Morphology and origin of lunar craters

Von R. S. Saunders, E. L. Haines, and J. E. Conel, Pasadena*

Summary: The general concensus among lunar geologists is that the majority of lunar craters, up to a few km in diameter, are of impact origin. This conclusion is based on morphologic comparison with terrestrial meteorite craters, consideration of lunar regolith formation by impact, direct observation of the morphology of small and microscopic craters on the lunar surface and experimental impact studies. Most large craters are also interpreted to be of impact origin. Although the morphology of unmodified craters changes somewhat with increasing size, these changes are completely gradational and there is no evidence to suggest that the predominant process of crater formation is different for large craters. However, selected craters of various sizes have been interpreted as volcanic.

Understanding the origin of the multi-ring basins presents greater difficulties. Theoretical treatments such as those of Bjork (1961) and Van Dorn (1969) seem to be the only approach. In such treatments it is necessary to include, in addition to hydrodynamic flow, large plastic deformation and brittle failure of the target material, processes that are known to accompany impact phenomena. Thus complete equations of state are required as well as a detailed microscopic (perhaps statistical) description of imperfections in rock mechanical properties. The required physical parameters and the calculations are clearly formidable.

Analysis of tracking data from Orbiter V has revealed positive graviational anomalies (mascons) over the circular maria (Mulier und Sjogren, 1968). While a number of theories for the origin of the mascons has been proposed (see Kaula, 1969 for a summary), the nature of the anomalous masses remains in doubt as does the mechanism whereby excess mass has been added to specific regions. Resolution of these questions will tell us much about the thermal and structural history of the Moon.

The production of the lunar regolith by impact processes has been studied by Shoemaker et al. (1970). The rate of regolith formation as a function of various parameters such as regolith thickness and energy distribution of incoming particles can be determined. Another parameter yet to be determined is the rate of lateral transport and mixing of surface materials during regolith production.

After the Moon has been studied and mapped in detail, to what extent will our observations apply to other planets? It is necessary to understand well the processes which modify the lunar surface before we can understand Mars, where additional unknown effects resulting from the interaction of atmospheric and subsurface volatiles with the regolith must be considered. Another planetary aspect of lunar crater studies is the extent to which such investigations have influenced terrestrial studies and provided new insights into Earth history. The primitive Earth, like the Moon, must have been repeatedly battered by asteroidal impact. Collisions which produced Imbrium-size basins must have occasionally disrupted the primitive terrestrial crust and surely must have had a profound influence on the Earth's crustal structure.

Acknowledgments

We thank D. B. Nash for helpful suggestions and Elsa Abbott for assistance with the figures. This paper presents the results of one phase of research performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS 7-100 sponsored by the National Aeronautics and Space Administration.

INTRODUCTION

The origin of lunar craters has been debated for many decades. The experiments of Hooke (1665), who made crater forms both by boiling, and dropping objects into, a viscous substance, suggested the framework for the major hypotheses of crater formation — by internal (volcanic) or external (impact) energy sources. Impact craters are of two types: (a) primary craters produced by the impact of material having a velocity exceeding lunar escape velocity, and (b) secondary craters produced by the impact of material ejected during the formation of a primary crater and impacting at less than lunar escape velocity. The volcanic craters with supposed lunar equivalents are those resulting from violent explosive volcanism as a single event (maars), explosive eruptions of tephra and lava (cinder cones) and volcano-tectonic depressions (calderas).

At present it seems clear that the majority of lunar craters were produced by impact but other small features can be found that are very likely the product of volcanism. The most pertinent studies interpret morphological evidence in terms of crater-forming processes while keeping in mind that the original morphology may have been modified since crater formation. Ardent supporters of the impact or the volcanic hypothesis each

*) R. S. Saunders, E. L. Haines and J. E. Conel, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, Cal. 91103, USA

admit that evidence suggests both processes have produced lunar craters. Present knowledge of impact mechanics is more sophisticated than in Wegener's time and the cataloque of well studied terrestrial volcanic and impact features for comparison with lunar forms has been greatly enlarged in comparison to what was known to Wegener. The greatest barrier to understanding of cratering processes at the present time still seems to be scale - for volcanic analogs we are limited to features a few tens of km in size; for impact models, to a few tens of meters in size.

Analysis of returned lunar samples shows that rocks of the mare surfaces are petrologically similar to basalt, an extrusive igneous rock. It is generally held that the mare basalts are a product of differentiation resulting from internal magmatic processes. The energy source to produce the melting is uncertain, but may have been radioactive decay, energy of accretion, or asteroidal impact. The returned lunar samples provide direct evidence for hypervelocity impact on the lunar surface in shock deformed and melted minerals and the many glass lined impact pits on the surfaces of rock fragments. Also, with the knowledge that at least the mare surfaces are composed of volcanic materials, which may be internally produced, there is more justification for the tentative identification of other volcanic features.

We begin this brief review with an outline of the ideas of Wegener, one of the first to compare in detail the morphology of experimentally produced craters with lunar craters. In the second part we discuss in order of increasing size the morphology of lunar craters and, for possible analogs, describe some of the current studies of terrestrial impact and volcanic craters.

SUMMARY OF WEGENER'S INVESTIGATIONS

At the time of Wegener's studies on lunar craters (1920, 1921) there were four principal theories dealing with the origin of these structures, the so-called bubble (Blasenhypothese), tidal (Gezeitenhypothese), volcanic (Vulcanhypothese), and impact (Aufsturzhypothese) hypotheses.

According to the *bubble hypothesis,* lunar craters and circular mountains originate as traces of burst bubbles in viscous magma on the Moon's surface. The hypothesis is criticized by Wegener (1921) on two grounds; (1) craters produced in laboratory experiments with boiling wax, plaster, chalk, etc. only superficially resemble lunar craters, and (2) bubble shapes and sizes are controlled by molecular or surface forces, which can play no essential role in determining the geometry of kilometer size features. Wegener concludes that while it is possible to obtain a range of bubble sizes within certain limits, there could never have been larger bubbles on the Moon's surface than are obtained in these experiments.

It is difficult to recognize how the bubble hypothesis, in the form described by Wegener, is represented in modern thinking on the origin of the Moon's surface features, other than microscopically as in vesiculation in lavas. We may, with Shoemaker (1962), identify it with processes like sudden release or explosion of steam or gas from beneath the lunar surface, or with the maar type of volcanism. Lava blisters (tumuli) have been recognized in terrestrial pahoehoe flows, and such structures, collapsed, may result in crater-like forms. Hawaiian tumuli range from 3 m to more than 20 m in width and up to more than 5 m in height and they are commonly elongate (MacDonald, 1967). Tumuli in Australia are up to 30 m high (Skeats and James, 1937). Presumably, with lower gravity, tumuli on the Moon could be larger provided with the requisite conditions for their formation was ever present on the Moon. Maars or collapsed tumuli can be included with other forms of volcanic activity.

In the *tidal hypothesis,* the Moon is assumed originally to have been molten and to have formed a solid crust. Gravitational attraction of the Earth is supposed to have fractured the crust and raised great tidal waves in the fluid interior which moved beneath the crust with rotation of the Moon. With the passage of each wave, liquid flowed out on the surface building circular ramparts near the fractures; the liquid withdrew with the ebbing of each tide. This process would be repeated with the successive passing of waves. Laboratory experiments by Ebert (1890) to simulate tidal waves using low melting temperature metal alloys actually produced such circular features on a solid metal crust.

Wegener argues that for this mechanism to have operated, the lunar crust must have had complete rigidity, and retained its shape despite the tidal wave beneath it. But the Earth's crust is known to respond to glacial loads. Wegener interpreted this to mean that the Earth's crust is deformable and floating on the interior. Thus, since terrestrial experience must, in his opinion, guide our thinking about the Moon, the lunar crust must also have floated and would have been exposed to the same tidal variations as the interior. Ebert's experiments are inapplicable since such experiments work only in situations where the surface crust adheres to walls of the containers used.

Presently, the tidal hypothesis is not regarded seriously by most lunar geologists. However, Firsoff (1959), adopting in part the hypothesis of Spurr (1949), proposes a combined bubble-tidal mechanism in which the tides, resulting from close approach of the Moon to the Earth, raise huge crustal blisters accompanied by near-surface melting. The domes collapse to create the multi-ring basins. Smaller craters are not described simply as gas bubbles, the case ruled out by Wegener, but as gas-rich magma pushing up lacolithic domes; the gases escape and the domes collapse to produce craters.

Recent attempts have been made to correlate transient lunar phenomena (supposed luminescence or volcanic activity) with tidal action of the Earth on the Moon (Middlehurst, 1967).

According to the *volcanic hypothesis,* lunar craters are volcanoes. Those with central peaks correspond to terrestrial forms which contain a younger cone in the summit crater. Flat, circular lunar plains are compared with the floor of Kilauea and are the result of flooding of existing features with lava flows. E. Suess (1895) imagined the mountain chains partly surrounding the circular maria to be great slag heaps accumulated near the margins of these flows much like glacial moraines. Wegener rejects this interpretation since such enormous deposits are never accumulated by great basalt flows on the Earth, and in any event the ablation necessary for moraine deposition is entirely lacking in this case.

Wegener argues against the volcanic hypothesis by pointing out that the normal terrestrial volcano is a steep conical mountain with a small summit crater (he describes a typical composite volcano) whereas lunar craters are rimmed depressions with floors below the level of the surrounding terrain. The only mechanism known to Wegener to produce a negative volcanic feature was volcanic explosion. However, terrestrial volcano-tectonic depressions and maars also produce negative features. Wegener believed that the fundamental nature of terrestrial volcanism was to produce mountainous topography; negative explosion features would, therefore, be short lived.

Part of Wegener's argument against the volcanic hypothesis is based on comparative sizes of terrestrial volcanic and lunar craters. The largest terrestrial crater known to

Wegener was 24 km (including enlargement by erosion). On the other hand, lunar craters range in size from the limits of visibility up to sizes of several hundred kilometers. From terrestrial experience, Wegener argues that under the volcanic hypothesis, we must suppose the smaller members of this nearly continuous ascending size sequence have a different origin (namely volcanic) than the larger members. Thus if all craters are ascribed to volcanism, we are forced to conclude that volcanic forces on the Moon have behaved entirely differently from those on the Earth.

Finally Wegener points out differences in the distribution and frequency of lunar craters and terrestrial volcanoes. While (according to Franz, 1912) the large maria basins are arranged in a belt inclined approximately 21° to the present lunar equator, the polar regions are covered with a multitude of small craters with younger ones scattered randomly over the older ones, with no recognizable influence of the point of origin of any one by the others. On Earth, on the other hand, volcanic activity is limited to zones of tectonic movement and volcanic craters cover only a minute fraction of the crust.

From study of high resolution photographs of the Moon's surface from Ranger, Surveyor, and Lunar Orbiter spacecraft, virtually all lunar geologists now agree that small volcanic landforms can be identified. A recent pictorial summary of much of the evidence is provided by Mutch (1970). The important features include domes, small dark-halo craters, and certain sets of alined craters, some situated along rilles, as well as lobate flow fronts on the mare surfaces. The recognition of flows leads to the belief that the maria are widely flooded with volcanic material. Petrographic analysis of the Apollo 11 and 12 rocks confirm that the rocks of Mare Tranquillitatis and Oceanus Procellarum are, in the areas sampled, igneous and closely resemble terrestrial basalts or microgabbro (see, for example, Anderson *et al.*, LSPET, 1970).

To support his contention that the *impact hypothesis* satisfactorily explains the majority of lunar craters Wegener (1920 a, b) made a systematic series of experiments on the impact process using powdered cement both for the target material and the impacting mass. Since the craters were produced manually, and with considerably less kinetic energy than hypervelocity impact processes, it was necessary to model actual rock mechanical properties by using very weak, noncohesive material. In an experiment, a spoonful of cement powder was thrown at a smoothed cement powder target. Crater-like depressions with circular rim deposits up to 12 cm in diameter were produced with sufficiently loose target material. Some of Wegener's experimental observations are as follows: (1) Central peaks were produced in experimental craters when the target medium consisted of a loose layer (about 1/10 of the expected crater diameter in thickness) overlying a compact substrate. (2) In general, comparisons of average depth/diameter ratios obtained experimentally (5.6 — 10.3) were less than values measured for lunar craters (7 — 70); but for small craters satisfactory agreement was noted. Comparisons of other measurements such as ratio of depth to rim height and the ratio of crater depth to altitude of the central peak were also good. These numerical results are the principal evidence upon which Wegener bases his case for the impact origin of lunar craters. (3) Using white plaster of Paris as the impacting mass, Wegener found the entire interior of the crater covered with a thin veneer of plaster which was sheared off abruptly at the crest of the rim. It was concluded that the rim had been produced by radial flow with the upper part truncated and thrown outward. (4) By sectioning the target it was found that the central peak consisted of a cone of target material, in place, overlain by a thin veneer of dispersed projectile. The central cone remained undisturbed because it lay on an axis of flow which had radial symmetry and which was everywhere directed outward. The compact substrate remained completely undisturbed. (5) Ray patterns were apparently considered to arise from dispersal of the powdery impacting mass (Wegener, 1921, p. 37), and not from the target material.

The relevance of Wegener's experiments for modelling impact processes on the Moon, and for resulting numerical comparison of dimensions of the features so obtained, is unclear. However, Wegener recognized the purely morphological-empirical nature of the comparisons. We note, in the next section, how his methods and conclusions compare with current ideas. Although Wegener's conclusion that most lunar craters are of impact origin is in agreement with current opinion on the subject, his experiments cannot be considered seriously to model actual mechanical processes associated with hypervelocity impact. The significance of comparisons between experimental craters and large lunar crater forms remains in doubt. Laboratory experiments correctly modelling target mechanical properties, proper impact velocities as well as body forces would, in fact, appear difficult to contrive. Although the craters produced by underground nuclear explosions and by impact are morphologically similar (Shoemaker, 1962), detailed modelling of the impact process even by nuclear explosion has been questioned on theoretical grounds (Bjork, 1961).

Studies of the production of hypervelocity impact craters up to about 10 m diameter (Moore *italics,* 1964 a) suggest that Wegener's choice of a powdered substance as the target material in his experiments was a fortunate one. Bjork (1961) indicates that under hypervelocity impact and for purposes of calculations, the target material can be considered a strengthless fluid since the pressures involved far exceed the yield strength. This situation would appear to apply locally even in small craters. Modelling of a large impact crater in a laboratory experiment requires use of essentially strengthless material.

MODERN MORPHOLOGICAL STUDIES

Modern investigations of crater morphology include: (1) detailed photo-geological studies of lunar craters of all sizes, (2) ground studies of terrestrial craters of impact, explosive, and volcanic origin, (3) attempts to simulate impact crater forms by hypervelocity projectiles in the laboratory and (4) direct numerical solution of the hydrodynamic hypervelocity impact problem. In this section we arrange the discussion of lunar craters according to size, and where the scale and morphology make comparison appropriate, we describe the geometry and formation mechanism of terrestrial craters, natural and man-made. A discussion of the processes which alter crater forms on both short and long time scale is also required to complete the description of crater morphology.

Microcraters

The smallest lunar craters are the tiny pits, sometimes called "zap pits" that were discovered on solid surfaces of returned lunar rocks, glasses and mineral fragments (e. g. LSPET, 1970: Anderson *italics,* 1970). Such craters are characteristically bowl-shaped with a glass lining. The diameters of the glassy bowls range between about 5 μm and a few millimeters (fig. 1). Small pits may occur either on single crystals or may span several crystals, surrounded by a zone of intensely fractured material. Plagioclase appears especially vulnerable to such fracturing. Material surrounding the pit in figure 1 appears partly to have spalled away leaving conchoidal fracture patterns. Pits with diameters on the order of a millimeter more frequently display discontinuous

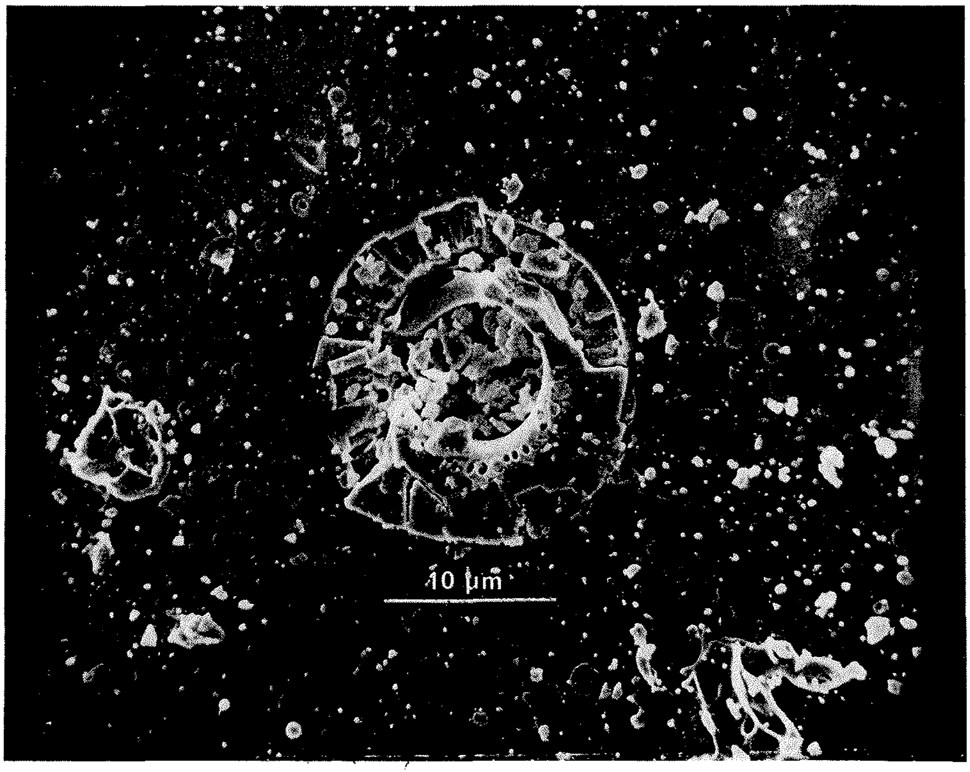

Fig. 1 Micro-crater on glass target. Electron micrograph showing smooth glassy crater 8µm in diameter. Crater bowl is filled with debris produced by impact. Dark, circular features on lower margin of crater probably result from coalescing of ejected glass shortly after impact. Beyond the crater, radial and concentric fractures extend for about 5µm (photograph courtesy of D. Nash and J. Devaney).

bowls, and may contain only discontinuous glassy blobs or droplets set against a background of shattered mineral grains.

It is generally accepted that the so-called "zap pits" are of impact origin and therefore provide microscopic evidence of the micrometeorite erosion process.

Small Craters

Craters in the regolith surface having diameters from a few centimeters to several tens of meters have been extensively studied in Surveyor photographs by Shoemaker and Morris (1968) and in photographs taken by Apollo 11 and 12 astronauts. The Surveyor observations show that most small craters in the diameter range from 10 cm to several meters are cup-shaped with concave floors and subdued convex rims; forms range from shallow, subdued craters to deep pits with sharp, raised rims (fig. 2, 3). Other types include shallow rimless craters and irregular, asymmetric craters.

Most of the craters in this size range have been interpreted (e. g. Shoemaker & Morris, 1968) as impact craters, some resulting from hypervelocity primary impact and some by secondary impact. Green (1970) has argued that some such craters arise from impact of volcanic bombs. Rimless craters have been interpreted to result from drainage of fine

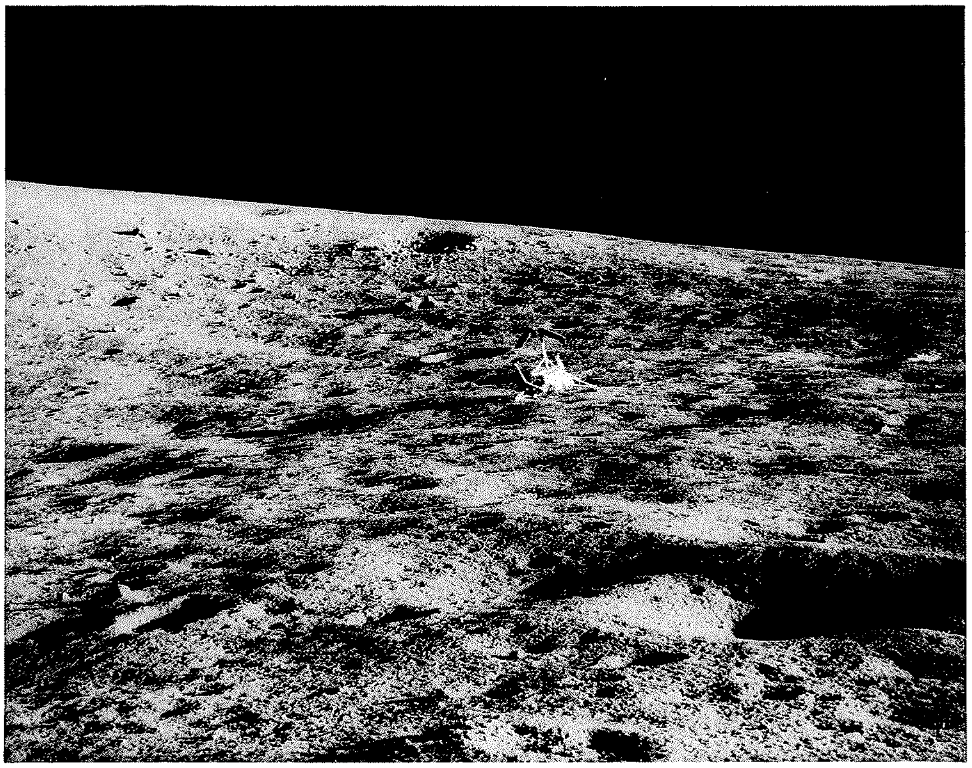

Fig. 2. Small craters on Mare Procellarum. In this picture, taken by Apollo 12 astronauts, a range of small-crater morphologies may be seen. The Surveyor III spacecraft, which landed in April, 1967, is seen in the foreground. The distance between the foot pads is approximately 3.5 m.

surface material into fissures, but some form of erosional modification of ordinary impact feature cannot be ruled out. Irregular craters may be of secondary impact origin (Shoemaker and Morris, 1968).

Experimental impact craters have been produced with morphologies similar to those seen on the Moon (Moore et al, 1964 b) that range in size from a few centimeters up to about 20 cm. Craters up to about 12 m in diameter are produced by missile impacts (Moore et al, 1964 c). Experiments on the impact process are presently limited to craters of this size, produced by projectiles having kinetic energies on the order of 10^{15} ergs or less. For comparison, the energy necessary to create the 1.2 km Meteor Crater in Arizona is estimated to be on the order of 10^{24} ergs (Bjork, 1961).

Experiments on hypervelocity impacts in layered (color coded) media reveal important facets of the deformation accompanying impact (Gault *et al.*, 1968). In noncohesive sand the surface material of the entire crater bowl moves upward and outward; the nearer the material to the surface, the greater the movement toward the rim (fig. 4). Noncohesive layers as deep as 1/2 rim diameter below the original surface are distorted downward when the impact is vertical. Cohesive layers penetrated by impact may display reverse saulting, generally by overthrust near the surface, contributing to the volume of the rim.

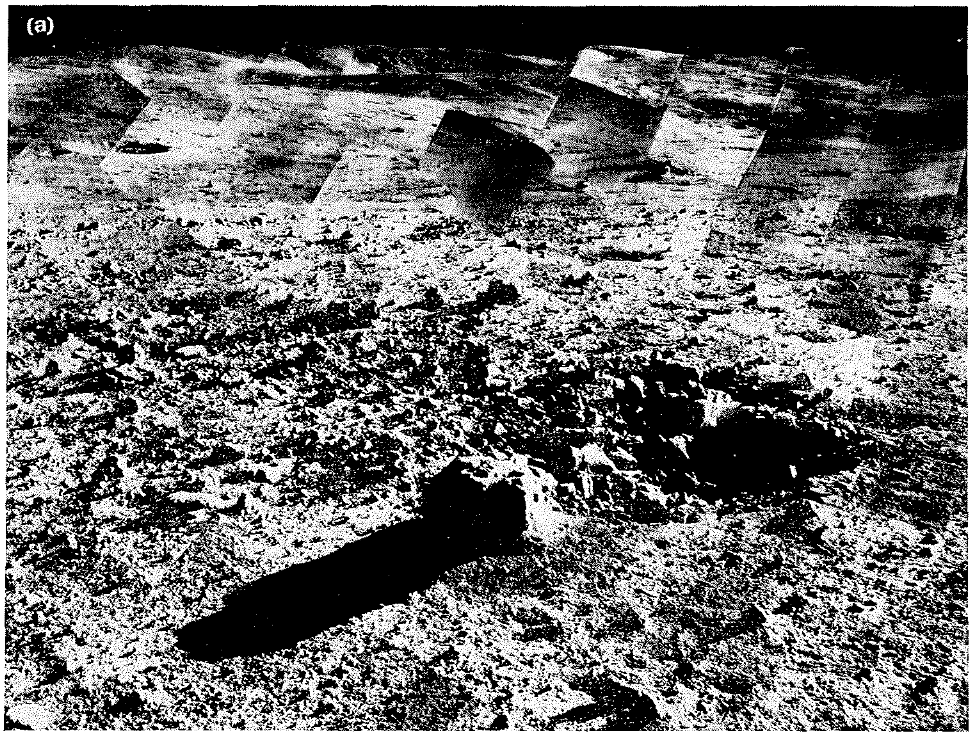

Fig. 3a. Irregular, blocky secondary crater on Tycho rim. This mosaic of Surveyor VII pictures covers a region looking N to NE from the spacecraft. The block-filled crater in the foreground is 3 m in diameter.

Most lunar craters in the size range up to a few tens of meters, whatever their origin, appear to be extensively altered (fig. 2). Most have rounded rims, are pock-marked by later small impacts, and have irregular rather than circular outlines. Such altered craters appear only in loose rubble of the regolith, and are subdued in varying degrees, often grading imperceptibly into the hummocky background which itself may result from extensive modification of an old cratered surface. This characteristic of small craters was reproduced experimentally by Gault (1970) by bombardment of a noncohesive surface with high speed particles having size-frequency distributions necessary to satisfy various scaling relationships. The modifications observed arise primarily from superposition of craters and from blanketing by ejecta from adjacent ones.

Discontinuous deposits near the centers of small craters were reported by Gold (1969) in photographs taken by Apollo 11 astronauts. These were interpreted as thin surficial layers of glass which resulted from solar flash heating that, through focusing action of the crater walls, melted fine surficial material. Alternate interpretations of these features are that they result from (1) impact of partly molten volcanic bombs (Green, 1970) or (2) the glass was shock melted, ejected, and then emplaced as fallback into the crater in which it was produced (Greenwood and Heiken, 1970). (3) H. J. Moore (personal communication) has suggested that such craters may be secondaries and the glass emplaced as a semi-molten plastic projectile. The subdued form of these lunar craters is thought to result from their formation by a low velocity projectile, since they are morphologically similar to secondary craters of this size range associated with the impact of an unarmed missile in water saturated sediments (Moore and Lugn, 1965 [fig. 3b]).

The impact hypothesis satisfactorily accounts for observed features and distribution of craters smaller than a few tens of meters in diameter. There is evidence that the lunar surface is, in general, composed of fragmented material (Shoemaker *et al.*, 1970; Tyler, 1968) and is saturated with craters in this size range (Trask, 1966). This saturation leads to a steady-state distribution of small craters whose distribution is of the form

$$N = AD^B \qquad (1)$$

where N is cumulative number of craters larger than or equal to diameter D, and A and B are empirically determined constants. If N is normalized to 10^6 km^2 and D is in m, A is equal to $10^{10.9}$ (Trask, 1966); at saturation, B is always -2 (Moore, 1964). In fact, the vast majority of craters smaller than a few tens of meters are formed entirely in fragmental regolith. The only terrestrial landforms which might have

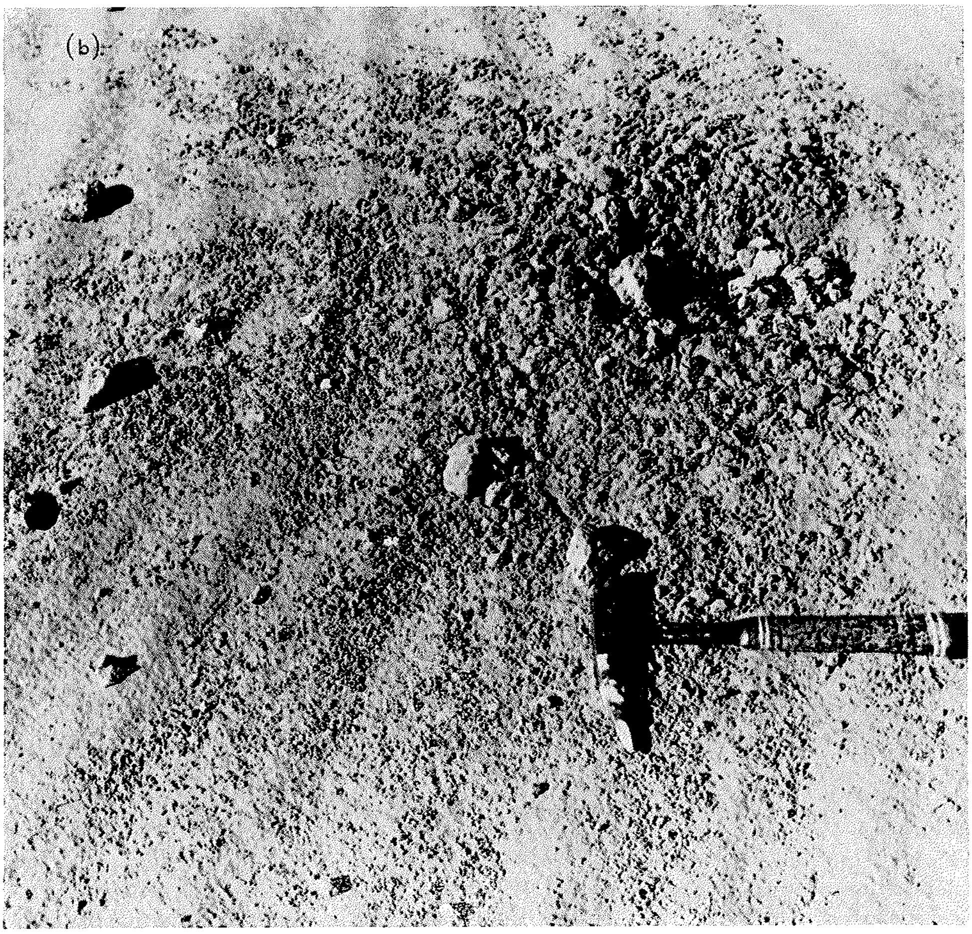

Fig. 3 b Secondary impact crater at White Sands Missile Range. This crater was produced by the impact of water saturated sediment excavated by the impact of an unarmed missile (H. J. Moore, personal communication, photograph courtesy of U. S. Army).

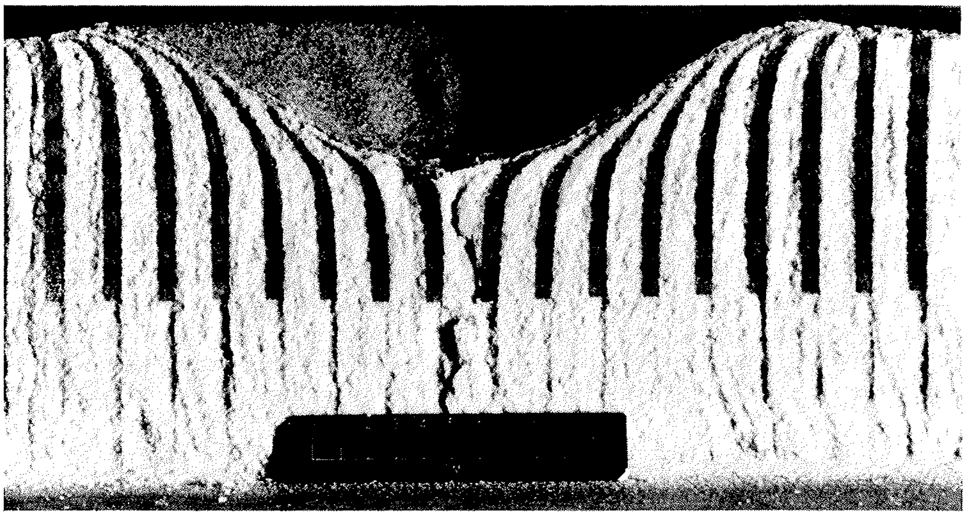

Fig. 4 Subsurface structure of experimental impact crater in sand. The relative distortion of the dyed layers indicates the degree of subsurface movement (V. R. Oberbeck, personal coummunication).

randomly distributed small craters are those associated with gas venting in ash-flow tuffs (acidic rocks). Since the maria appear to be underlain by basalt-like (basic rocks) flows, perhaps intercalated with multiple layers of regolith, the types of features seen on ash-flow tuffs would not be expected.

Craters of Intermediate Size

Craters of intermediate size (a few tens of meters up to 250 m) have been most intensely studied on the maria. These craters exhibit a variety of shapes; where crater depth is great enough to penetrate the lunar regolith and excavate subjacent bedrock, a new, distinctive crater form appears which differs substantially from the smooth basin shapes of smaller craters (Quaide and Oberbeck, 1968). Quaide and Oberbeck have defined four distinct morphologic types of fresh craters on the maria in the diameter range less than 250 m; normal cup-shaped, cup-shaped with central mound, flat bottomed, and concentric ringed (figure 5). Such crater forms can be produced in impact experiments using a noncohesive layer and a solid substrate (Quaide and Oberbeck, 1968). Although scaled down, these experimental forms are analogous to forms of larger lunar craters Normal cup-shaped craters generally have rim diameters 3.8 to 4.2 times greater than the fragmental surface layer. Craters with rim diameters 8 to 10 times the layer thickness form an inner concentric crater with a blocky rim. This inner crater is excavated from the subjacent resistant layer. Craters whose diameters are 4.2 to 8 times the fragmental layer thickness display flat floors with a central mound, similar in structure and morphology to the central mounds Wegener (1921) produced in craters in cement powder underlain by a solid base. Experiments of Oberbeck and Quaide indicate that the diameter distribution of the various morphologic types of fresh craters is determined by the thickness distribution of fragmental layer. Applying these observations to the Moon allows determination of the regolith thickness in a region. In this manner Quaide and Oberbeck (1969) determined median regolith depths and depth distributions in different mare regions. The depths so determined agree with regolith depths derived independently from crater diameter-frequency distributions (Shoemaker *et al.*, 1970).

In the intermediate size range and larger, the probability that some lunar craters are endogenic becomes greater since they may have survived since the volcanic emplacement of the mare flows. Apparently, the major surface volcanic activity ceased with the outpouring of the mare lavas; small associated features have subsequently been obliterated by impact events. Therefore, as crater diameters approach 250 m and larger, endogenic craters, if they exist, might be identified. McCauley (1969) among others has interpreted shallow craters (about 200—500 m) on the floor of Alphonsus (fig. 6) to be of volcanic origin, because smooth dark deposits surrounding these features blanket older craters and cracks in the adjacent terrain.

Large Craters

Unmodified lunar craters with diameters larger than 10 to 20 times the regolith thickness and up to 15 to 20 km in diameter are basin shaped with sharp raised rims. Concentric terraces and flat floors, characteristic of small and intermediate sized craters, are absent. An empirical relationship has been found between the depth of relatively unmodified large craters, measured from rim to bottom of the bowl, and rim diameter (Pike, 1969). The relationship is

$$\text{depth} = 0.155\,(\text{diameter})^{0.95}, \qquad (\text{for diameters} < 20\ \text{km}) \qquad (2)$$

or, roughly, crater depth is one-sixth rim diameter.

Fig. 5. Morphology of small craters on the maria. The crater types seen here are produced by interaction of the forming crater and a solid substrate beneath the regolith. N. Normal bowl-shaped, C. Concentric ringed, M. Central mound, F. Flat-bottomed (after Quaide & Oberbeck, 1969).

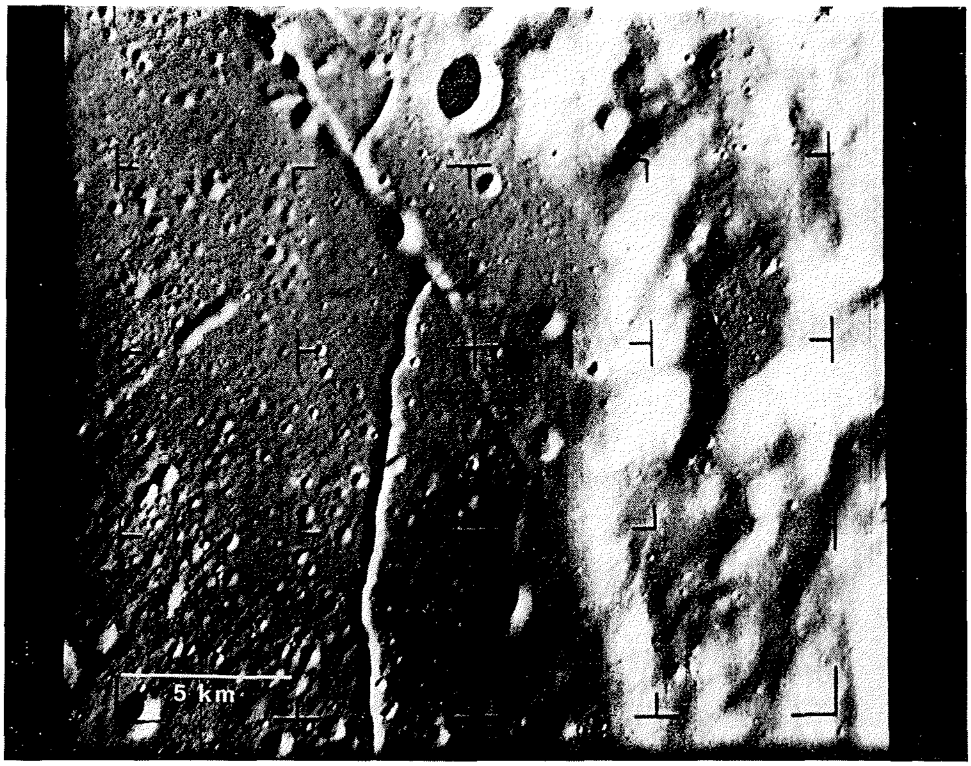

Fig. 6 Dark-halo craters on Alphonsus' floor. These craters are associated with a rille, their rim deposits appear to subdue the subjacent older terrain. They have been interpreted as volcanic. Picture taken by Ranger IX.

Craters smaller than about two kilometers in diameter are apparently modified more rapidly than the larger craters (fig. 7). This may be merely an effect of the scale of the principal modifying processes, *italics,* mantling by ejecta from nearby small craters. and erosion by small particle impacts. Thus examples can be found (Trask, 1969) in which a very subdued "soft-rimmed" crater a few meters in diameter is superposed on the thin ejecta field of a one km bright rayed crater. Modification of craters also results from superposition of younger craters and by mass wasting, *italics,* the slipping or flowing of loose material down slopes, which may produce irregular, sometimes polygonal craters (Pohn and Offield, 1969).

Detailed studies of rim structure in Meteor Crater, Arizona (Shoemaker, 1962) a crater of intermediate to large size in the classification used here, have shown that the stratigraphy of the rim deposits is reversed from that in the undisturbed stratigraphic column beneath; thus the rim material has been overturned, or folded back from the area occupied by the crater, and rim construction is not due simply to radial flow of the target material. Had Wegener's cement targets contained sufficient marker strata, he might have observed this characteristic of the deformation.

Examples of large craters (a few hundred meters up to several kilometers) generally interpreted to be of volcanic origin (Shoemaker, 1962) are features associated with rilles, as in the floor of Alphonsus (Carr, 1969). The occurrence of these craters on the floor of a rille as well as their alinement are taken as indicative of an internal origin

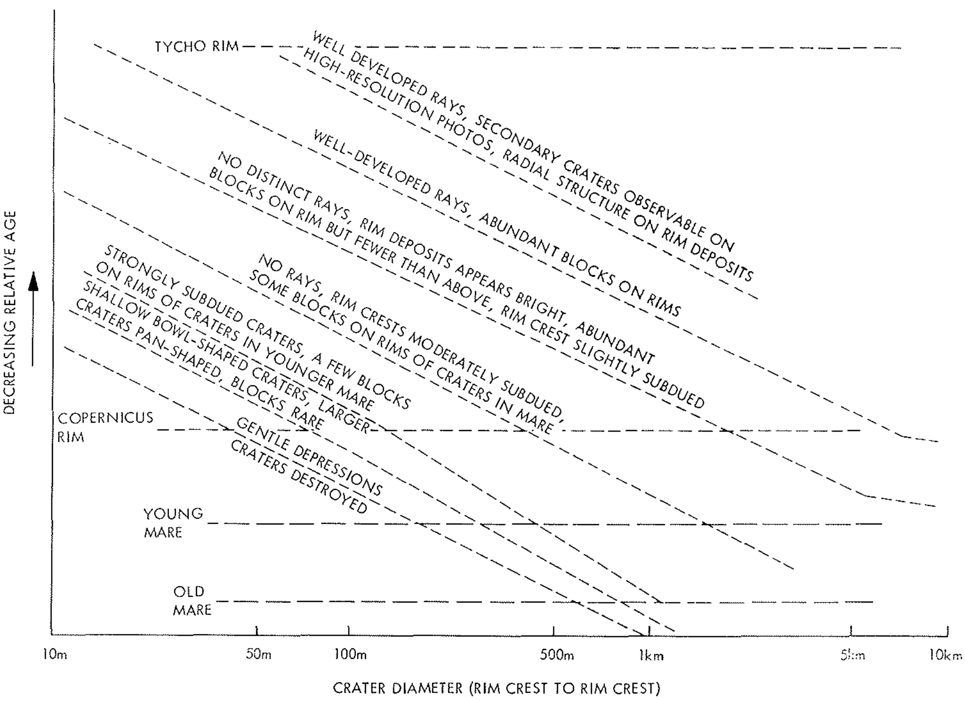

Fig. 7 Relation between diameter, morphologic features, and relative ages of mare craters. Horizontal lines are isochrons showing position of mare material and rim deposits of the craters Tycho and Copernicus. (after Trask, 1969).

(fig. 6). The 10 km crater Hyginus, a feature strongly suggesting collapse, and other smaller alined craters on the floor of the Hyginus Rille have been interpreted as possible volcanic craters (Wilhelms, 1968) analogous to terrestrial calderas. McCauley (1967 a) has described on the floor of the Orientale basin, a 35 km diameter supposed volcanic crater with sharp rim crest and apparently no secondary craters. The rim surface appears to be underlain by a thin layer of material which mantles subjacent features.

Complex Craters

Lunar craters larger than 20 km do not follow the depth-diameter relationship described by Eq. 2, but do not increase proportionally in depth with increasing diameter (Pike, 1969). Fresh large craters display a flat floor which is surrounded by a terraced wall (fig. 8) which appears to result from slumping of the wall under lunar gravity. Lunar Orbiter photographs of these floors show them to be rough and hummocky (fig. 9). Large complex craters may have a single central peak or cluster of peaks. The tops of peaks are distinctly below the rims of the craters in which they occur.

Slump terraces and flat floors are apparent in craters as small as 20 km diameter. In highly modified craters, the terraces eventually disappear. Craters smaller than 20 km diameter seldom develop well-defined terraces or flat floors. These craters, when eroded, however, develop radial erosion channels in the walls. Smaller craters in many places obliterate portions of a larger crater rim, thus giving the larger crater an irregular shape in plan view. Further examples are given by Pohn and Offield (1969).

The polygonality of larger craters may have its origin in the mass wasting resulting in selective terrace formation, or may result from excavation along pre-existing joint surfaces or crustal fractures during crater formation similar to the situation at Meteor Crater, Arizona (Shoemaker, 1962). Most craters in the size range 20 to 40 km, irrespective of apparent age, are not precisely circular. Craters with diameters greater than 40 km tend not to be polygonal even though associated bright rays and secondary craters indicate that they are quite young. However, older craters in this range may be polygonal.

Rays are the most transient of all features associated with impact craters. Rays consist of small secondary and tertiary craters, crushed debris, and fine material spread out radially from the parent crater. Many such span features are seen in the rays of the crater Kepler (fig. 10). The small scale of the depressions, rocks, and particles which constitute the rays make them early victims of mantling and erosion by small impact events. Somewhat less susceptible to small scale erosion are the radial throwout deposits outside the crater rim. These braided hummocky structures are several tens of meters in width, but examples several kilometers wide may be found around the multi-ring basins. Such features persist longer than rays because of their greater bulk. In a similar fashion sharp crater rims are preserved longer than rays irrespective of crater size.

The forms of clumpy rim and ray deposits and other features of positive relief in Wegener's experimental craters (1921, figs. 3, 4) suggest the structures produced were

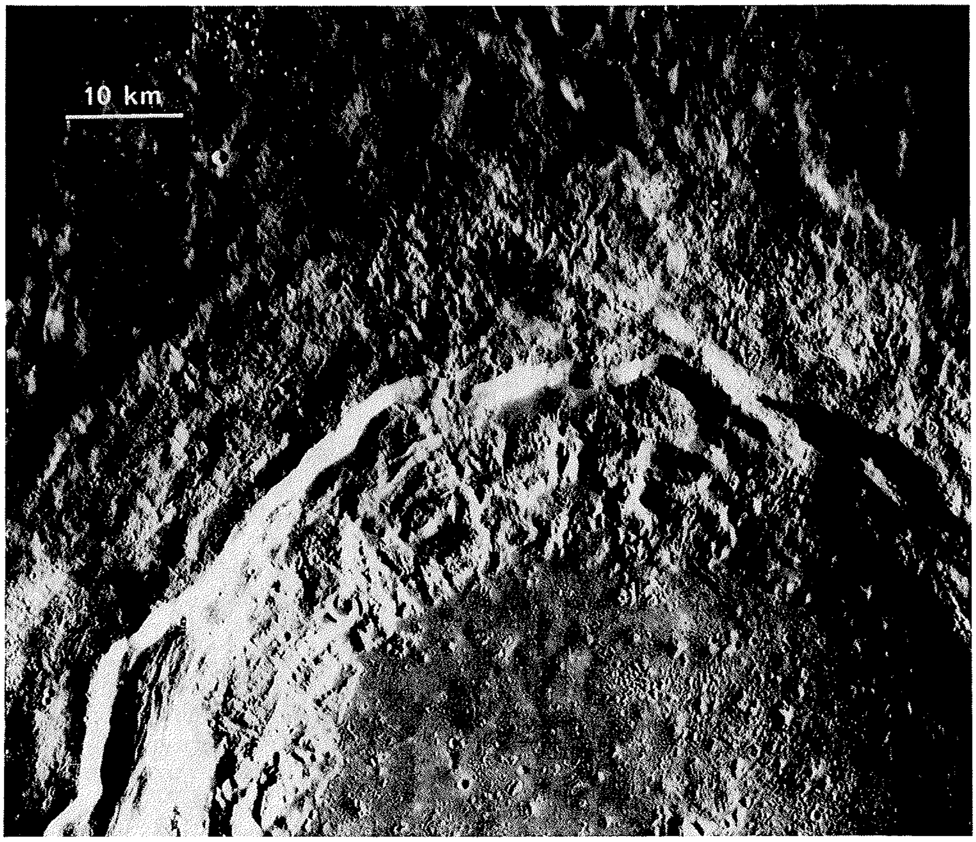

Fig. 8 Wall of Copernicus. Lunar Orbiter V picture of Copernicus illustrates relation between wall and floor material. Note the radial and concentric structure on the rim.

governed by surface forces between fine particles of the cement dust used. The resulting features only superficially resemble the uneven rim deposits in even small lunar craters (see fig. 10), which have a dunelike rounded appearance and have been so interpreted (Fisher and Waters, 1969). Hummocky rim deposits are a distinctive morphological feature of both manmade explosion craters and natural impact cratering events, and are an important means of distinguishing between impact and (maar-type) eruptive volcanic features (Shoemaker, 1962).

Current experiments (Gault *et al.*, 1968), field observations (Shoemaker, 1962), and theoretical treatments (Bjork, 1961) of the impact process indicate that most of the debris in the ray pattern arises from the target rocks with contribution of throwout from secondary craters, and not from the impacting mass itself.

Where it has been possible to study central crater peaks in known impact structures on Earth, it appears that these structures involve uplift of brecciated rock (Roddy, 1968; Wilshire and Howard, 1968), contrary to the results obtained by Wegener (1921). Thus crater peaks in large craters are not residual structures, nor are they related in a simple way to layering of the target material, but appear to result from a combination of processes including slumping and partial isostatic recovery.

Multi-ring Basins

Multi-ring basins are circular features hundreds of km in diameter characterized by a central basin, generally occupied by mare material, and by one or more concentric rings

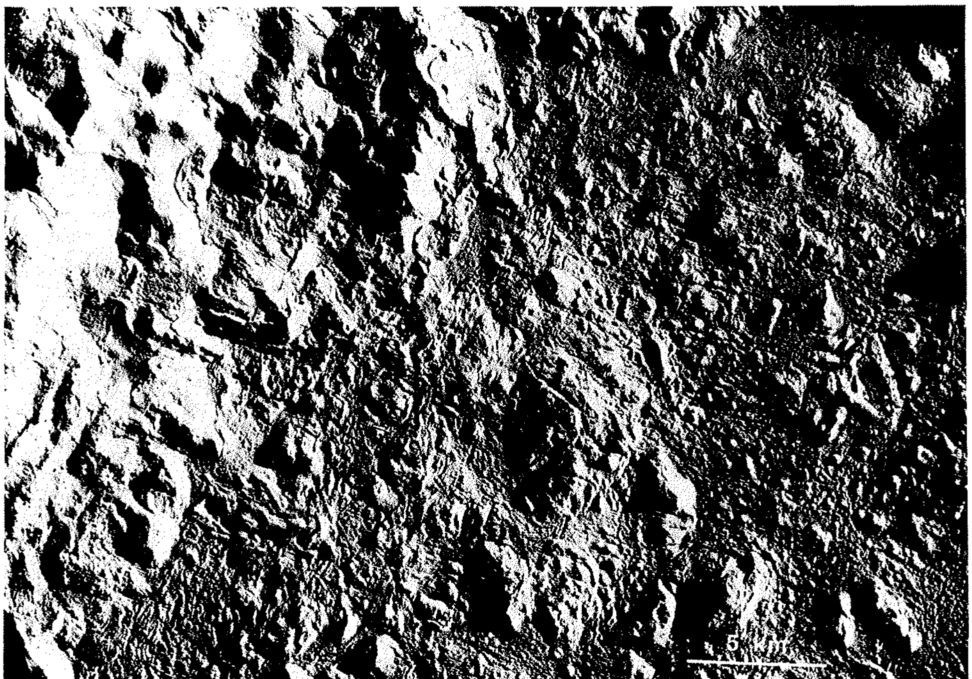

Fig. 9 Floor of Tycho. Detail of Tycho's floor showing texture suggestive of flow.

of mountainous topography. Mare Orientale (fig. 11) is the best exposed and apparently youngest and least modified feature of this type (McCauley, 1967 a, b; Wilhelms, 1970). Mare Imbrium is a flooded multi-ring basin. Dimensions of prominent multi-ring basins are given in Table 1. (Van Dorn, 1969).

TABLE I

MARE PARAMETERS

Mare	Coordinates	Ring	Diameter (km)
Imbrium	34°N—16°W	1	580
		2	700
		3	970
		4	1340
Serenitatis	27°N—19°E	3	670
Orientale	20°S—95°W	1	360
		2	480
		3	620
		4	930
		5	1460
Smythii	01°N—81°E	3	450
		4	670
		5	1060
Nectaris	16°S—33°W	3	260
		4	500
		5	860
Muscoviense	24°N—146°E	3	230
		4	470
		5	820
Humorum	24°S—39°W	4	440
		5	730
XVI	36°S—152°W	4	250
		5	500
XVII	02°N—129°W	4	240
		5	490
Clavius	58°S—15°W	4	220
		5	450
XV	03°S—159°W	4	200
		5	420
Grimaldi	07°S—68°W	4	200
		5	420
Byrgius	25°S—65°W	4	42
		5	100

The Orientale basin has a smooth, dark central mare, about 325 km in diameter, surrounded by five concentric rings (McCauley, 1967 a). The inner two, 360 km and 480 km in diameter, are rings of blocks between the central mare and the Rook Mountains. The Rook Mountains make the third scarp about 700 km in diameter, and the Cordillera scarp the fourth, about 930 km. The fifth ring is indistinct, consisting of elevated parts of pre-Orientale crater rims.

Of all the stratigraphic units related to the Orientale basin, the radially braided rim material is the most extensive. This material makes up the bulk of the Cordillera Formation (McCauley, 1967 a, b), a hummocky unit which extends outward from the ridge of the Cordillera Mountains in all directions. The cordillera Formation extends to the north and south about 1000 km from the basin center, and about 700 km east and west. Ridges in the radially braided pattern are 4 to 7 km wide. These ridges cross old craters such as Riccioli, Rocca, and Darwin.

The Montes Rook Formation (McCauley, 1967 b) predominates between the Montes Cordillera and Montes Rook, but small patches appear on the basin side of the Montes Rook. This material is much smoother than the Cordillera Formation, and its lineaments are more or less randomly oriented. Inside the Montes Rook the surface is somewhat smoother. Superposition relations indicate that material underlying this surface blankets the subjacent structure and laps upon and embays the elevated blocks of the Montes Rook. This material and associated closely-spaced hills are referred to as central basin plains material. Dark mare material laps upon the central basin plains material and Montes Rook Formation.

Mare Imbrium, whose basin is thought to be next older to that of Orientale, displays a ring system analogous to the rings of Orientale. Van Dorn (1969) has identified four such rings. The two inner rings are seen in the mare surface. The third ring is defined on the south and southeast by the Montes Carpathus and Montes Appenninus, respectively, on the east by the Montes Caucasus, and from northeast to northwest by the Montes Alpes and Montes Jura. The ring is mostly missing on the southwest side, although a few low hills may roughly outline this side of the basin. Radially braided ejecta, called the Fra Mauro Formation (Wilhelms, 1970) extends outward from this 970 km diameter ring. Inside this ring most of the area is covered by dark mare material except for a small segment called the Apennine Bench. The Bench does not show the coarsely braided structure displayed by the Fra Mauro Formation. One may speculate that if Mare Orientale were blanketed or flooded by dark mare material out to the Cordillera Mountains except for a small segment of the Montes Rook, this basin would have much the same appearance as Mare Imbrium. The shape of Mare Imbrium is complicated on its north-west side by the semicircular form of Sinus Iridum, a large post Imbrium-basin crater which has been flooded by the same dark material which covered Mare Imbrium.

Some of the still older mare basins share morphological features with Imbrium and Orientale. Serenitatis, Crisium, Humorum, and Nectaris display distinctly circular basins. Nectaris and Crisium show concentric rings outside their main basins.

There is nothing in ordinary experience or theory that allows us to understand the mechanics of formation of such large basins. Consequently, the theories of origin are speculative and verbal in nature. An intriguing impact model based on hydrodynamic theory has however been worked out by Van Dorn (1969). McCauley (1964) concludes that the major features of the Orientale basin were formed by a combination of impact and volcanic processes. He contends that the basin itself was excavated by a large impacting body which threw out debris and blanketed a roughly circular area 1,000 km in radius. The concentric scarps and radial fractures were produced contemporaneously with the blanket. Extensive flooding occurred during Imbrian time and filled the central basin of Orientale as well as many of the nearby craters.

In contrast to the impact origin previously proposed by Hartmann and Kuiper (1962), and McCauley (1964), Green has proposed a volcanic origin for the basin (Oriti and

Green, 1967). He interprets the concentric features as ring dikes and cone sheets. The first stage of this model involves regional doming and development of subradial and concentric fractures. Collapse of the dome is then supposed to have caused the formation of inward-facing concentric scarps. The associated fractures then filled with volcanic material to form ring dikes. Later doming or explosive phases may have formed cone sheets. Chain craters then developed by volcanic venting along radial fractures.

Green does not discuss the origin of braided rim facies or the secondary craters which may be identified out to at least 1,500 km from the basin center. The secondary craters closely resemble those that form as a result of major impacts. However, Green's central argument that the major scarps appear to have formed as a result of collapse is also consistent with an impact origin as developed by McCauley (1967 a, b). In McCauley's interpretation, the initial event was the impact of an asteroid near the center of the inner basin. The shock wave that was propagated outward caused large crustal segments to be thrust up and outward. The subsequent shock wave rarefaction resulted in crater excavation. Although much of the high-angle ejecta probably reached escape velocity, the low-angle ejecta impacted the lunar surface and formed secondary craters. A base surge produced by the collapse and spreading of a dense column of ejecta over the basin formed the braided rim deposit. The concentric scarps formed shortly after crater excavation, and in part before the end of base surge deposition, by gravitational collapse along circumferential fractures. Subsequent volcanic activity produced the mare and plains materials which occupy the central basin and low areas adjacent to the scarps. According to these ideas, vertical relief throughout the basin was probably never much greater than that presently observed.

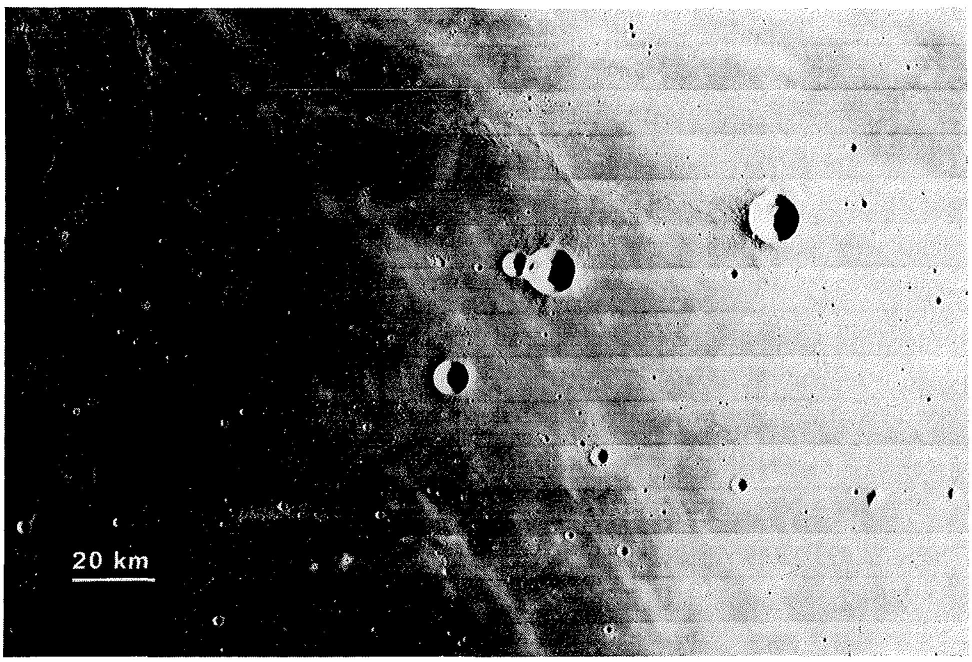

Fig. 10 Kepler ray. The light irregular streaks are rays emanating from the crater Kepler. Within the ray, small craters and crater clusters are more numerous than on surrounding mare surface.

Van Dorn's (1968, 1969) interpretation of the multi-ringed basins differs from McCauley's only in the mechanism of ring formation. According to Van Dorn, the rings are remnants of fluid-like waves that spread out from the point of impact, and are therefore analogous to surface waves emanating from, say, a pebble dropped in water. Initially the forces of the impact would have been so great and the movements so large

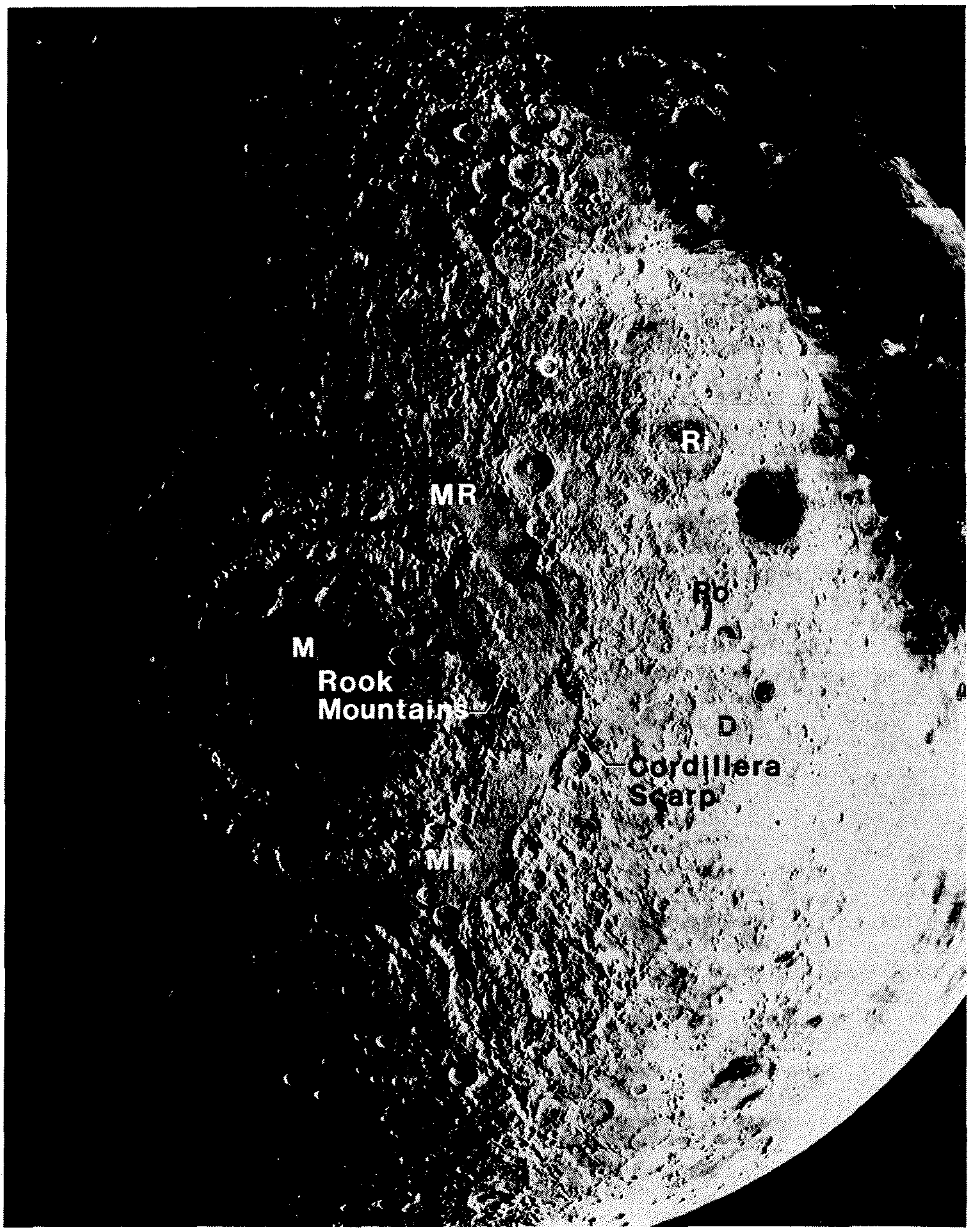

Fig. 11 The Orientale basin. The various features described in the text are labeled. Central mare basin, M; Montes Rook Formation, MR; Cordillera Formation, C, The craters Darwin, D; Riccioli, Ri; and Rocca, Ro.

that the strength of the "crust" could not withstand the motion. The rings were "frozen in" when the dissipating impact forces were reduced to the order of the strength of the crust.

The genetic relations, if any, between the multi-ring basins and the material which fills them has not been established. The finding of the Apollo missions that the maria are probably underlain at least in part by basalt-like volcanic rock however allows us to eliminate the hypotheses of dust fill (Gold, 1955) and ocean or stream sediment fill (Gilvarry, 1960, 1969). Two remaining questions of importance for lunar history are:

1. Is the mare fill a direct consequence of basin formation?

2. If not, what is the energy source for such melting in early lunar history?

References

Anderson, A. T., Jr., A. V. Crewe, J. R. Goldsmith, P. B. Moore, J. C. Newton, E. J. Olsen, J. V. Smith, and P. J. Wyllie, 1970, Petrologic History of the Moon Suggested by Petrography, Mineralogy and Crystallography, **Science**, v. 167, p. 587—589.

Bjork, R. L., 1961: Analysis of the formation of Meteor crater, Arizona: A preliminary report: Jour. Geophys. Res., 66, p. 3379—3387. Theoretical study of cratering processes.

Carr, M. H., 1969: Geologic map of the Alphonsus region of the Moon: U. S. Geol. Survey Misc. Geol. Inv. Map I—599.

Ebert, H., 1890: Ein Vorlesungsversuch aus dem Gebiete der physikalischen Geographie (Bildung der Schlammvulkane und der Mondringgebirge), **Ann. d. Phys.** Chem. N. F., v. 41 (277), p. 351—363.

Firsoff, V. A., 1959: Strange world of the Moon: New York, Basic Books, 226 p.

Fisher, R. V., and Waters, A. C., 1969: Bed forms in base-surge deposits: Lunar implications: Science, v. 165, p. 1349—1352.

Franz, J., 1912: Der Mond (Aus Natur und Geisteswelt, 90), 2. Aufl., S. 75, Leipzig.

Gault, D. C., 1970: Saturation and equilibrium conditions for impact cratering on the lunar surface: Criteria and implications: Radio Science, v. 5, No. 2, p. 273—291.

Gault, D. C., Quaide, W. L., and Oberbeck, V. R., 1968: Impact cratering mechanics and structures: in shock metamorphism of natural materials, B. M. French and N. M. Short, Editors, Mono Book Corp., 6747 Whitestone Rd., Baltimore, Maryland 21207.

Gilvarry, J. J., 1960: Origin and nature of lunar surface features: Nature, v. 188, p. 886—890.

Gilvarry, J. J., 1969: Nature, v. 221, p. 732.

Gold, Thomas, 1955: The lunar surface: Mon. Nat. Roy. Astron. Soc., v. 115, p. 585—604.

Gold, Thomas, 1969: Apollo 11 observations of a remarkable glazing phenomenon on the lunar surface: Science, v. 165, p. 1345—1349.

Green, Jack, 1970: Origin of glass deposits in lunar craters: Science, v. 168, p. 608—609.

Greenwood, W. R., and Heiken, Grant, 1970, Origin of glass deposits in luna craters: Science, v. 168, p. 610—611.

Hartmann, W. K., and Kuiper, G. P., 1962: Concentric structures surrounding lunar basins: **Lunar and Planetary Laboratory, Communications,** No. 12.

Hooke, R., 1665: Micrographia, London, Marytn and Allesley.

Kaula, W. M., 1969: Interpretation of lunar mass concentrations: Phys. Earth Planet. Interiors, v. 2, p. 123—137.

LSPET, 1970: Preliminary Examination of Lunar Samples from Apollo 12, **Science,** v. 167, p. 1325—1339.

Macdonald, Gordon A., 1967: Forms and structures of extrusive basaltic rocks, in Basalts: The Poldervaart treatise on rocks of basaltic composition. Vol. 1. Edited by Hess, H. H. and Poldervaart, Arie.

McCauley, J. F., 1964: The stratigraphy of the Mare Orientale region of the Moon, in Astrogeol. Studies Ann. Prog. Rept., August 1962—July 1963, pt. A: U. S. Geol. Survey open-file report, p. 86—98.

McCauley, J. F., 1967 a: Geologic results from the lunar precursor probes: AIAA paper No. 67—862, 8 p.

McCauley, J. F., 1967 b: The nature of the lunar surface as determined by systematic geologic mapping: In Mantles of the Earth and terrestrial planets, edited by S. K. Runcorn, p. 431—460.

McCauley: J. F., 1969: Geologic map of the Alphonsus GA region of the Moon: U. S. Geol. Survey Misc. Inv. Map I—586 (RLC 15).

Middlehurst, Barbara M., 1967: An analysis of lunar events: Rev. Geophysics, v. 5, no. 2, p. 173—189.

Moore, H. J., 1964: Density of small craters on the lunar surface, in Astrogeol. Studies, Annual Prog. Rept., Aug. 25, 1962 to July 1, 1963, pt. D, p. 34—51.

Moore, H. J. Gault, D. E., and Heitowit, E. D., 1964 a: Change of effective target strength with increasing size of hypervelocity impact craters: 7th Hypervelocity Impact Symposium, Tampa.

Moore, H. J., Gault, D. C. Heitowit, E. D., and R. V. Lugn, 1964: b, Hypervelocity impact craters in porous cohesive targets: U. S. Geol. Survey, Astrogeologic studies annual progress report, July 1, 1963 to July 1, 1964, pt. B., p. 93—143.

Moore, H. J., and Kachadoorian, R., and Wilshire, H. G., 1964 c, A preliminary study of craters produced by missile impacts: U. S. Geol. Survey, Astrogeologic studies annual progress report, July 1963 to July 1964, pt. B, p. 58—92.

Moore, H. J., and Lugn, R. V., 1965: A missile impact in water-saturated sediments, in Astrogeologic Studies Ann. Prog. Rept., July 1, 1964—July 1, 1965, pt. B: W. S. Geol. Survey open-file report, p. 101—125.

Muller, P. M. and Sjogren, W. L., 1968: Mascons: lunar mass concentrations: Science, v. 161, p. 680—684.

Mutch, T. A., 1970: **Geology of the Moon,** Princeton University Press, New Jersey, 324 pp.

Oriti, Ronald A., and Green, Jack, 1967: Alternate interpretations of the Orientale basin: The Griffith Observer, August 1967, v. 31, No. 8, p. 118—125.

Pike, R. J., 1969: Meteoritic origin and consequent endogenic modification of large lunar craters-A study in analytical geomorphology: U. S. Geol. Survey, open file report.

Pohn, H. A., and Offield, T. W., 1969, Lunar crater morphology and relative age determination of lunar geologic units: U. S. Geol. Survey Interagency Rept., Astrogeology 13, 35 p.

Quaide, W. L., and Oberbeck, V. R., 1968, Thickness determinations of the lunar surface layer from lunar impact craters: J. Geophys. Res., v. 73, p. 5247—5270.

Quaide, W. L., and Oberbeck, V. R., 1969: Geology of the Apollo landing sites: Earth-Sci. Rev., v. 5, p. 255—278.

Roddy, D. J., 1968, The Flynn Creek Crater, Tennessee, in Shock metamorphism of natural materials, B. M. French and N. M. Short, eds.: Baltimore, Jd., Mono Book, p. 291—322.

Shoemaker, E. M., 1962: Interpretation of lunar craters: in Zdenek Kopal. editor, Physics and astronomy of the Moon, London, Academic Press, p. 283—359.

Shoemaker, E.M. , Hait, M. H., Swann, G. A., Schleicher, D. L., Dahlem, D. H., Schaber, G. G., and Sutton, R. L., 1970, Lunar regolith at Tranquillity base: Science, v. 167, p. 452—455.

Shoemaker, E. M., and Morris, E. C., 1968, Television observation from Surveyor, in Surveyor project final report, pt. II, Science results, p. 58—109: Jet. Propul. Lab. Tech. Rept. 32—1265, Pasadena, Calif.

Skeats, E. W., and James, A. V. G., 1937, Basaltic barriers and other surface features of the Newer Basalts of western Victoria: Roy. Soc. Victoria Proc., v. 49, pt. 2, p. 245—278.

Spurr, J. E., 1949: Geology applied to selenology. IV. The shrunken Moon: Concord, N. H., Rumford Press, 207 p.

Suess, E., 1895: Einige Bemerkungen über den Mond. Sitzungsber. d. k. Akad. d. Wissensch. zu Wien (1) v. 104, p. 21—54.

Trask, N. J., 1966: Size and spatial distribution of craters, estimated from the Ranger photographs, in Ranger VII and IX, Part II, Experimenters' analyses and interpretations: Jet Propul. Lab. Tech. Rep. No. 32—800, p. 252—263, Pasadena, Calif.

Trask, N. J., 1969: Geologic maps of early Apollo landing sites: U. S. Geol. Survey, Accompanies Misc. Geol. Inv. Maps I—616 to 627.

Tyler, G. L., 1968: Oblique-Scattering radar reflectivity of the lunar surface: preliminary results from Explorer 35: Jour. Geophys. Res., v. 73, p. 7609—7620.

Van Dorn, W. G., 1968: Tsunamis on the Moon?: Nature, v. 220, p. 1102—1107.

Van Dorn, W. G., 1969: Lunar maria: structure and evolution: Science, v. 165, p. 693—695.

Wegener, A., 1920 a: Die Aufsturzhypothese der Mondkrater, **Sirius,** v. 53, p. 189—194.

Wegener, A., 1920 b: Versuche zur Aufsturztheorie der Mondkrater, **Nova Acta. d. Leop.-Carol. Deutsch. Akad. d. Naturf.,** v. 106 (2), p. 107—117.

Wegener, A., 1920 c: Die Entstehung der Kontinente und Oceane, 2. Aufl. Die Wissenschaft 66. Braunschweig.

Wegener, A., 1921: Die Entstehung der Mondkrater, Braunschweig, Sammlung Vieweg, Tagesfragen. **Natur u. Tech.** 55, 48 p.

Wilhelms, D. E., 1968: Geologic map of the Mare Vaporum quadrangle of the Moon: U. S. Geol. Survey Misc. Geol. Inv. Map I—548.

Wilhelms, D. E., 1970: Summary of lunar stratigraphy — Telescopic observations: U. S. Geol. Survey Prof. paper 599-F.

Wilshire, H. G., and Howard, Keith A., 1968: Structural pattern in central uplifts of cryptoexplosion structures as typified by Sierra Madera: Science, vol. 162, p. 258—261.