HISTORY OF THE LUNAR SURFACE

by

William K. Hartmann

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF ASTRONOMY

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1966

THE UNIVERSITY OF ARIZONA

GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my

direction by WILLIAM K. HARTMANN

entitled HISTORY OF THE LUNAR SURFACE

be accepted as fulfilling the dissertation requirement of the

degree of Ph.D.

Gerard P. Kuiper — Oct 15, 1965
Dissertation Director — Date

After inspection of the dissertation, the following members of the Final Examination Committee concur in its approval and recommend its acceptance:*

William G. Tifft — 10/15/65

Ray J. Weymann — 10/15/65

John S. Turner — 10-15-65

Spencer R. Titley — 10-15-65

*This approval and acceptance is contingent on the candidate's adequate performance and defense of this dissertation at the final oral examination. The inclusion of this sheet bound into the library copy of the dissertation is evidence of satisfactory performance at the final examination.

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgement the proposed use of the material is in the interest of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: William K. Hartmann

ACKNOWLEDGMENTS

I wish to acknowledge with thanks many helpful discussions with many teachers and colleagues of the Lunar and Planetary Laboratory: Dr. G. P. Kuiper, Messrs. Robert Strom, Rudolf LePoole, D. W. G. Arthur, E. A. Whitaker, A. B. Binder, D. P. Cruikshank, and C. A. Wood; of the Department of Astronomy: Drs. A. B. Meinel, R. Weymann, and W. G. Tifft; of the Department of Geology: Drs. Evans B. Mayo, S. R. Titley, J. S. Sumner, and P. E. Damon. Further, I wish to express thanks to many workers in the field of solar system science for help in correspondence and visits, and to the National Aeronautics and Space Administration through whose Grant NsG 161-61, much of this work was supported. Finally I wish to thank my wife, who helped to program a number of calculations and endured the rest of this paper's preparation, and my parents, whose constant encouragement throughout my life has made everything possible.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

The first chapters (I, II, III) review the problem of lunar history. Chapter II gives a chronological review of lunar science up to 1959. Chapter III reviews the present "state of the art" in a framework of nine relevant topics.

In lunar science, unlike most branches of modern science, there is controversy over even the most basic facts and assumptions. Yet the writer attempts to show that there exist valid observational tests of at least some hypotheses. Chapter IV reviews the analysis of crater counts, which are a useful tool here.

The well-preserved post-mare craters are first studied (V). A new review of meteoritic mass distribution and cratering theory is then used to show that the observed diameter distribution among post-mare craters would be produced by the impacts of asteroidal-type bodies (VI). This supports the hypothesis that the post-mare craters result from impacts of asteroidal fragments, predominantly.

A new value of the cratering rate on earth, derived from study of the 10^9 year old Canadian Shield, as well as other published values, is used to show that the maria are on the order 4×10^9 years old (VIII). This is in

accord with theoretical calcululations of heating due to radioactive isotopes, which suggest a maximum surface heating (hence lava outflow) at this time. Among the major maria, crater densities are found to differ by less than a factor three in a new analysis of published data, but it is suggested that mare ages vary by substantially less than this (VII).

New and old evidence for the impact origin of the larger lunar craters is summarized in Chapter IX.

In Chapters X and XI, evidence is given that although the mass distribution of impacting objects did not vary markedly throughout lunar history, the flux decreased from an early intense bombardment. The pre-mare craters outnumber the post-mare ones by a factor about forty, and it is estimated that the early bombardment flux averaged on the order 400 times the post-mare average value. There is evidence that the early intense bombardment began after the moon reached its present radius, and these results appear to support the hypothesis that the moon swept up a ring of fragmented circumterrestrial particles.

Chapter XII considers erosive effects in continental and mare regions, and Chapter XIII contains an attempt to order the large basins by age. New evidence is given (XI) that the basins formed by impact during the early bombardment period.

I. INTRODUCTION - SCOPE OF INVESTIGATION

Cosmic phenomena may be divided according to the linear scale involved. The present study concerns phenomena on a macroscopic scale. It attempts to describe the events which resulted in the more prominent resolvable features of the lunar globe - dark plains, highly cratered bright areas, arcuate mountain patterns, linear valleys. These may be termed global, or macroscopic properties of the moon. Global properties generally relate to the history of the moon as a planet and to the history of the moon's environment, the solar system.

At the time of this writing, much attention is being devoted to other lunar properties in preparation for the first manned flights to the moon, expected within a decade. These are the properties which affect the safety of lunar astronauts and their equipment. They bear as much relevance to lunar evolution as soil mechanics or fluvial geomorphology does to the evolution of the earth: they concern "skin effects". They may be termed local properties or small-scale properties. Contemporary conclusions about local properties, though they are necessary engineering requirements, may require revisions once observations can be made on the lunar surface conveniently, and rock samples returned. Therefore, much of the theory of small-scale lunar properties must await the future. This dissertation accordingly puts very little stress on the history of small-scale lunar properties.

While the present methods for studying local properties will be largely obsolete after the first lunar landings; the same is not true of methods now applied to the study of global properties. Almost by definition, these must be observed from a distance, and the present earth-based photographs thus form a library of great value in this field. For example, statistics of large craters, important tools in the present paper, can be best compiled from the earth. Of course, petrological, geochemical, geotectonic, and other information directly from the lunar surface is required before lunar history fully can be sketched, but it is worthwhile to exploit our present potential to the utmost. As will be shown, we can in fact lay down certain boundary conditions for the interpretation of forthcoming surface data, as well as educate ourselves in some rudiments of lunar and solar system history.

Finally, it should be noted that a proper planetological description of the moon's history requires a synthesis drawing on many fields - theoretical astrophysics, meteoritics, structural geology, geochemistry, and geophysics for example. It may be years before even a first order theory satisfies all workers.

II. CHRONOLOGICAL REVIEW OF LUNAR THEORY

This review of the literature will consider only work concerned with the genesis, evolution, and global properties of the moon.

Little significance need be attached to most pre-telescopic utterances about lunar evolution. Some of the earliest legends handed down over generations may be little more than campfire tales, known by the originator to be mere story, but believed by later tellers. But it may be significant that those stories became set, and that as long as four thousand years ago the priests of the most powerful nation on earth presented to the citizens a unified picture of the genesis of the moon and other celestial objects. These pronouncements were as widely known and respected by the Egyptian people of that day as current scientific popularizations are today (Hamlyn, 1965).

By 500 B.C. Greek astronomers under Pythagoras held that the moon was spherical, and we may date the concept of the moon as a separate planetary world of form analogous to the earth from this period. Democritus (ca. 400 B.C.) even held that the lunar markings were caused by great mountains and valleys (Baldwin, 1949, p.2). By 200 B.C. the approximate magnitude of the moon's diameter and distance had been measured through the work of Aristarchus, Eratosthenes, and other Greek natural philosophers. By 500 A.D. these figures were accurately known by many widely separated groups and had been measured in India within 6%. The decline of this knowledge in Europe in the Middle Ages, when the moon was held, for example, to be a great mirror reflecting features of the earth, ended by about 1600 in the controversy over Copernican and Keplerian astronomy (Abell, 1964).

In 1610, soon after the invention of the telescope, Galileo announced in his Siderius Nuncius the discovery of mountains, valleys, craters, and (erroneously) seas on the moon (Abell, 1964, p.44). Moore (1953) suggests that Galileo eventually became aware that there was no water in the lunar seas (maria), but the idea persisted to a much later day. Galileo further derived a height of about four times the height of terrestrial mountains for lunar peaks he observed illuminated beyond the terminator, and discussed the possibility of an atmosphere. He noted that the moon shines by reflected sunlight, concluded that the earth must do the same, and used this as a proof against those who argued that the earth was not to be included among the planets (Abetti, 1952). This work greatly strengthened the conception that the moon is an earth-like, planetary body.

During the next three centuries the moon's surface was largely bypassed by outstanding scientists, due partly to a growing belief that it was essentially dead. What Moore (1953, p.53) and Baldwin (1949, p.6) call the first reasonably accurate lunar map was produced by a city counselor of Danzig, Hevelius, in 1647. Hevelius also measured the heights of peaks in the lunar Apennines and Caucasus mountains to be 17,000 feet, nearly the correct value (Baldwin, 1949, p.6). Riccioli, in 1651, initiated the present custom of naming craters after scientists and philosophers. Tobias Mayer, in Göttingen, gave a complete geometric explanation of the lunar librations (Abetti, 1952, p.149) and in 1775 published (posthumously) a map which was not excelled until the mid-1800's.

In 1764 Lagrange proved dynamically that the moon must have an ellipsoidal figure. Laplace calculated the theoretical earthward bulge at 475 feet (Baldwin, 1949, p.7). The observed bulge was later found to be much larger than the theoretical, and this came to be a widely discussed problem of modern research.

What has been called modern selenography was initiated in the late 1700's by Johann Schröter at Lilienthal with a long and systematic set of observations to map lunar structures in detail and measure mountain heights. Schröter's observatory was destroyed in war in 1813 (Moore, 1953, pp. 55ff), but this sort of work spread among other observers.

Studies of lunar history, which require a good observational base, could scarcely be expected to have been productive at this time. Yet, many of the concepts which are accepted or debated now can be found, albeit in a very rudimentary form, in writings of well over 100 years ago. The brothers Marshall von Bieberstein (1802) attempted to show that all planets, including the moon, formed through accretion of meteoritic particles. Von Moll (unpublished, 1810 to 1820) wrote that the moon has always been a separate planet, younger than the earth, and formed by condensation of small particles. The hypothesis that lunar craters are results of meteoritic impacts is usually attributed to Franz Gruithuisen (1844), who apparently developed the idea in the 1830's. These papers are reviewed by Both (1962).

These theorists were severely hampered by the poor quality of observations. Von Moll thought the maria to be an older, darker surface seen through a more recent, brighter crust (the continental areas). Gruithuisen (and others) thought the moon inhabited, and claimed observations of cities, snow, changes, and new formations.

Selenography, the pursuit of accurate positions and dimensions, and the search for changes occupied observers. Many were careful and talented. Examples are Lohrmann, (1824), and Beer and Mädler (1837) in Germany, and in Italy, Father Secchi, who used photography and careful mapping to look for changes in the crater Copernicus in the 1850's (Abetti, 1952, p.191).

This selenography, however, was limited in scope. The primary object was description. Selenology (planetology applied to the moon) had not been practiced yet with any success. For example, Beer and Mädler (1837, p.250) merely described a "southeast-northwest direction of mountain ridges" south of Mare Serenitatis, and it was not until more than half a century later that Gilbert (1893) made the simple discovery that all these linear ridges are part of a great global system converging in the center of Mare Imbrium. Apparently, the quest for increased resolution and finer and finer detail blinded observers to macroscopic, global patterns, a key tool in planetary studies.

Perhaps selenographic studies reached their most exciting days in the last half of the 1800's with the announcement that the small crater Linné had disappeared or drastically changed appearance (Moore, 1953). A controversy over this raged for many years. With the possibility that the moon might not be dead, a great many amateurs were attracted to making drawings, measurements, and maps of lunar features, and the British Astronomical Association's lunar section became the world center for this work. The reputed changes in Linné have been attributed by most modern students to too literal interpretation of old maps, but careful selenographic work has established dimensions, slopes, and positions which are basic to many modern morphological studies.

The high point in 19th century thought about the moon, and perhaps the first truly modern approach was an address given on Dec. 10, 1892 by the retiring president of the Philosophical Society of Washington, and Chief Geologist of the United States Geological Survey, G. K. Gilbert (1893). This work not only summarizes the thoughts of a prominent geologist of the time, but also provides a mine of ideas which are reflected in much modern work. It is remarkable in bringing geology, physics, and astronomy all to bear on lunar history - i.e. in being problem-oriented, not method-oriented. It is such a classic that it will be treated here in some detail.

Gilbert first reviews some theories of the lunar surface. Of course, the main problem in the eyes of the 19th century scientist was the origin of the craters. In favor of the volcanic theory, Gilbert cites his own estimate of one thousand volcanic craters in the states and territories of Utah, Nevada, Arizona, and New Mexico, giving an areal density approximately one tenth that of lunar craters. With the observation that on earth, "every district has been at one time or another a field of volcanic activity", concludes that the areal density of terrestrial craters, integrated over history, is not discordant with that of lunar craters. But Gilbert rejects the volcanic theory on morphological grounds: the terrestrial craters are smaller and of different form from lunar craters. He notes that all lava-producing craters are of markedly different shape, and that maars (steam explosion craters), though of roughly lunar shape, could explain only the smallest lunar craters.

The tidal theory, popular in Gilbert's day, stated that from vents along fissures opened by tidal stresses, repeated upwellings of lava, driven by tides, produced circular craters. Gilbert rejects this for lack of visible fissures. The ice theory, modifications of which still appear, held that an icy mantle or crust on the moon was locally melted by volcanic heating, producing craters. Gilbert rejects this for not explaining small rim craters superposed on larger ones or central peaks.

The meteoric (or meteoritic) theory in its most common form attributes lunar craters to impacts of interplanetary meteorites. Gilbert traces the idea as far back as Proctor's The Moon, published in 1873. Gilbert rejects this form of the theory on several grounds, primarily: (1) "...it is incredible that even the largest meteors of which we have direct knowledge should produce scars comparable in magnitude with even the smallest of the visible lunar craters." Gilbert recognizes but does not favor the possibility that the bombardment by large meteorites occurred so long ago that terrestrial scars have been obliterated by orogeny and erosion. (2) Gilbert states that projectiles striking at large angles from the vertical would produce elliptical craters, and presents an account of experiments and calculations to show that the observed near-circular shapes are incompatible with the collision parameters of interplanetary bodies, according to this assumption.

Gilbert invented his own moonlet theory to avoid the difficulties he cites for the meteoritic theory. In the moonlet theory, the impacting bodies are not interplanetary, but local: a ring of small earth satellites. Gilbert states

> It is my hypothesis that before our moon came into existence the earth was surrounded by a ring similar to the Saturnian ring; that the small bodies constituting this ring afterward gradually coalesced, gathering first around a large number of nuclei, and finally all uniting in a single sphere, the moon. Under this hypothesis the lunar craters are the scars produced by the collision of those minor aggregations or moonlets, which last surrendered their individuality.

This idea avoids the first difficulty of the meteoritic theory in that the moonlets are hypothesized to be large, and the second in that the collisional approach velocities are not interplanetary but practically zero, so that vertical impacts are common. The moon is hypothesized to have been perturbed by approaching moonlets so that its "equator may have occupied successively all parts of its surface, without ever departing widely from the plane of the moon's orbit" (p.275). These statements touch on problems raised in most modern theories: Where did the moon itself form? Where did the colliding bodies come from? What variations have occured in the moon's orientation and orbit?

The rest of Gilbert's paper is devoted to the mechanics of impact and the origin of various observed structures. The first has been improved upon, though Gilbert properly raises questions of plastic deformation, fusion of meteoritic and lunar material at impact, central peak formation by rebound, and other questions which have yet to be answered in detail. Gilbert's discussion of individual structures includes the calculation that the colliding body which formed the Imbrium basin had a diameter of 80 to 100 miles; the discovery of radial "sculpture" and "furrow" systems around Mare Imbrium, attributed to gouging by flying fragments from the impact explosion; the statement that maria are lava flows resulting from fusion on impact (the idea that they are lava he traces as far back as Meydenbauer in 1882); and the hypothesis, attributed to William Würdemann in Washington, that "white streaks" (rays) originated when "a meteorite striking the moon with great force, spattered some whitish matter in various directions", the great distances being a result of low gravity and lack of air drag. In conclusion, Gilbert gives a lower limit to the moon's age on geological grounds: the moon may have been "...already a finished planet in Paleozoic time" (age $> 5 \times 10^8$ years).

The next decades showed that Gilbert was ahead of his times. Astronomers saw little profit in turning their attention to this dead world. More amazingly, geologists suffered from a similar lack of interest, although they probably had little access or acquaintance with the neccessary astronomical photographs and other data. Many of the published papers of the next years were by industrious amateurs, who observed visually with their own telescopes and reported their drawings, measures, and speculations. Most of these will not be reviewed here. Neither the meteoritic hypothesis nor the moonlet theory of Gilbert was universally accepted.

In 1895 Eduard Suess reiterated the volcanic hypothesis, pointing out that both the earth and the moon must have been involved in extensive melting and fracturing, and attributing many lunar structures, such as the Alpine valley, to great volcanic fissuring of the lunar crust. Shoemaker (1962a, p.287) has stated that "At the close of the 19th century the consensus among both geologists and astronomers was still firmly in favor of volcanic origin of the craters."

C. H. Darwin (1898), in his study of the tides, extrapolated the tidal evolution of the moon's orbit backward to show that the moon must have once been very near the earth, and then suggested that the moon was broken off the earth when solar tides, in resonance with the earth's free vibration period, disrupted the nearly unstable and rapidly rotating planet.

The astronomer W. H. Pickering (1906) made an extensive comparison between Hawaiian and lunar volcanic structures, and endeavored to show that they were indeed morphologically similar. His photographs, however, compared objects which were greatly different in scale.

Shaler (1907), in a major review, presented one of the first dualistic hypotheses, concluding that the craters were volcanic but that cataclysmic impacts melted material to form the lava of the maria.

In 1910 the suggestion that the mare material might be dust was published, probably for the first time (Baldwin, 1963, p.295), by T. J. J. See.

The inadequacy of communications in lunar science at this time is illustrated by W. H. Steavenson's (1919) independent announcement of the great system of parallel "furrows" south of Mare Serenitatis - the same system which Gilbert had shown 26 years before to be radial to Mare Imbrium. Steavenson also proposed either volcanic activity or grazing impacts as the causal mechanism. He favored impacts for the furrows, but leaned toward volcanism for most craters.

A great number of papers were published during the following three decades, describing lunar features and debating, often in only qualitative and subjective terms, the merits of various hypotheses. Dominant was the controversy between meteoritic and volcanic genesis for various structures. It would require too much space here to describe these papers further.

In 1925, a "Committee on Study of the Surface Features of the Moon", whose members represented astronomy, geology, volcanology, and physics was formed at The Philosophical Society of Washington with the objective of gaining new measurements of surface properties and structures, and avoiding "suggestions of possible modes of formation". One part of the required data listed was "statistical information on the frequency of lunar craters" (Wright, Wright, and Wright, 1963). This approach did not produce much work on the history of the moon, but it did result in a great wealth of observational data obtained over the next few decades.

In 1935, The International Astronomical Union adopted the map and catalogue of Named Lunar Formations, published by Blagg and Müller (1935), in an effort to standardize lunar nomenclature and cartography.

A statistical study of craters by Young (1940) showed the linearity of a log-log plot of diameter frequencies. Young took as real certain discontinuities and departures from his curve and concluded that they stemmed from populations of craters of intrinsically different type.

Chamberlin (1945) applied new geophysical knowledge in a paper on "The Moon's Lack of Folded Ranges". He noted abundant faulting but no folding and a complete lack of orogeny in post-mare time as opposed to the earth. It was his idea to consider planetological differences in searching for an explanation. A number of hypothetical causes of orogeny on earth were noted to be less effective on the moon: (1) no erosion implies no filling of geosynclines, (2) small size of the moon implies quicker cooling, (3) lower density implies less differentiation (4) no transport of eroded material implies no shifting of mass and no consequent shift of rotation axis (which was noted to be less effective in producing stress anyway because of the lesser rotation velocity).

In the same year the first part of a lengthy, three volume study was published by the geologist, J. E. Spurr

(1945a, 1945b, 1948). Spurr proposed igneous origins for virtually all lunar structures, and because of this, his work came to be little known a few years later when the craters were widely interpreted as meteoritic. Spurr is more frequently referred to now, and perhaps his greatest contribution is the recognition of global "grids", a term he coined for vast systems of lineaments showing global symmetry. Spurr also recognized that the mare surfaces possess more nearly uniform ages than the older basins which they occupy. He discussed at length "uplift and subsidence" origins for mare basins, hypothesized vast crustal disturbances, and found more evidence for igneous activity than is usually accepted today.

R. B. Baldwin's book, "The Face of the Moon" (1949) convinced most students that the lunar craters were meteoritic impact scars. In a synthesis of some of his earlier work (1942, 1943) and new data, Baldwin extrapolated the morphological properties of terrestrial explosion craters to show a fit with the properties of the larger lunar craters and described a time sequence of events that fits with the observed lunar structures. Even the huge basins he attributed to impacts, making them extreme cases in the cratering process. The earthward axis of the moon is longer than predicted by hydrostatic theory, and Baldwin interpreted this as evidence for a fossil tidal bulge, formed long ago before the moon had been forced to its present distance from the earth by tidal interaction. This led to the hypothesis that the moon was at one time largely molten, and provided further evidence for Baldwin's strong belief that the maria are lava flows. In Baldwin's reconstruction, the magma is released by collapse of a great buckled dome surrounding the Imbrium impact site and formed by the impact.

Important work on the origin of the solar system in the early 1950's held implications about the history of the moon. Kuiper (1951) used dynamical and physical considerations to argue that the planets formed from very massive proto-planets, and that the earth-moon system most probably corresponds to a binary development governed by the protoplanetary density distribution, instead of the normal large primary with satellite system. Urey (1952) used chemical and physical arguments to show that the particles from which the planets actually formed must have been small and cold, not the incandescent material of earlier conceptions. Urey also supposed the lunar mare material to be lava created by the melting of lunar rock by impacts, and that the impact period of lunar history was of a duration comparable to the cooling time of the lava seas. Kuiper (1953) explained density difference among planets by variations in loss of silicates during molten phases of their histories.

In 1954, Kuiper published a lengthy discussion of the moon's history. A key point was the proposal that the moon at least partially melted as a result of heating by radioactive material:

> Depending on the precise value adopted for the conductivity of loosely packed, accreted material, one finds that all spheres larger than about 100 km. in diameter will have melted at least close to the center; substantially larger spheres will have melted almost entirely, leaving only an outer shell of few kilometers of nearly unaltered accreted material.

It is this melting which, in Kuiper's view, accounts for the lava. The craters are impacts of fragments from a sediment ring left over after the moon's formation and swept up by the moon as it receded from the earth under tidal influence. This ring had a mass of about 10^{22} grams estimated from crater sizes. The Imbrium planetesimal struck during the melting period, and was the largest of the impacting bodies at 150 km. diameter and 6×10^{21} grams mass (p. 1110). These conclusions initiated some controversy, and Urey (1955a) criticized such points as the failure to explain the distribution of the lunar maria (held by Urey as concentrated near the center of face), the absence of an explicit explanation of the fact that sediment rings are not known around other planets without moons, and especially the hypothesis that the moon could have melted without losing its ancient crust and mountainous relief. Kuiper (1955) listed in reply empirical evidence that the maria were indeed flows of lunar lava from the moon's interior, not rock melted by impacts as Urey suggested.

Gold (1955) suggested that the maria were not lava of any sort, but rather vast deposits of dust eroded from the surface and transported by migration of particles to low-lying areas.

Alfvén (1955) reviewed calculations of the moon's past dynamical history published in the same year by Gerstenkorn, who found the moon near the earth 2.7×10^9 years ago. Alfvén affirms that in any calculation the moon must have once been near the Roche limit, and that if Gerstenkorn's time scale is accepted, one must assume the moon to have been captured by the earth. Alternatively, Alfvén wrote, the moon's material may have been originally thrown off from the earth during extensive mass loss accompanied by growth of a high-density core resulting from phase transition in mantle material.

Measurements of radioactivity in meteorites were used to calculate the thermal history of planets. Urey took chondrites as the closest compositional match to the material of the early solar nebula and found in a 1956 calculation that a moon formed at low temperatures may never have melted. However, a difficulty in these calculations has always been the uncertainty in the initial abundances of radioactive isotopes.

Von Bülow, in a 1957 review of the lunar surface, reiterated the position that tectonic processes formed most of the lunar features, including craters. He saw in the maria and grid patterns a global fault and graben system, which he interpreted as scars of great crustal upheaval due to outgassing as the moon went through the final stages of its evolution. He viewed the earth and moon as analogous except that the smaller moon evolved faster, and he saw analogs in mare and ocean basins. He concluded that "a conception of general planetary tectonics is not unfounded".

Öpik (1958), who had published several earlier studies of asteroidal and meteoritic impacts, pointed out that among the larger bodies colliding with the planets, comets may outnumber the asteroidal meteorites.

Kuiper (1959), after a program of visual observation with large telescopes, reasserts that the moon was "largely molten 4.5 billion years ago". He finds examples of horsts, graben, extrusion dikes, and other tectonic activity. The Apennine surface was "deposited in viscous condition" and has flowed and faulted after deposit. Comet impacts, secondary ejecta or "scar" craters, and volcanoes are described. The maria are again attributed to lava flows.

Urey, Elsasser, and Rochester (1959) explain the non-equilibrium figure of the moon as a result of inhomogeneous composition, with the outer parts cold and more rigid than the earth since formation. Complete heating is ruled out since the non-equilibrium figure could not have been maintained. The statistical implications of the model indicate that 10^4 to 10^5 objects formed the moon, if the largest high-density objects were part of the same population as the others.

On September 12, 1959, the first man-made object to reach the moon crashed just outside the crater Autolycus, after a launching in the U.S.S.R. two days before and a flight during which a lack of a lunar magnetic field was recorded (Markov, 1962, p.373). On October 7, 1959, the far side of the moon was photographed for the first time by an automatic interplanetary station launched in the U.S.S.R. three days before. A primary discovery was the scarcity of maria in the newly photographed zone (Lipskii, 1962).

Following these events, there was a deluge of literature about the moon. Much of it has been required or inspired ultimately by the United States program to send men to the moon's surface. In spite of the fact that much of the work deals with small-scale properties necessary for spaceship design but outside the scope of this paper, the remaining, relevant papers are too numerous to review here in detail. Instead, Part III of the present paper has been designed to give a relevant summary of problems, unrestricted by the requirements of a chronological review. A majority of the most fundamental ideas about lunar history are at least represented in the literature already reviewed, and a number of more recent papers are referred to in Part III.

III. BRIEF REVIEW OF MODERN WORKING HYPOTHESES: ASSUMPTIONS

In this section some ideas about various aspects of lunar history are reviewed. Appropriate references are given, but the discussion is problem-oriented and not limited by requirements of a complete literature survey or chronological order.

A. Origin of the Moon

The least understood question about the moon is perhaps the most basic: how and where did it form? The question leads back to the dark era of planet formation. A great deal of theorizing and speculating has been done to illuminate events in this era. Most writers assume that the moon's mass was added primarily by gravitational accretion of particles. The source and mass distribution of these particles is uncertain, and locale of formation, relative to the earth, is perhaps the most widely contested point of all.

Hypotheses may be ordered by increasing complexity. Because the earth-moon mass ratio is unique among planets, a problem arises analogous to that in the case of theories of the solar system's origin: how complex, how improbable a set of circumstances actually resulted in the phenomenon?

If one is convinced of the uniqueness of a phenomenon, is he not forced to an intrinsically "improbable" series of events to account for it?

The following list illustrates the variation in proposed accounts of the moon's origin:

1) The earth-moon system is the planetary analog of a binary star; the mass distribution within the protoplanet led to production of two primary nuclei instead of fragmentation into a primary and satellite system (Kuiper, 1951, p.406). After the earth and moon formed, and the protoplanet mass of some 10^{30} grams was dissipated, a sediment ring representing an unconsolidated satellite, of mass about 10^{22} grams, was swept up as the moon receded from the earth under tidal influence (Kuiper, 1954, p. 1110).

2) The moon was accreted from particles captured near the earth in the three-body system of sun, earth, particle. The particles were mostly of diameters in the range 10 to 100 km. (Ruskol, 1961). The density of particles increased toward the earth, and the moon formed from a condensation in the swarm at a distance of about 5 to 10 earth radii (Ruskol, 1963).

3) The moon broke away from the body of the earth due to disturbances of a rapidly rotating earth by solar tides (Darwin, 1898) or formation of a dense core in the

earth (Ringwood, 1960, p.253; Wise, 1963). The material re-consolidated to form the moon outside the Roche limit.

4) The moon was formed as a separate body in the solar system (in a separate proto-planet) and captured by the early earth (Kuiper, 1951, p.406; Urey, 1952, 1960a; Alfvén, 1954). Alfvén places the moon's original orbit just inside that of Mars.

5) The moon was one of the earliest, first-generation bodies formed in the solar system. Most of the other first-generation bodies were disrupted and later formed into other bodies. The moon's low density is characteristic of the early solar nebula, and later bodies incorporated fewer volatiles and had higher densities. In subsequent time, as the present planets were forming, the moon was captured by the earth (Urey, 1962).

6) The moon was formed apart from the earth and captured in a three body process when it and a second body approached the earth. The second body fell into the earth some 10^6 to 10^7 years later and spattered debris which were swept up by the moon, forming craters (Urey, 1965).

In this paper no single hypothesis of the moon's origin is accepted or assumed.

B. Date of Origin of the Moon

Data obtained from isotopic age analysis of meteorites and terrestrial rocks (Anders, 1962) apparently confines the period of planet formation to a relatively short interval of some 10^8 years approximately 4.6×10^9 years ago. There appears to be no substantial reason to question the assertion that the moon formed in this period, and the figure is accepted here.

It has been suggested that the hypothesized, subsequent capture of the moon could have occurred as little as 2 or 3×10^9 years ago (Alfvén, 1955). This figure has been derived in attempts to compute the past orbital dynamics of the earth-moon system. Geological consequences of the event might be visible, but precambrian geology is probably not well enough documented to confirm or disprove it. It is likely that the calculations make erroneous assumptions, especially about the body tides in the earth, and that the moon was orbiting the earth at least 4×10^9 years ago.

C. Interplanetary Environment during the Moon's Formation

In order for planets to have grown at all, the density of the interplanetary medium must have been substantially higher than it is now. The earth today sweeps up material at a rate probably not exceeding 10^{13} grams/yr.

(cf. Mason, 1962, p.1). To accrete an earth of over 10^{27} grams would take more than ten thousand times the age of the solar system. As discussed by Kuiper (1951), the assumption that the present elemental abundances of the planets result from dissipation of a massive solar nebula of cosmic composition implies that the original nebula had a mass of the order one hundred times the present planetary masses, and a correspondingly higher density than the present interplanetary medium. Kuiper (1951, p.376) gives an initial average solar nebula density of 10^{-9} gm/cm^3 and derives 10^{-6} gm/cm^3 as the Roche density which initiates self-gravitational contraction of a protoplanet at the earth's distance from the sun. The material was cold, and snowflake-like particles of ices were probably present (Urey, 1952). Fowler, Greenstein, and Hoyle (1962) conclude that by the time the sun was becoming luminous, i.e. in a stage probably analogous to T Tauri stars, light element synthesis was occurring in planetesimals which had already grown to dimensions 1 to 50 meters and were composed of silicates and oxides in an icy matrix. Ringwood (1960) considers accretion of planetesimals "up to perhaps 100 km. diameter". In the present paper no assumptions are made about the mass distribution of the material accreted to form planets.

Three possibilities can be proposed for the environment of the moon's initial growth. None of these is required by the present study.

1) The moon formed in a nebular medium, the outgrowth of the original solar nebula, in an orbit around the sun (Urey, 1962).

2) The moon formed in the protoplanetary cloud of another planet, in an orbit around that planet, presumably the earth (Kuiper, 1951).

3) The moon formed in a debris cloud broken off of and near to the earth (Ringwood, 1960; Wise, 1963).

D. Origin of Craters and Basins

The huge depressions occupied by maria have been hypothesized to be great tectonic basins (von Bülow, 1957; Fielder, 1963). Alternatively, the circular mare basins (but not the irregular ones) have been ascribed to impacts (Baldwin, 1949, 1963; Urey, 1952; Kuiper, 1954). Hartmann and Kuiper (1962) use the term "basin" to distinguish the large, circular, flooded depressions, usually surrounded by concentric and radial tectonic patterns, from the smaller and simpler craters and the irregular depressions. The present paper presents further evidence favoring the impact hypothesis.

It may be assumed that the great majority of "field" craters visible from the earth (diameter > 2 km.) formed as a result of impacts of bodies from outside the moon. Numerous craters of a few kilometers diameter are held to be volcanic, and these can generally be readily identified morphologically and by the tendency to occur in chains. Ample justification for these remarks is found in the work of Baldwin (1949, 1963), Kuiper (1959), and others, and additional evidence is presented here. The only other (unlikely) alternative which could be reasonably considered is that some collapse or explosion process, internally generated and unknown on earth, created circular craters.

Large numbers of craters a few kilometers in diameter and smaller, frequently occurring in clusters near large craters, have been studied by Shoemaker (1962a, 1965) and are attributed by him to "secondary" impacts of fragments blown out of larger "primary" craters caused by impacts of extra-lunar objects.

Among craters smaller than about 500 meters in diameter, there appear in great numbers shallow, "soft" craters whose origin is still subject to debate. First photographed by Ranger VII in 1964, these range in size down to less than a meter. Other hitherto unrecognized crater types have been found at these small diameters: shallow, cone-shaped pits with relatively pointed bottoms, various depressions of irregular shape, and elongated troughs. There is evidence that impacts, collapses, and drainage pits may all be represented among these smaller objects (Kuiper, 1965, p.49ff.; Shoemaker, 1965, p.115 ff.). These small structures are not considered in great detail here.

E. Origin of Impacting Bodies

Once it was sufficient merely to contrast an impact origin with an internal origin for craters. With our increased knowledge of both the moon and the early solar system, it is now of interest to inquire into the nature of the bodies which struck the moon. Three broad alternatives exist:

1) The impacting bodies were the last fragments of the planet-forming material, either in the solar nebula, in a protoplanetary cloud, or in a swarm resulting from partial disruption of the early earth. Planet formation was thus one continual process, ending with the cratering of which we now see the scars. This has been implicitly assumed in many theories (see also Gilbert, 1893; Ruskol, 1961).

2) The impacting bodies were a fundamentally different group of objects from those out of which the moon formed, and these bodies were unique to the early solar

system. Parameters which could distinquish these bodies might be, for example, location, composition, or mass distribution. Kuiper (1954) proposed that the moon swept up a "sediment ring" of bodies which had not been able to form a second satellite of the earth beyond the moon's initial orbit. Alternatively, the objects might be a group of planetesimals perturbed out of their original orbits in the solar system after they and the planets had formed from smaller bodies.

3) The impacting bodies were members of the same asteroidal and cometary populations which still strike the earth today. The space density of these would be hypothesized to have been higher in early times to account for the large number of craters. In any case, it is clear that some fraction of the lunar craters come from these objects.

In this paper, evidence is presented in conflict with hypothesis 1) and favoring either 2) or 3).

F. Thermal History of the Moon

The subject of planetary thermal histories, especially that of the moon, is presently in a state of flux and some controversy. It is widely held that lava is present in great quantities on the surface (see I, below) and that this is evidence for considerable melting of the moon at some time. Current hypotheses include:

1) The moon was never melted or highly heated. The lava comes from impact-induced melting only, and the non-equilibrium figure implies rigidity since the moon's origin (Urey, 1952, 1955, p.424); Urey, Elsasser, and Rochester, 1959).

2) The moon is one survivor of several pre-planetary objects, whose surfaces only were partially melted by adiabatic compression of gasses in the solar nebula (Urey, 1962, pp.146-147).

3) The moon was at least partially melted by radioactive uranium and potassium isotopes (Kuiper, 1954, p.1101).

4) The moon was at least partially melted by short-lived radioactive isotopes, especially Al^{26} (Brown, 1947; Urey, 1955b; Fish, Goles, and Anders, 1960). Such material may have been produced by nucleosynthesis in the early solar system (Fowler, Greenstein, and Hoyle, 1962). U and K isotopes were less effective than the short-lived isotopes.

5) The moon was heated primarily by tidal friction. Kopal (1963b) calculated that if the effective viscosity of the moon were higher than about 10^{18} gm/cm sec, heating by 1000°K could result from periodic tidal dilation associated with an eccentric orbit. Viscosity much less than 10^{17} gm/cm sec would result in negligible heating. The

viscosity of the earth's outer mantle is estimated at 10^{22} gm/cm sec (Gutenberg, 1951, p.413).

6) The moon was heated primarily by gravitational and accretive heating during its early formation. Ringwood (1960) rules this out for small bodies such as the moon, but believes it may dominate in larger bodies such as the earth and Venus.

Case 3) or 4) will be favored by the evidence presented here, and case 1) will be excluded.

Levin (1962) and Kopal (1962) have pointed out that if the interior of the moon melted, convective cooling could be efficient, and Kopal suggests convective cooling in a period of the order 10^7 years after heating ceases.

G. Internal Structure of the Moon

This subject is closely related to that of the moon's thermal history, but no explicit deductions about the moon's interior are made in this paper. Several possible situations have been proposed:

1) The moon never melted, is homogeneous, and is composed of intrinsically less dense material than the earth. The moon has always been rigid enough to support the non-equilibrium figure.

2) The moon has a heterogeneous but non-layered structure. Inhomogeneities result from incorporation of

bodies of varying density during accretion and are responsible for the non-equilibrium figure. The moon has always been colder and more rigid than the earth (Urey, Elsasser, and Rochester, 1959).

3) The moon has at least partially melted and differentiatied, but has less iron than the earth and hence low density and little or no iron core. Radioactive material may be concentrated in the surface layers if the differentiation was complete enough. The non-equilibrium figure may be supported by surface layers which became sufficiently cool to support the stress soon after the melting stage (Kuiper, 1954). Calculations for varying compositions suggest the liklihood that the moon has at least approached melting near its center (MacDonald, 1961; Kopal, 1962; Levin, 1962; Runcorn, 1963). Some of these suggest that the moon's center is still molten and that convection cells create the non-equilibrium figure (Kopal, 1962; Runcorn, 1963).

H. Composition of the Moon

The mean density of the moon, mass 7.35×10^{25} grams and radius 1.738×10^{8} cm, is 3.33 gm/cm^3 (Wildt, 1961, p.161). The uncompressed density is estimated to be 3.38 to 3.41 gm/cm^3 (Urey, 1962, p.135). Clearly, the density distribution and probably the composition differs significantly from that of the earth, whose mean density is 5.52 gm/cm^3 (Wildt, 1961, p.161). Three possible explanations are:

1) The moon formed earlier than the earth and accreted a higher percentage of volatiles from the early solar nebula. Its composition is more nearly solar than most of the planets (Urey, 1952, 1962).

2) The moon formed in an environment, perhaps removed from the earth, which was more depleted in heavy elements or less depleted in volatiles than the proto-earth as a result of some differentiation process in the solar nebula or protoplanets (e.g. see Fowler, Greenstein, and Hoyle, 1962).

3) The moon's low density results from different differentiation processes inside the earth and moon. Low density volatiles were more effectively lost from the earth (Kuiper, 1953; Ringwood, 1959).

The iron content of the moon has been considered by several authors. Urey (1960b) estimates 10 to 11% by mass; Kopal (1962), 11 to 14%; Levin (1962) about 14%. This compares with 22% and 28% for two groups of chondrite meteorites and about 28% for the earth (Kopal, 1962; Urey, 1962). A model by Levin (1962) proposes an iron core of radius .39 $R_☾$, and Runcorn proposes .06 to .37 $R_☾$; both models, of course, presuppose melting and differentiation.

I. Nature of the Moon's Surface Layers

The maria are held by most students to be lava deposits. This position has also been taken by the author (Hartmann and Kuiper, 1962) and will be defended here. An alternative hypothesis is that of Gold (1955) that the maria are deposits of eroded dust.

The continental surfaces, between prominent craters, were hypothesized by Kuiper (1954) to represent an original, accreted crust, never melted or differentiated. Such a crust would be "a few kilometers" thick, according to Kuiper (1954, p.1101), of "nearly unaltered accreted material". Among larger craters, "there are regions which have never been disturbed by large impacts" (p. 1104). Shoemaker (1962b, p.116) questions this, saying that "all parts of the terrae lying outside of craters may be covered with the rim material or with more distant ejecta from very large craters. The search for an original surface on the moon may prove illusory as it has on the earth". Shoemaker's statement has meaning only if the cratering process is regarded as distinct from the accretion process. If they are held the same, a cratered, rubbly surface will be the original, accreted surface by definition. Kuiper held the cratering period to be a distinct phase of lunar history.

If the surface layers were appreciably heated or melted, the continental surface may be quite distinct from an accreted surface, chemically and structurally, even apart from a layer of more recent ejecta rubble or dust overlying it. An extreme example of such a model is Runcorn's (1963), with a 9.6 km thick granitic crust and a highly differentiated interior. Recent studies implying a lunar origin of tektites have lent support to a more silicic crust than might otherwise be expected (O'Keefe and Cameron, 1962; O'Keefe, 1963). Early conclusions that tektites derive from sedimentary rocks have been revised by recent studies (Chao, 1963; Lowman, 1963) indicating at least compatibility with an origin from silicic igneous rocks. Igneous rocks, especially after darkening by simulated solar irradiation have always given the best fit to the colorimetry of the lunar surface (Sytinskaya, 1957; Hapke, 1964; Binder, Cruikshank, and Hartmann, 1965).

IV. ANALYSIS OF LUNAR CRATER DIAMETER DISTRIBUTIONS

A. Crater Counting as a Tool

The lunar craters offer exceptional opportunities for studies in lunar history. Historical inferences can be drawn from the following crater studies: (1) stratigraphic relationships among obvious rim structures and less obvious ejecta sheets, (2) morphological evidence of distortion of older craters in certain areas, and (3) statistical studies which show differences in distribution in different areas. None of these has been adequately exploited in the past. In 1955, Kuiper (p.823) described as "especially promising the setting-up of local time sequences (based on damage inflicted by object A on object B, etc.) and connecting these time sequences". Information from these three types of work must be ultimately synthesized, and this is attempted in the present paper. Only since 1960 has work in these fields been published at more than sporadic intervals, and there now exist several systematic programs to glean information from planetary crater distributions. Among earlier papers in this field, Shoemaker and Hackman's (1962) on stratigraphy, Fielder and Jordan's (1962) on crater distortion, and Dodd, Salisbury, and Glaser's (1963) on diameter distributions are outstanding examples.

B. A Note on the Mode of Crater Formation

Fortunately for our purposes, success in interpreting crater counts is not completely dependent on the mode of origin of craters. By most accounts, the duration of a single crater-forming process is very much less than the duration of lunar history, as evidenced by overlapping and the paucity of post-mare craters. This is accepted here as fact. Therefore, craters are considered to be good time-markers. More fortunately, the larger craters are almost certainly impact scars, formed suddenly. Most competent students of the moon have felt no need to question this statement since Baldwin's (1949) classic work, which established a morphological similarity between terrestrial explosion craters and lunar craters. Other evidences for impact origin abound, and the list of ancient meteorite craters on the earth is now rapidly growing. The craters on Mars, photographed July 14, 1965 by Mariner IV, are in accord with an enhanced meteoritic flux there. Shoemaker (1965), Kuiper (1965), and LePoole (1965, personal communication) have summarized evidence that most craters smaller than one or two kilometers in diameter are of secondary impact and collapse origin, and this complicates the analysis of small crater distributions. The present paper will derive more evidence bearing on the formation of craters, but the subsequent discussion will be as general as possible, and, wherever feasible, not couched solely in terms of one pre-conceived hypothesis.

C. Sources of Data

The complete compilation of lunar crater diameters (D) for all craters of D > 3.5km by Arthur and his associates (1963, 1964, 1965) provides basic data for many studies of lunar history. Arthur's catalogues are more complete, especially at small diameters, than the catalogues of Young (1953) and others. The statistics studied by Young (1940) and used by others such as Fielder (1961a) and Baldwin (1963), as well as the crater counts in limited regions, e.g. by Öpik (1960), Baldwin, (1963), and Dodd, Salisbury, and Glaser (1963) can now be greatly extended. Arthur and his co-workers have kindly made available the original measures, often in advance of publication, for use in the present paper.

Another invaluable source of data is the library of Ranger photographs taken near the moon by Ranger VII (July 31, 1964, U.T.), Ranger VIII (Feb. 20, 1965, U.T.) and Ranger IX (March 24, 1965, U.T.). These show craters as small as D = 1 meter, and allow the scale of diameters to be extended to six orders of magnitude. However, as described above, many of the craters smaller than D = 1 km are now thought to be of non-meteoritic (i.e. non-primary) origin. Until the many proposed types of smaller craters can be certainly distinguished, they are of limited value for historical interpretation. The Ranger photographs, in the form of negative and positive 35mm films made from originals at the Jet Propulsion Laboratory, Pasadena, are extensively used here.

D. Techniques of Analysis

As pointed out by Young as early as 1940, the distribution of lunar crater diameters is closely logarithmic, i.e. dlogN/dlogD is a constant, where N is a cumulative count of craters larger than diameter D.

This raises the question of how best to compile and present the data. This has frequently been done by cumulative counts of N, as defined above. LogN vs. logD is a linear plot. The use of N has several disadvantages. First, it is in principle a smoothing process because the value at D is dependent on values at all larger D's. Second, if one observes a small area, such as one kilometer square in the Ranger photographs or the interior of a certain crater, one cannot empirically measure the number of say, 10 km craters in that area; thus, small areas do not give a direct measure of the plotted variable. Finally, for many applications, such as spaceship design or lunar erosion studies, one wants to know the number of craters in a given size range. This is presented directly by an incremental plot, but a differential of N(D) must be taken to learn the same information. Other methods of presenting counts purposely introduce an artificial smoothing for the sake of clarity. For example, one can plot the nearly hyperbolic distribution curve on a linear scale and draw a subjective fit, then plotting on a log-log plot the fitted line rather than the scattered points. This has the disadvantage of removing the presented results several generations from the original data.

In this paper, incremental plots are used. Equal log increments in D are chosen first, and then measures divide the craters into these classes, and finally counts determine the number in each class. This has the great advantage that any photograph of any area, from a few meters square to the whole visible disk, if it resolves more than, say, ten craters in a given logD increment, gives a direct, useful statistic. Also, the resulting log-log plots of the statistics show the reader at once the original data, and since the curves are nearly linear, least squares fitting is easy.

It must be remembered that the incremental plot is in essence a histogram, while the cumulative plot is a continuous curve. This is required if the former is to show the actual counts of craters in the chosen D intervals. Yet one may define F, an incremental equivalent of N, as the number / unit log interval. Incremental plots may easily be converted to cumulative plots. It can be shown that the slope of the straight line in the two kinds of plots is in principle, and usually in practice, the same. The demonstration follows:

Let D = diameter (1)

N = cumulative no. craters of diameter > D/area

F = incremental no. craters of diameter in $\Delta \log D$/area

Then given $\Delta \log D$, $\log F = \log \Delta N$

or $F = \Delta N$

But $\Delta \log N / \Delta \log D = \text{const.} = B$ empirically

$$\Delta N / N = B \, \Delta \log D$$

$$\Delta N = N \, \Delta \log D \, B$$

Then $\log F = \log \Delta N = \log(N \, \Delta \log D \, B)$

or $\Delta \log F = \Delta(N \, \Delta \log D \, B)/(N \, \Delta \log D \, B)$

$$= \Delta N / N$$

$$= B \, \Delta \log D$$

so that $B_{incremental} = B_{cumulative}$ (2)

If one chooses enough increments in D, thus forcing ΔD to a small increment, the relation holds. In practice, if the line slopes steeply on the log-log plot, the values of N and F change very rapidly with D, and in fact N may closely approximate F. Experience shows that published log-log plots of N(D) and F(D) have slopes nearly the same within the precision of the data, but in a questionable case, one should compare similar plots.

Finally, the choice of logD increments must be made. If the unit increment is too large, real variations in B are masked and the approximation in Equation (2) is destroyed. If it is too small, statistical variations become noticeable. The writer worked for some time with increments of a factor 2, and was finally convinced that smaller increments would be more useful. Discussions with R. LePoole have been helpful on this point. The present work is therefore treated in increments of a factor $\sqrt{2}$.

Least squares analysis can be applied to plots of F(D). The function is linear as noted above, and is expressed in Equation (1). This can be rewritten

$$\log F = A + B \log D \qquad (3)$$

Let F' be defined as an observed statistic. To simplify notation, define:

$$y = \log F \qquad x = \log D \qquad (4)$$
$$y' = \log F'$$

Then we have the least squares solutions:

$$A = \bar{y} - B\bar{x} \qquad B = \frac{\Sigma(x - \bar{x})\,\overline{\bar{x})^2}}{\Sigma(x - \bar{x})^2}$$

These solutions give estimates of A (the y intercept), and B, (the slope of the log-log function F(D) (cf. Hoel, 1954, chapt. 7). The assumption is made here that the data points are of equal weight. This is not strictly valid, but in nearly all cases the requirement was made that at least 10 craters be counted in the logD increment, and most points represent 3 to 50 times that number of craters. Therefore, most of the data points are held to be of fairly high accuracy. An estimated standard deviation, s, can be obtained for each of these two constants as follows. For the estimated standard deviation of A we have from the definition of s (Hoel, 1954, chapt. 4):

$$s_A = \sqrt{\frac{\sum (y' - y)^2}{n}} \qquad (6)$$

where n is the number of data points. To assign a standard deviation to the slope B, we may use the method of finding confidence limits for hypothetical values of B (Hoel, 1954, p.231). It is known that a Student's t distribution is followed by the variable

$$t = s_B \sqrt{\frac{(n - 2) \; \Sigma(x - \bar{x})^2}{\Sigma(y - y')^2}} \qquad (7)$$

If we find in a table the half-width of the t interval (±t) corresponding to a probability .68, for the given (n - 2), then this t value substituted into Equation (7) gives s_B).

E. Example of a Diameter Distribution Reduction - All Craters

Let us make the rather naive assumption that there are no basic differences among craters - no sub-families which might affect statistics. In this case one would count all visible craters on the moon and determine the distribution law. In the present case, however, only the first three quadrants were available in catalogues at the time of writing.

Foreshortening at the limb of the moon causes a selection effect favoring large craters. Small craters may easily go undetected. This was tested empirically: a camparison of distributions between the whole first quadrant and the central area defined below confirmed that inclusion of limb regions introduced a measurable deficiency of small craters. Therefore limb regions outside a certain boundary in xi-eta coordinates were excluded in all parts of this paper. This restriction is illustrated in Figure 1. The included regions total about 58% of the first three quadrants' surface area. The fourth quadrant, which includes mostly continental regions, will not be available for about six months from the time of writing.

The reduction process will now be described. The frequency F is here defined as follows:

$$F = \frac{\text{incremental number of craters in unit } \Delta\log_{\sqrt{2}} D}{\text{km}^2} \qquad (8)$$

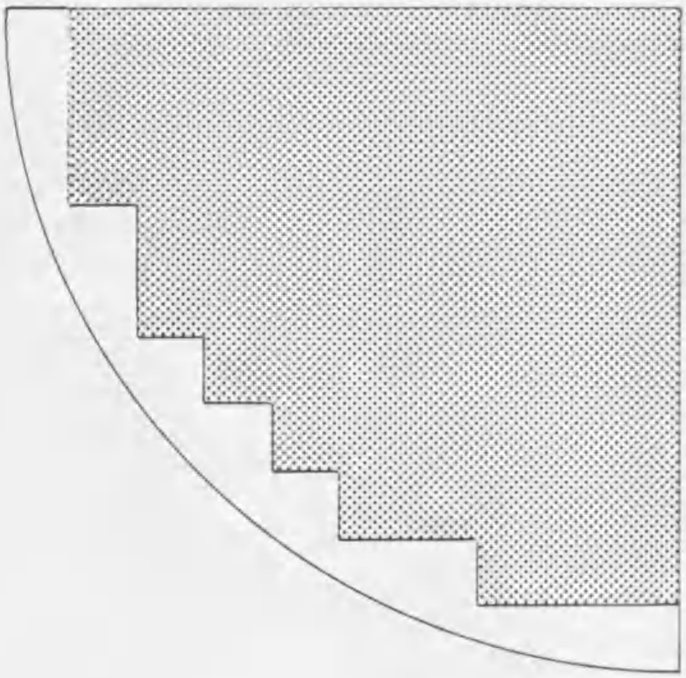

Figure 1. Area used in crater counting.

Limb regions beyond the illustrated xi-eta boundary in each quadrant were excluded to avoid bias in favor of larger craters.

The craters, each recorded on an IBM card, were sorted according to D in one-kilometer intervals, and then sorted into equal log increments to the base $\sqrt{2}$. The sequence in D (km) is thus 1, 1.4, 2, 2.4,... The total area studied was found by counting equal-area blocks in the Orthographic Atlas of the Moon (Arthur and Whitaker, 1960). Each block was two degrees in longitude and 0.01 lunar radius in eta, with an area approximately 1054km^2. The total number of craters in a given log D increment, divided by the total area studied, is a measure of F. The total area in this case, i.e. of the non-limb portions of the first three quadrants, is 8.19×10^6km^2. The same method was used to estimate area in the case of counts of craters with a particular background; for example, in determining F for post-mare craters, the mare area was counted block by block.

A plot of F(D) is shown in Figure 2 for all craters. The calculation of curve-fitting constants A and B is given in Table I as an example. The total number of craters represented in Figure 2 is 6084.

Some discussion of Figure 2 follows. MacDonald (1931) published an early study of the crater distribution using 2154 craters measured by Fauth. Fauth had published his statistics with the craters divided into 15 diameter intervals of different widths. In the analysis, MacDonald

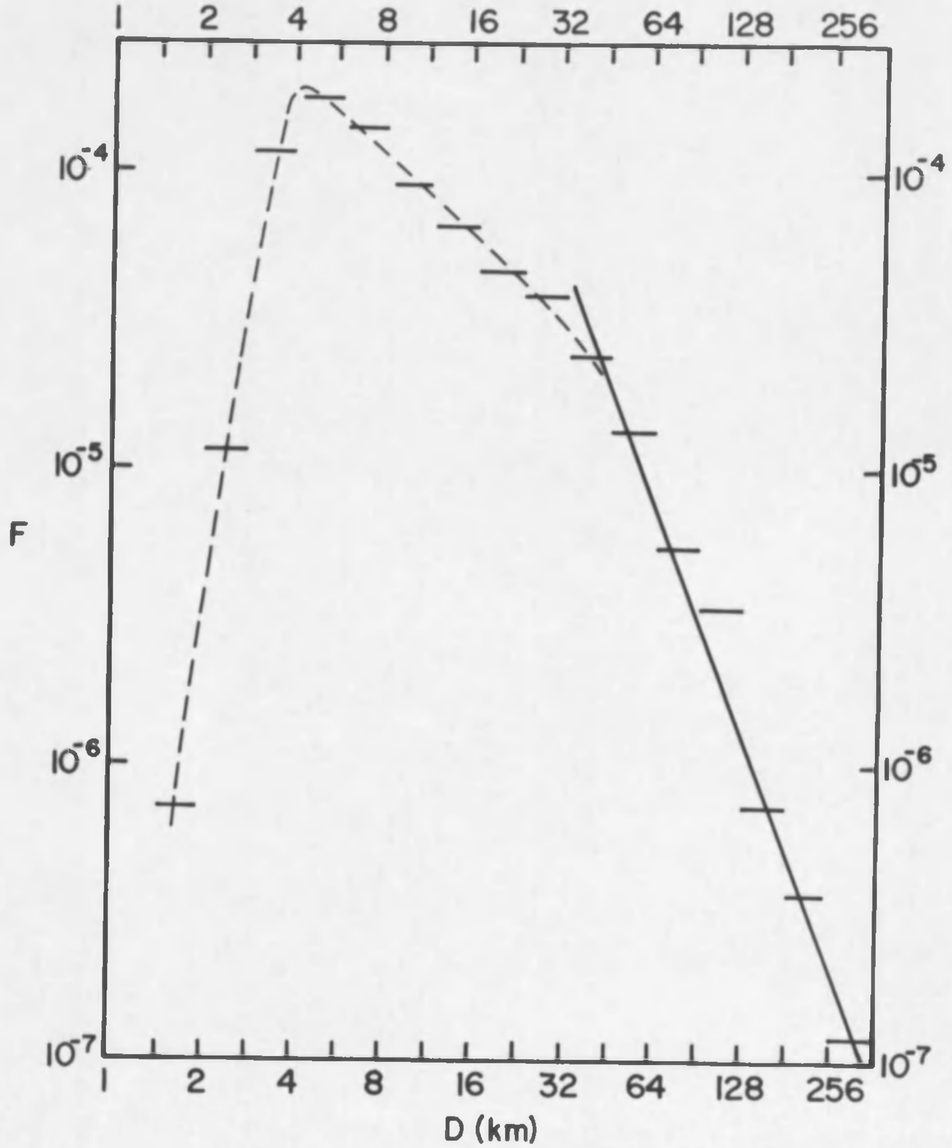

Figure 2. F(D) for all craters; quadrants I, II, III.

Table I. Solution for all craters; Quadrants I, II, III.

D	logD	$\overline{\log D}$ x	F	y'=logF	$(x-\bar{x})$	$(x-\bar{x})y'$	$(x-\bar{x})^2$	Bx	y	(y'-y)	$(y'-y)^2$
32	1.505	1.580	2.48(-5)	-4.605	-0.451	-2.08	0.203	-4.12	-4.49	-0.11	0.0121
45	1.656	1.731	1.34	4.872	.300	+1.46	.090	4.51	4.88	+ .01	.0001
64	1.806	1.881	5.50(-6)	5.259	.150	+0.79	.022	4.90	5.27	+ .01	.0001
90	1.956	2.031	3.42	5.465	.000	0.00	.000	5.29	5.66	+ .20	.0400
128	2.107	2.182	7.34(-7)	6.134	+ .151	-0.92	.023	5.70	6.07	- .06	.0036
181	2.258	2.333	3.67	6.435	.302	-1.94	.091	6.08	6.45	+ .01	.0001
256	2.408	2.483	1.22	6.913	.452	-3.12	.204	6.48	6.85	- .06	.0036
362	2.558										
		14.221		-39.683		-1.65	.633				.0596

$B = -1.65/.633 = -2.61$ $\qquad s_B = 1.109\sqrt{.188} = .474$

$A = \bar{y} - B\bar{x} = -5.669 + 5.301 = -0.368$ $\qquad s_A = \sqrt{.0596/7} = .092$

$$\log F = -.368 - 2.61 \log D$$

$$A = -0.368 \pm .092$$

$$B = -2.61 \pm .47$$

divided the number of craters in each interval by the width of the interval, thus defining a parameter

$$n = \frac{\Delta N}{\Delta D}, \tag{9}$$

the number of craters per kilometer interval in D, using the definitions in Equation (1), p.43. Now let

$$\begin{aligned} & \Delta N = \text{number of craters in } \log D \\ \text{and} \quad & \Delta D = \text{logarithmic interval of } D = cD \\ \text{where} \quad & c = \text{arbitrary constant} \end{aligned} \tag{10}$$

Then the slope in this sort of analysis will be

$$\frac{d\log n}{d\log D} = \frac{d\log\frac{\Delta N}{cD}}{d\log D} = \frac{d(\log\Delta N - \log c - \log D)}{d\log D}$$

$$= \frac{d\log\Delta N}{d\log D} - 1 = B - 1 . \tag{11}$$

Thus, the slope found by the method of MacDonald is more negative (steeper) by one than B, used here and defined originally in Equations (1) and (2). The method used by MacDonald is still in use, notably in a new study being conducted at Smithsonian Astrophysical Observatory (C. R. Chapman, private communication, 1965).

MacDonald discovered the power law distribution, noted a "falling off" of craters at diameters larger than about 50km, and suggested that a "significant excess" of craters between 35 and 45km marked a break which appears in "almost all relations so far established for lunar objects". He also raised the possibility that the excess, or break, marked a division between "craters and walled plains".

Young (1940) used MacDonald's techniques and Equation (9) to analyse his own measures of 1166 craters. In his diagram including all craters, he recognized MacDonald's excess as a discontinuity or maximum curvature, and placed it at about 50km. Young (p.316) repeated the suggestion that this discontinuity might divide two different classes, the "walled-plain and ringed-plain types of craters". Fielder (1961, p.219), using the same data, confirmed the discontinuity and also implied a possible anomaly in the original population of craters. Figure 2 shows the discontinuity at about 32km. However, as pointed out in an earlier report on this work (Hartmann, 1964a, p.202) the mixing of all craters in a diagram of this sort complicates analysis. The initial assumption of no statistically important sub-families is wrong: there are post-mare craters, older continental craters, etc. The discontinuity in Figure 2 will be linked later to the presence of the old, continental craters in the sample.

For the slope, B, MacDonald gave a value corresponding to -0.9 averaged over all craters of D $\geq$ 5km, and Young, -1.5 for all craters of D > 16km. As mentioned above, these values, which average over the entire available range in D, neglect the discontinuity and are of little interpretive value. It is the straight segment of the curve at large D, whose slope is most likely to be significant. For this segment, Young's value corresponded to B = -2 (D > 50km); the present study gives -2.6 ± 0.5 (D > 32km), as found in Table I. Modern determinations are probably more accurate than the early studies; the early catalogues of craters were incomplete. Certainly more meaningful figures can now be obtained than Young's -1.5, which has been recently quoted and applied (Jaschek, 1960). The preceeding four paragraphs update and correct several points in the earlier report (Hartmann, 1964, p.2).

The other fitting constant, A, has little meaning in this case because sparsely cratered maria are mixed with highly cratered continental areas. However, A is derived in Table 1 as an example.

F. Summary

Lunar craters of different types are useful in defining periods of lunar history. It is important to distinguish carefully the type of crater being counted. Because virtually all large craters (D > 2km) mark primary impacts, and because the smaller craters are of mixed and often uncertain origin, the largest craters are especially useful for historical interpretation. An interesting property of the log-log diameter distribution is its linearity, allowing easy least squares fitting.

When all craters (excluding limb regions) are counted, a linear branch with $D > 32$km and slope $B = -2.6 \pm 0.5$ is found. The computation of these figures is presented in detail in Table 1, which serves as an example of the method.

V. A FUNDAMENTAL DIAMETER DISTRIBUTION - POST-MARE CRATERS

It has just been suggested (in the discussion of Figure 2) that one cannot easily interpret crater counts if they are made without regard to regional background, crater density, or crater structure. One regional background stands out as the crater counting surface <u>par excellence</u>: the maria. They are smooth, uniform, and relatively featureless. Visual inspection shows that post-mare craters cover only a small fraction of the total area, so there is no distortion of the distribution function by overlapping; yet enough area and enough craters are present to give good statistics. The craters are well-preserved, and appear for the most part to be of similar structural type.

Significantly, there is not a wide spread among crater densities on different maria. Post-mare crater distribution is relatively uniform at a much lower density than the continental crater distribution, as can be confirmed by visual inspection of photographs. This suggests that the mare surfaces all date from a restricted period in lunar history, a hypothesis which will be examined in greater detail in Chapter VII.

Most of the mare surfaces occur in the first three quadrants of the moon, and as complete crater catalogues of these were available (cf. Chapter IVC, p.40), the present study of the distribution of large post-mare craters is virtually complete (pending photographs of limb and far side regions by lunar probes).

F(D), defined in Equation (8), is found to have the following form for post-mare craters of $D > 4$km counted on earth-based photographs of mare surfaces in the first three quadrants (excluding limb regions; cf. p. 46):

$$\log F_{PM} = -3.15 - 1.77 \log D \tag{12}$$

$$A = -3.15 \pm 0.10$$

$$B = -1.77 \pm 0.09$$

The Ranger photographs extend the available diameter range more than three orders of magnitude. Ranger VII landed in Mare Cognitum, and Ranger VIII, in Mare Tranquillitatis. The combined measures, from both earth-based and Ranger photographs, for all post-mare craters are shown in Figure 3.

Figure 3 includes a rather comprehensive set of measures of Mare Cognitum craters, most of which were made in the six months following the Ranger VII flight. A few measures of Mare Tranquillitatis craters were added after the Ranger VIII flight. In these measures, all crater-like depressions were counted. It soon became apparent that the "soft", shallow depressions, constituting the

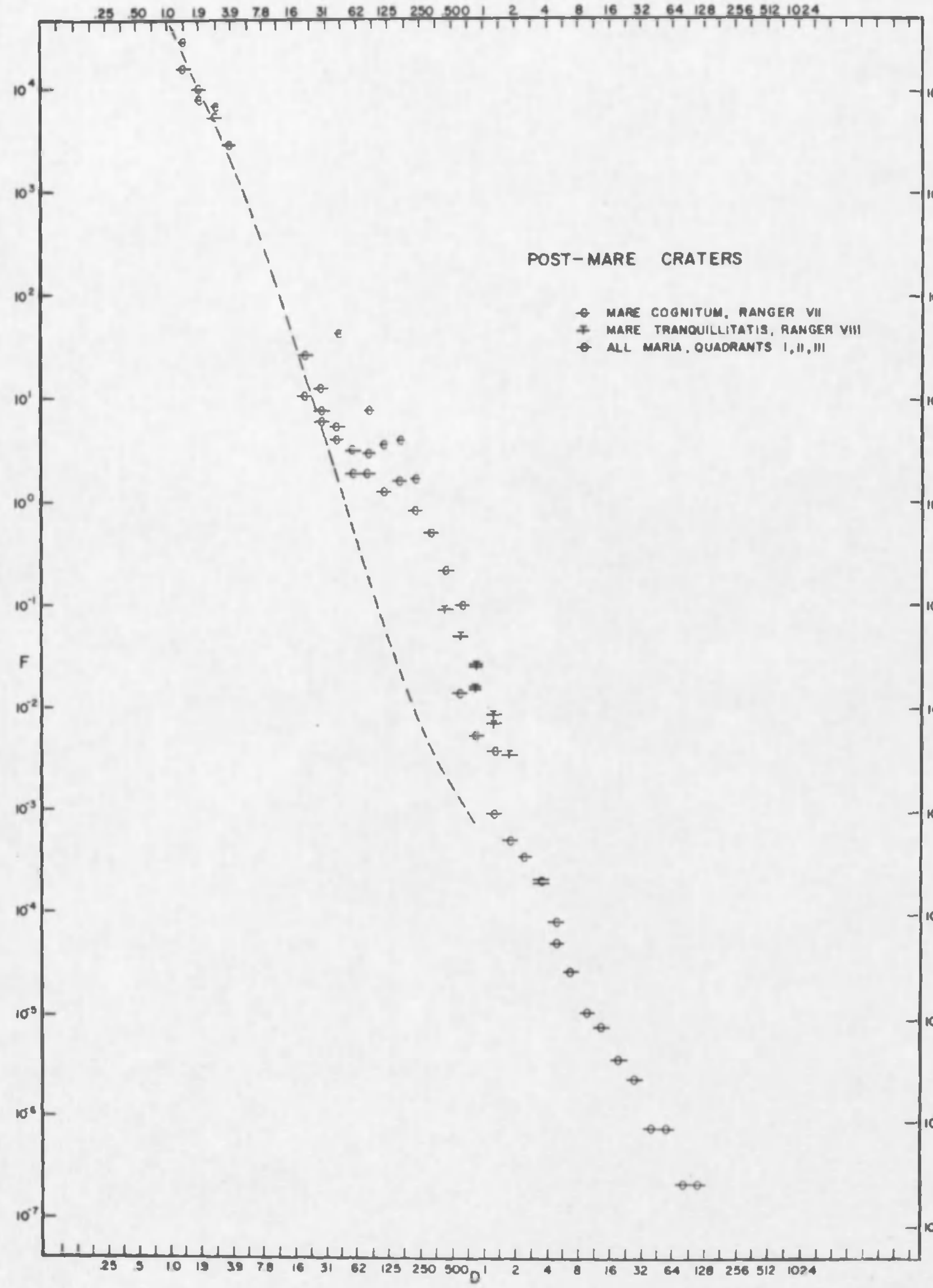

Figure 3. F(D) for post-mare craters.

Dashed line includes "sharp" craters only. Other points include all visible depressions.

majority of the structures between 16 meters and 1 kilometer diameter were of uncertain origin. It has since appeared likely that the "soft" craters are different, genetically as well as morphologically, from the "sharp" craters, which are assumed to mark primary impacts. There has been not only uncertainty but also some controversy over the origin of craters of $D < 1km$, and various mechanisms have been proposed, including primary impacts, secondary impacts, collapse, and drainage. Probably all of these types are present; evidence is accumulating that many "soft" craters are collapses typical of certain terrestrial lava flows (Kuiper, private communication, 1965). Several crater types are illustrated in Figure 4.

The soft craters are a universal feature of surfaces which have a smooth, mare-like appearance as seen from the earth. They appear both on the true, dark mare surfaces and on the light but level regions found in the uplands, e.g. the floor of Ptolemaeus and nearby depressed zones, but they are not found on light and hilly true continental surfaces. The light, smooth areas, intermediate in several ways between mare and continental surfaces, remain a puzzling feature of the moon.

Until the origin of all craters of diameter less than a kilometer is clearly understood and agreed upon, they remain of limited use for historical interpretation. Accordingly, they are not considered in much further de-

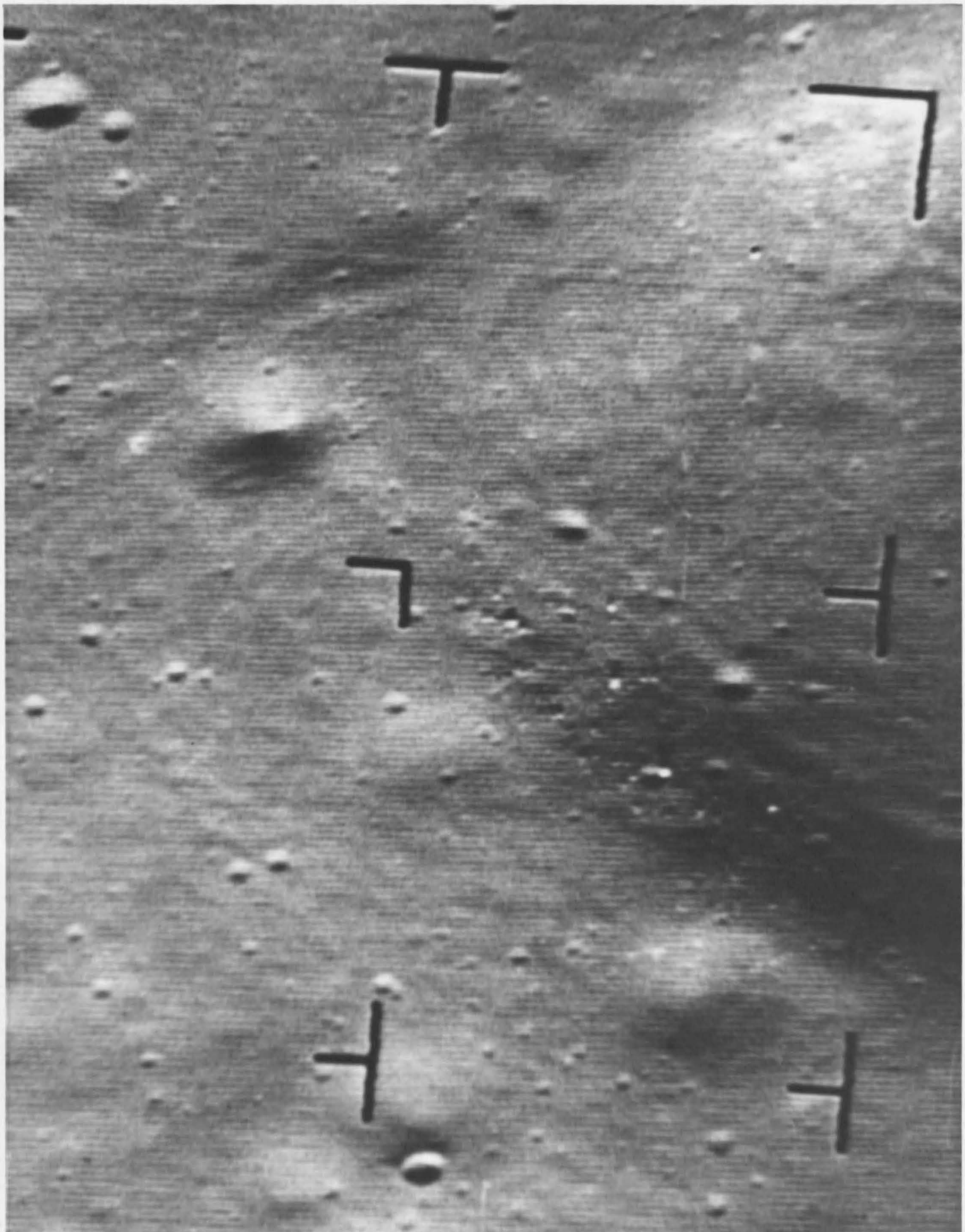

Figure 4. Crater types (Mare Tranquillitatis; Ranger VIII).

This illustrates sharp (bottom), dimple (upper left center), and numerous soft (scattered) craters. Some unusual rubble appears on the inner wall of a large crater (center right).

tail here. However, it is of at least qualitative interest that the "sharp" craters can be counted separately. They can be selected by subjective, yet repeatable criteria (R. LePoole, private communication, 1965). Recent unpublished measures by LePoole have been converted by the author to the units used here, and the result, included in Figure 3 as a dashed line, serves as an estimate of the frequency of primary impact craters.

The first photographs in each Ranger sequence show large enough areas that statistics may be obtained on craters of diameter one kilometer and larger, i.e. primary impact craters. Therefore, least-square solutions may be obtained for mare regions smaller than described in Equation (12). For Mare Cognitum, applying the restriction $D > 1.4$km, we find from Ranger VII and earth-based photos,

$$\log F_{PM\ \mathrm{Cognitum}} = -2.62 - 2.17 \log D \qquad (13)$$

$$A = -2.62 \pm 0.09$$

$$B = -2.17 \pm 0.23$$

Of Equations (12) and (13), the first should be taken as the more significant for general usage because of the greater area covered. $B = 2.0$ may be taken as an average value of the slope for all post-mare craters of $D > 1$km, with an estimated S.D. of 0.2.

VI. METEORITIC MASS DISTRIBUTIONS - PREDICTION OF SLOPE B OF CRATER DIAMETER DISTRIBUTION LAW

A. Meteoritic Data

The following definitions will be used:

M = mass of any impacting body (14)

$f(M)$ = incremental frequency parameter for interplanetary bodies (units defined in Chapter VIII to give a cratering rate - impacts/km^2/10^9 yr.) analogous to $F(D)$.

When it is necessary to specify certain types of interplanetary bodies, subscripts will be used. We may define

$$d\log f / d\log M \equiv b \qquad (15)$$

In the discussion of this chapter, b is the most important parameter of the interplanetary material, and the units of f can remain arbitrary. Observations suggest that for various types of interplanetary material, and for various mass ranges accessible to observation, b has various constant values. Therefore if all types of interplanetary masses striking some planetary surface are considered together, the log-log plot of f(M) should show linear segments. Some of the relevant observations and determinations of b are described below.

In the last chapter, craters of $D > 1$km were discussed. As will be shown in Chapter VIII this corresponds to a mass range of $M > 1.5 \times 10^{11}$gm, approximately. This lower limit for the mass range studied here is of the same order as the mass of the Tunguska comet fall of 1908, and more than a thousand times greater than the largest observed meterorite fall, Sikhote-Alin, 1947 (Krinov, 1963). A lunar crater of D = 128km, the upper limit for post-mare craters in the last chapter, requires a mass of about 10^{18} grams. Therefore we must find b characteristic of small asteroids and cometary nuclei in the mass range 10^{11} to 10^{18} grams.

Öpik (1958, 1960)tabulated fluxes diameter distributions of bodies in this mass range near the earth. According to his estimates the cometary flux exceeds the asteroidal flux at M $\gtrsim 3 \times 10^{15}$gm, and the value of b is, approximately, -0.53 for small asteroids, -0.83 for asteroids of M $> 10^{21}$gm, -0.9 (uncertain) for Apollo asteroids, and -0.7 for comet nuclei. Brown (1960) concluded that both stone and iron meteorite falls (M $\leq 4 \times 10^{6}$gm) are characterized by b $\simeq$ -0.76, and in an analysis of asteroid observations by Kuiper and co-workers, Brown again found b = -0.76. Hawkins (1963) analyzed stone and iron falls and concluded that b for stones is about -1.0, but for irons, about -0.7. According to Hawkins, comets outnumber stones for M $\gtrsim 10^{14}$gm, but irons outnumber both at all masses $\lesssim 10^{10}$gm. Kiang (1962) reviewed published asteroid counts, extended these with new counts, and found the slope in a logN - magnitude diagram to be 0.375 over a range of ten magnitudes from the sixth brightest asteroid on down. Multiplication by -5/3 converts this slope to a b value, namely b = -0.63 for asteroids of $M \gtrsim 10^{13}$gm. Marcus (1965) attempted to show mathematically that accreted planetesimals would have b between -0.33 and -1.0, and that during collisions the value of b approaches -0.67. Finally, we note that the linearity of the post-mare crater distribution in Figure 3 testifies to the constancy of b over the entire mass range 10^{11} to 10^{18}gm, and to the probability that one type of object is responsible for most craters of D > 1km. Table II summarizes the available information about b.

Neither the nature of the impacting masses nor the value of b is certain. Whether the masses are cometary or asteroidal, the value of b is probably between -0.55 and -0.80. If the particles are asteroidal, or have the mass distribution characteristic of asteroids, the value of b is probably close to -0.63, although we have no guarantee that the Apollo asteroids, which have been ejected from the Mars-asteroid region by perturbations and pass near the earth, have exactly the same b value as the asteroids in the surveys used by Kiang.

Table II: Mass Distribution of Interplanetary Objects

The table gives values of b, defined in Equation (15) for various mass ranges. The mass range for post-mare craters of D > 1km is roughly 10^{11} to 10^{18}gm.

Type of Object	Reference	Approx. Mass Range (gm)	Estimated b
All Meteorites	Opik (1960)	$<5 \times 10^{6}$	-1.1
Stone Meteorites	Brown (1960)	$< 10^{6}$	-0.77
	Hawkins (1963)	"	-1
Iron Meteorites	Brown (1960)	$<5 \times 10^{6}$	-0.76
	Hawkins (1963)	"	-0.7
Apollo Asteroids	Opik (1960)	$\sim 10^{15}$	-0.9?
	Hawkins (1963)	"	-0.7?
"Mars" Asteroids	Opik (1960)	$10^{16} - 10^{21}$	-0.53
	Brown (1960)	$10^{14} - 10^{21}$	-0.75
	Kiang (1962)	$10^{13} - 10^{21}$	-0.63
Comet Nuclei	Opik (1960)	$>10^{17}$	-0.7

B. Cratering Theory

In addition to the definitions of Equations (1) (p. 43), (14), and (15) (p. 61), let

E = energy available to form crater (16)

V = velocity of impacting body at impact.

It has been found that in large terrestrial explosion craters

$$D = \text{const. } E^k \quad (17)$$

This equation will be discussed in more detail in Chapter VIII, part D. As shown there, k for post-mare lunar craters of D > 1km probably lies between 1/3.1 and 1/3.5.

C. Prediction of Lunar Crater Diameter Distribution

Assume that the full kinetic energy of impact is applied to crater formation. Then

$$D = \text{const. } (\tfrac{1}{2}MV^2)^k \quad (18)$$

Assume some constant, modal impact velocity can be used to describe all impacts. Then

$$D = \text{const. } M^k \quad (19)$$

But $$f(M) = \text{const. } M^b \quad (20)$$

Thus $$F(D) = \text{const. } D^{b/k} \equiv \text{const. } D^B \quad (21)$$

Equation (21) predicts the slope B of the log - log plot of F(D) for lunar craters (i.e. Figure 3), for diameters ≫ 1km.

With b ranging from -0.55 to -0.80 and 1/k ranging from 3.1 to 3.5, we would predict

$$B = -2.2 \pm 0.3 \text{ (estimated S.D.)} \qquad (22)$$

if the nature of the impacting masses is unknown. If the impacting masses have an asteroidal mass distribution, then b is -0.63, and we predict

$$B = -2.1 \pm 0.1 \text{ (estimated S.D.)} \qquad (23)$$

From Chapter V, we may take the observed value as

$$B_{obsvd.} = -2.0 \pm 0.2 \qquad (24)$$

It is concluded that the post-mare lunar craters resulted from the impacts of objects having a mass distribution very close to that presently observed among the asteroids (beyond Mars). The objects are indeed hypothesized to be predominantly Apollo-type asteroids, perturbed from the region of Mars.

D. Comparison with Other Results

Jaschek (1960) made an analysis similar to that above and reached virtually the same conclusion, namely that the asteroidal mass distribution predicts the lunar crater diameter distribution. However, his paper may now be criticized on several grounds: For B he applied Young's value of -1.5, which has been shown (Chapter IV, p.53) to be rather meaningless. For 1/k he applied 2.5, which is much lower than acceptable modern values. Incidentally, Jaschek concluded that for smaller (meteoritic) masses, the Poynting-Robertson effect would make b more negative and attributed an observed value of -1 to this. Actually, the Poynting-Robertson effect would make the slope more gentle for small masses; b would be more positive. The probable steepening in slope from about -0.6 for large masses to about -0.9 for meteoritic masses indicates that the Poynting-Robertson effect is not noticeable in mass distributions for observed objects of $M \geqslant 10^4$gm (lower limit of Brown's statistics).

Shoemaker, Hackman, and Eggleton (1962) improved Jaschek's calculations, and predicted a slope B = -2.7. Their crater counts did not confirm this and they therefore concluded that the mass distribution of the crater forming objects was significantly different from that presently observed among small solar system objects. The improved data used here render this conclusion doubtful.

Öpik (1960), independently concluded that the craters were of primarily asteroidal origin. His method was to list diameter distributions of interplanetary objects, noting that B in the crater diameter distribution equals the exponent in the asteroid diameter distribution. To argue that this implies an asteroidal origin for craters is to assume that k in the energy scaling law (Equation 17) is 1/3, somewhat higher than the value accepted here.

VII. NATURE AND RELATIVE AGES OF MARIA

A. Evidence for Lava Flows

The following list summarizes evidence in favor of the hypothesis, accepted here, that the maria are lava flows produced for the most part during a high temperature period of lunar history. The crater distribution observations are readily explained in this paper by this hypothesis. Conclusive evidence can come only through petrologic analyisis of mare rock samples.

1) Color and albedo differences across the lunar surface prove that a variety of surface material is present. The moon is blanketed neither by a uniform layer of cosmic material nor by a uniform layer of lunar material.

2) The colorimetry and photometry of the lunar maria is consistent with that of terrestrial lavas (Sytinskaya, 1957) which have been discolored by irradiation (Binder, Cruikshank, and Hartmann, 1965). Most other terrestrial rocks, especially non-igneous rocks, do not show lunar characteristics at all.

3) Individual units in the maria, mapped by slight color differences brought out in special photographic techniques (E. A. Whitaker, unpublished), are bounded by scarps of very low relief, on the order of 10 meters. These units

are interpreted as individual flows of the thickness indicated by the relief (Kuiper, 1965).

4) Mare material is found in several cases at the foot of tectonic fault scarps - a natural location for lava extrusion (Hartmann, 1964b, c). Instances are arcuate maria at the foot of a concentric scarp around Mare Orientale and a patch of mare material at the foot of a scarp radial to the Humboldtianum basin.

5) Remnant flow structure appears to be visible in high resolution Ranger photographs (Kuiper, 1965). Kuiper refers to this as a "tree bark" pattern.

6) "Soft", shallow craters and conical shallow craters of the type shown in Ranger photographs have been found in terrestrial lava flows (Kuiper, 1965 and in press).

7) That the ratio of displaced lunar mass to impacting mass in a typical impact event is large, possibly of the order 10^3, explains the fact that the moon is not blanketed by a uniform cosmic layer. Yet the mare material cannot simply be eroded matter collected in depressions, as proposed by Gold (1955), because many low areas show no trace of it. Structural and color features in the maria also argue against this hypothesis.

8) The lava did not result from impact melting, as proposed by Urey (1952, 1962). Variations in Archimedian (post-basin, pre-mare) crater density in various basins are much greater than variations in post-mare density; this

shows that the basins pre-date the mare surfaces by widely varying amounts.

9) Present understanding of planetary evolution predicts a high or maximum temperature period for the subsurface layers, resulting from radioactive heating. This provides a natural explanation for a mare epoch, a period of widespread lava flooding.

10) Morphological studies of certain flooded and partially flooded craters, and of lineament systems, suggests that prior to flooding by mare material, great regions of the crust broke, sometimes along pre-existing fractures (Spurr, 1945a, b, 1948; Hartmann, 1964b, c). This is consistent with observation of terrestrial lavas and with theoretical expectations of lunar expansion due to heating (Hartmann, 1964b, c; cf. Urey, 1955a).

11) Certain craters (e.g. Kirch, Aristillus) appear to be post-mare and yet are partly flooded. They are not post-basin, pre-mare craters. (Were this so, they would not be so well preserved. For each large Archimedian crater, e.g. Plato, Archimedes, many smaller ones must have been formed as shown by Equation (12). The smaller ones have been destroyed by the flooding, and isolated examples in an excellent state of preservation would not be expected.) Therefore, the partial flooding suggests that the maria lavas were laid down in successive flows, in accord with 1), 3), and 5) above.

B. Relative Ages of Mare Surfaces

The density of impact craters on mare surfaces is a measure of the surface's age. Therefore maria may be ordered by increasing age if post-mare crater densities are found to vary significantly. This is indeed the case.

Absolute ages cannot be found, nor can it be said that Mare A is X times older than Mare B, until variations in meteoritic flux with time, if any, are known. Fielder (1963), for example, has attempted to derive the ages of maria by crater densities and concludes that "it is unlikely that any mare is older than 7 x 10^8 years", and that differences in age of a factor seven exist over large regions. These conclusions rest on the assumption that the interplanetary flux was constant from the beginning of the moon's surface's formation and are almost certainly wrong, as indicated by this paper (cf. Chapters X and XI).

Several studies of crater density variations have been published and data extracted from these is used here. Fielder (1963) used Young's data for craters of D $\geqslant$ 10km. Baldwin (1963) used Shoemaker and Hackman's data for craters of D $\geqslant$ 1.6km, but he published raw data which allow comparisons of crater densities for several lower limits of D. Dodd, Salisbury, and Smalley (1963) made complete studies for several selected mare areas. Equation (13) of this paper provides data for Mare Cognitum.

The studies to date are neither definitive nor consistent. If too large craters only are counted, not enough are available for good statistics; Fielder's data suffers from this fault. If too small craters are included, observational errors become significant; Baldwin's listing of maria may be criticized for this. Ordering the maria by relative crater density using Fielder's and Baldwin's tables yields only roughly similar results. Mare Serenitatis, the youngest in Fielder's table is slightly older than average in Baldwin's. Dodd, Salisbury, and Glaser give plots of F(D) which are more thorough than the tables of Fielder and Baldwin, but only a few areas were studied.

For these reasons a new listing is presented in Table III. The data given in the references described above has been reanalyzed as follows. The total number of craters / km^2 with $D > 4km$ and several other lower limits was computed from the available data. The average crater density for all maria was computed by dividing the total number of craters counted by the total area. Observed counts are expressed in Table III as fractions of the average. In the reduction of the counts by Dodd, Salisbury, and Smalley and by Hartmann, the average crater density over all maria was determined from this paper. It appears that the best determination is given with a lower limit of about 4km, large enough to be readily resolved but small

Table III. Crater Densities on Different Mare Surfaces

Reference:	RBB	RBB	WKH	DSS	RBB	GF	RBB	Value assumed here
Lower limit D: (km.)	1.6	3.2	4	4	6.4	10	12.8	
M. Serenitatis	1.03	.76		.61	.34*	.28*	.24*	.7
P. Epidemiarum	.77	.76			.71		.71*	.8
M. Humorum	"	"			"	.53*	" *	.8
M. Nubium	"	"			"	.54*	" *	.8
M. Crisium	.92	.70			.74*	.91*	.94*	.8
O. Procellarum						.73		.9
M. Imbrium	1.01	.95		1.06	.74	.78	.72*	.9
M. Nectaris	1.11	.96			.38*	.86*	.40*	1.0
M. Frigoris	1.10*	1.26		1.57	1.52	1.13	1.69*	1.4
M. Foecundit.	.99*	1.14			1.52	1.62*	.97*	1.5
L. Somniorum	1.10	1.26			1.52	2.10	1.69*	1.6
M. Tranquill.	1.20	1.37			1.73	2.16*	1.73*	1.7
M. Cognitum			1.96					1.8
Appendix								
M. Seren., outer dark zone				.54				.6
M. Seren., central portion				.69				.7

Notes:

Values in this table are $\frac{\text{crater density observed}}{\text{average crater density, all maria}}$

* Values given less weight because of paucity of craters, foreshortening, etc.

notes on Table III (cont'd.)

RBB: Baldwin, 1963, p. 296

WKH: This paper

DSS: Dodd, Salisbury, and Smalley, 1963.

GF: Fielder, 1963a

Baldwin grouped Palus Epidemiarum, Mare Humorum, and Mare Nubium in a single count. The same applies to Mare Frigoris and Lacus Somniorum.

Maria are listed in estimated order of increasing age. However, relative crater density is not expected to be directly proportional to age.

enough that many craters can be counted, thus maximizing accuracy.

The youngest surfaces are at the top of Table III, and the oldest, at the bottom. To repeat, the age is not directly proportional to the relative crater density because the meteoritic flux was probably not constant during the mare-forming period. From Table III, it is concluded that the major maria differ in crater density by not more than a factor three (at least when integrating over large areas). Because the high crater densities probably result from early intense bombardment (Chapter XI), not great age, it is concluded that the ages of major maria vary by not more than a ratio 1.2 to 0.7, i.e. less than a factor 1.7.

It is interesting to note that the irregular maria stopped their flooding first, by considerable margins. Of the circular basins (whose ages are discussed in Chapter XIII), the younger have mare surfaces of average age, while some of the older apparently have the youngest mare surfaces. In this context, a result of Dodd, Salisbury, and Smalley should be pointed out: the lighter surface in central Mare Serenitatis is younger than the dark border (see Figure 5).

It happens that one of the oldest and one of the youngest mare surfaces are juxtaposed. Figure 5 shows these two - Mare Tranquillitatis and Mare Serenitatis,

Figure 5. Old and young mare surfaces.

Mare Tranquillitatis (center) has higher crater density and presumably greater age than Mare Serenitatis (upper left).

VIII. DETERMINATION OF CRATERING RATE FOR LARGE CRATERS - CALCULATION OF ABSOLUTE MARE AGE

A. The Canadian Shield as a Meteorite Counter

The flux of meteoritic material onto planetary surfaces during the history of the solar system must be known in order to establish any theory of planetary evolution, and, as discussed by Shoemaker, Hackman, and Eggleton (1962), it may provide a dating method of importance comparable to isotopic dating.

Determination of the present rate of infall of large objects by direct observation is nearly impossible because of the scarcity of large falls. No visible crater has been definitely seen to form on the moon, and records of large crater formation on the earth are also nonexistent. Neither of the two largest recorded falls in recent history resulted in a major observable crater. The Tunguska fall of 1908 was probably cometary, and although its mass was exceptionally large for a fall, the interaction between the atmosphere and this loosely bound object greatly reduced the potential for crater formation (Krinov, 1963). The Sikhote-Alin fall of 1947 was much less energetic, and involved a nickel-iron meteorite of some 7×10^7 grams mass with an initial fall velocity of 14.5 km/sec (Krinov, 1963). This could suffice to form a crater of 100 meter diameter, neglecting energy losses to the atmosphere (see part D, below). However, in fact, the object began to break up in flight and the largest of many craters was 26.5 meters in diameter (Krinov, 1963). Thus, observations of presently falling objects are of little use because (1) not enough big objects fall, and (2) even the biggest objects observed lose a great deal of energy in passing through the atmosphere, so that resulting crater diameters are not representative. An alternate method is the use of old exposed surfaces of known age as counters. This technique has the advantage that one integrates over time back to the origin of our counting surface, and thus can get average values applicable to appreciable fractions of solar system history.

The shield areas of the earth, being exceptionally ancient stable areas where mountain formation has ceased, are ideal counting surfaces. The Canadian shield is the best studied of these. Three major provinces are distinguished by the clustering of isotopic age determinations around three values in three different regions (Stockwell, 1962). Each clustering indicates a period of orogeny accompanied by folding and metamorphism of existing rocks, and intrusion of new material. In the Kenoran province this occurred 2.5×10^9 years ago; in the Hudsonian, 1.7×10^9 years; in the Grenville, 0.95×10^9 years. Because the uncertainty in dating is estimated by Stockwell at $\pm 0.15 \times 10^9$ years, it is immediately apparent that our determinations of flux can scarcely have more than one significant figure.

Since the time of the last orogeny in each province, listed above, each has been stable in spite of subsequent orogenies in neighboring provinces. Peneplanation must be nearly completed in each province before that province becomes a good counting surface, and therefore the exposure age is less than the time since orogeny. As typical peneplanation times can run well over 10^8 years, this correction is worth investigating. Table IV shows the estimated exposure age in each province. The corrections applied in the oldest provinces are the largest to compensate for longer erosion times after peneplanation.

B. Crater Survival

Craters of diameter less than a certain limit are useless in this work because they could not have survived erosion throughout the exposure age of the counting surface. This lower limit on the diameter is estimated in the following way.

A catalogue of all suspected impact craters was listed for each. Log diameter was plotted against log age in an attempt to find an age limit marking the longest

Table IV. Exposure Ages in the Canadian Shield

	Time since Orogeny	Age of oldest overlying rocks (10^9yr)	Estimated mean exposure age (10^9yr)
Kenoran Province	2.5 ± .15	2.5 to 1.7	2.0
Hudsonian Province	1.7 ± .15	1.7 to 0.9	1.4
Grenville Province	0.95 ± .15	< 0.9	0.75

survival at any given size. It is important to note that it is not crucial to include only genuine meteorite craters, since we are interested in measuring the survival time of any structure of impact crater morphology. Also, because the age scale ranges over nine orders of magnitude, the estimated age can be off by at least one order and still be of use. Because the suspected impact craters in the Canadian shield were detected by aerial survey, the survival time to be measured is defined as the time after which a circular structure is still recognizable by surface expression, given optimum survival conditions such as those in a stable shield area.

Figure 6 shows the log diameter - log age plot for craters known to be meteoritic and for structures of less certain origin. As expected, the small craters are typically young, because they can resist erasure for only short periods. The line defines the upper limit of survival time under optimum conditions. Figure 6 suggests, at least by extrapolation, that a crater larger than 10 km diameter should be able to survive throughout the history of the Canadian shield; even if such a crater formed in the Kenoran province immediately after peneplanation, we should still see it. Therefore, the counts made here will be restricted to craters of diameter larger than 10 km.

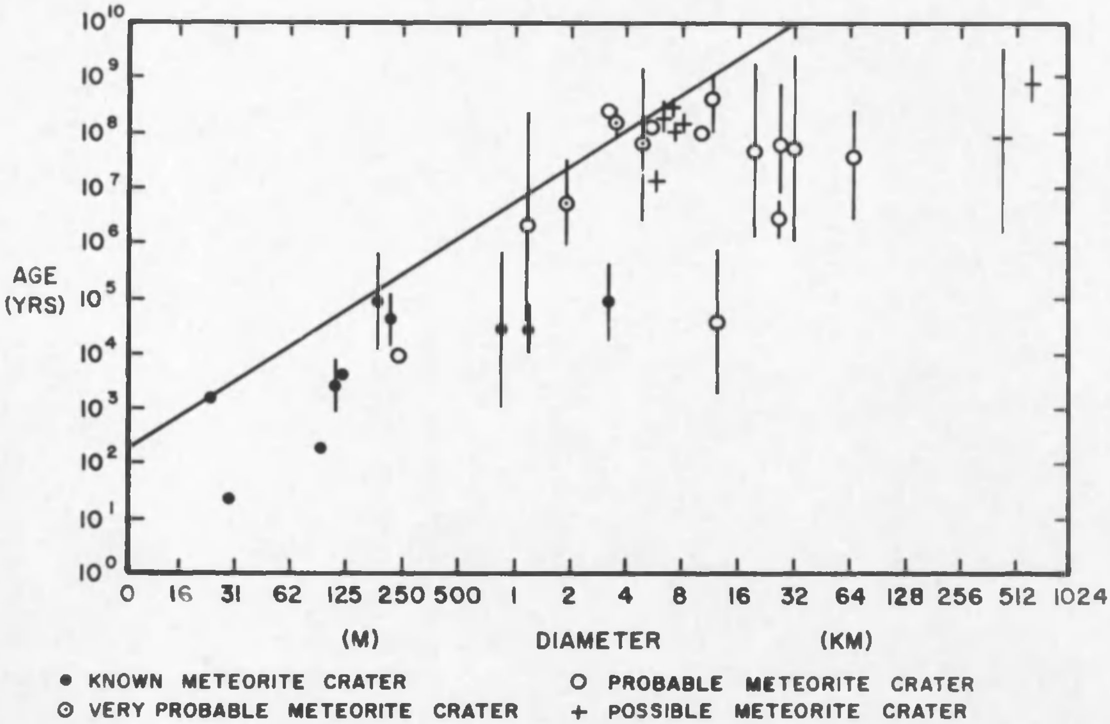

Figure 6. Crater Survival Time

Crater age vs. crater diameter is used to estimate maximum survival time of terrestrial craters under ideal conditions. Assumed maximum survival time is given by the straight line.

C. Meteorite Break-up

It is known that many meteorites break up during their passage through the atmosphere (Nininger, 1963). A cluster of close, small craters thus results instead of a single, large crater. An example is the Sikhote-Alin fall discussed in section A. Conceivably, if all craters were counted indiscriminately, the estimated flux would be too high, and biased toward small craters. There are several reasons to believe that the present estimate is not so biased: (1) Impact craters larger than 10km must have been caused by bodies of mass nearly 10^{14}gm (see section D, below). For such large bodies, substantial break-up in the atmosphere may be infrequent. (2) The few cases of multiple craters used in this study were twin craters. In each case it was assumed that only one parent body was responsible, and it was clear that the parent must have been larger than the 10^{14}gm necessary to form a 10km diameter crater.

D. Relation of Crater Diameter to Impacting Mass

This relationship is discussed by Shoemaker, Hackman, and Eggleton (1962), and Baldwin (1963), among others. The following discussion is based primarily on their work. From experience with large explosions on the earth, we have the following relation between crater diameter D and energy E:

$$D = CE^k \tag{25}$$

where C and k are constants. The full kinetic energy of impact is assumed to be available in formation of large craters. On the earth the initial kinetic energy upon entry into the atmosphere gives only an upper bound on D because of energy loss in the form of drag, an effect of decreasing importance toward large masses (Heide, 1964). With V as the final impact velocity and M as the mass, we have

$$D = \frac{C}{2k} M^k V^{2k} \tag{26}$$

Shoemaker, Hackman, and Eggleton state that k lies between 1/3 and 1/3.4, results which have been established empirically in large explosions, as well as theoretically. Baldwin discusses in detail the differences between experimental explosions and the lunar crater-forming process, and concludes that k varies with crater size. For craters in the diameter range we will consider, we will assume that k lies between 1/3.1 and 1/3.5. This represents a correction to an earlier published version of this analysis (Hartmann, 1965a; 1/3.06 was used). From Shoemaker's equations, allowing for uncertainty in k and other factors, C in cgs units lies in the interval 2.15 x 10^{-3} and 3.97 x 10^{-3}. Impact velocity is now the only parameter left in converting from crater diameter to impacting mass. The impact velocity varies both from one planet to another and from one type of impacting body to another because of differences in orbital velocities, gravity fields, and energy losses to atmospheres. It is thus convenient to list several equations for D(M) with different impact velocities. These approximate equations are listed below.

$$D = (9 \text{ to } 19)\ M^{1/3.3} \quad \text{for } V = 2.5 \text{km/sec}$$

$$D = (14 \text{ to } 28)\ M^{1/3.3} \quad 5 \text{ km/sec}$$

$$D = (22 \text{ to } 44)\ M^{1/3.3} \quad 10 \text{ km/sec}$$

$$D = (33 \text{ to } 66)\ M^{1/3.3} \quad 20 \text{ km/sec}$$

$$D = (51 \text{ to } 102)\ M^{1/3.3} \quad 40 \text{ km/sec} \qquad (27)$$

These relations are plotted in Figure 7. The exponent $k = 1/3.3$ used here represents a best estimate. The linearity of the crater diameter distribution (log-log plot) suggests that k is nearly constant over the entire range. Its value is likely to be found in the range 1/3.1 to 1/3.5 mentioned above, and if either extreme actually applies, the diameters estimated from Equation (27) could be in error by a factor 2.

E. Crater Counts and Calculation of Cratering Rate

Table V shows the calculation of the cratering rate in each province. While our counts deal only with

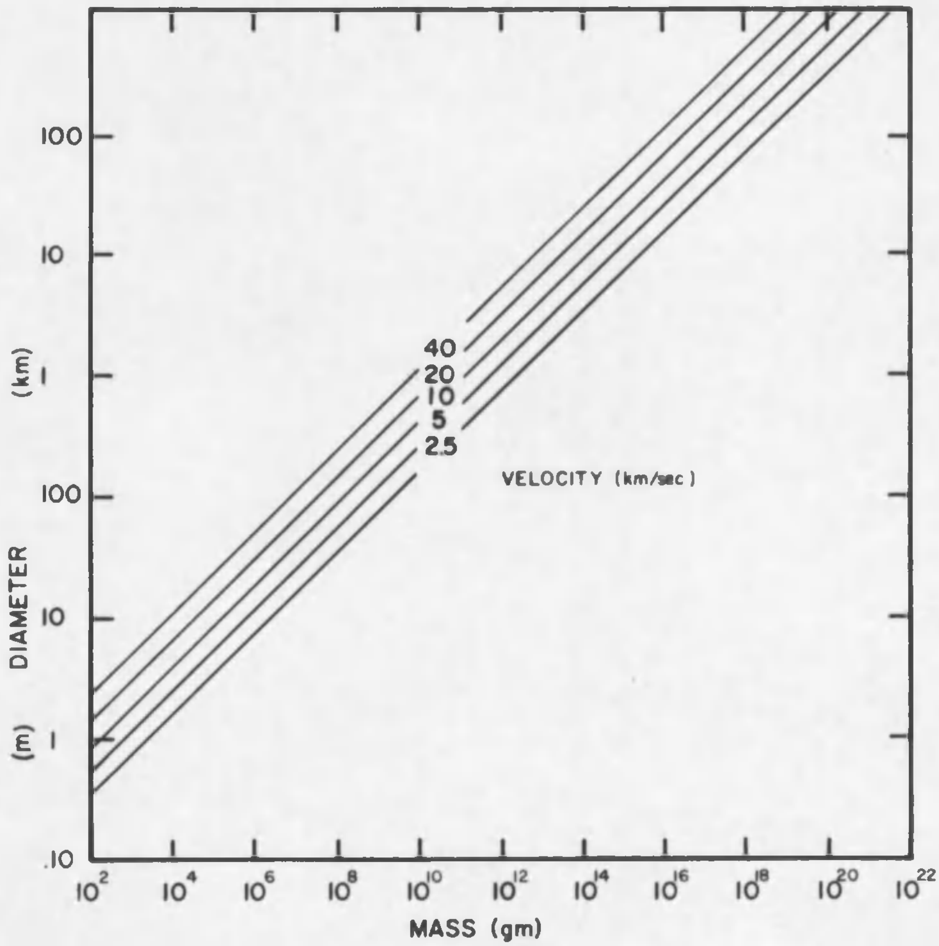

Figure 7. Impacting mass vs. crater diameter.

Table V: Calculation of Cratering Rate in Canadian Shield

Province	Crater & Diam. (km)		Min. No. Craters D > 10km	Max. No. Craters D > 10km	Area Studied (km^2)	Exposure Age (yr)	Cratering Rate $\frac{no. > 10km}{km^2\ 10^9 yr}$	$\frac{no. > 4km}{km^2\ 10^9 yr}$
Kenoran	Clearwater*	16 32	1	8	$1.3(10^6)$	$2.0\ (10^9)$	$0.4(10^{-6})$ to $3\ (10^{-6})$	$0.2(10^{-5})$ to $2\ (10^{-5})$
	Lac Couture	16						
	Menihek	8 9						
	Hudson Bay	440						
Hudsonian	Deep Bay*	14	1	6	$1.2(10^6)$	$1.4\ (10^9)$	$0.6(10^{-6})$ to $4\ (10^{-6})$	$0.4(10^{-5})$ to $2\ (10^{-5})$
	Carswell	29						
	Sudbury	40						
Grenville	Mecatina	12	.6	5	$1.2(10^6)$	$0.75(10^9)$	$0.7(10^{-6})$ to $6\ (10^{-6})$	$0.4(10^{-5})$ to $3\ (10^{-5})$
	Manicouagan	65						

*Craters most likely of meteoritic origin the number of craters larger than 10km, it is convenient to define the cratering rate numerically by the number of craters larger than 4km (the limit of lunar crater counts from earth-based photos and still of the same order of size as terrestrial craters counted). Then

$$\text{cratering rate} = R \equiv \frac{\text{no. craters larger than 4km}}{\text{km}^2 \quad 10^9\text{years}} \tag{28}$$

To convert from the number of craters larger than 10km to the number larger than 4km, we appeal to the observation that lunar craters in the range 1km to 100km diameter are distributed according to Equations (12) and (13). Therefore we will use

$$N_D = \text{number of craters of diameter} > D \equiv \text{const.}D^{-2.0} \tag{29}$$

Therefore $$\frac{N_4}{N_{10}} = \left(\frac{10}{4}\right)^{2.0} = 6.25 \tag{30}$$

This figure is entered as a correction factor in the next to last column of Table V.

Column 3 in Table V gives the minimum number of meteoritic craters in each province, based on a count of only the most probable meteorite craters, or in effect on the assumption that as little as one-third of the observed craters are meteoritic. Column 4 gives the maximum number estimated from the existing counts by assuming that (1) all observed craters are meteoritic, (2) on the basis of Figure 6, not more than twice this number could have been eroded away, and (3) equation (29) should be followed by large enough samples (a large number of small craters requires the presence of a few big ones). The area of each province, given in column 5, is a rough estimate of the well surveyed area, based on a total shield area of $4.5 \times 10^6 km^2$. The exposure ages of column 6 are those calculated in section A.

The fundamental assumption underlying this determination of cratering rate is that at least some of the structures listed here are meteorite craters. The structures are those listed by Beals, Innes, and Rottenberg (1963), found during a search of the Canadian Air Photo Library photographs for possible fossil craters. If more than one-third of the listed craters are meteoritic, then the rates found in Table V must approximately bracket the true rate. This statement is made on the grounds that if there ever had been more than about twenty meteoritic craters on the present Canadian shield (corresponding to the maximum rate in Table V), we would see them (Figure 6), and that for our minimum rate we have assumed that about one-third of the craters are meteoritic.

This discussion also leads to the interesting conclusion that certain suspected very large impact craters (Nastapoka Island arc, D = 440km; Gulf of St. Lawrence, D = 288km; Ungava Bay, D = 240km) listed by Beals, Innes, and

Rottenberg are either (1) non-meteoritic, or (2) pre-Kenoran, i.e. pre-Canadian shield, in age. This follows from the distribution of crater diameters: if there are three meteorite craters larger than 100km, there should be on the order of 300 craters larger than 10km, and by the discussion of section B, these should have survived. They are, in fact, not found. These three large, circular features, which approach the dimensions of lunar mare basins, may therefore have formed more than 2×10^9 years ago, during the intense bombardment which is discussed in Chapter XI. Smaller craters formed then have, of couse, been erased during the subsequent orogenies.

In conclusion, Tabel V indicates a cratering rate R between 0.3×10^{-5} and 2×10^{-5} craters of $D > 4km/km^2/10^9yr$, or by Equation (27) assuming a modal impact velocity of about 18km/sec, a flux between 0.3×10^{-5} and 2×10^{-5} objects of $M \gtrsim 1 \times 10^{13}gm/km^2/10^9yr$. According to the calculations of Heide (1964), such masses lose less than 10% of their entry velocity in passage through the atmosphere, so that our assumed impact velocity corresponds to an entry velocity of probably not more than 19km/sec.

F. Comparison with Other Determinations

Shoemaker, Hackman, and Eggleton (1962) employed a method in essence the same as that used here, but with less attention to crater survival time to determine the cratering rate in the central United States over the last 0.24×10^9 years. They counted cryptovolcanic structures and their reduction gave a mean rate R of 6×10^{-5} craters larger than about 3km / km^2 / 10^9yr. Through Equation (29) this would reduce to a value about 3×10^{-5} craters larger than 4km / km^2 / 10^9yr, expressed in the units used here. It is possible to use the raw data of Shoemaker, Hackman, and Eggleton to rederive the flux, taking into account the considerations in this paper. In an area of about 7.06×10^5 km^2 with a mean exposure age of about 2.32×10^8yr, they find ten cryptovolcanic structures, all of which they assume for this calculation to be true astroblemes. Eight of these are thought to correspond to craters larger than 3km diameter. From Figure 6, we might expect the survival time of craters of this size to be closer to 0.6×10^8yr, but these cryptovolcanic structures are in fact not well-preserved; they are visible only as "root structures". The oldest has an age estimated at about 4×10^8yr, even older than the mean exposure age. In calculating R, it is crucial to know the original crater size because of the strong dependence of frequency on size. The uncertainty in original size of these astroblemes, if such they be, introduces an uncertainty of, say, a factor four in the calculated cratering rate. Perhaps as large an uncertainty comes from the questionable origin of the structures. But just as in section E, we may argue that if one or two of the structures really are astroblemes, the true value of R is bracketed by the present calculation. The assumption that between one and eight craters larger than 3.5km formed in this area in the last 2.35×10^8yr gives a cratering rate R between 0.5×10^{-5} and 4×10^{-5} craters of $D > 4$km / km^2 / 10^9yr.

The terrestrial rate can also be estimated from present day observations of asteroids and from extrapolations of present day observations of small meteorite falls. Three published determinations are considered here.

Öpik (1958) tabulated the flux due to both cometary and asteroidal objects of large mass. For craters of $D >$ 4km ($M > 1.0 \times 10^{13}$gm) the total flux is about 4.5 (10^{-5}) objects / km^2 / 10^9yr. About 0.3 of these objects are held to be cometary. Because the cometary material suffers extreme energy loss to the atmosphere, the terrestrial cratering rate would be more nearly 3.1×10^{-5} craters / km^2 / 10^9yr.

Brown (1960) made a similar study in which the distribution of masses among recorded stone and iron meteorite falls was fitted to the observed asteroidal mass distribution to give a table showing impact frequency from 1 to 10^{11} grams mass. In our units, Browns value of F from meteorite impacts would be 0.9×10^{-5} to 4.3×10^{-5}.

Hawkins (1960, 1963) reviewed the statistics of observed finds and falls, and concluded that while stone meteorites outnumber irons at small masses, the situation reverses at large masses. The two types have mass distributions with different values of b. Hawkins' work would suggest that the published determinations of flux for large masses are too low. In our units, Hawkins value of F for stones is about 2×10^{-5}, but for irons, 25×10^{-5}. The former figure agrees with other determinations of total flux, but the latter is about an order of magnitude higher. Hawkins (1965, private discussion) agrees that there is a high uncertainty in published determinations of the flux and in the values of b, on which his high iron flux rests, and also notes that the number of asteroids passing near the earth is probably many times that so far observed.

It should be noted that the cratering rates derived here from the papers of Öpik, Brown, and Hawkins depend on the conversion from impacting mass to crater diameter, Equation (27). For example, if the mass to form a 1-km crater is actually twice that given here, then these three determinations will be cut by a factor of about 1.6, according to Equation (15) and Table II.

Table VI includes a listing of the terrestrial cratering rates found above. It is assumed in Table VI that the cometary masses are relatively ineffectual cratering agents because of atmospheric breakup.

G. Lunar Cratering Rate

The terrestrial cratering rates of sections E and F must now be converted to lunar rates.

Even if the mass influxes were the same on the earth and moon, the cratering rates would differ because the impact velocities differ (see Equation (27), p. 85). In the case of the earth, a modal impact velocity of 18km/sec, corresponding to an entry velocity of 18 to 19km/sec, was assumed in section E, on p. 90, and in section F. Further discussion of impact velocities is given by Shoemaker, Hackman, and Eggleton (1962). At 18km/sec, a mass of about 9.3×10^{12}gm creates a crater 4km across by Equation (27). On the moon the modal impact velocity, undiminished by any atmospheric effects, probably lies closer to 14km/sec. Shoemaker, Hackman, and Eggleton (1962) used 12km/sec for this figure and Kuiper (1965, private discussion) has suggested 15km/sec. Smalley (1965, private correspondence) has pointed out that the approach velocity at infinity for terrestrial and lunar impacts should be the same. This requires

$$V_{\oplus}^2 - V_{☾}^2 = 2G\left[\frac{M_{\oplus}}{R_{\oplus}} - \frac{M_{☾}}{R_{☾}}\right] \qquad (31)$$

where V = impact velocity

M = planetary mass

R = planetary radius

The impact velocities of 18km/sec for the earth and 14 km/sec for the moon are consistent with Equation (31) and assume that the predominant impacting masses are meteoritic (asteroidal), not cometary. At 14km/sec, a mass of about 1.7×10^{13}gm creates a crater 4km across. The mass ratio of bodies forming craters of this size on the earth and moon is thus 1.86 (see preceding page). According to the results of Chapter VI (Equation (15), and p.63),

$$\Delta \log f \cong -0.63 \Delta \log M. \qquad (32)$$

The lunar crater requires a more massive body by 1.86 than its terrestrial counterpart, and therefore the lunar cratering rate is about 1.5 times less than the terrestrial, for a given diameter.

An additional series of corrections is required because the terrestrial and lunar flux are not identical. It is assumed here that (1) the net effect on the earthward side of the decrease in flux due to the moon's lower gravitational field and the increase due to the focusing effect of the earth is a decrease in flux by 0.8, consistent with Öpik (1960); (2) the greater effectiveness of comet impacts on the moon causes an increase in cratering rate by 1.3; (3) the effect of the moon's lower gravity on crater size (i.e. through effects on the cratering process) is negligible; (4) during most of post-mare lunar history the moon was at nearly its present distance from the earth, so that the focussing effect is constant.

Table VI lists both the terrestrial and lunar cratering rates as found from the data of various authors, concluding with best estimates of both rates.

H. Age of the Lunar Maria

The crater density averaged over all maria is 1.0×10^{-4} craters of D > 4km / km^2 (using the data discussed in Chapter V; cf. also Figure 3, p. 57). Virtually all of these craters are ascribed to primary impacts. The cratering rate resulting from primary impacts is 2×10^{-4} craters of D > 4km / km^2 / 10^9yr (Table VI). Division of these two figures gives an age for the maria of 5×10^9yr, assuming a constant cratering rate through post-mare time. This result is held to be within an order of magnitude of the true mare age, in view of the estimated accuracy of the numbers quoted above and in view of certain points discussed below.

One other estimate, entirely independent, is available. This is based on isotopic age determinations for meteorites and on the theory of the thermal history of the moon. Observations (Anders, 1963) suggest that the planets formed in relatively short period of several times 10^8yr beginning about 4.7×10^9yr ago. The meteoritic material went through a melting process about 4.4×10^9 to 4.6×10^9 yr ago (Anders, 1963, p. 439). Theoretical investigations

Table VI: Terrestrial and Lunar Cratering Rates

$$\text{Cratering rate} \equiv \frac{\text{No. craters of } D > 4\text{km}}{\text{km}^2 \quad 10^9\text{yr}}$$

Reference used for basic data	Estimated Cratering Rate x 10^4	
	Earth	Moon
Öpik (1958)	3.1	2.2
Brown (1960)	0.9 - 4.3	0.6 - 3.0
Hawkins (1963)	27	19
Shoemaker, Hackman & Eggleton	0.4 - 4	0.3 - 3
This paper	0.3 - 2	0.2 - 1.4
Best estimate	3	2

of the moon's thermal history, such as those by MacDonald (1961) and Kopal (1962), though complex, generally indicate that the maximum heating within a hundred kilometers of the lunar surface would occur less than 2×10^9yr after the consolodation of the moon. If short-lived isotopes were an important heat source, this period may have been much shorter, perhaps on the order of 10^8yr. Therefore it is likely that the lunar maria are, on the average, about 4.2×10^9yr $\pm$ 0.3×10^9yr (estimated s.d.).

The isotopic age determination is considered the better determination, and the cratering calculation is considered supporting evidence for the assertion that the maria average about 4×10^9yr in age.

I. Summary

A new determination of cratering rate and mass influx on the earth is made from counts of craters in the Canadian Shield. Comparison with four other results by different methods is made, and conversion to lunar cratering rate is given. In units of craters of $D \geq 4$km / km^2 / 10^9yr, the cratering rates on the earth and moon are 3×10^{-4} and 2×10^{-4}, thought to be within an order of magnitude of the truth. This figure is used to give an independent confirmation of a mare age of about 4×10^9yr, based on isotopic age analyses of meteorites.

IX. NEW EVIDENCE FOR THE IMPACT ORIGIN OF LARGE CRATERS

To some, the hypothesis of lunar cratering by impact is so firmly established that no new evidence need be listed. Yet the author believes that the recurrent questioning of this hypothesis, the new evidence for volcanic activity found in Ranger photographs, and the recent publication of a book by Fielder (1965) devoted to the hypothesis that virtually all lunar structures are volcanic justifiy the inclusion of the following remarks.

The strongest modern evidence for the impact origin of craters has been given by Baldwin (1949, 1963). His primary argument has two parts. First, the well-preserved lunar craters fit exactly on several diagrams which plot morphological properties of explosion craters vs. diameter. This is interpreted to establish the explosive nature of lunar craters and rule out subsidence calderas or other craters which develop slowly by volcanic processes. Second, Baldwin argues that only impacts of cosmic bodies could provide the energy required to form the large craters (of the order 10^{32}ergs). No volcanic explosions which could occur on the moon are known to provide this energy (the most energetic earthquake events provide about 10^{25}ergs; the annual release of earthquake energy is only about 10^{26}ergs: Jeffreys, 1962, p.107).

New evidence is added by Chapters VI and VIII. In Chapter VI it was shown that the larger lunar craters show a diameter distribution which just matches that which would be produced by impacts of asteroidal objects, within the precision of the data, and in Chapter VIII, that the number of larger craters is within an order of magnitude of that expected from cosmic impacts. Were the volcanic hypothesis accepted, the first result would have to be attributed to coincidence, and the second would have to be shown wrong.

A final new discussion can be derived from the Ranger photographs, which show for the first time in detail craters of one to four kilometers, called "one kilometer craters" below. These can be compared with a considerable number of terrestrial volcanic craters which at first glance appear remarkably similar. (Comparison of ten- or hundred-kilometer lunar craters with terrestrial examples is difficult because of the scarcity of suitable cases of the latter.) A series of these is illustrated in Figures 8 through 11. For comparison, Figure 12 shows a similar view of Meteor Crater, Arizona, Figure 13, a nuclear explosion crater, and Figure 14, a lunar example of comparable size. Though the Mexican craters (Figures 8 - 10) lack thorough study, on the basis of published accounts, limited observations by the author from ground and air of each crater, and direct comparison by the author with Kilauea (Figure 11) and other Hawaiian

Figure 8. Sykes.

Pinacote volcanic field, Sonora, Mexico.
Photo by author.

Figure 9. Elegante

Pinacote volcanic field, Sonora, Mexico.
Photo by author.

Figure 10. MacDougal.

Pinacote volcanic field, Sonora, Mexico.
Photo by author.

Figure 11. Kilauea.

Halemaumau collapse crater; photo by author.

Figure 12. Meteor Crater.

Photo by author.

Figure 13. Sedan.

Nuclear explosion crater.

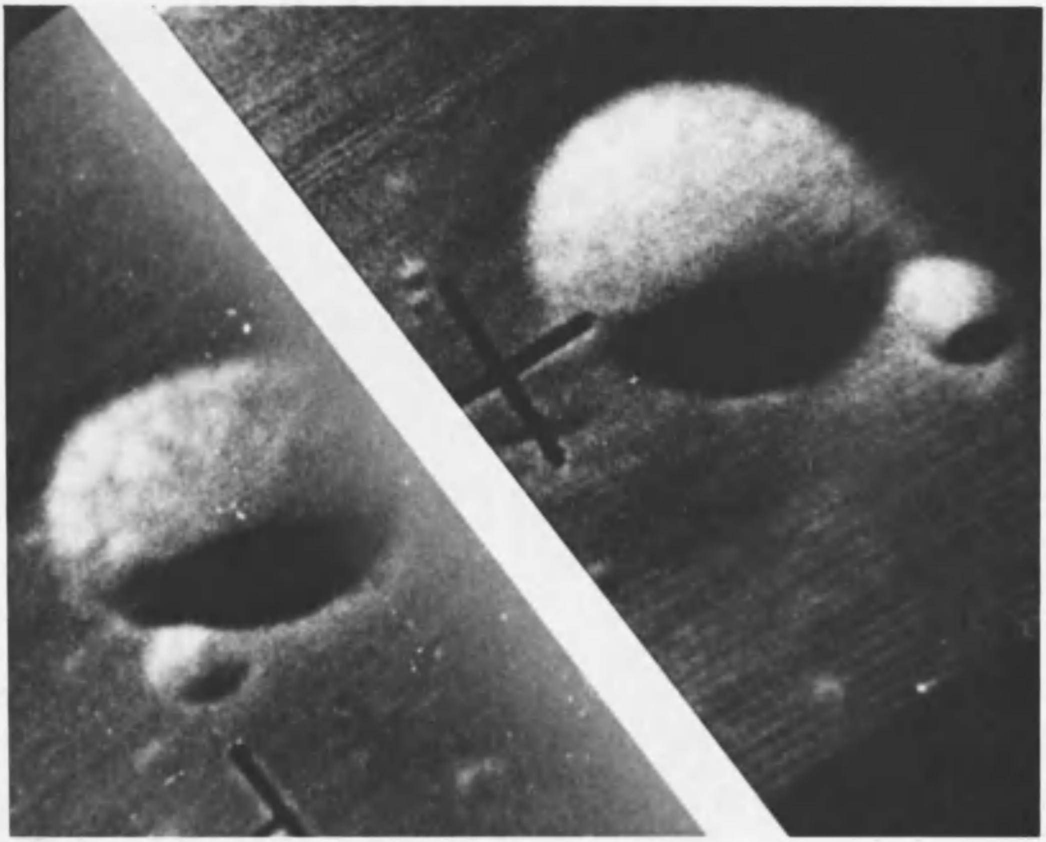

Figure 14. Lunar craters (Mare Cognitum; Ranger VII).

craters which have been exhaustively studied, all of these craters may be ascribed to collapse around a volcanic vent. These are among the closest terrestrial matches to lunar craters. Although several would fit closely on Baldwin's curves for explosion craters and in fact resemble them, close study reveals certain differences. First, all the volcanic craters display vertical cliffs of tens to hundreds of meters height where the lava broke during collapse. The bedding of the lava flows is clearly revealed in these cliffs. In the Mexican craters (age $> 10^4$yr) erosion has produced talus slopes which round off the floors and provide the bowl shape typical of explosion craters. The Hawaiian craters, still forming, have abrubtly rising vertical walls and relatively flat floors produced by ponding of lava ("lava lakes"). This morphology (Figures 15 and 16) is more typical of fresh collapses. Large nuclear explosion craters have bowl, or parabolic profiles, although locally steep walls may form during subsequent slumping. Second, meteoritic and explosion craters have "hummocky" rims composed of buckled surface layers and debris thrown out with roughly inverted bedding, a distinguishing characteristic pointed out by Shoemaker and Hackman (1962). The rims of the volcanic craters, if raised at all (no ejecta may exist), are typically smooth. Figures 8 through 10 illustrate the transition from a high, steep rim to none at all. The rims of the Mexican craters are composed of

Figure 15. Wall of a Hawaiian pit crater (Mauna Loa).

Photo by author.

Figure 16. Rim of Halemaumau.

Kilauea caldera rim at right; photo by author.

thinly bedded tuff. Figure 17 compares the rim morphology of a volcanic and a meteoritic crater. Third, the terrestrial craters, both in Mexico and Hawaii, occur in lava fields dotted with cinder cones. An example of this mixed crater and cone terrain is shown in Figure 18.

Of these characteristics of volcanic craters, the vertical walls do not appear in any of the well-resolved craters on the Ranger photographs. The resolution is not sufficient to determine the rim structure of any sharp "one kilometer" craters in detail, but somewhat larger lunar craters clearly show the hummocky structure. Clear examples of cinder cones are unknown in any Ranger or other photographs of the moon. Thus, the morphological evidence favors an impact origin for the sharp, "one kilometer" craters.

All this is not to say that "one kilometer" volcanic craters are totally absent. A few examples of volcanic craters of this size may be mentioned. One is the chain crater, e.g. those along the Hyginus rille. This linear array appears to be clearly of internal origin, as many authors have pointed out. Second is the dark halo crater, of which several examples in Alphonsus were photographed by Ranger IX. Figure 19 shows an example whose position on a graben-like rille and smooth blanketing dark halo suggest a maar or collapse type crater surrounded by a layer of fine ejecta, similar to the Mexican craters, Figures 8 - 10.

Figure 17. Volcanic and meteoritic crater rims.

Left: Elegante (volcanic), showing smooth rim.
Right: Meteor Crater, showing hummocky rim.
Photos by author.

Figure 18 . Crater and cinder cone field.
Near Flagstaff, Arizona; photo by author.

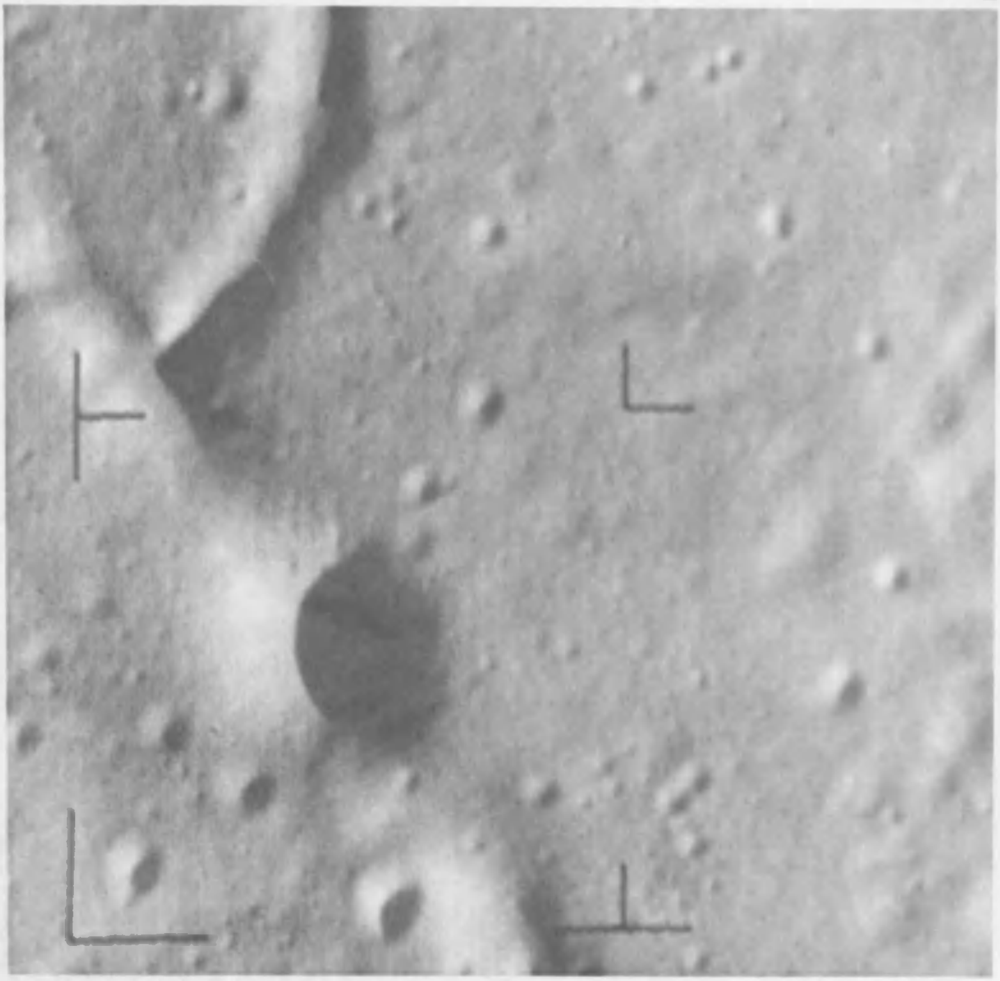

Figure 19. Possible lunar volcanic crater.
Dark halo crater in Alphonsus (Ranger IX).

On the basis of the above, it is concluded that (1) virtually all well-defined ("sharp") post-mare craters larger than about 4km were produced by cosmic impact, (2) in the size range from about 1 to 4km, numerous maar and/or collapse type craters analogous to those illustrated may be found, although these are greatly outnumbered by impact craters, and (3) as found in Chapter V, "soft" craters whose origin is uncertain and beyond the scope of this paper predominate at diameters less than 1km.

X. CHANGES IN METEORITE FLUX DURING SOLAR SYSTEM HISTORY

A. Introduction

It follows from Equation (15), p. 61, that the mass distribution of the cosmic objects striking the moon may be expressed by

$$\log f = b \log M + C \qquad (33)$$

The linearity of the lunar crater diameter distribution of Figure 3, above a certain limit in D, testifies that this equation holds over a large range in M, as discussed in Chapter VI. Specifically, a single value of b applies for all $M \gtrsim 10^{13}$gm, as found on p. 95, at least through post-mare time.

It will now be shown in part B that b, the slope of the log-log mass distribution, has remained approximately constant since the origin of the oldest lunar features. In part C, it will be shown that C, a measure of the total flux, has decreased since then. In the following chapter details of the early, high-flux period will be considered.

B. Constancy of Mass Distribution through Time

The lunar craters were not all formed at once. They show marked differences in state of preservations, and some obviously formed before the maria while others formed after.

This paper, up to this point, has been concerned only with post-mare craters and post-mare time; yet continental regions clearly pre-date the maria and earlier time periods can be studied. a simple division of craters into two groups, "old" and "young", can be made. "Young" craters include all the post-mare craters and others which have fresh-looking, undamaged, sharp rims. "Old" craters include those with battered rims and exclude any formed after the maria. Figure 20 compares the diameter distributions of these two groups. Because the older non-mare surfaces are not uniform in their ability to preserve craters, variations in absolute crater densities occur over small regions, and therefore only relative frequencies are plotted. Thus, Figure 20 has an arbitrary scale on the ordinant. The curves were normalized by dividing the number of craters in each interval by the total number of large craters of $D > 35$km. Evidence will be given below for the conclusion that in even the oldest populations, craters of $D > 35$km are all preserved well enough to be counted, so that the total number of these provides a good normalization index. Figure 20 illustrates that both the "young" and "old" groups appear to have the same slope, B. The deficiency of small craters among the older group will be attributed in Chapter XII to some erosion process.

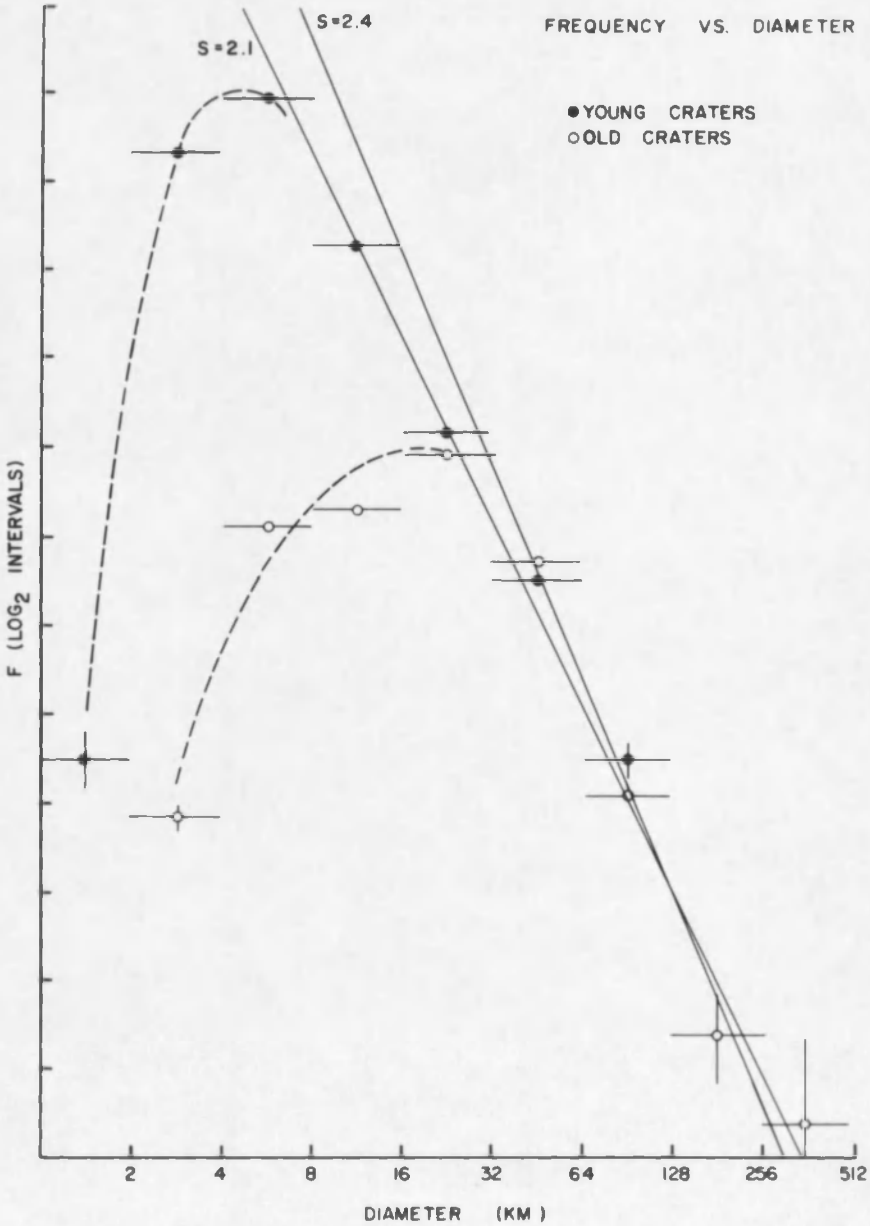

Figure 20. F(D) for old and young craters.

A second demonstration of the approximate constancy of B is shown in Figure 21. In this case the craters have been divided into five classes instead of two. These are the five classes defined by Arthur, et. al. (1963, p.76): class 1 has the sharpest rims and the best preservation; class 5 is the most battered. The five classes all fit approximately onto a single line defining an upper envelope, and, incidentally, also show an orderly progression in their turnoff points with the older classes being more deficient in small craters. The fact that the same value of B is associated with all five classes testifies not only to the constancy of B within the precision of the data, but also to the remarkable consistency with which the classification system has been applied.

A third, more quantitative evidence for the near-constancy of B has been more recently derived (the above two were published by Hartmann, 1965b). This is the analysis of continental craters. Most continental craters clearly formed in a period pre-dating the maria, and their diameter distribution is characteristic of an earlier period than that of the maria. A "pure continental" region was selected in quadrant III, and the diameter distribution was analysed. The region was large, including a north-south strip near Alphonsus and the region near Tycho south of Mare Nubium. An example of this heavily cratered terrain is shown in Figure 22. The diameter distribution

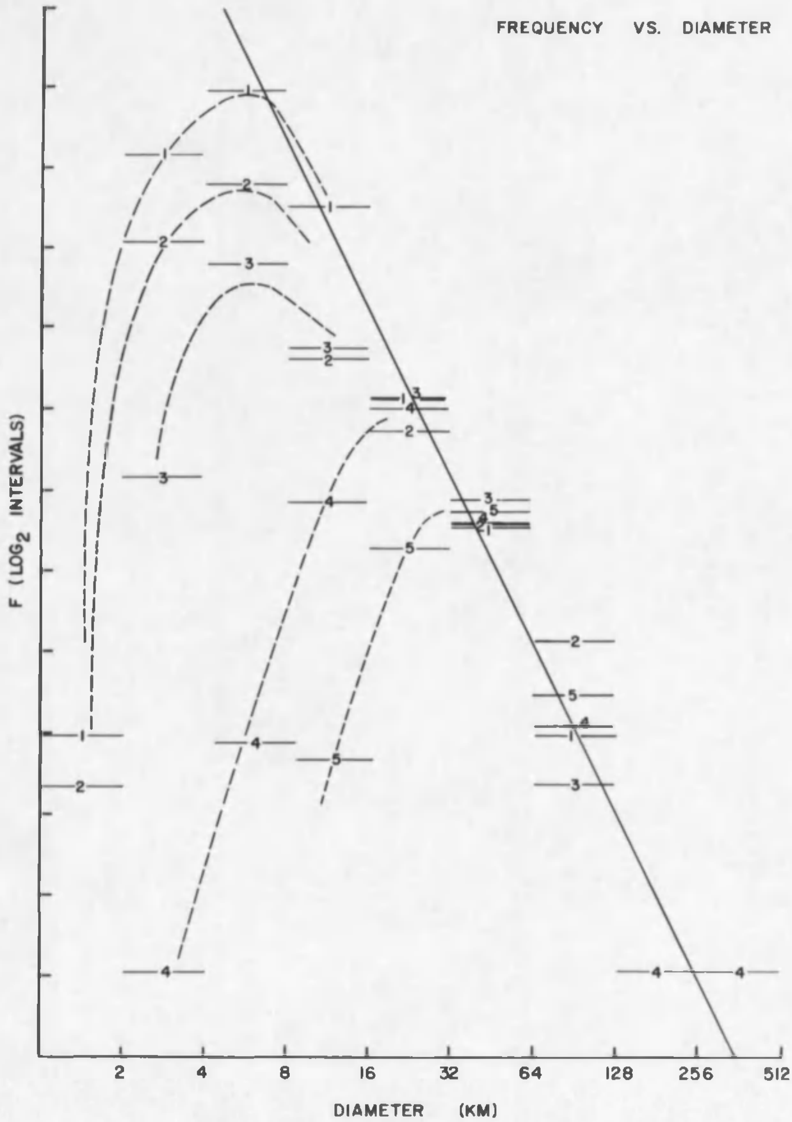

Figure 21. F(D) for five age classes of craters.

When normalized (arbitrary ordinate scale), the five age (damage) classes define a common envelope.

Figure 22. "Pure continental" region.

of "pure continental" craters, in absolute units of F, in Figure 23. The post-mare crater distribution is included for comparison. Also included in Figure 23 are a number of large basin systems which extend the diameter range; this addition will be discussed in more detail in the next chapter. Suffice it to say that if the craters only are included, analysis of the linear branch for D > 32km gives:

$$\log F_{Continental} = -0.81 - 2.16 \log D$$
$$A = -0.81 \pm 0.04$$
$$B = -2.16 \pm 0.10 \qquad (34)$$

If the large basins are also included, then for D > 32km, analysis gives:

$$\log F_{Cont.+Bas.} = -0.61 - 2.26 \log D$$
$$A = -0.61 \pm 0.08$$
$$B = -2.26 \pm 0.08 \qquad (35)$$

Because the continental craters vastly outnumber the post-mare craters, it may be fairly concluded that the best estimate of B = -2.2 ± 0.1 is actually characteristic of the pre-mare period. The value found for post-mare craters, p.60, was B = -2.0 ± 0.2. Any change in B is thus at the limit of detectability. Interpreted literally through Equation (21), these results would imply a slight change in the mass distribution of the meteorites from b = 0.67 in pre-mare time to b = 0.61 in post-mare time, though the precision is probably to small to support this.

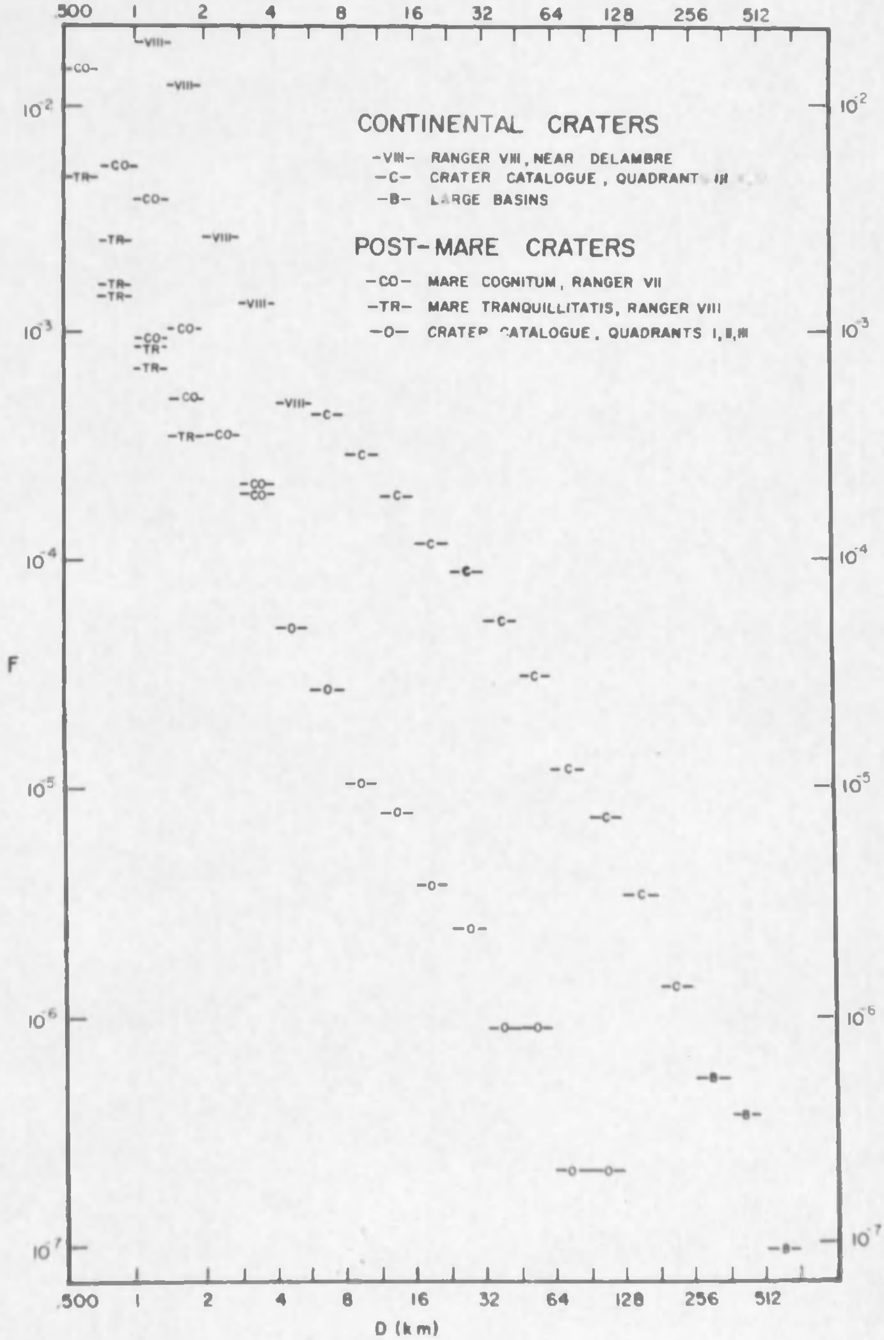

Figure 23. F(D) for post-mare and continental craters.

It is concluded that the mass distribution of cosmic objects striking the moon has remained approximately constant throughout lunar history, i.e. in pre-mare time, as measured from continental craters, in post-mare time, as measured from post-mare craters, and at the present moment, as measured from observations of meteorites and asteroids. Probably the value of b has been close to that presently observed among asteroids and has been within the interval -0.65 ± 0.05. Certainly the largest lunar craters were not formed first and the small ones last, in an almost monotonic sequence, as has sometimes been surmized.

C. Change of Space Density through Time

A D = 64km in Figure 22, branches of nearly equal slope in both pre-mare and post-mare craters parallel each other. Solutions of Equations (12), (13), (34), and (35) indicate that pre-mare crater density exceeds the post-mare density by a factor 50. Yet it has been found that the maria are on the order 4×10^9yr old and probably formed well within the first one fifth of lunar history. About 98% of lunar impacts occurred within the first 20% of lunar time; clearly the cratering rate, the flux of cosmic objects, and C in Equation (33) have decreased.

On the other hand, we have seen that an extrapolation of the present cratering rate backward gives an age for maria which is consistent with expectations based on isotopic dating of meteorites and the earth. The cratering rate is thought to be known to better than an order of magnitude, and thus during post-mare the flux probably has changed by less than an order of magnitude. Therefore, the decrease in flux must have been rapid and early.

The early intense bombardment period is examined in more detail in the next chapter.

XI. THE EARLY INTENSE BOMBARDMENT OF THE MOON

A. Introduction

In the preceding chapter it was shown that early in lunar history the meteoritic flux must have been higher than at present. In this chapter it will be shown that this high flux and the formation of most craters were confined to a distinct period.

This idea is not new. Kuiper (1954) hypothesized it after observing certain relatively smooth regions among the continental craters. These he attributed to an original, accreted surface, never disturbed by large impacts (see p.36). There is now evidence, however, that some smooth continental regions may result from some modification of the original surface, perhaps even a very early flooding by lava. For example, some of these regions photographed by Ranger IX show structure previously known only in maria and not found on crater walls or other rougher surfaces. Alter (1963) used similar reasoning to support an intense bombardment period: he noted examples of ancient scarps which suggested to him that the continental surfaces were not built up by unlimited impact. Urey (1952, 1960c) suggested an intense bombardment on different grounds: he assumes the maria to be floods of lava from rock melted immediately by impact, and because the older mare surfaces do not bear craters caused by ejecta from younger mare basins, he concludes that the duration of the cratering of the moon was less than the filling and cooling time of a large body of molten lava, i.e. on the order 10^6yrs. Chapter VII of this paper summarized reasons for believing Urey's initial assumption wrong.

B. New Evidence for Early Intense Bombardment

The continental craters show some variety in appearance, from sharp "Class 1" craters to more battered, shallower, and usually softer "Class 5" craters, but it is held that this is to be expected of impact craters subsequently deformed by isostatic adjustment, volcanic activity, tectonic activity, and later impacts. The diameter distribution of the continental craters over all diameters measurable from Ranger and earth-based photography is shown in Figure 24, where the post-mare distribution is also included for comparison (this represents an extension of the diameter scale over Figure 23). It is of similar form to that of the post-mare craters and nearly parallels it with a higher crater density. On these grounds, it is concluded that the continental craters are predominantly impact craters, just as are the larger post-mare craters.

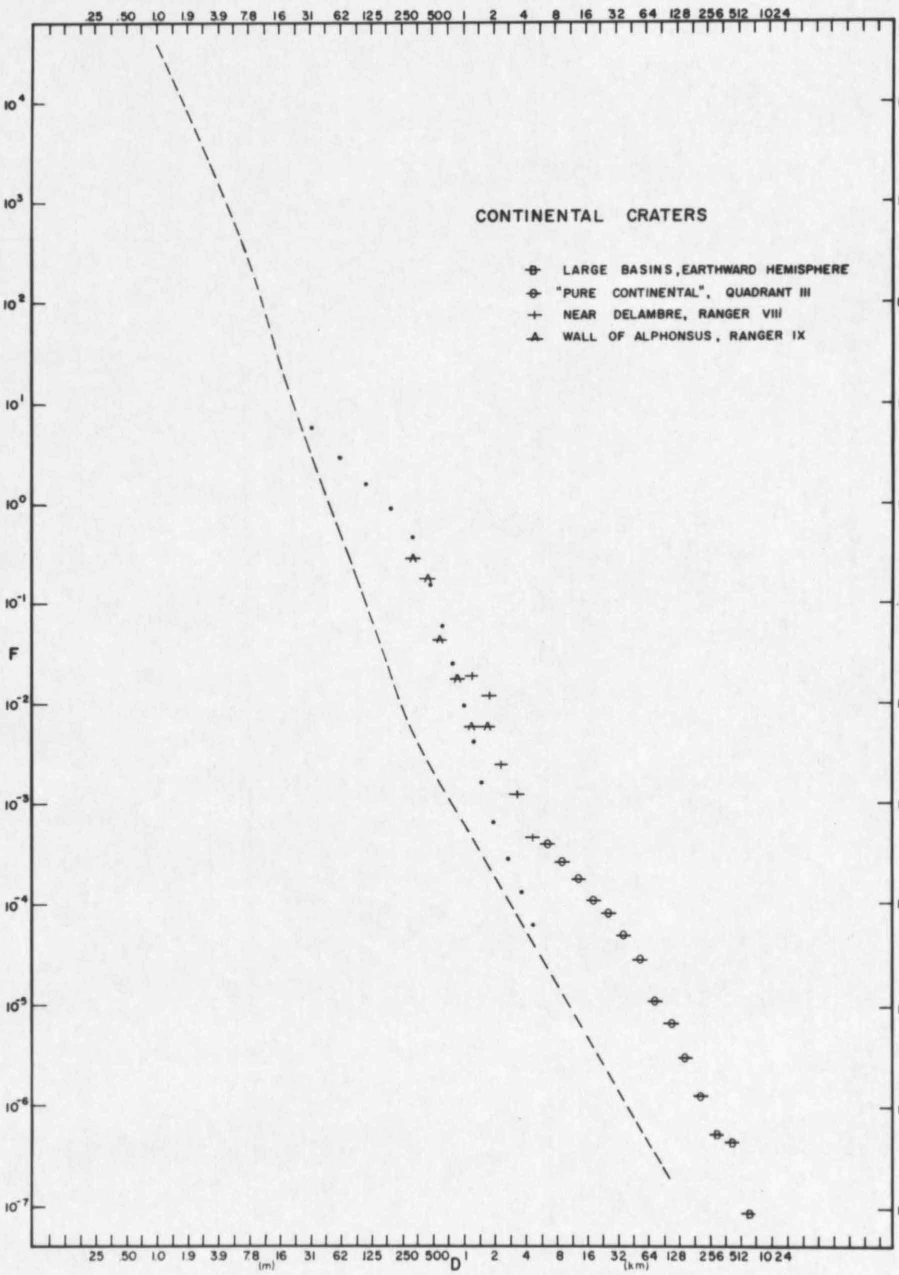

Figure 24. F(D) for continental craters.

Dashed line: post-mare "sharp" craters.
Dotted line: all post-mare craters.

Although there is a break in the continental curve, which will be discussed in the next chapter, the branch above D = 32km runs nearly parallel the post-mare curve and may be used to compute the factor by which the continental craters outnumber the post-mare craters. Equations (12) and (35) best describe the distributions, and Equations (13) and (34) may be used for comparison. At D = 64km, both parallel branches are well-defined, and the continental craters outnumber the post-mare craters by a factor about 45. Since the two curves are not exactly parallel, different results apply to different diameters, and at the large end of the post-mare distribution, D = 100 km, the factor drops to about 36.

All of these craters formed in the interval between the last stages of lunar formation (when the lunar radius reached its present value), and the mare period when the flooding occurred, an interval of several times 10^8yr according to the discussion of page 96. This interval is probably on the order of 0.1 post-mare time. Therfore the pre-mare flux must have averaged on the order of 400 times the average post-mare flux.

Fielder (1963a) has written, "Any hypothesis which involves an assumption that there was an anomalous era during which most of the craters were formed (or in which few craters were formed) is ad hoc." Fielder's assumption that the cratering rate has been constant is, in itself, *ad hoc*, in the writer's opinion; it led Fielder in the same paper to conlude that no mare is older than 7 x 10^8 yr. The writer holds that the above discussion demonstrates that these parts of Fielder's paper should be revised.

C. Basins

The large, circular basins and their structural systems have been described in detail in several earlier papers (Hartmann and Kuiper, 1962; Hartmann, 1963, 1964b). Figure 25 shows the systems mapped to date. Are these huge structures simply the result of great impacts?

To answer this question, an attempt was made to add the basins to the F(D) diagram, Figures 23 and 24. Should the basins fit one of the crater curves, their genetic relation to craters would be established. In plotting the figures, and throughout the preceding chapters, limb regions were rejected to avoid biasing toward large craters. However, the large basins can be detected out to the very limb of the moon by rectified photography, as dimonstrated in Figures 26 and 27. Therfore the entire front hemisphere may be used as a counting surface for basins. The inner ring of each multi-ring system was measured, as there is evidence (Hartmann and Kuiper, 1962;

Figure 25. Basins systems.

This figure outlines radial and concentric systems surrounding lunar basins.

Figure 26. Mare Smythii.

Illustrating the detection of basins at the extreme limb by rectified photography.

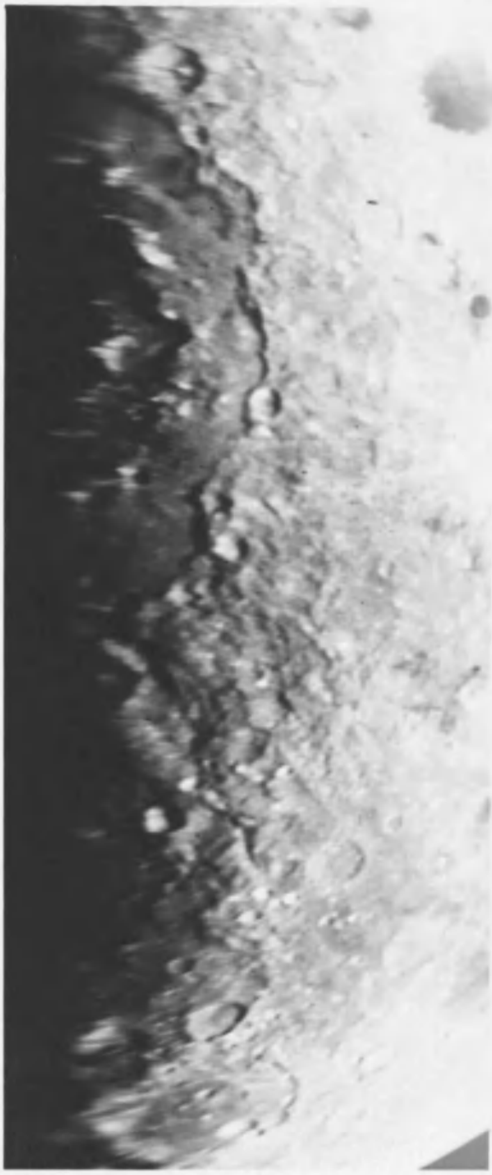

Figure 27. Mare Orientale.

Illustrating detection of basin systems at the extreme limb by rectified photography.

Fielder, 1963a) that the outer rings are produced by faulting. Three extra points, marked "B" on Figures 23 and 24, were added in this way. Though of lower statistical significance than the other points, they lie precisely on the extension of the continental crater curve. Equations (34) and (35) compare the solution with and without these three points; at diameters above 32km, where the lower linear branch begins, the two equations give virtually identical results. Therefore it is concluded that the circular basins are giant impact craters dating from the pre-mare intense bombardment period.

D. Historical Implications

The pre-mare bombardment must have averaged about 400 times the post-mare average, as stated above. The flux may have been even greater at its peak. From where did these objects come?

Several possibilities may be considered: (1) the objects represent the final, dwindling stages of lunar accretion; (2) they were planetesimals left over after the formation of the planets; (3) they result from a much higher early ejection rate of objects from the asteroid belt; (4) they result from a much higher early ejection of comets from the cometary cloud; (5) they result from the sweeping up of debris around the earth as tidal friction forced the moon outward from the earth.

As for (1), Kuiper's observation (section A), affirmed here, suggests that the bombardment began after the lunar surface had formed at the moon's present radius. Additional support for this results from the above: the statistics show that only about 50% of the "pure continental" surface is covered with craters of $D > 1$km. Unlimited overlapping of craters does not seem to have occured (see also the next chapter). It appears that the moon did not grow from the crater-forming objects, but from much smaller objects, perhaps of metric dimensions as suggested by Fowler, Greenstein, and Hoyle (1962).

Evidence against the second possibility is contained in a recent paper by Anders (1965). Anders finds that the asteroids ejected into the nearer regions of the asteroid belt after a collision are fragments of objects having an original, nearly Gaussian, mass distribution with a peak frequency at about 10^{20} or 10^{21}gm, and he suggests that the asteroids in their original state were accreted planetesimals with a nearly Gaussian mass distribution. Collisional fracturing has produced the power law mass distribution now observed, in accord with Hawkins (1960) and, in part, Marcus (1965) (see also pp. 62-63). If the original planetesimals of the solar system had a mass distribution departing markedly from a power law, they may be ruled out as the agents for lunar cratering.

There is also some evidence against a very high ejection rate for asteroids in early solar system history. Only after the first few collisions within the central asteroid belt could a population of fragments build up in the neighborhood of Mars, to be perturbed toward the earth. According to Anders (1965) the collisional half life of a single asteroid would be on the order 6×10^9 yr, so that collisions among all the asteroids could build up a fragment population rather quickly. In fact, exposure ages of meteorites indicate collisions every few 10^8yr. However, the resistance of the families of fragments to further perturbation toward the earth appears great, and the ejection rate would gradually increase as more fragments build up in this region. Thus, if Anders' picture of asteroid fragmentation is correct, it appears unlikely that a burst of asteroid ejection would occur in pre-mare time.

Little is known of the history of evolution of the comets, and it would be purely an _ad hoc_ assumption to suggest that the cometary flux was initially extremely high and capable of producing a crater diameter distribuion characteristic of fragmented projectiles similar to the asteroids.

The remaining hypothesis, that the pre-mare bombardment resulted from debris in the earth's vicinity, now is favored. This debris must have been in the form of fragmented particles, similar to the smaller asteroidal fragments, since the pre-mare and post-mare crater distributions are of nearly the same form. Gilbert (1893) and Ruskol (1961) hypothesized that such particles existed and that the moon accreted from them, but we have already ruled out accretion from them (case 1, above). Kuiper (1954) suggested that they formed a "sediment ring" which was swept up as the moon receded from the earth. That the earth-moon system itself is unique is perhaps the best answer to the criticism that the other terrestrial planets have neither such a ring nor a large satellite to sweep it up. That is, perhaps the debris which caused the intense bombardment are remnants of the unique process by which the moon came to be the satellite of the earth.

XII. EROSION, EJECTA, AND CRATER OBLITERATION

A. Introduction

Parts of the present chapter are based on material prepared in collaboration with G. P. Kuiper for the Experimenters' Analysis and Interpretations for the Ranger VII flight (Heacock, Kuiper, Shoemaker, Urey, and Whitaker, 1965), and part on an earlier paper by the author (Hartmann, 1964a).

The term "erosion" refers to all processes by which rock or soil is loosened or moved. On the moon, externally produced erosion results from incoming particles ranging in mass from asteroidal to atomic. A given square centimeter will have been hit repeatedly by the very small and very numerous particles; radiation and atomic particles cause "sputtering", and particles up to about a gram mass cause what is here called "sandblasting". Impacts of still larger particles are less frequent and more widely dispersed; they cause distinct craters which do not erode inter-crater areas except insofar as ejected material causes "blanketing" and "secondary cratering". The larger craters themselves also have a cookie-cutter effect in destroying their own area; this is called "obliteration".

Table VII summarizes the effect of these external erosive mechanisms. In addition, there is deformation of the surface by various internal agencies. All of these effects must be considered in interpreting crater diameter distributions, crater morphology, and surface history.

B. Sputtering and Sandblasting

According to a recent report by Wehner (1964), a layer approximately 17cm thick should have been sputtered entirely off the moon in the last 4.5×10^9yr, assuming that the solar wind intensity has been constant. Low energy ions are primarily responsible, and velocities of ejecta typically exceed escape velocity.

McCracken and Dubin (1964) and others have found that the total influx of particles of mass less than 1gm (the range in which most of the mass is concentrated) amounts to a layer roughly 1 or 2cm thick over the whole moon if the present flux is extraplolated back over 4.5×10^9yr. These particles will have built up a pulverized or fragmented layer because each particle ejects many times, perhaps 100 to 1000 times, its own mass at less than escape velocity. This layer will stabilize at some intermediate depth, perhaps 20cm, because ejection is severly impeded by the porous structure of the of the pulverized layer, which may approach a "fairycastle" structure. In addition, each sandblasting particle may knock nearly its own

Table VII: Lunar Erosive Mechanisms

	Mare	Continent
External		
Sputtering	Loss of 17cm	Loss of 17cm
Sandblasting	Loss of 1-2cm Fragments to ~20cm	Loss of ~50cm Fragments to ~20cm
Ejecta	Fragments to 10cm - 2m	Fragments to 20m - 200m
Obliteration	None	Disappearance of small craters
Internal		
Flooding	Major distruction	Isolated "disguised" patches
Tectonic Activity	Minor faulting	Major faulting
Isostatic Adjustment	Minor	Smoothing of large craters

mass off the moon entirely, resulting in a net loss of a layer on the order of one centimeter deep.

Only the post-mare sandblasting effect was considered in the above paragraph. Because the pre-mare period saw an intense bombardment by fragments numbering about 45 times the post-mare total, it appears that the oldest of the pre-mare, continental surfaces should have suffered about a 50cm net loss, as well as having the 20cm blanket.

C. Ejecta and Secondary Cratering

Figure 28 illustrates some large (2m diameter) blocks thrown from Meteor Crater, Arizona, during its formation. Boulders of similar dimensions are rare on mare surfaces, though a few may be seen in Figure 4. Whatever their origin, it is clear that there must exist ejecta in some form on the moon.

Some rubble is thrown out in the form of blocks large enough and with momentum enough to make secondary craters. Shoemaker (1965) has studied the craters made by ejecta blocks around both fresh nuclear explosion craters and large lunar craters. He finds that the diameter distributions of such craters show slopes B of about -3.5 to -4.0. (In fact, he identifies most of the craters smaller than several hundred meters, whose distributions show such steep slopes, as secondaries.)

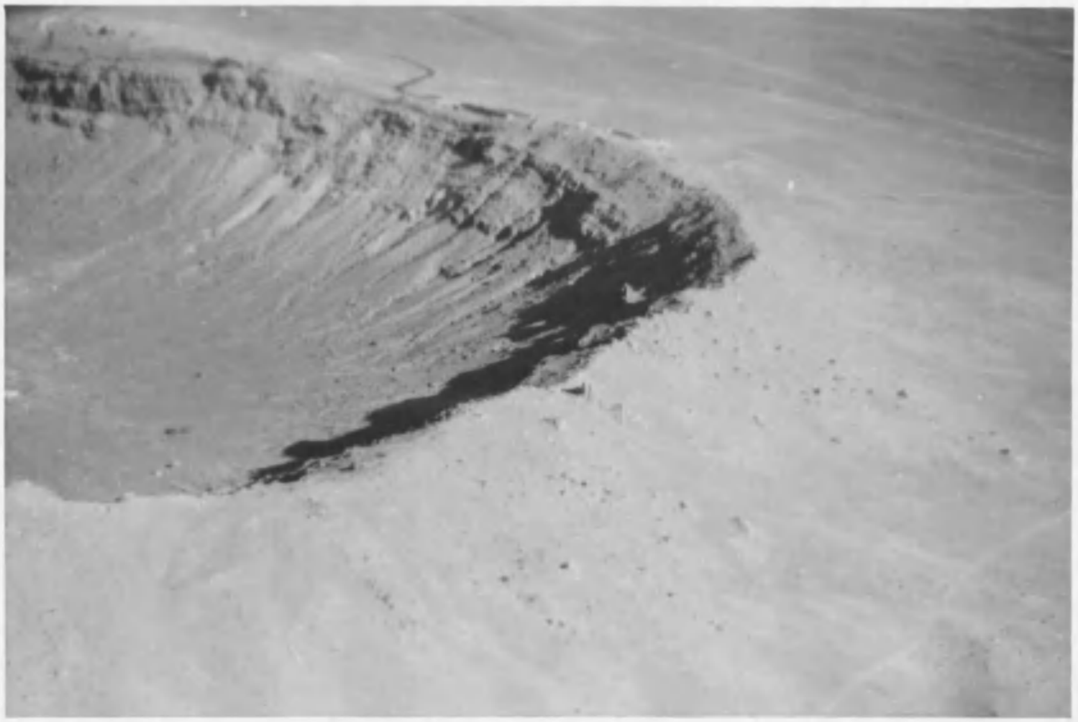

Figure 28. Ejecta blocks at Meteor Crater.
Phto by author.

It is clear that such craters do exist on the moon. As Figure 29 illustrates, they are usually clustered within a fes diameters of their primary. Although the number and identification of secondary craters, most of which measure less than 2km across, is beyond the scope of this paper, it is to be pointed out that in the densely cratered continental regions, almost every point is within a few diameters of a major crater, and hence secondaries may be relatively uniformly distributied. For example, the inner wall of Alphonsus, a surface almost certainly pre-mare, shows a B value of about -3.1, steeper than the mare value and suggesting an admixture of secondaries. Shoemaker's hypothesis that secondaries dominate even on the maria for $D \gtrsim$ a few hundred meters appears questionable because of the large average distance from major craters. Only pulverized material is known to be thrown these large distances. Because of the tremendous accelerations involved, and the already fragmented nature of the surface layers, especially continental, it may be that large solid blocks can be thrown only a few crater diameters.

Some material, probably ranging from powdered to loosely compacted, is thrown large distances to form the observed rays. Judging from high speed photographs of nuclear explosions, this material is ejected in spurts in the nature of gas jets breaking through the initial

Figure 29. Secondary craters around Langrenus.

Photo: Lick Observatory.

ruptures in the great dome of earth rising above the explosion. Ray deposits apparently never exceed depths of about 10m, as their relief has never been observed from the earth. However, most of the mass of certain post-mare craters may be confined to their rims and rays, so that deposits of several meters may not be uncommon.

Finally, a certain amount of material must be spread beyond crater rims in thin, feathering veneers reaching to many crater diameters. At one time there was thought to hold a principle known as Schröter's rule, which stated that the volume of a well-preserved crater is equalled by the volume of its raised rim. High resolution studies now reveal cases where this is violated; part of the rim volume must be raised an buckled crust as well as ejecta, and a non-ray portion of ejecta must spray beyond the immediate rim. In continental regions, these veneers probably overlap. The total volume of all continental craters and basins of $D > 1km$, if distributed uniformly over all continental surfaces, would form a layer on the order of 1.3km thick. (Most of this comes from craters of $D \sim 150km$; each increment of logD in Figure 27 contributes about 10^{-1} to 10^{-2}km.) Of course, most of this material is concentrated in the original crater rims, but if 2 to 20% of it is dispersed beyond the rims, then the densely cratered continental regions may have an inter-crater debris layer averaging

20 to 200m thick. The maria, with only 1/45 the continental crater density would have a correspondingly thinner debris layer; furthermore, since the ray systems of post-mare craters are distinct and non-overlapping, it is probable that the <u>inter</u>-crater debris sheet on maria is very thin, on the 10cm to 2m thick, depending on the distance to the nearest large craters.

D. Obliteration

The main result of this effect is that smaller craters are preferentially destroyed by overlapping of successive generations of craters. This may be seen from the following model:

Define: D_o = crater diameter in initial distribution

D_1 = " " " new generation of overlapping craters

a = area considered

n' = average number of craters of diameter D_o (per unit interval ΔD_o) destroyed by a single overlapping crater of diameter D_1

N' = number of craters of diameter D_o (per unit interval ΔD_o) destroyed by all overlapping craters of diameter D_1

η' = number of craters of diameter D_o (per unit interval ΔD_o) destroyed by all overlapping craters

Suppose that a crater of diameter D_1 overlaps a crater of diameter D_o (i.e. the D_1 impact follows upon the D_o impact). Assume as a first approximation, that if $D_1 >$ D_o the latter crater is obliterated, while if $D_1 > D_o$ both craters remain detectable.

The fraction of the D_o craters destroyed by a single D_1 impact, if $D_1 > D_o$, is the area of the D_1 crater divided by the area considered. By the definitions in Equations (1) and (2), the number of craters per unit ΔD in a is proportional to D^{B-1}. Therefore,

$$n' = \frac{\pi D_1{}^2}{4a} \; C \cdot D_o^{B-1} \qquad \text{if } D_1 > D_o$$

and

$$= 0 \qquad \text{if } D_1 < D_o \quad (36)$$

Therefore, the number of D_o craters destroyed by all new D_1 craters is

$$N' = \frac{\pi D_1{}^2}{4a} \; C \, D_o^{B-1} \; C \, D_1{}^{B-1} \qquad \text{if } D_1 > D_o$$

$$= 0 \qquad \text{if } D_1 < D_o \quad (37)$$

Therefore, finally, the total number of D_o craters in area a destroyed by all larger, overlapping craters is

$$\mathcal{n}' = \frac{\pi C^2}{4a} \; \frac{1}{D_o{}^{-B+1}} \int_{D_o}^{D_{Max.}} D_1{}^{B+1} \, dD_1$$

$$= \frac{\pi C^2}{4a(B+2)} \; \frac{D_{Max.}^{B+2} - D_o{}^{B+2}}{D_o{}^{-B+1}} \qquad \text{(excluding } B = -2\text{)} \quad (38)$$

or

$$= \frac{\pi C^2}{4a} \; \frac{1}{D_o{}^3} \; \log \frac{D_{Max.}}{D_o} \qquad \text{(if } B = -2\text{)} \quad (38a)$$

Therefore, the fraction of craters of diameter D_o destroyed by each generation of overlapping craters (note that C is proportional to a) is

$$\frac{n}{C\ D_o^{B-1}} = \frac{\pi C}{4a} \left[D_{Max.}^{B+2} - D_o^{B+2}\right] \quad (\text{if } B \neq -2) \qquad (39)$$

or

$$= \frac{\pi C}{4a} \log \frac{D_{Max.}}{D_o} \quad (\text{if } B = -2) \qquad (39a)$$

This result shows that the fraction of destroyed craters increases toward small diameters, and it can be seen that each successive generation of inpacts increases the deficiency of small craters.

Two additional effects modify this simple model. First, as pointed out by Kuiper (1964, private communication), a given large D_1 crater is more effective at obliterating small D_o craters than large ones. Therefore, one may modify the exponent of D_o in Equation (36) to read $B - 1 - \epsilon$. Second, larger craters tend to have wider rims and ejecta blankets, so that the exponent on D_1 in Equation (36) may read $2 + \Delta$.

E. Internally Produced Effects

1) Flooding. The major flooding which produced the present mare surfaces clearly buried much of the surface. Probably the pre-mare surface features were completely destroyed in most areas during this flooding. Another type of flooding may appear in the smooth but bright

continental areas. Some of these may be areas of early limited flooding, now covered over by later ray and ejecta layers. This appears to have happened in the northern part of the basin near Schiller, for example, where some of the true dark mare material may still be seen under high lighting. If such "disguised" flooding occurs in the continental areas, even the "pure continental" crater counts may be distorted.

2) Tectonic adjustments. An increasingly large body of evidence, such as studies of the lineament systems (Hartmann, 1963, 1964b; Strom, 1964) supports the view that the entire lunar surface has undergone tectonic activity, probably maximized during the early flooding period. Figure 30, in addition to illustrations in the writer's 1963 and 1964 papers, cited above, illustrates lineaments of a radial system, in this case Imbrium, along the borders of a region of continental breakup and flooding. These structures were hypothesized to result from faulting along fractures produced by the basin-forming impacts. Figure 31 adds a new high-resolution view of a lunar graben-type rille, from Ranger VIII. Figures 32 through 35 add some new illustrations of analogous terrestrial sturctures. Production of such features on the moon, especially in pre-mare time, adds to the difficulty of detecting the oldest craters (Fielder, 1963b).

Figure 30. Lineaments and flooding.

Figure 31. Rille (Mare Tranquillitatis; Ranger VIII).

Figure 32. Thingvellir graben, Iceland (aerial view).

Figure 33. Scarps at margin of Thingvellir graben.

Graben floor at left. House (upper left) gives scale it is built on collapsed mass which produced this fissure. Photo by author.

Figure 34. Parallel faulting, Tucson.

Analogous to hypothetical faulting which produced parallel lunar lineaments. Rincon Mts., photo by author.

Figure 35. Tension fissure, Iceland.

Characteristic of innumerable Icelandic fissures attributed to tension in the mid-Atlantic ridge. Similar results are suggested for the moon due to lunar thermal expansion. Photo by author.

3) Isostatic adjustments. Baldwin (1963, p. 193) attributes much of the modification of old craters to this agency, in accord with his observation that the depths of floors have been reduced faster than the rim heights.

F. Applications

The continental crater diameter distribution (Figures 23 and 24) shows a significant bend at D = 32km. As already discussed on page 117 (and Figures 20 and 21), the older classes of craters appear to be increasingly deficient in small craters, relative to either the slope of the post-mare distribution or to an extrapolation from large diameter continental craters.

The obliteration theory of section D was programmed and iterated with $B - 1 - \epsilon = -2.3$, and $\Delta = 0.1$. As illustrated in Figure 36, it qualitatively predicts a deficiency of small craters, but accounts for only about half the observed effect and does not reproduce the rather sharp discontinuity at about 32km. Such a sharp discontinuity in the mass distribution of pre-mare impacters, though possible, is not expected. It is tentatively concluded that the deficiency of craters results from a combination of obliteration, internal and external erosive processes, and a possible observational difficulty in recording all small craters.

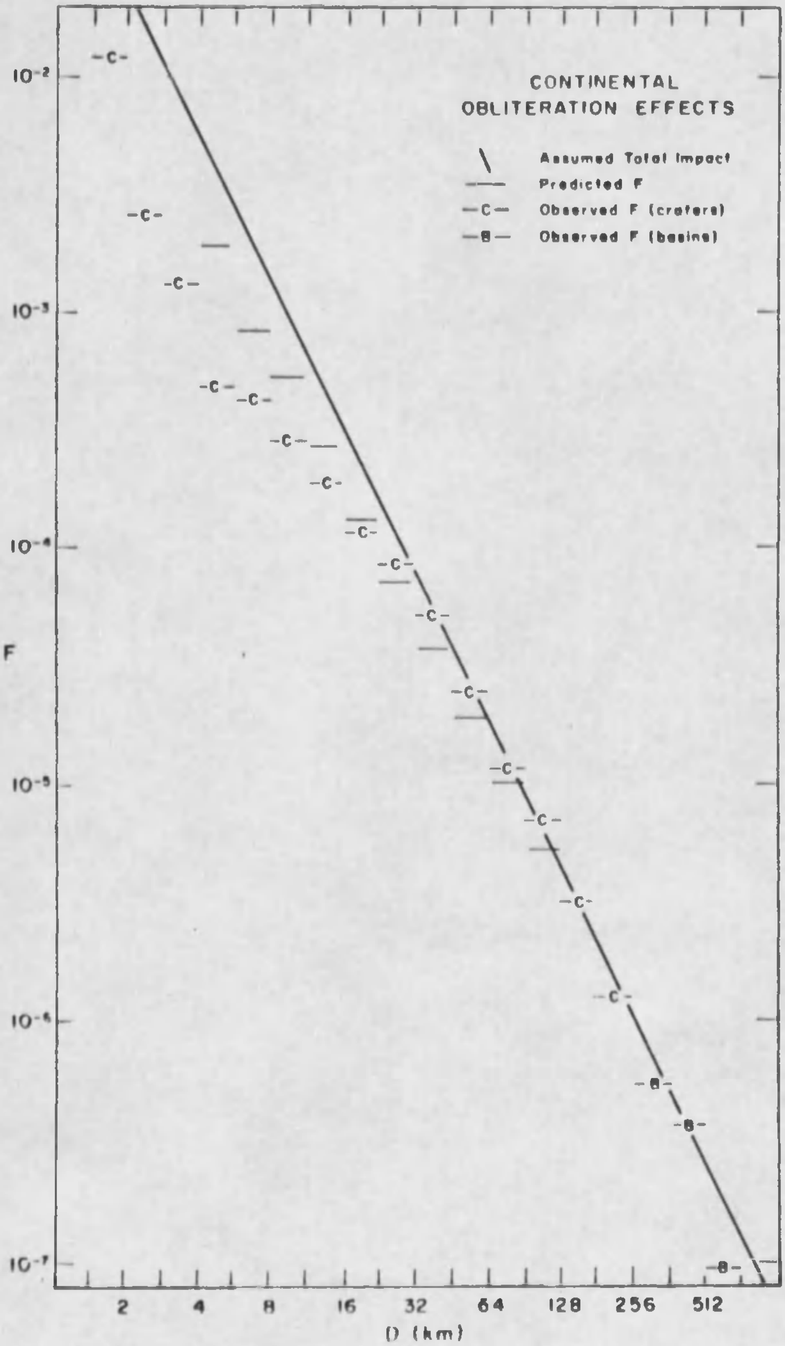

Figure 36. Theoretical obliteration effect.

XIII. RELATIVE AGES OF MARE BASINS

In Chapter VII the mare surfaces were ordered according to age. In this chapter the underlying basins themselves are so ordered.

Archimedian (post-basin, pre-mare) craters are the main key to this study. Archimedian crater densities are found to vary considerably, although the post-mare crater densities are nearly uniform. Hence the basin ages, which are a function of the total (Archimedian plus post-mare) crater density, vary. Because the cratering rate was probably not constant during the pre-mare period, the basin ages are not proportional to this total crater density.

The Archimedian crater density in several basins was studied as follows. It is clear that the Archimedian craters are unlikely to survive the deep flooding in mare centers. Therefore, counts were made only in a certain zone around the outer edge of each mare and the inner edge of its rim. The width of the zone was picked according to the apparent degree of preservation of Archimedian craters, so as to give a diameter distribution complete down to some minimum diameter. These counts, added to the post-mare counts (in some cases negligibly small), were then compared with post-mare and continental crater densities. By the hypotheses of this paper, and by definition, the post-basin crater density of each basin should fall between the post-mare and continental curves.

Secondary criteria of more subjective nature were also used to order the basins by age. In some cases no crater statistics could be obtained because of foreshortening, and these criteria were the only ones available. Morphological differences, such as rim sharpness, rim height, distinctness of ejecta blankets, and preservation of radial and concentric systems appear to be inversely related to age. Physical processes such as erosion and isostatic adjustment may be responsible for these differences.

Visual inspection of the borders of Mare Nectaria and the Apennine rim of Imbrium shows such a high difference in Archimedian crater density that Urey's (1952, 1960a, c) hypothesis of lava flooding by impact fusion, implying a zero Archimedian time interval, may be at once be ruled out.

Table VIII lists the circular basins in order of increasing age. As reported in Chapter XI, the basins are interpreted as giant impact features. The figures of Table VIII are interpreted as showing that the basins did form during the early intense bombardment. All of the figures are subject to improvement pending more complete Archimedian crater surveys.

Table VIII Post-Basin Crater Densities

Basin	Estimated Post-basin crater density / Post-mare crater density: Arithmetic	Log$_{10}$
Average mare	1.0	0.0
Orientale		
Imbrium	4	0.60 ± 0.20
Crisium	16	1.20 ± 0.16
Humboldtianum		
Nectaris	34	1.53 ± 0.13
Near Schiller	35	1.55 ± 0.12
Humorum	37	1.57 ± 0.10
Grimaldi		
Serenitatis		
S. E. Limb		
Janssen		
Pure Continental	45	1.65 ± 0.07

XIV. CONCLUSIONS - SUMMARY OF LUNAR HISTORY

A chronological summary of lunar history will now be given. References to evidence discussed in this dissertaion will be given by chapter numbers in parentheses.

The moon and the other planets formed probably in a period of time about 4.5×10^9 to 4.7×10^9 years ago. The place of the moon's origin, and the means through which it came to be associated with the earth are unknown.

The moon accreted out of bodies of mass less than 10^{13} grams, so that at the time its present radius was reached, there were few or no craters larger than a few kilometers diameter (XI). Probably the bulk of the moon's mass accreted in the form of smaller bodies such as the metric-sized objects hypothesized by Fowler, Greenstein, and Hoyle (1962).

After the moon had reached its present radius, but in the first few 10^8 years of its existence, an intense bombardment began. The flux averaged on the order of 400 times the present flux, and the peak bombardment was probably still more intense. The objects ranged from at least 10^{13} grams mass up to about 10^{22} grams (VIII, XI), with a mass distribution characteristic of collisionally fragmented objects, nearly identical to that presently found among the asteroids (XI, VI). They formed craters which are still visible, covering about 50% of the continental surfaces, and the most massive among them formed basins, among which the Imbrium basin is the largest and best known example (XI). If the moon was ever within a few radii of the earth, it was moving out at this time toward its present orbit, and the bombarding objects may have been part of a ring, unique to the earth-moon system among the terrestrial planets. Nectaris and Humorum are examples of the earliest basins while Imbrium formed later, near the end of the intense bombardment (XIII). Erosion and ejecta have affected the continental surfaces to a depth on the order of tens to hundreds of meters; obliteration has caused loss of some smaller craters (XII).

During the latter part of the intense bombardment period, expansion of the moon due to radioactive heating, and possibly other forces as well, subjected the lunar surface to stresses which produced fracturing, faulting, and the first manefestations of the lunar grid systems (Hartmann, 1963, 1964b). These systems intermingled with symmetric fracture systems surrounding the basins.

Toward the end of the intense bombardment, but still probably within the first 10^9 years of lunar history, the subsurface temperature in the outer part of the moon exceeded the melting point (probably peaking close to it), and a period of flooding began (Hartmann, 1963, 1964b). The fractured and brecciated zones beneath the basins gave to the lava access to the surface. Faulting continued, especially in radial and concentric fracture zones around the basins, and some lava rached the surface along these faults (Hartmann and Kuiper, 1962). Lava inundated some other portions of the surface, forming irregular maria and a few scattered flooded craters.

Of the present mare surfaces, some of the oldest may have been subjected to the tail-end of the intense bombardment; they now show up to 1.8 times the mean mare crater density. Most of the circular mare surfaces are within 25% of the mean mare crater density, and hence the flooding is thought to be confined to a certain early period (VII).

The post-mare portion of lunar history, though the longest portion, has been the least eventful. The post-mare craters are well-preserved (V), and they formed predominantly by the impacts of asteroidal fragments (VI, IX). The mare surfaces average on the order of 4×10^9 years in age (VIII). Erosion processes have affected the maria to a net depth on the order of 0.1 to 2 meters.

Figure 38 gives an early version of this history in schematic form (from Hartmann, 1964b) and Figure 39 illustrates in greater detail the initial stages of this history, showing the intense bombardment and the still earlier accretive flux.

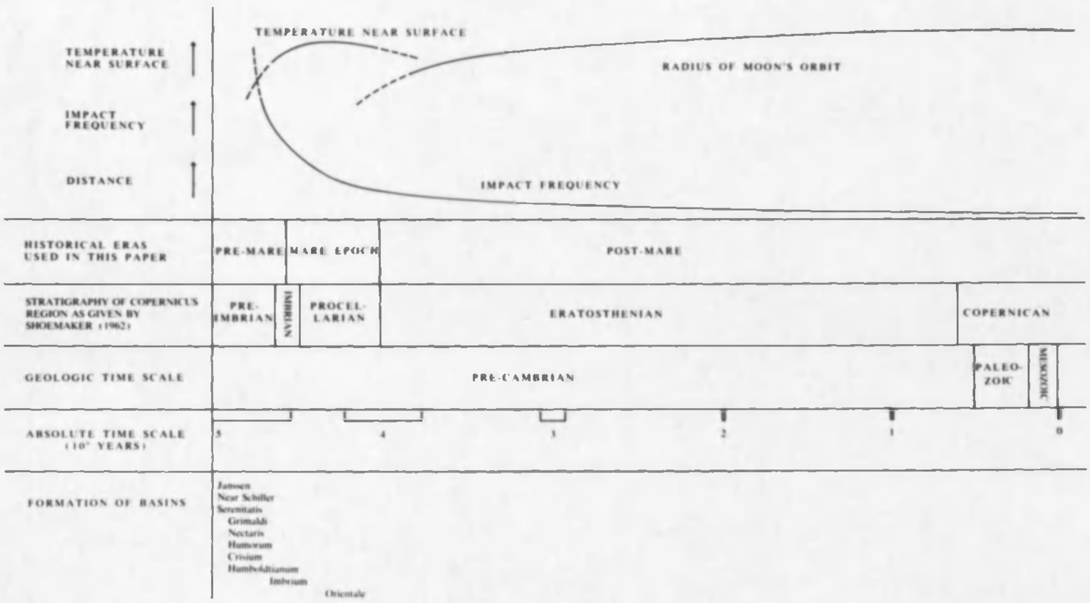

Figure 37. Schematic diagram of lunar history.

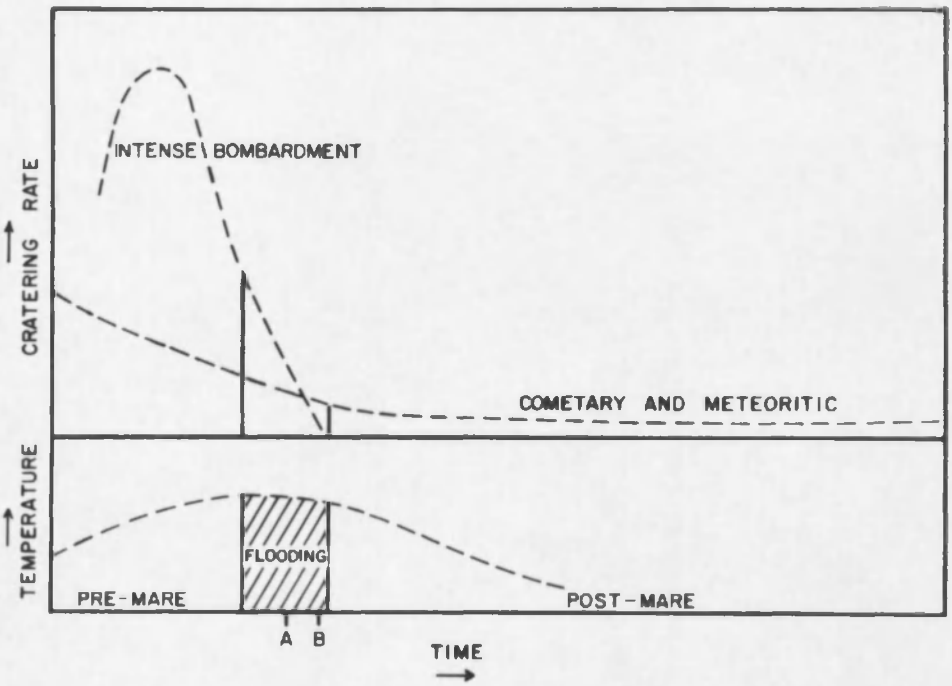

Figure 38. Schematic outline of early lunar history.

Revised from Figure 37 to show early intense bombardment.

REFERENCES

Abell, George 1964, Exploration of the Universe (New York: Holt, Rinehart, and Winston).

Abetti, Giorgio 1952, The History of Astronomy (New York: Henry Schuman).

Alfvén, H. 1954, On the Origin of the Solar System (Oxford: Clarendon Press).

----------.1955, "The Origin of the Moon", Irish A. J., 3, 245.

Alter, D. 1963, "The General Background of the Lunar Surface", P.A.S.P., 75, 30.

Anders, Edward 1963, "Meteorite Ages", in The Moon, Meteorites, and Comets, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: University of Chicago Press).

----------.1965, "Fragmentation History of Asteroids", Icarus, 4, 399.

Arthur, D. W. G., Agnieray, A. P., Horvath, R. A., Wood, C. A., and Chapman, C. R., 1963, "The System of Lunar Craters, Quadrant I", Comm. Lunar and Planet. Lab., 2, 71.

----------.1964, "The System of Lunar Craters, Quadrant II", Comm. Lunar and Planet Lab., 3, 1.

Arthur, D. W. G., Agnieray, A. P., Pellicori, R. H., Wood, C. A., and Weller, T., "The System of Lunar Craters, Quadrant III", Comm. Lunar and Planet. Lab., 3, 61.

Arthur, D. W. G., and Whitaker, E. A. 1960, Orthographic Atlas of the Moon, ed. G. P. Kuiper (Tucson: University of Arizona Press).

Baldwin, Ralph B. 1942, "The Meteoritic Origin of the Lunar Craters", Pop. Astr., 50, 365.

----------.1943, "The Meteoritic Origin of Lunar Structures", Pop. Astr., 51, 117.

----------.1949, The Face of the Moon (Chicago: University of Chicago Press).

----------.1963, "The Measure of the Moon" (Chicago: University of Chicago Press).

Beals, C. S., Innes, M. J. S., and Rottenberg, J. A. 1963, "Fossil Meteorite Craters", in The Moon Meteorites, and Comets, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: University of Chicago Press).

Beer, W. and Mädler, J. H. 1837, Der Mond (Berlin: Simon Schropp and Co.)

von Bieberstein, Marshall 1802, "Untersuchungen über den Ursprung und die Ausbildung der gegenwartigen Anordnung des Weltgebaeudes".

Binder, A. B., Cruikshank, D. P., and Hartmann, W. K. 1965, "Observations of the Moon and of the Terrestrial Rocks in the Infrared", Icarus, 4, 415.

Blagg, Mary A. and Müller, K. 1935, Named Lunar Formations, (London: Percy Lund, Humphries, and Co., Ltd.).

Brown, Harrison 1947, "An Experimental Method for the Estimation of the Age of the Elements", Phys. Rev. 72, 348.

----------.1960, "The Density and Mass Distribution of Meteoritic Bodies in the Neighborhood of the Earth's Orbit", J. G. R., 65, 1679.

von Bülow, K. 1957, "Tektonische Analyse der Mondrinde" Geologie, 6, 565.

Chamberlin, Rollin T. 1945, "The Moon's Lack of Folded Ranges" J. G. R., 53, 361.

Chao, E. C. T. 1963, "The Petrographic and Ghemical Characteristics of Tektites, in Tektites, ed. J. A. O'Keefe (Chicago: University of Chicago Press).

Darwin, G. H. 1898, The Tides (New York: Houghton Mifflin Co.).

Dodd, R. T., Salisbury, J. W., and Smalley, V. G. 1963, "Crater Frequency and the Interpretation of Lunar History", Icarus, 2, 466.

Fielder, G. 1961, Structure of the Moon's Surface (London: Pergamon Press).

----------.1963a, "Nature of the Lunar Maria", Nature, 198, 1256.

----------.1963b, "Erosion and Deposition on the Moon", Planet. Space Sci., 11, 1335.

----------.1965, Lunar Geology (London: Lutterworth Press).

Fish, R. A., Goles, G. G., and Anders, E. 1960, "The Record in the Meteorites, III.", Ap. J., 132, 243.

Fowler, W. A., Greenstein, J. A., and Hoyle, F. 1962, "Nucleosynthesis during the Early History of the Solar System", Geophys. Journ. R. A. S., 6, 148.

Gilbert, G. K. 1893, "The Moon's Face", Bull. Phil. Soc. Wash., 12, 241.

Gold, T. 1955, "The Lunar Surface", M. N., 115, 585.

Gruithuisen, F. 1844, Der Mond und seine Natur (Munich).

Hapke, B. 1964, "Effects of a Simulated Solar Wind on the Photometric Properties of Rocks and Powders". Cornell Research Paper CRSR 169.

Hartmann, William K. 1963 "Radial Structures Surrounding Lunar Basins, I", Comm. Lunar and Planet. Lab. 2, 1.

----------.1964a, "On the Distribution of Lunar Crater Diameters", Comm. Lunar and Planet. Lab., 2, 197.

----------.1964b, "Radial Structures Surrounding Lunar Basins, II", Comm. Lunar and Planet. Lab., 2, 175.

----------.1965a, "Terrestrial and Lunar Flux of Meteorites in the Last Two Billion Years", Icarus, 4, 157.

----------.1965b, "Secular Changes in Meteoritic Flux through the History of the Solar System", Icarus, 4, 207.

Hartmann, W. K., and Kuiper, G. P. 1962 "Concentric Structures Surrounding Lunar Basins", Comm. Lunar and Planet. Lab., 1, 51.

Hawkins, G. S. 1960, "Asteroidal Fragments", Ap.J., 65, 318.

---------.1963, "Impacts on the Earth and Moon", Nature, 197, 781.

Heacock, R., Kuiper, G.P., Shoemaker, E.M., Urey, H.C. , and Whitaker, E.A. 1965, Ranger VII, J.P.L. Report 32-700.

Heide, F. 1964, Meteorites, (Chicago: Univ. Chicago Press).

Hoel, P.G. 1954, Introduction to Mathematical Statistics , 2nd edition, (New York: John Wiley and Sons, Inc.).

Jaschek, C.O.R. 1960, "Earth Satellites and Lunar Formations" The Observatory, 80, 119.

Jeffries, H. 1962, The Earth, (Cambridge: Univ. Press).

Kiang, T. 1962 "Asteroid Counts and their Reduction", M.N. 123, 509.

Kopal, Z. 1962 "The Internal Constitution of the Moon", Planet. Space Sci., 9, 625.

---------.1963, "Gravitational Heating of the Moon", Icarus, 1, 412.

Krinov, E.L. 1963, "The Tunguska and Sikhote-Alin Meteorites", in The Moon, Meteorites, and Comets, ed. B. M. Middlehurst and G.P. Kuiper (Chicago: University of Chicago Press).

Kuiper, G.P. 1951, "On the Origin of the Solar System", in Astrophysics, ed. J.A. Hynek (New York: McGraw-Hill).

---------.1953, "Satellites, Comets, and Interplanetary Material", Proc. Natl. Acad. Sci., 39, 1153.

---------.1954, "On the Origin of the Lunar Surface Features" Proc. Natl. Acad. Sci. 40, 1096.

---------.1955, "The Lunar Surface - Further Comments", Proc. Natl. Acad. Sci., 41, 820.

---------.1959, "The Exploration of the Moon", Vistas in Astronautics, 2, (London: Pergamon Press).

----------.1965, "Interpretation of Ranger VII Records", J.P.L. Technical Report 32-700, p.9.

Levin, B. J. 1962, "Thermal History of the Moon", in The Moon, ed. Z. Kopal and Z. K. Mikhailov (New York: Academic Press).

Lohrmann, W. G. 1824, Topographie der Sichtbaren Mondoberflache (Dresden-Leipzig).

Lowman, P. D. 1963, "Relation of Tektites to Lunar Igneous Activity", Icarus, 2, 35.

Lipskii, Y. N. 1962, "Points from a study of the First Photographs of the Reverse Side of the Moon", Planet. Space Sci., 9, 565.

MacDonald, G. J. F. 1961, "Interior of the Moon", Science, 133, 1045.

MacDonald, Thomas L. 1931, "Studies in Lunar Statistics III, The Number and Area of Lunar Objects", J.B.A.A., 41, 288.

Marcus, A. H. 1965, "Positive Stable Laws and the Mass Distribution of Planetesimals", Rand Corp. Mem. RM-4458-PR.

Markov, A. V. 1962, The Moon; A Russian View" (ed.) (Chicago: University of Chicago Press).

Mason, Brian 1962, Meteorites, (New York: Wiley and Sons, Inc.)

McCracken, C. W., and Dubin, M. 1964, "Dust Bombardment on the Lunar Surface", in The Lunar Surface Layer, ed. J.W.Salisbury and P.E.Glaser (New York: Academic Press).

von Moll, K.E. 1810-1820, "Über den Zusammenhang der Gebirgsbildung mit dem Erschienen der Feuerkugeln" (Munich: unpublished).

Moore, Patrick 1953, A Guide to the Moon (New York: W. W. Norton and Co., Inc.).

Nininger, H. H. 1963, "Meteorite Distributions on the Earth", in The Moon, Meteorites, and Comets, ed. B. M. Middlehurst and G.P. Kuiper (Chicago: University of Chicago Press).

O'Keefe, J. A. 1963, "The Origin of Tektites", in Tektites ed. J. A. O'Keefe (Chicago: Unoversity of Chicago Press).

O'Keefe, J. A., and Cameron, W. S. 1962, "Evidence from the Moon's Surface Features for the Production of Lunar Granites", Icarus, 1, 271.

Öpik, E. J. 1958, "On the Catastrophic Effects of Collisions with Celestial Bodies", Irish A. J., 5, 34.

----------.1960, "The Lunar Surface as an Impact Counter", M.N., 120, 404.

Pickering, W. H. 1906, "Lunar and Hawaiian Physical Features Compared", Mem. Amer. Acad. Arts Sci., 13, 149.

Proctor, R. 1873, The Moon (London).

Ringwood, A. E. 1959, "On the Chemical Evolution and Densities of the Planets", Geochim. Cosmochim. Acta, 15, 257.

----------.1960, "Some Aspects of the Thermal Evolution of the Earth", Geochim. Cosmochim. Acta, 20, 241.

Runkorn, S. K. 1963, "The Interior of the Moon", J.P.L. Report No. 32-529.

Ruskol, E. L. 1961, "The Origin of the Moon, I", Sov. Astr., 4, 657.

----------.1963, "The Origin of the Moon, II", Sov. Astr., 7, 221.

Saari, J.M., and Shorthill, R.W. 1963 "Isotherms of Crater Regions on the Illuminated and Eclipsed Moon", Icarus, 2, 115.

See, T. J. J. 1910, "Origin of the so-called Craters on the Moon by the Impact of Satellites, and the Relations of these Satellite Indentations to the Obliquities of the Planet", Pop. Astron., 18, 173, 137.

Shaler, N. S. 1907, "Comparison of the Features of the Earth and Moon", Smithsonian Contr. to Knowledge, 34, 1.

Shoemaker, E. M. 1962a, "Interpretation of Lunar Craters", in Physics and Astronomy of the Moon, ed. Z. Kopal (New York: Academic Press).

----------1962b, "Exploration of the Moon's Surface", Amer. Scientist, 50, 99.

----------1965, "Preliminary Analysis of the Fine Structure of the Lunar Surface", J.P.L. Report 32-700.

Shoemaker, E. M., and Hackman, R. J. 1962, "Stratigraphic Basis for a Lunar Time Scale", in The Moon, ed. Z. Kopal and A. K. Mikhailov (London: Academic Press).

Shoemaker, E. M., Hackman, R. J., and Eggleton, R. E. 1962, "Interplanetary Correlation of Geologic Time", Advances in Astronaut. Sci., 8, 70.

Spurr, J. E. 1945a, Geology Applied to Selenology, I (Lancaster, Pa.: Science Press).

----------.1945b, Geology Applied to Selenology, II (Lancaster, Pa.: Science Press).

----------.1948, Geology Applied to Selenology, III (Concord, N.H.: Rumford Press).

Stockwell, C. H. 1962, "A Tectonic Map of the Canadian Shield", in The Tectonics of the Canadian Shield, ed. J. S. Stevenson (Toronto: University of Toronto Press).

Strom, R. G. 1964, "Analysis of Lunar Lineaments, I" Comm. Lunar Planet. Lab., 2, 205.

Suess, Eduard 1895, "Einige Bemerkungen über den Mond" S. B. Akad. Wiss. Wien. Math.-Naturwiss. Kl. 104, pt.1, 21.

Sytinskaya, N. N. 1957, "Origin and Nature of the Outer Covering of the Lunar Surface according to Data of Comparative Study of the Albedo-Color Diagram", Uch. Zap. Leningrad Univ., 190, 74.

Urey, H. C. 1952, The Planets, (New Haven, Yale Univ. Press).

----------.1955a, "Some Criticisms of 'On the Origin of the Lunar Surface Features', by G. P. Kuiper", Proc. Natl. Acad. Sci. 41, 423.

----------.1955b, "The Cosmic Abundances of Potassium, Uranium, and Thorium, and the Heat Balsnces of the Earth, the Moon, and Mars", Proc. Natl. Acad. Sci., 41, 127.

----------.1960a, "The Origin and Nature of the Moon", Smithsonian Report for 1960, 251.

----------.1960b, "Lines of Evidence in Regard to the Composition of the Moon", Proc. of First Internatl. Space Sci. Symp., ed. H. K. K. Bijl, 1114.

----------.1960c, "The Duration of Intense Bombardment Processes on the Moon", Ap. J., 132, 502.

----------.1962, "The Origin of the Moon and its Relationship to the Origin of the Solar System", in The Moon ed. Z. Kopal, and Z. K. Mikhailov (New York: Academic Press).

Urey, H.C., Elsasser, W.M., and Rochester, M.C. 1959, "Note on the Internal Structure of the Moon", Ap. J., 129, 842.

Wehner, G.K. 1964, "Sputtering Effects on the Lunar Surface", in The Lunar Surface Layer, ed. J. W. Salisbury and P. E. Glaser (New York: Academic Press).

Whitaker, E. A. 1962, "Evalusation of the Russian Photographs of the Moon's Far Side", Comm. Lunar Planet. Lab. 1, 67.

Wildt, Rupert 1961, "Planetary Interiors", in Planets and Satellites, ed. G. P. Kuiper, and B. M. Middlehurst (Chicago: University of Chicago Press).

Wise, D. U. 1963, "An Origin of the Moon by Rotational Fission during Formation of the Earth's Core", J.G.R., 68, 1547.

Wright, F. E., Wright, F. H., and Wright, H. 1963, "The Lunar Surface: Introduction", in The Moon, Meteorites, and Comets, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: University of Chicago Press).

Young, J. 1940, "Statistical Investigation of the Diameters and Distribution of Lunar Craters", J.B.A.A., 50, 309.