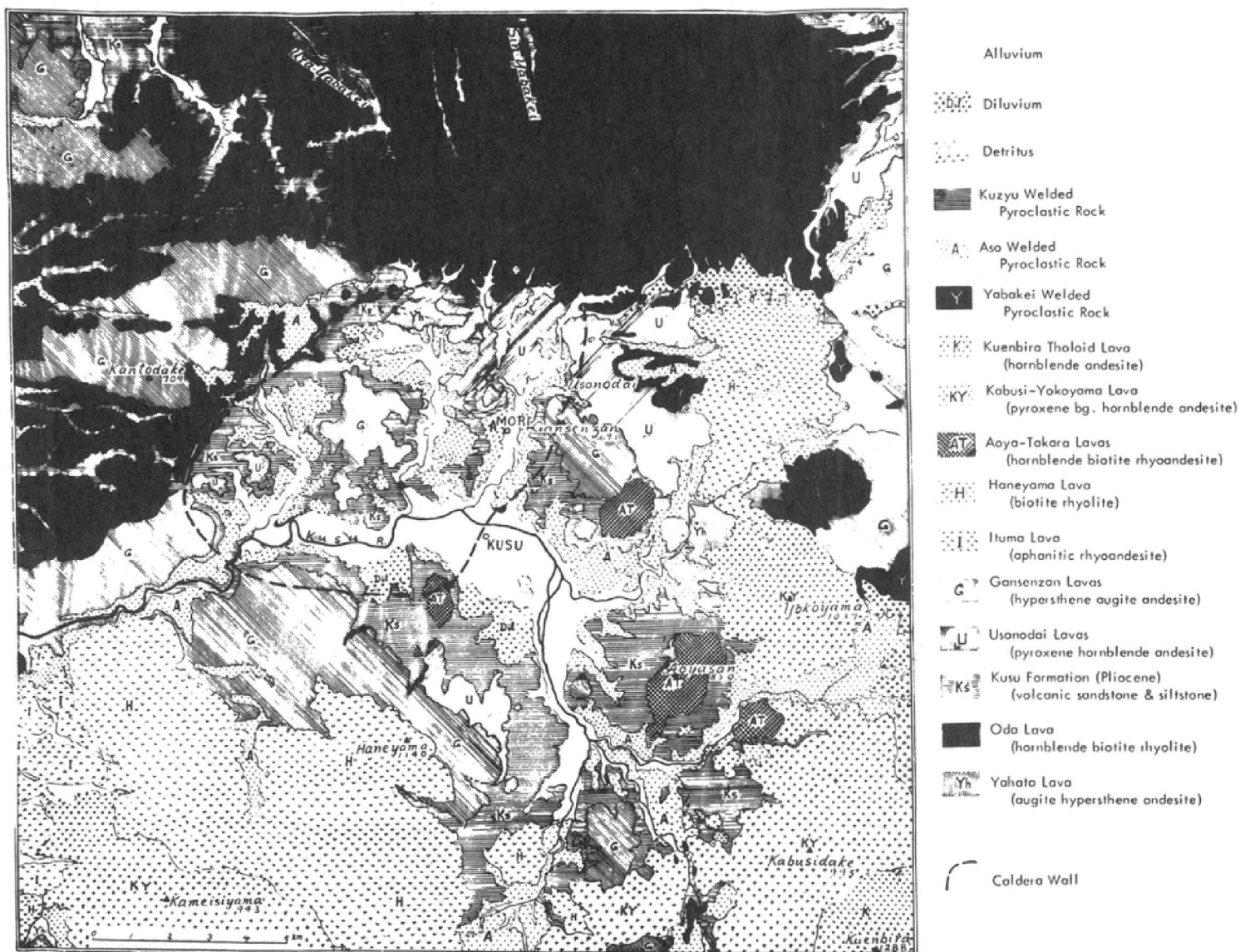


FIGURE 2. GEOLOGIC MAP OF KUSU CALDERA.

Three types of welded rocks are observed: (1) augite-bearing olivine hypersthene rhyolite, (2) augite-bearing hypersthene rhyolite, and (3) biotite rhyolite. The last of the three is the youngest and the most extensively developed. It is found far to the south and southeast as many detached masses. These Ono ignimbrites are very dense, compact, completely welded, lava-like hyaline rocks. At one outcrop, the writer observed a downward transition into a tuffaceous sediment one meter thick, containing some charred coal. The original upper non-welded or less-welded parts have been entirely eroded away, and still the welded part has a thickness of from 100 m to 200 m. Thus the original pyroclastic flow must have been on an enormous scale. The age of extrusion is believed to be Miocene.

Toyo Caldera

Judging from the horizontal as well as vertical distribution of Ono ignimbrites, the centre of the eruption must be on the northern side of the Oita-Kumamoto tectonic line, which directly passes through the centre of the great Aso. The related caldera is believed to lie near the groups of Kuzyu and Hanamure. From the tremendous thickness of the welded rock as well as from the extraordinary degree of welding, as described above, the caldera must have been colossal. The greater part of the caldera wall has been broken away, perhaps by fault movement along the Oita-Kumamoto Line, excepting for a part of the southeastern rim. The caldera is presumed to be larger than Aso, enclosing the most prominent volcanic group of the Kuzyu district in central Kyusyu together with the two calderas, Asono and Kuzyu. To this hypothetical caldera, the name of Toyo is given after the ancient name of the province.

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THE CASCADE RANGE VOLCANO-TECTONIC DEPRESSION OF OREGON

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ABSTRACT

Recent papers by several authors have suggested a genetic relationship between grabens, calderas, and ignimbrites. It is suggested that mappable and inferred early Pliocene to recent faults formed a High Cascades volcano-tectonic depression (similar to the present Rio Grande graben of New Mexico) whose northern end in Oregon is the Hood River valley and whose southern end is the Klamath Valley. Crater Lake caldera (like Valle Grande caldera) lies within this down-dropped block, as does the Three Sisters volcanic complex. Although the ring of peaks which Hodge (1925) once called the remnants of the caldera wall of Mount Multnomah have been shown to be individual necks of Pliocene volcanoes, it is believed that they may well also represent the trace of a more ancient caldera or ring-structure, an early Pliocene ur-Mount Multnomah now buried and concealed by the extensive lavas from the volcanoes erupting through the ring-structure fractures.

Introduction

Recent papers by Mackin (1960) and Smith and others (1960) suggest that there is a genetic relationship between calderas, ring structures, grabens, and great effusions of ignimbrite or welded tuff in the Basin and Range Province of North America and elsewhere. This relationship is amply supported by the position of Crater Lake, located within the northern extension of the Klamath graben (Fig. 1). The Rio Grande valley of New Mexico (Fig. 2) is another example of a graben of similar proportions (Kelley, 1954) averaging 32 miles wide, at least 200 miles long, containing the Valle Grande caldera. This caldera is partially filled with later volcanic cones, a peripheral ring of domal volcanoes, and surrounded by a vast expanse of welded tuff (Smith and others, 1960).

Many calderas in other parts of the world have been shown to be intimately associated with elongated fault depressions (Van Bemmelen, 1935, etc.; Williams, 1941, p. 315-324).

The Cascade Volcano-Tectonic Depression

The presence of well-defined north-south faulting in the High Cascades has long been noted, in fact a number of such deep-seated faults may be traced by the alignments not only of the major peaks, but also by many of the several hundred cinder cones and volcanic plugs mapped by Williams (1957) between Mount Jefferson and Crater Lake. An even more important earth fracture suggested first by Thayer (1936, p. 16), noted by Callaghan (1938, p. 19) and sketched by Baldwin (1964, p. 59) as forming the eastern border of the older or western Cascades, and the western edge of the high Cascade lavas, has been interpreted from topographic and geologic evidence as being a normal fault with at least several thousand feet of displacement, down-dropped to the east. Along the Columbia River, the west-dipping basalts in Dog Mountain and the aligned vents of the Wind Mountain-Shellrock Mountain intrusions, combined with abrupt change in the elevation of the Eagle Creek Formation-Columbia River Basalt contact (down on the east) locate the position of the west fault (Allen, 1932, unpublished manuscript).

Hodge (1938) and his students noted the 50-mile-long Hood River fault, which has an escarpment of nearly 1,000 feet, down-dropped on the west. After a gap of 25 miles, the next mapped segment of the east fault may be represented by the recent escarpment of Green Ridge, which extends for at least 20 miles north of the large cinder cone of Black Butte, near the headwaters of the Metolius. Other segments may be inferred from aligned vents (Williams, 1957).

Unfortunately later volcanism has mantled the depression along much of its course, so that it will probably remain hypothetical except for the unlikely event that deep drilling or geophysical methods may some day tell us more concerning the depths.

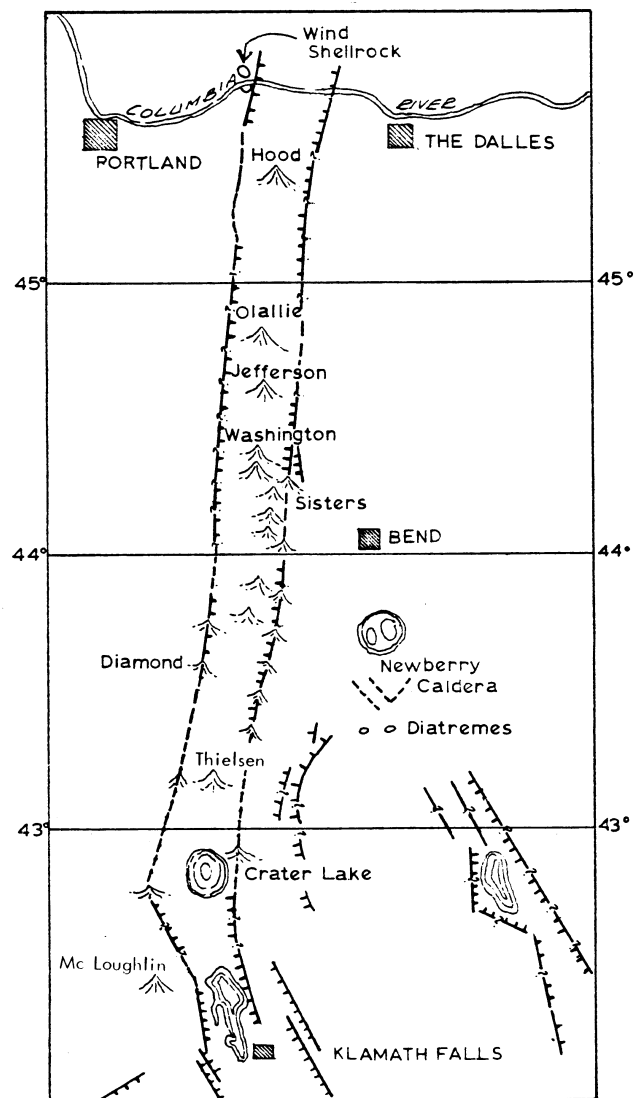


Figure 1. Faulting and volcanic structures in the High Cascades of Oregon.

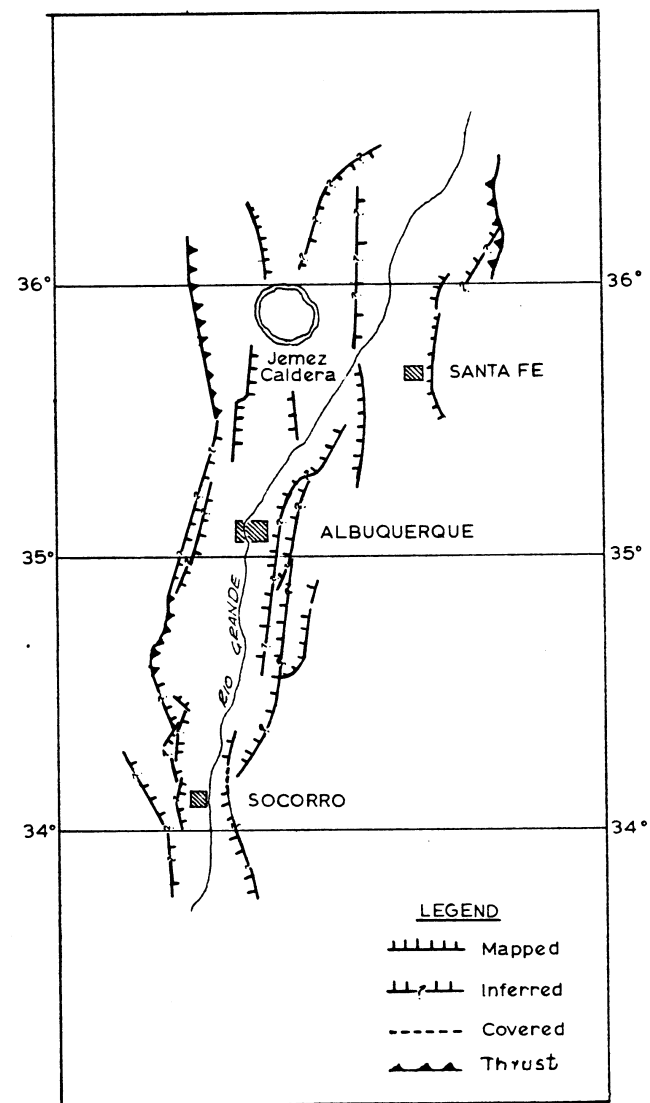


Figure 2. Faulting along Rio Grande depression and Jemez or Valle Grande Caldera (after Kelley, 1954).

It might also be worthy of note that the southern extension of the recent Klamath graben trends toward the great Medicine Lake caldera described by Anderson (1941). The Summer Lake-Silver Lake-Fort Rock depression, 60 miles to the east of Crater Lake, trends northwesterly towards the Newberry caldera, and might, if extended, intersect the High Cascades depression near the Three Sisters area.

Mount Multnomah Revisited

Williams (1944) rather caustically dismissed the Hodge (1925) hypothesis of the origin of the Three Sisters volcanic complex under the title "The myth of Mount Multnomah"; and he was right, insofar as the recent topographic development of the area outlined by Hodge is concerned. However, Williams failed to consider the possibility of an earlier caldera occupying the identical position -- a caldera which can be deduced, perhaps, from the position of the very vents used by Hodge as representing the old rim. The later history of numerous other calderas throughout the world has involved all degrees of filling and, indeed, complete obliteration by later volcanic activity. Frequently, these later volcanoes come up along the same ring fractures that produced the original caldera (Williams, 1941, p. 254, Krakatoa; p. 293, Newberry; p. 305, Glen Coe; p. 306, Mull). It is the suggestion of this writer that there may have been an ur-Mount Multnomah caldera, but that it was an early Pliocene one, which has been completely filled by later lavas, and can be hypothecated from the position of the vents outlined by both Hodge and Williams.

The Rattlesnake-Danforth ignimbrite sheet, which during the early Pliocene covered at least 10,000 square miles in central and eastern Oregon (Campbell and others, 1958, p. 1678) has heretofore had no hypothetical source. Ur-Mount Multnomah would be such a possible source.

References

- Allen, J.E., 1932, Contributions to the structure, stratigraphy, and paleontology of the lower Columbia River Gorge, Oregon: Univ. Oregon master's thesis, 97 p., 5 plates.
- Anderson, C. A., 1941, Volcanoes of the Medicine Lake highland, California: Calif. Univ. Dept. Geol. Sci. Bull., vol. 25, no. 7, p. 347-422, illus., maps.
- Baldwin, E. M., 1964, Geology of Oregon, 165p., 92 figs. (2nd ed.)
- Callaghan, Eugene, and Buddington, A. F., 1938, Metalliferous mineral deposits of the Cascade Range in Oregon: U.S. Geol. Survey Bull. 893, 141p., 22 pls., 7 figs.
- Campbell, Ian, Cone, J. E., Rogers, J.J.W., and Whitfield, J.M., 1958, Possible correlation of the Rattlesnake and Danforth formations of eastern Oregon (abst.): Geol. Soc. America Bull. vol. 69, no. 12, pt. 2, p. 1678.
- Hodge, E. T., 1925, Mount Multnomah, ancient ancestor of the Three Sisters: Oregon Univ. Pub., vol. 3, no. 2, 160 p., 94 figs., map.
- _____, 1938, Geology of the lower Columbia River: Geol. Soc. America Bull. vol. 49, no. 6, p. 215-219.
- Kelley, V. C., 1954, Tectonic map of a part of the Upper Rio Grande area, New Mexico: U.S. Geol. Survey map, OM 157, scale 1:190,080.
- Mackin, J. H., 1960, Eruptive tectonic hypothesis for origin of Basin-Range structures (abst.): Geol. Soc. America Bull., vol. 71, no. 12, pt. 2, p. 1921.
- Smith, R. L., Bailey, R. A., and Ross, C. S., 1960, Calderas: aspects of their structural evolution and relation to ring complexes (abst.): Geol. Soc. America Bull., vol. 71, no. 12, pt. 2, p. 1981.
- Thayer, T. P., 1936, Structure of the North Santiam River section of the Cascade Mountains in Oregon: Jour. Geol., vol. 44, no. 6, p. 701-716.
- Van Bemmelen, R. W., 1935, Vulcano-tektonische depressies op Sumatra: Hand 25ste. Nederl. Nat. en Geneesk. Cong., Leiden.
- Williams, Howel, 1941, Calderas and their origin: Calif. Univ. Dept. Geol. Sci. Bull., vol. 25, no. 6, 107p., 37 figs.
- _____, 1944, Volcanoes of the Three Sisters region: Calif. Univ., Dept. Geol. Sci. Bull., vol. 27, p. 37-84.
- _____, 1957, A reconnaissance geologic map of the central portion of the High Cascade Mountains: Oregon Dept. Geology and Mineral Industries map, with text.

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SHATTER CONES AND ASTROBLEMES

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ABSTRACT

Seventeen shatter-coned cryptoexplosion structure sites are now known from around the world, including some not fully confirmed. A review of their characteristics reinforces the belief that shatter cones are stigmata of astroblemes -- ancient meteorite impact scars. Lately several other types of conical structures have been confused with shatter cones, so an effort has been made here to differentiate, in the writer's opinion, these pseudo-shatter cones.

Introduction

Since 1947, I have attempted to establish shatter-coning as a criterion for astroblemes, ancient meteorite impact sites. No attempt will be made here to review this subject as my opinions on its many varied aspects have already been covered in several papers (Dietz, 1947; 1959; 1960; 1961a; 1961b; 1963; 1964; and Dietz and Butler, 1964). Suffice it to say my reasoning has been that shatter cones are a peculiar type of fracturing caused by intense shock waves and their orientation is such that the shock waves arrived from above. This, in turn, suggests their creation by meteorite impact, but an intra-terrestrial origin cannot, of course, be entirely ruled out as yet. We are still faced with the problem of identifying a definitive astrobleme--perhaps by the eventual discovery of associated meteorite debris or other compelling evidence. However, I feel that we are rapidly closing in on the problem and, with reference to the Meteor Crater, Ariz., story, are "in the twenties." It will be recalled that 40 years passed, 1890 to 1930, before Meteor Crater received general scientific acceptance as a bona fide meteorite crater. But once this prototype was established several others were quickly identified around the world by the argument of analogy.

The shatter-coning phenomenon

Shatter cones are striated cup-and-cone structures, most common in carbonate rocks but also known from shale, sandstone, quartzite, granite, and so forth. The striated surfaces radiate from a small parasitic horsetail-like half-cone on the face of the master cone-- a pattern which serves to differentiate these striations from the parallel grooving of slickensides. Unlike slickensides, shatter cones also have positive faces on the cone and negative faces on the cup. The apical angle varies but is usually close to 90°. Cones vary greatly in size from less than 1 cm to as much as 12 m in length. With shatter cones, "a picture is worth a thousand words" so some examples are shown in Figures 1 through 4.

An illuminating theoretical study of shatter-coning recently has been made by Johnson and Talbot (1964). They conclude that shatter cones are shock-fractures formed along an interface between plastic and elastic rock response. The horsetail-like striations may be caused by the plastic domain moving relative to an elastic domain. They point out that no other known type of fracture displays this remarkable pattern of radiating ridges and grooves which adds credence to the judgment that shatter cones result from some unusual type of fracture mechanism. They conclude that: (1) Shatter cones are produced as a result of the interaction of an elastic precursor in a shock front with an inclusion or inhomogeneity; (2) the susceptibility to shatter-coning is a function of the shape of the Hugoniot of the rock in which the shock wave is propagating; (3) shatter-cone formation requires shock-wave strength of such a magnitude rarely produced (if ever--author's note) in a volcanic explosion; (4) the distribution of shatter cones should be symmetrical, about the point of origin of the shock wave; (5) if the transmitting medium is stratified rock, certain strata may contain shatter cones, while others may not, depending on the susceptibility of the individual strata to shatter-coning; (6) shatter cones will be oriented with their axes

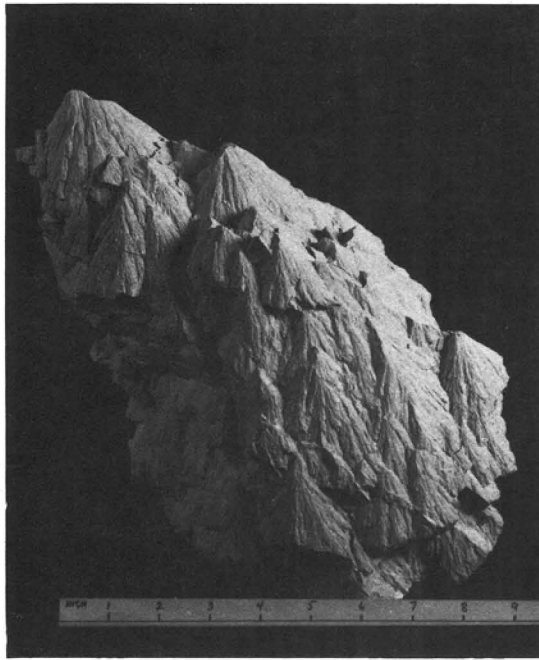


Figure 1. A large block of shatter-coned Knox dolomite from the center of the Wells Creek crypto-explosion structure in Tennessee. Note common orientation of the cone axes.

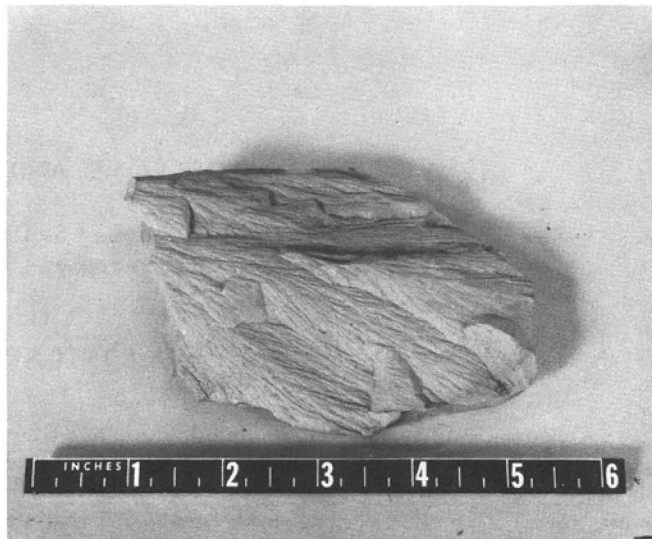


Figure 3. A shatter dolomite slab from the Sierra Madera structure, a presumed astrobleme in Texas. Note the common orientation of the cones and the horse-tail effect which is the hallmark of shatter cones.

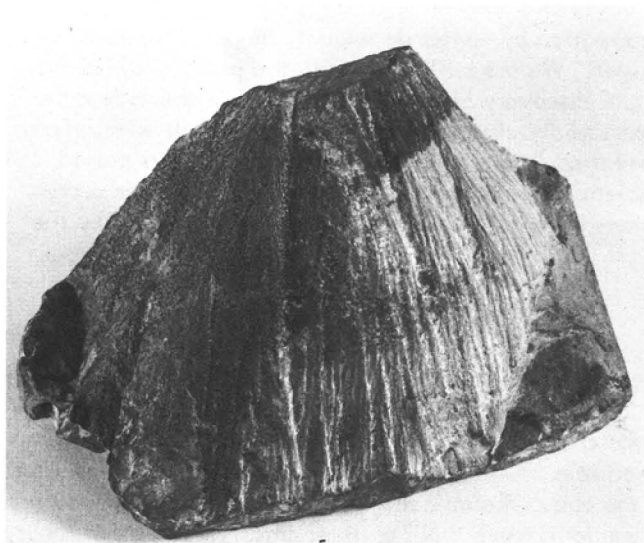


Figure 2. Shatter cone in Ordovician dolomite from the Kentland presumed astrobleme in Indiana. Note the horsetail-like packets on the master cone, the most distinctive aspect of shatter cones. Note also that weathering (left side) destroys surficial detail unlike, for example, in the pseudoshatter cones from Cerro Colorado, N.M., where the rugosity apparently has been created by weathering (compare Elston and Lambert, 1965).

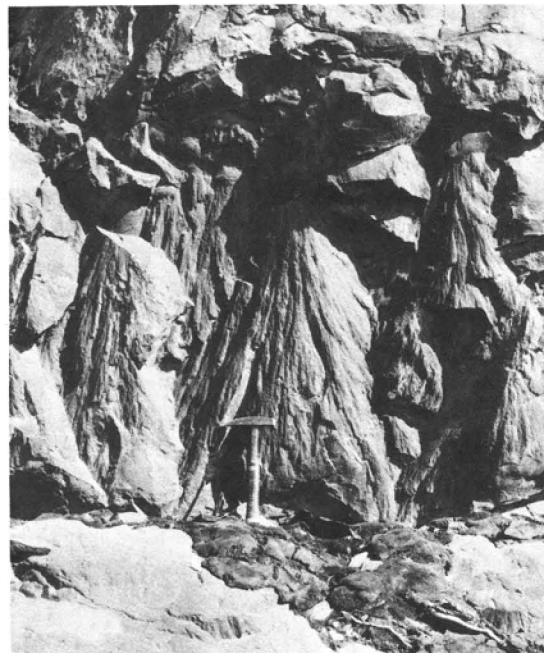


Figure 4. A group of large shatter cones in Mississagi quartzite in the up-turned ring along the southern border of the Sudbury structure. When these rocks are returned to their presumed pre-event position, the cones point inward toward ground zero at the center of the Sudbury lopolith.

Table 1. List of known shatter-coned structures.

No.	Structure	Location	Date	First Published Reference	Notes
1	Steinheim Basin	Germany	1905	Branca & Frass	Elegant shatter-coning. Coesite stishovite and meteoritic spherules in "sister" Reis Basin structure.
2	Kentland	Indiana	1933	Shrock & Malott	Coesite. Formerly excellent shatter cones.
3	Bosumtwi Crater	Ghana	1934	Rohleder	Needs reconfirmation.
4	Wells Creek Basin	Tennessee	1936	Bucher	Excellent shatter cones.
5	Crooked Creek	Missouri	1954	Hendriks	Fair shatter cones.
6	Serpent Mound	Ohio	1960	Dietz	Fair shatter cones. Coesite reported but needs confirmation.
7	Flynn Creek	Tennessee	1960	Dietz	Shatter-coning poorly developed.
8	Sierra Madera	Texas	1960	Dietz	Excellent shatter-coning.
9	Vredefort Ring	South Africa	1961	Hargraves	Grand scale shatter-coning.
			1961a	Dietz	
10	Decaturville	Missouri	1963	Dietz	Fair shatter-coning.
11	Carswell Lake	Canada	1964	Innes	Poorly known.
12	Clearwater Lake	Canada	1964	Dence	Shatter-cone development poorly known.
13	Sudbury	Canada	1964	Dietz	Excellent cones.
14	Middlesboro	Kentucky	In press	Dietz	Poor cones.
15	Manicouagan	Canada	Unpublished	Dence & Manton	Poorly known.
16	Nicolson Lake	Canada	Unpublished	Dence	(?)
17	Glosse's Bluff	Australia	Unpublished	Crook & Crook	"Abundant shatter cones."

directed toward the point of impact or explosion; (7) it is impossible to predict the size of shatter cones in terms of present theory; (8) the majority of shatter cones will have apical angles very close to 90° ; (9) the intensity of shatter-coning will depend upon the number of inclusions in the rock; (10) fine-grained homogeneous rock will favor shatter-cone formation.

The Johnson and Talbot analysis is in accord with many field observations: (1) Shatter cones generally seem to be oriented toward ground-zero which means that the shatter-coning event instantaneously preceded the plastic upheaval of the rocks. (2) In small shatter-coned structures, the shatter cones are developed in the central bulls-eye, but in large ones such as Vredefort and Sudbury they occur far out in the upturned ring. This is consistent with shatter-coning not being developed in the domain of the plastic shock wave but only after the impulse has degenerated to the level where any elastic precursor shock-wave is formed. (3) Impactite and mineralogical transformations (coesite, stishovite, maskelynite, and so forth) seem not to be associated with shatter cones suggesting instead that they are formed some distance from the most intense shock overpressures, probably where the pressure ranges from 100 to 20 kilobars depending upon the Hugoniot of the rock. However, using the ratio of asterism to line broadening on x-ray diffraction patterns made on single crystals of mostly either quartz or calcite, Simons and Dacheille (1965) have found evidence of crystallite damage presumably owing to shock damage in several shatter cones provided by the author. Carter (1965) has also found basal quartz deformation lamellae in a shatter cone from Vredefort Ring. He has noted the same effect at Meteor Crater and he suggests that impact shock overpressures between 35 to 60 kilobars are indicated.

Johnson's and Talbot's analysis is the first attempt to provide a sound theoretical basis for the shatter-coning phenomenon. Undoubtedly their conclusions will be revised as further study is made but it is certainly a good beginning. To date experimental work and theoretical analysis on shatter-coning has been quite limited so that empiricism still rules—a gap which should be eliminated. However, the work done thus far generally has added support to the belief that shatter cones may well be stigmata of astroblemes.

Distribution of shatter-coned sites

My preference for the astrobleme interpretation of shatter-cone sites is based upon an assessment of all known localities where such fracturing is found. This number has increased in recent years from a few to several, and currently to 17 known sites around the world. These are listed in Table 1, chronologically

by time of discovery. At the time of my summary paper of less than a decade ago (Dietz, 1959) only four sites were known. Little can be learned from any single site but taken together an impact origin provides the best answer. For example, the proponent of cryptovolcanism might reasonably explain away the lack of any hydrothermal effects or volcanic products at any particular site but not collectively at all shatter-coned structures. Similarly he might reasonably explain the upward orientation of shatter cones in some particular site by the explosion of a steam pocket which was trapped above the presently preserved structure; but this is not convincing when it can be shown that an upward or inward orientation is the general situation. Of course, this reasoning depends upon there being only one cause for shatter-coning.

As already noted, the identification of shatter-coning can be problematical. I have always tended to consider the shatter cones at Flynn Creek to be not as fully confirmed as those which I have collected elsewhere. They are of rather marginal quality. However, Roddy (1963 and personal communication) who is mapping the structure in great detail assures me that Flynn Creek is definitely shatter-coned in its center although there is a very limited outcrop area of shatter-coned rock. The Canadian "fossil meteorite craters" of Beals and his associates were worked upon for many years without any shatter-coning being observed. But lately they have been found. They recently have been reported from Carswell Lake by Innes (1964); from Clearwater Lake West by Dence (1964); from Manicouagan, where they have been discovered by Dence and Manton, marginal to the large central uplift (personal communication). I can personally add confirmation to those from Carswell Lake and Clearwater Lake West as being rather poor but nevertheless probably genuine examples of shatter cones so far as one can judge from seeing a hand specimen. They are developed in gneiss; such coarsely crystalline rocks tend not to display the phenomenon in fine detail. Both of these identifications were made by observers well acquainted with the shatter coning phenomenon elsewhere. Still another new Canadian locality for shatter cones apparently is Nicholson Lake, N.W.T. (Dence, personal communication). Nicholson Lake is an irregularly shaped lake approximately seven miles in diameter forming part of the Dubawant River drainage system. The deformation affects Precambrian granitic rocks. Reconnaissance geological and geophysical work during June 1965 is said to strongly support a meteoritic origin.

A most interesting new shatter-coned site has been discovered in Australia, the first from that continent (Crook, personal communication). This structure is Glosse's Bluff in the Amadeus Basin about 150 miles west of Alice Springs. It has Ordovician in the core and Devonian in the surrounding ring syncline. Crook reports shatter cones as abundant and the rock in the core is brecciated to a depth of at least 3000 feet below the surface. A photograph of one of these striated conical surfaces sent to me appears to be probably a genuine shatter cone although one cannot be fully certain from a photo alone. The diameter of the structure is about 2.5 miles, this distance being measured from outer wall to outer wall of the bluff which rises roughly from the surrounding plain. However, this topographic relief marks only the central portion of the structure and the true diameter may be in excess of four miles. A complete description by Crook and Cook will be published eventually.

The early description of shatter cones from the Lake Bosumtwi Crater by Rohleder (1934) provides a possible tie with a highly probable modern meteorite-crater instead of a cryptovolcanic feature. Further evidence for its impact origin is indicated by coesite-bearing impactite found at Lake Bosumtwi (Littler and others, 1961). Rohleder's description is brief and is supported only by a poor sketch. But his identification is probably valid as he was immediately struck by the similarity of these fractures with those he knew of at Steinheim Basin in Germany. However, on recent visits both Monod and Chao (personal communication) have been unable to confirm their presence so some further study of this question is sorely needed. A possible shatter-coned piece of Coconino sandstone from Meteor Crater, Arizona, found by Chao and noted by Dietz (1963) is also questionable and cannot really be admitted as evidence for shatter-coning in a modern meteorite crater.

Pseudo-shatter cones, in writer's opinion

As already noted, the shatter-coning phenomenon can be beautifully developed as in the carbonates at Steinheim Basin or at Wells Creek Basin, or it can degenerate to the point where it is difficult to differentiate it from common types of rock fractures. The so-called slickensides found in some meteorites of the brecciated chondrite class may be closely related to shatter-coning (Dietz, in press, b). On the other hand, many other structures of conical form have been confused with shatter cones. Among these we may list: cone-in-cone; coal cones; the "striated cones" of Cerro Colorado in New Mexico; and the fibrous crystalline conical habit such as found in the zeolite mineral pectolite. Of course, all natural

cones are not necessarily shatter cones just as all spherical rocks are not necessarily concretions. Some discretion must be used in identifying shatter cones but, when well developed, shatter-coning invites no confusion. Nonconical but striated surfaces have also been confused with shatter cones especially slickensides, plumose fracturing and stylolites, but apparently never by those well acquainted with true shatter cones.

Bucher (1963) has described alleged "double shatter cones" in bituminous coal from West Virginia. In my opinion such coal cones are not shatter cones although they bear fairly close superficial resemblance. They were first described in the 19th century (Garwood, 1892; Gresley, 1892). Tarr (1932) describes these coal cones as a diagenetic structure related to cone-in-cone, but presumably of somewhat different origin. Price and Shaub (1963) describe this "cone-in-cone" from West Virginia coal in some detail concluding that they are pressure cones caused by loading or tectonic stress. They compare them to the cones which can be generated in a cylinder of any brittle material (such as a cement pillar) by shearing through axial compression. Unfortunately the specimens studied were picked out of a coal bin and never seen in place which seriously hampers understanding them. Whatever their origin, however, these coal cones rather clearly are not shatter cones and should not be confused with them.

In a treatment which is difficult for me to understand, Amstutz (1965) has decided that the shatter cones present at both the Decaturville and Crooked Creek structures in Missouri are, in fact, not shatter cones at all. This is in marked contrast with the general consensus of opinion, which I share, that both of these cryptoexplosion structures contain without question bona fide shatter cones. In Amstutz' view, the cones at Crooked Creek are of a diagenetic type related to cone-in-cone while those at Decaturville were somehow created by the regional tectonic stress field. In November 1965, I participated with about 75 other geologists in a Geological Society of America field trip through Missouri which visited these two cryptoexplosion structures. In the discussions which ensued, no one questioned the conical structures found in the central eye of both of these cryptoexplosion structures as being other than bona fide shatter cones. Of course, there was by no means any universal agreement with my contention that these structures are astroblemes.

Elston and Lambert (1965) have described what they consider to be possible shatter cones in a volcanic vent, Cerro Colorado near Albuquerque in New Mexico. Recognizing that these features are somewhat (at least!) different from normal shatter cones, they have termed these "striated cones." They claim that there are no objective criteria by which shatter cones can be distinguished from their striated cones. They do note the greater coarseness of the largest striae on striated cones from Cerro Colorado, and the greater ease with which the Wells Creek shatter cones break out of the rock. In my opinion, these striated cones and shatter cones bear virtually no resemblance; it requires great imagination to see any similarity at all. Some points of difference may be listed as follows: (1) Some striated cone specimens show some conical curvature but complete cones are not found. (2) They are weathering surfaces and not fracture planes, as it is impossible to obtain these striae on any freshly broken surface. (3) The striae on true shatter cones are rapidly lost when exposed to weathering but those on the Cerro Colorado striated cones are enhanced by weathering, in fact they seem to be the result of differential weathering. (4) The so-called striae are not really striae at all but rugose markings. R. Hargraves, W. Manton, and N. Short (personal communication), all of whom have worked extensively with shatter cones, concur in my opinion that these definitely are not shatter cones.

Monod (1963) quoted Karpoff as finding shatter cones in North Africa, confined to a thin horizon and extending at least 15 km, which has led him to dismiss the validity of shatter-coning as a shock criterion. It seems evident that Karpoff was in fact describing a cone-in-cone layer as this is their typical appearance when shatter cones massively and locally invade a rock mass. In the central United States Carboniferous cone-in-cone horizons have been traced for as much as 500 miles from Indiana to Missouri (Wanless, personal communication). By recent correspondence between us, Monod agrees with this judgment. Shatter cones and cone-in-cone are strikingly different structures which should not be confused even in the hand specimen. They certainly cannot be confused in the field as cone-in-cone occurs along a thin stratum while shatter cones invade an entire rock mass.

Orientation of shatter cones

Both the reality and the significance of orientation of shatter cones have been questioned. However, shatter cones do show a remarkably preferred orientation within any particular rock unit although the various megabreccia blocks may be variously oriented. Exceptions to the common orientation do occur and most common (although still rare) is the case of the completely inverted cone. I have seen examples at Kentland, Decaturville and Steinheim Basin. The appearance of disarray commonly arises from seeing

cone segments rather than full cones which can occur 90° or a little more apart. However, the plotting of numerous cone segments at Vredefort (Manton, 1965), Crooked Creek (Hendriks, 1954) and Wells Creek has proved a common orientation. Hendriks' (personal communication) plotting of several hundred cone segments at Crooked Creek showed an upward orientation and with a steep angle to bedding. Even more detailed plotting at Wells Creek, reveals orientation at a steep angle to bedding and directed inward toward ground zero or, alternately, outward and pointed away from ground zero (Stearns, personal communication). This confusion arises from the fact that it is impossible to determine tops and bottoms of beds (which units are inverted and which are not). Stearns prefers the upward orientation as being real for it is difficult to envision a shock wave propagation toward a point of common convergence.

Shatter cone orientation similar to that at Vredefort Ring is reported from Sudbury (inward-pointing cones when the upturned rocks are returned to their pre-event position) although the observations are confined to a quite limited section along the south side of the structure (Dietz and Butler, 1964). However, it is understood that International Nickel Co. geologists have further confirmed this orientation in other portions of the Sudbury ring and have satisfied themselves that shatter-coning is peculiar to the Sudbury area, that is, not found in similar rocks away from Sudbury.

Suggestions for further research

Further studies are needed before any final understanding of shatter-coning will be attained. Some useful studies would include the following: (1) A search for additional shatter-coned sites; (2) further theoretical studies of the type initiated by Johnson and Talbot but including laboratory experimentation, especially with hypervelocity bullets; (3) further integration of the shatter-cone criterion with other indications of shock--coesite, microfracturing, and so forth; (4) reconfirmation, if possible, of shatter-coning at the Bosumtwi Crater, a presumed modern meteorite crater.

Two speculations

Two speculations come to mind which bear upon the astrobleme problem. Firstly, it seems worthwhile to search carefully for some remnant of meteoritic material as presumed astroblemes. Although these "cosmic bullets" are largely self-annihilating, the evidence, from Meteor Crater for example, is that a minute fraction escapes destruction. Along the anterior margin of the bolide, compressional and reflected refraction shock waves may cancel out, saving portions of the body from vaporization. Ultrabasic stones far exceed nickel-irons in their commonness; hence we should look for ultrabasic xenoliths which possibly could be "cosmoliths," xenoliths of cosmic origin. Since any aluminum-26 usually would have decayed below measurable levels, their identification would be difficult and perhaps in some cases impossible. Ultrabasic xenoliths, of unknown source, are found at both Vredefort and Sudbury but in thin section they seem much like other terrestrial ultrabasics. Those at Vredefort, from the Parys Quarry, are bounded by shock-fractured surfaces.

Secondly, it seems possible that the carbonate type diamonds especially of the Chapada Diamantina district in Bahia, Brazil, of Eocambrian age, may be related to an astrobleme. It has been amply demonstrated that diamonds generally are of hyperabyssal origin, having come up from the mantle in Kimberlite pipes. However, diamonds are known from three stony meteorites (the ureilites--Novo-Urei, Gopalpara and Dyalpur) and one siderite, Canyon Diablo where carbonado-type diamonds were apparently uniquely created by the impact (Anders, 1965). In this example, the iron carbide mineral cohenite was apparently the parent material but it is known from experimental work that diamonds may be created by shock in target rock rich in graphite, for example, graphitic granite or graphitic phyllite. Carbonados are small nodular aggregations of minute diamonds. Shock-created carbonados show a preferred crystal orientation; under x-ray diffraction such studies might provide a clue.

References

- Amstutz, G. C., 1965, A morphological comparison of diagenetic cone-in-cone structures and shatter cones: *Geol. Prob. in Lunar Research*, Ann. N.Y. Acad. Sci., 123, art. 2, p. 1050-1056.
Anders, E., 1965, Diamonds in meteorites: *Sci. American*, vol. 213, no. 4, p. 26-36.
Branca, W. and Fraas, E., 1905, The cryptovolcanic Steinheim Basin (in Germ.): *Kgl. Preuss. Akad. Wiss. Abh.*, 64 p.
Bucher, W. H., 1936, Cryptovolcanic structures in the United States: *Intern. Geol. Congr. Rept.* 16th,

- USA, Wash., D. C., 2, p. 1055-1084.
- _____, 1963, Cryptoexplosion structures caused from without or from within the earth? (Astroblemes or Geoblemes?): *Am. Jour. Sci.*, no. 261, p. 597-649.
- Carter, N., 1965, Basal quartz deformation lamellae--a criterion for recognition of impactites: *Am. Jour. Sci.*, no. 263, Nov., 786-806.
- Dence, M. R., 1964, A comparative structural and petrographic study of probable Canadian meteorite craters: *Meteoritics*, vol. 2, no. 3, p. 249-270.
- Dietz, R. S., 1947, Meteorite impact suggested by orientation of shatter cones at the Kentland, Indiana, disturbance: *Science*, vol. 105, no. 2715, Jan., p. 42-43.
- _____, 1959, Shatter cones in cryptoexplosion structures (meteorite impact?): *Jour. Geol.*, vol. 67, p. 496-505.
- _____, 1960, Meteorite impact suggested by shatter cones in rock: *Science*, vol. 131, no. 3416, p. 1781-1784.
- _____, 1961a, Vredefort Ring structure; meteorite impact scar: *Jour. Geol.*, vol. 69, no. 5, p. 499-516.
- _____, 1961b, Astroblemes: *Sci. America*, vol. 205, no. 2, p. 2-10.
- _____, 1963, Astroblemes: ancient meteorite impact structures on the earth: Chap. 10 in *The Moon, Meteorites and Comets*, Univ. Chicago Press, Middlehurst and Kuiper, eds.
- _____, 1964a, Sudbury structure as an astrobleme: *Jour. Geol.*, vol. 72, no. 4, p. 412-434.
- _____, (in press, a), Shatter cones at the Middlesboro Structure, Kentucky: *Meteoritics*.
- _____, (in press, b), Striated surfaces on meteorites: shock fractures, not slickensides: *Meteoritics*.
- Dietz, R. S., and Butler, L. W., 1964, Shatter cone orientation at Sudbury, Canada: *Nature*, vol. 204, no. 4955, p. 280-281.
- Elston, W., and Lambert, P., 1965, Possible shatter cones in a volcanic vent near Albuquerque, New Mexico: *Geol. Prob. in Lunar Research*, Ann. N.Y. Acad. Sci., vol. 123, art. 2, p. 1003-1016.
- Garwood, E. J., 1892, *Geol. Magazine*, vol. 29, p. 334-335.
- Gresley, W. S., 1892, *Geol. Magazine*, vol. 29, p. 432.
- Hargraves, R. B., 1961, Shatter cones in the rocks of the Vredefort Ring: *Geol. Soc. S. Africa Trans.*, vol. 64, p. 147-161.
- Hendriks, H., 1954, The geology of the Steelville quadrangle, Missouri: *Missouri Div. Geol. Survey and Water Resources*, ser. 2, vol. 36.
- Innes, M. J. S., 1964, Recent advances in meteorite crater research at the Dominion Observatory, Ottawa, Canada: *Meteoritics*, vol. 2, no. 3, p. 219-241.
- Innes, M., and Dence, M., 1965, Nicholson Lake and Pilot Lake Craters, N.W.T., Canada (abst.): *Meteoritical Soc. meeting*, Odessa.
- Johnson, G. P., and Talbot, R. J., 1964, A theoretical study of the shock wave origin of shatter cones: master's thesis, AFIT, Wright-Patterson AFB Ohio, 92 p.
- Littler, J., Fahey, J., Dietz, R. S., and Chao, E., 1961, Coesite from the Lake Bosumtwi Crater, Ashanti, Ghana: *Geol. Soc. America Sp. Paper* 68, 218 p.
- Manton, W. I., 1965, The orientation and origin of shatter cones in the Vredefort Ring: *Geol. Prob. in Lunar Research*, Ann. N.Y. Acad. Sci., vol. 123, art. 2, p. 1017-1049.
- Monod, Th., 1963, Contribution to setting up a list of circular disturbed areas of known, possible or supposed meteoritic origin (in French): *Inst. Franc. Afrique Noire*, Dakar, Senegal, 45 p.
- O'Connell, E., 1965, A catalog of meteorite craters and related features with a guide to the literature: *Rand Co.*, (pvt. pub.), 218 p.
- Price, P. H., and Shaub, B. S., 1963, Cone-in-cone in coal: *West Virginia Geol. and Econ. Surv.*, Rept. Inv. No. 22, 9 p.
- Roddy, D. J., 1963, Geologic section across the Flynn Creek structure: *Astrogeologic studies*, Ann. Rept., Aug. 62 -- July 63, Pt. B, 53-73.
- Rohleder, H., 1934, On the finding of fracture phenomena and striated surfaces on the basin rim of the cryptovolcanic Lake Bosumtwi, Ashanti (in German): *Centr. Min. Geol. A*, p. 316-318.
- Shrock, R., and Malott, C., 1933, The Kentland area of disturbed Ordovician rocks in northwestern Indiana: *Jour. Geology*, vol. 41, no. 4, p. 337-370.
- Simons, P., and Dacheille, F., 1965, Shock damage of minerals in shatter cones: *Geol. Soc.*, Kansas City meeting, abst., p. 153-154.
- Tarr, W. A., 1932, Cone in cone: in *Treatise on Sedimentation*, 2nd ed., by W. H. Twenhofel, p. 719-721, Williams & Wilkins Co., Baltimore.

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AN INDEPENDENT ASSESSMENT OF THE RANGER VII-IX RESULTS

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ABSTRACT

The writer, a quite independent scientist possessed of some experience in the volcano-tectonic aspects of Geology, and in Meteoritics, expresses disquiet at the apparent suppression, in the official interpretation of the Ranger VII-IX photographs, of the viewpoint of those who favour endogenous lunar eruptivity as the major surface sculpturing agency. He suggests that these scientists made a far more accurate prediction of what Ranger would reveal than those who adhere to meteoritic theory of major cratering. He believes that the supposition that the Moon cannot have engendered sufficient heat to cause large scale internal melting and volcanism, and the supposition that the Moon's surface must have been cratered by numerous large asteroidal or cometary 'meteorites' colours this official interpretation: and that neither must necessarily prove to be correct, therefore it is not unscientific to suggest large scale volcanism involving extensive surface degassification and deposition from the gas emission has been the key factor in producing the strange, barren, pock-marked wastes that are revealed by the close-up photography, and also the prominent giant rayed craters. He suggests that the rays of these craters cannot be ejection rays, and the surface-cauldron character of some of the rayed craters further raises objections to the cometary hypothesis now officially favoured.

Introduction

The success of the Ranger programme has excited world-wide admiration for the technical achievement: yet the scientific appreciation of these results recently published by Kuiper (1965) on behalf of the "Experimenter Team" may reasonably be challenged, and, besides challenging the deductions themselves, one may justifiably question whether deductions drawn by a team of such unbalanced composition are really quite worthy of the achievement. There would appear to be just one geologist in the team listed by Kuiper, and he a scientist whose manifest bias towards establishing the reality of cratering by impact explosion on Earth and Moon does not, surely, make him a suitable substitute for a geologist of more orthodox outlook and experience, one versed in studies of endogenous eruptive processes. Reading the report one feels that a distinguished astronomer is battling with a problem which has become largely geological in character.

The independent scientist, observing this programme from a detached viewpoint and owing no allegiance to any official body or "establishmentarian" doctrine, may declare openly that it looks very much as if the lack of representation of orthodox geological viewpoints in this much-publicised assessment indicates that there is a policy of suppression aimed at scientists who favour endogenous lunar eruptivity as the principal surface moulding agency - yet I am assured, and I accept the assurance, that it is not so, and that all viewpoints are officially encouraged. It is also stated that this team has no official status in its interpretative function, and the assessment is only one of several such assessments by scientists provided with the necessary data. Yet there is a danger in the publicity given to only one viewpoint in these days of mass media since scientists on the fringe of and outside this field of research do get the impression that these views are officially supported and represent a careful assessment by scientists of all colour of opinion. I do not believe that this question is anything but an open one in the present state of knowledge, and I would make a plea for publication of a more full spectrum of opinions in the case of future probes, to prevent the possibility of unscientific prejudice of the lunar controversy, a vital one in the development of science in our time. I would also make a plea for less positivity in what are merely expressions of opinion - less use of the verbs "is" and "was," and more use of "may be" and "possibly," and so forth.

There can be no question that there are many scientists who favour endogenous eruptivity rather than meteorite impact as the major cratering agency, and these scientists managed to arrive at conclusions

not markedly at variance with the revelations of the Ranger VII - IX close-up photographs. They achieved this by working on gross patterns revealed by the traditional long range telescopic methods. We must not disregard the wealth of evidence obtained from the study of the gross patterns because we now have close-up photographs - in Selenology, as in Geology, the gross detail is no less informative than the fine detail and over-emphasis of the latter may lead us into the position where we cannot see the wood for the trees. A photograph taken from the Moon of Australia would be more informative than the most perfect close-up of a small part of the Nullarbor Plain! I believe, myself, that enough of the clues were revealed in telescopic photographs to resolve this age-long riddle, and that the fact that my own interpretation (1965, in press) advanced prior to Ranger VII - IX, has required little modification may not be without significance - the same cannot surely be claimed for any meteoritic theory advanced prior to these successes.

The volcanic theory, starting with Hooke, owes much to Spurr (1944-1949). In the last two decades, it has been advanced by Green and Poldervaart (1960), Firsoff (1959, 1961), Moore (1961, 1963, and many other publications), Fielder (1963, and many other publications), Kosyrev (1959, 1963), and myself (1962a, 1963b, 1963, 1965, and in press) - amongst others. Reading the Experimenter Team's report (Kuiper, 1965) one may be excused for suspecting that many of the "new" ideas incorporated in this drastic revision of meteoritic theory have been borrowed from such authors. Although it was obviously not the intention of Dr. Kuiper to give this effect, the uninformed reader is likely to believe that these are the deductions of the Experimenter Team itself, interpretations which only became reasonable after access to close-up photographs. It is, perhaps, unfortunate that so few references are given (Kuiper, 1965). I enumerate below some of the suggestions which I have myself advanced prior to Ranger VII - IX or which I have supported, and in parenthesis I name other scientists who have advanced or supported these ideas.

1. Excessive expansion of eruptives reaching or approaching the lunar surface, producing light froths or tracteries (Fielder, Firsoff, McCall).
2. The belief that the central peaks must be volcanic (Moore, McCall).
3. The belief that all ridge summit craters must be volcanic (McCall).
4. The recognition that the ridging of some central peaks and nearly all ridge craters is systematically related to Fielder's pan-lunar or Maria-focussed tectonic fracture systems (McCall).
5. The recognition that many nicks or grooves in crater walls have the character of graben structures (sector graben), not of grooves scored by meteoritic ejecta; and that these are related in their vectors to the same pan-lunar or Maria lineament systems (McCall).
6. The recognition that the whitening observed in many craters is probably analogous to the whitening that temporarily obscures the walls and outer slopes of volcanoes such as Ol Doinyo Lengai, Tanganyika, and may be due to deposition of salts, and so forth, from volcanic gases (McCall).
7. The recognition that the lunar surface is likely to display a virtual absence of rocky material (McCall).
8. Realisation that subsidence of a volcano-tectonic nature and not eviscerating explosion is a major (if not the major) lunar cratering agency (Spurr, Green and Poldervaart, Moore, McCall).
9. Recognition of the lack of shake down effects, indicating that no great eviscerating explosion accompanied crater formation in many cases, and no solid material issued from many craters (Moore, McCall).

Surely one can see many of these ideas partly or wholly incorporated in the revised theory of the Experimenter Team? The team may well, however, have been ignorant that these ideas had ever previously been suggested, for the members of this group were conspicuous by their absence at the 1964

conference of the New York Academy of Sciences which specifically discussed the geological aspects of lunar research. It is not unlikely that their non-attendance at this important conference was on account of the fact that they did not then consider many of the ideas now favoured in the Experimenter Team's interpretation as worthy of serious consideration, because of certain philosophic constraints on their thinking. These constraints are still evident in the revision (Kuiper, 1965): We now have an uneasy marriage between many ideas favoured by volcanists and the old fantasy of the Imbrian collision coupled with the interpretation of rays as ejection rays. I do not know if members of the Experimenter Team ever suffer lingering doubts - whether they ever suspect that this large scale retreat towards secondary vulcanism may be a precursor to a complete abandonment of the meteoritic position. The tide is certainly running strongly in favour of the volcanist, but because of the possibility of the meteoritist further retreating to what I call the perfect defense (see below) it may well prove difficult to establish the reality of endogenous eruptivity (if, indeed, it is the correct interpretation) unshackled from this last reservation.

The Philosophic Constraints

Two constraints are suggested:

- (1) The belief that the Moon can never throughout its history have experienced sufficient internal heating to give rise to internal melting on a large scale, eruptivity and surface volcanic activity.

Urey has expressed (1952) and reiterated (1960) this view, yet it is not universally accepted, and Ringwood (1960) has advanced arguments which question the validity of the basis for the calculation made. The fact that lunar over-all density (3.34) and average chondrite meteorite density (3.50) show close agreement is not significant: the Moon must, I believe (following Levin), like other planetary bodies show a density increase towards its interior, and one might just as well suggest the Earth (5.52) was not derived from chondritic material. I believe that scientists have over-emphasised the role of radiogenic material as internal heat sources for the planetary bodies. Ringwood (1960) has suggested other sources, and implied that radiogenic heat cannot conceivably be the only major internal planetary heat source. There is, also, still considerable argument as to the distribution of radiogenic material in chondrites, the basis for Urey's calculation in the first place and many scientists accept an asteroid sized parent for meteorites, including eucrites and howardites, which clearly stem from silicate melts, having textures characteristic of dolerites. To discount the possibility of endogenous lunar vulcanism on a large scale is therefore, I believe, premature.

- (2) The belief that the Moon must inevitably have suffered cratering by the impact and explosion of giant asteroidal meteorites or comets, frequently throughout its history.

Many astronomers support this view, yet it may still be regarded as an open question. It is emphasised in support of meteoritic hypotheses that even small meteorites would drive in to impact on the atmosphereless lunar surface at unabated cosmic velocity, and this statement introduces a niggling doubt when one views the Ranger VII - IX photographs. There are innumerable small craters, it is true, but does not the surface look very like that of a frothy pudding, pierced by gas outlets? Are not the craters too uniform in type? Is there not a lack of patterns of primaries of small size? Do not many of the small craters reveal, on close examination, features suggestive of endogenous origin? Is there not too much perfection and lack of interference seen in the small craters? Are there not areas such as the wall of Alphonsus (Kuiper, 1965, fig. 20) quite devoid of anything that could be a sizeable meteorite crater, yet the frequency of meteorite strike without an atmospheric barrier will be much greater than on earth and the size of the masses generally larger, lacking the agency of atmospheric break-up? Is there not a remarkable lack of any small structures that can be definitely recognised as meteorite scars? In a previous paper I suggested that the ultimate anomaly of the lunar surface might well be the relative absence of visible meteorite scars -- the Ranger VII - IX results have strengthened my belief that this may be so. This view probably appeared absurd in 1964 before Ranger VII left the pad - does it appear quite so absurd now?

The truth could be that we do not know enough about the origins and movements of meteoroids, asteroids and comets to be able to make such certain predictions of asteroidal or cometary collision as have been confidently advanced. Such collisions would have to have been very numerous to account for the lunar Maria and giant craters, and, remember, approach of meteorites to the Earth/Moon system on

collision course is a very special case, likely to be extremely rare: of the 2000-odd known asteroids very few have orbits that could conceivably bring them onto such paths. No doubt the computer has provided the desired answer, but how much faith have we in this? Because Chapman (1964) (a scientist for whom I have the greatest respect) has computed that australites come from Tycho, must we believe this? (I do not, because I do not interpret Tycho as a meteorite crater.) Computations depend on what is put in in the first place; they do not always give the right answer unless every item on which the programme is based is known for certain to be true (and this cannot, surely, be claimed for many computations involving the Moon).

The paucity of meteorite scars on the lunar surface may very well pose yet a further enigma, but such enigmas are not unknown to science (for example, Continental Drift).

I conclude then that we neither have to reject endogenous vulcanism nor do we have to believe that the Maria and Tycho must be vast meteorite scars simply because astronomers tell us such vast meteorite scars must be there.

It is, I believe, not unscientific to depart from these constraints.

The "Perfect Defense"

The Experimenter Team is in a position to retreat to the "perfect defense." It is already apparent that any familiar lump of volcanic rock that may chance to be recovered from the lunar surface in the future is likely to be labelled "impactite" by the Experimenter Team. Even should the four corners of the Moon yield nothing but an unrelieved vista of volcanogenic material and volcanic structures, it may well be that the reply will be offered that the record of lunar impact is wholly obscured by a secondary volcanogenic sheath, consequent on impact. To such a reply, advanced in the last resort, there might well be no means of certain refutation.

Among the arguments that the volcanist can offer now, in opposition to this concept of secondary vulcanism, are those that involve the systematic relationship of crater shape, internal structures, and distribution to the pan-lunar tectonic pattern recognised by Fielder (1963) and McCall (1965, and in press). The meteoriticist must, perforce, accept the reasonability of the theory of pan-lunar fracturing by the agency of meteoritic impact alone if he discounts endogenous vulcanism utterly. And this theory is by no means easy to accept.

The resemblance of the lunar surface patterns to those of certain terrestrial anorogenic zones (McCall, 1965 and in press) is so striking that the meteoriticist has to accept a remarkable coincidence: the supposition that you can produce a subsidence caldera or surface cauldron form as a secondary result of impact-explosion has no real support, and the most convincing of all the arguments for endogenous vulcanism advanced in New York in 1964 may well have been the caldera analogy. It is very easy for the scientist lacking geologic knowledge to dismiss this analogy, but difficulties are apparent to the geologist.

The cometary hypothesis now advanced for rayed craters is based on slender grounds. It seems to be derived from a study of certain small crater markings on Ranger VII photographs. One suspects that the knowledge that these markings are situated in the rays of Tycho and Copernicus rather than any intrinsic difference between these markings and adjacent craters led to their differentiation as secondaries. It is possible that this differentiation simply stems from the idea that some trace of the supposed ejection rays must be recognisable on close-up photographs. But what if the rays are not ejection rays at all as several scientists have proposed (Moore, 1963; Devadas, 1962; McCall, 1965 and in press)?

There is very good reason to disbelieve the theory of ejection rays - not the least the fact that rays pass outwards into fracture lines and consistently share vectors with them: the fact that the rays may be tangential (for example, Tycho [McCall, 1965]) and the evidence from Byrgius (McCall, 1965). Whittaker's photograph (Kuiper, 1965, fig. 4) is remarkable - I distrust the drawings (Kuiper, 1965, fig. 1) because the artist seems to have been endeavouring to draw lava scarps terminal to flows, not what can actually be seen in the photographs (Kuiper, 1965, fig. 2), which are far less convincing. I accept that there is some evidence for flows of some sort - the shapes are very convincing in figure 4 - but I have pointed out prior to the Ranger probes (McCall, 1965 and in press) that just because we can see the forms of effusion we must not assume flows of silicate melt - such are exceedingly unlikely to be able to operate in vacuo. These may be secondary flows of accrued, plastic volcanogenic material, not necessarily composed of silicates and similar to the surface material seen in the Ranger photographs, but moved bodily downslope after deposition. The most significant feature in this photograph is not the flows themselves - it is the fact that the rays of Aristarchus, like those of other rayed craters, clearly overprint

everything else virtually right up to the crater rim. Such a relationship seems highly improbable if the rays are ejection rays as supposed in the cometary theory (Kuiper, 1965). The crucial point is that large rayed craters, of the same scale as Alphonsus, show the same surface-cauldron character, reflected in step-faulting, beaks, sector-grabens, and central volcanic eminences (McCall, 1965 and in press). With such volcano-tectonic modifications superimposed in a structure of these dimensions one would expect secondary eruptions to largely obscure the rays, which must, if they are indeed ejection rays, be early produced features.

These arguments cannot perhaps pierce the perfect defense but at least I can offer below what I believe is, perhaps, a more realistic interpretation of the lunar surface.

A More Realistic Interpretation?

The Ranger VII - IX photographs reveal many important facts:

- (a) The Moon has a monotonous "snow-like" surface which extends through Maria and the walls and floors of some large caldera-like craters. It seems to be easily collapsed and many craters are clearly collapse structures.
- (b) No abrupt fault scarps are evident, the relief being strangely subdued, rounded off - yet there seems to be a reflection of a subjacent fracture pattern beneath the surface cover, which cannot be very thick; this pattern could only have developed in brittle material.
- (c) The surface material is neither brittle nor loose. It seems to be stiffly plastic and coherent.
- (d) Rocky material is almost completely absent in the areas studied in close-up photographs: the few supposed boulders recognised by Kuiper (1965) may equally be tumescence structures formed by endogenous agencies (gas escape?) in the plastic surface cover. One such feature is clearly too large in relation to the enclosing crater to be of meteoric origin, and in fact none may be of meteoric origin, primary or secondary.
- (e) There is no litter of meteorites as many authorities suspected would be revealed. If meteorites have struck this surface perhaps they have pierced it on account of their velocity? Could they perhaps have pierced it without cratering effects?
- (f) There seems to be a lack of small craters or crater patterns that clearly suggest meteoritic origin; superficial examination may suggest this origin but a close examination generally reveals objections to this interpretation. The small craters show little sign of raised rim shadows, and a raised rim is the expectation of meteorite craters.
- (g) There are many ridge summit craters that can only be volcanic.
- (h) The fine crater detail displays a regularity of crater outline not seen in the case of the majority of larger craters, but there are some much larger craters and many ridge summit craters which show identical perfect forms. The implication of congenesis is inescapable. The poverty of component forms which I have emphasised in connection with gross patterns (McCall, 1965) is even more obvious in close-up photographs.
- (i) The very small craters show astonishing perfection of form, and a high degree of non-interference. They seem to be spaced rather like vesicles.

My proposal (1965 and in press) that the Moon possesses an extra layer, a volcanogenic envelope of material akin to fumarolic deposits of terrestrial volcanoes but not evanescent on the Moon because of the lack of rain to dissipate it - an envelope that has gradually accrued throughout selenological time - is not at variance with these conclusions. I expected the Ranger photographs to show barren vistas of such material, punctuated by craters appearing in smaller and smaller scale. I believe that Moore's somewhat lighthearted display (New York Academy of Science Conference, 1964) of a projection slide

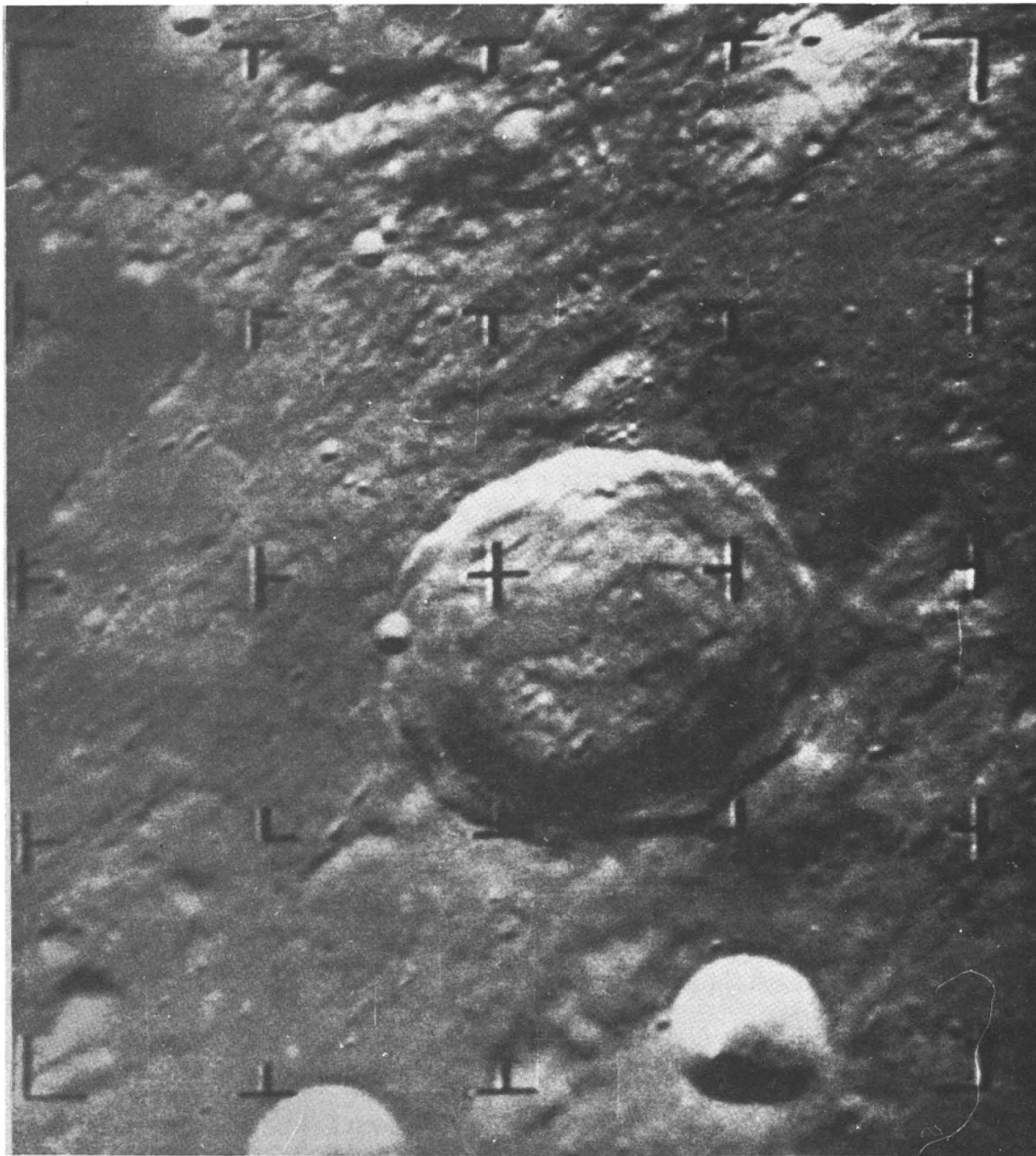


Figure 1. Crater Delambre (diameter 51 km) seen in a Ranger IX photograph.
(Height 756 km, 7 minutes before impact.)

showing strikingly lunar craters in his breakfast porridge was to the point - it was a prediction of what the close-ups would reveal.

Let us now take a look at Delambre (fig. 1). Ranger VIII (Ano., 1965, p. 157) revealed a small, perfect crater with an even rim, situated exactly astride the rim of the larger and older crater Delambre. This crater must be younger than Delambre as it interrupts a group of step-fault traces in the wall of Delambre. Though it is a kilometre or so in diameter its form is typical of many of the smaller lunar craters including some of the very smallest. Now it is clear nothing solid or molten came out of the small superimposed crater, otherwise the step-fault traces would be obscured close to its rim. It is also clear that the superimposed crater was formed without explosion, otherwise the step-fault traces would be disturbed and they are not. This is the most perfect example of lack of shake-down, an effect stressed by Moore and myself (Moore, 1961; McCall, 1962, 1965). The only possible mechanism by which a crater of this form could be formed in this position is, I believe, by the agency of venting of gas, not explosively. The surface material appears to be bowed out into an arcuate projection in the wall of Delambre on the south side of this superimposed crater. One can only believe that a stiffly plastic* material would suffer this distortion without fracture.

I believe that all the craters of this simple type are simply reflections of venting of gas through the volcanogenic envelope - which is probably not composed of silicates. One cannot seriously dispute that if gas venting on a large scale is reflected by the majority of the Moon's innumerable small craters, it must have been a primary endogenous eruptive process, not a secondary process consequent on meteorite strikes.

Such gas venting may well have been more marked in lunar vulcanism than on Earth. The initial internal heating may have been less abrupt and intense and the substantial loss of volatiles by the Earth after initial accretion and before atmospheric retention may have been replaced by a prolonged degassification. The eruptions may even have been relatively cold but Kosyrev's observations (1963) suggest otherwise. But there are many possible explanations - the reality is that endogenous vulcanism has probably moulded the lunar surface, and that it is not very similar in kind to terrestrial vulcanism, gas production being predominant, due in all probability to both the effect of both the surface vacuum condition and internal factors related to the smaller size of the planetary body (McCall, 1965 and in press).

Future Probes

Money spent on a probe aimed at one of the previous Ranger impact areas might not be ill-spent. It would give certain information as to the effect on the lunar surface of impacts at this velocity. Unfortunately the Ranger programme has been concluded - otherwise a probe with this aim and one into the rayed-crater Copernicus which shows surface-cauldron structure would have been of immense scientific value.

The Lunar Rays - A Possible Answer

Did Ranger VII solve the age-long riddle of the lunar rays, perplexing features only visible under certain lighting conditions, and casting no shadows? On the Ranger VII photographs the areas occupied by bright rays resolved in close-up into clusters of small craters. I believe that the rays are simply a colour effect due to the grouping of numerous small craters in dense clusters along the traces of crudely radial fracture lines in the brittle rocky substratum now obscured by a shallow, plastic veneer. The colour effect, a whitening, is probably due to gas phase deposition within and around these small craters** (see footnote on following page).

* In using the term "plastic" I have in mind a dominantly non-silicate envelope, which I favour for reasons given here and elsewhere. However, I believe that Halajian's underdense silicate cohesive model (New York Acad. of Sci. Annals, 1965, vol. 123, p. 708) could be the answer; the fact that the lunar surface appears to be dark in colour perhaps favours this substance rather than non-silicate fumarolic material which, in terrestrial occurrence, is seldom dark. It is possible that pumice fragments could behave in the plastic manner indicated under the gravitational and other physical conditions pertaining on the lunar surface, but I strongly favour a cohesive cover.

They are, I believe, congenetic with the whitened areas which appear along the crests of many wrinkle ridges, which also reflect veneered-over fracture lines, and reflect gas escape up an imperfectly radial fracture system focussed on major centres of volcanic activity, but here and there deflected into the grid lineament vectors, the gas coming up the fractures, as in fields of terrestrial fumarolic activity, rising through the plastic veneer by means of innumerable blow-holes. It is important to note that though rays are best seen in association with major craters, which I believe to be nothing more than foci of eruptive tumescence and gas release, and Kuiper (1965) believes to reflect cometary impacts, rays are also associated with quite small craters, a point perhaps overlooked in the formulation of the cometary hypothesis.

References

- Anon., 1965, Ranger VIII photographs: *Brit. Astron. Assn. Jour.*, vol. 75, p. 157-164.
- Chapman, D., 1964, On the unity and origin of the Australasian tektites: *Geochim. et Cosmochim. Acta*, vol. 28, no. 6, p. 841-880.
- Devadas, P., 1962, The origin of lunar rays: *Brit. Astron. Assn. Jour.*, vol. 72, p. 380.
- Fielder, G., 1963a, Lunar tectonics: *London, Quart. J. Geol. Soc.*, vol. 119, p. 65-94.
- _____, 1963b, The nature of the lunar Maria: *Nature*, vol. 198, p. 1256-1260.
- Firsoff, V. A., 1959, *The strange world of the moon*: London, Hutchinsons.
- _____, 1961, *The surface of the moon*: London, Hutchinsons.
- Green, J., and Poldervaart, A., 1960, Lunar defluidisation and its implications: 21st International Geol. Congress, Proc., vol. 21, p. 15-33.
- Kosyrev, N., 1959, Volcanic activity on the moon: *Priroda*, vol. 3, p. 84-87.
- _____, 1963, Volcanic phenomena on the moon: *Nature*, vol. 198, p. 979-980.
- Kuiper, G. P., 1965, Lunar results from Rangers 7 - 9: *Sky and Telescope*, vol. 29, p. 293-308.
- McCall, G. J. H., 1962a, Tensional stress and lunar patterns: *Nature*, vol. 196, p. 255-256.
- _____, 1962b, Lunar terminology: *Brit. Astron. Assn. Jour.*, vol. 72, p. 336.
- _____, 1963, Distribution and origin of lunar craters: *Nature*, vol. 197, p. 273.
- _____, 1965, The caldera analogy in selenology: *New York Acad. Sci., Annals*, vol. 123, art. 2, p. 843-875.
- _____, in press, The concept of volcano-tectonic undation in selenology: *Advances in Space Sci.*, vol. 8.
- Moore, P., 1961, Lunar craters and the moon's crust: *Brit. Astron. Assn., Jour.*, vol. 71, p. 362-363.
- _____, 1963, *Survey of the moon*: London, Eyre and Spottiswood.
- Ringwood, A. E., 1960, Some aspects of thermal evolution of the earth: *Geochim. et Cosmochim. Acta*, vol. 20, nos. 3 and 4, p. 241-259.
- Spurr, J. E., 1944-1949, *Geology applied to selenology*: Science, Rumford and Business Presses (4 volumes).
- Urey, H. C., 1952, *The Planets*: Oxford University Press.
- _____, 1960, The origin and nature of the moon: *Endeavour*, vol. 19, p. 87-99.

** Fumarolic whitening is favoured but the whitening may well be simply due to the presentation of internal slopes of craterlets to the sunlight in the ray zones. This explanation could account for the rays having no positive relief and appearing only at certain lighting conditions. The explanation of the rays as simply zones of minute craterlets also satisfies the requirements of vectors shared with other lineaments, reinforcement, tangential arrangement, and passage through "dead ground" slopes without interruption (the Byrgius effect). I believe it could cover the barrier effect quoted by Green (*New York Acad. of Sci., Annals*, 1965, vol. 123, p. 387-388).

Postscript:
Comment made at the end of the conference

This paper, aimed at giving the volcanist interpretation a fair hearing (even the media of press hand-outs and conferences are beyond the volcanist not directly involved in lunar research as a full-time pursuit, and few volcanists are directly involved, and so must always suffer some disadvantage) and to encourage representation of many opinions in future quasi-official assessments, has been misconstrued in the press. It must be emphasised that neither was the suppression of scientific data ever suggested in presentation or preliminary draft, nor was there any criticism of the competence of the individual scientists of the Experimenter Team.

I have further been accused of bias but must suggest that all scientists approaching such a problem have some bias, due to their experience. It would, for instance, be absurd for me to assess the mathematics of impact explosion, but I can contribute to volcanological assessment with a foundation of much experience of this field of geology. Bias towards one or the other interpretation is not, I think, to be deplored in these discussions. Controversy and independent thinking are the lifeblood of science and without them science would scarcely advance – though controversy must be a thing apart from personal mud-slinging. And so I admit to favouring the volcanist interpretation, yet regarding the question as still completely open – we are still far from the state of knowledge at which one or the other hypothesis can be discounted, and we must still explore all possibilities.

G. J. H. McCall

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EVIDENCE FOR THE UNITY OF PROVENANCE OF TRUE METEORITES AND AGAINST THE DERIVATION OF CERTAIN AEROLITE GROUPS FROM THE MOON

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Introduction

It has been suggested, from time to time, that one or another of the groups of stony meteorites (aerolites) may have had a lunar provenance. Obviously the derivation of the common metallic meteorites from our satellite is inconceivable in default of a lunar magnetic field and because of density considerations, but the close agreement between chondrite and lunar density values has provided an attractive prop (albeit possibly fortuitous) for such hypotheses. Urey (1959) proposed that most of the stones and a few irons (such as the unique Horse Creek "pseudo-octahedrite") have a lunar provenance, while the remainder are of asteroidal provenance. Goles, Fish and Anders (1960) have criticised this on the grounds of anomalously high K^{40}/Ar^{40} ages derived from chondrites, though unable to satisfactorily explain anomalies of cosmic ray exposure ages (Anders, 1963).

In the five years that have passed since Urey's proposal was advanced much new evidence has accrued and one might have expected this suggestion to have passed into the limbo of original suggestions not found to be compatible with the evidence - yet the lunar provenance of certain stony meteorites has lately been speculated on in a paper dealing with oxygen isotope ratios of meteorites (Taylor and others, 1965) - now it is the basaltic achondrites that are suggested. This suggestion cannot, I believe, be seriously entertained - I propose to show, briefly, that we have evidence from four Western Australian meteorites which, in itself, puts the arguments for the lunar provenance of achondrites or chondrites clear out of court. Also that the discovery of a dominantly silicate-composed stony-iron of unique type from this State containing subordinate metal of virtually identical character to that of Horse Creek indicates that such unusual alloys are due to a chemical effect quite compatible with "Prior's Rules," already suggested by Ringwood (1961), an effect easily explained without resorting to a special provenance apart from the common iron meteorites.

The basaltic achondrites

The Mount Padbury meteorite (McCall, 1965c; McCall and deLaeter, 1965; Cleverly, 1965; McCall and Cleverly, 1965), a mesosiderite containing eucrite inclusions virtually identical with the Moore County eucrite (Hess and Henderson, 1949), and the Dalgara meteorite, another mesosiderite containing howardite inclusions (hypersthene, not pigeonite accompanying the bytownite feldspar) (McCall, 1965, p. 476-487), both also display metallic nodules evincing fine to medium Widmanstätten patterns on etching, patterns typical of octahedrites - the most common group of iron meteorites (figs. 1-4). There can thus be no question of provenance of the basaltic achondrites apart from the common irons. This meteorite also contains hypersthene achondrite (diogenite) and olivine achondrite inclusions - the latter texturally and compositionally not quite like the unique Chassigny meteorite, being coarsely brecciated and composed of olivine Fa_9 not olivine Fa_{33} . These non-basaltic achondrite types (calcium-poor) must also stem from the same provenance as the common irons. The hypersthene achondrite is closely related chemically to the common olivine hypersthene chondrite group (Mason, 1962, p. 110-111), so this evidence has a bearing on the chondrites, discussed below.

The chondrites

Bencubbin (Simpson and Murray, 1932; Lovering, 1962; McCall and deLaeter, 1965; McCall, 1965a) contains enstatite chondrite enclaves within a meteorite of stony-iron character but not within one of the four recognized stony-iron sub-classes (Lovering, 1962; McCall, 1965a, 1965e) (fig. 5). The



Figure 1. Eucrite enclave in mesosiderite - Mt. Padbury meteorite.
(Scale bar in inches.)

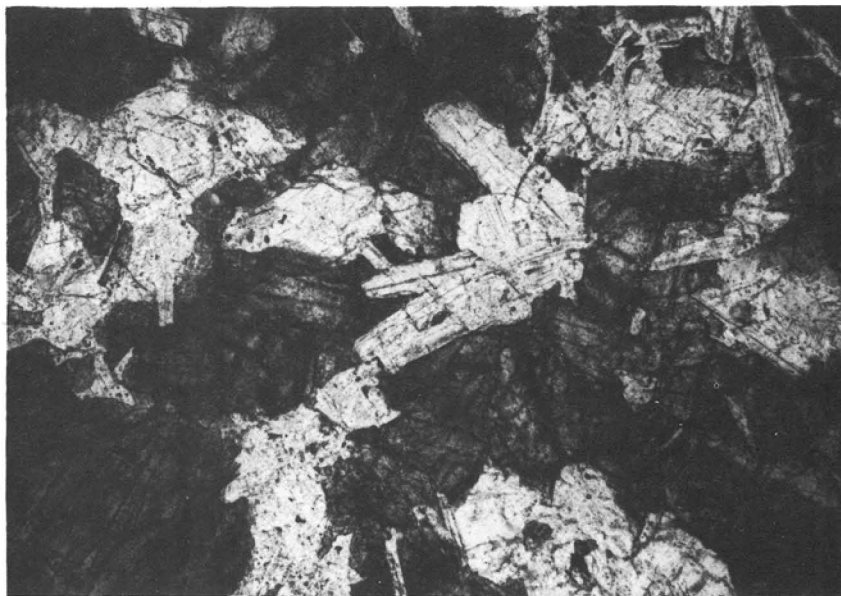


Figure 2. Photomicrograph of eucrite material included in the Mt. Padbury meteorite. (x 25, P.P.L.) (Pigeonite dark, bytownite light.)

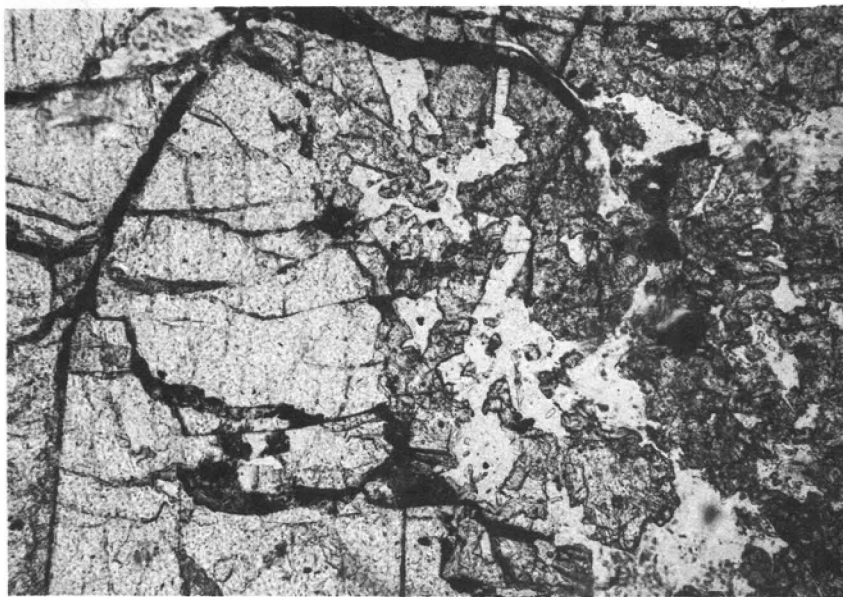


Figure 3. Howardite area in the Dalgara meteorite (stony fragment). (x 100, P.P.L.) (Hypersthene gray, bytownite white: the phenocryst is olivine.)

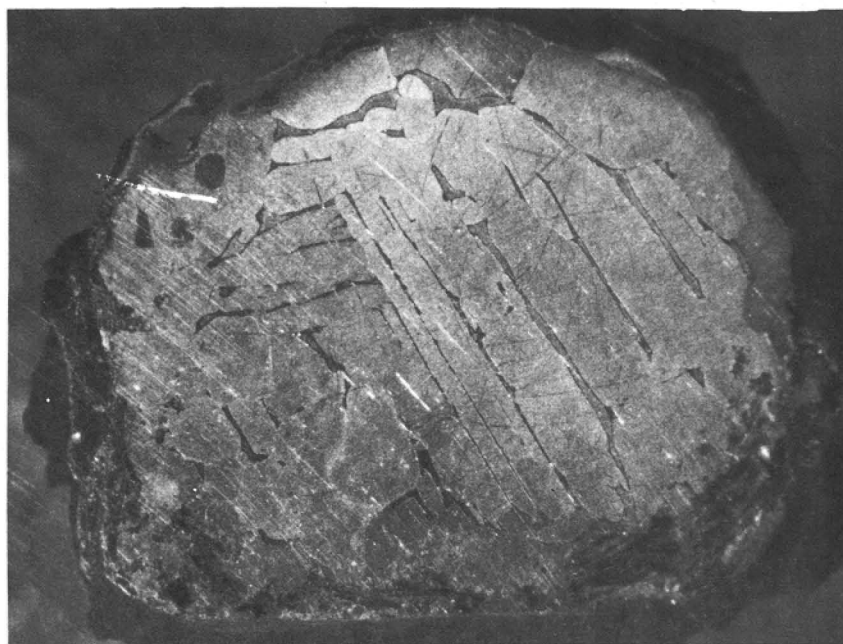


Figure 4. Fine to medium Widmanstätten pattern produced by etching a cut and polished nodule of metal from the Mt. Padbury mesosiderite. (Scale, x 10.)

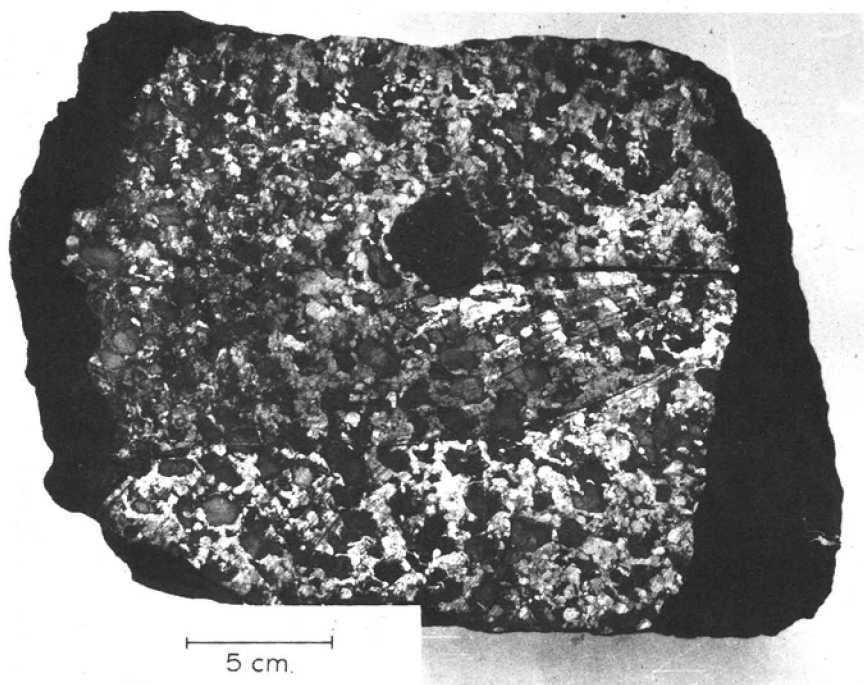


Figure 5. Enstatite chondrite inclusion in the Bencubbin stony-iron meteorite. (Scale, enclave 5 cm maximum diameter.)

host material is predominately composed of nickel-iron showing no regular etch pattern but close to the hexahedrites in composition ($\text{Fe/Ni: } 16/1$) and pure clinoenstatite (Fs_{10}). This association of low nickel content in metal phase and low iron content in silicate phase conforms to Prior's Rules, though the meteorite was unknown at the time at which they were formulated. The "piggy-back" association, similar to that observed in the case of Mt. Padbury, virtually established the unity of provenance of enstatite chondrites with the common range of iron meteorites, accepted widely as asteroidal or ultimately planetary (Cleverly, 1965; Hess and Henderson, 1949). No one has ever suggested seriously that hexahedrites have a provenance otherwise - that is, apart from the octahedrites and ataxites. Indeed the three diverse and reasonably well-defined alloy pattern groups that make up the range of iron meteorites (apart from anomalous types like Horse Creek) can be adequately referred to differences in physico-chemical controls on cooling and solidification within a continuous composition range - significantly there are no real compositional hiatuses such as would surely be inevitable in the case of diverse provenance.

We are left with only one possible reservation for the chondrites - the separation of common chondrites from the very small (rare) enstatite chondrite group numbering only a half dozen. Yet Pribram, the only fall for which adequate evidence of orbital character has been obtained (Mason, 1962, p. 9) was, as far as I know, a common chondrite! And, to hammer a last nail into the coffin, we have already seen that the diogenite achondrite is included in Mt. Padbury, and this type is clearly chemically related to the commonest group of chondrites, and may well only be a "recrystallised" variety of the olivine hypersthene chondrite. One cannot now seriously doubt that the provenance of chondrites and achondrites is asteroidal (though there may have been an ultimate parent of planetary size, and there may have been several asteroidal parents). Lunar provenance cannot, then, be invoked to remove the anomaly of cosmic-ray exposure ages and some other explanation must be found - several others have, in fact, been suggested.

The "pseudo-octahedrites"

The unique Horse Creek iron has been found, with the very similar metallic fraction of Mount Egerton (McCall, 1965d), to owe its anomalous, fine, regular etch-pattern not to schreibersite lamellae but to inclusion of silicon in the metallic phase (the new mineral *Perryite*, $(\text{Fe, Ni})_2\text{Si}$ is involved - Henderson, written communication to the writer). Such a phenomenon of total reduction of the iron and other elements has already been recognised by Ringwood (1961) in the case of the enstatite chondrites

and is in accordance with the expectation of Prior's Rules - once again a meteorite subsequently discovered conforms to this farsighted deduction. This pattern is a metallurgical oddity developing in a few meteorites with nickel iron present of the composition of hexahedrites (c.6% nickel iron), and requires no further explanation, in itself. The association of this alloy with pure enstatite (Fe_0) in Mount Egerton, in coarse achondritic aggregate, suggests that enstatite achondrites cannot have a separate provenance from the iron meteorites, and the chemical affinity between this group and the enstatite chondrites supports this view.

Conclusion

The four Western Australian meteorites - Mt. Padbury, Dalgara, Bencubbin, and Mt. Egerton themselves testify to the unity of provenance of virtually all true meteorites - presumably asteroidal. We must not look to the true meteorites in our search for lunar ejectamenta, whether by primary volcanic agencies or secondary impact-originated ejection (the latter is an obvious expectation of the cometary impact explosion theory now favoured by Kuiper [1965] and others) as I have pointed out elsewhere (McCall, 1965b). Some scientists (Chapman and Larson, 1963) still favour lunar provenance for tektites, but this is an entirely different question. I have elsewhere (McCall, 1965b) put forward my belief that the lack of continuing arrival of tektites, besides very weighty objections to the interpretation of the giant rayed craters, Tycho, Copernicus, and so forth, as cometary-impact scars (McCall, 1965b, and this volume, page 33), must prove fatal to the theory of lunar provenance of tektites - though admitting that the controversy of tektites appears to be a mass of apparently irresolvable contradictions, proliferating the deeper one enquires. At least, however, the case of true meteorites is clear-cut - they are not of lunar provenance.

References

- Anders, E., 1963, Meteorite Ages and the Early History of the Solar System, in *Origin of the Solar System*: R. Jastrow and A.G.W. Cameron, eds., New York, Academic Press, p. 95-142.
- Chapman, D., and Larson, H. K., 1963, The Lunar Origin of Tektites: N.A.S.A. Tech. Note D., p. 1556.
- Cleverly, W. H., 1965, The Field Occurrence of the Mount Padbury Meteorite: *Roy. Soc. West. Aust. Jour.*, 48, p. 55-59.
- Goles, G. G., Fish, R. A., and Anders, E., 1960, The Record of Meteorites; former environment of stone meteorites as deduced from $\text{K}^{40}/\text{Ar}^{40}$ ages: *Geochim. et Cosmochim. Acta*, v. 19, p. 177-195.
- Hess, H. H., and Henderson, E. P., 1949, The Moore County Meteorite: *Am. Mineralogist*, v. 34, p. 494-507.
- Kuiper, G. P., 1965, Lunar Results from Ranger 7 - 9: *Sky and Telescope*, v. 29, p. 293-308.
- Lovering, J., 1962, Evolution of Meteorites, in *Researches on Meteorites*: C. B. Moore, ed., New York, Wiley, p. 179-197.
- McCall, G. J. H., 1965a, The Four Western Australian Stony-irons (abst.): Section C, A.N.Z.A.A.S 38th Mtg., Proc., Hobart, Tasmania.
- _____, 1965b, The Caldera Analogy in Selenology: *New York Acad. Sci. Annals*, v. 123, Art. 2, p. 843-875.
- _____, 1965c, Advances in Meteoritics in Western Australia: *Meteoritics*, v. 2, p. 315-325.
- _____, 1965d, A Meteorite of Unique Type from Western Australia - the Mount Egerton Stony-iron: *Miner. Mag.*, v. 35, p. 240-.
- _____, 1965e, New Material from, and a Further Consideration of, the Dalgara Meteorite and Crater: *Miner. Mag.*, v. 35, p. 476-487.
- McCall, G. J. H., and Cleverly, W. H., 1965, A Newly Discovered Mesosiderite Containing Achondrite Fragments - the Mount Padbury Meteorite: *Nature*, v. 208, p. 851-852.
- McCall, G. J. H., and de Laeter, J. R., 1965, Catalogue of Western Australian Meteorite Collections: *W. Aust. Mus. Spec. Publ.*, v. 3, 138 p.
- Mason, B. H., 1962, *Meteorites*: New York, Wiley, 274 p.
- Ringwood, A. E., 1961, Silicon in the Metal Phase of Enstatite Chondrites and Some Geochemical Implications: *Geochim. et Cosmochim. Acta*, v. 25, no. 1, p. 1013.

- Simpson, E. S., and Murray, D. G., 1932, A New Siderolite from Bencubbin: *Miner. Mag.*, v. 23, p. 32-37.
- Taylor, H. P., Duke, M. B., Silver, L. T., and Epstein, S., 1965, Oxygen Isotope Studies of Minerals in Stony Meteorites: *Geochim. et Cosmochim. Acta*, v. 29, no. 5, p. 489-512.
- Urey, H. C., 1959, Primary and Secondary Objects: *Jour. Geophys. Res.*, v. 64, p. 1721-1737.

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THREE-DIMENSIONAL MODELS TO ILLUSTRATE LUNAR GEOLOGY

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ABSTRACT

A set of isometric block diagrams has been prepared which illustrates the structure and stratigraphy of the Montes Apenninus and Copernicus regions. Conceived originally to convey lunar geological concepts to management-level personnel and non-geological scientists, these diagrams have also been useful as teaching aids and as realistic models for lunar exploration planning.

The basic concepts which are illustrated on these three-dimensional models reflect the lunar stratigraphic nomenclature published by the U.S. Geological Survey. The surface relief features of the two regions are drawn to scale from topographic control provided by the U.S. Air Force LAC series and are enhanced by high-resolution earth-based photography.

Introduction

Geological maps of the lunar surface have been available since 1962 when the Kepler (Hackman, 1962) and Copernicus (Shoemaker, 1962; Shoemaker and Hackman, 1962) maps were published by the U. S. Geological Survey at scales of 1:1,000,000. These maps, which were constructed on topographic base maps of the U.S. Air Force's LAC Series, included structure-stratigraphic sections of several regions on the Moon. In addition, two-dimensional hypothetical lunar models have been constructed (Westhusing and Crowe, 1964; Geyer and Van Lopik, 1965) to illustrate lunar geological exploration problems. The models of this report (Figs. 2,3 and 5,6) represent an initial attempt to construct accurate three-dimensional scale models to illustrate the stratigraphic concepts proposed by Shoemaker and Hackman (1962). The horizontal and vertical control of these models is based on the U.S. Air Force's LAC topographic maps (nos. 25, 39, 40, 57, and 58). The surface geological interpretations from which the subsurface inferences were drawn were obtained from geological maps provided by the U.S. Geological Survey.

The Montes Apenninus and Copernicus regions were selected for illustration because they lie along stratigraphic strike adjacent to the basin of Mare Imbrium and therefore show similarities in geological development. The thickness of subsurface units around the Imbrian Basin have been inferred by Marshall (1961) and Eggleton (1963), who have studied the depth/diameter ratios of "ghost" craters and constructed isopach maps of some of the inferred ejecta blanket deposits and lava flows. The profiles of craters in the subsurface are shown on the models as idealized parabolic "disturbed" zones whose deepest parts correspond approximately to one-fifth the crater diameters. This ratio is roughly the same order of magnitude as that obtained by the drill in Meteor Crater (Shoemaker, 1963) and Brent Crater (Beals, Innes, and Rottenberg, 1963). Due to the general nature of these drawings, no attempt was made to differentiate allogenic and authigenic breccias or to show possible effects of isostatic rebound on the floors of the large impact craters.

The small-scale surface views of these illustrations, coupled with comparatively thin subsurface units, necessitated exaggerating the vertical scale approximately six times.

Surface Geology of the Moon: Montes Apenninus Region

Figure 1 is an index map of the Montes Apenninus region. Figure 2 shows a block diagram of this same region which has been inverted with respect to the index map. This arrangement provides the best perspective for viewing the major physiographic and geologic features of the region. This diagram shows two views of the area: a surface view as might be seen by an astronaut orbiting several hundred kilometers above it; and a subsurface geological interpretation of the region. Superimposed on the surface are

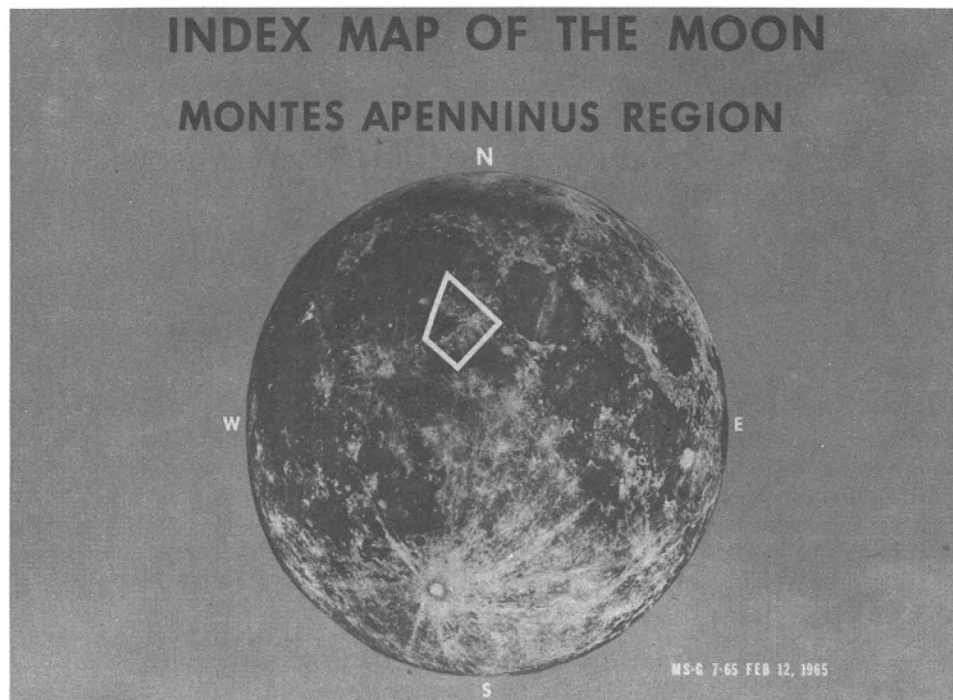


Figure 1. Index map of the Moon, Montes Apenninus Region (courtesy George C. Marshall Space Flight Center, Huntsville, Ala.)

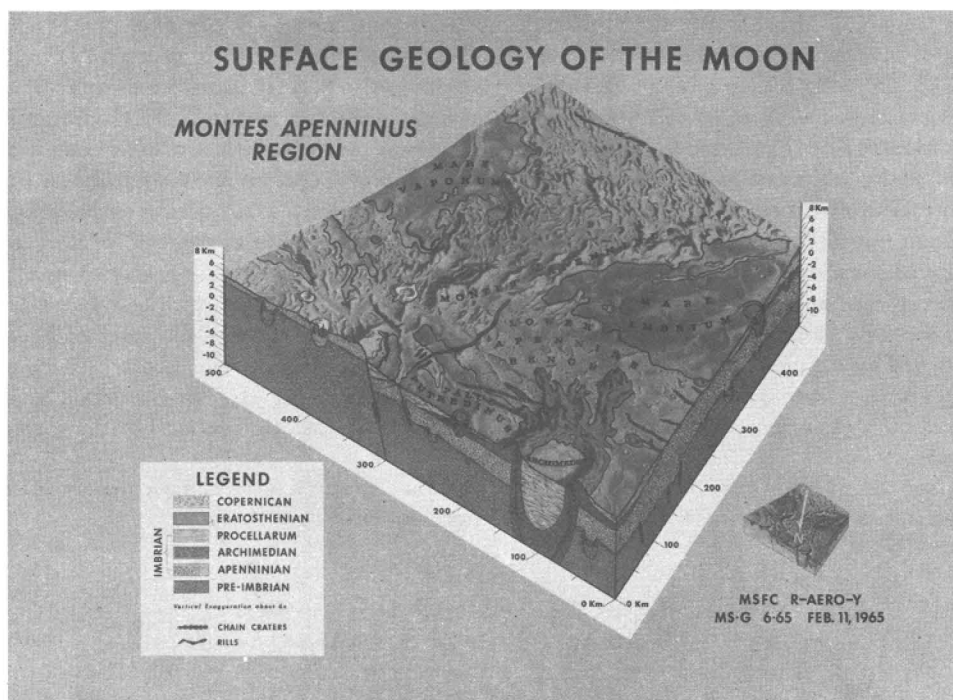


Figure 2. Surface geology of the Moon, Montes Apenninus Region (courtesy George C. Marshall Space Flight Center, Huntsville, Ala.)

the names of the major physiographic features and lines which delineate the named lunar geological formations. The legend at the lower left identifies the periods of lunar geological time.

The surface features include the Montes Apenninus chain and the dark, lava-covered floors of Mare Imbrium, Mare Vaporum, and Palus Putredinis. The Lower Apennine Bench is clearly indicated with its rough, hummocky surface projecting above the floors of the adjacent maria. The large, lava-filled crater, Archimedes, is situated on the northeastern end of the Lower Apennine Bench. Many small craters, domes, rills, and chain craters are shown on the maria floors. Directly to the south of the Montes Apenninus is a set of fractures which radiates from the center of Mare Imbrium. This fracture set was originally referred to as the "Imbrian Sculpture" by G. K. Gilbert (1893).

The pre-Imbrian system includes rocks of unknown composition and texture. By analogy with the Earth, one might postulate that the pre-Imbrian deposits are composed of crystalline, igneous rocks. The possibility exists, however, that these deposits may be an agglomerate of undifferentiated meteorite fragments. The surface of the pre-Imbrian deposits is interpreted as an unconformity which was probably exposed for millions of years to meteorite bombardment and geological activity. Thus, the presence of buried craters and faults lying along this unconformity is a likely possibility.

The Imbrian deposits are situated stratigraphically above the pre-Imbrian deposits and, therefore, are younger. The Imbrian System has three subdivisions: the Apenninian, the Archimedian, and the Procellarum. According to Shoemaker (1962) and Hackman (Shoemaker and Hackman, 1962), the Imbrian Basin was formed by the impact and subsequent explosion of a giant meteor. The Apenninian deposits were laid down by the ejection and deposition of a blanket of debris resulting from the Imbrian event. The two large normal faults shown on figures 2 and 3 resulted from large blocks of material moving downward toward the center of the Imbrian crater. These faults produced the Montes Apenninus on their upthrown blocks and the Lower Apennine Bench and a stratigraphically continuous buried shelf on their downthrown blocks.

The crater Archimedes and its associated deposits formed next. This crater is on the northeast end of the Lower Apennine Bench. The debris blanket of Archimedes and other craters which post-date the Imbrian event and pre-date basin filling have been named Archimedian deposits (Hackman, 1963).

The smooth, dark-colored materials which filled the basins are stratigraphically younger than the Archimedian deposits. They formed during a period of widespread filling named "Procellarum" after the material which filled the Oceanus Procellarum. This material, probably of volcanic origin, followed the curvature of the Moon and filled the depressions to an almost common level (Shoemaker, 1962; Shoemaker and Hackman, 1962; and Marshall, 1961).

The Eratosthenian system consists of material ejected from the crater Eratosthenes and other craters of similar morphology and low to medium albedo which overlie mare material and other Imbrian material. The most notable characteristic of these craters and their associated deposits is their lack of associated ray systems (Shoemaker, 1962; Shoemaker and Hackman, 1962; and Marshall, 1961).

The Copernican system consists of debris from Copernicus and other ray craters of similar morphology and relatively high albedo. Rays are interpreted as brightly colored patches on the lunar surface which are associated with concentrations of secondary craters which emanated from primary Copernican craters (Shoemaker, 1962; Shoemaker and Hackman, 1962; and Marshall, 1961).

Subsurface Geology of the Moon: Montes Apenninus Region

Figure 3 shows only the northern quadrant of the region of figure 2. The two white circles on the surface correspond to areas having 10 and 50 km radii. Each circle has a corresponding depth of investigation, which can be studied by using active seismic methods. For example, refraction seismic techniques can measure the depth and seismic properties of rocks down to approximately one-fifth the distance between the energy source and receiver. If sufficient energy were developed to transmit a series of shock waves over a 100 km range, this would provide depth information up to 20 km. An experiment such as this would provide valuable information concerning the seismic properties and depths of all the major lunar formations. With the proper receiver arrays it would be possible to delineate buried subsurface anomalies such as craters, grabens, faults, and pre-Imbrian basement irregularities. By comparison, a 10-km radius area would have a practical depth limitation of 4 km and would afford the opportunity to investigate only the Procellarum, Archimedian, and Apenninian deposits. Of course, the practical limit of the source to receiver distance will probably be determined by the weight of explosive required to transmit seismic waves over a given distance.

Gravity and magnetic surveys conducted within the circled areas would provide abundant data

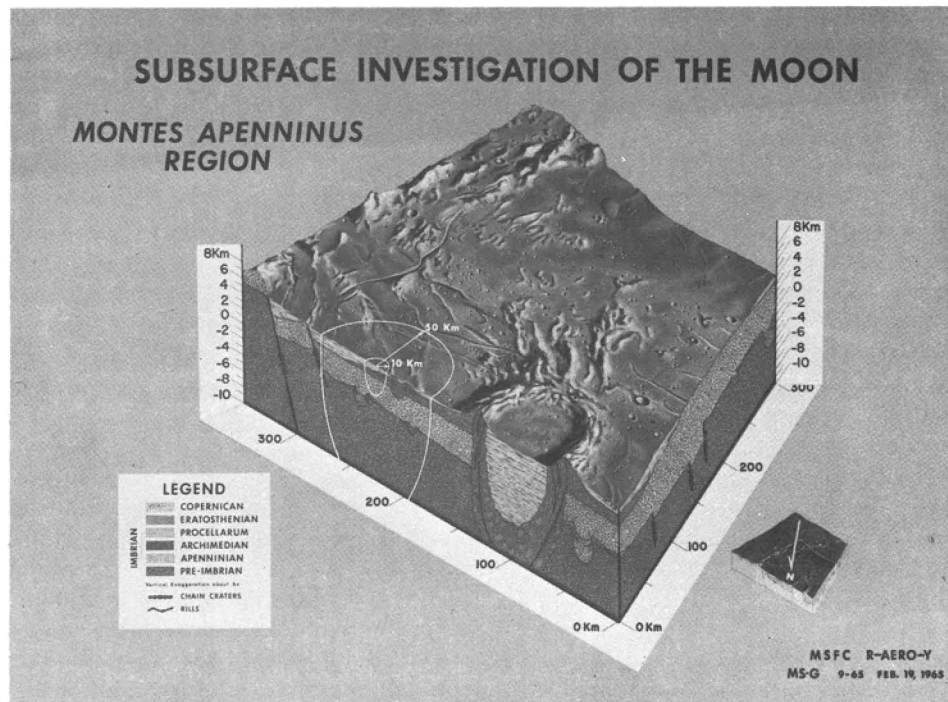


Figure 3. Subsurface investigation of the Moon, Montes Apenninus Region (courtesy George C. Marshall Space Flight Center, Huntsville, Ala.)

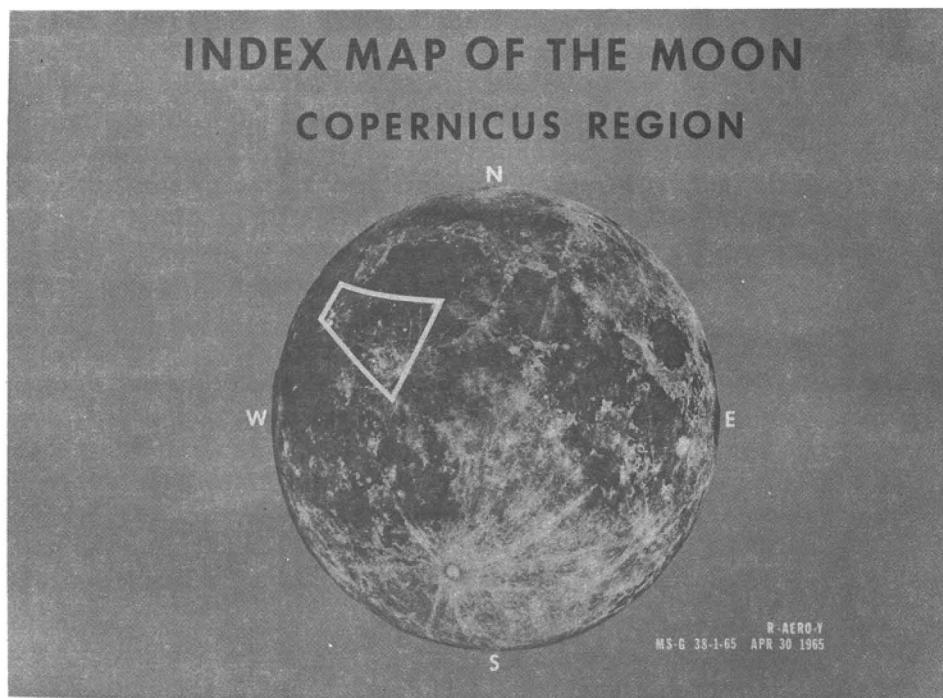


Figure 4. Index map of the Moon, Copernicus Region (courtesy George C. Marshall Space Flight Center, Huntsville, Ala.)

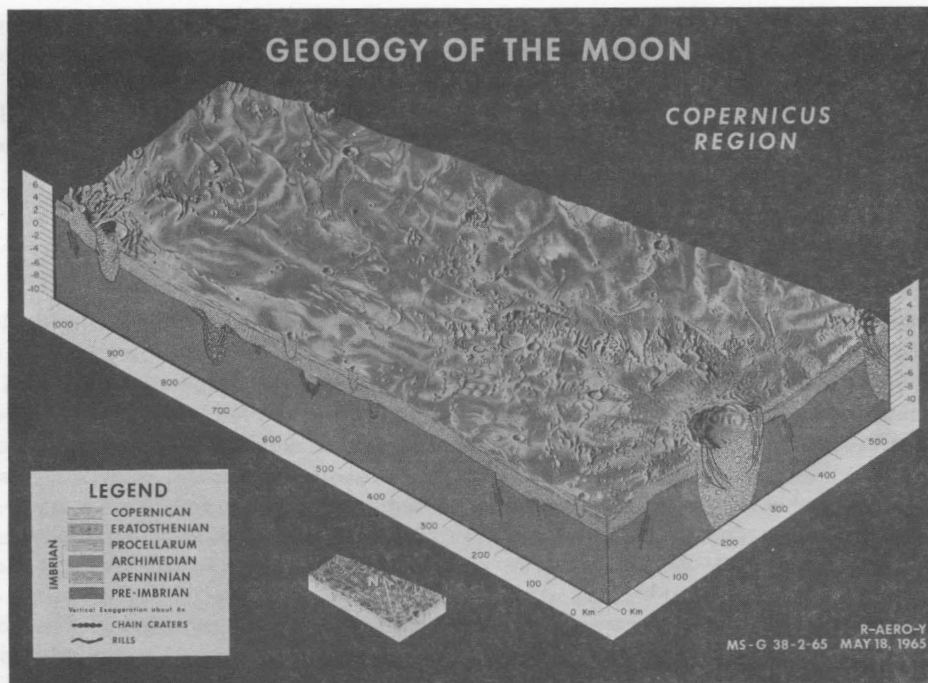


Figure 5. Geology of the Moon, Copernicus Region (courtesy George C. Marshall Space Flight Center, Huntsville, Ala.)

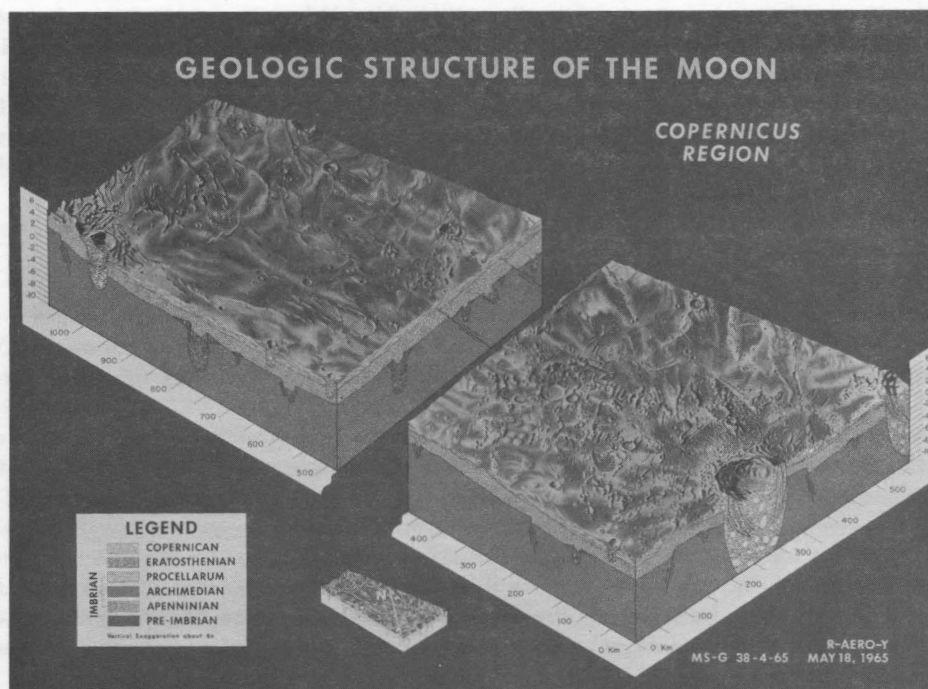


Figure 6. Geologic structure of the Moon, Copernicus Region (courtesy George C. Marshall Space Flight Center, Huntsville, Ala.)

on the subsurface geometry of rock bodies and could detect the presence of buried features such as faults, craters, basement configuration, and so forth. Other geophysical surveys which should be conducted along traverses and in all of the lunar boreholes include measurements of a broad spectrum of natural and induced electromagnetic radiation. By correlating and integrating all of the geophysical and geological data obtained from areas such as those in figure 3, our knowledge of the surface and subsurface configuration of the Moon will become more precise.

Geology of the Moon: Copernicus Region

Figure 4 is an index map of the Copernicus Region. Figure 5 shows an isometric block diagram of this same region. The craters shown on this diagram include Copernicus (center, southeast panel), Eratosthenes (upper edge, southeast panel), and Aristarchus (upper end, southwest panel). The Carpathian Mountains are the east-west trending ridge of rugged terrain situated between Copernicus and Eratosthenes. The Procellarum deposits of Mare Imbrium make up the dark-colored material which fills the lowlands. Many surface details including domes, domes with craters, primary, secondary, and chain craters, rills, and wrinkle ridges are indicated on the Procellarum deposits.

The sequence of geological events shown in this area is the same as that indicated for the Montes Apenninus Region (Fig. 2, 3). According to the impact-explosion hypothesis for the origin of the Imbrian Basin, the Apenninian ejecta blanket was distributed radially around the entire basin. Since the area of this illustration is situated at approximately the same distance to the center of the Imbrian Basin as the Montes Apenninus Region, the distribution and thickness of the Apenninian and related deposits are about the same in both areas.

Geologic Structure of the Moon: Copernicus Region

Figure 6 shows two parallel cross-sections separated by approximately 475 km. This presentation graphically shows the major difference between the Montes Apenninus and Copernicus regions. The Montes Apenninus form a part of an almost continuous ring of mountains around the southeastern rim of Mare Imbrium. In the Copernicus Region, the Carpathian Mountains are a part of this chain of mountains. In crossing this region, however, the axis of the Carpathian Mountains plunges to the west beneath the Procellarum deposits.

The two normal faults shown in the central cross-section are downthrown toward the Imbrian Basin. The upthrown block of the southernmost fault forms a shallow shelf which is continuous with the Carpathian Mountains and the upthrown block of the fault nearest the basin forms a lower shelf which is analogous to and possibly continuous with the Lower Apennine Bench.

Conclusions

An overriding objective of lunar geological exploration will be to construct accurate three-dimensional lunar structural and stratigraphic models based on surface and subsurface geological and geophysical information. The geological history of the Moon will be developed as a result of integrating such models from many different regions.

The models shown in this report reflect the major lunar stratigraphic concepts in vogue today. It will be an important objective of future generations of lunar explorers to determine their validity.

Acknowledgment

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References

- Beals, C. S., Innes, M. J. S., and Rottenberg, J. A., 1963, Fossil Meteorite Craters, in The Solar System, vol. IV; the Moon, Meteorites, and Comets (Chap. 9): B. Middlehurst and G. P. Kuiper, eds., Univ. Chicago Press, p. 235-284.
- Eggleton, R. E., 1963, Thickness of the Apenninian Series in the Lansberg Region of the Moon: Astrogeologic Studies, Annual Progress Rept., August 25, 1961 to August 24, 1962, Part A - Lunar and Planetary Inv., U.S. Geol. Survey, p. 19-31 (quoted by permission of the U.S. Geol. Survey).
- Geyer, R. A., and Van Lopik, Jack R., 1965, Use of Geophysical Measurements in Lunar Surface analysis, in Geological Problems in Lunar Research: New York Acad. Sci. Annals, v. 123, art. 2, p. 1160-1174.
- Gilbert, G. K., 1893, The Moon's Face: A Study of the Origin of its Features: Phil. Soc. Washington Bull., v. 12, p. 240-292.
- Hackman, R. J., 1962, Geology of the Moon, Kepler Region: U.S. Geol. Survey Misc. Geol. Inv. Map I-355 (LAC 57).
- _____, 1963, Stratigraphy and Structure of the Apenninian Region of the Moon: U.S. Geol. Survey Astrogeologic Studies, Ann. Prog. Rept., August 25, 1961, to August 24, 1962, Part A, Lunar and Planetary Inv., p. 2-10 (quoted by permission of the U.S. Geol. Survey).
- Marshall, C. H., 1961, Thickness of the Procellarian System, Letronne Region of the Moon, in Geological Survey Research 1961: U.S. Geol. Survey Prof. Paper 424-D, p. 208-211.
- Shoemaker, E. M., 1962, Interpretation of Lunar Craters, in Physics and Astronomy of the Moon: Zdeněk Kopal, ed., Academic Press, p. 283-359.
- _____, 1963, Impact Mechanics at Meteor Crater, Arizona, in The Solar System, vol. IV; The Moon, Meteorites, and Comets (Chap. 11): B. Middlehurst and G. P. Kuiper, eds., Univ. Chicago Press, p. 301-336.
- Shoemaker, E. M., and Hackman, R. J., 1962, Stratigraphic Basis for a Lunar Time Scale, in The Moon: Zdeněk Kopal and Zdenka Mikhailov, eds., Academic Press, p. 289-300.
- Westhusing, J.K., and Crowe, C., 1964, Techniques for Lunar Water Exploration, Final Rept. July 1, 1963 to Sept. 30, 1964: Texas Instruments, Inc., AD 608957, 398 p.

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SOME THOUGHTS ON LUNAR TECTONICS

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ABSTRACT

The impasse between meteorite-craterists and volcanists is seemingly solvable if one takes a sufficiently wide-angled view, in which the maria are regarded as tectonic plates. Something of a structural mosaic can be discerned. Since the various sizes of Lunar crustal plates have terrestrial counterparts which (in one size or another) are aliquots of the total surface, the fragmentation patterns become a function of the sphere itself and no extraneous forces need be called upon. The rigidity of the crust of a sphere is demonstrated in the height of the mountains it supports, on moon and earth alike. In view of the brittleness and rigidity of the crust, the adjustments lie along the linear mountain zones that separate the plates forming the mosaic. The moon's mountains, expressed as a ratio of the diameter of the sphere, are six times as high as terrestrial mountains, which is exactly what would be expected if similar vertical tectonic force systems operate on both bodies. Thus, if the rigidity of the earth's crust is adequate for rocket operations, so also is the moon's.

Introduction

At the American Academy of Science conference on Geological Problems in Lunar Research in New York in May, 1964, there was a fairly even division between the meteorite-impact hypothesis and the volcanist view that moon craters are volcanic in origin, and that the larger lunar features are thus tectonic features. The division of opinion on the face of it is not easily resolved because no common meeting ground could be found. If one assumes that some of the smaller craters are meteorite-impact craters and that there is no essential difference between the small depressions and the large depressions, then all equidimensional lunar features are meteorite craters, which would mean that no fundamental fragmentation pattern has been recognized. If, on the other hand, one assumes that the larger lunar features, the maria, are tectonic depressions, then as one works down the table of scales it is equally difficult to draw any line and say that craters below a certain size are not also tectonic or volcanic. The controversy thus has reached an impasse. It is not enough to say that the meteorite-impact theory does not seem plausible, in that the larger scars demand a meteorite of a size that would have knocked the moon out of orbit. That is merely an opinion and not easily provable.

To a tectonically-minded structural geologist, the Conference on Geological Problems in Lunar Research of 1964 provided something of a surprise in that men of science with little knowledge of tectonics should cite a purely tectonic feature - the Vredefort structure - as a classic example of a terrestrial meteorite crater. The tectonic history of that phenomenon has an intimate bearing on the disposition of the greatest goldfield in the world; it has received a corresponding amount of study, and it is now fairly well established as a superlative example of superlative vertical tectonics. To call on astronomy to solve this purely tectonic problem seems unnecessary.

Although rejecting the meteorite hypothesis for tectonic reasons, it may not be out of place to mention that the only meteorite I have ever seen in situ has remained in situ because it is too big to move. This meteorite, the greatest known, is of the metallic type, and is situated near Grootfontein, South West Africa. It merely embedded itself very partially in the hard pan soil, without causing even the suspicion of a crater. The visible portion, which is the bulk of it, allows an estimate of the weight. It comes to about 60 tons. That it caused no crater whatever would seem to demand an explanation. Hypothetical calculations of the size of a meteorite needed to produce a depression of a certain size must contain a few imponderable factors in the light of the above.

The situation demands a fresh approach. Since a study of details has remained inconclusive, a wide-angle view is advocated, with an eye to form. Where, indeed, is there a similar opportunity to study a heavenly body "in the round"? Where is there a better opportunity to practice geological

photo-interpretation? What tools are there at our disposal other than a knowledge of form or a faculty for the interpretation of a pattern? The absence of weathering as we know it should leave the primordial structure of the moon's crust visible if it has not been obscured by other events.

Fundamental Premises

It is generally accepted that the pull of gravity on the surface of the moon is about one-sixth of what it is on the surface of the earth, gravity being a function of the mass. It is acknowledged that there is virtually no atmosphere on the moon and no surface water, hence no mechanism other than a comparatively feeble gravity for the horizontal transport of material. Thus there would be no stratified sediments as we know them on our planet, and no geosynclines; and no folded mountains, since the stratified sediments provide ready-made slip planes which encourage the yielding to directed pressure. Directed horizontal pressure is a necessary feature of folded mountains. It is believed (by the present author, at least) that directed pressure can be attained by the sinking of a linear block into the igneous environment of the mantle where the block becomes weakened and plastic. The all-directional compressive crustal force is given direction normal to the trough, along which the crust has been weakened.

The all-directional potential crustal force is the direct result of gravity which produces a doming effect in the crust - or in cross section an arching effect. This generalization should apply to any solid-crusted spherical body of sufficient size that gravity is the dominant force. Any heavenly body which is essentially spherical is dominated by gravity. It is probably safe to say that the moon comes into this category (even though we have seen only one profile, the one normal to our line of vision). Haldane has calculated that if a man were the size of the moon he would have to approximate sphericity, the approximate shape of the moon, because a projecting skull would be crushed like an eggshell by the moon's gravitational force.

There is a noticeable tendency to discount the force of gravity, because on the laboratory scale it is infinitesimal compared to nuclear forces. On the global scale, however, the nuclear and magnetic forces have tended to cancel out, whereas gravity is directly proportional to mass.

Gravity is the reason for the sphericity of heavenly bodies, and gravity is the only force that holds such a body together. In any spherical heavenly body, gravity has to be by far the dominant force or the body would not approach sphericity.

The point we are leading up to is that on a spherical body, shaped essentially by gravity, yet without the folded mountains, the tectonic manifestations will all be those of vertical tectonics; that is, the ups and downs of blocks of the crust relative to one another. This is the only way the brittle crust in the absence of folding can adjust itself to the vagaries of the plastic zone that underlies it.

Some Lunar Features with a Tectonic Message

Polygonal plates: The polygonal shape of Crisium is the ideal shape of a crustal plate. Crisium is a type unit of its particular size (Brock, 1964). Four of the nearby maria belong to the same size-group, although their boundaries are not as clearly defined. However, some linear boundaries are noteworthy, for instance Serenitatis bounded on two sides by linear mountain ranges, Haemus and Caucasus. The rather linear boundaries of the larger maria areas tend to be masked by minor convolutions related to features of a smaller size group.

It is noticeable that many of the craters are also polygonal, Copernicus and Plato being elegant examples. That particular shape is almost diagnostic of the tesserae of a mosaic (Brock, 1956). Where three fractures or linear zones of weakness meet, there is a very strong tendency for them to meet at angles approaching 120°. This is a fundamental law of form, found in as varied natural phenomena as honey combs, mud-cracks, basaltic columns, and crustal mosaics. It constitutes the reconciliation between radial structures and concentric, and is found wherever units of equal size grow concentrically at an equal pace to meet their neighbouring units engaged in the same procedure.

The polygonal shape is utterly incompatible with the meteorite-impact crater concept.

The maria of the western block, the finer pattern of maria, have a terrestrial counterpart in oceanic basins of the South Atlantic. The coarser maria of the eastern block have a terrestrial counterpart in units the size of the West African craton, or an oceanic equivalent - the North American basin. This relationship suggests that the major lunar features are aliquot parts of the total area of the moon's surface, that is, no extraneous forces need be invoked. The pattern is a crustal pattern related to the sphere itself.

Lineaments: Lineaments have been defined as alignments of geological or geographical features too precise to be fortuitous. There are many of these on the moon, but usually of no great degree of continuity. If we allow, however, that sinuosities caused by a finer pattern do not invalidate a gross alignment like the edge of major maria areas, then there are lineaments approximating 90° in length, comparable to the diameter of the unit they bound. There are lines of craters all of equal size with a spacing that suggests order as opposed to chaos.

The mountain ranges are linear zones of uplift, clearly with terrestrial counterparts (with the difference already noted that the moon lacks folded sediments).

Radial structures: There are lineaments radiating from certain craters, such as Tycho, Bullialdus and Kepler. Most of these are tangential to their respective crater, and many of them relate one crater structurally to another. Although the rays have not been explained adequately, the Encyclopaedia Britannica refers to them bluntly as faults. There are some lunar faults that have a visible escarpment or throw.

It is difficult to say on the given evidence whether the faults caused the siting of the craters, or whether the craters caused the faulting. The tangential relationship, however, suggests the former. There are arcuate lineaments such as the boundary of Mare Imbrium.

There are some visibly open clefts, unfilled with debris, which are possibly akin to rift valleys. The style may be different because of the differing gravity, the tendency to stay open, and the lack of any mechanism other than a relatively feeble gravity for the filling of them.

Evidences of vertical tectonics: As long ago as 1928 Schwartz pointed out that certain craters contained an uplifted crustal cylinder. Here is evidence of vertical tectonics, seemingly quite analogous to the Vredefort.

The central or focal position of numerous craters, like Copernicus centred in its upland area and Kepler centred in its maria area, seem to be a manifestation of order. The central position of the cone of many craters would seem analogous to that of the Vredefort hub with relation to the Rand Basin. The citing of the Vredefort as a terrestrial equivalent of lunar structures may be perfectly correct, but not as an example of a meteorite crater. On the contrary, the Vredefort provides a model for vertical tectonics on the moon. The Rand Basin is 180 miles long and roughly half as wide, that is $2\frac{1}{2}^\circ$ by $1\frac{1}{2}^\circ$; its mobile heart, the Vredefort hub, mathematically centred within the Rand Basin, represents the central core. The greatest volcanic activity related to the Vredefort story happened late – after the basin floor had subsided about 25,000 feet, and possibly after the mobile heart had risen.

On the Rigidity of the Lunar Crust

The differences of the moon's tectonic features from terrestrial ones can mostly be accounted for by the particular physical conditions of the lunar environment. The likenesses are by and large more noteworthy than the differences. The former convince us that we are dealing with the fragmentation of the crust of a sphere on the moon just as on earth.

It would be misleading, if not downright untrue, to say that the moon tectonically is a model of the earth, but the similarities are such that clearly the tectonic features of the two bodies appear to represent the fragmentation of the crust as it adapts itself to the plastic contents of the sphere. The likenesses are noteworthy in that they bespeak brittleness and rigidity. The difference can be explained in a straightforward manner. Terrestrial troughs or geosynclinal belts accumulate great thicknesses of water-lain sediments which in due course become folded and uplifted. The lunar mobile belts do not, because of the absence of transporting agents, water and wind.

Let us view the crust functionally. On earth, dimensionally, it is no more than a skin, and it can be thought of as a skin, that is with the function of a skin. The chief function of a skin on anything organic or inorganic is to protect what is underneath. The earth's skin, when fractured or lacerated, heals up with a new skin forming over the wound.

The earth's crust of necessity has a rigidity and a brittleness. The brittleness allows of the fragmentation of the crust which, in turn, allows the crustal plates to adapt themselves to the mantle. The rigidity allows the crust to support mountain ranges. If it were not so, the mountains would simply founder into their foundation. They have not done so at least since Tertiary or even Mesozoic times.

Likewise the moon's crust supports mountains on a still grander scale, relatively. The moon's lesser pull of gravity may have the effect of accentuating vertical tectonics. If, however, the moon's

crust will support mountains relatively six times as high as the earth's highest mountains, then the moon's crust must be of the same order of rigidity as the crust of the earth, hence more than adequate.

Thus, if the rigidity of the earth's crust is adequate for rocket operations, so also is the moon's. The landings will be of the order of one-sixth as hard, and the force required to get into orbit from the moon will be a sixth of that required to get off the earth.

The Dust Bowls

Many if not most of the hollows are apt to be dust-filled. The great temperature range on the moon will have favoured mechanical disintegration of the rocks and the product of disintegration will find its way by gravity to the lower levels. The mountains, the crater rims, and the plateaus which represent the uplifted blocks all appear to show a fair proportion of their surface to be solid rock, practically free of dust.

It goes without saying that a landing on the rocky terrain will be a good deal safer than a landing in an unknown thickness of debris of unknown quality. There is no first-hand knowledge about the coarseness or fineness, nor of the closeness of packing of the rock debris. The present contribution cannot encompass that question, but confines itself to the question of the rigidity of the crust - the quality that controls the tectonics of the moon.

Tectonics and Volcanicity

Tectonics and volcanicity are inseparable. Whenever a fault extends deep enough to tap a magma reservoir an eruption may occur. Naturally the zones of greatest tectonic activity, the geosynclinal areas, are also volcanic areas, but this does not provide the best lunar analogy because geosynclines as we know them do not occur on the moon, for reasons already stated.

The most likely terrains in which to look for analogies are the volcanic plateau regions, which occur in every continent, notably areas in which vertical tectonics with numerous deep-seated nearly vertical faults are common. In the Rift Valley region of Africa, specifically in the Western Rift near the southern flank of Ruwenzori, a map of the volcanic area looks uncommonly like many lunar areas.

The typical moon crater is not the typical terrestrial volcanic cone, but there are well known composite craters, notably Aso in Kyushu, which resembles a carbuncle, which can almost certainly be matched on the moon. Aso occurs near the junction of two volcanic arcs. Similar cruxes should be sought on the moon.

Conclusion

The moon has a rather different tectonic expression from the earth because the former has no weathering and no mode of transport nor of stratified deposition of rock debris. There are, however, enough lunar tectonic features with a terrestrial counterpart for us to be reasonably certain that the crust of the moon has a fragmentation pattern entirely comparable to that of the earth. Evidences of order as opposed to chaos would appear to rule out the meteorite-impact hypothesis, which if true could only result in chaotic patterns.

From the tectonic evidence it is reasonable to deduce that the rigidity of the moon's crust is comparable - mass for mass - with that of the earth. If this be so, the rocky part of the moon's crust is competent to stand up to any stresses that human devices may impose on it during a landing on and take-off from the moon.

References

- Brock, B. B., 1956, Structural mosaics and related concepts: T. G. S. S. A., vol. 59.
_____, 1958, Aspects of form and the fragmentation of the crust of a sphere: G.S.S.A. Proceedings, vol. 61.
_____, 1964, Lunar and terrestrial structural models on a common sphere: New York Acad. Sci. Conference on Geological Problems of Lunar Research.
Schwartz, E.H.L., 1928, Terrestrial and lunar faults compared: Jour. Geology, vol. 36, no. 2, p. 97.

LUNAR DUST THICKNESS DETERMINATIONS USING MICROWAVE RADIOMETERS

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ABSTRACT

This paper reports on analytical and experimental investigations of microwave radiometric temperatures associated with porous dust layers over underlying rock.

At millimeter wavelengths, the difference between radiometric temperature of various terrain surfaces are primarily the result of differences in their emissivities. Emissivity is a function of the complex dielectric constant of the materials at the surface as well as subsurface layers, the roughness of the surface, and the angle at which the surface is observed. The differences in dielectric constant between dust of submillimeter size and solid rock, with or without vesicles, should allow the determination of dust thickness on the moon using interference techniques. The potential of this system is further enhanced for lunar application because vacuum conditions and the lack of interstitial free water will reduce attenuation factors.

An analytical model for predicting temperature variations is considered first, followed by a comparison with experimental data.

* * *

Passive microwave radiometric measurements can be separated into two general categories: continuum and spectral radiation measurements. The source of emitted power by continuum radiation in the microwave range is the major area of interest for geological and geophysical mapping of planetary surfaces and near subsurface lithologies. Continuum radiation does not exhibit resonance conditions as a function of frequency and applies to most natural radiation of interest such as terrain.

All objects not at absolute zero radiate some energy. In fact, the hotter the object the more it radiates by the Stefan-Boltzmann law (assuming a black or gray body). Radiometers measure a portion of this total radiated energy. Infrared radiometers measure energy near the peak of the radiation curve where the temperature T is in the exponent of the expression, while a microwave radiometer measures energy at much lower frequencies and (from the Rayleigh approximation) the energy is linearly proportional to temperature. Microwave electronics is capable of measuring extremely small quantities of energy on the linear part, that is, the lower frequency portion of the radiation curve. A close examination of microwave radiometric formulations reveals the main variables to be thermometric temperature, emissivity, and frequency. Also involved in actual measurements of radiometric brightness temperatures are reflections from nearby bodies and sky sources such as the sun, earth, and galactic center.

Thermometric temperature is a function of local residual temperature, solar heating, thermal conductivity, thermal emissivity, and thermal absorptivity, all of which are functions of the physical parameters of the rock or soil in question, that is, color, grain, size, porosity, grain angularity, free water content, chemical composition and lineations, both mineral and tectonic.

Emissivity is a function of the complex dielectric constant, frequency, polarization and scattering. Again, these factors are functions of the physical parameters listed above.

The frequency, as a variable, may offer some problems in instrumentation but in general is selectively observable. From this, it is seen that the physical parameters of planetary crustal material is the common denominator which must be determined before definite radiometric temperature predictions can be made.

When dealing with radiometric measurements that will be taken from lunar orbiters or actually on the lunar surface, several factors will enhance the accuracy of the obtained data and simplify data reduction as opposed to reduction of the same data for earth: the lack of a significant atmosphere will negate oxygen, water and (OH) absorption bands; a low constant background temperature, as long as the sources mentioned earlier are avoided, will not only furnish a good calibration point but will also eliminate the effect of background reflections from the lunar surface; the complete lack of free water

at the lunar surface and near subsurface; the limited range of particle sizes at the surface as derived from the Ranger photographs; low terrain slope angles over broad areas (Kopal, 1964).

An example of present-day capability at 35 Gc, a superheterodyne system can have 0.4° sensitivity with a 1 second integration time. The sensitivity is the usually quoted ΔT , and represents the signal temperature to obtain an output signal-to-noise ratio of 1.0. The sensitivity is inversely proportional to the square root of the integration time, thus limiting the sensitivity to the time available for making the measurement.

One type of microwave radiometer is the comparison radiometer. It switches the input between two sources. The output of this type of radiometer can be linearly proportional to temperature and read out in absolute temperature if one of the sources is a reference source. Or, if it is desired to compare two temperatures (different sources, or polarizations), the radiometer output will be proportional to the temperature difference of the sources.

Four lunar models have been selected by Space-General Corporation for theoretical and experimental analysis concerning passive microwave radiometric response of the moon. Two systems have been examined at this time and two are still in progress.

The first model is that suggested by Gold (1962, 1963) and has many adherents in the scientific community. This model is one in which a layer of the fine dust covers the entire lunar surface. The thickness of this dust layer is the main point of disagreement among its adherents. In general, the mountainous areas of the moon are considered to be covered by a relatively thin dust layer, possibly a few centimeters, while the maria has thicker cover, possibly meters thick, and filled craters such as Ptolemaeus have a dust layer hundreds of meters thick.

The second model is that suggested by Goddard and others (1964). This model consists of a shattered rock layer of heterogeneous material lying on basement rock. The average grain size decreases from the base to the top of the debris layer because fragments in the upper part have been broken a greater number of times and have been ejected from smaller impact craters. Near the base the rock fragments may be several centimeters in diameter, while those near the surface are probably finely pulverized. In analyzing this model, we utilized a three-layer system with a relatively coarse fragmental rock overlying basement material and a fine dust overlying the coarse shattered layer.

The third model of a frothy vesicular lava over a basement rock as suggested by Kopal (1964) and Green (1961), for at least parts of the lunar surface, was not analyzed because vesicles approaching wavelength dimensions complicated the arguments of radiometric radiation and required modification of the existing programs. However, a cursory examination indicates this model is also capable of being analyzed.

The fourth model being examined is that suggested by Warren (1963). This consists of a skeletal fuzz that covers most of the lunar surface. The substance is considered to be open-textured, highly porous maze or meshwork of randomly oriented linear units with or without nodes. This is similar to the model set forth by Hibbs (1963), who explains how a "skeletal fuzz" might be formed. Again, this type of structure complicates the radiometric radiation arguments and complete analyses are not ready for presentation at this time.

The two models considered in the following arguments are diagrammatically shown in Figure 1 and formula derivations are contained in Appendix A.

The rock parameters used in the following analysis are median values extracted from literature concerning lunar exploration. If, at some later date, these parameters are found to be in error, it will not change the theory but will require only the insertion of the new numbers.

The specific gravity of the solid basement material near the lunar surface was taken to be 2.70, ejecta rubble as 2.20 and lunar surface dust as 0.5. Two dielectric constants were used; one of 8.5 which is representative of dense earth rocks. The other was 4.5, arrived at from lunar radar studies by Hagfors (1965). These dielectric constants were then adjusted to the lower specific gravities using dielectric constant mixing formula. Therefore, both earth analogs and moon data have been used in the computations and curve derivations. The loss tangent, that is, the ratio of the real and imaginary parts of the dielectric constant, was taken as 0.005, which is within the range suggested by Troitsky (1962). These values give reasonable values for the surface dust layers, the dust values being in the range of 1.37 to 1.56. There have been high resolution measurements made of the polarization properties near the limb of the moon that indicate a surface dielectric constant of between 1.5 and 1.7 (Mayer, 1964).

Thermometric lunar temperatures were assumed to be 400°K for the top cm and 150°K below cm for lunar days and an equilibrium temperature of 150°K for lunar nights. No theoretical model has been formulated for passing of the terminator at this time. These temperatures are probably a little on the extreme side with 400°K somewhat high and 150°K somewhat low.

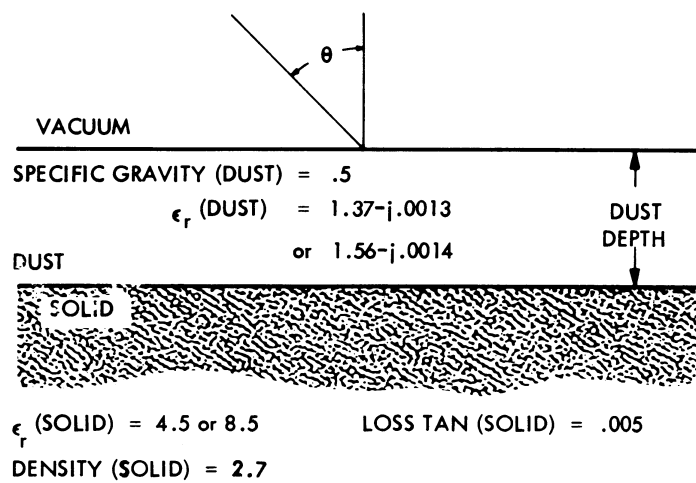


FIGURE 1a. DUST MODEL

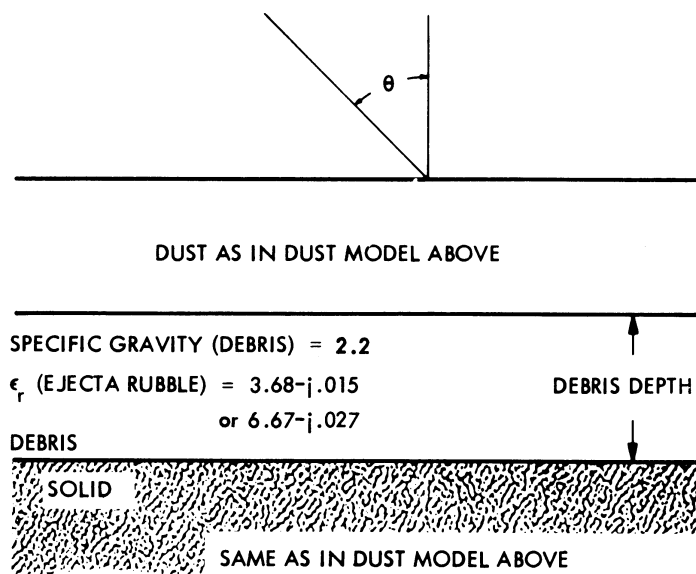


FIGURE 1b. DEBRIS MODEL

Results

The results to be presented in this section are based on the theory discussed in the appendix. For reasons of economy, curves representing only a limited number of the wide variety of possible parameter values characterizing the lunar surface are discussed here. However, a cursory glance at additional cases which have been computed, but not completely analyzed, indicates that these are representative of the entire class of cases representing the models discussed above.

We first discuss the dust model (Model 1) under nighttime observation conditions. The apparent temperature is determined by equation (3) of the appendix with $T_2 = T_3 = 150^\circ\text{K}$. A dielectric constant of 4.5 was assumed for the basement material. Figures 2, 3, and 4 show the temperature of the horizontally polarized radiation as a function of the zenith angle θ for various wavelengths and dust thicknesses D . The monotone decrease of the radiation temperature with angle is a consequence of the behavior of the Fresnel reflection coefficients. The reflectivity approaches one at near grazing angles so that the emissivity approaches zero. A glance at these figures further shows that higher temperatures are associated with greater dust thicknesses at a given wavelength. Note, however, that the separation between the curves representing different layer thicknesses varies with wavelength. As will be seen more clearly later, this phenomenon can be used as the basis of a technique for determining dust layer thickness.

While Figures 2, 3, and 4 give an indication of the absolute temperature to be expected, measurements of the horizontally polarized radiation alone have the disadvantage of requiring measurements of the absolute temperature to be made with an accuracy of the order of one degree. While this may be achieved at frequencies below (say) 13 KMC, it is extremely difficult at high frequencies. However, temperature differences of less than one degree may be measured accurately. Thus, it is suggested that measurements using both horizontal and vertical polarizations be made. The difference between these two temperatures, $T_v - T_h$, which can be precisely determined is, therefore, a more suitable quantity for use in the analysis. Figures 5, 6, and 7 are plots of these differences as a function of angle for different wavelengths. At a zenith angle of zero degrees, the differences vanish because there is no difference between vertical and horizontal polarization. Similarly, the differences vanish at grazing incidence because the reflectivity approaches one irrespective of polarization. However, at intermediate angles, the difference in the behavior of the respective Fresnel coefficients ensures a significant temperature difference.

In particular, the angular range $60^\circ \leq \theta \leq 80^\circ$ appears to be extremely useful. As an example, let us examine the case $\theta = 60^\circ$ more closely. Figure 8 shows the difference between the vertical and horizontal temperature as a function of dust depth for $\theta = 60^\circ$.* For any layer thickness and a suitably chosen set of frequencies, there is a characteristic distribution of values of $T_v - T_h$. If the dust layer is thin, all values of $T_v - T_h$ corresponding to long wavelengths lie close together, but are well separated for short wavelengths. Conversely, if the dust layer is thick, values of $T_v - T_h$ corresponding to long wavelengths are well separated but those corresponding to short wavelengths are close together. Consequently, by the use of several frequencies which are suitably chosen, the dust layer thickness can be determined. The results presented here refer, of course, to a particular value of the lunar thermometric temperature (150°K). If the thermometric temperature is not known precisely, an equivalent formulation which uses $(T_v - T_h)/T_h$ as the basic dependent variable may be preferable. In this way the effect of the thermometric temperature is eliminated, at least for the case of a uniform temperature which should exist at night.

We next turn our attention to the debris model (Model 2), under nighttime conditions. The apparent temperature is determined by Equation (4) of the appendix with $T_2 = T_3 = T_4 = 150^\circ\text{K}$. Figure 9 compares the temperature of the horizontally polarized radiation at a wavelength of 2.22 cm emitted by Model 2 with two cases ($D = 5\text{ cm}$, and $D = 100\text{ cm}$) from Model 1. Qualitatively, the curves are the same, although these are quantitative differences. In particular, the dependence on incidence angle is somewhat more pronounced in Model 2 (note that the curve for Model 2 is closer to that of Model 1 ($D = 100\text{ cm}$) for small incidence angles while it is closer to Model 1 ($D = 5\text{ cm}$) at large incidence angles).

* The curve labeled $\lambda = 30\text{ cm}$ behaves in a peculiar fashion for depths less than 10 cm. It is believed that this is a result of the fact that the dust layer is only a small fraction of a wavelength thick in this region and hence outside of the range of validity of the theory presented in the appendix.

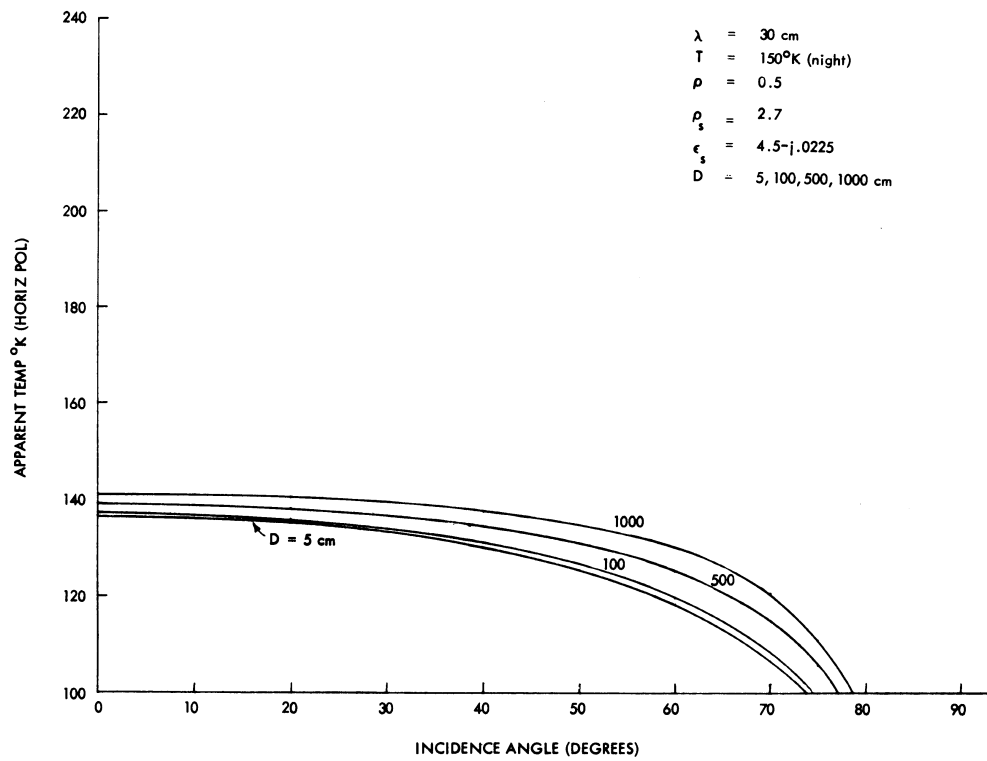


FIGURE 2. DUST THICKNESS - 30 CM

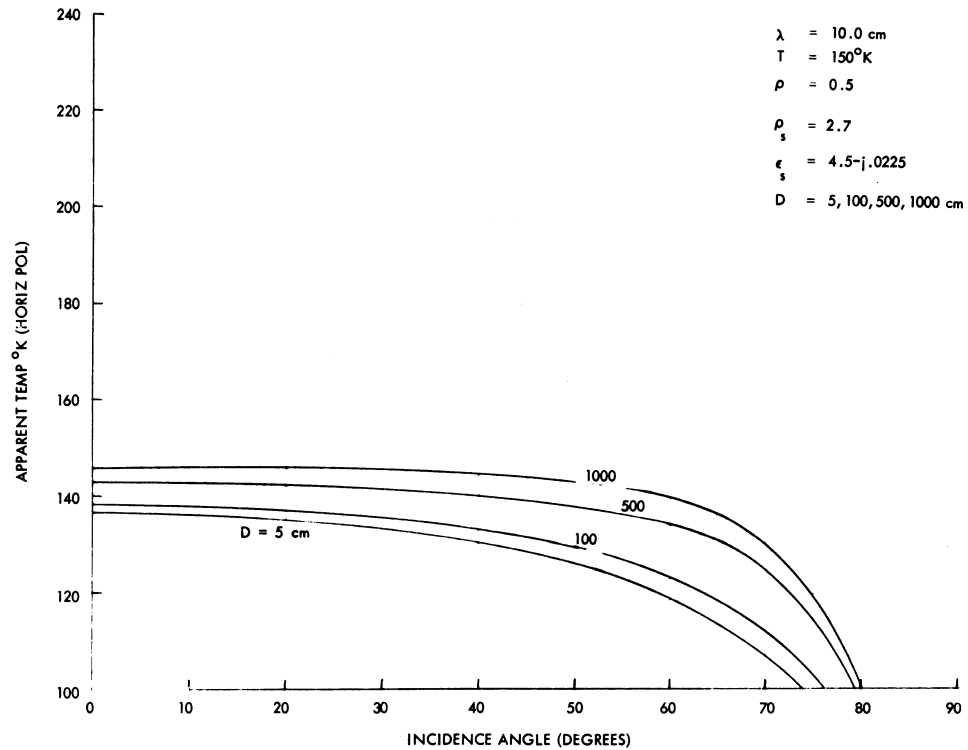


FIGURE 3. DUST THICKNESS - 10 CM

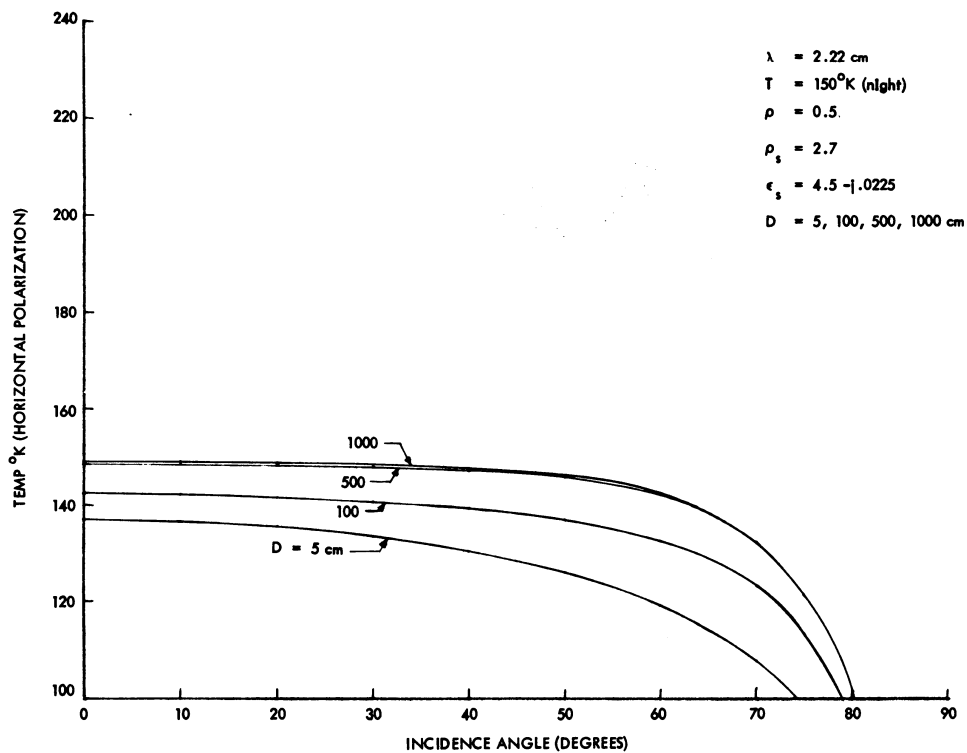


FIGURE 4. WAVELENGTH - 2.22 CM

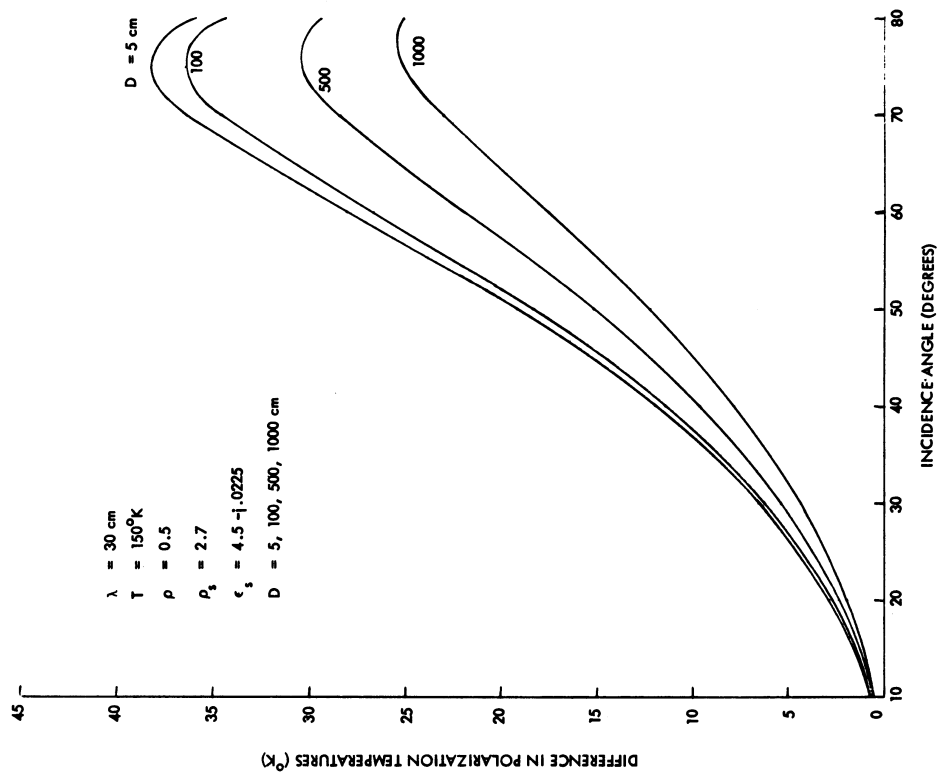


FIGURE 5. DIFFERENCE IN POLARIZATION TEMPERATURES
AT 30 CM

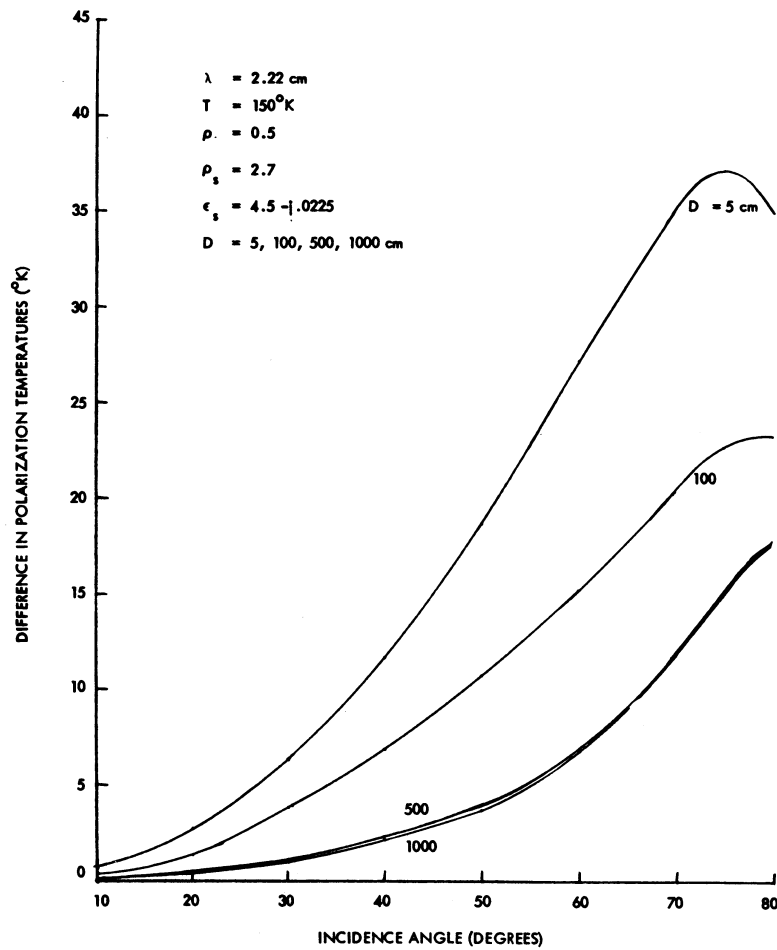


FIGURE 7. DIFFERENCE IN POLARIZATION TEMPERATURES
AT 2.22 CM

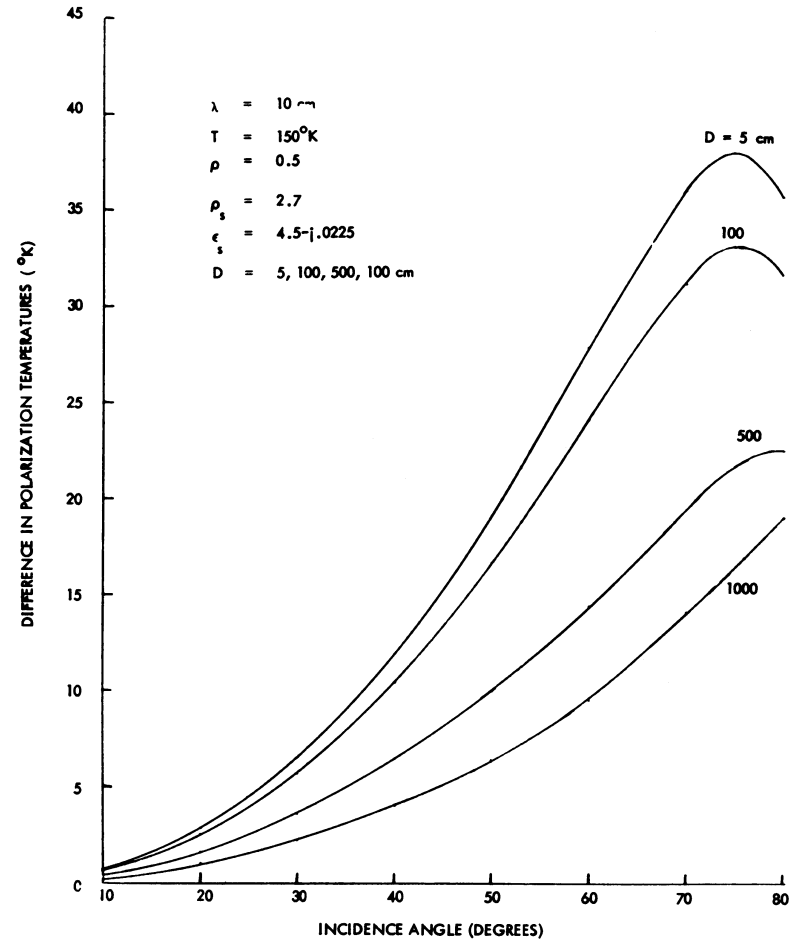


FIGURE 6. DIFFERENCE IN POLARIZATION TEMPERATURES
AT 10 CM

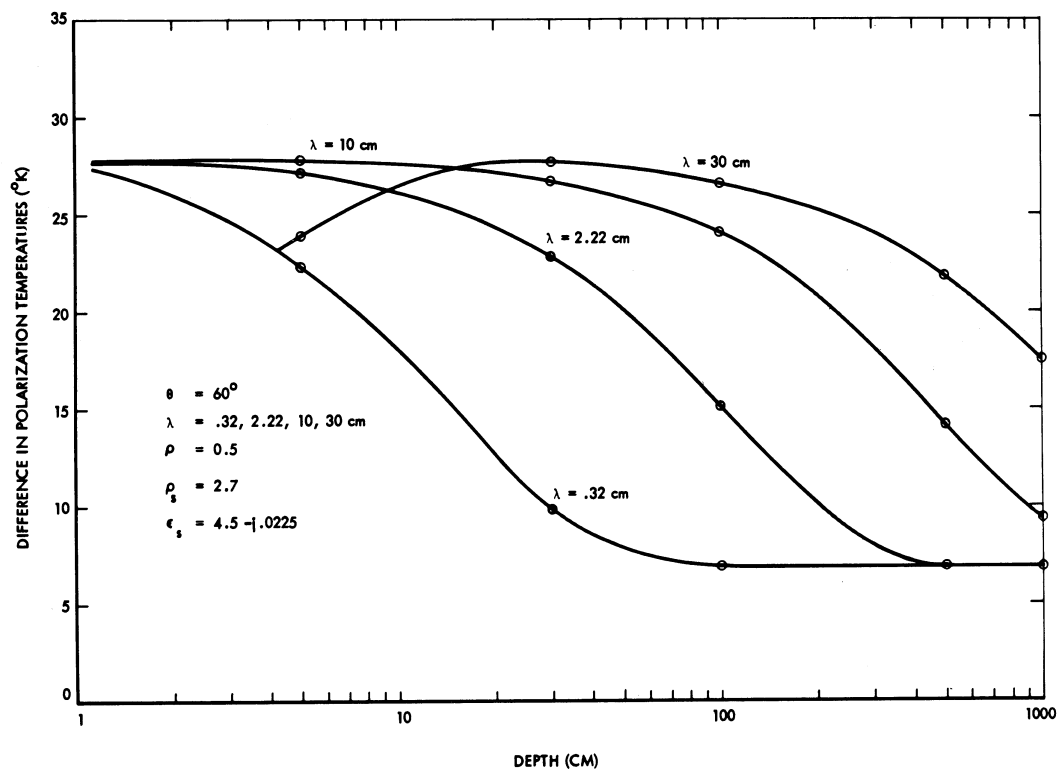


FIGURE 8. TEMPERATURE DIFFERENCE VS DUST THICKNESS

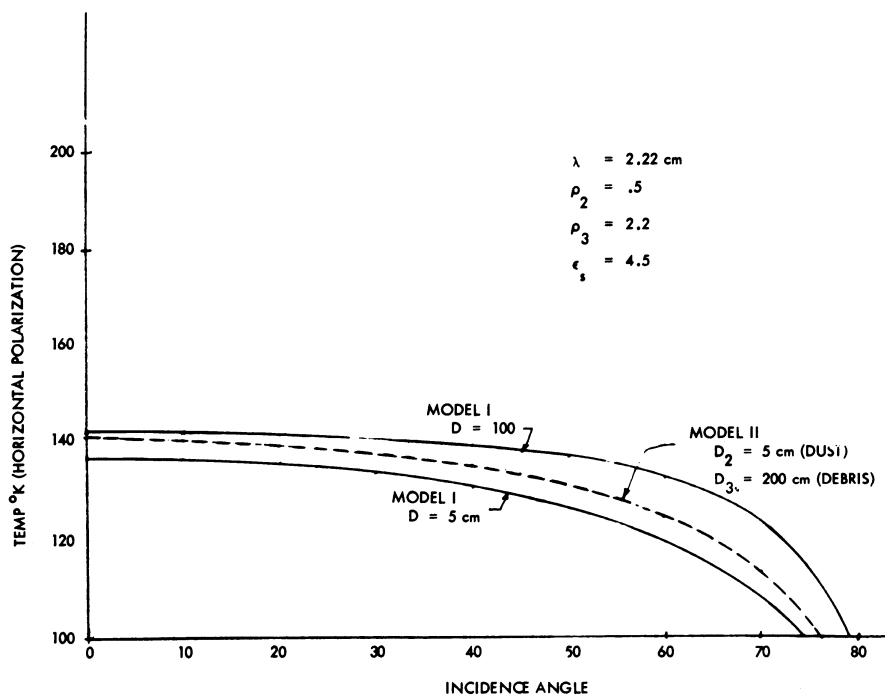


FIGURE 9. MODEL I VS MODEL II

By making measurements at a number of different angles, this difference may be used, if necessary, to help decide between a dust and a debris model. If the choice is the debris model (whether determined by this means or otherwise), the analysis proceeds much as in the case of the dust model. The use of multiple frequencies at suitable angles of observation should allow a determination of the thickness of the dust and debris. However, because of the presence of an additional layer of material, more frequencies than would be necessary for Model 1 alone would be necessary in order to make the finer distinctions which will be required.

Conclusions

The calculations which have been performed on some representative lunar surface models indicate that it is feasible to determine lunar dust thickness and other subsurface features by radiometric means. They also indicate that there is an optimum set of frequencies for determination of dust thickness dependent on the dust density and thickness to be determined.

APPENDIX A

Theory of Microwave Emission from Layered Media

A simplified theory of thermal emission from a layered medium, which should be adequate for an initial investigation of the usefulness of radiometric techniques in lunar exploration, will be presented in this section. Figure 1a illustrates the compound medium to be considered. Each of the n layers consists of a uniform isotropic medium, with a specified complex dielectric constant and thermometric temperature. Medium 1, in particular, may be considered to be the space above the lunar surface. It is desired to determine the apparent temperature of the radiation leaving the interface between media 1 and 2 and propagating into medium 1 when known quantities of radiation are incident on medium 2 from above and medium $n-1$ from below. The latter quantity is just the thermometric temperature of medium n , which is of semi-infinite extent.

In solving the resultant electromagnetic problem, assumptions regarding the nature of the surfaces bounding the various media are required. For simplicity, it will be assumed that the surfaces are relatively smooth (radii of curvature of protuberances small compared to a wavelength) so that reflection and transmission of electromagnetic waves is almost specular and given by the well-known Fresnel coefficients. Furthermore, the radiometer beam will be assumed to cover a sufficiently large portion of the surface so that the thickness of the various layers, which are random functions of position about some mean are averaged. The depths d_i indicated in Figure A-1 represent these means. Because of the assumed roughness, the phases of waves which are multiply reflected in a given layer do not add coherently. Instead, intensities (or, equivalently, temperatures) are added. This assumption also requires that the thicknesses of any layer should not be too small compared to a wavelength in the medium under consideration.

In the following, the angle of emission in medium 1, with polar coordinates θ, φ , will be fixed and, for simplicity, not indicated explicitly in the notation. The choice of θ, φ fixes, of course, the propagation directions in the other media. Radiation with known temperatures $T_-(+0)$ and $T_+(-d_{n-1}-0)$ are impinging on the boundaries between media 1 and 2 and media $n-1$ and n , respectively. Here, and in the following, the subscript $+$ indicates upward propagating radiation while subscript $-$ indicates downward propagating radiation. The argument of T_{\pm} indicates the depth below medium 1. Since it will be necessary to distinguish between the upper and lower side of a given surface, the symbols $+0$ and -0 are used in the argument to specify the upper and lower side of the surface respectively.

There are $4(n-1)$ quantities $T_+(+0), T_+(-0), T_- (+0), T_- (-0) \dots T_+(-d_{n-1}+0), T_+(-d_{n-1}-0), T_-(-d_{n-1}+0), T_-(-d_{n-1}-0)$ of interest (that is, the upward and downward traveling radiation at each boundary). Of these quantities, $T_-(+0)$ and $T_+(-d_{n-1}+0)$ are assumed known. Furthermore, if the principal quantity of interest is the radiation emitted into medium 1, then $T_-(-d_{n-1}-0)$ need not be calculated since, as will be seen below, it does not couple into the other equations. Thus, in general, $4n-7$ equations are necessary to determine the unknown temperatures.

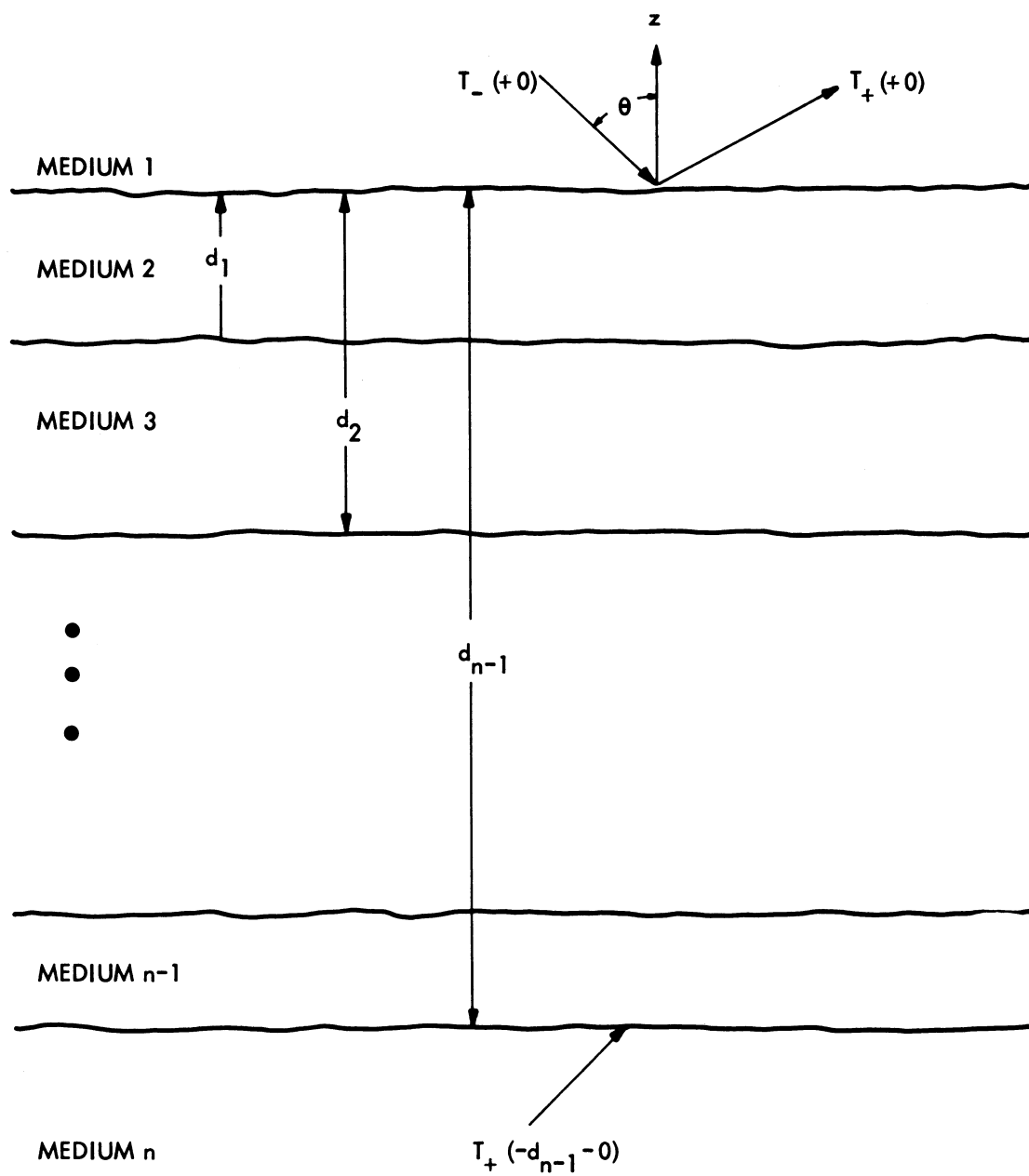


FIGURE A-1. THICK, MULTILAYERED MEDIUMS

At a depth d_i , ($i = 0, 1, 2, \dots, n-2$) one has

$$T_+(-d_i+0) = \rho_{i+1, i+2} T_-(-d_i+0) + \epsilon_{i+1, i+2} T_+(-d_i-0) \quad (1)$$

$$T_-(-d_i-0) = \rho_{i+1, i+2} T_+(-d_i-0) + \epsilon_{i+1, i+2} T_-(-d_i+0)$$

where $\rho_{i,j}$ is the absolute square of the Fresnel reflection coefficient between media i and j and $\epsilon_{ij} = 1 - \rho_{ij}$. Equations (1) simply state that radiation traveling in a particular direction away from a boundary is the sum of that part of the incident radiation propagating in the specular direction which is reflected and that part of the incident radiation in the adjacent medium moving along the same path (making due allowance for refraction) which is transmitted. At the lowest boundary ($z = d_{n-1}$), one can also write an equation of the same form as the first of Equations (1). Since $T_-(-d_{n-1}-0)$ is not needed, the second of equations (1) need not be written. Thus, we have a total of $2(n-1) + 1 = 2n - 3$ equations of the form shown in Equations (1).

The remaining equations which are necessary for a solution are obtained by solving the radiative transfer equations in the various media. Since each layer is uniform, the transfer equation has constant coefficients and can be readily solved. In medium i ($i = 2, 3, \dots, n-1$) the downward propagating radiation at $z = -d_{i-1}$, has a temperature

$$T_-(-d_{i-1} + 0) = T_-(-d_{i-2} - 0) e^{-\tau_i} + \delta_i \quad (2)$$

where τ_i is the "optical thickness" of medium i (which will depend on the angle θ) and δ_i is the temperature of the radiation emitted by medium i which reaches the surface d_{i-1} . There is a similar equation for upward propagating radiation. Since there are $n-2$ media between the surfaces $z = 0$ and $z = d_{n-1}$, we obtain a total of $2(n-2)$ equations of the form (2).

Thus, equations (1) and (2) provide a total of $2n - 3 + 2(n-2) = 4n - 7$ equations. This is the required number.

Special cases

The lunar surface models discussed earlier correspond to the cases $n = 3$ and $n = 4$. It will be assumed that specular reflection of radiation from the sun is not being observed so that $T_+(+0) = 0$. The results are then independent of the azimuthal angle φ .

We consider the case $n = 3$ first. Assuming that media 2 and 3 have thermometric temperatures T_2 and T_3 , respectively, the apparent temperature of the radiation leaving the lunar surface is found to be

$$T_+ = \epsilon_{12} \frac{T_3 \epsilon_{23} e^{-\tau} + T_2 \left[1 - \epsilon_{23} e^{-\tau} - \rho_{23} e^{-2\tau} \right]}{1 - \rho_{12} \rho_{23} e^{-2\tau}} \quad (3)$$

where τ is the optical depth in medium 2.

In the case $n = 4$, let T_2 , T_3 , and T_4 be the thermometric temperature of media 2, 3, and 4, respectively, and τ_i the corresponding optical thickness. The apparent temperature of the radiation leaving the lunar surface is found to be

$$T_+ = \epsilon_{12} \frac{T_2 A + T_3 B + T_4 C}{\Delta} \quad (4)$$

where

$$\Delta = e^{\tau_2 + \tau_3} \left[1 - \rho_{23} \rho_{34} \right] \left\{ 1 - \rho_{12} \rho_{23} e^{-2\tau_2} - \frac{\rho_{12} \rho_{34} \epsilon_{23}^2}{1 - \rho_{23} \rho_{34}} e^{-2\tau_2 - 2\tau_3} \right\}$$

$$A = a \epsilon_{23} \left[1 - e^{-\tau_2} \right] + b \left[e^{\tau_2} - 1 + \rho_{23} (1 - e^{-\tau_2}) \right]$$

$$B = a \left[e^{\tau_3} - 1 + \rho_{23} (1 - e^{-\tau_3}) \right] + b \epsilon_{23} \left[1 - e^{-\tau_3} \right]$$

$$C = a \rho_{23} \epsilon_{34} e^{\tau_3} + b \epsilon_{23} \epsilon_{34} e^{-\tau_3}$$

and

$$a = e^{-\tau_3} \rho_{34} \epsilon_{23}$$

$$b = e^{\tau_3} \left[1 - \rho_{23} \rho_{34} \right]$$

References

- Goddard, E. N., and others, 1964, Project Apollo Geological Field Investigations: NASA Headquarters, Part II Appendix.
- Gold, T., 1962, Processes on the Lunar Surface, and The Moon: Academic Press, Z. Kopal and Z.K. Mikhailov, ed., p. 433-439.
- _____, 1964, The Structure of the Moon's Surface, and The Lunar Surface Layer: Academic Press, J. W. Salisbury and P. E. Glaser, ed., p. 345-353.
- Green, J., 1961, Geology of the Lunar Base: North American Aviation, Inc., SID 61-358, p. 27.
- Hagfors, T., 1965, Evidence of a Tenuous Surface Layer on the Moon as Derived from Radar Observations: In press, submitted to Science.
- Hibbs, A. R., 1963, A Hypothesis that the Surface of the Moon is Covered with Needle Crystals: Icarus, Vol. 2, p. 181-186.
- Kopal, Z., 1964, Introduction, The Lunar Surface Layer: Academic Press, J. W. Salisbury and P. E. Glaser, ed., p. 345-353.
- Mayer, Cornell H., 1964, Thermal radio radiation from the Moon and Planets: IEEE Special Issue Radio and Radar Astronomy Trans., either MIL-8, no. 3 and 4, July-Oct. 1964, or AP-12, no. 7, Dec. 1964.
- Troitsky, V. S., 1962, Radio Emission of the Moon, and The Moon: Academic Press, Z. Kopal and Z. K. Mikhailov, ed.
- Warren, C. R., 1963, Surface Material of the Moon: Science, vol. 140, no. 3563, p. 188-190.

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ENGINEERING SURFACE MODELS FOR LUNAR MOBILITY DESIGN CRITERIA

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ABSTRACT

This paper discusses the lunar surface models which have been used as design criteria in lunar exploration and mobility studies. These surface models are called Engineering Lunar Model Surface (ELMS) and Engineering Lunar Model Obstacles (ELMO). Although these models have been used as design criteria, they, like all models, should be improved as Surveyor data and better techniques become available to classify the lunar terrain and its roughness.

Introduction

Currently, the moon and its associated problems are occupying a significant portion of the research effort of the scientific community. Definite answers must be provided to the significant problems regarding the moon's surface characteristics, if adequate design criteria are to be established for future lunar basing and surface exploration. The major problem encountered in establishing lunar surface mobility design criteria is that too little is known regarding small-scale topography. If a conservative view is adopted, then the engineer must design for a "worse case" moon where it has been assumed that the two main problems are (1) abnormally low bearing strength exhibited by theoretical types of lunar soil models, and (2) a relatively high percentage of the surface covered by slopes of more than 15° in the landing area caused by local protuberances, or depressions; that is, boulders, craters, fractures, slump blocks, and so forth. The Apollo design criteria are basically for a Lunar Excursion Module (LEM) which can land and take off on a "worse case" moon without turning over due to landing on a high slope or sinking deeply into a structurally weak soil. In planning for lunar exploration, the scientific mission planner must consider the use of roving type vehicles for increased mobility. The purpose of this paper is to present the basic lunar surface models which have been used in such studies.

Nomenclature

- c = Coefficient of soil cohesion, lbs/in².
- ϕ = Angle of internal friction (between grains), degrees.
- K_ϕ = Modulus of soil deformation due to frictional ingredients of the soil, whose dimensions are dependent on n , lbs/in ^{$n+2$} .
- K_c = Modulus of soil deformation due to cohesive ingredients of the soil, whose dimensions are dependent on n , lbs/in ^{$n+1$} .
- n = Exponent related to the shape of the pressure-sinkage curve, dimensionless.
- K_1 = Slip parameter reflecting the degree of soil compactness, 1/in.
- K_2 = Slip parameter reflecting the fundamental shape of the soil shear curve, dimensionless.
- H_{\max} = Maximum traction available from soil characteristics, lbs.

W	=	Weight of vehicle per contact area, lbs.
W_t	=	Total weight of the vehicle, lbs.
P	=	Ground pressure per track, lbs/in ² .
Z	=	Sinkage in the soil, in.
R	=	Motion resistance, lbs.
R_i	=	Internal resistance, lbs.
R_t	=	Total motion resistance, lbs.
DP	=	Draw Bar Pull, lbs.
b	=	Width of bearing surface, per contact area, in.
HP	=	Power, hp.
A	=	Total area in contact with the ground, in ² .
l	=	Length of bearing surface per contact area, in.
E	=	Drive motor to track efficiency, percent.

Background

Past experience in payload design studies has demonstrated that all payload and performance are bounded by very stringent limitation on allowable volume and weight. The roving time, velocity, and the selection of the terrain profiles over which the vehicle must operate will determine the amount of electrical power or weight which must be allowed for mobility. To evaluate the performance of a series of proposed lunar surface roving vehicle designs, two engineering lunar surface models (ELMS) and (ELMO) (Mason and others, 1964; Olivier and Valentine, 1965) were developed through the combined efforts of the NASA-Kennedy Space Center and Marshall Space Flight Center teams.

Development of Engineering Lunar Surface Model (ELMS)

A. Assumptions and guidelines

1. Specific traverses were selected which represented both the maria and uplands regions.
2. Within a representative area of the lunar surface a distribution of specific slopes and the lengths of these slopes may be predicted by a random process.
3. The percent distance covered and the frequency of occurrence of all slopes in any specific region are independent of distance. In other words, the micro-structure profiles directly resemble a scaled-down macro-structure profile.

B. Approach

The basic data for the model were developed by selecting a series of 20 traverses of 100 km length on the LAC*, 57, 58, 75, and 76. Charts were prepared by the U.S. Air Force and NASA. These traverses were randomly located near the Copernicus, Lansberg, Kepler, Mt. Rhipaeus, and Le-trone areas of the Oceanus Procellarum region. Ten of these traverses represented the maria profiles, and ten represented the upland profiles. Gross profiles, developed from the map contour data, shadow studies of surface photographic data, and other data were used to provide a slope distribution frequency

* Lunar Charts.

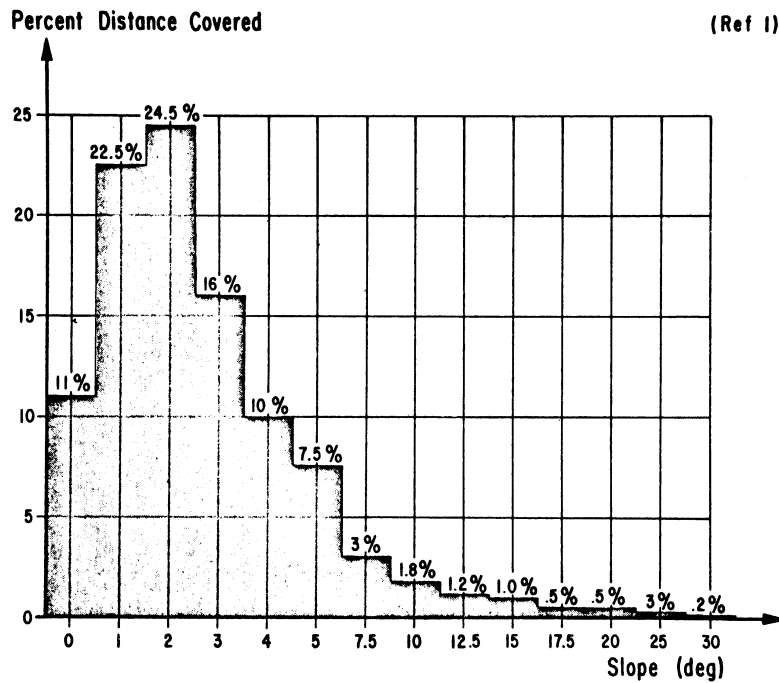


FIG. 1. MARIA LUNAR SURFACE PROFILE

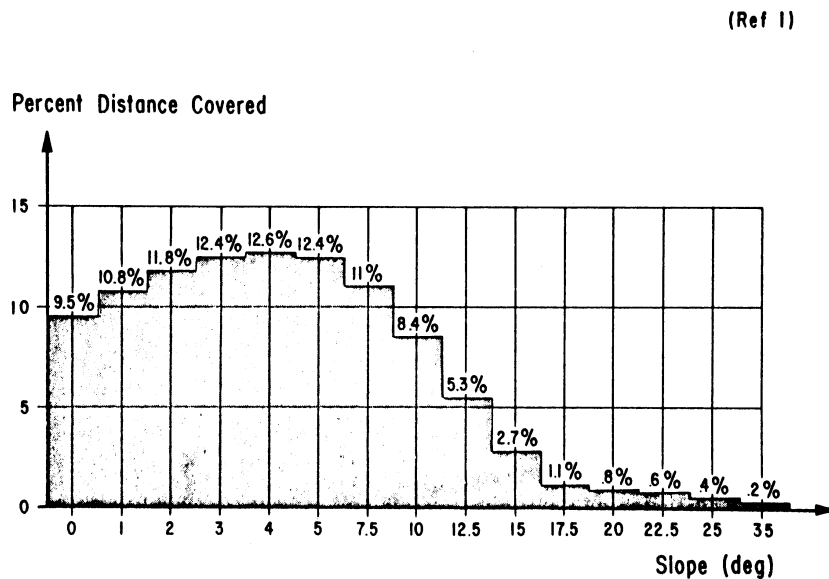


FIG. 2. UPLAND LUNAR SURFACE PROFILE

and percent of total distance of each slope. Slopes were measured in both positive and negative directions. Figure 1 shows the percent total distance for Maria Lunar Surface Profile versus Slope. Figure 2 shows the percent total distance for the Uplands Lunar Surface Profile versus Slope.

C. Soil parameters for mobility

1. Although the slope frequency distribution diagram gives one an indication of the terrain profile, it is still necessary to determine what soil parameters should be used with the model profile. Bekker (1962) in his work with locomotion and soil studies evaluated soils in terms of a series of constants. These constants are divided into two categories:

a. Soil strength:

c (cohesion)

ϕ (friction)

b. Soil deformation:

K_{ϕ} (friction modulus of deformation)

K_c (cohesive modulus of deformation)

n (exponent of sinkage)

K (slip coefficient)

2. Values for these constants have been determined for various types of terrestrial soils and values have been postulated for lunar soils based on the terrestrial laboratory data. Bekker (1962) indicates that the lunar soil, in the absence of an atmosphere and the absence of water, will probably not consist of the saturated plastic clay types, but will probably be similar to sand, gravel, or dry mineral powder. Many other investigators of the lunar surface and its characteristics also postulate (based on thermal, photometric, and radar data) that the soils will probably consist of gravel, sand, lava, pumice, or even fine powder. If the lunar soils are of the granular type, they will probably not exhibit the cohesive forces which result from moisture present between the grains. Laboratory data (Wong and Kern, 1963) have indicated that the modulus of cohesion (K_c) is equal to zero for both pumice and quartz sand in atmosphere and in vacuum. The soil properties selected for the ELMS model were $c = 0$, $K_c = 0$, and $\phi = 32^\circ$, typical values for a cohesionless dry sand type of soil. Laboratory data (Bekker, 1960) indicate that the value of n (exponent of sinkage) for terrestrial soils ranges from a minimum of 0.5 for loose, minimum soils to a maximum of 1.25 for hard-packed high strength soils. These experimental data also imply that the value of K_{ϕ} (friction modulus of deformation) ranges from a minimum of 0.1 for a fine pumice or a fluffy, dust type soil to a maximum of six for a hard, dry-packed sand. In selecting these constants for the ELMS, the values for n and K_{ϕ} for each slope were selected such that the small slope material would have values of $n = 0.5$ and $K_{\phi} = 0.5$, respectively, increasing to values of $n = 1.25$ and $K_{\phi} = 6$ for slopes of 25° . Slopes larger than 25° were considered hard surfaces. Tables 1 and 2 illustrate the ELMS Maria and Uplands models. A sample problem is presented in the appendix.

D. Slippage factors for mobility

In addition to the values of c , K_c , K_{ϕ} , n , and ϕ , as illustrated in Tables 1 and 2, in terms of mobility one must consider some additional parameters. These parameters are the slippage factors K_1 and K_2 . The slippage factors K_1 and K_2 as proposed by Bekker and other expressions as defined by Janosi and Hanamoto are the result of the interactions of the particular soil and wheel combinations. Terrestrial data have indicated that K_1 values range from 0.3 for average type soils to approximately 1.0 for the brittle or coherent soils while K_2 values range from 1.0 for the brittle or coherent soils to approximately 3.0 for loose dry sands. The values for K_1 and K_2 for relatively smooth wheels, as selected for the ELMS, were $K_1 = 0.2$ and $K_2 = 1.25$. Thus by a careful selection of a certain set of c , K_c , K_{ϕ} , n , ϕ , K_1 , and K_2 it is possible to establish a model which represents a "worse case" moon surface from the standpoint of determining mobility performance estimates.

E. Energy required for mobility

Through the use of a computer program, developed to determine mobility energy requirements and using the ELMS (slope, soil, and slippage) data, the energy requirements for a vehicle traversing a smooth surface can be calculated. The energy, as determined, did not include that energy required to negotiate obstacles on that surface.

TABLE 1

MARIA SURFACE MODEL AND SOIL CONSTANTS

<u>*Slope Angle</u> <u>(Degrees)</u>	<u>Percent of Total</u> <u>Distance Covered</u>	<u>Soil Constants**</u>
0°	11.0	$K\phi = .5$ $n = .5$ (loose, fluffy, dust)
1°	22.5	
2°	24.5	
3°	16.0	
4°	10.0	
5°	7.5	$K\phi = 1.0$ $n = .75$
7.5°	3.0	
10°	1.8	$K\phi = 3.0$ $n = 1.0$ (loose, dry, sand)
12.5°	1.2	
15°	1.0	
17.5°	.5	
20°	.5	
25°	.3	$K\phi = 6.0$ $n = 1.25$ (hard, compacted, sand)
30°	.2	
		hard surface

* Distribution of positive and negative slopes is 50-50, i.e., +2° slopes cover 12.25% of total distance.

** $c = 0$
 $K_c = 0$
 $\phi = 32^\circ$

(Ref 1)

TABLE 2

UPLANDS SURFACE MODEL AND SOIL CONSTANTS

<u>*Slope Angle</u> <u>(Degrees)</u>	<u>Percent of Total</u> <u>Distance Covered</u>	<u>Soil Constants**</u>
0°	9.5	$K\phi = .5$ $n = .5$ (loose, fluffy, dust)
1°	10.8	
2°	11.8	
3°	12.4	
4°	12.6	
5°	12.4	$K\phi = 1.0$ $n = .75$
7.5°	11.0	
10°	8.4	$K\phi = 3.0$ $n = 1.0$ (loose, dry, sand)
12.5°	5.3	
15°	2.7	
17.5°	1.1	
20.0°	.8	
22.5°	.6	$K\phi = 6.0$ $n = 1.25$ (hard, packed sand)
25.0°	.4	
35°	.2	hard surface

* Distribution of positive and negative slopes is 50-50.

** $c = 0$
 $K_c = 0$
 $\phi = 32^\circ$

(Ref 1)

Development of Engineering Lunar Model Obstacles (ELMO)

A. Discussion

During the development of ELMS, it was realized that, depending upon the mechanism which produced the lunar features, the surface could be littered with many obstacles of indeterminate size and distribution. The obstacles could be present in great numbers and various sizes, if the surface features were produced by either meteoroid impact or volcanic phenomena.

1. Impact obstacles

Impact features on the earth such as the Meteor Crater, Arizona, discussed in detail by E. Shoemaker (1963), show debris consisting of unsorted angular fragments ranging from micron size to great blocks 30 meters across. Cratering data at Sudan Crater (Roberts, 1964) have shown that craters produced in alluvium by a nuclear device produced a large number of secondary craters in the immediate vicinity (2 to 5 crater radii) of the primary crater. In the area of the primary and secondary craters there were large amounts of debris ranging from fine grains and pebbles to blocky material of at least one meter in size. Thus many obstacles may be encountered, if the lunar features were produced by impact.

2. Volcanic obstacles

If the moon's features were formed by volcanic activity, then large calderas, ash and lava flows, pressure ridges, splatter cones, and other volcanic features will be present, as described by Green (1962). The lava flows will probably consist of a highly vesicular type material and the surface will be extremely rough; however, if large ash flows are present, the roughness will be somewhat subdued. In any event, the volcanic terrain produced by the lesser gravity and vacuum conditions will be difficult to negotiate.

Based on the various terrestrial analogues which have been produced either by meteoroid impact or volcanic phenomena, the designer can postulate what size obstacles and their distribution that he might expect his lunar roving vehicle to encounter. Since in the early phase of ELMS there was no way to determine the expected obstacle size and distribution, a performance reserve of 20 percent was considered adequate for obstacle mobility requirements in addition to the performance requirements as determined by ELMS. Such an estimate is sufficient for preliminary design studies, but these estimates must be more firmly established, if the design is to be more realistic design for exploration.

B. Assumptions and guidelines

Since no analytical technique could be found to describe the microprofile of the lunar surface and to be used for computing the required energy for mobility performance, a synthetic technique, Engineering Lunar Model Obstacles (ELMO) (Olivier and Valentine, 1965) was conceived. The basic assumptions for ELMO were as follows:

1. The reference plane is horizontal, thus calculated energy values do not include the energy required to ascend a given slope upon which the obstacles are dispersed.
2. No shift in vehicle mass is considered due to center of gravity height.
3. The vehicle moves in only two dimensions, only wheels on one side were considered.
4. All wheels are considered rigid.
5. Wheel slip, drive train energy losses, and other inefficiencies are not considered.
6. Wheel spacing is assumed constant.
7. Dynamic effects of the moving vehicle are not considered.
8. Only positive changes in potential energy are considered.

(Ref 19)

Obstacle Size = 50 cm	Obstacle Spacing = 20 cm
Vehicle Mass = 3000 kg	No. of Axles = 2
Wheel Diameter = 200 cm	Drive Train Efficiency = 0.6
Energy Required for Mobility (ELMS) 0.30 $\frac{\text{kw} \cdot \text{hr}}{\text{km}}$	
Equal Mass Distribution	

Percent of Mobility Energy for Obstacles

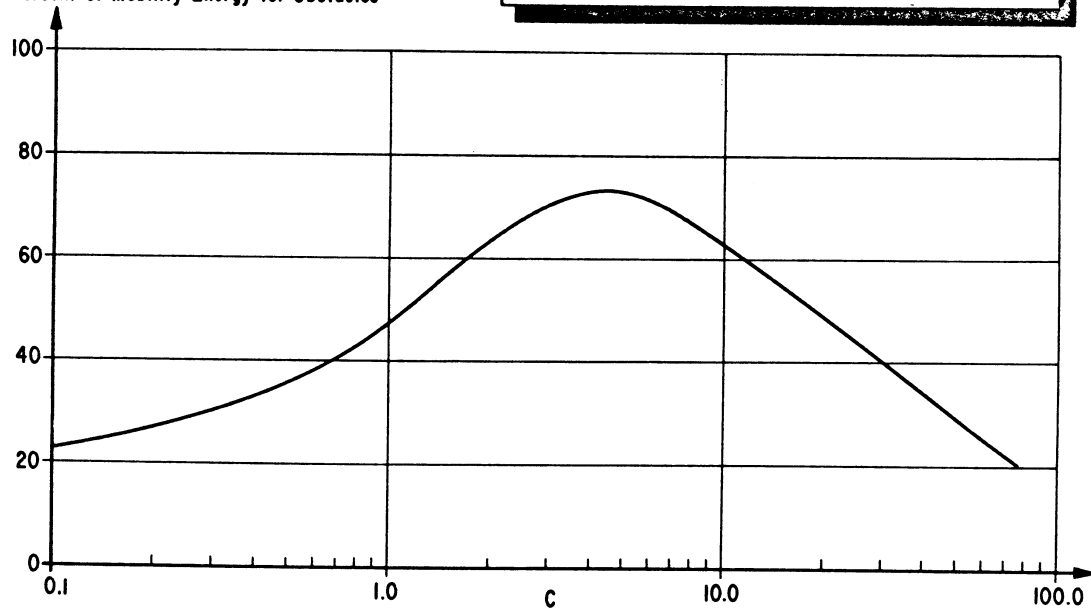


FIG. 3. PERCENT OF MOBILITY ENERGY FOR OBSTACLE NEGOTIATION VERSUS C

ELMO uses two parameters, terrain definition spacing and terrain elevation to describe surface roughness. Terrain definition spacing can be either random or a specified constant value. Terrain elevation is chosen randomly according to a particular distribution function. Thus the surface profile produced by this technique yields a series of discrete points. In this technique the term "obstacles" refers to a terrain feature with an elevation of less than two and one-half times the vehicle wheel diameter.

C. Discussion of obstacle distribution equation

ELMO uses a constant spacing of the obstacles with a random obstacle height. Obstacle height is chosen by a random process whereby a maximum height, Y_{\max} , is specified and the obstacle heights are varied from zero to Y_{\max} based on the arbitrarily chosen distribution exponent.

The equation used to describe the obstacle distribution is:

$$Y = Y_{\max} (RN)^c$$

Where RN, a Random Number which varies from zero to one and has a rectangular distribution function, c is the obstacle size distribution exponent, and Y is the obstacle height that the wheel is traversing. Using this equation and moving the wheel over these obstacles the change in potential energy referenced to the initial starting point can be determined.

D. Energy required for mobility

Since there was so little known about the lunar surface roughness, prior to Ranger VII, VIII, and IX, ELMO provided a technique for generating parametric data for analysis and these data were used to generate energy profiles based on assumed lunar obstacle sizes and spacing. Parametric data generated by ELMO (Fig. 3) indicated that if the obstacles were 50 cm high and were spaced at 20 cm intervals, then when $c = 80$, a performance reserve of at least 20 percent above that determined by ELMS must be included for negotiation of this obstacle distribution. If one assumes the lunar surface obstacles and their distribution have a value of $c = 40$, then the energy required increases to 35 percent (Fig. 3). Thus ELMO has demonstrated that the prior estimate of 20 percent for energy allowed obstacle performance reserve was low and that the value of energy for obstacle negotiation can be of such magnitude as to require its inclusion in any mobility analysis.

Conclusions and Recommendations

Throughout the lunar mobility studies, we have been faced with the problem, "What's the moon's surface really like?" We have attempted by ELMS and ELMO to define a surface and its obstacle distribution through the use of available data. ELMS and ELMO are techniques to help solve a problem, but like all techniques they need to be improved and modified to establish their validity. Based on the author's unpublished interpretation of Ranger VII photographic data, the lunar surface features in the Maria appear to be distinctly random in distribution and that the microstructure profile appears to directly resemble the macrostructure profile. Microstructure roughness, as developed from photometric analysis (Shoemaker, 1965) of the last P3 Ranger VII camera data, indicated a terrain much smoother than anticipated. Since Surveyor is to soft land on the lunar surface, the landing dynamics experiment and the additional photographic data should help to clarify the surface roughness problem. Based on the Ranger VII data, ELMS appear to be a conservative model. ELMO is strictly a synthetic model, and should be studied further to see if it can really define a terrain and its roughness. Other techniques such as the use of spectral analysis and statistical terrain classification techniques (Kozin and others, 1963; Wood and Snell, 1960) have been developed and used to describe terrain and its roughness. Recently a technique called Bi-Parameter Universal Random Surface (BURS) (Schloss) has been proposed to define terrain through the use of surface curvature or second derivative. Although several techniques have been developed and used for mobility criteria, there is still a tremendous amount of work which needs to be done to better define both the terrestrial and planetary terrain surfaces and their roughness characteristics.

APPENDIX

The soft soil mobility of an off-the-road land roving vehicle is determined by many vehicle and soil parameters such as number of wheels or tracks, shape and size of ground contact area, center of gravity location, soil characteristics, vehicle speed, and so forth. The following simplified analysis will be used to illustrate how some of the soil constants as postulated in ELMS can be used in a soft soil mobility analysis. A vehicle which uses tracks for mobility will be selected for analysis.

Statement of the Problem

A lunar roving vehicle weighing 2,328 pounds on the lunar surface is equipped with tracks for mobility. The vehicle tracks, in contact with the surface, have a width of 12 inches and a length of 97 inches. Each track supports a vehicle load of 1164 pounds. The centerline of the tracks are 12 ft apart and there is no elastic deformation of the track. The soil model will be the ELMS loose fluffy dust soil ($K_\phi = .5$, $n = .5$, $K_c = 0$, $c = 0$, and $\phi = 32^\circ$) and the vehicle will operate on level terrain and slippage effects between soil and tracks will be neglected.

To Be Determined

- A. The maximum tractive effort available from the soil.
- B. The sinkage of the vehicle in the soil.
- C. The total resistance (R_t) created by the soil and the vehicle during motion.
- D. The Draw Bar Pull (DP) available to do external work.
- E. The horsepower (HP) required to drive the vehicle at 5 miles/hour over a loose, fluffy dust, level terrain assuming a power transfer efficiency of 80 percent (the drive motor to the track).

Solution

A. To determine the maximum tractive effort (H_{max}) produced by the soil we use the Bekker equation (Bekker, 1960b) for a tracked vehicle while recognizing that it neglects the effect of slippage between the tracks and the soil:

$$H_{max} = Ac + W_t \tan \phi$$

since $c = 0$ from the ELMS model, the equation becomes

$$H_{max} = W_t \tan \phi$$

where ϕ is the angle of internal friction and W_t is the total weight of the vehicle, using $W_t = 2,328$ lbs and $\phi = 32^\circ$ from the ELMS model, then

$$H_{max} = 1455 \text{ lbs.}$$

Thus in frictional soils ($c = 0$) the tractive effort depends only on the vehicle weight and the angle of internal friction and not the contact area.

Since the tracked vehicle as stated in the problem has a large track contact length with respect to the width, the effect of the slippage constants K_1 and K_2 can be neglected in this simplified analysis. However, if a comparison must be made of the track versus the wheel from an overall mobility standpoint (various soils, obstacles, and so forth) then these constants must be considered in the mobility analysis.

B. The depth of sinkage (Z) can be determined using the Bekker equation (Bekker, 1962) for the sinkage of a track or a high deflection elastic wheel in soils:

$$Z = \left[\frac{p}{\frac{K_c}{b} + K_\phi} \right]^{1/n}$$

where

$$p = \frac{W_t}{2bl} = \frac{2,328}{(2)(12)(97)} = 1.0 \text{ lb/in}^2$$

since $K_c = 0$ from the ELMS model, the equation reduces to

$$Z = \left[\frac{P}{K_\phi} \right]^{1/n}$$

using $P = 1.0 \text{ lbs/in}^2$, $n = 0.5$, and $K_\phi = 0.5$ then the sinkage/track

$$Z = 4 \text{ inches sinkage}$$

The vehicle track will sink into the soil four inches before it will exert a bearing pressure of 1.0 lb/in^2 .

C. The total resistance (R_t) to motion created by the soil and the vehicle during its motion is due to the soil compaction and the internal resistance due to friction in the bearings, links, and so forth of the track.

1. The rolling resistance due to compaction of the soil can be determined by using the Bekker equation (Olivier and Crambit, 1963):

$$R = \frac{b [P]^{n+1}}{(n+1) \frac{K_c}{b} + K_\phi} \frac{1}{n}$$

where

b = width of the bearing surface per contact area.

Since $K_c = 0$ from the ELMS model, the equation becomes

$$R = \frac{b [P]^{n+1}}{(n+1) [K_\phi]^{1/n}}$$

using $b = 12 \text{ inches}$,

$$\begin{aligned} P &= 1.0 \text{ lbs/in}^2, \\ K_\phi &= 0.5, \text{ and} \\ n &= 0.5 \end{aligned}$$

then

$$R = 32 \text{ lbs/track}$$

The motion resistance due to both tracks is equal to 64 pounds.

2. The internal resistance (R_i) due to the friction in bearings, links, and so forth, of the track can be determined as follows:

$$R_i = fW_t$$

where

f = coefficient of internal friction, approximately 0.04 for a small tracked vehicle,

using

$$W = 2,328 \text{ lbs and } f = 0.04$$

then

$$R_i = 93.12 \text{ lbs. for both tracks.}$$

Thus the total resistance (R_t) is

$$R_t = R_i + R$$

or

$$R_t = 93.12 + 64 = 157.12 \text{ lbs.}$$

D. The draw bar pull (DP) of the vehicle available to do external work (slope climbing, acceleration, towing equipment, and so forth) can be determined as follows:

$$DP = H_{\max} - R$$

where H_{\max} is equal to 1455 pounds, and R is equal to 64 pounds, as previously determined, then

$$DP = 1391 \text{ pounds.}$$

E. The horsepower (HP) required to drive the vehicle at 5 mph over a loose, fluffy dust, level terrain can be determined as follows:

$$HP = \frac{(R_t)(V)}{(550)(E)}$$

$$HP = \frac{(\text{Total Resistance})(\text{Velocity})}{(\text{Drive motor to track efficiency})(550 \text{ ft-lbs/sec-hp})}$$

using

$$R_t = 157.12 \text{ lbs.}$$

$$V = 7.30 \text{ ft/sec (5 mph), and a drive motor to tracks efficiency of 80 percent,}$$

then

$$HP = 2.6 \text{ hp.}$$

This analysis demonstrated how the ELMS soil constants can be used to determine some of the capabilities of a vehicle. In a complete mobility analysis, many other parameters must be determined before the vehicle mobility capabilities can be established.

References

- Bekker, M. G., 1960a, Off-the-road locomotion: University of Michigan Press, Ann Arbor, Mich.
- _____, 1960b, Theory of land locomotion, University of Michigan Press, Ann Arbor, Mich.
- _____, 1962, Mechanics of locomotion and lunar surface vehicle concepts, TM 62-217, October.
- Bensko, J., Cortez, J. L., Fields, S.A., and Weathers, H., 1963, Lunar surface conditions, MTP-M-63-1, March 15, 1963.
- Gold, T., 1963, Structure of the lunar surface: Cornell University Center for Radiophysics and Space Research, CRS Report 156.
- Green, J., 1962, Geosciences applied to lunar exploration: The Moon, Z. Kopal and Z. Mikhailov, eds., Academic Press, Chap. III, p. 169-205.
- Halajian, J. D., 1962, The case for a cohesive lunar surface model: Grumman ADP Report 04-04-642, June 1962.
- Hapke, B., and Van Horn, H., 1963, Photometric studies of complex surfaces with applications to the moon: Cornell Univ. Center for Radiophysics and Space Studies, CRS Report 139.
- Janosi, Z., and Hanamoto, B., The analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils, Land Locomotion Laboratory: USA O.T.A.C.
- Kopal, Z., and Mikhailov, 1962, Physical studies of the lunar surface: The Moon, Academic Press, p. 371-471.
- Kozin, F., Cota, L. J., and Bogdanoff, J. L., 1963, Statistical studies of stable ground roughness: AOTAC Report 8391, November 1963.
- McCracker, C. W., and Dubin, M., 1963, Dust bombardment on the lunar surface: NASA TN D-2100, February 1963.
- Mason, R., McCombs, W., and Cramblit, D., 1964, Engineering lunar model surface (ELMS), TR-83-D, September 4, 1964.
- Olivier, J., and Cramblit, D., 1963, Mobility on the lunar surface: MTP-M-63-1, March 15, 1963.
- Olivier, J., and Valentine, R., 1965, Engineering lunar model obstacles (ELMO), KSC TR-145-D, March 8, 1965.
- Rogers, J., and Vaughan, O. H., 1964, Lunar environment and interpretation of the surface of the moon and its atmosphere: NASA TM X-53124, September 3, 1964.
- Roberts, W. A., 1964, Notes on the importance of shock crater lips to lunar exploration: Icarus, Vol. 3, p. 344.
- Ryan, J. A., 1963, Lunar miscellany: Douglas Report SM-43544, April 1963.
- Schloss, M., Quantifying terrain roughness on lunar and planetary surfaces: AIAA Paper No. 65-389.
- Sharnov, V.V., 1962, The nature of the lunar surface: The Moon, Univ. Chicago Press, Chap. IX.
- Shoemaker, E., 1963, Impact mechanics at Meteor Crater, Arizona: The Solar System, Vol. IV, The Moon, Meteorites and Comets, Univ. Chicago Press, Chap. XI, p. 301-336.
- Shoemaker, E. M., 1965, Part II Experimenter's analysis and interpretations: JPL TR 32-700, p. 127-133.

- Troitskii, V. S., Nature and physical state of the surface layer of the moon: *Soviet Astronomy*, vol. 6, no. 1, July and August 1962.
- Wong, R. E., Kern, C., 1963, Test program for determining soil constants in vacuum: Ref. NASw 642, September 1963.
- Wood, W. S., and Snell, J. B., 1960, A quantitative system for classifying landforms: U.S. Army, Quartermaster Research and Engineering Center, Natick, Mass., Tech. Rept. EP-124.

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COMPARATIVE STUDY OF LUNAR AND MARTIAN CRUSTS

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ABSTRACT

Morphological features of Martian craters are described and compared with lunar craters. Craters in Martian deserts are abundant but not so large and their walls are leveled by erosion, while larger ruined craters are found in Mare Sirenum.

These characteristics suggest that Martian deserts are more silicic corresponding to the lunar terra, and Martian maria are more basic corresponding to lunar ocean basins (maria). Compared to lunar maria, Mare Sirenum resembles irregular maria more than typical circular maria. Existence of craters on Mars as well as on the moon suggests that craters are one of the characteristic features of original crusts of terrestrial type planets, and that they result from degassing and convective processes.

Canals are interpreted as tectonic lines, which are developed by the mutual interaction with the atmospheric circulation, namely, the well-known migration of water vapor.

Introduction

For earth-bound observers, surface markings on Mars are visible with the resolving power of 100 – 200 km, according to the condition at each opposition. With this severe limitation, longitude and latitude of reference points were measured and maps were prepared by many observers. Our resolving powers were too poor to see fine details on the surface, for example to detect surface relief directly; hence the study of Martian crust was beyond our access.

Thanks to the recent successful flight of the U.S. Mariner IV Mars rocket, details of the Martian surface were revealed for the first time with estimated resolution limit of 2 km. The camera started operation above Propontis-Azania in the northern hemisphere, moved across the equatorial region and Amazonis, to Mare Sirenum in the southern hemisphere, and farther south to Phaethontis where it met the evening terminator. Thus, Mariner IV secured detailed photographs of both deserts and maria, and, in the region east of Trivium Charontis, it crossed the canals, Erebus and Orcus.

The dimension of the photographic frame is about 250 km square, so the photographs reveal topographic features never seen before by earth-bound observers. Craters on the moon are well known and easily visible even with small telescopes, but craters of the same dimensions on Mars escaped detection by terrestrial observers. The most brilliant discovery of Mariner IV was that the Martian surface is scattered with craters similar to those on the moon.

Latitude and longitude of Trivium Charontis and Mare Sirenum

The position of the center of each photograph was published by the Jet Propulsion Laboratory, and the orientation of each photographic frame was shown on their key map. The exact position of each photograph is of essential importance for interpretation. The JPL key map is a copy of the Lowell-Slipper map (Slipher, 1962). Comparing this map with others, such as Antoniadi-Ebisawa (Ebisawa, 1960) and Camishel-de Mottoni (Dollfus, 1963), we find some differences in positions of main surface markings. However, we shall limit our attention here to the track of the Mariner camera.

On Slipper's map the center of Trivium Charontis is put at latitude 12° N., while on other maps it is 20° N. In the southern hemisphere, the whole Mare Sirenum is closer to the equator compared with the others. For example, the latitude of the northwestern tip of Mare Sirenum is given as 15° S. by Slipper, while it is put at about 20° S. by others. The northeastern end of Mare Sirenum and the northern tip of Gorgonum Sinus are 26° and 21° S. respectively on the Slipper map, while they are 30° and 28° S. on other maps.

These differences are critical for the interpretation of Mariner photographs: For example,

according to the JPL key map, Mariner photo no. 8 is located inside Mare Sirenum, while it is in the southeastern corner of the Zephyria desert when referred to other maps. From photo no. 10 to no. 12, the camera sweeps along Atlantis according to the Slipher map, while it remains in Mare Sirenum on other maps.

Another critical difference is concerned with photos nos. 2 and 3. According to the Slipher map, canals Erebus and Orcus cross the frames of nos. 2 and 3 in their southern parts, while by the other maps the canals cross the northern part of each frame.

Determination of longitude and latitude of surface markings is a very difficult task, and it is always affected by large errors. As we have no other reliable data at present, and partly because the Ebisawa and de Mottoni maps include secular changes of markings in position and form in recent years, we shall adopt the latter in this paper for the interpretation of Mariner photographs.

Figure 1 is the orthogonal projection of Mars centered at longitude 180° and latitude 0° . The position of each marking is referred to Ebisawa-Antoniadi, and the darkness of surface markings from Pro-pontis to Amazonis is at the same season as the Mariner observation. They (the markings? - ed.) are a synthesis based on our observations at the Kwasan Observatory in recent years. Numbered points are referred to the centers of frames of Mariner photographs.

Morphological features of deserted areas

Mariner photo no. 7 may well be a typical aspect of a deserted area. It is an eastern part of Zephyria, well off Mare Sirenum. This area is crossed by the canal Tartarus. However, Tartarus is not a prominent canal. At least, this canal is not continuous, but fragmental, and rather may be considered

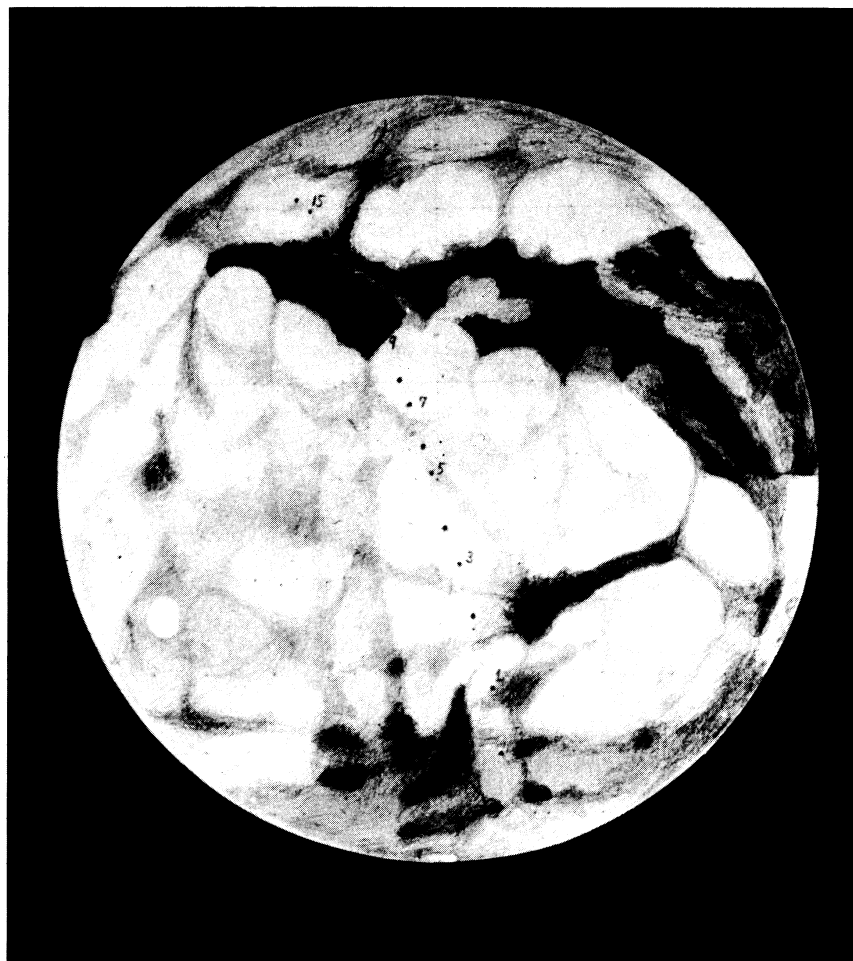


Figure 1. Map of Mars.

as an assembly of irregular small patches. The author observed the area bounded by Tartarus and Titan turned shadowy when, in the northern summer, a dark wave proceeded from Propontis across the equator to this region. Except for that season, this area appears orange in color as in other deserted lands.

The Mariner photograph reveals that this area is jam packed with craters as in lunar terra. Average crater dimension in this area is estimated as 20 to 30 km. However, many of the craters are leveled down, probably by wind erosion, and are barely visible as gentle relief above the desert surface.

Numbers 4 and 6 present another view of deserts. The sun is high above these regions (zenith angle of the sun is 14° , 19° , and 22° for nos. 4, 5, and 6 respectively, and 29° for no. 7). Taking into account the shortness of shadows, these desert areas may be considered to be covered with eroded craters as in no. 7. Or, if the surfaces of the deserts were really flat, ancient craters might have been eroded away in these areas. In any case, such is the unique landscape of Martian deserts. On the moon, no definite erosion effects are observable.

Comparing Mars craters with those of the moon, another point of difference is the depths of the floors of some craters. In the upper left part of no. 7 (viewed with data block at bottom) we see a crater with a diameter of 27 km. The northern part (left side) of the crater wall casts a sharp shadow on the floor. From the length of the shadow it is estimated that the floor is about 5.5 km in depth. A crater pair at the center of no. 8, whose diameters are 34 km (northern) and 40 km (southern), also have deep floors. Both have a depth of about 6.8 km. Comparing these figures with average lunar craters, we know that some Mars craters have deeper floors.

One more point of difference, rarely seen on the moon, is an extensive outer slope of some Martian craters. The pair of craters in no. 8 is an example. Their outer slopes extend about 11 km before they merge into the surrounding level of the desert. Another example of extended outer slope is seen at the center left of no. 7. The diameter of the crater is about 21 km, and the northward extension of the outer slope is about 9 km.

We cannot evaluate the angle of slope directly, because the crater floor may not be level with the surrounding desert. However, well developed outer walls suggest that these objects are not like lunar calderas, but are more like incipient strato volcanoes. Different morphology may be due to difference in crustal thickness at the time of crater formation.

Search for canals

The Mariner photo no. 2 covers the southern part of the boundary region between Azania desert and Phlegra. This area may be crossed by the canal Erebus. Number 3 shows the northwestern end of Mesogaea. This is the region crossed by the canal Orcus. According to observations from the earth, these two canals are diffuse and not uniform in width. They are visible only at limited season: In the northern summer, when the moisture from the pole proceeds equatorwards through Propontis, Phlegra and diffuse canal Titan II become very dark, and Azania appears as an isolated island. At this period, observation of permanent markings including canals is very difficult. As the season advances, darkness of these areas fades out gradually and complex patterns appear. However, these areas are covered almost always with cloud masses which emerge over Propontis and are drifted westwards over Elysium. At the end of the northern summer, these regions enter the autumnal dry season, and canals and other dark markings fade out. At the time of Mariner observation, these regions were already in the dry season and only faint evening mist was observed every day. Thus, the meteorological condition was not favorable for canal observation. In addition, the zenith angle of the sun was small at the time of Mariner photography, so that shadows were not long enough to show details of surface relief.

In spite of this, Mariner photos nos. 2 and 3 reveal a unique feature not seen in other desert areas, such as in nos. 4 to 8. In these two pictures, we see a train of irregular markings running from the upper left corner to the center of the bottom side. In no. 2, near the center of the frame, we see a shallow oval depression, whose north-south dimension is about 104 km. The western part of the wall is very low or absent, and it gradually turns into a very dark streak. In no. 2, we see a very complicated train of grabens and septa.

Both pictures reveal tectonic lines at the place where so-called canals are expected. The area covered by each Mariner photograph is limited to 300 km square or so. Therefore, we are not sure whether the extension of these tectonic lines coincides in length with the observed canals. However, Mariner photographs suggest that the nature of canals is tectonic; in some they are a train of craters, and in another, a bundle of clefts and grabens.

However, this does not mean that all tectonic lines observed are canals. The development of canals depends partly upon the particular meteorological condition in the Martian world, namely, the seasonal migration of vapor from pole to pole and the associated erosion pattern. We shall return to this problem in due course.

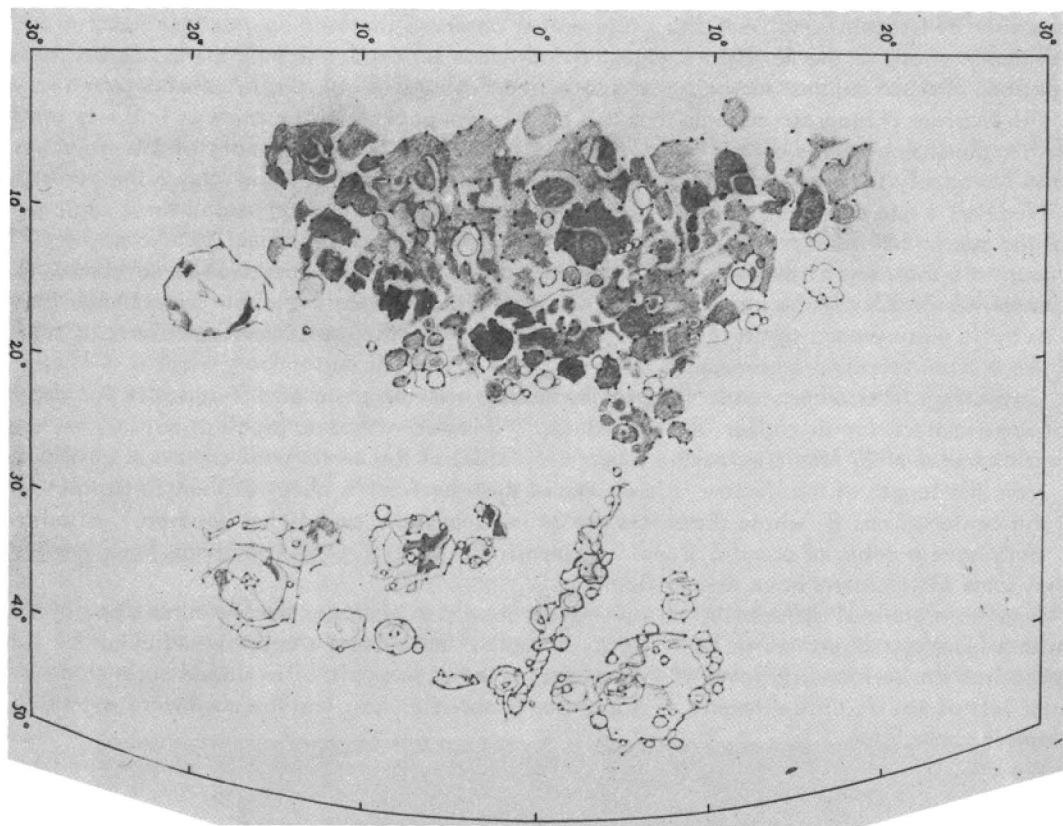


Figure 2. Mare Australis.

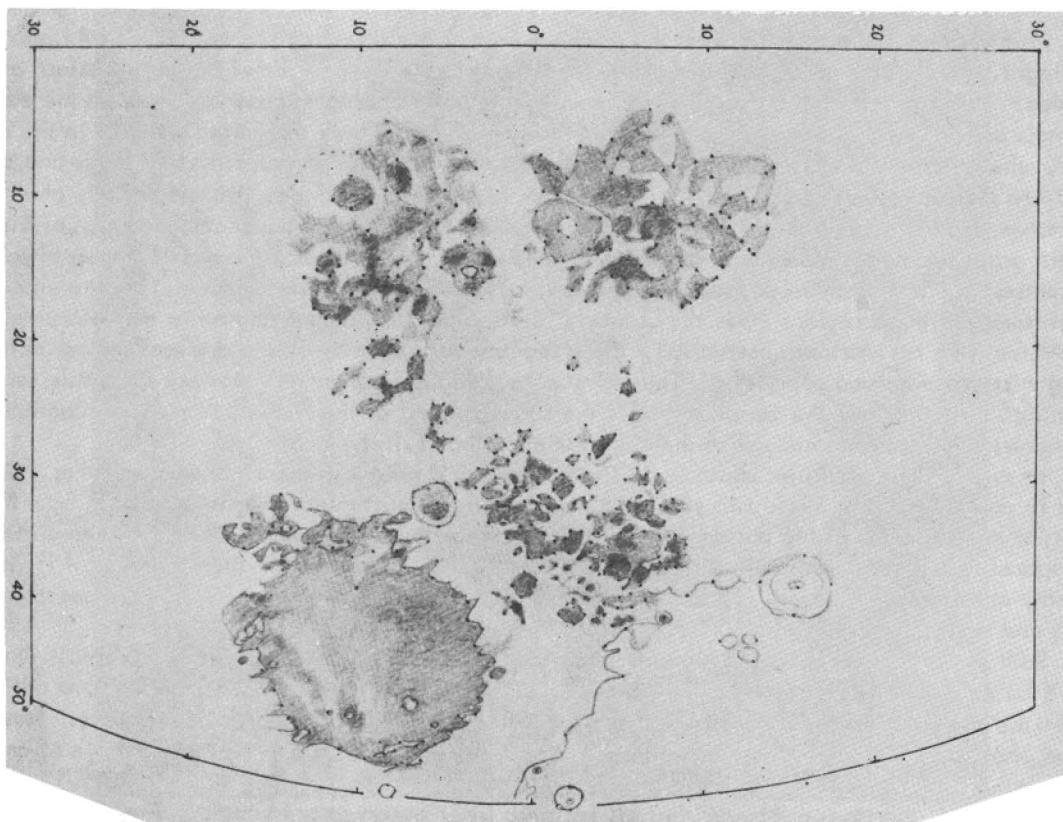


Figure 3. Mare Smythii, Mare Marginis, and Mare Crisium.

Craters in Martian maria

As in deserted areas, craters were found in Mare Sirenum. However, compared with those in deserts, we find larger craters in this mare: For example, in the Mariner photo no. 10, parts of two large craters are seen in the upper and right-hand sides of the frame. Their diameters are more than 108 km and 103 km respectively. The giant crater in no. 11 is 163 km in diameter, and the next large crater in the upper left corner is 65 km in diameter.

The wall of the giant crater is half destroyed. Similarly, on the moon we find larger craters in maria; many of them are so-called "ruined" craters, namely parts of their walls are absent. On the other hand, the crater walls in Martian deserts are perfect, but leveled down by erosion. Also, in lunar terra, ruined craters are not common.

In Martian deserts, we observed craters with well developed outer slopes, while in maria, we found no similar craters. The comparisons enumerated here suggest that both lunar and Martian maria are basic, and terra are more acidic.

The detailed topography of the giant craters in no. 11 is very interesting. There are many parasitic craterlets and clefts along the northern part of the outer wall. Inside the floor, we see a group of small domes about 3.5 km in diameter. Their distribution is related to clefts and tectonic lines in these regions. Possible erosion patterns may be pointed out in this photograph as follows: The soft appearance of clefts is contrasted to the roughness of corresponding lunar clefts. Along the eastern part of the wall, the crater floor near the inner wall is bright. Provided the crater wall is made of bright silicic rocks, this pattern suggests a talus along the steep inner wall.

The Mariner photographs showed that Mare Sirenum is scattered with many craters. On the moon, we have two kinds of maria, circular and irregular. Circular maria, such as Mare Crisium and Mare Serenitatis, have dark, flat basins and the craters are few in number. There seems to be no similarity between Mare Sirenum and this type of lunar maria. Mare Sirenum may be compared with irregular lunar maria such as Mare Australis, Mare Smythii, and Mare Marginis. Figure 2 is the orthogonal view of a part of Mare Australis visible from our earth, reduced by calculation from the observation at Kwasan Observatory when the libration condition was favorable. The upper straight line is the limb of the moon at the time of observation, and in the lower half of the map we see Rheita Valley and Janssen. Figure 3 shows Mare Smythii, Mare Marginis and circular Mare Crisium. The floor of Mare Australis is neither flat nor uniformly dark. Rather, it may be considered as a close aggregation of craters with dark floors, many of them ruined craters.

The so-called ruined craters are characteristic of lunar maria. Their origin is commonly ascribed to melting by a later lava flow. However, lava-flow patterns surrounding ruined walls are seldom seen. Another hypothesis supposes a thin silicic film floating over a basic layer. It is broken in pieces, and fragments are drifted aside by convections in the original maria (Miyamoto, 1960). In this interpretation, the ruined walls remain unfinished from the beginning.

We are not sure whether other maria in Mars show similar features. However, no maria in Mars are circular: Solis Lacus and Aurorae Sinus are nearly circular, but irregular patches in them are observable even from the earth. The basin of Mare Acidalius is very dark and uniform, but its outer boundary is not circular. The only exception is Syrtis Major. It is nearly circular and has a dark and uniform basin. Thus, lunar analogy suggests that most Martian maria are scattered with large and small ruined craters as in Mare Sirenum.

Other markings

Photographs with green filter show, in general, higher contrast than those with orange filter, especially in desert areas. An example is no. 13 with orange filter and no. 14 with green filter in Phaethontis. This effect was expected, because the surfaces of deserts are orange in color and the constituent rocks of crater walls are gray.

Besides light and shade accompanying surface relief, there are complicated fine mottles apparently not related to local relief. The most remarkable patches are seen in the upper left corner of no. 7. Along the tectonic lines in no. 3, high contrast in relief and existence of many small patches are remarkable in view of the small zenith angle of the sun. It is noteworthy also, if we consider that sand storms would ultimately smooth out such tiny patches during geological time. Can they be attributed to repeated lavafloes and ash falls new and old, as we see in the Oregon lava fields, or are they some form of life that can withstand sand storms? Evidence from the Mariner photographs is not definitive about this point, but they suggest possibilities both of magmatism and plant life. The study of the environment

needed for life on the Martian surface, and theoretical considerations about the Martian mantle, do not conflict with our speculation: Putting aside cosmogonical considerations, accumulation of heat under the crust liberated from radioactive substances is sufficient to supply ample energy for magmatism. The moon is about one-half the diameter of Mars, but calculation shows that the internal temperature is raised to the melting point of rocks (MacDonald, 1963).

Topography and atmospheric circulation

Lunar terra are covered with the network of tectonic lines. The same may be true for Mars. However, provided canals are tectonic lines, they are not so numerous as in the moon. In this respect, the effect of erosion should be considered. On Mars, diurnal and seasonal temperature variation is very large, and the atmosphere contains small amounts of water vapor. We also know that winds blow there, through cloud observations. Therefore, we expect disintegration and decomposition of surface rocks and wind erosion effects. The type of erosion on Mars may be similar to that of arid regions on our earth, but it will go on at a much slower tempo. A characteristic feature of wind deflation is that it does not always smooth out the relief. On the contrary, under certain conditions, it acts in the opposite direction. On the Martian surface, the role of wind erosion is not always to bury maria and grabens in deserts; low-lying land and valleys are less arid and hence decompose more rapidly. The products of such decomposition are scattered by sand storms in wide areas. Thus giant craters may possibly develop into oases or depressions, and some tectonic lines may develop into canals, being favored by erosion, when they are properly located along the course of vapor migration (Miyamoto, 1957). Of course, most of the original tectonic lines might have vanished from the surface, buried under the sands of deserts. We know that local topographical circulation is organized into a systematic general circulation in the Martian world, and at the same time, surface relief has been shaped to form certain definitive vapor courses during its long history.

Concluding Remarks

The discovery of craters on the Martian surface is the most important achievement of the Mariner Mars flight. Morphology of craters in maria and in deserts shows that Martian deserts and maria correspond to lunar and terrestrial terra and maria. Since the crusts of the earth, moon, and Mars are composed of two layers, terra and maria, it seems very probable that magmatic differentiation took place at the time of crustal formation at the surface of these three planets. Craters may be one of the characteristic features due to degassing processes and later magmatism. This leads to the conclusion that we had ample reason to expect craters on Mars (Miyamoto, 1961). However, before the Mariner flight, we had no means of estimating quantitatively the degree of erosion in the Martian world, so that we could not predict with certainty whether the oldest craters would survive above the sand level of deserts. Mariner observation proved that craters survive there in spite of erosion.

On the moon, without erosion, the oldest craters are well preserved. On our earth, the oldest craters have long since been destroyed but, owing to mighty orogeny, new ones are created. These newcomers bear somewhat different features because a thick crust now exists and because the composition of magma is modified by inclusions, degassing, and other processes.

Our conclusion is that the nature of the crust of earth, moon, and Mars is the same and that their apparent differences are due to variance in the degree of differentiation, erosion, and orogeny. With respect to these processes, Martian crust is intermediate between earth and moon.

Acknowledgments

The author would like to extend grateful thanks to the University of Oregon and the New York Academy of Sciences, sponsors, and to the organization staffs of the Lunar Geological Field Conference in Oregon, whose kind invitation, financial support, and nice offices enabled him to study and enjoy the basaltic lava fields in Oregon. His deep thanks are also due to Dr. James Q. Gant, General Secretary of the International Lunar Society. Dr. Gant's personal aid enabled the author to visit the United States. His constant encouragement and invaluable discussion concerning lunar geology are acknowledged gratefully. The author is also indebted to Mr. R. W. Carder of ACIC, St. Louis, whose kind and quick supply of Mariner photographs was the essential source of the present article.

References

- Dollfus, A., 1963, Visual and photographic studies of planets at the Pic du Midi: G. P. Kuiper and B. M. Middlehurst, ed., *The Solar System*, Vol. III, Chap. 15.
- Ebisawa, S., 1960, *Inst. Astrophys. and Kwasan Obs. Univ. Kyoto, Contr.*, No. 89. Cf. also: E.M. Antoniadi, *La Planète Mars*, 1930.
- MacDonald, G. J. F., 1963, *The interiors of the planets: Origin of the Solar System*, R. Jastrow and A. G. W. Cameron, eds.
- Miyamoto, S., 1960, *Planet: Space Sci.*, Vol. 2, 256 = *Inst. Astrophys. and Kwasan Obs., Univ. Kyoto, Contr. No. 90*.
- Miyamoto, S., 1957-1963, *Inst. Astrophys. and Kwasan Obs., Univ. Kyoto, Contr. Nos. 71, 87, 105, and 124*.
- Miyamoto, S., 1961, *The strolling astronomer*, Vol. 15, no. 1-2, 23. = *Inst. Astrophys. and Kwasan Obs., Univ. Kyoto, Contr. No. 106*.
- Slipher, E. C., 1962, *Mars*. Cf. also, G. de Vaucouleurs, *Precision Mapping of Mars. La Physique des Planètes, XI Colloq. Intern. d'Astrophys., Liège, 1962, Chap. 34*.

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ABSTRACTS

CLASSIFICATION OF THE THERMAL ANOMALIES ON THE TOTALLY ECLIPSED MOON

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Surveys of the disk of the moon in the far infrared during the December 19, 1964 eclipse have revealed thermal anomalies on the major ray craters (as expected from previous work), several hundred hot spots, and extended enhancements in seas and portions of seas. The anomalies have been identified primarily with craters, but a significant number are associated with white areas, rilles, and other features. The interpretation of these thermal features will be discussed.

* * * * *

INTERPRETATION OF POSSIBLE VOLCANIC FEATURES SHOWN BY RANGER PHOTOGRAPHY

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Four possible interpretations of the small craters shown by Ranger photographs include (1) primary meteoroid impact, (2) maar cratering, (3) secondary impact from large meteoroid impact ejecta, and (4) secondary impact from volcanic bombs thrown from large volcanic centers. The range of volcanic debris from a volcanic center on the moon is estimated at 250 kilometers accepting Gorshkov's (1959) upper limit of 600 meters/sec for an initial velocity. In spite of the much higher initial velocities for meteoroid impact debris, the range for 90 percent of meteoroid ejecta, as estimated by Gault and Shoemaker (1963), is only 30 kilometers because of the high ejecta angles.

The crater distribution on the floor and rim of the lunar crater Delambre suggests an incoming angle of some 5 degrees for projectiles if this origin is favored for the Delambre floor and rim craters. This low angle together with the circularity of these Delambrean craterlets suggests that ballistic shadowing of the interior wall of Delambre by material thrown from Theophilus is practically impossible and that either a closer directed volcanic blast is responsible for the crater pattern observed or that the floor and rim craters of Delambre are internal in origin. Details of the floor of Alphonsus including ash-like patterns around craters both on and off rilles, subparallelism of rilles with crater walls, and extension of the median ridge to the interior rille of the adjacent Ptolemaeus suggest a volcanic origin for this crater. No Imbrium ejecta blanket appears evident; it probably does not exist either in Alphonsus or anywhere on the moon. The fused crater alignments, flow patterns, and grabens shown in Ranger 7, 8, and 9 may have numerous terrestrial analogs in Iceland, Kyushu, Kamchatka, the Galapagos, Canary and Hawaiian Islands, the Azores, Guatemala, Java, and western United States. The associations of most of the features seen by Ranger, exclusive of the very small craters (which have at least four plausible explanations), indicate that volcanism is the dominant surface-shaping mechanism for the lunar surface.

* * * * *

ON THE ORIGIN OF LUNAR CRATERS

N. Boneff

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The Lunar Committee of the International Academy of Astronautics (Paris)* aims to organize on the moon an international laboratory, naturally after the imminent conquest of our satellite. We have recently proposed in this committee as one of the fundamental problems for this laboratory, the problem of the origin of lunar craters.

Until the conquest of the moon there are only two ways of elucidating this fundamental problem: (1) direct studies of terrestrial craters (the present conference; N. A. Kozyrev - Kamtschatka), (2) studies based on the theory of probabilities (continuous probabilities).

It is this last way that we have followed during the last thirty years (1936). We have studied, more specifically, the distribution of craters on the lunar surface by the method of "probabilities of causes" the importance of which for these applications has been pointed out by H. Poincaré. By the help of these "probabilities of causes," we have studied in the past some regions of the lunar surface suspected of being the field of intense volcanic activity. The result of this study considerably favors the volcanic hypothesis or its variance (there is a question of craters of visible dimensions).

The observations of lunar volcanic eruptions of N. A. Kozyrev in the "suspect" regions seems to confirm our deductions based on the theory of probabilities. This is an indication that the way we have chosen is a good one.

* The author is a member of this committee.

* * * * *

THE NATURE AND ORIGIN OF CENTRAL UPLIFTS IN IMPACT CRATERS

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Large terrestrial craters attributed to meteorite impact have a complex structure involving central uplifts and peripheral depressions. Observations at Canadian craters show that uplifts are basement rocks with characteristic deformation structures most strongly developed at their top. Many shock-induced structures observed microscopically from these rocks would not survive annealing for even a few hours at normal volcanic temperatures.

A theory of formation of central uplifts based on the Canadian and other terrestrial craters is presented, involving yielding of the crater floor under gravity in response to release of hydrostatic pressure.

* * * * *

PHOTOMETRIC INVESTIGATIONS OF SIMULATED LUNAR SURFACES*

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Grumman Aircraft Engineering Corporation, Long Island, N. Y.

An experimental attempt is made to infer certain physical properties of the lunar surface from terrestrial specimens that reproduce the lunation curves of the moon at all viewing angles. An improved photometer capable of examining areas about an order of magnitude larger than previously examined is used to measure the brightness-phase relationship of a number of granular, vesicular and dendritic specimens.

Good agreement with the lunar photometric curves at 0°, 30° and 60° longitudes is obtained with fine powders, coarse volcanic ash particles, furnace slags, scoriae, sea corals, meteorites, etc. The results confirm previous findings with regard to the low albedo and high porosity of the lunar surface but go beyond them in indicating that it is no longer necessary to postulate a layer or veneer of fine dust on the moon in order to account for the lunar photometric data since "macrorough," cohesive specimens satisfy this data equally well when they are sufficiently dark and porous and are examined by a "large" photometer. The experiments also indicate that the material composition, consistency and actual scale of roughness of the lunar surface are not properties that can be inferred from the photometry of the surface alone but could be inferred if this portion of the lunar data is correlated with other portions measured at longer wavelengths.

* Performed under NASA Contract No. NAS 9-3182.

* * * * *

CAPABILITIES OF A PRESSURE-SUITED SUBJECT TO PERFORM LUNAR SCIENTIFIC TASKS

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Tests to evaluate the capability of a pressure-suited subject to perform lunar scientific tasks were conducted on three types of volcanic surfaces in the Bend, Oregon area. These surfaces were a basaltic lava, an obsidian lava, and a loose pumice ash fall. The test program was designed to ascertain that the scientific activities described by the Apollo Mission Planning Task Force in the design reference mission (Grumman Aircraft report No. LED 540-12) are within the capabilities of a subject wearing a pressure suit. These activities included active geological and geophysical experiments and passive geophysical experiments.

Although there are still improvements that need to be made in the Apollo space suit, the results of this program indicate that an astronaut in a space suit is capable of performing all of the scientific tasks presently planned for the Apollo mission.

* * * * *

POSSIBLE CONNECTIONS BETWEEN RHYOLITE ASH-FLOW PLATEAUS,
RING-DIKE COMPLEXES, AND LUNAR CRATERS: A PROGRESS REPORT *

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At the New York Academy of Sciences Conference on Geological Problems in Lunar Research in May 1964 the author suggested that the Tertiary calc-alkalic Mogollon Plateau volcanic province of southwestern New Mexico represents (1) the surface expression of a ring-dike complex, and (2) a terrestrial analog of an endogenic lunar crater 75 miles in diameter. Since then, a year of field work has resulted in much new evidence.

The ring-dike complex, consisting of several discontinuous belts of arcuate rhyolite plug domes, has so far been traced around the southern two-thirds of the circumference of the Mogollon Plateau. Newly documented points of similarity to a lunar crater include (1) a basalt-covered "inner plain," (2) a "central peak" consisting of a relatively young complex volcano that rises about 3,000 feet above the "crater floor" but stands 1,600 feet below the highest part of the "crater rim," (3) indications of at least two "secondary craters" superimposed on the main "crater" (probable calderas $1\frac{1}{2}$ and 3 miles in diameter), (4) inner "crater walls" once probably terraced by a combination of faulting and depositional processes (but later terraced by fluvial processes), and (5) active thermal springs south of the "central peak" (a possible cause of "obscurations" under lunar conditions).

The interpretation of some lunar craters as the surface expressions of ring-dike complexes has been strengthened by Ranger IX photographs, which show the walls of Alphonsus to be composed of discontinuous, elongated, rounded, and relatively smooth segments. Individual segments resemble the rhyolite plug domes that surround the relatively undissected Pleistocene Valles (Jemez) caldera of north-central New Mexico, interpreted as the near-surface parts of a ring-dike by Smith, Bailey, and Ross in 1961. Details visible on the Ranger photographs are all compatible with the interpretation offered here.

* Research supported by NASA grant NGR-32-004-011.

* * * * *

RESOLUTIONS PROPOSED
AT THE
OREGON LUNAR GEOLOGY FIELD CONFERENCE, 1965

By Nicholas M. Short

* * * * *

RESOLUTION NO. 1

WHEREAS considerable disagreement exists as to the volcanic or impact origin of many individual lunar and planetary surface features, and

WHEREAS also recognizing that a similar diversity of views exists as to the internal versus extraterrestrial origin of certain features of similar form and size on Earth, even where extensive studies have been carried out, and

WHEREAS in the foreseeable future on-site planetary geological studies and sample returns will be limited in scope, so that evaluation of the origin of surface features on the Moon and planets will of necessity be based on few data,

THEREFORE, be it resolved that we, the participants of the Oregon Lunar Geology Field Conference of 1965, suggest that an important direction of research during the prelunar and planetary landing periods should be the intensive study of available geological, geochemical, and geophysical methods of the three-dimensional characteristics of selected terrestrial structures including, 1) at least one whose meteorite impact origin is generally accepted and, 2) one or more structures formed by volcanic explosion, caldera subsidence or other volcano-tectonic processes. Upon completion of thorough studies, these structures might then serve as prototypes or reference models for each morphological and/or genetic class.

BE IT FURTHER RESOLVED that we, the participants in this Conference, wish to go on record as encouraging development of any program designed to establish one or more terrestrial craters as prototypes of their respective classes. We strongly recommend that such craters be explored fully by suitable geological means including, wherever possible, deep and shallow core drilling, in-hole logging, surface geophysical surveying and geochemical methods. We further express our desire to cooperate with any responsible organization or agency that proposes a specific program to carry out such detailed investigations of impact and volcanic craters.

RESOLUTION NO. 2

WHEREAS a clearer understanding of terrestrial crater morphology and genesis can be expected to contribute to our knowledge of interpretation of lunar and planetary craters, and

WHEREAS also it has been noted that terrestrial craters of volcanic origin are well displayed and available for study in the Pacific Northwest, as for example Hole in the Ground in the vicinity of Bend, Oregon, and

WHEREAS both the interest in and scientific capability for investigation of these craters and related phenomena were manifested by the delegation of conferees to the Oregon Lunar Geology Conference of 1965,

WHEREFORE, be it resolved that we herewith encourage and exhort appropriate officials of the State of Oregon to seek financial and other support for programs of investigation of these craters and related phenomena as a contribution to the United States and international space programs and to the State of Oregon's resource inventory.

THE LIST OF SIGNATORIES

Dr. John E. Allen	George Kocher
Dr. E. Azmon	L. Kopecky
W. R. A. Barager	G. A. MacDonald
G. T. Benson	A. R. McBirney
R. E. Brown	G. J. N. McCall
R. P. Bryson	Shotaro Miyamoto
Winifred Cameron (with reservations)	C. Oftedahl
K. L. Currie	J. R. Raymond
M. R. Dence	A. Roberson (by H. Kato)
R. S. Dietz	P. Robinson
Lawrence Dineen	J. R. Rogers
W. E. Elston (Resolution No. 1 only)	L. Ronca
D. E. Folgelson	J. A. Ryan
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