THEORETICAL GRAVITY ANOMALIES OF SOME LUNAR SURFACE FEATURES

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ABSTRACT

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By

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The gravity fields present over lunar surface features represent an important potential source of information about the nature of the subsurface structures of these features. This information may in turn contribute directly to an understanding of the origin of such features and of their place in lunar history in general. Furthermore, the determination of the gravity anomalies actually present over lunar surface features by local gravity surveys may enable a choice to be made between alternative theories of their origin. In this study, models were adopted for the subsurface structures of lunar craters, domes, lava tubes, rilles, and maria ridges, and the gravity anomalies that would exist over these structures were calculated by various approximate methods.

Craters. If the lunar craters are meteoritic in origin, those ranging in diameter from 0.5 to about 20 km will be characterized by negative gravity anomalies, due to an underlying breccia lens of shattered rock, whose form will be dictated by the form of the breccia

lens and whose amplitude will be directly proportional to the diameter of the crater and to the density contrast between the breccia and country rock. On the hypothesis that the craters are of internal origin, possibly analogous features on earth exhibit both positive and negative gravity anomalies and complicated structures. These anomalies, however, are generally related to regional anomalies of greater extent.

Domes. If the lunar domes are laccoliths, they should be characterized by positive gravity anomalies resulting from the subsurface intrusive rock. If due to the serpentinization of peridotitic material, however, they should exhibit negative anomalies with amplitudes possibly reaching tens of milligals.

Lava tubes. If lava tubes exist near the lunar surface, their negative anomalies should be detectable and their form delineated by careful surveys.

Rilles. In those lunar rilles that appear to be graben structures, the faulting involved may cut both the mare material and the sub-mare basement. The resulting displacements will produce gravity anomalies which will reveal the relative densities of the mare and basement materials.

Maria ridges. If these ridges are due to serpentinization, they should be characterized by negative anomalies. If they are volcanic features, they may be underlain by feeder dikes producing positive anomalies of narrow width. Ridges formed by the burial of crater walls will reveal negative anomalies of considerable width, while ridges due to subsidence and compression will exhibit positive gravity anomalies of regional extent.

The reduction of lunar gravity data will parallel terrestrial procedures. The lunar free air correction will be about 0.187 mgal/m, while the elevation correction for the moon will be less than half its terrestrial value. The lunar tidal correction may have an amplitude of several milligals, but the rate of change of the correction will be small. Axial rotation, the main source of the latitude effect on earth, will result in only slightly more than a 1 mgal difference in gravity from the lunar equator to pole.

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CHAPTER I

INTRODUCTION

For untold ages the moon has been for man an object of influence and interest. Its apparent size in the sky (equal to that of the sun), its curious shadings of light and dark areas, and particularly its rapid eastward motion against the background of stars, accompanied by the continually changing phases, all contributed to making the moon the most important object in the ancient's heavens, apart from the sun itself. Today, interest in the moon continues: in fact, it is probably at an all time high. However, we no longer need the reoccurring phases to order our lives, or the moonlight to find our way at night. Rather, today the moon is the focus of so much interest simply because it is the earth's closest neighbor in space, and as man's efforts enable him to be free of earth's restraints, it was inevitable that the moon would be his first stopping place.

To the unaided eye the moon reveals few of its secrets. The basic distinction of light and dark regions is easily seen, but little else. It was with the introduction of the telescope to astronomy by Galileo in 1609 that the first real stride forward was made in understanding the nature of the moon and its various features. Since that time ever larger telescopes, combined with various auxiliary devices, have provided man with views of the face of our satellite of ever-increasing clarity and definition. These views have shown that the surface of the moon differs greatly from that of the earth, in spite of the fact that the two bodies are closely associated in space and have apparently been so for a considerable part of their respective histories, if not from their very formation. A major reason for this difference is evidently the moon's lack of a substantial atmosphere. On earth, the continuous operation of the various geological agents such as wind and water, which of course require an atmosphere, tends to obliterate or alter radically the record of ancient events originally written in the materials of the earth's crust. Lacking this atmosphere and the consequent gradational agents, the moon's battered face may preserve a record of events whose traces have long since disappeared from the earth, events perhaps reaching far back in time to the origin of the earth itself. Therefore, an understanding of the moon, while interesting in itself, might greatly facilitate understanding the origin and development through time of our earth as well.

To progress toward such understanding, theories are required to account for the moon's surface as it is seen today in all of its barren glory. Down through the years since Galileo there has been no lack of such theories. Speaking broadly, these theories can be considered as belonging to one of two groups: the "external" or "exogenous" theories which interpret the moon as a relatively inert object which has been

acted upon down through the ages by certain external agents; and the "internal" or "endogenous" theories, which consider the moon's present aspect to be primarily due to forces acting from within the body of the moon itself. In recent years investigators have generally fallen into the "meteoritic" camp, which feels that the impact of meteorites has been the dominant process in molding the moon, and the "volcanic" camp, which maintains that volcanism, in its broadest sense, has predominated, although numerous other ideas are also defended strongly. With the advent of the space age the possibility of resolving some of the questions concerning the origin of the various lunar features and obtaining data which could serve as the basis for definitive conclusions seemed near. Now (1970), over a decade into the space age, we find that the excellent data provided by the various lunar missions have given few definite answers but have raised many more questions. The nature of even the very largest of the lunar features such as the maria themselves is still contested. Someone has referred to these data as a mirror in which each man sees reflected his own particular theory. It is now becoming evident that even the early manned lunar landings themselves cannot be expected to resolve many of these questions, and that a reasonably complete understanding of the moon's surface and its origins will undoubtedly remain a long-range goal. On the earth, where geologists have had the opportunity of years of first-hand examination, the origin of many features is still an open question. In dealing with the moon, from which no one had until very recently ever examined even one rock specimen, it is quite understandable that no definite conclusions have as yet been reached in many areas.

It is evident, then, that any approach or method which would provide some information concerning the actual, or at least the probable, nature of the subsurface structure of any given lunar surface feature might also contribute to the resolution of the question of its origin and development through time. An analysis of the gravitational field over a feature is one such method. Until very recently the only method generally available for study of the moon was by direct observation of its surface from a considerable distance. The topographical configuration of a lunar surface feature can be analyzed rather well by observation alone, especially if the feature is large, but as is evident, the surficial expression of any feature is only a two-dimensional view of what must be a three-dimensional structure. The surface of the moon is an interface between outer space and the body of the moon itself. Many surface features will be underlain by characteristic structures, but these are hidden from our direct view. Drilling is an obvious way to obtain accurate subsurface information, but with only a limited number of drill holes the volume actually sampled is very small. Also, the equipment necessary for really deep drilling is not likely to be transported to the moon in the near future. Yet, as long as subsurface density contrasts exist, distortions in the moon's overall gravity field will be present, and will represent an important potential source of information about the subsurface structure of the moon. These gravitational effects can be detected by gravity meters whose size and weight makes them likely candidates for inclusion on early manned lunar missions. As is well known, it is impossible to determine uniquely the structure and density distribution that exist below the surface solely from an analysis of the gravity field. At best, the gravity data will reveal "a shadowy and ambiguous picture of the density distribution underneath the ground." (Grant and West, 1965). Yet when combined with information obtained from more direct geological studies the gravity information can be very important.

The gravity method, then, must rightly be considered just one of several approaches to the study of any given feature, all of which have their contribution to make to the final understanding of the nature of the feature in question. Because of its ability to "see" beneath the ground, however, the gravity method has a somewhat unique role to play. Nevertheless, its view is hazy, and ultimately other more direct approaches must make the final decision toward which gravity has helped to point the way. These remarks could apply to most other geophysical methods as well. That is, they compliment, rather than supplant, other methods of geological investigation, and the best, most probable interpretation will result from a synthesis of all of the available data. In the case of the moon, however, at least for some considerable time, the geological knowledge from direct first-hand observation will undoubtedly also be limited and therefore the geophysical data will probably not be capable of a unique or even highly probable interpretation.

On the other hand, use should certainly be made of all avenues of information, and in the absence of deep drilling on the lunar surface, geophysical methods will probably be the main source of subsurface information and therefore should be utilized fully.

Although the usefulness of the gravity method and the role it can play in lunar exploration are generally acknowledged, up to the present little has been done in the way of actual, quantitative calculations designed to demonstrate the amplitude, form, and implications of the gravity anomalies that may be associated with various typical lunar surface features. This being the case, the purpose and methods of this study are as follows:

1. To determine the subsurface structures that are anticipated beneath various lunar surface features as predicted by different theories of their origins and development.
2. To model these subsurface structures as to scale and anticipated density contrasts and to determine likely ranges in these properties.
3. To calculate, using various approximate methods, the gravity anomalies that would exist over these subsurface structures, and to examine the implications of these anomalies and, where applicable, their role in the interpretation of the nature and origin of the features.
4. To investigate the various corrections and controls required to conduct a gravity survey in the lunar environment designed to detect these anomalies.

This approach has been applied to a number of lunar features in the following chapters. The information derived in this study may serve as a guide in determining the amplitude and form of the gravity anomaly over a feature, which would then be important in determining such things as instrument range requirements, elevation and position controls, and the accuracy of the corrections used in the reduction of the raw data. The gravity anomalies here determined are similar to what in terrestrial work would be called the complete Bouguer anomaly. After surveys are actually conducted and the anomalies defined, a comparison with the calculated anomalies might serve as a first step in understanding the nature of the actual subsurface structure of the feature and in determining which of the theories under consideration are incompatible with the observational data.

CHAPTER II

CRATERS

Craters are the most distinctive features of the lunar surface, aside from the maria themselves. As many as 300,000 of these relatively shallow, bowl-shaped depressions range in diameter from perhaps one kilometer up to as much as two hundred and fifty kilometers. Recent spacecraft and manned exploration have revealed countless thousands more whose diameters range down to microscopic size. Since the craters were first observed by Galileo in 1609 there has been no lack of theories concerning their origin. These theories are discussed in historical perspective very well by Shoemaker (1962) as well as by Kopal (1962), and Green (1965a). The debate over the origin of the craters is particularly important in that a person's views on this question will invariably influence his thinking on the origins of many of the other features as well.

In the last twenty years or so thinking on the origin of the lunar craters has been greatly influenced by the work of Ralph Baldwin (1949, 1963, 1965) on the meteoritic impact hypothesis. His greatly detailed work with the statistical relationships between various crater parameters apparently gave a firm, quantitative basis for understanding the origin of a crater as a near-instantaneous, explosive event resulting from the collision of a meteoritic body with the moon. While admitting the possible igneous nature of some of the lunar features, for the great majority of the lunar craters Baldwin (1965) has said "They can only be of meteoritic-impact origin. The 136-year argument is over."

Yet in recent years this view has been increasingly questioned by some workers. The scatter in much of Baldwin's data is considerable. Green (1963) has argued, for example, that terrestrial features such as calderas have depth-diameter ratios that scatter around the same curves as those found by Baldwin for meteoritic craters. Shoemaker (1962) has stated that "By their very nature the statistical arguments are inconclusive, and do not lead to the determination of the origin of a single crater. The evidence that has been adduced for the impact origin of lunar craters is thus insufficient." In addition, the excellent pictures returned to earth by the various spacecraft, manned and unmanned, showing what appear to be igneous features have helped to re-open the entire question. Even the manned lunar exploration may not answer many of these questions immediately. As just one example of the difficulties involved, it is noted that meteoritic material, which on earth might go far toward supporting the impact origin of a feature, will presumably be almost universally present on the moon because of the lack of an atmosphere. Therefore, any approach which can make some contribution to helping to resolve the question of origins should be investigated. The gravity anomalies that may be associated with the craters caused by meteorite impact are discussed below, followed by a similar discussion for crater-like structures caused by various types of internal activity.

The investigations of most workers concerned with the interpretation of the lunar craters have of necessity been centered primarily on the surficial characteristics of the crater as seen from an external point. However, any given crater must be underlain by a subsurface structure that is directly related to the processes that created it, whether those processes be manifestations of internal or of external agents. Any endogenous origin postulated to account for the crater by some form of volcanic action will obviously involve subsurface sources of magma, intrusions, fractures, etc., while an impact origin will result in fracturing of the rock beneath the crater to a considerable depth, producing what has been called an "impact breccia". In neither case would these subsurface structures necessarily be obvious or even visible to surficial examination alone, but in both cases density contrasts in these structures might well produce significant anomalies in the gravity field over the crater which could be detected by gravity meters. In order to predict the gravity anomaly that might be present over any given crater, whatever the origin, it is first necessary that a model for the subsurface structure be adopted.

Impact Craters

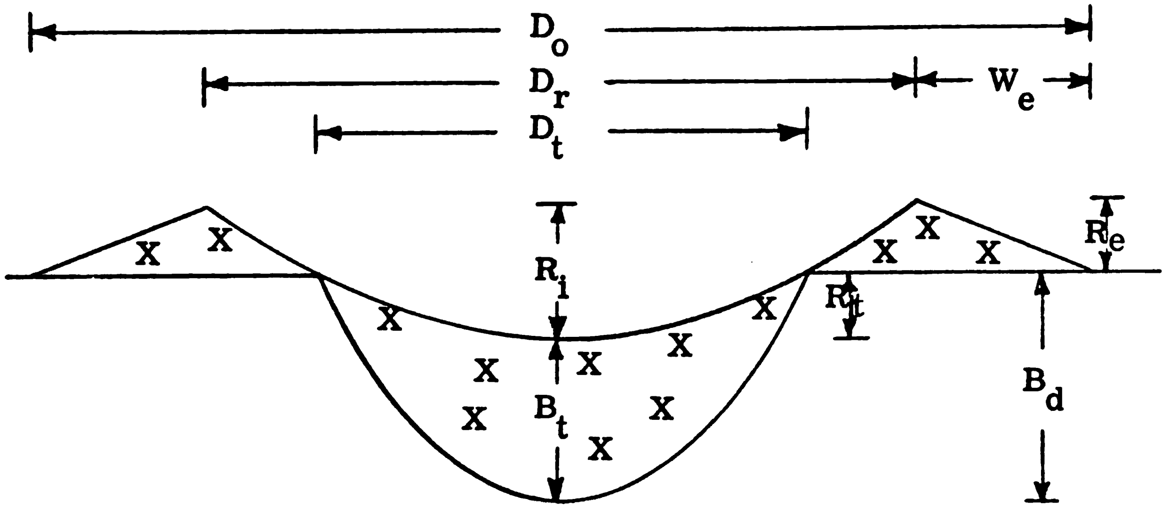
Figure 1 defines the various crater parameters that will be used below. There has been no general agreement among authors as to standardized symbols for these parameters. Pike (1968) summarizes the nomenclature used by various workers and introduces his own list. The symbols of Figure 1 for the surface geometry of the crater are those used by Pike (1967, 1968) with additional symbols for breccia depth, thickness, and volume. The most extensive investigations into the relationships that exist between the various topographic dimensions of impact craters are those of Baldwin (1949, 1963, 1965). As a result of his statistical studies on craters of all sizes Baldwin concluded (1963) that the rim crest diameter D_r and the interior relief or crater depth R_i of terrestrial meteorite and explosion craters and of lunar craters, all ranging over diameters from about 9 m up to about 32 km, are related according to the equation

$$\log D_r = 0.0256 \log R_i^2 + \log R_i + 0.6300 \qquad (1)$$

with all dimensions in feet. The corresponding equation for metric units (meters) is given by Baldwin as

$$\log D_r = 0.0256 \log R_i^2 + 1.0264 \log R_i - 2.3461. \qquad (2)$$

Unfortunately these two equations, which should yield identical results except for a conversion factor, in fact do not. For example, according



D_o, overall crater diameter

D_r, rim crest diameter

D_t, true crater diameter

R_i, interior relief (crater depth)

R_e, exterior relief (rim height)

R_t, true crater interior relief

W_e, exterior rim slope width

B_d, breccia depth

B_t, breccia thickness

V_b, breccia volume

Figure 1. Schematic impact crater section with crater parameters defined.

to equation (1) a crater whose diameter is 12,000 ft has a depth R_i of 1545 ft or 470.9 m. Equation (2) however, gives a depth R_i of 455 m for the same crater diameter D_r of 3,657.6 m or 12,000 ft, a difference of some 16 m or about 4%. In spite of this discrepancy, and the possibility that the five significant figures given by Baldwin in these equations may not really be warranted (see the discussion of the work of Pike below), equation (2) is adopted here as the relationship to be used between D_r and R_i. Similarly, Baldwin's relations between the rim crest diameter D_r and the exterior relief or rim height R_e,

$$\log R_e = 0.004366 \log D_r^3 - 0.008506 \log D_r^2 + 0.9098 \log D_r + 1.5987 \quad (3)$$

and between the exterior rim slope width W_e and the rim crest diameter D_r

$$\log W_e = \log D_r - 0.70 \quad (4)$$

and between the rim crest diameter D_r and the true crater diameter D_t

$$D_t = 0.83 \ D_r$$

are also adopted for use here, with all dimensions being in meters. To complete the model of the crater, the additional assumption is made, following the work of Innes (1961), that the floor of the crater has the shape of a paraboloid of revolution. These equations and assumptions then allow the calculation of all the pertinent dimensions of the topographic feature that is an impact crater.

In some recent investigations, Pike (1967, 1968) has re-examined the statistical relationships between these various crater parameters. In particular, from an analysis of over 600 fresh appearing lunar and terrestrial craters ranging in diameter from about ten meters up to about fifteen kilometers he finds that Baldwin's rather complex, curvilinear equations relating R_i to D_r and R_e to D_r can be replaced by the much simpler relationships

$$R_i = 0.155\ D_r^{0.95} \tag{6}$$

and

$$R_e = 0.048\ D_r^{0.95}x \tag{7}$$

with all crater dimensions being in kilometers. From the form of these equations, Pike concludes that the shape of fresh impact craters is in accord with a dimensional relationship known as the law of allometric growth, which was originally formulated by biologists and states that the rate of relative growth of an organ, y, is a constant function of the rate of relative growth of the total organism, x, such that

$$y = ax^b$$

where a and b are constants. For equations (6) and (7), the allometric condition would require the exponents to be 1, and this is very nearly the case. If the "growth" of impact craters is truly allometric this would imply that all fresh, unaltered impact craters, whatever their diameters, would have the same shape (be geometrically similar). Baldwin's equations, on the other hand, predict that the smallest craters will be relatively the deepest, with the larger craters becoming progressively more shallow, relative to their diameters. Table 1 compares the depths of craters of various diameters as predicted by equation (2) (Baldwin) and equation (6) (Pike). At the smaller diameters agreement between the two is good (at D_r=0.5 km they give identical depths), but according to Pike a crater of diameter 10 km should be some 22% deeper than Baldwin predicts. However, as will be discussed below, lunar craters much larger than 10 km in diameter, where the discrepancy between the depths as predicted by the two equations would be the greatest, have almost certainly had their shape and structure altered by processes not directly related to impact, and therefore would require a more complex model. Pike has also found that the floor of a crater can be closely approximated by a hemi-ellipse rather than a paraboloid of revolution as adopted in the present study. However, the exact configuration of the floor of a crater will have only a very small effect on the gravity anomaly predicted over the crater. The relationships determined by both Pike and Baldwin are utilized in the calculations of the anomalies below, and the differences they predict are noted.

The above equations and assumptions allow the calculation of all of the necessary surficial dimensions of a crater, but they give no

TABLE 1

DEPTHS OF IMPACT CRATERS AS PREDICTED BY BALDWIN (EQUATION (2)) AND PIKE (EQUATION (6))

Crater diameter D_r (km)	Baldwin crater depth R_i (m)	Pike crater depth R_i (m)
0.5	80	80
1	147	155
2	270	300
5	595	715
10	1074	1381

clue as to the subsurface structure that might exist beneath an impact crater, which might be detectable by gravity methods. However, it has become evident from many different lines of investigation that an event such as the impact of a large meteorite on the surface of the earth or moon should result in the fracturing and shattering of a substantial volume of bedrock beneath the crater floor, thereby changing its physical properties and perhaps making this disrupted zone susceptible to geophysical measurements. In particular, such brecciation might, in the case of an impact into solid rock, produce a large body of shattered material whose overall density is less than that of the country rock, which would then in turn result in a gravity low over the crater. The investigations of various Canadian workers such as those of Beals et al (1963), Innes (1961, 1964), Beals and Halliday (1965), and Dence (1964, 1965) on craters of the Canadian Shield have been particularly important in the development of present ideas concerning impact crater subsurface structures and their geophysical expressions. In order to complete the model of an impact crater needed to predict the gravity anomaly expected over it, the form and dimensions of the breccia body beneath the crater must be specified, and the investigations referred to above are directly applicable here.

It is evident that the zone of brecciation beneath an impact crater will not be separated from the undisturbed country rock by an absolutely sharp boundary. Nevertheless, there should be a reasonably well defined surface between the completely brecciated rock and the country rock which, even though it may be fractured, is still essentially in place. The brecciated rock bounded by this surface and the floor of the crater is called the breccia lens. It would be difficult if not impossible to calculate the exact form and size of the crater and this lens directly from first principles for a meteorite impact. However, from an analytical investigation of this problem Rottenberg (Beals et al, 1963) found that for an impact into granite gneiss the surface separating the region of brecciation from the region of simple fracture would have a depth at the center of the crater of about one-third of the crater diameter. This surface will obviously come to intersect the surface of the ground somewhere in the vicinity of the crater's rim, and undoubtedly in a radially symmetrical crater this surface would have the shape of some solid of revolution. In his study of a number of the Canadian craters Innes (1961) found that the assumption that this surface had the shape of a paraboloid of revolution, which enabled the total volume of the breccia to be calculated, lead to quite consistent results with the deep drilling data and the observed gravity fields. For example, at the Brent crater in Ontario, a presumed ancient impact crater about 3.2 km in diameter, the volume of breccia as determined from the above model agreed with that determined by drilling to within about 10% and within about 5% of that obtained from an analysis of the gravity field and the density of the breccia as found by drilling. From an analysis of the drill records obtained at the Deep Bay crater in Saskatchewan, Innes (1964) gives a cross-section of the subsurface structure which indicates that the lower surface of the breccia intersects the floor of the crater at about the level of the original plain (see Figure 1). Therefore, to complete the crater model adopted here, the breccia depth B_d is taken to be equal to one-third of the true crater diameter D_t, or

$$B_d = D_t/3 \tag{8}$$

and the lower surface of the breccia lens is assumed to be a paraboloid of revolution, intersecting the crater floor at the original level of the plain. The breccia lens therefore has the shape of a solid bounded by two paraboloids of revolution (the other being the crater floor) and containing a total breccia volume V_b of

$$V_b = (\pi/8)\, D_t^2 \left[D_t/3 - R_t \right]. \tag{9}$$

That the depth of the breccia is about one-third of the crater diameter, however, was determined by assuming an impact into granite gneiss, and the Canadian craters, which seem to support that figure, are in rock of that general type. The possibility exists, of course, that the lunar surface layer might be of quite a different nature, and naturally leads to the question of the validity of this model for craters in other types of material. However, the fact that the relationships found by Baldwin and Pike can represent well the dimensional ratios of explosion pits and craters ranging from bomb and shell craters through terrestrial meteorite craters to the lunar craters themselves, which certainly must cover a variety of impact materials, seems to indicate, as Innes (1961) has said, that "crater dimensions seem to be remarkably insensitive to the properties of the material." Shoemaker (1963) gives section drawings of Meteor Crater in Arizona, which is in sedimentary rocks, and of the Jangle U nuclear explosion crater, which was in alluvium. For both, the ratio B_d/D_t, as determined from direct scaling from those sections, is very nearly 1/3, as adopted in the model used here. Short (1966) describes a series of experiments by Gault in which tiny, hypervelocity projectiles were fired into sand and other target materials, resulting in craters that "have morphologies and internal structures remarkably like those natural impact craters which have been studied by drilling and excavation." In view of these lines of evidence, in this study it is assumed that the form and structure of an impact crater is independent of the nature of the target material. The equations relating the various crater parameters of the model adopted here are summarized in Table 2, and are numbered in the order that they were introduced above.

Having adopted a model for an impact crater, there remains the question of the nature and magnitude of the density contrast that will exist between the breccia and the country rock, upon which the amplitude of the gravity anomaly will of course depend, and the question of the limits, if any, on the range of crater diameters for which this model is valid. From the Canadian craters that have been well studied it has become evident that the breccia lens is not completely uniform in structure or density contrast but rather may be quite complex.

TABLE 2

RELATIONSHIPS BETWEEN CRATER PARAMETERS

Equation

(2) $\log D_r = 0.0256 \log R_i^2 + 1.0264 \log R_i - 2.3461$

(3) $\log R_e = 0.004366 \log D_r^3 - 0.008506 \log D_r^2 + 0.9098 \log D_r + 1.5987$

(4) $\log W_e = \log D_r - 0.70$

(5) $D_t = 0.83 D_r$

(8) $B_d = D_t/3$

(9) $V_b = (\pi/8) D_t^2 \left[(D_t/3) - R_t\right]$

For equations (2) through (5), units are meters.

Melting and shock metamorphism may produce a wide variety of lithologies within any one crater with distinct layering due to slumping and fallback during the process of crater formation (Dence, 1964, 1965; Short, 1966). Any gravity anomaly, however, will reflect the overall density contrast of the breccia lens as a whole, and no further attempt will be made here to delineate structures within the breccia body itself.

In general the terrestrial craters investigated by the Canadian workers have negative Bouguer gravity anomalies. Of a list of eleven craters given by Dence (1967) nine have negative anomalies while two of the smaller craters, Flynn Creek, 3.5 km in diameter, and Jeptha Knob, 2 km in diameter, both of which are in sedimentary rocks, have anomalies of zero and +1 mgal respectively. The negative anomalies over the remaining craters are due to both the reduced overall density of the breccia and to the later sedimentary rock fill in the craters which is less dense than the country rock, but the two effects can be distinguished in craters where drilling has been done. It seems that craters in sedimentary rocks have weaker anomalies than those of the same size formed in crystalline rocks. Dence (1967) has suggested that this may be due to the fact that the stronger crystalline rocks can support cavities and voids in the breccia indefinitely, producing a stronger (negative) anomaly, while the lighter, weaker sediments will collapse and fill the voids. At the Brent crater, which is in gneiss, the country rock has a density of 2.67 g/cc while the average density of the breccia, although varying considerably within short distances along the drill cores, averaged about 2.50 g/cc, giving a density contrast of -0.17 g/cc. In sediments the density contrast would presumably not be as great. Exactly how these terrestrially determined values would apply to the lunar environment is uncertain, in the absence of definite knowledge of the composition and state of the lunar materials at depth. For a lunar impact into material with physical properties similar to solid, crystalline rocks the lesser lunar gravity, which would probably allow the breccia to support void spaces more easily than on earth, and the (presumed) lack of deposition of secondary minerals in the voids by ground water or degassing might result in a density contrast between breccia and country rock considerably greater than that found in terrestrial craters of corresponding size. Shoemaker (1966) has suggested that brecciation and fragmentation of solid rock materials on the moon could result in an increase in specific volume of 30% or more. If 2.67 g/cc is considered to be an approximation of the initial density of such a material, an increase of 30% in the specific volume would result in a breccia of density 2.05 g/cc, giving a density contrast of -0.62 g/cc. On the other hand, experiments involving the exposure of molten samples of various rock types to a high vacuum as might be encountered on the moon have resulted in frothy, porous masses of quite low bulk densities (Dobar, 1965; Dobar et al, 1964). A mean density of 1.76 g/cc was found for such a froth of basaltic composition and 0.97 g/cc for granitic composition. If an impact were to occur in such a material or in deep material of a fine, powder-like texture, the effects of compaction and shock welding could conceivably result in a breccia of increased density, with a subsequent positive anomaly. Although such a situation may not seem likely, the possibility does exist. Additionally, there could be further complications due to effects such as melting of rock at the time of impact. In view of these uncertainties it would not seem justifiable to attempt to select a certain, definite value for the density contrast and assign it to our crater model. Rather, the anomalies will be calculated independently of the density contrast. Then, if further evidence allows the selection of a particular value, (ultimately to be determined by on-site examination of rocks in or near a crater), the anomaly predicted for that value can immediately be found. Alternatively, if the crater model is valid, a determination of the actual anomaly over a given crater would allow the bulk density contrast of the breccia to be determined from the following data.

One further question to be considered is that of the range of crater diameters for which the model is valid. As was mentioned above, the investigations of Pike and Baldwin seem to indicate that the general equations relating the various crater dimensions can be applied to craters only a few meters in diameter or even smaller. However, as diameter decreases so also does the gravity anomaly, and for very small craters the anomalies would be so small that they will be virtually undetectable, particularly if measurements are being made in a geologically unfamiliar environment such as on the moon, where uncertain regional effects and subsurface structures could complicate the gravity picture considerably. Therefore, rather arbitrarily, the smallest crater considered here is taken to have a rim crest diameter D_r of 0.5 km. Attempting to determine an upper limit on the applicability of the model is somewhat more involved. For terrestrial craters, particularly those investigated by the Canadian workers, there seems to be a definite distinction between craters of "simple" structure, which essentially correspond to the model adopted here, and "complex" craters, which, while retaining the normal meteorite crater characteristics such as evidence of a raised rim and subsurface breccias, differ from the simple crater model primarily by the presence of a pronounced central uplift. Dence (1964, 1965) has discussed these two types of craters and found that of ten craters studied and presumed to be due to impact, the six smallest, ranging up to 10 km in diameter, can be well represented by a simple model similar to that used in this study. The other four, ranging from 20 to 65 km in diameter, all have definite central uplifts. In some of the craters this uplift is surrounded by additional annular rings of uplift and depression, reproducing the essential features of structures like the Vredefort ring. Petrographic considerations (shock metamorphism) and overall geometry seem to support a meteoritic origin for both the simple and complex types. In the Manicouagan-Mushalagan structure, which is nearly 65 km in diameter, the central uplift, about 15 km in diameter, stands nearly 300 m above the surrounding level despite being considerably eroded, and is surrounded by a ring graben which may be downthrown as much as 1 km or more. That the simple-complex distinction is a gradational one seems indicated by the East Clearwater crater (Dence, 1965) which is about 20 km in diameter. Superficially an eroded simple impact crater, its gravity anomaly is not as large as would be expected from the simple crater model. Drilling has revealed that the crater floor is shallower than predicted and there is a pronounced central uplift. Some mechanism apparently operates in terrestrial craters above approximately 15-20 km in diameter to raise much nearer the surface rock which was originally at a considerable depth beneath the crater floor. Isostatic adjustment would seem to be one possible mechanism. DeSitter (1956) has suggested that a crustal plate as small as 20 by 20 km might be significantly affected by isostatic adjustment. Alternatively, Dence has suggested that such an uplift might possibly result at the time of impact due to shock wave reflection from some horizontal discontinuity beneath the crater such as the Mohorovicic or Conrad discontinuities. Because the rocks previously at depth now occur nearer the surface in these craters, the geophysical properties of these rocks will be less anomalous than those of the breccias, and the gravity readings over the central uplift, for example, will approach the "normal" values found outside the crater, but may be flanked by gravity lows due to the effects of an annulus of breccia. Just such an anomaly is found at the Carswell Lake structure in Saskatchewan, where the central high is flanked by lows of about 10 mgal.

Recently, studies by Pike (1967, 1968) have called attention to the fact that a similar transitional zone from simple to complex structure may exist for the lunar craters, and that this transition is also made in the 10-20 km diameter range. He has summarized the surficial differences that seem to exist between the two crater types, some of which are reproduced in Table 3. Of particular interest are the relationships found between R_i, the crater depth, and D_r, the rim crest diameter, for the larger craters. Pike's work (equation (6)) on this relationship for craters up to about 10 km in diameter has already been discussed. However, Pike found that for craters above about 15 km in diameter the slope of this relationship abruptly lessens, and for these larger craters the corresponding relationship becomes

$$R_i = 0.880\ D_r^{0.35} \tag{10}$$

so that these craters will be significantly shallower for their diameters compared to those below about 10 km diameter. That an entirely new mode of origin is unlikely for the larger craters is indicated by the fact that the D_o/D_r relationship, which relates horizontal dimensions of the crater rather than vertical, is unchanged across the 10-20 km boundary. Apparently the craters have had a common mode of origin and the larger craters have had their vertical dimensions altered (lessened) by post-impact processes, which produce the differences noted in Table 3. Since many of the craters over 10-20 km in diameter have flat floors which are widely interpreted as some form of volcanic

TABLE 3

CONTRASTING PROPERTIES OF SIMPLE AND MODIFIED LUNAR CRATERS, AFTER PIKE (1968)

Attribute	Simple Craters	Modified Craters
Size range (D_r)	Generally under 10-20 km.	Generally over 10-20 km.
$R_i:D_r$ (km)	R_i=0.155 $D_r^{0.95}$	lower slope; not isometric.
$R_e:D_r$ (km)	R_e=0.042 $D_r^{0.98}$	lower slope; not isometric.
$D_o:D_r$ (km)	D_o=1.4 D_r	D_o=1.4 D_r
Floor configuration	Partial hemi-ellipse	Flat
Rim crest profile	Even	Uneven
Central eminences	None	Present in fresh craters
Inner rim slope shape	Smooth	Terraced
Rim crest polygonality	Generally absent	Generally present
Rim crest craterlets	Rare	Often present

material, it seems possible that the extrusion of such materials may well be related to the forces producing the topographic changes that Pike has described.[1] Pike lists seven possible mechanisms suggested by various workers for the emplacement of the material in the flat-floored craters, the seventh of which is his own. They are:

(1) Global melting epochs brought on by continued decay of radioactive minerals within the moon;

(2) Widespread melting due to upward transferral of heat by convection currents;

(3) Localized melting due to direct change of a portion of the impact energy into heat, or shock melting;

(4) Both localized and regional melting and defluidization caused by accumulated heat resulting from continuing tidal flexing of the moon;

(5) Volcanism induced in an impact region by lowering of the thermal conductivity of the lunar crust by brecciation below an impact crater, easy access of magma through the breccia lens, and the presence of an impact-induced thermal anomaly near the lunar surface;

(6) Subcrustal melting in response to reduction of overburden pressures below large craters, with subsequent intrusion into the fractured crater region; and

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[1]See Quaide et al, (1965) for a discussion of the effects of gravity alone in the modification of lunar craters over 10 km in diameter.

(7) Magma generated beneath large lunar craters by stresses developed during isostatic readjustment of the impact-produced mass disequilibria.

In view of the number of possible mechanisms listed above, and the lack of quantitative data on which to base predictions of subsurface structures, it would seem to be premature to attempt to create a model of "the" complex crater. Since from the discussion above it seems clear that several lines of evidence suggest that a diameter of some 10-20 km is the threshold separating structurally and volcanically modified terrestrial and lunar craters from relatively simple and unaltered ones, we will be concerned below with the calculation of the gravity anomalies for impact craters only within the diameter range from 0.5 to 20 km. The important parameters for such craters, found from the relationships given in Table 2, are shown in Table 4. It may be noted in Table 2 that all parameters involving vertical rather than just horizontal crater dimensions (see Figure 1) are not directly proportional to the crater diameter but reflect Baldwin's curvilinear relationships of equations (2) and (3). However, if Pike's argument that all fresh, unaltered impact craters are very nearly geometrically similar is valid, then the parameters of a crater of any diameter can be obtained simply by direct scaling up of the values given in Table 4 for a crater of diameter D_r of 0.5 km, since his and Baldwin's equations for the depth-diameter ratios are in agreement for this diameter, as shown in Table 1.

Table 4 gives all of the information necessary to create a three dimensional model of an impact crater. A gravity anomaly will exist over the crater because of the brecciation and fragmentation caused by the impact. This anomalous mass will consist of two parts which in nature will be essentially continuous but which are separated into the breccia lens and the rim. That the rim is anomalous mass is obvious, but its structure is more uncertain. Many investigators (e.g., Baldwin, 1963) have considered the rim to be composed simply of material excavated from the crater and dumped by the force of the explosion onto the surrounding landscape. Schröter's Rule, expressing the alleged equivalence of the volume of the crater below the original plain with the volume of the rim, has often been cited as supporting this interpretation. Pike (1967), however, has clearly demonstrated the non-validity of Schröter's Rule as applied to the lunar craters. Dence (1965) has called attention to the fact that the rim of the New Quebec crater is composed largely of bedrock which was uplifted and somewhat fractured rather than being composed of debris ejected from the crater itself. In any case, the rim will be composed of material whose overall density will contrast somewhat with that of the country rock. There seems to be no essential reason why the density of the rim should be equal to that of the breccia lens as a whole. One could probably argue that it would be either greater or smaller. It is here assumed that the overall density of the rim and the breccia lens are equal, and that they would both therefore contrast equally with the country rock. Since,

TABLE 4

CALCULATED IMPACT CRATER PARAMETERS

Crater structure			Simple				Complex
Crater diameter D_r (km)	0.5	1.0	2.0	5.0	10.0	TRANSITIONAL ZONE	20.0
True diameter D_t (km)	0.42	0.83	1.66	4.15	8.30		16.60
Rim height R_e (m)	21	40	74	171	320		599
Rim width W_e (km)	0.1	0.2	0.4	1.0	2.0		4.0
Crater depth R_i (m)	80	147	270	595	1074		1924
True depth R_t (m)	59	107	196	424	754		1325
Breccia depth B_d (m)	138	277	553	1383	2770		5530
Breccia thickness B_t (m)	79	170	357	959	2016		4205
Breccia volume V_b (km^3)	0.0056	0.0469	0.3834	6.471	54.58		455.4

however, the rim is a topographic feature above the level of the surrounding plain and crater floor, even though its mass is anomalous, the gravitational effect of this mass would presumably be removed in an actual survey as a terrain correction. An estimate of the density of the rim to be used in this correction could be obtained by direct inspection. Even if this estimate is not exact the error in the total crater anomaly will be slight because, as will be shown below, the contribution of the rim to the total anomaly is very small.

The gravity anomalies over the craters can be calculated in a number of ways. The method used here is an approximate one given by Nettleton (1942) and is based on the fact that the vertical gravity effect of a thin, horizontal lamina is directly proportional to the solid angle subtended by the boundary of the lamina at the point of observation. Since the crater and its subsurface structure is assumed to be radially symmetrical, horizontal sections will be circular. In order to determine the maximum anomaly present, the observation point was taken to be the center of the crater floor. The anomaly will be due to the mass deficiency of the breccia lens, on the assumption that the effect of the rim is eliminated by a terrain correction. The breccia lenses of the craters for which the anomalies were calculated (those of diameters D_r of 0.5, 1, 2, 5, 10, and 20 km) were divided into ten horizontal circular laminae, each of which therefore had a thickness of 1/10 B_d or 1/30 D_t, since the breccia depth has been assumed to be 1/3 of the true crater diameter. The radius of each lamina or disk could be found from the assumption that the breccia-country rock interface is assumed to be paraboloidal in section, and the radius selected is that which makes each disk intercept this interface at its median plane. As a result, the volume of each disk will closely approximate the actual volume of its portion of the breccia lens. The upper disks of the breccia lens are not complete but are ring shaped, being bounded on the inner side by the floor of the crater. The effect of these annular disks was found by simply subtracting from the entire disk the effect of the smaller disk that would fit inside the crater floor in each case. The varying depths of the craters, according to Baldwin (equation (2)), meant that the center of the crater floor, the observation point, would not necessarily coincide with the top of one of the chosen disks. The disk within which the center of the floor fell was therefore divided into two disks, a solid one below and an annular one above, and their effects were calculated separately. In order to obtain an estimate of the gravitational effect of the rim as well, the rim was approximated by one annular disk, with a thickness equal to the height of the rim and a width of one half of the width of the entire rim as measured at the original ground level. This disk therefore had a cross-sectional area equal to that of the rim itself, and was positioned as shown in Figure 2. This figure illustrates, for a crater of diameter D_r of 0.5 km, the structure of the crater as predicted by the model adopted here and the various disks used to approximate that structure. Structural diagrams for craters of other diameters would resemble Figure 2 except that the depth of the crater and the height of the rim would vary according to Baldwin's relationships, as shown by the data of Table 4. On the other hand, if Pike is correct, then all fresh impact craters, of whatever diameter, will be very nearly geometrically similar to the one of Figure 2.

If we now assume further that the mass of each disk is concentrated on the median plane of that disk (the dotted lines of Figure 2), the vertical component of the gravity effect at the center of the floor of the crater will be directly proportional to the solid angle subtended at the center by these median planes. Since these median planes are circles, and since the center of the floor is directly above (or below) their centers, the solid angle ω subtended by the median plane of the disk can be found from the equation

$$\omega = -2\pi\left[\frac{1}{(R^2+1)^{\frac{1}{2}}} - 1\right]$$

where the depth to the center of the disk from the point of observation is defined as unity and R is the radius of the disk expressed in units of this depth. Nettleton (1942) gives a chart relating the solid angle to the depth-radius ratio for such disks. In order to assess the accuracy of the solid angles as determined from this chart relative to those calculated directly from the formula given above, for several series of disks the total subtended angle was determined both by the chart and by calculation. In no case did the results differ by more than 2%, and

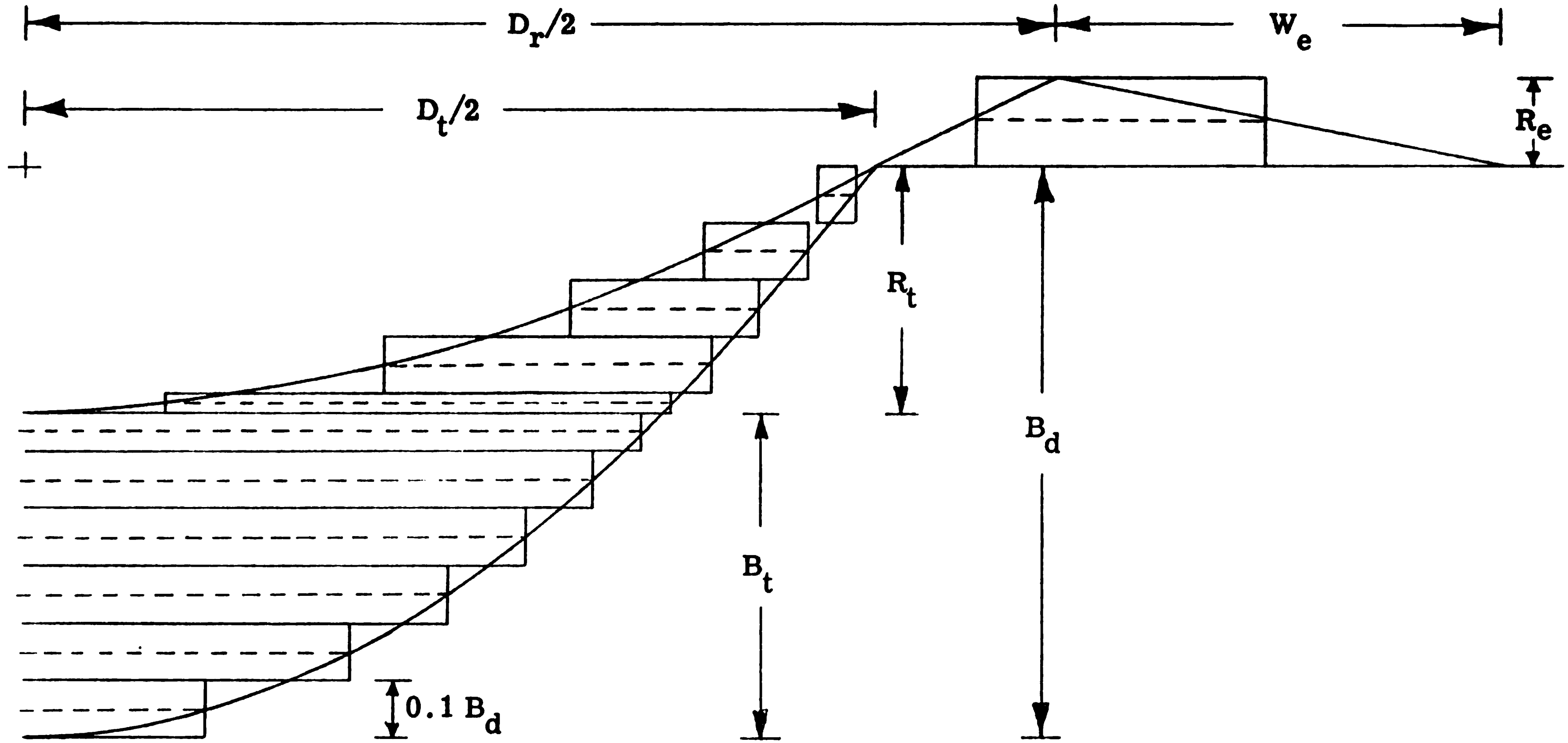

Figure 2. Scale cross-section of half of an impact crater of diameter D_r of 0.5 km, showing the disks used to approximate the anomalous mass of the breccia lens and the rim. Dotted lines are the median planes of the disks.

therefore the solid angles as determined by Nettleton's chart were considered adequate.

Having determined the solid angles subtended by the median planes of the disks (or annulus, for the disks above the level of observation), the vertical gravity effect g, in milligals, is given by

$$g=6.66\,\omega\sigma t \qquad (11)$$

where ω is the solid angle, σ is the density contrast in grams per cubic centimeter, and t is the thickness of the disk in kilometers (from Nettleton (1942) with a conversion factor). The total anomaly will be simply the sum of the effects of the individual disks. The anomaly obtained in this manner is the difference between a gravity reading obtained with the anomalous mass of the breccia lens present and what that reading would be if the lens were not anomalous. The effect of the rim is assumed to have been accounted for in the terrain correction. It is here noted that the effects of the anomalous material below the level of the observation point at the center of the crater floor (that portion of the breccia lens lying below the center of the crater floor) and the anomalous mass above this level (the upper part of the breccia lens and the rim) will be opposite in sign. For example, if the density contrast is negative (anomalous mass less dense), as would appear reasonable, the material in the lower portion of the breccia lens would of course produce a negative anomaly, but the effects of the upper portion of the lens and the rim, also having a negative density contrast, would be to produce a positive effect at the center of the crater floor, (on the assumption that the density of the country rock is used in the terrain correction), thereby decreasing the absolute value of the anomaly. The effect of this upper mass is, however, quite small. Figure 3 shows the percentage by which the anomalous mass of the rim would decrease (in absolute value) the amplitude of the maximum anomaly caused by the breccia lens, assuming that the density contrast of both the rim and the breccia lens with the country rock was the same. Normally, as was mentioned above, the effect of the rim would be allowed for in the terrain correction, using the appropriate density in the correction. Even if in the reduction of the data the rim were considered to be non-anomalous, having the same density as the country rock, the error would be small (Figure 3), ranging from less than 3% for a crater of diameter 0.5 km to 1% for a crater 20 km in diameter. If impact craters are all geometrically similar (Pike) rather than becoming gradually shallower relative to increasing diameter (Baldwin), then the effect of the anomalous mass of the rim would be about 3% for a fresh, unaltered impact crater of any diameter. In the following, the effect of the rim is assumed to be accounted for in the reduction of the data, and the anomalies calculated are those due to the breccia lens itself. Since the breccia lens has by far the greatest part of its volume below the center of the floor of the crater, deviations of an actual crater in particulars such as the shape of the crater floor, the height and dimensions of the rim, and the exact density contrast

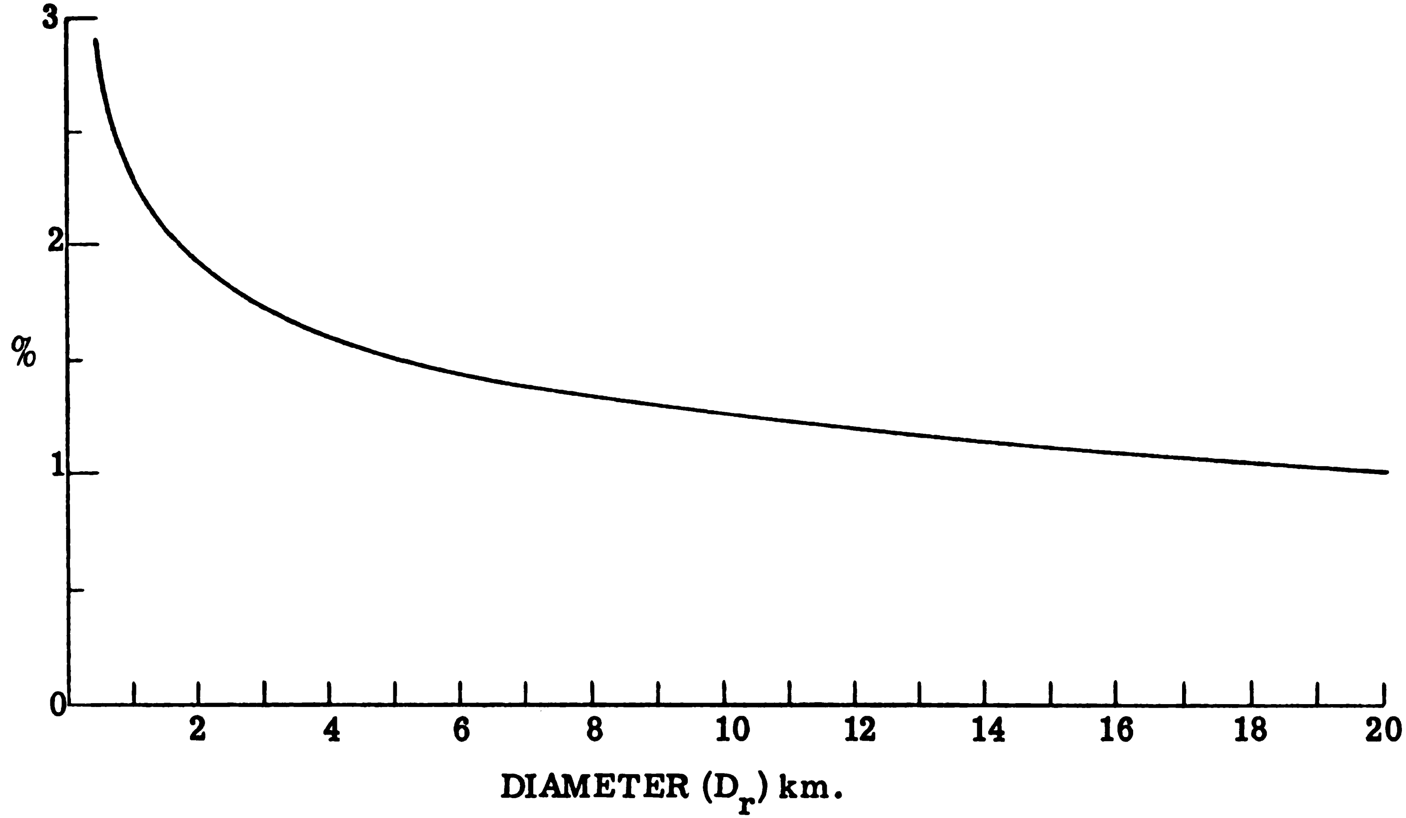

Figure 3. Relationship between the diameter of a crater and the percentage by which the maximum crater anomaly is diminished due to the anomalous mass of the rim.

selected for the rim material, from the model adopted here will have only a small effect on the total crater anomaly.

The results of the calculations of the gravity anomalies as observed at the center of the floors of craters of various diameters are given in Figure 4, assuming that the effects of the rim are removed in the terrain correction by choosing the appropriate density, and that the density of the country rock is used in the remaining terrain effects. The solid line of Figure 4 gives the central anomaly magnitude for craters on the assumption that the density contrast between the breccia and country rock is -1.0 g/cc. The slight curvature of this line reflects the progressive shallowing, relative to the diameter, of craters as found by Baldwin. If, as Pike has argued, crater "growth" is allometric, then the gravity anomaly over a crater will be directly proportional to the crater's diameter, and the broken line of Figure 4 will be valid. This being the case (see also Quaide et al, 1965), the relationship between the central gravity anomaly and the diameter of the crater represented by the broken line of Figure 4 can be expressed by the equation

$$g = 3.88 \sigma D_r \qquad (12)$$

where g is the peak anomaly in milligals, σ is the density contrast between the breccia and the country rock in grams per cubic centimeter, and D_r is the rim crest diameter of the crater in kilometers. Figure 5 expresses in graphical form the relationships of equation (12). If,

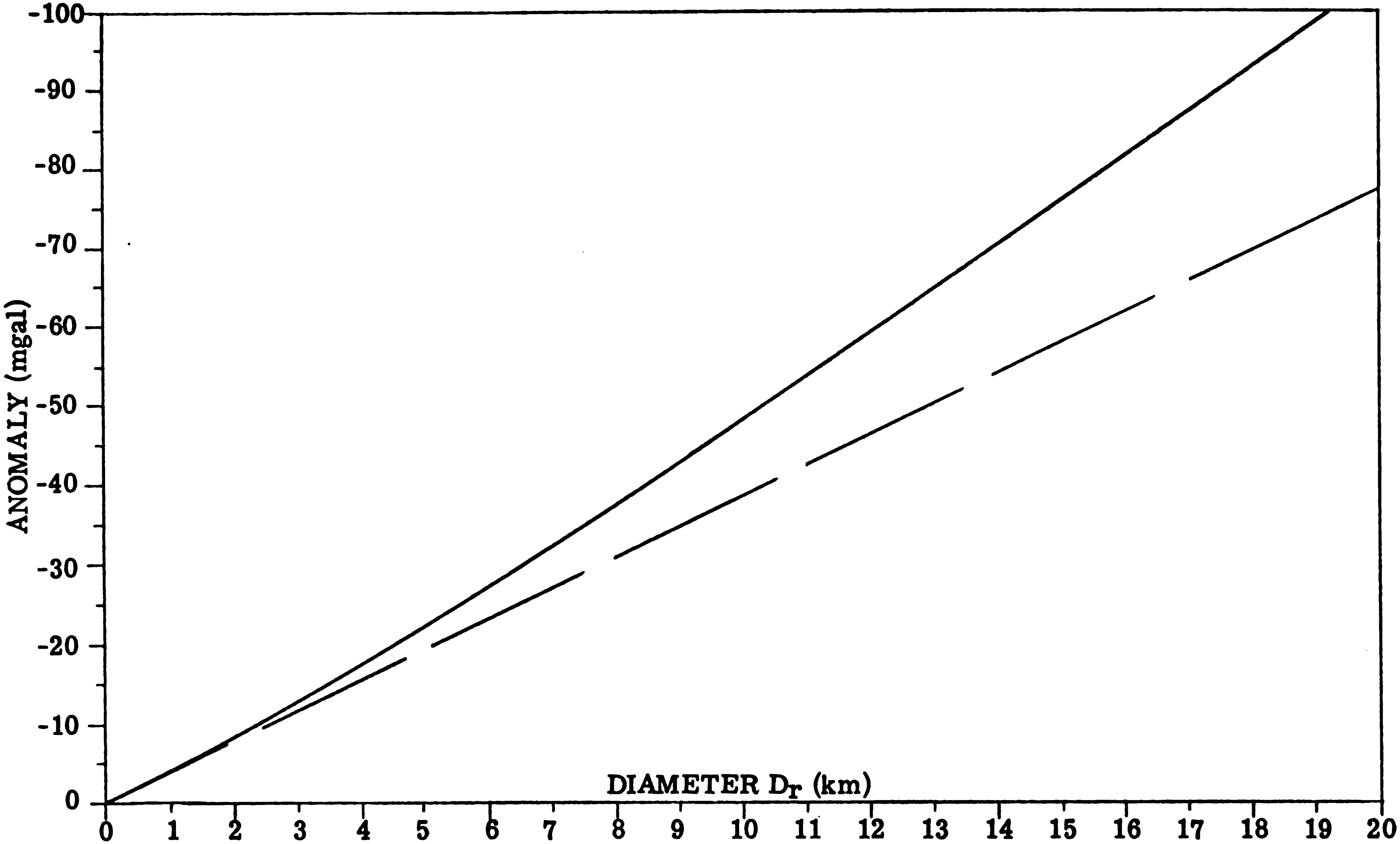

Figure 4. Relationship between crater diameter and central gravity anomaly for an assumed density contrast of -1 g/cc between breccia and country rock, for craters whose surficial dimensions are those given by Baldwin (solid curve) or meet the allometric criterion of Pike (broken line).

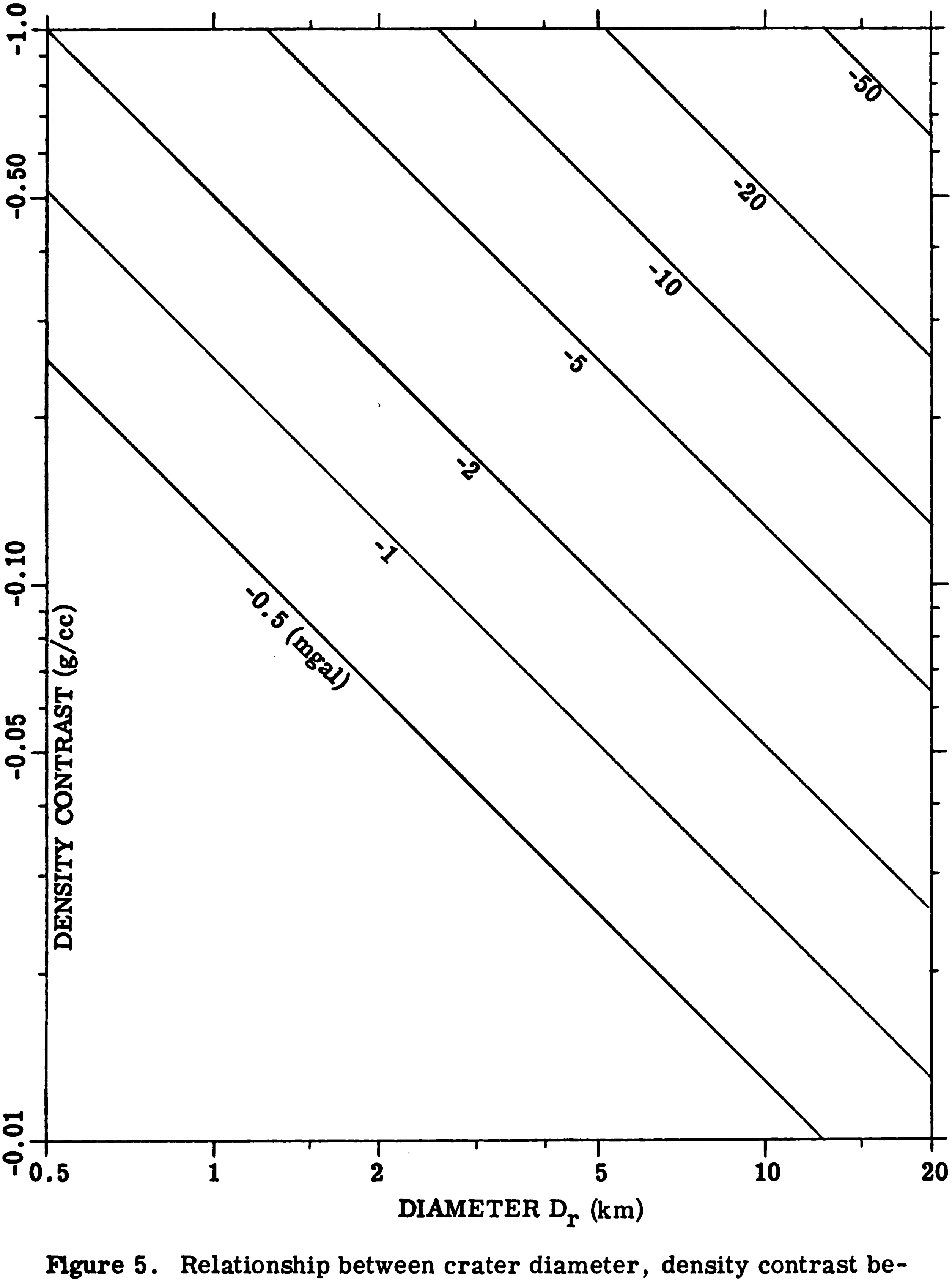

Figure 5. Relationship between crater diameter, density contrast between breccia and country rock, and central gravity anomaly.

for example, an actual survey on the moon could detect anomalies only with a magnitude of, say, one milligal or more, Figure 5 would immediately reveal what combinations of density contrast-crater diameter values would give this anomaly. Also, for example, if upon actual inspection it appears reasonable to believe that some given crater is an impact crater for which the present model is valid, then the overall density contrast of the breccia lens can be easily determined.

The shape of the gravity profile over the crater can be calculated in a manner slightly more complicated than that used above. Off the axis of a horizontal circular disk it is difficult to evaluate the solid angle subtended by the disk. Nettleton's chart can be used only for disks that are buried some distance below the point of observation. Therefore, the chart was used to determine the effects of the lower disks of the breccia lens, and the gravitational effects of the upper portion of the lens were calculated by means of terrain correction tables (Bible, 1962). The gravity profile was determined by calculating the amplitude of the anomaly at three stations off the axis of symmetry of the crater shown in Figure 2 which, according to Pike, closely approximates the geometrical shape of any fresh impact crater. This being the case, only the relative profile is plotted in Figure 6. As previously, it was assumed that the rim effect is to be eliminated in the data reduction. For any given crater, the actual value of the peak anomaly in milligals can be found from Figure 5 or equation (12).

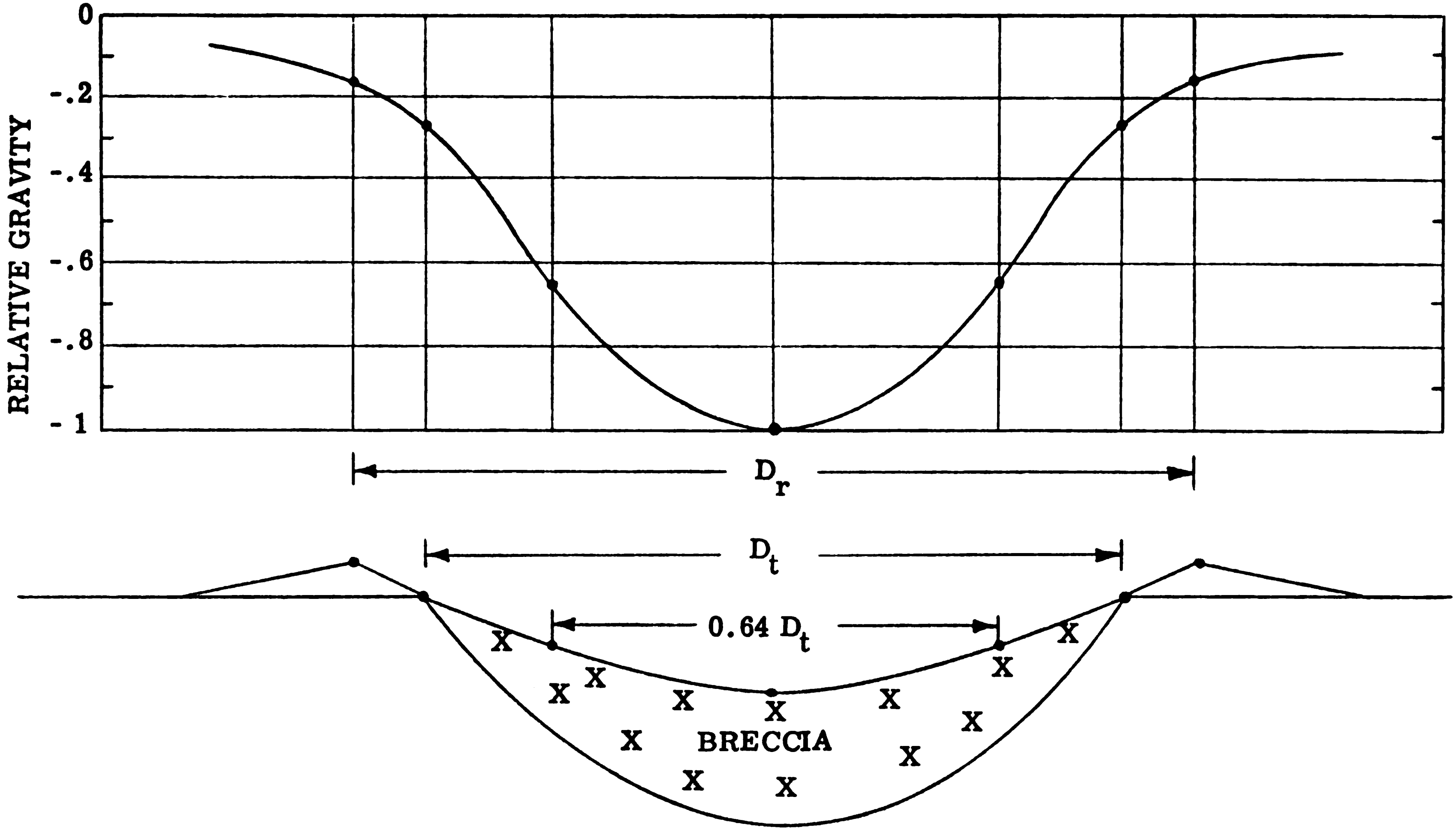

Figure 6. Relative gravity profile over an impact crater. The anomaly is due to the breccia lens formed beneath the level of the original plain. Heavy dots on curve represent calculated values. Dots on crater represent observation points. Gravity values in milligals are found from equation (12).

The question of the values of the density contrast that will be likely in the lunar environment has already been discussed. On-site examination would seem to be required for any firm estimates. A gravity profile over a lunar crater of undoubted impact origin would allow, by the use of equation (12) or Figure 5, an estimate of the density contrast of the breccia to be made. This figure could then be used as a first approximation in the attempt to interpret other craters in terms of the model used here.

To summarize, an impact crater model was adopted from which all important crater dimensions, both topographic and subsurficial, can be found. This model seems to be reasonably valid for fresh, unaltered lunar impact craters with rim crest diameters up to 10-20 km. The amplitude and form of the gravity anomalies over these craters due to the underlying breccia were calculated. If, as appears to be the case, all impact craters are geometrically similar at their moment of formation, the relationship between the peak gravity anomaly over the crater, the crater diameter, and the density contrast between the breccia lens and the country rock is a simple one, expressed by equation (12). An accurate estimate of the density contrast likely in the lunar environment does not seem possible at the present time: on-site inspection appears to be necessary. Impact craters up to 10-20 km in diameter should be characterized by anomalies of the form shown in Figure 6. Craters over about 20 km in diameter, even if originally due to impact, appear to have had their structures modified considerably by post-impact processes.

Craters of Internal Origin

In contrast to the meteoritic impact hypothesis stand those theories which account for the origin of the lunar craters solely or primarily in terms of internal processes. It was possible to establish a reasonably consistent model of the structure of an impact crater. The establishment of a similar consistent, single model of a lunar crater on the assumption of internal origin does not seem possible, primarily because so many different modes of origin, all related to internal processes of one sort or another, have been suggested down through the years. These different theories might predict greatly differing subsurface structures, even though all are internally based. Shoemaker (1962) has given an excellent summary of the historical development of the main theories that have been advanced in the years since the invention of the telescope to account for the origin of lunar craters. Shoemaker divides theories which attribute the origin of the craters to internal activity into three main classes, using the German terminology. The "Blasenhypothese", in its most extreme form, accounted for the lunar craters by the bursting of huge bubbles of gas escaping from the interior of the moon, although more realistically the activity that produces the terrestrial maars might be considered in this category. The "Vulkanhypothese" maintained that lunar craters are analogous to terrestrial calderas. The term "caldera", however, can apparently be applied to almost any approximately circular feature on earth which appears to have been related in some way to volcanic activity. Such structures may include calderas formed by violent explosions such as at Krakatoa and Crater Lake and also those formed by relatively quiescent subsidence as on the Hawaiian shields. The third class, the "Gezeitenhypothese", or tidal hypothesis, maintained that the tidal effects of the earth on the crust of a fluid moon produced fractures resulting in the craters. In its original form it is not seriously held today, although attention has been directed to the effects of earth-tides on lunar degassing in general (Green, 1965b). The boundaries between these classes were (and are) quite nebulous, each worker having his own particular version of what has actually occurred on the moon. In addition, there have been numerous theories advanced which do not fit easily into any of these classes but still involve some sort of internal activity, such as escaping water which would result in pingo-like structures and the "craters of uplift and collapse" of Currie (1965). Through the years there have also been theories involving coral reefs, asphalt, dust storms, snow, vegetation, and atomic bombs (Green, 1965a).

At the present time almost all investigators concerned with the moon concede that there has been some volcanic activity on the lunar surface. The real question of course is one of degree. Shoemaker (1962) generally favors an impact origin for the majority of the lunar craters. He believes that only the small lunar chain craters are likely to be volcanic in origin, presumably being analogous to terrestrial maars. Other workers, however, have argued that there are reasonable terrestrial volcanic analogs for even the large lunar craters, and that in general the lunar craters "are analogous, at least in broad outline, to many of the large calderas and volcanic ring structures found on earth." (Moore and Cattermole, 1967). Green (1963) maintains that the tidal effects on the moon due to the earth (because of the eccentricity of the moon's orbit) and the lesser lunar gravity would both contribute to enhanced volcanic activity, and he states that a lunar maar of 15 km diameter might be the equivalent of one of perhaps 4 km diameter here on earth. He also predicted that lunar craters of diameter less than about 15 km diameter would be of the maar type while those over 15 km would be primarily of the caldera type.[1] In contrast to Shoemaker, Green believes that the large lunar craters have many features in common with caldera-type structures on earth (Green, 1963, Table 5). Elston (1965) argues for the analogy between features such as the 90 mi diameter Mogollon Plateau volcano-tectonic basin of New Mexico and the large lunar ring-structures. McCall (1965) concludes that the

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[1]It is of interest to note that this distinction between maar and caldera type lunar craters falls exactly in the diameter range of 10-20 km that Pike (1968) interprets as being the threshold between simple, unaltered meteorite craters and those whose impact characteristics have been changed by post-impact processes, as discussed in the previous section.

large lunar craters are "surface cauldrons, genetically closely related to terrestrial calderas." Clearly the impact-volcanic question of the origin of lunar craters is not resolved.

Our concern here is with the role of gravity observations in the resolution of this question. Two approaches seem possible. One is to attempt to construct a likely model of the subsurface structure of a "lunar caldera" and calculate the gravity anomaly over it. Alternatively, since the interpretation of the lunar craters as calderas involves their comparison with terrestrial features, the gravity anomalies actually observed over these structures on earth could be analyzed and applied to the lunar environment. The first approach involves the establishment of a model for the subsurface structure of a caldera. Perhaps the classic paper on terrestrial caldera structure is that of Williams (1941). He establishes firmly the fact that most calderas are the result of subsidence and not to simply violent explosion, and divides calderas into a number of differing types based on the characteristics of actual examples observed here on earth. Of particular interest here are two of his types, which generally seem to include what most workers feel are reasonable analogs of lunar features. His Krakatau (Krakatoa) type owes its origin "primarily to the withdrawal of magmatic support from beneath volcanic cones by the rapid and voluminous discharge of pyroclastic ejecta, chiefly in the form of pumice. Such calderas of Krakatau type are found particularly on composite volcanoes built of andesitic and dacitic materials...", and include such examples as, of course, Krakatoa, Crater Lake, and Aso and Aira in Japan. A second type is the Kilauean, which is characteristic of basalt shield volcanoes, and which results when "rapid effusion of lava from fissures on the flanks of a cone or intrusion of magma as dikes and sills drains the central conduit and causes foundering at the central vent.", the classical example of which is naturally Kilauea. This type, however, seems to resemble strongly William's Glen Coe type, and later workers apparently consider the two types, Kilauean and Glen Coe, to be essentially identical.[1]

To attempt to model the subsurface structure of the differing types of terrestrial calderas for the purpose of calculating the gravity anomalies, or of even one type, for that matter, would seem to be a very difficult task because of the great variety of, and uncertainty about, such structure. A more direct approach might be to examine the results of actual gravity surveys made over such calderas, and in the last few years such results have been increasingly forthcoming. Of particular interest here has been the work of various Japanese investigators on calderas in those islands, which has been summarized by Yokoyama (1961, 1963) and Malahoff (1969), especially the fact that these gravity investigations have apparently revealed the existence of two classes of calderas analogous to the Krakatoa and Glen Coe types of

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[1] McCall (1963) has further argued that the Krakatoa type is simply a special case of the Glen Coe type, illustrating the perhaps obvious fact that nature recognizes no man-made categories, but that all transitional forms may exist.

Williams. Five Japanese calderas show strong negative gravity anomalies, ranging from -10 to -46 mgal. These calderas are all associated with great amounts of pumice and ignimbrite (the Krakatoa type). Two calderas, Oosima in Japan and Kilauea, show positive gravity anomalies of +15 and +9 mgal respectively (the Glen Coe type), with the positive anomalies apparently due to the more dense lava in the throat of the vent or in shallow magma chambers beneath the surface. This information is summarized in Figure 7.

Are these caldera types, assuming they are actually distinct, analogous to the lunar craters? And if they are, would the operation of similar mechanisms on similar materials in a different environment, as on the moon, result in similar structures and anomalies? It seems difficult to answer, or even to attempt to answer, such questions in a meaningful, quantitative way. Even if we could consider the calderas of Figure 7 with negative anomalies to be closely analogous to lunar structures we are left with the ambiguity that we have already found in the previous section that lunar impact craters might also be expected to show negative anomalies. For example, Hakone caldera, with a diameter of 11 km, shows an anomaly of -10 mgal. But, according to Figure 5, if an impact crater of 11 km diameter were underlain by a breccia lens of density contrast -0.122 g/cc, a not unreasonable value, it too would exhibit an anomaly of -10 mgal, and we would then have two contrasting models of very different structures, both of which were consistent with the gravity data.

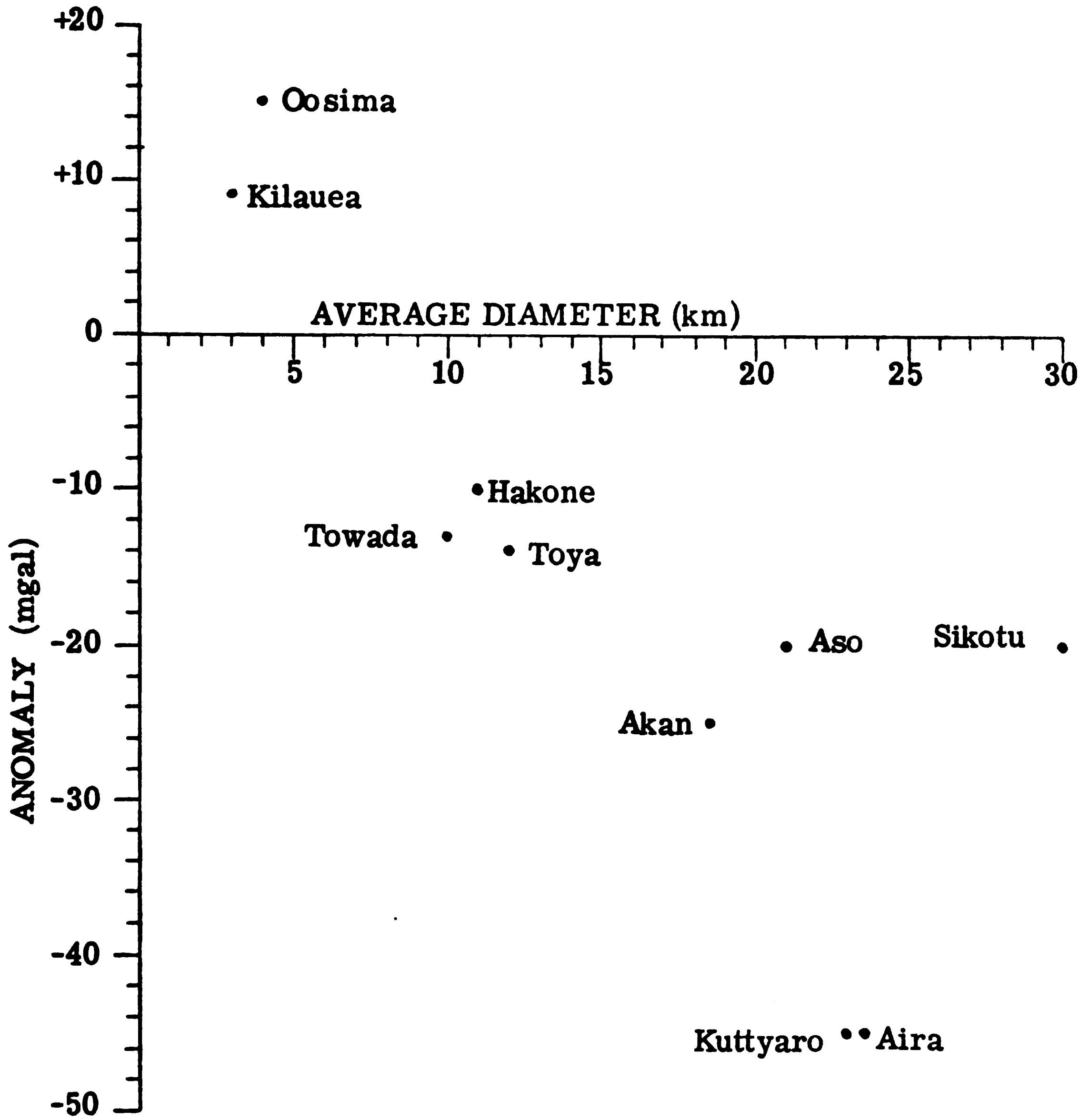

Figure 7. Gravity anomalies associated with various terrestrial calderas. Data from Yokoyama (1963) and Malahoff (1969).

Clearly, in such a case additional geological information is needed to help resolve the question of origins. One possible means of differentiating these two crater forms might, however, come from an examination of the gravity field surrounding the crater to a considerable distance beyond the rim. If a crater is of internal origin, then because of subsurface sources of magma, fracture zones, intrusives, etc., the gravity anomaly over the structure should be directly related, although perhaps not in an immediately obvious way, to the regional gravity field of the area. For example, Yokoyama (1966) has noted that four calderas, Sikotu, Hakone, Toya, and Towada, all under 20 km in diameter (the diameter range generally being considered here and in the section concerned with impact craters), have their low gravity values superimposed on regional highs, which he interprets as meaning that "there are upheavals of the basements beneath the calderas.", i.e. there is a direct relationship between the location of the caldera and the regional structure as revealed by gravity work. On the other hand, such a relationship would of course not be expected for an impact crater. Rather, impact craters should be distributed essentially at random, with no respect for regional trends. The same argument should hold for magnetics. For example, Lowman (1965) has concluded that the Sierra Madera structure in Texas, thought by many to be an eroded impact crater, is actually the result of displacement and brecciation by a syenite intrusion. This conclusion is based primarily on the apparent relationship of the structure to a positive magnetic anomaly, which would be characteristic of an intrusion, while impact breccia would normally produce a negative anomaly, as a result of the random arrangement of the breccia fragments (Innes et al, 1964). However, because of the lack of a detectable magnetic field, magnetic methods will undoubtedly be limited on the moon.

There is always the further possibility that lunar internal activity may manifest itself in a form which would produce structures not really analogous to any found here on earth. A fact that to me has always seemed a rather serious stumbling block to considering terrestrial calderas to be analogs of lunar craters is that terrestrial calderas generally represent a later evolutionary stage in the development of what was originally a positive topographic feature, such as Krakatoa, Crater Lake, and Kiluaea, but on the scale of the larger lunar craters such positive features are not found on the moon, although craters of all degrees of freshness are seen. Advocates of the caldera nature of lunar craters seem to generally ignore this fact, but McCall (1965) has addressed himself to this point by stating that "The first, positive phase of buildup of a volcanic pile, present in the case of all terrestrial caldera centers is not represented - if there was a first stage of tumescence at all it was abortive - or largely so, little or no gas and no lava being vented at the surface.". This being the case, it follows that the subsurface structure might differ from that of terrestrial calderas in significant ways as well. It is quite clear that, in the interpretation of the origin and structure of the lunar craters the gravity data can only provide clues, which must of course be examined in the light of the available direct geological evidence.

Most of the previous discussion of this chapter on lunar craters, whether of impact or internal origin, has pertained to craters of about 20 km diameter or less. When one considers the larger craters, many further complications may arise. Even if originally due to impact, for example, a large lunar crater might subsequently have its form and structure altered in any number of ways, some of which have already been mentioned and any of which could affect the gravity field considerably. Of particular importance is the fact that the effects of a large meteoritic impact might be such as to result in immediate volcanic activity (Ronca, 1966). The resulting crater would then exhibit the characteristics of both an impact and volcanic origin, and the interpretation of such a structure would be undoubtedly a complicated procedure. A similar origin has been proposed for a number of terrestrial features such as the Sudbury structure (Dietz, 1962). In view of the disagreement that still exists about the origins of such terrestrial features as Sudbury, the Rieskessel, and the Vredefort Dome, even after years of first hand examination by many geologists, there is no doubt that a real and genuine understanding of the nature and origins of the various lunar craters will remain a long range goal, taking us many years into the future.

CHAPTER III

DOMES

Lunar domes are low, generally circular blister-like swellings in the lunar surface, ranging up to about 17 km in diameter and some 700 m high (Baldwin, 1963) although some similar but more irregularly shaped features may be as much as 80 km across (Salisbury, 1961) and over 1000 m high. Their slopes are therefore quite low, averaging perhaps 3^{o}, and frequently domes are found to possess exactly central craterlets at their summits. They usually occur in clusters, and there is general agreement that they are features of the maria (Quaide, 1965) and also of some of the large craters with mare-like interiors (Kopal, 1966), although it would be difficult to detect them even if they did exist in the upland regions. According to Baldwin (1963) and Quaide (1965) however, they are not found near the centers of the maria but are restricted to the border regions or to areas where evidence indicates a shallow fill of mare material. A well developed group of domes near the crater Marius in Oceanus Procellarum was shown on a widely circulated Orbiter II photograph. The domes shown are from approximately 3.5 to 17 km in diameter and from 300 to 500 m high. Some have central craters and seem to be formed by material superimposed on the original surface, while others seem to be due to the updoming of the original surface layers.

A number of differing genetic theories have been advanced to account for the domes. Perhaps the most obvious suggestion is that they are shield volcanoes or laccoliths (Quaide, 1965; Fielder, 1965). Salisbury (1961) however, interprets them as being uplifts in the lunar surface due to a mineralogical phase change with an accompanying increase in volume. Baldwin (1963) favors this phase change hypothesis or the laccolithic interpretation. At least one other possibility is that they are the result of subsurface ice, perhaps being analogous to terrestrial pingos. The gravity anomalies associated with domes according to these different theories are discussed in turn below.

Serpentinization Origin

The suggestion that the lunar domes may be due to the serpentinization of olivine-rich rocks by waters emanating from below the lunar surface is apparently due to Salisbury (1961). The reaction between olivine and water at various temperatures and vapor pressures has been considered by Bowen and Tuttle (1949). They found that at temperatures of less than 400°C water will serpentinize forsterite to produce serpentine and brucite. If silica is also added, the serpentinization will occur at temperatures less than 500°C with an accompanying large increase in volume. They point out that an interpretation of most terrestrial serpentines is in best accord with the hypothesis that the serpentine resulted from the introduction of fluids into rocks containing olivine which was already completely crystallized. This reaction can be approximately represented by the equation

$$\text{OLIVINE + WATER} \leftrightarrows \text{SERPENTINE + HEAT} \qquad (13)$$

which would proceed to the right at temperatures of 500°C or less, and would involve a volume increase of about 25%. Hess (1955, 1962) has suggested that serpentinization of periodotitic material in the earth's mantle where rising waters cross the 500°C isotherm could account for a wide variety of epeirogenic movements either upward, due to the increase in volume of the serpentine, or downward, due to a reversal of equation (13) by a rise of the 500°C isotherm or to an increase in the near-surface temperatures by volcanism with a consequent expulsion of water vapor. From the relationship between seismic velocity, density, and percentage of the rock serpentinized (Hess, 1962) for example, he concludes that the oceanic "layer 3", whose seismic velocity averages around 6.7 km/sec, is peridotite which has been 70% serpentinized.

Salisbury (1961) has extended Hess' concepts to include the moon, to account for the lunar domes. That is, he suggests that, in accord with equation (13), escaping waters from inside the moon in crossing the 500°C isotherm would serpentinize the (assumed) peridotitic material of the moon's surface layers, and the consequent increase in volume would push up the domes. He feels that such a mechanism "would be more than adequate to produce domical structures" and even

argues that this process could account for the central craters on some domes as being due to a reversal of equation (13), with a corresponding decrease in volume caused by excess heat generated by the original serpentinization itself or by a release of the excess water vapor. Unfortunately his presentation is entirely non-quantitative. No attempt is made to connect the actual dimensions of lunar domes with what is known or might reasonably be inferred about the lunar subsurface. One point seems clear: Salisbury's drawings indicate that he sees the serpentinization process as operating on the entire layer of lunar material lying between the lunar surface and the $500^{\circ}C$ isotherm.

Walter (1965) has criticized Salisbury's theory as follows. Lowman (1963) has calculated the pressure-depth relationship for the moon. As might be anticipated, his calculations indicate that the increase in lithostatic pressure with depth is considerably less for the moon as compared to the earth. The lunar pressure-temperature gradient has been calculated by MacDonald (1961) on the assumptions that the moon's internal heat is radiogenic and the moon is chronditic in composition. These data taken together indicate that the $500^{\circ}C$ isotherm would be located at a depth of about 90 km below the lunar surface, and, as Walter has pointed out, it is difficult to see just how a typical lunar dome of perhaps 10 km diameter, which is a rather localized feature, would owe its origin to a process occurring at a depth approaching 100 km. This, along with the fact that "serpentinization might often result in elongated or imbricate uplifts and thus fails to explain the generally circular outlines of lunar domes", leads Walter to reject the serpentine hypothesis.

It seems to me that both of these objections can be met rather directly, although to my knowledge Salisbury has not done so. There are elongated, imbricate topographic features on the moon whose heights and widths are comparable to those of domes; they are, of course, the maria ridges. Salisbury, in his original work (1961) does not discuss serpentinization as a possible mechanism for the origin of the ridges, but if this process is actually responsible for the domes it would seem that serpentinization along a subsurface fracture zone could produce a feature much like the ridges observed in many of the maria.[1] The second objection, that the 500°C isotherm is too deep to produce structures as localized as the domes is not easily met by Salisbury's original suggestion that serpentine is generated in the entire layer of the moon between the 500°C isotherm and the lunar surface. However, I would suggest that the important point here is that the serpentinization occurs at temperatures <u>under</u> 500°C, not just <u>at</u> 500°C. Assume, for example, that the maria are filled with peridotitic material to a depth of not more than a few kilometers, and that the mare basement is composed of some contrasting (more acidic ?) rock type. Then, even if the 500°C isotherm were some 100 km deep, the process of serpentinization could not occur until the olivine-rich materials were encountered by

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[1] This mode of origin for lunar ridges is considered in more detail in Chapter VI.

the rising waters, which might be at a much shallower depth and at a temperature considerably below 500°C. In this view, the serpentine body within a dome would be bounded on its lower surface not by the 500°C isotherm but by the mare-basement interface, which would presumably be at a much shallower depth. These suggestions are incorporated schematically in Figure 8.

In order to place this hypothesis on a more quantitative basis, an "average" lunar dome was selected to serve as a basis for further calculations. This dome is assumed to be circular in plan, having an overall diameter of 10 km and a height of 300 m, giving an average slope of about 3.5°. These dimensions seem to be fairly typical. In addition, to facilitate calculation, it is also assumed that the shape of the dome is that of a spherical cap lying on the lunar surface. In order to calculate the depth to the lower surface of the serpentine body, it is noted that complete serpentinization results in a volume increase of about 25% (Hess, 1955). A free volume expansion of 25% in a unit cube would result, of course, in a volume of 1.25 and in a dimensional expansion of the cube root of 1.25 or about 1.08. If we assume that our typical dome is due to the complete serpentinization of the underlying material, and further assume that the upper surface of the serpentine body lies no deeper than the level of the original plain (that is, 300 m below the top of the dome), then we have essentially two possibilities. If the serpentine is confined at the bottom but is free to expand without resistance in all other directions, the serpentine body would

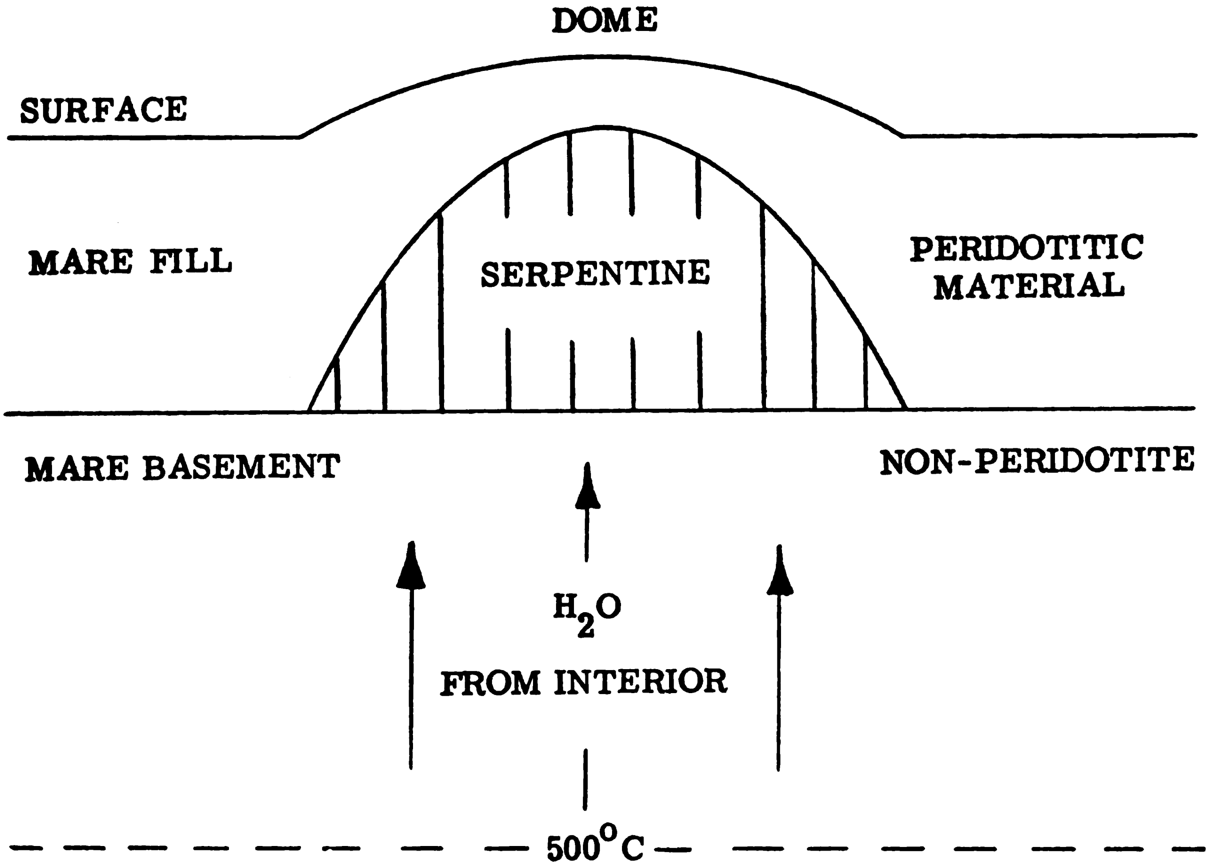

Figure 8. Schematic section of a lunar dome resulting from serpentinization of mare material.

have to extend to a depth of 4050 m below the level of the original plain.[1] On the other hand, if the expansion is confined at the bottom and at the sides as well, as might seem more realistic for a subsurface mass, the only free direction will be up, i.e. the expansion will be one-dimensional, and the depth of the lower surface of the serpentine will be no deeper than 1500 m below the level of the original plain.[2] If the mare material is only, say, 25% serpentinized rather than 100%, the depth of the lower surface of the serpentinized body, for our 300 m high dome, simply becomes four times as great or about 6000 m for a free expansion in the vertical direction. It seems evident therefore, that the depth to the bottom of the serpentine would not be deeper than some 10 km at most. Such a depth is too shallow to encounter the 500°C isotherm, but is quite comparable to various estimates for the depth of the mare material itself (see Chapter V). Therefore if the lunar domes are in fact due to this mineralogical phase change, it seems reasonable to believe that the mare material, but not the basement rock, is involved in the serpentinization process.

In order to calculate the gravity anomalies over such a dome, a three-dimensional model is needed to define the shape of the subsurface serpentine body. The surficial dimensions of the dome are those already described as "typical" (diameter of 10 km and height of 300 m)

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[1] The expansion is equal to the height of the dome, 300 m, which is in turn equal to 0.08 of the length of the original rock column, which was then 300/0.08 or 3750 m long. Upon expansion of 1.08 times, this column becomes 4050 m long.

[2] Here, 300/0.25 equals 1200 m of original rock, which when expanded 25% becomes 1500 m long.

and, as before, it is assumed that the top of the serpentine lies no deeper than the original plain level, or 300 m beneath the summit of the dome, and that the lower surface of the serpentine is a horizontal plane presumably representing the mare-basement contact. For mare material that has been 100% serpentinized this lower surface will be at a depth of 1500 m below the original surface or 1800 m below the top of the dome, for an assumed expansion in the vertical direction only. In addition, on the assumption that the elevation of any point on the dome above the original ground level is a measure of the amount of expansion that has taken place beneath that point, the point will then be underlain by a column of serpentine whose lower surface lies at 1500 m below the original plain and whose thickness is equal to five times the elevation of that point above the original ground level (see footnote 2, page 57 for a sample calculation). If the dome has the shape of a portion of a sphere, as assumed here, it can be shown that the upper surface of the serpentine body will be closely approximated by a paraboloid of revolution. For rock which has been only 50% or 25% serpentinized the lower surface of the body will lie at a depth of 3000 and 6000 m respectively while the upper surface is in all cases close to the shape of a paraboloid. Figure 9 illustrates the shape and position of these subsurface bodies beneath our "typical" dome.

The gravity anomalies over these serpentine bodies were calculated in the same way as were those over the breccia lenses of the impact craters of Chapter II. For the three degrees of serpentinization of

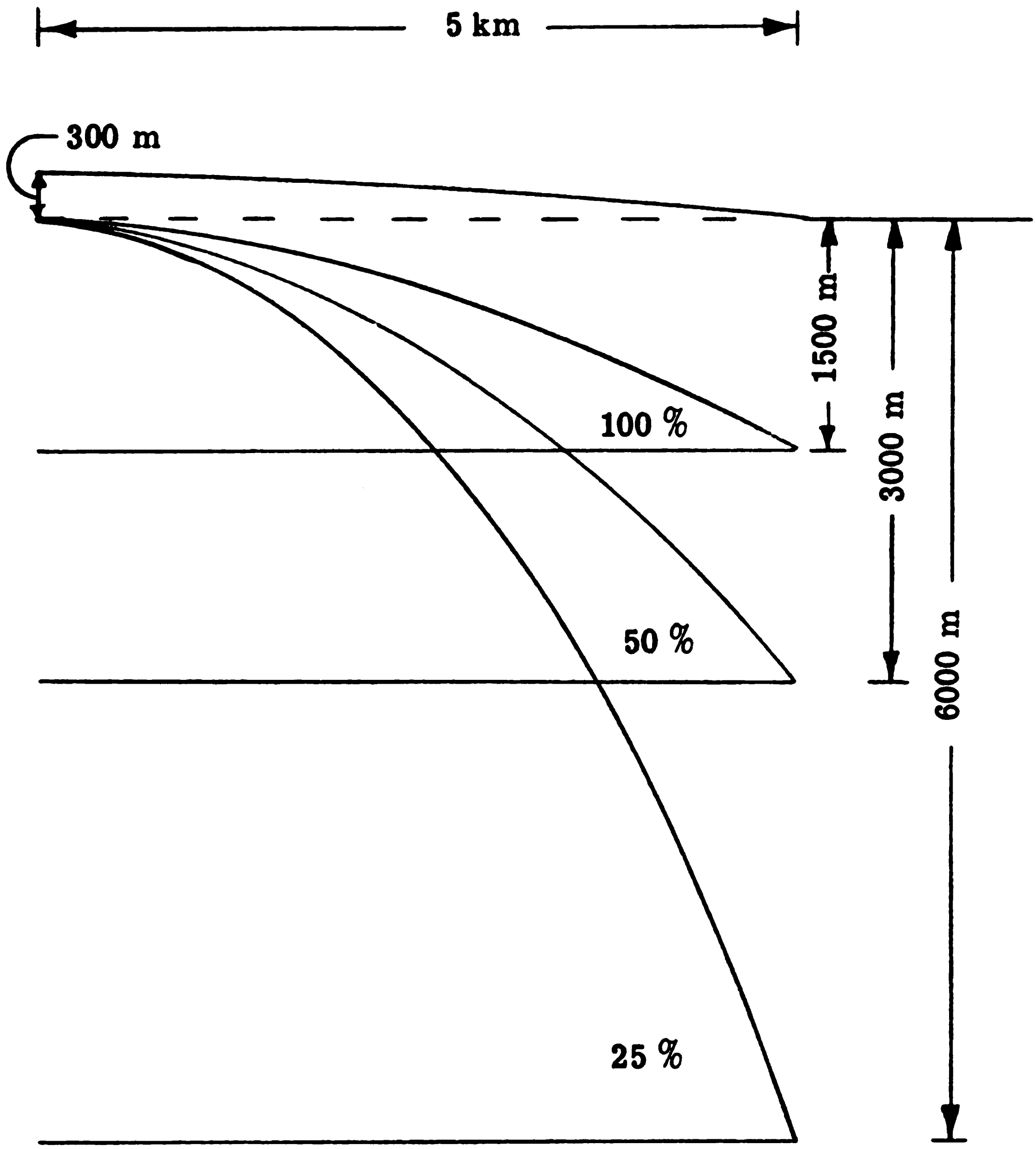

Figure 9. Scale cross-section of half of a lunar dome of 10 km diameter and 300 m height, showing the size and shape of the underlying serpentine body for rock which has been 100%, 50%, and 25% serpentinized, on the assumption that the serpentine body lies 300 m below the top of the dome. The lower surface of the serpentine represents the mare-basement contact.

the country rock, 100%, 50%, and 25%, the anomalous bodies of Figure 9 were approximated by a series of horizontal circular disks, each disk having a thickness of 250 m and its median plane just tangent to the paraboloidal shape of the upper surface of the serpentine. This required, for rock 100%, 50%, and 25% serpentinized, six, twelve, and twenty-four disks respectively. The gravity anomaly due to any one disk is then proportional to the solid angle subtended by the median plane of the disk at the point of observation. These solid angles were determined, as they were for impact craters, by Nettleton's charts (1942). The density contrast between the serpentine and the peridotitic material is given by Hess (1962), the contrast for 100% serpentine being -0.75 g/cc (the serpentine being less dense), for 50% being -0.38 g/cc, and for 25% being -0.19 g/cc. The anomaly due to any one disk is given by equation (11) and the total anomaly is simply the sum of the individual disk values. The anomaly was calculated for five points on the dome over each of the three serpentine bodies, the results being shown in Figure 10. For domes of dimensions other than those of our "typical" dome but of the same general height/diameter ratio of 300m/10km or 3%, it is noted that the anomalies over such domes will be different in magnitude from those values given here by the same proportion as the ratio of the dimensions of the domes to those of our "typical" one.

It seems evident, then, that if the serpentinization hypothesis for the origin of lunar domes is correct, these domes should show

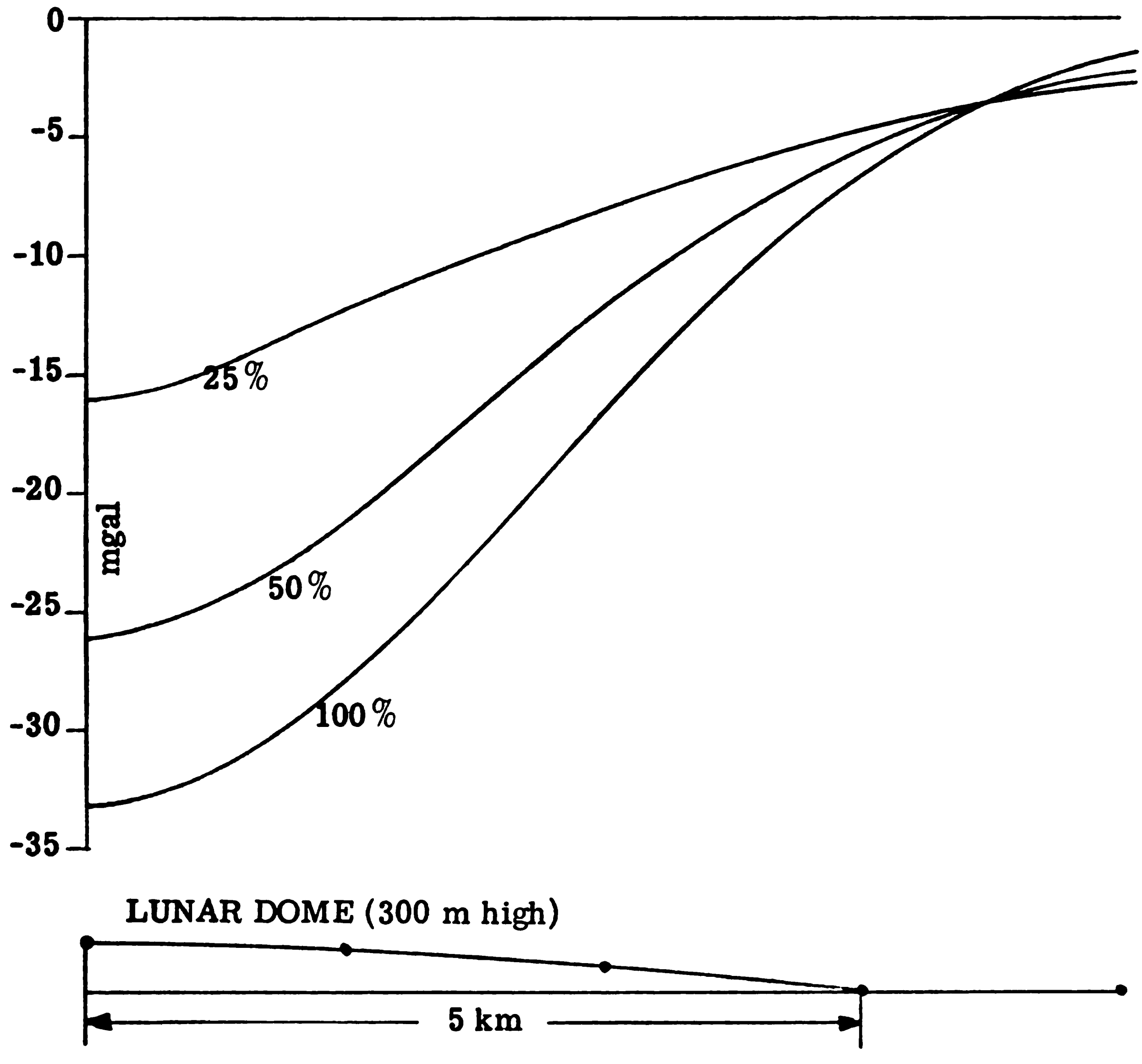

Figure 10. Gravity profiles over the serpentine bodies of Figure 9 for rock 100%, 50%, and 25% serpentinized. Dots on dome are points for which the anomalies were calculated.

strongly negative gravity anomalies, amounting to perhaps some tens of milligals. The height and diameter of the dome and the magnitude and form of the anomaly are the basic data observable at the surface. These, in turn, will be related to the depth, shape, thickness, and density contrast of the subsurface rock body. Of course, not all of the subsurface data can be determined from the gravity anomaly. Nevertheless, other geological data could help to narrow the choice of a subsurface model considerably. For example, seismic work might reveal the depth of the mare-basement contact, placing limits on the depth of the lower surface of the serpentine, and might even, if the seismic velocity of the anomalous body could be found, permit an estimate of the percent of serpentinization in the body from the data given by Hess (1962), or petrological examination of the mare material may reveal the degree of serpentinization. A prominent negative gravity anomaly over a lunar dome would be an important observation consistent with the serpentinization hypothesis, but additional data from other geophysical and geological investigations would be required to identify the nature and structure of the subsurface anomalous mass more exactly.

Laccolithic Origin

A widely considered hypothesis for the origin of the lunar domes is that they are laccoliths or perhaps shield volcanoes. At first thought laccoliths and shield-type volcanoes might be considered to be manifestations of essentially one type of volcanic activity. Yet, as is well known, on the earth shield volcanoes are characteristic of quiescent, basaltic volcanism, while laccoliths are generally accepted as being the result of the intrusion of more acidic, more viscous magma into a layered rock sequence. In fact, O'Keefe and Cameron (1962) have argued that if the domes are laccoliths this is then evidence for acidic rather than basic volcanism on the moon, and this, along with other evidence, leads them to suggest that the maria are welded tuffs, rather than basalt lava flows. They have further argued that basalt would not tend to accumulate around a feeder but would spread out to form a sill, and also that if the maria were basalt flows this would not provide the "weak strata" necessary for laccolithic intrusions, whereas alternating ash flows and welded tuffs presumably would.

A number of alternative arguments, however, immediately come to mind which suggest that the maria are basaltic, but that this does not necessarily imply that the domes cannot be laccoliths. Kuiper (1966), for example, holds that the maria are basalt lava flows, and this appears to have been confirmed by the analysis of the maria surficial material by both Surveyor V and VI (Turkevich et al, 1967, 1968). The fact that some domes exhibit central craters and that some appear to be composed of material superimposed on the mare surface but yet have low slopes of just a few degrees seems to indicate that they are analogous to terrestrial shield (basaltic) volcanoes. Yet, as on the Orbiter photographs referred to above, these shield-like domes occur directly associated with other domes that appear to be due to the updoming of the surface layers from below, and it would seem reasonable to assume that both types are manifestations of the same type (basaltic) volcanic activity. Also, laccoliths are, at least in some cases, found on earth in sequences of basalt extrusive rocks. For example, Murata and Richter (1961) have described a laccolith in the wall of the Kilauea caldera in Hawaii as being some 900 ft long and 90 ft thick which at the time of emplacement was overlain by somewhere between 135 and 350 ft of bedded lavas. On the moon, where the upper portion of a basalt flow might consist of a very frothy, vesicular layer perhaps some ten meters thick (Kuiper, 1966) a sequence of such flows would certainly seem to provide the required layers of weakness for the injection of magma. Also, because of the lesser weight of the overlying rock on the moon, along with the normal fluidity of basaltic lava, such injection might spread over a much wider area in the lunar environment producing laccoliths much more sill-like than those on earth normally associated with acid volcanism, and thereby account for the small height of a typical lunar dome relative to its diameter. It is therefore concluded that even though most, but not all, terrestrial laccoliths are associated with more acidic rather than basaltic volcanism, the interpretation of the lunar domes as laccoliths and some shield volcanoes associated with the basaltic material of the maria is a distinct possibility.

In order to calculate the gravity anomalies that might be associated with such laccolithic intrusions a three-dimensional model is, of course, needed. Initially, so as to make the results obtained directly comparable to those of the previous section, the same "typical" dome of diameter 10 km and 300 m height is adopted as the standard, although the gravity effects over domes of other diameters will also be noted.

The depth to the intrusion is an important variable to be considered. Since it is evident that if the domes are laccoliths they would be intruded into the layered mare material and would not be features of the mare basement, the intrusions would then of course lie no deeper than the thickness of the mare itself, which is probably a depth of not more than a few kilometers or a couple of tens of kilometers at most, since the domes tend to occur in the shallow border regions of the maria. They could presumably occur at any shallower depth, ranging up to the surface itself, in which case we would have extrusion and a feature resembling a shield volcano.

The exact shape that the intrusion would assume is uncertain. Reasons have been given above for believing that if the domes are laccoliths produced by basaltic volcanism characteristic of the maria, they might be much more sill-like than terrestrial laccoliths. For these reasons, it is here simply assumed that the shape of the intrusion is identical to the topographic expression of the surface of the dome above the level of the original plain. This in turn means that stretching or thinning of the rock layers overlying the intrusion is ignored, but in view of the low slopes involved this would seem to be reasonable.

Terrestrial laccoliths can apparently be the result of injection of magma laterally from a central stock, as in the Henry Mountains of Utah, or from below, the feeder being more or less vertical beneath the floor of the laccolith. For the lunar domes, as many of them exist as discrete, very symmetrical features, injection from below seems most probable. The exact nature of a feeder would be difficult to determine. Would just one conduit be most likely, or perhaps many? Because of this uncertainty, in the initial gravity calculations below, the effects of feeders are not included but will be considered later.

The final important variable is the density contrast between the intrusive and the country rock. On earth, the usual expectation would probably be for the density contrast to be positive, that is, for the intrusive to be denser than the host rock, resulting in a positive gravity anomaly. Just this situation was observed by Greenwood and Lynch (1959) in Texas for a laccolith of one and one-half miles diameter. There a density contrast of 0.5 g/cc (2.45 for the layered sediments, 2.95 for the intrusion) resulted in an anomaly of +2.2 mgal. On the moon, however, the intrusion would be presumably injected into igneous material rather like itself in chemical composition, and the density contrast might be therefore diminished. However, extrusive rocks on the moon might have their bulk densities considerably reduced by violent degassing when extruded into a vacuum while intrusives, because they remain under some confining pressure, might be expected to solidify to a more dense state. Dobar (1966) found that basalt upwelled in a vacuum under laboratory conditions had a mean density of

1.76 g/cc. This is not necessarily near the mean density of the maria even if they are basalt flows, as this violent outgassing might affect only a relatively shallow surface layer of a flow, the bulk of the flow solidifying to a considerably denser condition. In any case it seems likely that whatever the actual densities involved are, the intrusion, because of its non-exposure to a vacuum will be denser than the country rock, and a density contrast of perhaps 0.5 g/cc might be a not unreasonable value. Therefore, in the calculations made below, the density contrast between the intrusive and extrusive materials is assumed to be positive with a value of 0.5 g/cc. If further investigations should provide a reason for revising this figure either upward or downward the anomaly magnitudes found here can be easily revised accordingly because, of course, the size of the anomaly is directly proportional to the density contrast.

Figure 11 is a cross-sectional diagram of half of a lunar dome showing the location and shape of the intrusion for a typical depth of 2000 m, the depth being measured from the level of the original plane to the top of the intrusive. The gravity anomaly over the dome due to the intrusive was calculated for various depths to the body by approximating it by three horizontal disks each 100 m thick and of diameters such that the median plane of each disk was just tangent to the upper surface of the body. The anomaly was then found exactly as already described in previous sections, being proportional to the solid angle subtended by the median plane and to the disk's thickness, and was

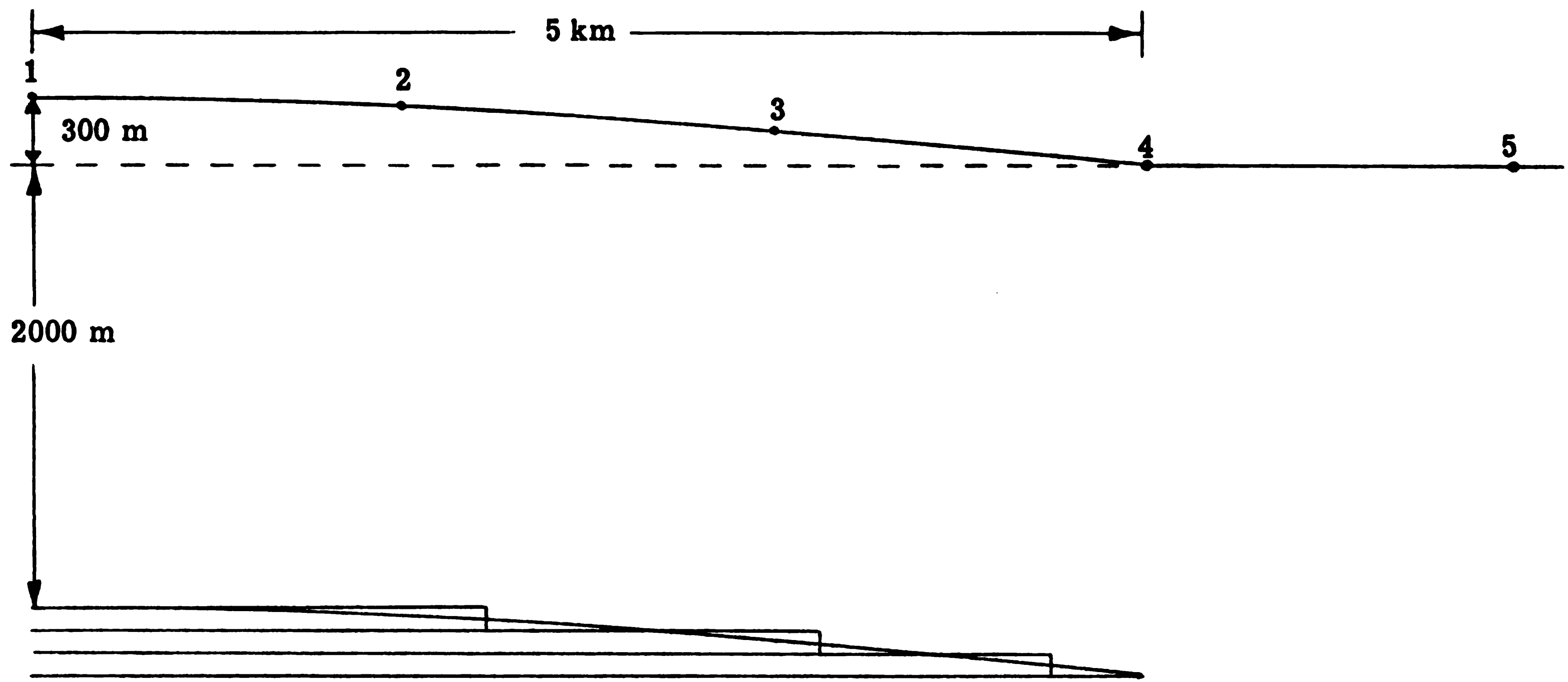

Figure 11. Scale drawing of half of a lunar dome and the subsurface laccolithic intrusion, for a depth to the top of the intrusion of 2000 m beneath the original plain level. The three horizontal disks used to approximate the intrusion are shown. The numbered dots are the stations for which the anomaly was calculated.

evaluated by equation (11) (page 37). As stated above, 0.5 g/cc was the density contrast and the effect of a feeder was not considered at this point.

Figure 12 shows the relationship obtained between the magnitude of the peak anomaly, as it would be found at an observation station located at the summit of a dome (station 1 of Figure 11) and the diameter of the intrusive body for various depths of the top of the body beneath the original plain level. The actual calculations were carried out only for a dome of diameter 10 km, but direct scaling allowed the results to be extended to intrusives of greater and lesser diameters, on the assumption that our original height/diameter ratio of 300m/10km or 3% remained constant. The uppermost curve of Figure 12 gives the peak anomaly over the body if its lower surface coincided with the original plain, i.e. it is an extrusion. This would presumably represent the case of a shield volcano. However, this curve is probably not very realistic, as the material extruded would not have been subject to the confining pressure that we argued would create the positive density contrast. Also, additional magma chambers or intrusive bodies beneath a shield volcano might alter the anomaly significantly. In any case, the mode of origin of a shield volcano should be relatively obvious from direct visual observation alone.

The gravity profiles over the dome as observed at stations 1 through 5 of Figure 11 have also been calculated for various depths to the intruding body, the depth being measured from the original plain

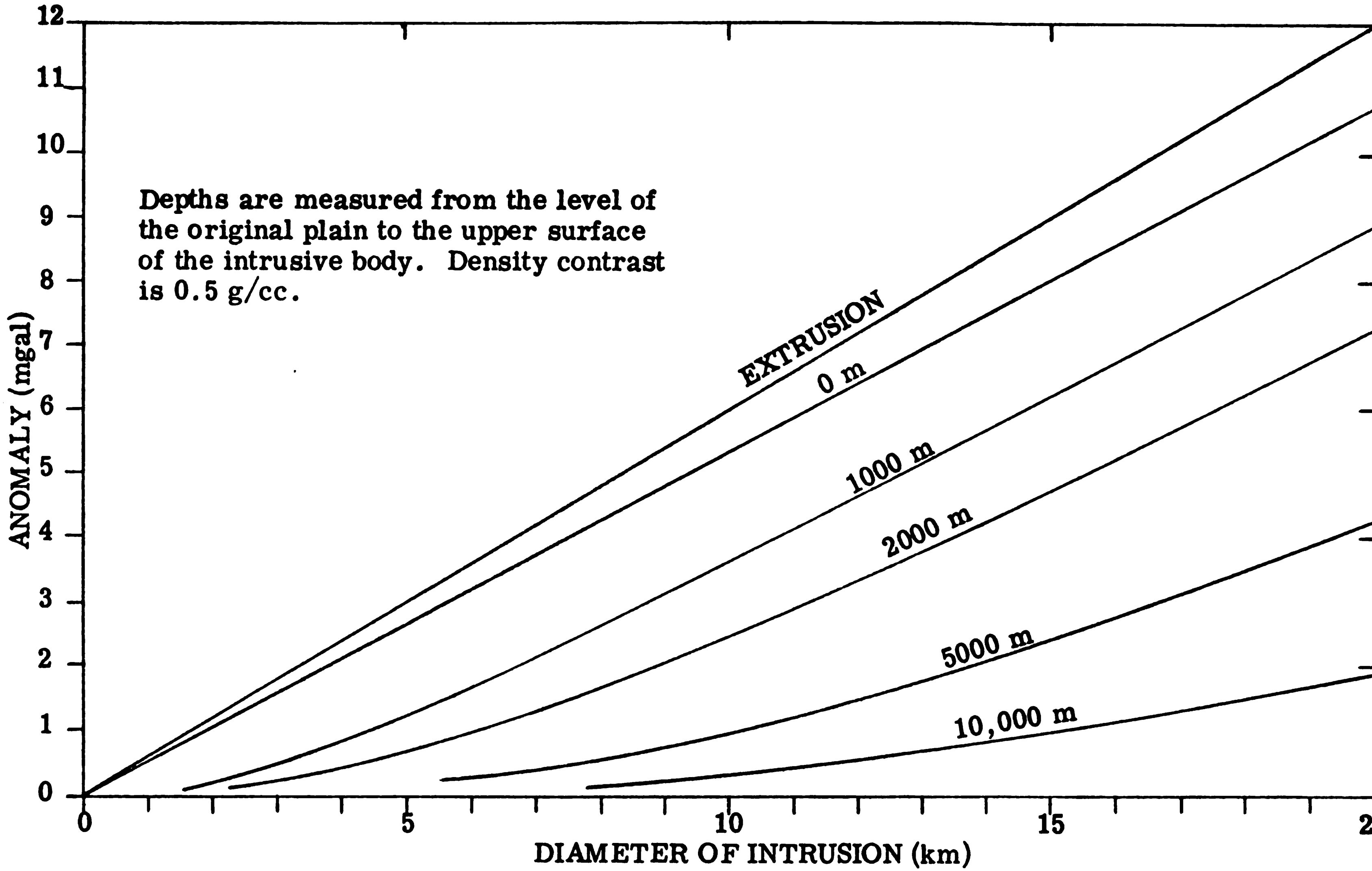

Figure 12. Relationships between the maximum anomaly and the diameter of the intrusive body, for various depths from the original plain level to the top of the intrusive, for bodies with a thickness/diameter ratio of 300 m/10km or 3%.

level to the top of the intrusive. Figure 13 shows these profiles. As would be anticipated, with increasing depth the anomaly exhibits a decrease in amplitude and an increase in width.

The exact shape and placement of the feeder (or feeders) in a laccolith is not easily established because under normal conditions it would not be exposed. In order to estimate the effect that a feeder might have on the gravity field over our "standard" dome described above it was assumed that the feeder was a vertical cylinder, centrally located, with a diameter of 300 m, which is equal to the thickness of the laccolith itself. The cylinder was assumed to have an infinitely deep lower surface to provide a maximum effect and to have a density contrast of 0.5 g/cc, as did the main intrusion. The anomaly due to the feeder alone, as observed from the top of the dome for various depths measured from the original plain level to the top of the laccolith to which the feeder leads is shown in Figure 14. These data were calculated from the standard gravity formula for the effect on the axis of a buried vertical cylinder. As is seen in Figure 14, even for intrusive bodies near the surface, the contribution of the feeder is quite small, less than half of a milligal. It seems likely that the effects of a feeder can be neglected, at least in a first approximation, without serious error unless the feeder is very large.

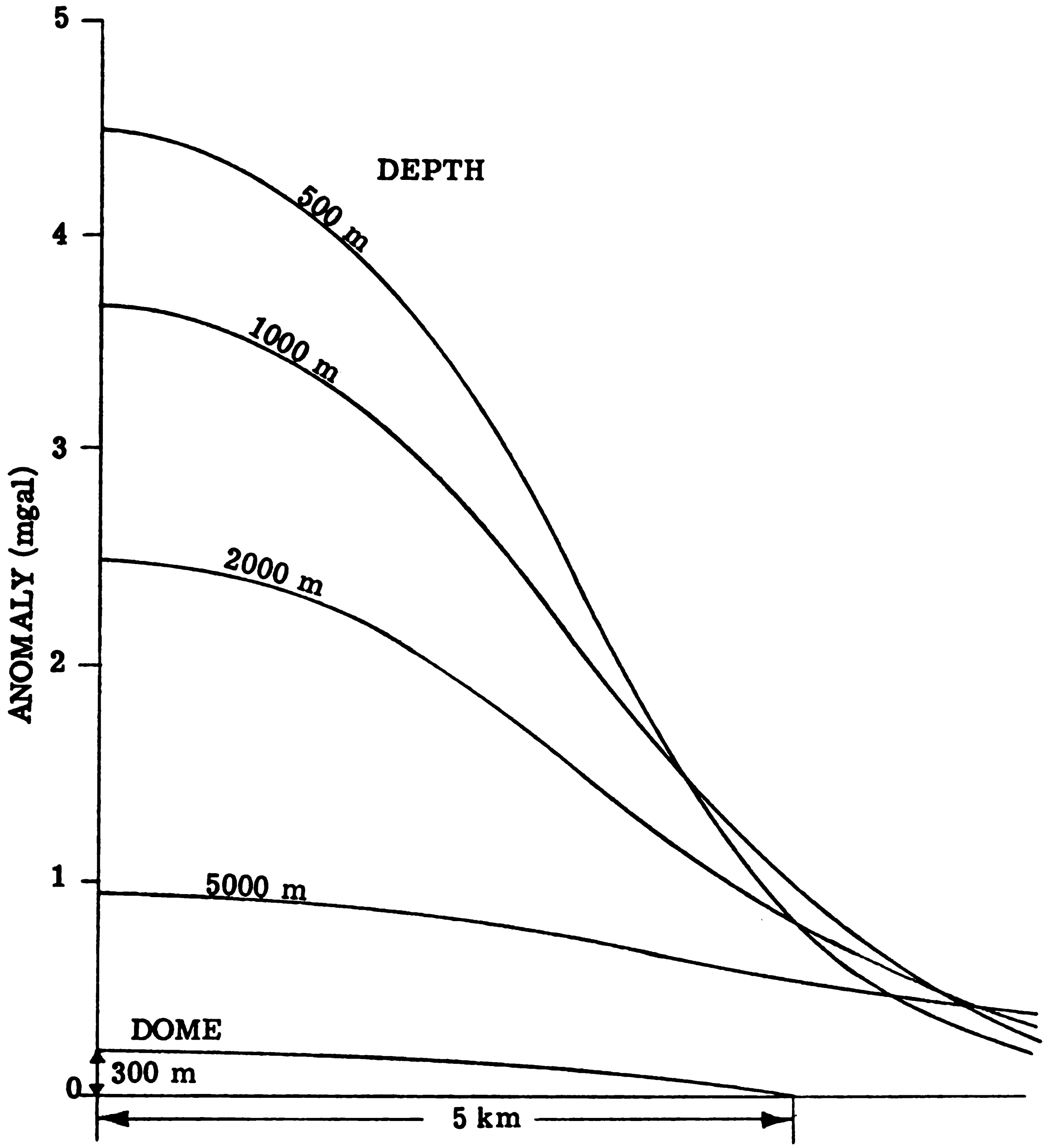

Figure 13. Gravity profiles over a dome of 10 km diameter underlain by a laccolithic intrusion, for various depths from the original plain to the top of the intrusion. The density contrast is a positive 0.5 g/cc.

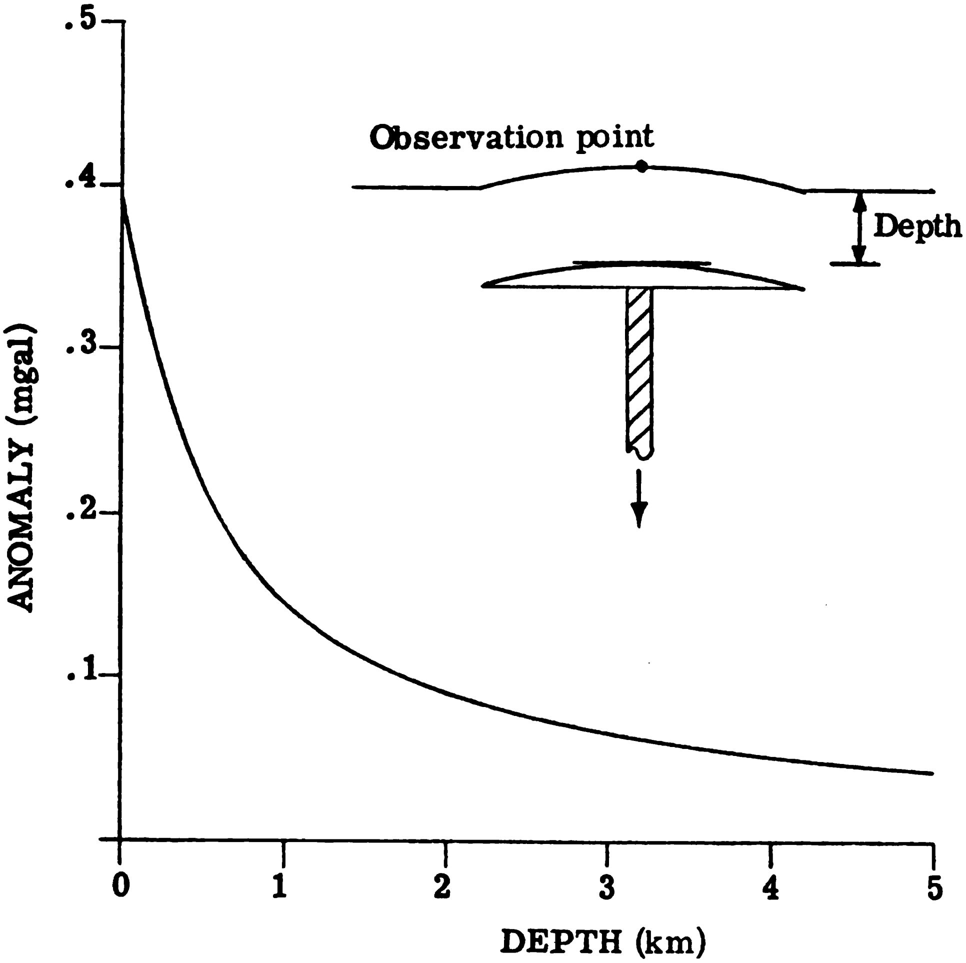

Figure 14. Anomaly-depth relationship for laccolith feeders (cross-ruled in sketch) which are assumed to be vertical cylinders 300 m in diameter and infinitely deep. The depth is from the original plain level to the top of the intrusive, which is 300 m thick. The density contrast is 0.5 g/cc.

Ice Origin

The possibility of ice at or near the lunar surface has been discussed by several workers (e.g. Gold, 1966) and has received renewed attention recently by the discovery of sinuous rilles that some attribute to the action of running water (Lingenfelter et al, 1968). MacRae (1965) has suggested that the lunar domes may be a result of subsurface ice, being analogous to terrestrial pingos. These features on earth, however, usually exhibit central craters which evidently become larger with time, eventually resulting in a degenerate feature resembling a crater somewhat like those due to impact. Currie (1965) has mentioned a cratered pingo in Greenland whose diameter, depth, and rim height have almost exactly the ratios predicted by Baldwin's relationships for impact craters. Some pingos may begin to grow again with renewed activity, resulting in an uplift within a crater, which MacRae believes may be analogous to the well-known spherical central uplift in the lunar crater Alpetragius. It seems evident that some terrestrial pingos, at certain stages in their development, may resemble certain lunar features, but it does not seem that pingos, as a class, should be considered analogous to lunar domes, as a class, as there are too many observed differences. There is always the possibility that some individual lunar features may be due to ice action, however, and gravity methods might help to reveal this. Such a feature would undoubtedly give rise to a negative anomaly because of the lesser density of the ice and water involved as compared to rock materials. The form and magnitude of the anomaly would depend on the size and shape of the subsurface structure. MacRae simply mentions a "lens-shaped" ice body in terrestrial pingos. In any case, as a rough first approximation the subsurface model already adopted here for the origin of lunar domes by serpentinization would probably serve for a pingo-like structure as well, with a body of ice mixed with mare material substituting for the serpentine (Figures 9 and 10). The anomaly over such a body might run to some tens of milligals (negative) depending on the depth of the body and the percentage of ice within it. Discriminating between the two possibilities (serpentine or ice) would then of course require additional information which might be obtained from on-site geological investigations.

It appears then that for lunar domes gravity surveys might be very helpful in delineating subsurface structures and pointing toward certain hypotheses as likely or eliminating others as unlikely. If the domes are due to serpentinization, they should be characterized by strong negative anomalies, while laccoliths might reasonably be expected to produce positive anomalies. Shield volcanoes will have anomalies depending on the density contrast of the lavas with the country rock and on the nature of subsurface magma chambers and intrusions, but their origin should be obvious from direct observation. Pingo-like structures may also result in negative anomalies. In all cases, a firm likely identification of the origin and structure of a dome, or any other feature, can be made only in the light of all other geological evidences as well.

CHAPTER IV

LAVA TUBES

If the lunar maria are in fact basalt flows, as seems likely, they may exhibit some of the features found associated with such flows here on earth. Among these features are those known as lava tubes or lava tunnels, which apparently form when still-fluid lava flows from beneath a solidified crust, draining what may have been a subsurface channel for the lava. The resulting void may be a number of meters in width and perhaps many kilometers long. Such features are well known in the various flood basalt provinces around the world (e.g. Ollier and Brown, 1965).

Green (1963) has called attention to the fact that if such tubes or tunnels exist on the moon they might serve as excellent installation sites for permanent or semi-permanent manned bases. They would provide shelter from various solar radiations and from smaller meteorites. Green also indicates that many terrestrial lava tubes, even though having ages of many tens of thousands of years, exhibit virtually no collapse effects at all, and speculates that such a feature on the moon could be easily sealed and pressurized, providing complete facilities for lunar exploration.

This being the case, locating and delineating the extent of such features in the lunar environment might be quite important. Since the tunnels are of course empty they should produce negative gravity anomalies at the surface, and therefore gravity methods might be useful in the search for such features. A similar type of investigation on earth might be the search for bedrock valleys in regions covered with glacial drift, and the same general techniques might apply. The size of the anomaly will depend of course on the shape, extent, and depth to the feature as well as on the density contrast. Since lava tubes are generally very long in relation to their cross-sectional dimensions, they can be considered to be two-dimensional. In cross-section they have varying shapes: triangular, nearly square, circular. In any case, however, the gravity effect of such a feature can probably be closely approximated by simply considering it to be a two-dimensional horizontal cylinder, with the result that the well known standard formulas for the magnitude and form of the anomalies will apply.

The density contrast will be simply the bulk density of the country rock, since the tube is empty. For basalt, this might be a density of near 3.0 g/cc. However, the density of the basalt in the upper portion of a flow might be considerably less than this value because of extrusion into a vacuum on the moon. Therefore, a density of 2.0 g/cc has been used as the density contrast between the empty tube and the surrounding rock. If another density contrast is finally considered more likely, the anomalies calculated here can simply be scaled up or down proportionally.

The anomalies anticipated over lava tubes of various diameters for differing depths to the center of the tube are shown in Figure 15, assuming that the tubes can be approximated as horizontal, two-dimensional circular cylinders, and that the country rock density is 2.0 g/cc. Figure 16 shows the gravity profile perpendicular to the axis of the cylinder. These data were derived from the standard formula

$$g=0.0419 \frac{\sigma R^2}{Z} \frac{1}{1 + X^2/Z^2}$$

where g is in milligals, R is the radius of the tube, Z is the depth to the tube's center, and X is the horizontal distance from the axis of the tube to the observation point, all dimensions being in meters.

From Figure 15 it is evident that for lava tubes a few meters or tens of meters in diameter the anomaly will not be very large, particularly if the tube lies at some depth. In early manned exploration, however, the lava tubes of any use will of course be those quite near the surface (straight line of Figure 15), and these might well be detected by a gravity survey, particularly because such a survey need extend only a short distance away from the tube, as the halfwidth of the anomaly is equal to the depth of the tube's center which in turn is just the radius of the tube if it is tangent to the surface. In such a survey over a small area designed to determine the extent of such a feature, elevation and position control problems, as well as regional effects, would be minimal, and anomalies of the sizes indicated might well be detected and usefully analyzed.

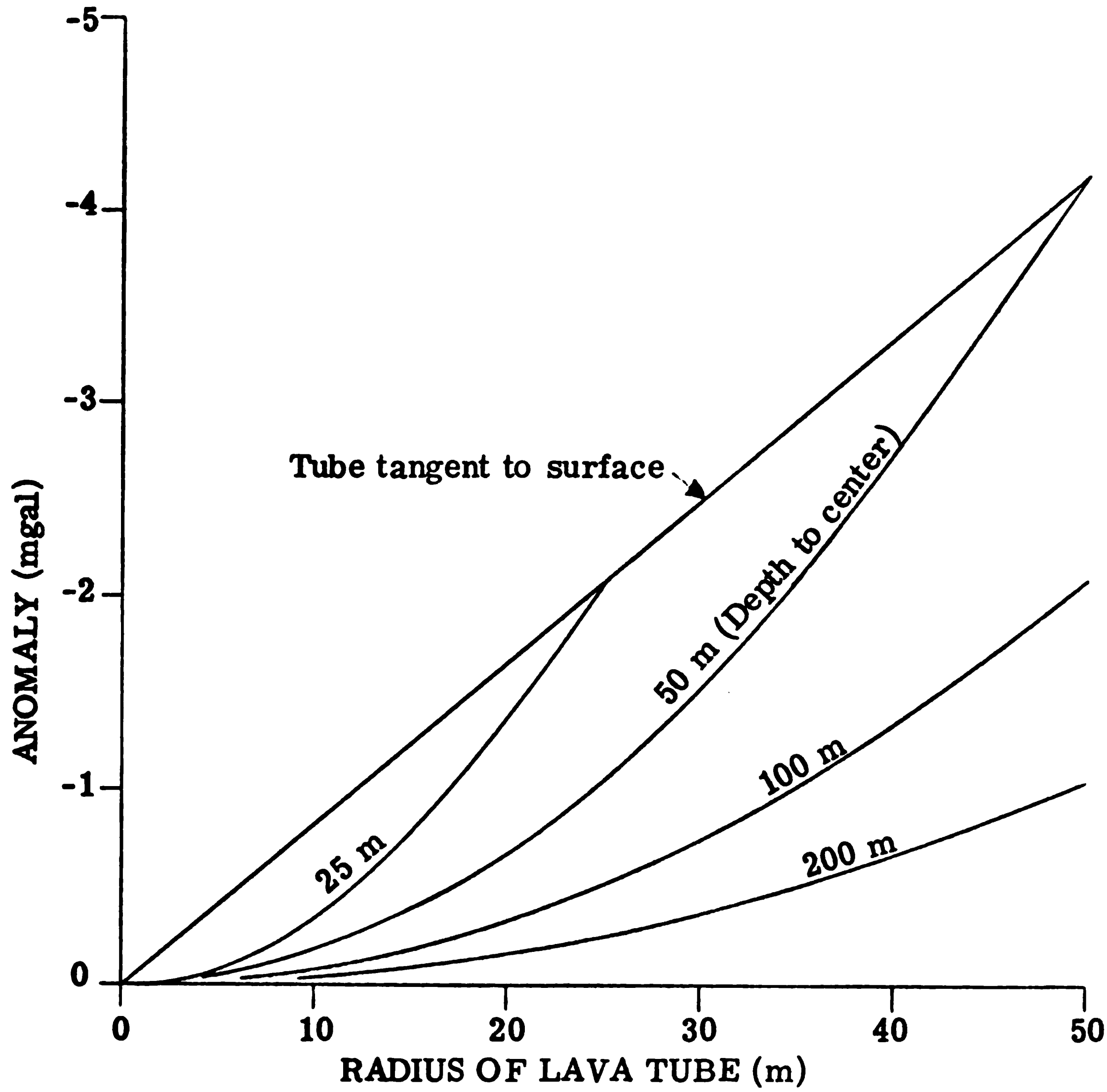

Figure 15. Relationship between the maximum gravity anomaly and the radius of a lava tube, for various depths to the center of the tube. The density contrast is 2.0 g/cc.

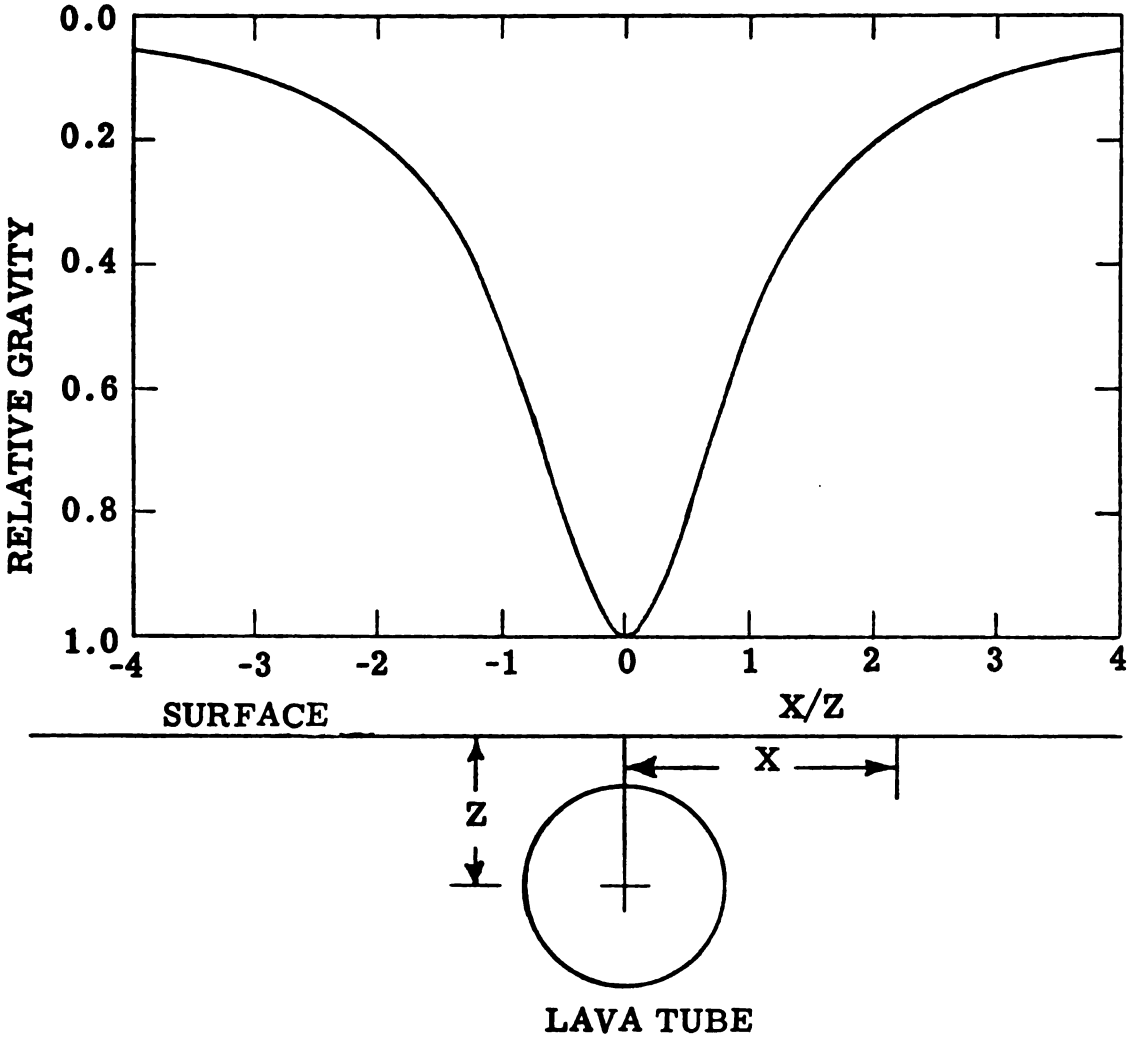

Figure 16. Relative gravity profile over a lava tube.

CHAPTER V

RILLES

Rilles are elongated depressions or trenches in the lunar surface which may be hundreds of kilometers in length but usually are only a few kilometers wide with depths generally only a fraction of the width. Many hundreds of rilles are known and they are primarily associated with the maria or with the immediately adjacent upland areas. They are by no means all identical, and virtually all workers agree that several distinct classes of rilles exist with perhaps differing modes of origin. Several investigators have proposed classification schemes for the various types of rilles. Following Quaide (1965), the rilles can be divided into four classes: the sinuous rilles, the irregularly branching rilles, the arcuate rilles, and the straight rilles. These are considered briefly in turn.

The sinuous rilles, as the name implies, generally follow very curving, contorted paths although the general trend of the rille may be in one direction along the lunar surface. A very significant fact concerning these rilles is that they frequently have a crater or crater chain located at their heads, and that the rilles then follow the general slope of the lunar surface away from the crater. Perhaps the best known example is Schröter's Valley, although many others are known

as well. Many more of these interesting features have been revealed by the various Lunar Orbiters, and some of these are very narrow features located on the floors of larger depressions such as the Alpine Valley. The very sinuous, meandering nature of these features and their strong similarity to terrestrial river channels has reopened the entire question of water erosion on the moon (Lingenfelter et al, 1968), although other mechanisms such as glowing avalanche eruptions have also been suggested (Cameron,1964).

The irregularly branching rilles are characterized by frequent branching and spoke-like extensions. They are often found on the floors of what appear to be old craters such as Gassendi and are also well displayed near the crater Triesneker. The same pattern, almost resembling ordinary mudcracks, has been observed in the floors of some craters on the lunar farside by the Orbiters. Such rilles seem to be related to an updoming of the area from below with a consequent fracturing in the overlying more brittle layers, and therefore appear to be due to tension.

Also apparently due to tension are the straight and arcuate rilles. The straight rilles may be hundreds of kilometers long and up to about five kilometers in width with much shallower depths. They frequently occur in sets and may exhibit an en echelon pattern as does the best example of the type, the Ariadaeus-Hyginus system. Many such rilles seem to have served to localize some form of degassing of the lunar interior, as many exhibit chains of craters along portions of their length. These rilles almost always occur in the border areas of the maria where the mare material is probably relatively shallow.

The arcuate rilles occupy a similar setting, generally along the edges of the maria, and are concave in plan toward the mare centers. The best examples occur along the eastern margins of Mare Humorum. Here the rilles are located mostly in the upland material, but are very near the edges of the mare.

From the morphology of the straight and arcuate rilles, elongated narrow trenches with inward sloping walls, they seem to be graben type structures, the result of normal faulting which in turn would seem to indicate an origin resulting from tension. Their location in the mare border regions seems to confirm this origin. If the maria have in fact foundered due to the infilling of the mare material (or for whatever reason), and this seems to be indicated by features such as the tilted craters along the borders of Mare Humorum and the Straight Wall, then these rilles occur in just those areas, the mare borders, where tension should have resulted as the lunar crust was stretched as the mare basin subsided. The straight and arcuate rilles, then, seem to be downdropped blocks of the lunar crust along normal faults resulting from tension, and the crater chains along such rilles presumably represent volcanism resulting from the release of pressure associated with the faulting.

Undoubtedly the gravity anomalies associated with the sinuous rilles would give important clues concerning the processes that originally formed them, and the anomalies over the crater chains along some rilles would provide good data pertaining to certain types of volcanism on the moon. However, the simple, unaltered rilles that appear to be just downdropped blocks may provide the most important information of all, that relating to the relative densities of the maria and the uplands. This is perhaps the most important question which gravity might easily answer, namely, is the bulk density of the mare material greater or less than that of the uplands, and by how much? An answer to this question is critical to the interpretation of the nature, structure, and origin of the maria, and will have important implications for understanding lunar history in general.

The usual assumption in recent years seems to have been that the maria are filled with a material whose overall density is greater than that of the uplands, and that this fact at least partially explains why the maria tend to be (but are not always) the lower areas on the lunar surface. Baldwin (1968) for example, states that "... it is probable that the density of the lava after solidification is about 0.4 g/cc greater than that of the country rock", and according to O'Keefe (1968) the Surveyor working group on lunar theory and processes adopted a value of 3.0 g/cc for the density of the highlands and 3.2 g/cc for the maria.

Recently a remarkable step forward in the analysis of the moon's gravity field was made with the publication by Muller and Sjogren (1968) of a gravity map of much of the lunar nearside, the data being obtained from an analysis of 80 lunar orbits of the Lunar Orbiter V spacecraft. The most significant result of this investigation was the recognition of large positive gravity anomalies, as observed from a normalized height of 100 kilometers, over all five of the nearside ringed maria and over Mare Orientale, ranging from about +60 mgal over Mare Humorum to +230 mgal over Mare Imbrium. Muller and Sjogren originally speculated that these "mascons" (mass concentrations) were asteroidal-sized bodies associated with the formation of the maria buried some 50 km beneath the lunar surface. Other interpretations, however, soon followed. Stipe (1968) agreed that the positive anomalies were due to meteorites, but he believes they may be vuried as deeply as perhaps 300 km. Conel and Holstrom (1968) have shown that a slab-like circular body at the lunar surface could produce an anomaly of the form and magnitude actually observed over Mare Serenitatis. For example, they show that mare material of density contrast 1.1 g/cc with the less dense upland material, which presumably underlies the maria, could duplicate the observed anomaly if it were 14 kilometers thick at the center, or density contrast 0.5 g/cc if it were 30.8 km deep at the middle and tapered to essentially nothing at the edges. Their geological interpretation is of a basin filled with perhaps solid basalt. O'Keefe (1968), however, has made the important point that if such an interpretation is correct the original source of the lavas would have to have been some hundreds of kilometers deep; otherwise there would be no anomaly. Kane and Shoemaker

(1969) likewise account for the Mare Imbrium anomaly by a plate-like slab of basaltic material perhaps 30 km thick and of density 3.0 to 3.2 g/cc imbedded in the lunar crustal material of density 2.5 to 2.7 g/cc, a density contrast of 0.5 g/cc. Wise and Yates (1969), however, argue that the "basalts" have an overall density essentially the <u>same</u> as the rest of the crust, and that the positive anomalies are due to the solid intrusion of plug-like masses of denser material from below a Moho-like discontinuity some 30-80 km deep into the bottoms of the original mare craters soon after their formation. Gilvarry (1969a, 1969b) brings things to a full circle by arguing that the mare material is actually <u>less</u> dense than the rest of the lunar crust, being sedimentary material which was eroded from the highlands by running water and deposited in the mare craters which had previously, because of a period of internal heating in the lunar body, become completely isostatically compensated. As Gilvarry maintains that the moon is no longer capable of yielding, these sediments are a mass excess, even though less dense than the surrounding rock, and thereby produce the observed positive anomalies.

It is clear that knowing the actual density contrast between the mare fill and the upland material, which apparently forms the basement of the maria, would be of great interest indeed. This knowledge would immediately eliminate some of the theories mentioned above. However, the problem with determining this density contrast by gravity observations is that the interface across which this density contrast occurs, the mare fill-mare basement contact, is nearly horizontal, sloping only slightly downward toward the deeper parts of the maria, and is therefore not directly susceptible to detection by gravity except over very long distances with resulting complications due to regional effects and unknown density changes at depth. Normal faulting, however, and particularly high angle normal faulting as is evidently found in the straight and arcuate rilles, is an excellent mechanism for converting vertical density contrasts to horizontal ones which might then be easily found by gravity measurements made over only a limited area, eliminating or greatly reducing the effects of regionals. If the rilles, where not altered by volcanic activity, are simply blocks of the lunar surface downdropped along steep normal faults, then a gravity profile across the rille should reveal the existence of horizontal density contrasts and in particular the nature of the mare-basement contact, whose density contrast would presumably be the most pronounced. This is schematically shown in Figure 17. This is exactly the structure of the East African Rift Valley, perhaps the nearest terrestrial analog of the lunar rilles, as given by Girdler (1963), where a negative anomaly of about 50 mgal apparently results from the lighter upper block of crustal material dropping into the denser rock beneath.

The straight and arcuate rilles are all very long and shallow with respect to their widths and therefore can be very well represented by two-dimensional features in gravity calculations. Their maximum

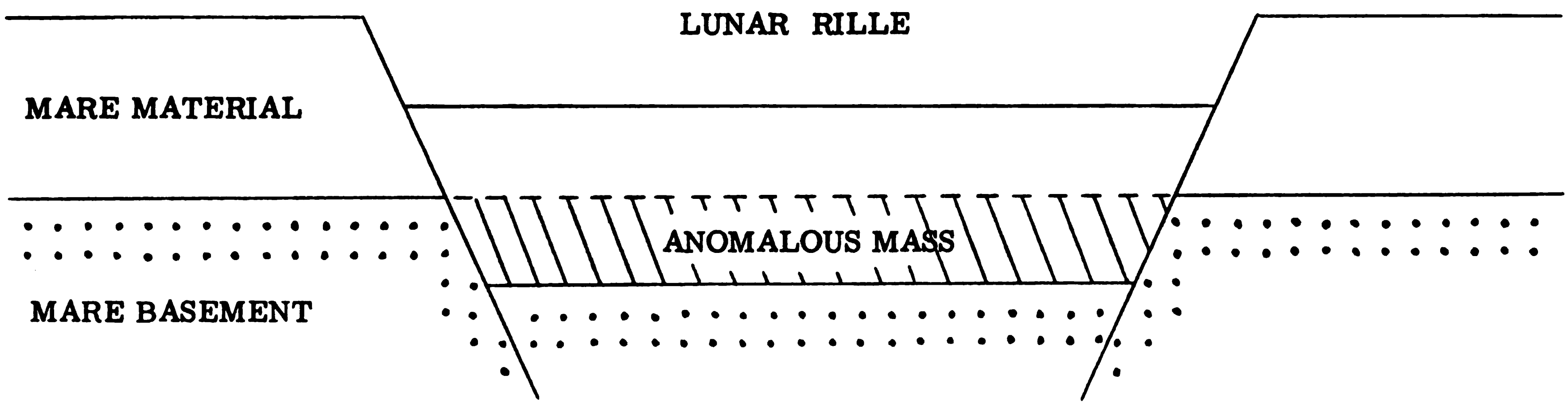

Figure 17. Schematic section of a lunar rille caused by tension. Cross-ruled anomalous mass will produce a gravity anomaly.

widths are about 5 km (Quaide, 1965). Fielder (1961), in a detailed discussion of the Ariadaeus Rille, also gives a maximum width of about 5 km with depths ranging from some 600-1200 m and wall slopes "by no means vertical". Kopal (1962) gives maximum depths for the rilles of about 300-500 m. For purposes of calculation here, a width of 5 km and a depth of 500 m are selected as representative. The slopes of the walls generally appear steep but not vertical, and here are assumed to be 65^{o} from the horizontal. This angle is also assumed to be the actual slope of the fault plane as it continues below the surface.

The gravity anomaly over such a feature will be due to any vertical density contrasts that have been displaced by the faulting. Such density layerings may exist within the mare material itself (alternating vesicular layers within solid lava, perhaps) but these would probably occur frequently enough so as to be not important individually, simply serving to reduce the overall bulk density of the material. It is here assumed that the most likely density interface that would give rise to an anomaly upon being faulted is that between the mare material and the basement, the basement presumably being identical to the uplands. The depth to this interface would certainly be variable. Most investigators seem to agree that the depth of the mare fill at the centers of the maria may be on the order of a few kilometers, but that, whatever its true nature, it feathers out to nothing at the mare edges. Since rilles generally occur in the border regions of the maria, the depth to the mare-basement contact may be rather shallow, perhaps even being exposed in some rille walls. If this is the case, such rilles would be important geological sites indeed. Naturally, this contact would not be found in those rilles that lie entirely within the uplands, but only in those occurring within the maria.

In the following calculations the anomalies have been determined for depths of 500, 1000, and 1500 m to the basement contact. Seismic work might be useful in actually determining this depth on the moon. If the depth is known, the size and shape of the anomalous body follows immediately from the geometry of the rille. The one remaining variable, the one about which information is being sought, is the density contrast. If the rille exhibits a positive anomaly, the mare material is denser than the basement and vice versa. In the following work, the anomalies have been calculated for a density contrast of 0.5 g/cc, both positive and negative. For other densities, the anomalies will be changed proportionally.

Figures 18, 19, and 20 illustrate the gravity profiles over our standard rille for depths to the mare-basement contact of 500, 1000, and 1500 m respectively. These anomalies were calculated with the use of a graticule following the method given by Hubbert (1948), with a depth increment of 100 m and an angle increment of 0.075 rad, each resulting compartment producing an anomaly of 0.1 mgal for a density contrast of unity. The abrupt changes in slope of the anomaly

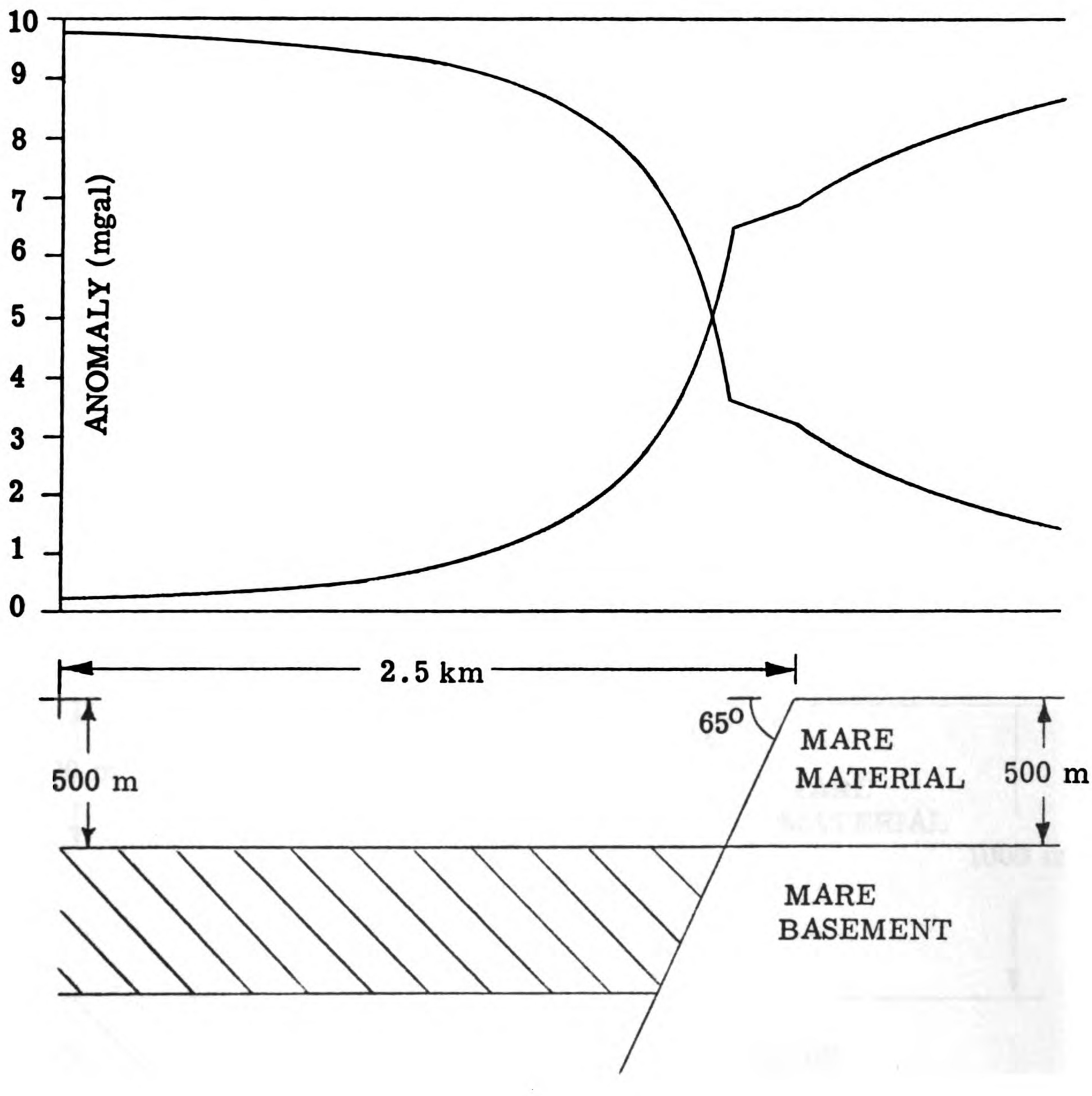

Figure 18. Half of the profile of the gravity anomalies over a lunar rille 5 km wide and 500 m deep with sides of slope 65° and a basement depth of 500 m, for both positive and negative density contrasts of 0.5 g/cc. The anomalous mass is cross-ruled.

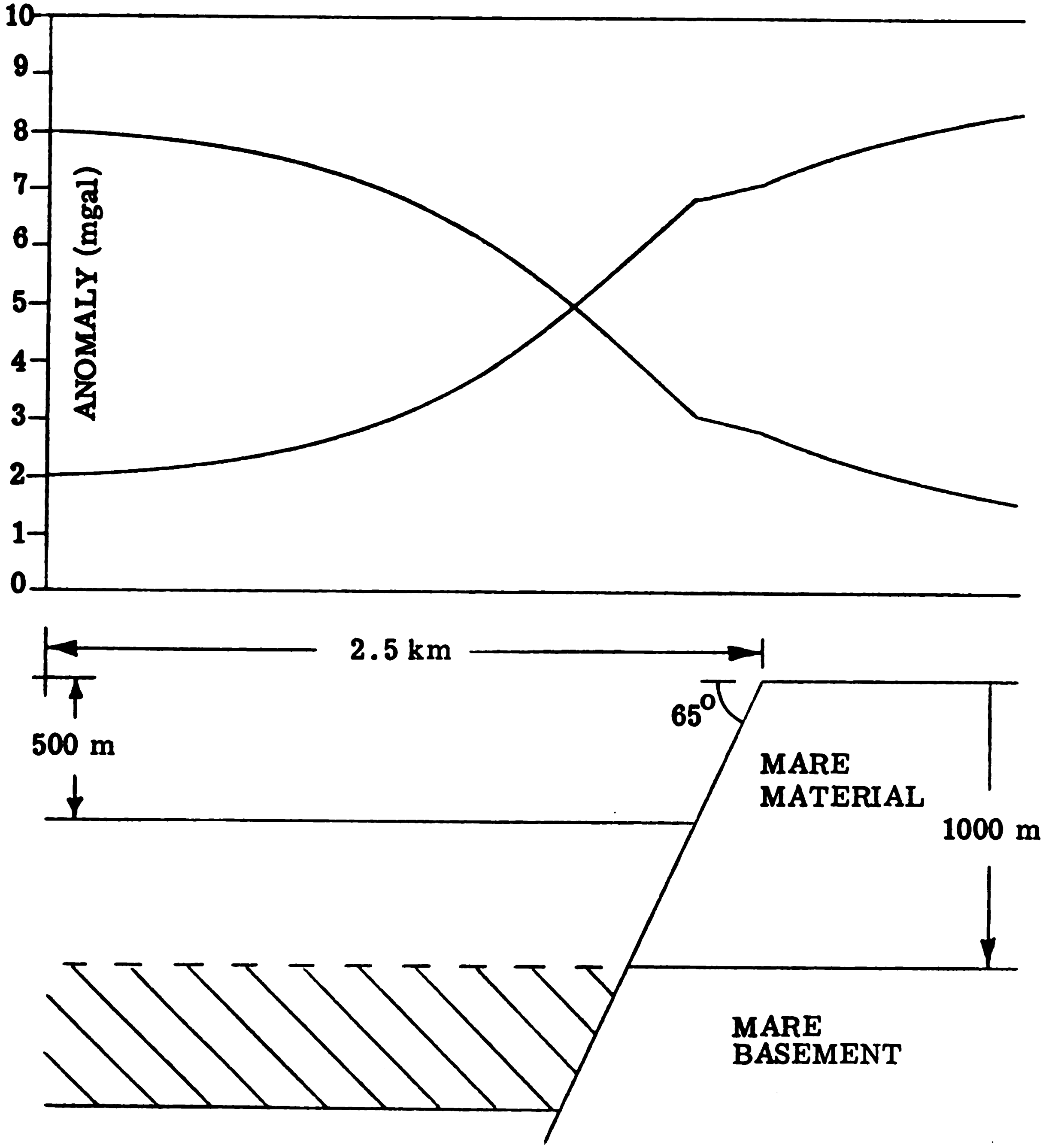

Figure 19. Half of the profile of the gravity anomalies over a lunar rille 5 km wide and 500 m deep with sides of slope 65° and a basement depth of 1000 m, for both positive and negative density contrasts of 0.5 g/cc. The anomalous mass is cross-ruled.

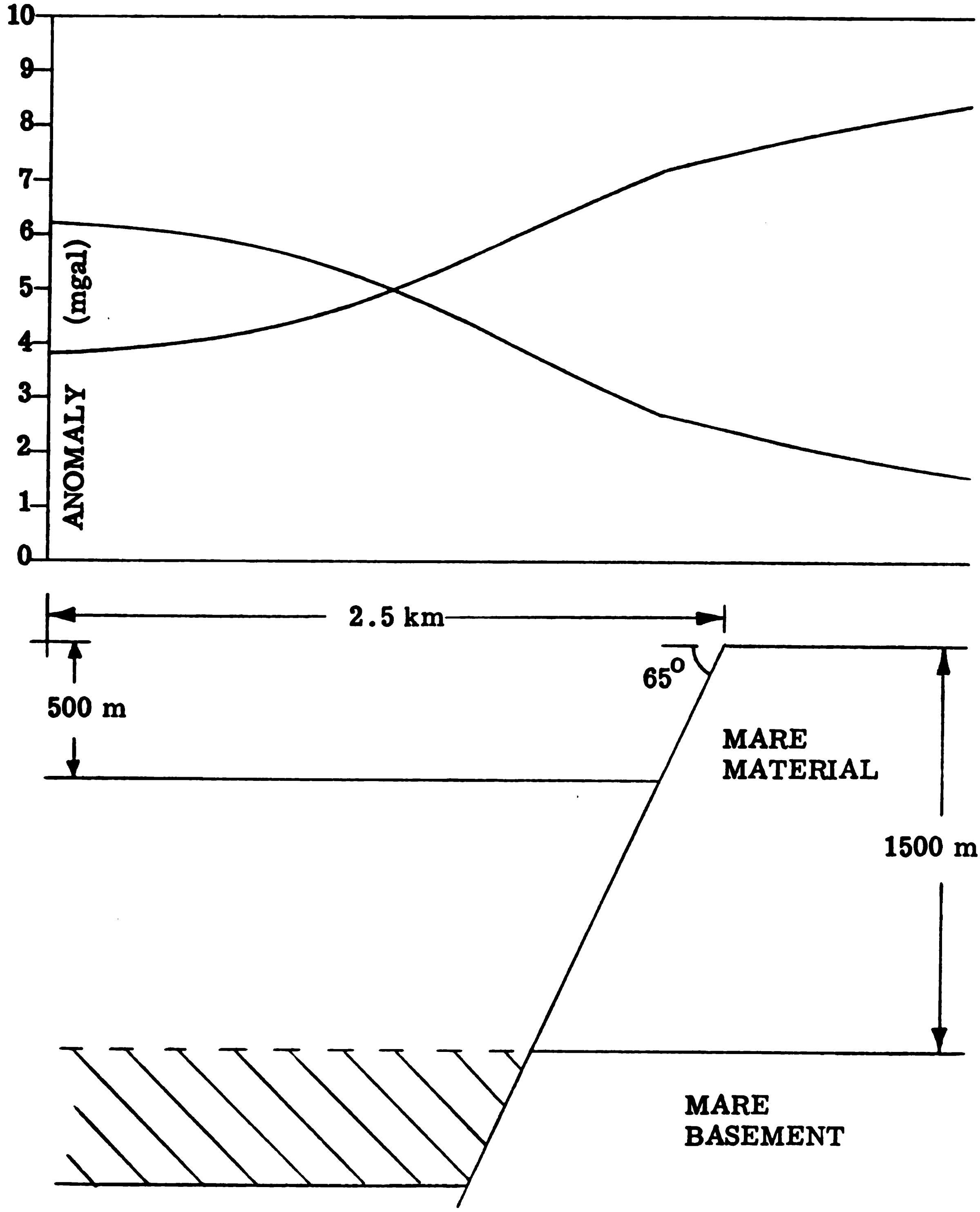

Figure 20. Half of the profile of the gravity anomalies over a lunar rille 5 km wide and 500 m deep with sides of slope 65° and a basement depth of 1500 m, for both positive and negative density contrasts of 0.5 g/cc. The anomalous mass is cross-ruled.

profiles arise from the changes in elevation of the observation point as it moves from the floor of the rille up the sloping rille wall and out along the level of the original plain. The magnitude of the anomaly, whether positive or negative, should immediately provide an estimate of the mare-basement density contrast, especially if the depth to the basement is known. Even if this depth is unknown, however, if the model of a tensional rille adopted here is valid, then even a single gravity observation made on the floor of such a rille, when compared to an observation made on the original plain might reveal which is the denser, the mare material or the basement rock, which is presumably identical with the highlands. This would be valuable information indeed and very useful in the interpretation of the origin of the maria and of the moon itself.

CHAPTER VI

MARIA RIDGES

The maria ridges (or wrinkle ridges) are irregularly trending low ridges which occur only on the maria. They may be hundreds of kilometers in length with widths on the order of 10 to 20 km, but this is quite variable, with some ridges exhibiting an en echelon structure. According to Kopal (1966) photometric work has revealed that the actual slopes of the ridges are very low, usually around one degree, and this implies that their elevations above the general plain level are not more than some 200 to 300 m. An astronaut standing on the moon would probably be completely unable to recognize such a ridge as a topographical feature. Some ridges tend to be concave in plan toward the centers of the circular maria, as are the arcuate rilles, but the ridges in such cases are always located nearer the mare centers than the rilles are. Other ridges are quite sinuous and irregular.

There appears to be no question that the ridges are in some way or ways related to the formation of the maria. A number of differing theories have been offered to explain the origin of these features. Among these are the suggestions that the ridges are due to the serpentinization of the mare material (serpentinization origin), to the extrusion of material from fissures (extrusive origin), to the burial of pre-existent ridges by the mare material (buried ridge origin), or to compression resulting from subsidence (compressional origin). It seems possible that these theories may not be mutually exclusive, and that perhaps several of them may be valid for certain particular ridges found on the moon. Each of these theories is considered in turn below.

Serpentinization Origin

The serpentinization hypothesis has already been discussed in some detail in Chapter III in connection with the origin of the lunar domes, and thus will not be repeated here. To my knowledge no one has specifically extended that hypothesis to include the ridges, but there seems to be no reason why this could not be done. If the maria are peridotitic in nature, then presumably escaping water from the lunar interior along fractures beneath the maria could serpentinize this material and the resulting increase in volume would push up the ridges. The subsurface structure beneath such a ridge would be much like that shown in Figure 9 depending on the degree of serpentinization of the material. However, since the ridges can be considered to be two-dimensional because of their great lengths, Figure 9 would then represent a cross-section of the ridge perpendicular to the axis of the ridge rather than a section along a diameter of a dome. The magnitudes of the anomalies over domes as shown in Figure 10 would be increased by a factor of about 1.5 for ridges of similar sectional dimensions, this being the ratio between the gravity effect of a near-surface buried two-dimensional horizontal cylinder to a buried sphere of the same cross-section (Dobrin, 1960). The half width of the anomaly will also be increased by about 30%. On the serpentinization hypothesis, then, the lunar ridges should be characterized by negative gravity anomalies of some tens of milligals, with the anomaly profiles having half widths roughly equal to the widths of the ridges themselves.

Extrusive Origin

According to this hypothesis, the lunar ridges are volcanic piles built up over feeder dikes during fissure eruptions. This mode of origin was considered in some detail by Quaide (1965) who assumed that the activity that produced such features might be similar to fissure eruptions on earth like those of the basaltic fields of Iceland. Fielder (1965) also strongly supports the extrusive origin from fissures of the ridges.

If this hypothesis is correct, the extrusive material forming such a ridge on the moon must have been very fluid, as the slopes involved are on the order of one degree. Such fluidity would be characteristic of a basaltic type of volcanism. This extrusive material would presumably exhibit little density contrast with the mare material itself, which also may well be extrusive igneous rock. If, however, the fissures underlying the ridges are filled with solidified magma, this could result in a gravity anomaly. Reasons have already been discussed in connection with laccoliths for believing that on the moon an intrusive body would solidify to a denser state than the corresponding extrusive material. It would seem that the same arguments could also be applied to solidification within fissures to form dikes, although perhaps to not quite the same degree. It would seem reasonable, however, to conclude that such dikes would exhibit at least some positive density contrast with the extrusive material because of their solidification under at least some confining pressure rather than under direct exposure to a vacuum as with the extrusive.

Since the maria ridges are of great length relative to their widths, they can be considered to be two-dimensional features. They are frequently on the order of 10 km wide, but on the assumption of an extrusive origin the dikes underlying the ridges would probably be much narrower than this. The actual width of any single dike might be as small as a meter or less or as great as perhaps many tens of meters. Many dikes, rather than just one, might underlie any given ridge, forming a dike swarm or zone whose total width might be much greater than that of any one dike, perhaps amounting to hundreds of meters. If the dikes within such a swarm were separated by distances roughly comparable to their individual widths, the gravity effect of the swarm would be about the same as that of a single dike of a width equal to that of the swarm and a density of the average of the dike and country rock within the dike zone. The actual density contrast that would exist between dike and country rock on the moon is uncertain. In the calculations below this density contrast is assumed to be positive, with a value of 0.5 g/cc. The amplitude of the anomaly for other density contrasts can of course be easily obtained by direct scaling.

If these dikes are assumed to be vertical, the one remaining variable that will affect the amplitude of the gravity anomaly associated with the dike is the depth to its lower boundary. A dike will presumably terminate at depth in the intrusive body from which it came. This depth would likely be no nearer the lunar surface than the mare-basement contact but could possibly be considerably deeper. Here the gravity anomalies over the dikes have been calculated for various depths to this lower boundary. It is assumed that the dikes are vertical and that their upper surfaces coincide with the surface of the moon.

The gravity anomalies that would exist over these dikes were calculated by means of the standard formula as given by Garland (1965), for dikes of widths ranging from 10 to 2000 m and for depths to the lower surface ranging from 500 to 50,000 m. The results of these calculations are shown in Figure 21.

The gravity profiles perpendicular to the strike of the dikes were also calculated for various ratios of the width or thickness of the dike to the depth of the dike's lower boundary, with the maximum gravity value over the center of the dike taken to be unity. These data are shown in Figure 22, with the actual value of the peak anomaly in milligals for any dike of known thickness and depth being found from Figure 21. These figures reveal that unless a dike is hundreds of

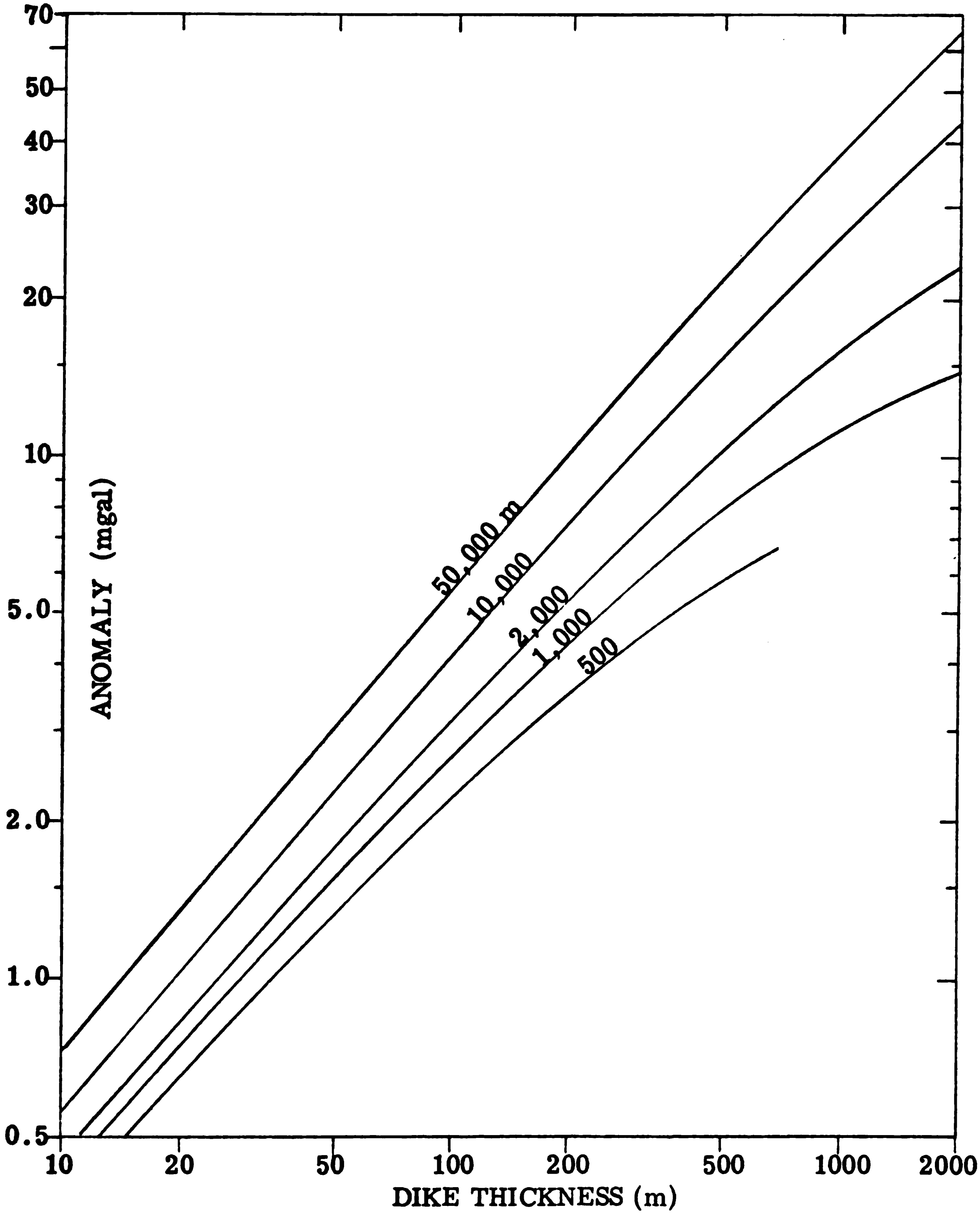

Figure 21. Relationship between thickness and maximum gravity anomaly for various depths to the lower boundary of vertical dikes having a positive density contrast of 0.5 g/cc.

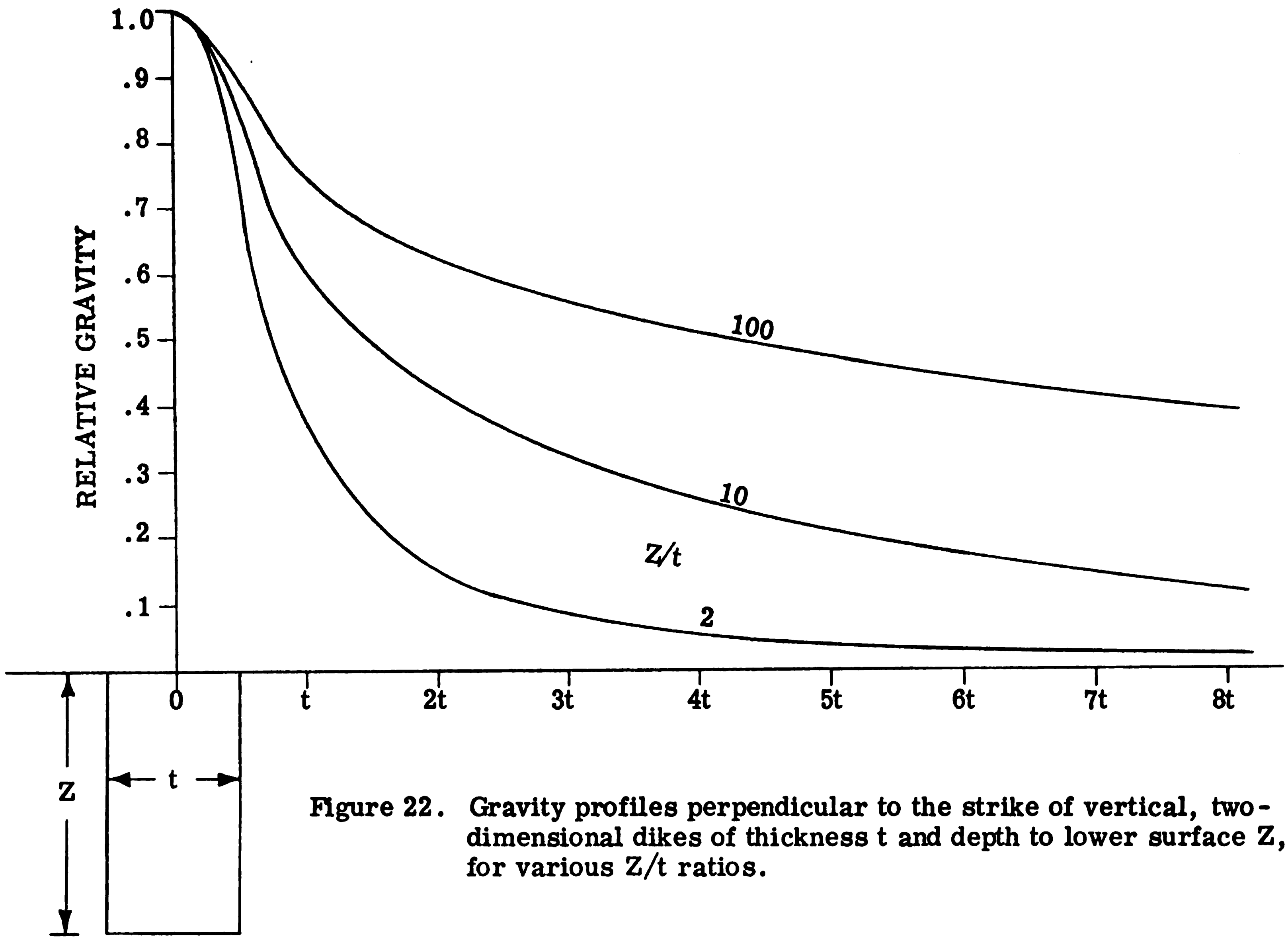

Figure 22. Gravity profiles perpendicular to the strike of vertical, two-dimensional dikes of thickness t and depth to lower surface Z, for various Z/t ratios.

meters wide and/or exhibits a marked density contrast with the country rock the anomaly will not be large, amounting to perhaps a few tens of milligals at the very most. The amplitude of the anomaly is not particularly sensitive to differences in the depth of the lower surface of the dike, and no firm conclusions about this depth seem possible based only on the gravity data. Figure 22 shows that even if a dike extends to a considerable depth relative to its width the anomaly drops off rather rapidly away from the dike's center. Therefore, if the lunar ridges are in fact extrusive features underlain by dikes of a positive density contrast with the country rock, positive gravity anomalies of rather low amplitudes and narrow widths relative to the widths of the ridges themselves would be anticipated over these features.

Buried Ridge Origin

According to this hypothesis, the maria ridges are the surficial expressions of sub-mare ridges or crater walls that have been buried by the mare fill, the present surficial expression of the features being due to the shallow depth of burial of the original ridge or wall and to possible differential compaction of the mare fill. Such an origin is most obvious for the various "ghost" craters of the maria, which are clearly craters which have been overwhelmed to a greater or lesser extent by the material forming the maria. It is not likely that all maria ridges originated in this manner. Nevertheless, Baldwin for example (1965) has pointed out that the ring of which Sinus Iridum is a part is completed by a series of ridges in Mare Imbrium, which he interprets as resulting from the buried portion of the original crater wall.

Perhaps the best example of ridges that may have originated in this manner are those found in the region of the Straight Wall. According to Alter (1964), who gives several excellent plates of this region, the Straight Wall is some 130 km long and 300 m high, having a slope of about 41^{o}. This normal fault lies on a north-south diameter of a large, ancient ring-structure, the Straight Wall Plain, which is some 210 km across. The half of this ruined ring on the upland side of the Straight Wall is clearly visible, but on the downthrown seaward side of the Wall the other half of the ring is absent, apparently buried beneath the mare. However, under low sun angle conditions a series of ridges are visible on the mare surface which rather obviously complete the ring and which therefore appear to be due to the buried ancient crater wall which foundered along the Straight Wall fault. If this is correct, then the presence of this buried crater wall might well be detectable by gravity methods.

In order to estimate the amplitude and form of the gravity anomaly that would exist over such a buried wall the various dimensions of the subsurface structure must be known. It appears on photographs as if the mare fill feathers out completely at the base of the upland eastern wall of the ring and just covers the buried seaward wall in the west. No direct method of estimating the depth of the mare material away from the ridges is apparent. However, directly south of but immediately adjacent to the 210 km diameter Straight Wall Plain is Deslandres, another very similar ancient ring-structure virtually identical in size, but which is not flooded with mare material. It would seem reasonable to assume that the various dimensions of Deslandres approximate the pre-flooding dimensions of the Straight Wall Plain. These dimensions of Deslandres were determined from the Lunar Chart LAC 95 (Purbach) of 1961. Although the walls and floor of Deslandres are irregular, the crest of the wall appears to average about 1500 m above the relatively flat floor and about 600 m above the surrounding plain. The horizontal distance from the wall crest to the base of the wall on the interior of the ring and to the level of the plain on the outside appears to be about 20 km.

Figure 23 gives an east-west section of the Straight Wall Plain on the assumptions that its pre-flooding dimensions were similar to those exhibited at the present by Deslandres and that as a result of flooding and foundering the mare material just touches the base of the inner upland wall and just covers the downdropped wall. The post-flooding crater Birt, which lies just seaward of the Straight Wall, is also shown in section, its dimensions being obtained from the same map. If this subsurface model of the Straight Wall Plain is valid it can be seen that the interior walls of Birt would cut the entire mare section and penetrate the pre-mare basement as well,

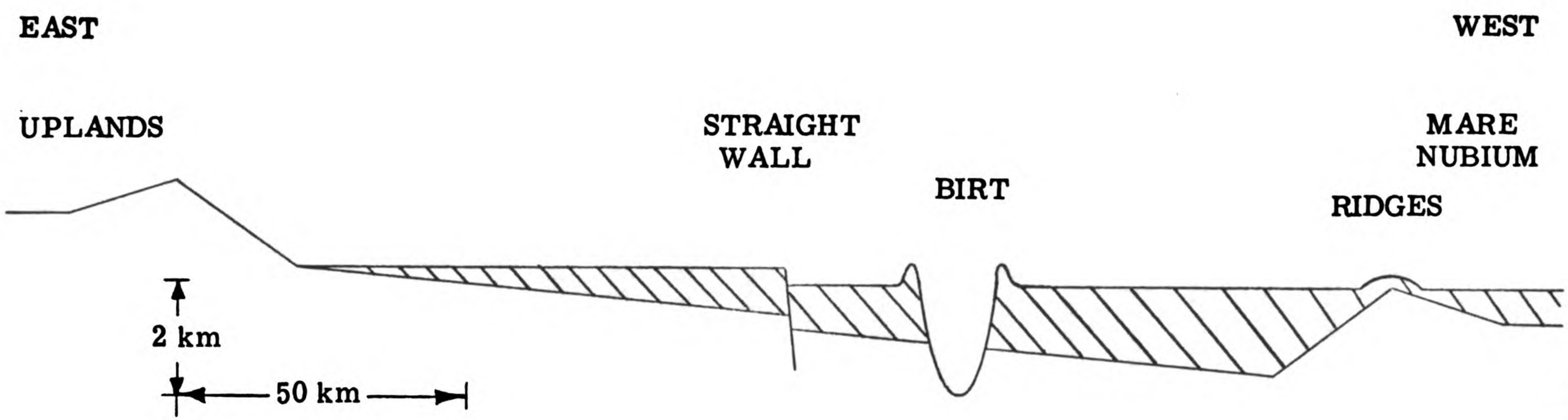

Figure 23. Generalized east-west section of the Straight Wall Plain. The mare fill is cross-ruled. Vertical exaggeration is ten times.

whereas the Straight Wall itself would exhibit only mare material in its face. It is interesting to note that the map referred to above shows a break in slope in the inner wall of Birt some 600-800 m above the bottom of the crater. Whether this is the result of a change in lithology across a boundary such as the mare-basement contact predicted here is of course uncertain, but in any case such localities would be very important geological sites, at which a great deal could undoubtedly be learned about the history and origin of the maria.

It seems evident that the upward projection of the buried seaward wall of the Straight Wall Plain could produce a gravity anomaly over the surface ridges. A section of this portion of the area is given in Figure 24. The gradual rise landward to the east in the mare-basement contact has been ignored in this section as it is less than 1° and would simply contribute to a regional effect over the entire plain.

The gravity anomaly over the buried ridge was calculated by assuming that the ridge could be considered to be two-dimensional and by breaking this buried ridge up into horizontal slabs 100 m thick. The gravity effect of such a slab in milligals is (Nettleton, 1942, with a conversion factor)

$$g = 13.35\ \theta \sigma t \qquad (14)$$

where θ is the angle subtended by the median plane of the horizontal slab at the point of observation, σ is the density contrast in g/cc, and t is the slab thickness in km. As the surficial ridges are rather

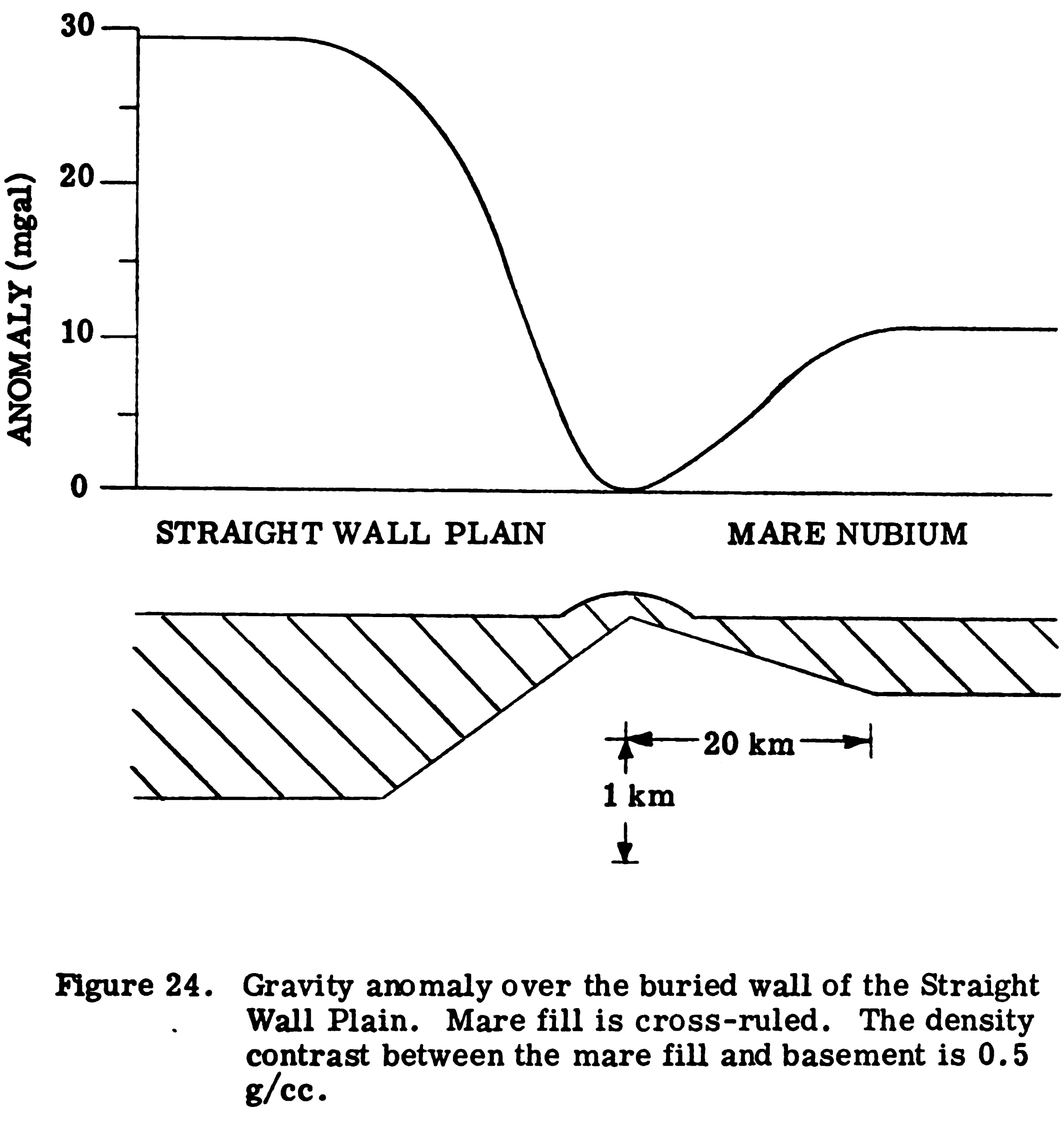

Figure 24. Gravity anomaly over the buried wall of the Straight Wall Plain. Mare fill is cross-ruled. The density contrast between the mare fill and basement is 0.5 g/cc.

irregular and are only schematically shown in Figure 24, the anomaly was calculated as if observed at the level of the plain itself.

The problem of the density contrast between the mare material and the mare basement has already been discussed. In the calculations here it was assumed that the mare fill is denser than the basement, the contrast being 0.5 g/cc. The form and amplitude of the resulting negative gravity anomaly over the buried wall of the Straight Wall Plain is also shown in Figure 24. It would appear, then, that on the buried ridge hypothesis the maria ridges should be characterized by negative gravity anomalies with amplitudes of perhaps some tens of milligals and widths considerably greater than the width of any one surficial ridge, reflecting the greater width of the buried structure beneath the mare surface.

Compressional Origin

According to this hypothesis the maria ridges are compressional folds in the mare fill material formed by the subsidence and foundering of the mare basement by tilting and/or faulting. Therefore, the ridges would be located over those areas where the mare material is thickest, in contrast to, for example, the buried ridge hypothesis which requires exactly the opposite condition. Ronca (1965) gives a detailed consideration of subsidence, tilting, and compression as applied to Mare Humorum. He interprets Mare Humorum, a near-circular mare some 400 km in diameter, as a basin which subsided by tilting and normal faulting and was filled with volcanic material which was compressed by the subsidence to form the well known system of ridges which arcs along the eastern side of the mare. These ridges should therefore mark the area of greatest subsidence of the mare basement and greatest thickness of mare fill. That the subsidence of the basement was at least partially due to tilting seems clear from the fact that craters such as Gassendi on the north and Doppelmeyer on the south are strongly tipped toward the center of the mare. However, numerous rilles are located on the eastern and western sides of the mare, indicating that faulting may also have played a part in the subsidence. Ronca gives a maximum thickness of about 2 km for the mare fill under the ridges in Mare Humorum, with a thinning of this material to essentially nothing at the mare edges.

In order to calculate the gravity anomaly that would exist over the maria ridges due to this thicker underlying material the hypothetical east-west section of Figure 25 was adopted. This is a cross-section of Mare Humorum from the crater Mersenius D in the west to the crater Hippalus in the east. The surficial elevations and dimensions were obtained directly from Lunar Chart LAC 93 (Mare Humorum) of 1962, with the curvature of the moon neglected. Following Ronca, the maximum thickness of the mare material is assumed to be about 2 km. In order to illustrate the effects of both tilting and faulting the mare basement is assumed to slope uniformly to the maximum

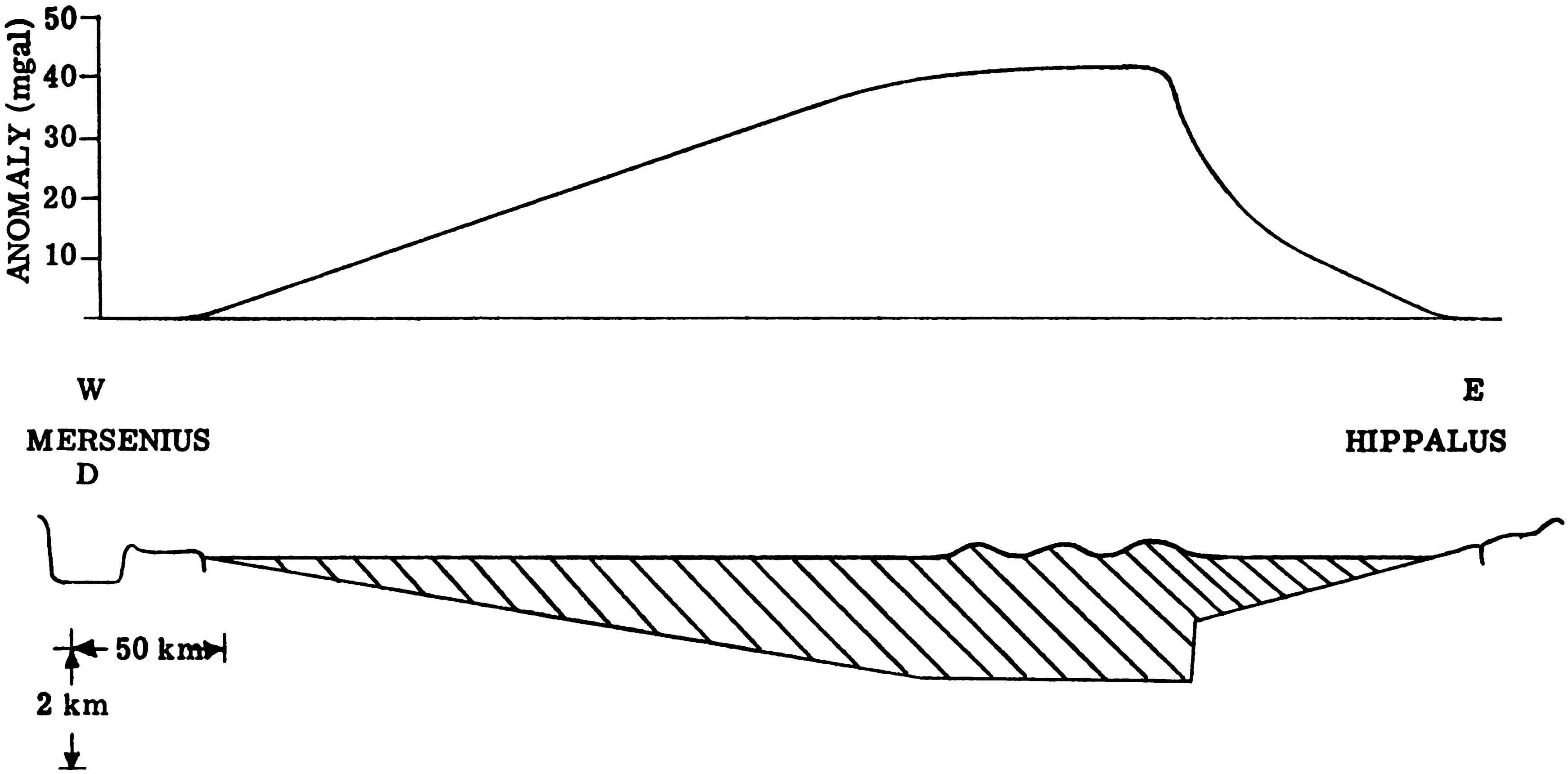

Figure 25. West to east cross-section of Mare Humorum with the calculated gravity anomaly assuming the Mare is filled with material of density 0.5 g/cc greater than the basement. The ridges shown are schematic.

depth beneath the ridges in the west but to be broken by a normal fault from a depth of 1 km to 2 km in the east, the fault having a slope of 45^{o}, which is approximately the slope of the Straight Wall, probably the best example of lunar normal faulting.

Four slabs, each 250 m thick, were used to approximate the anomalous mass of the mare fill. Because of the great length of the ridges relative to their widths and to the thickness of the mare material, these horizontal slabs were considered to be two-dimensional. The relationship of equation (14) therefore provides the means of determining the gravity anomaly over the mass. As in previous sections the density contrast between the mare basement and the more dense mare fill is assumed to be 0.5 g/cc.

The gravity anomaly over Mare Humorum on this hypothesis is also shown in Figure 25. The anomaly over the thickest part of the mare fill runs to over 40 mgal relative to the continental regions. Even more evident is the width of the anomaly. It is obviously not confined to the ridges themselves but is essentially a regional anomaly encompassing the entire mare. This is in contrast to the anomalies predicted for the ridges by the other hypotheses considered here, which were more localized over the ridges themselves.

The interpretation of gravity anomalies in a relatively unfamiliar environment as is encountered on the moon will become progressively more uncertain as one passes from distinctly localized anomalies to those of regional extent, primarily because of the lack of knowledge concerning horizontal density variations at depth. An understanding of the origin of anomalies which involve entire maria, for example, will be closely linked to an analysis of the overall gravitational field of the moon. Such an analysis is beyond the scope of this study, which has been generally confined to the smaller of the lunar surface features, but has been touched on briefly above in connection with the lunar mascons. At the present time investigations are proceeding rapidly in the definition of the moon's overall field, although the physical cause of the regional effects found over the maria remains in doubt. From the point of view of this present study the importance of these investigations lies primarily in the fact that they are providing, with ever increasing clarity, the gravitational background upon which the more localized anomalies studied here will be superimposed. Such investigations will therefore form the base from which the interpretation of these smaller anomalies will begin.

CHAPTER VII

CORRECTIONS AND CONTROLS

A gravity anomaly is the difference between a measured gravity value and a calculated theoretical value for the same point. The theoretical value will incorporate the effects of all known factors that could cause significant variations in the observed gravity except for subsurface density variations. Normally, in the reduction of gravity data from actual surveys, a mathematically equivalent procedure is adopted, whereby the effects of the various factors which may influence a gravity reading, other than subsurface density changes, are compensated for by the use of certain corrections which are applied to the observed gravity data before the isolation of the anomalies is attempted. Among the corrections normally used in the reduction of gravity observations on earth are the free air correction, the Bouguer correction (the combined effect of these two being called the elevation correction), the terrain correction, the tidal correction, and the latitude correction. Each of these corrections will be considered below as it relates to the lunar environment.

Free air correction. The mass and radius of the moon can be determined by the analysis of standard astronomical data. According to Glasstone (1965) the moon's mass is 7.35×10^{22}kg and its average radius is 1738 km. If, as a first approximation, the moon is assumed to be spherical and the internal density is assumed to be a function of the radius only, the gravitational acceleration in gals at the lunar surface will be given by the equation

$$g=G\,M/R^2 \qquad (15)$$

where g is the acceleration, M is the mass, and R is the radius of the moon, and G is the gravitational constant. Substitution of the values given above for the moon yields a gravitational field of about 162 gals at the moon's surface. For the earth Glasstone (1965) gives values for the mass and radius of 5.975 X 10^{24}kg and 6371 km respectively. For these values, equation (15) gives a field of about 982 gals, so that the average acceleration at the surface of the moon is slightly less than one-sixth that of the earth. This means of course that a gravity meter designed for lunar use must be capable of operation in this much lower field. The vertical gradient of gravity at the surface of the earth or moon can be obtained by differentiating equation (15) as follows.

$$dg/dR= -2GM/R^3= -2g/R \qquad (16)$$

For the moon, the vertical gradient is then -0.187 mgal/m, or only about 61% of the corresponding value of -0.308 mgal/m for the earth. This means that for any desired gravity precision in mgal the elevation controls on the moon can be somewhat less rigid than in terrestrial work.

The rate of change of the vertical gradient with increasing elevation, however, will be greater for the moon than for the earth, primarily because of the moon's smaller radius. This rate of change can be evaluated by differentiating equation (15) again.

$$d^2g/dR^2 = 6GM/R^4 = 6g/R^2 \quad (17)$$

Using the values of radius and mass given above, the rate of change of the vertical gradient for the earth is 0.145×10^{-6} mgal/m^2, but for the moon it is 0.322×10^{-6} mgal/m^2, or about 2.2 times as great as for earth. For example, neglecting the rate of change of the vertical gradient of gravity with increasing elevation in a terrestrial survey will result in an error of 0.65 mgal for a 3000m elevation difference, but for the same change in elevation on the moon the error will be 1.43 mgal.[1] For lesser elevation differences, however, the error will also be decreased, being only about 0.07 mgal on earth and 0.15 mgal on the moon for an elevation difference of 1000 m. Therefore, in early surveys on the moon where controls are not rigid and elevation differences are not great the assumption that the vertical gradient is constant will be a reasonable one. In more exact surveys, however,

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[1] For the earth a change in elevation of 3000 m will result in a change in the vertical gradient of $0.145 \times 10^{-6} \times 3000 = 0.435 \times 10^{-3}$ mgal/m. To a first approximation the average difference over the interval will be half this value, and this figure times the 3000 m elevation difference is $0.2175 \times 10^{-3} \times 3000 = 0.65$ mgal. A similar calculation holds for the case of the moon.

particularly in rugged areas, for maximum control the change in the vertical gradient with elevation should probably be taken into account.

Bouguer correction. The Bouguer correction compensates for the gravitational effect of any material lying between the observation station and the datum level by approximating such material as an infinite horizontal slab whose thickness is the elevation difference involved. From the standard formula for the gravitational effect of an infinite slab (e.g. Garland, 1965) an acceleration of 0.042 mgal/m is found for material of density 1 g/cc. This value is independent of the overall gravity field but is directly proportional to the density of the material.

Elevation correction. The effects of the free air correction and the Bouguer correction are opposite in sign. Since both are directly proportional to the elevation difference between the observation station and the datum plane their effects are usually combined into the elevation correction, EC, which can be expressed in mgal/m by the relationship

$$EC=0.187-0.042\,\sigma \qquad (18)$$

where σ is the density of the material in g/cc. For observation stations above the datum plane the correction is added to the observed gravity value and is subtracted for stations below the datum. Figure 26 relates the elevation correction for the moon to the density used in the Bouguer rediction. Also shown are estimates for the densities of the lunar uplands and maria, 2.9 g/cc and 3.3 g/cc respectively, determined from an analysis of Apollo 11 data, as reported by Watts (1970). If the density of the near-surface lunar material is at least 2.0 g/cc the elevation correction will be less than 0.1 mgal/m, or less than one-half of its terrestrial value. In effect, to keep within any given gravity precision in mgal on a lunar survey elevation controls need be less than half as stringent as on earth. The actual density (or densities) used in the elevation correction will probably be best determined by on-site inspection.

Terrain correction. The terrain correction compensates for deviations of the actual topography in the vicinity of a gravity station from the Bouguer slab. Its use in lunar gravity surveys will duplicate its use terrestrially, as this correction is independent of the overall field. As with the elevation correction, the densities used will be best determined from on-site examination. As on earth, the lunar terrain correction will be negligible in relatively flat areas such as the maria, where most early surveys will probably be conducted. Only in areas of fairly rugged topography will this correction be important, and its use will be governed by the same considerations as apply on earth.

Tidal correction. A sensitive gravimeter will record changes in the gravitational field within which it is located that are caused by the attraction of various celestial bodies. If one is searching for

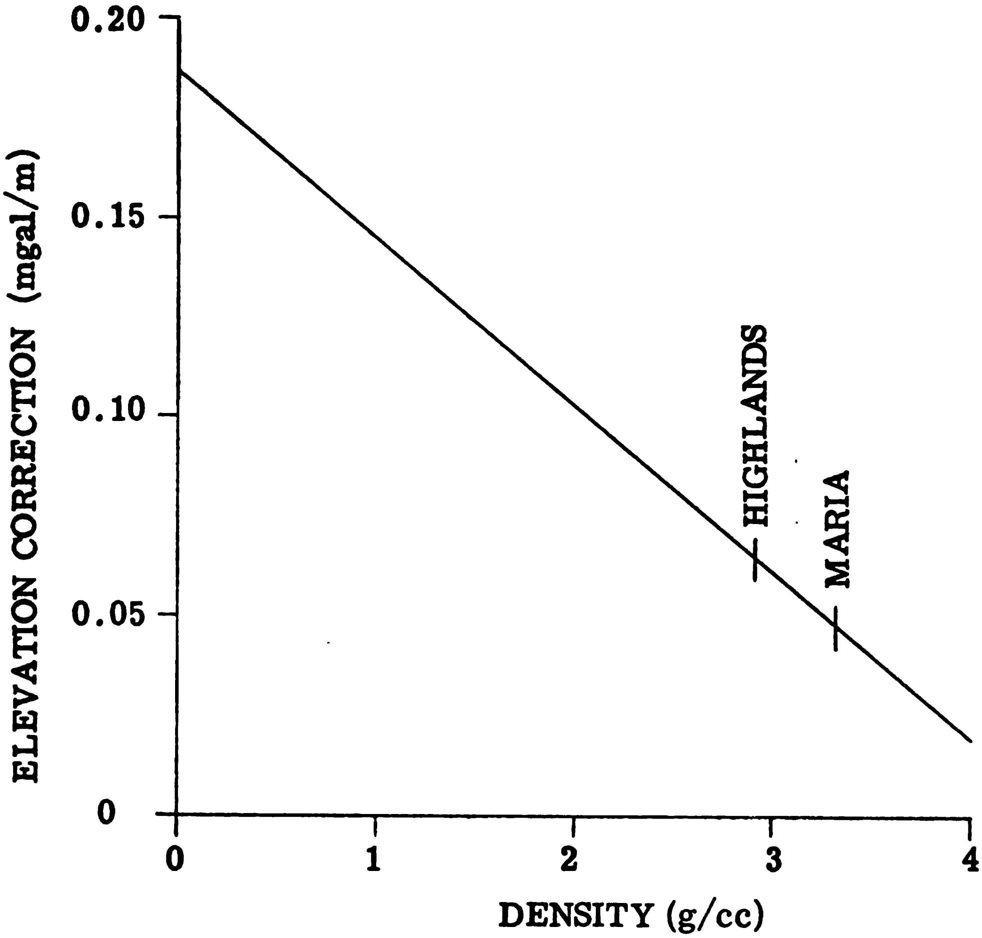

Figure 26. The lunar elevation correction.

gravity anomalies due to density changes within the body of the earth, for example, these effects due to external bodies can be allowed for by means of a tidal correction. On the earth the main tide producing bodies are the sun and moon, with the effects of the moon representing about two-thirds of the total because of its lesser distance. The primary cause of variations in these tidal effects is the changing positions of the sun and moon relative to a point on the earth due to the earth's rotation. Since the tide producing force reaches a maximum twice for each rotation of the earth, when the observation point is both toward and away from the tide producing body, the primary tidal effect due to the sun will have a cycle of half of a solar day, 12 hours, while the primary effect due to the moon will have a cycle of about 12 hours and 25 minutes. The maximum gravity change on earth due to these effects is about 0.3 mgal.

For an observer on the moon the primary tide producing bodies will be the sun and earth. Because of the moon's smaller radius, however, the tidal effect of the sun on the moon will be only about one-fourth as great as on earth, and this small effect will not be considered further here. The earth will be by far the dominant body as far as tides on the moon are concerned. However, to a first approximation there will be no variation due to the moon's rotation in the tidal effect of the earth on the moon, since the moon's rotation and revolution are synchronous, and therefore (neglecting librations) the position of the earth is fixed in the sky relative to any given location on the lunar surface. There will, however, be effects due to the varying earth-moon distance in the course of the month. These effects will be greatest at a point at the center of the earthward hemisphere of the moon (the sub-earth point), where the earth would be at the zenith. Heiland (1940) has shown that the vertical component of the tidal force due to a body of mass M at a distance d from a point on a body of radius R is given by

$$g = \frac{-3GMR}{2d^3} (\cos 2\theta + 1/3) \qquad (19)$$

where θ is the zenith distance and G is the gravitational constant. According to Glasstone (1965) the maximum and minimum earth-moon distances are 4.07×10^5 km and 3.56×10^5 km respectively. For the sub-earth point on the moon $\theta = 0^o$. Substitution of these values into equation (19) yields a tidal effect due to the changing earth-moon distance of 1.01 mgal. For locations on the moon other than the sub earth point this value will be diminished by the factor θ in equation (19). These calculations indicate that the gravitational field of the moon at the sub-earth point will fluctuate by about one mgal in the course of a lunar month due to the varying earth-moon distance, the overall field being diminished most when the distance is least.

These considerations, however, are valid only for a completely rigid moon. In fact of course the moon will yield to some extent to these forces and as a result the value of the lunar field as determined at the sub-earth point will be diminished even further when the earth-moon distance is least because this point will rise and be displaced farther from the moon's center. According to Urey et al (1959), for a completely yielding moon this displacement would be 16.2 m. An estimate of the gravitational effect of such a displacement can be made by simply assuming, as a first approximation, that the moon's radius has expanded by 16.2 m, since the total mass within the moon obviously remains constant. The reduction in gravity that would result at any point on the moon due to such an expansion can be simply shown to be identical to that given by the free air correction for the moon (equation (16)), which will be 3.0 mgal for an elevation change of 16.2 m. The maximum tidal effect on a completely yielding moon would then be about 4 mgal, of which 3 mgal would be due to yielding. In reality, of course, the moon does have rigidity, and therefore the actual amplitude of the tidal effect at the sub-earth point will be something less than about 4 mgal. In fact a measure of this effect would provide an estimate of the internal strength of the moon. For localities away from the sub-earth point the variations will be correspondingly smaller.

These changes in the gravitational field of the moon will occur with a period of about 27.3 days, the lunar orbital period. In order to estimate the time rate of change of the tidal effect, let us assume that this tidal variation can be approximated as a sine function. Differentiation of the sine function gives a maximum rate of change of

$$dy/dt = A\,2\pi/P \qquad (20)$$

where A is the amplitude and P is the period of the function. As the moon obviously does have some rigidity, if we estimate A to be 1.5 mgal, corresponding to a total tidal variation of 3 mgal, and P is 27.3 days, the maximum rate of change is 0.014 mgal/hr. This is considerably lower than the corresponding rate for the earth, because of the much longer period of the change. Even though the amplitude of the tidal effect on the moon may be as much as ten times that on earth, correcting for these effects should not be difficult, and for surveys of only a few days duration the assumption that the correction is linear should not introduce any serious errors.

Latitude correction. In terrestrial gravity surveys, the theoretical gravity value to which a reduced gravity observation is normally compared is that given by the international gravity formula (Dobrin, 1960),

$$g = 978.049\,(1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi) \qquad (21)$$

where g is in gals and ϕ is the latitude. In effect, equation (21) automatically incorporates the latitude correction for the earth. This correction is necessary because the ellipsoidal shape of the earth and the effects of the earth's rotation combine to result in a gravity difference of about 5,200 mgal between the equator and the poles. Differentiation of equation (21) yields a rate of change of gravity with latitude of 0.82

mgal/km at 45^{o} latitude, where the effect is a maximum. If the international formula were not used in a terrestrial survey, the data would reflect a strong poleward regional trend.

The international gravity formula is based on many accurate observations of gravity at various places on earth. Such data are not available at present for the moon. However, a first approximation of the latitude correction for the moon can be made by direct comparison with the earth. The primary source of the latitude effect on earth is the earth's rotation, which produces a decrease in the gravity field as one approaches the equator. The remainder is due to the earth's ellipsoidal shape. The centrifugal acceleration, a, on a rotating sphere is

$$a = \omega^2 R \qquad (22)$$

where ω is the angular velocity and R is the radius of the body. On the assumption that the earth is a sphere of radius 6.371×10^{6} m rotating with an angular velocity of 7.29×10^{-5} rad/sec, equation (22) yields a centrifugal acceleration of about 3,400 mgal at the equator. Therefore, of the 5,200 mgal total difference from equator to pole in the gravitational acceleration at the earth's surface, over 65% is due to the rotation of the earth. The lunar rotation, however, will give rise to a much smaller effect. Substitution of the lunar rotation rate, 2.66×10^{-6} rad/sec, and the lunar radius, 1.74×10^{6} m, into equation (22) reveal that the moon's rotation will result in only a 1.23 mgal difference in gravity from the lunar equator to pole, a very small gradient.

Axial rotation, which on earth is the source of almost two-thirds of the 5,200 mgal latitude effect, will have essentially negligible consequences on the gravitational field of the moon. Deviations of the moon from sphericity may require a further latitude correction and perhaps a longitude correction as well, but in any case it seems likely that such corrections will be quite small. In early lunar gravity surveys these effects could be treated as regionals from which the more localized anomalies such as those discussed in this study could be isolated by standard methods.

CHAPTER VIII

CONCLUSIONS

The gravity method, with its unique ability to detect density contrasts beneath the level of observation, holds great promise for lunar exploration and the analysis of lunar surface features. The gravity field over any given feature represents an important potential source of information concerning the nature of the materials and structures underlying the feature, which in turn may provide important clues to understanding the genesis of the feature and its relationship to lunar history in general. For the following lunar features, subsurface models were adopted and the gravity anomalies over these models were calculated by various approximate methods as they would be observed at the lunar surface by a local gravity survey. The various appropriate corrections to the raw gravity data as they relate to the lunar environment were also investigated.

Craters. Broadly speaking, lunar craters are generally considered to be either meteoritic or volcanic in origin. It is possible that both processes may have had a hand in the formation of the larger lunar craters. However, it is probable that only one process was involved in the origin of any given crater under about 20 km in diameter.

Apparently at the moment of formation all meteorite craters are geometrically similar and will be underlain by a breccia lens of shattered rock. Such craters, up to about 20 km in diameter, should be characterized by negative gravity anomalies due to the decreased density of this breccia, whose form will be dictated by the form of the breccia lens and whose amplitudes will be directly proportional to the diameter of the craters and to the density contrast between the breccia and the country rock.

For craters of internal or volcanic origin the gravity picture will be somewhat more complicated. Calderas, generally considered to be the most reasonable terrestrial analogs of possible lunar volcanic craters, are of several differing types, and exhibit both positive and negative gravity anomalies of varying amplitudes. These anomalies, however, will normally be related to more widespread, regional anomalies because of the relationship of volcanic activity to more deepseated processes, whereas meteoritic craters should show an essentially random distribution, and whose anomalies should therefore show no significant correlation with regional effects.

Domes. A mineralogical phase change from olivine to serpentine and the intrusion of laccolithic bodies are among the origins suggested for lunar domes. A phase change would result in a less dense body of material underlying the dome, and consequently such domes would be characterized by negative gravity anomalies, possibly with amplitudes as great as tens of milligals. On the laccolithic hypothesis, however, the domes should exhibit positive gravity anomalies due to the intrusive material solidifying to a denser state than the country rock. The amplitudes of such anomalies will depend on a number of factors, among them the depth, size, and density contrast of the intruding body.

Lava tubes. The origin of lava tubes is understood from the study of such features on earth. If they exist on the moon, they may form convenient, ready made structures in which permanent lunar bases or depots could be established. If these features lie near the lunar surface beneath the maria, they may be detectable by local gravity surveys by the negative gravity anomalies they will produce. While the amplitudes of such anomalies will be small, careful surveys should reveal them and enable such structures to be delineated.

Rilles. Lunar rilles are of several types. Of particular interest are the long straight rilles which appear to be graben structures. From their locations on the moon it seems likely that the faulting involved in such features may cut both the mare material and the sub-mare basement. As a result of these displacements gravity surveys over these rilles may reveal which, the mare fill or the mare basement, is the denser. A positive anomaly over the rille would mean the mare fill is denser and vice versa, and the amplitude of such an anomaly would provide an estimate of the density contrast involved. Such information would be of great significance in the interpretation of the nature and history of the maria.

Maria ridges. The gravity method may contribute to the resolution of the question of the origin or origins of the maria ridges. According to the serpentinization hypothesis, as was the case with domes, the ridges would be underlain by serpentine less dense than the surrounding country rock, which would result in the presence of negative gravity anomalies over the ridges. If the ridges are extrusive volcanic piles they may be underlain by feeder dikes which could give rise to positive gravity anomalies, but of rather narrow widths, reflecting the limited widths of the dikes relative to the entire ridges. Some ridges appear to be due to the burial by the mare material of pre-existing ridges or crater walls. If, as seems likely, the mare material is denser than the basement rock, these ridges should exhibit negative gravity anomalies of considerable width. Other ridges may be compressional in origin, resulting from the subsidence of basins filled with mare material. Such ridges should exhibit positive gravity anomalies of regional extent.

Corrections. The reduction of gravity data obtained in local lunar surveys will be similar to that required in terrestrial surveys. The lunar free air correction will be about 0.187 mgal/m or about six-tenths of the terrestrial value. The elevation correction will depend on the Bouguer density chosen, but will probably be somewhat less than half the value on earth, which will allow greater freedom in the determination of station elevations on the moon. The use of the terrain correction on the moon will be governed by the same considerations as apply terrestrially. The lunar tidal correction may have an amplitude as much as ten times the corresponding correction on earth, but because of the much longer period of the change the rate of change of the correction will be small. Axial rotation, the main source of the latitude effect on earth, will result in only about a 1 mgal difference in gravity from the lunar equator to pole. Further latitude and longitude effects can be treated as regionals in early lunar gravity surveys and eliminated by appropriate procedures.

REFERENCES CITED

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Alter, Dinsmore (1964). Lunar Atlas. Dover Publications. 343 pp. New York.

Baldwin, Ralph B. (1949). The Face of the Moon. U. of Chicago Press. 239 pp. Chicago.

__________ (1963). The Measure of the Moon. U. of Chicago Press. 488 p. Chicago.

__________ (1965). A Fundamental Survey of the Moon. McGraw-Hill. 149 pp. New York.

__________ (1968). Lunar Mascons: Another Interpretation. Science, V-162, pp. 1407-1408.

Beals, C. S. and Halliday, I. (1965). Impact Craters of the Earth and Moon. Journal of the Royal Astronomical Society of Canada, V-59, pp. 199-216.

Beals, C. S., Innes, M. J. S., and Rottenberg, J. A. (1963). Fossil Meteorite Craters. In "The Solar System" Ed. Middlehurst and Kuiper, V-4, pp. 235-284. U. of Chicago Press. Chicago.

Bible, J. L. (1962). Terrain Correction Tables For Gravity. Geophysics, V-27, pp. 715-718.

Bowen, N. L. and Tuttle, O. F. (1949). The System $MgO-SiO_2-H_2O$. Geological Society of America Bulletin, V-60, pp. 439-460.

Cameron, W. S. (1964). An Interpretation of Schroter's Valley and Other Lunar Sinuous Rills. Journal of Geophysical Research, V-69, pp. 2423-2430.

Conel, J. E. and Holstrom, G. B. (1968). Lunar Mascons: A Near-Surface Interpretation. Science, V-162, pp. 1403-1404.

Currie, K. L. (1965). Analogues of Lunar Craters on the Canadian Shield. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 915-940.

Dence, M. R. (1964). A Comparative Structural and Petrographic Study of Probable Canadian Meteorite Craters. Meteoritics, V-2, pp. 249-270.

__________ (1965). The Extraterrestrial Origin of Canadian Craters. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 941-969.

__________(1967). Personal Communication.

DeSitter, L. U. (1956). Structural Geology. McGraw-Hill. 621 pp. New York.

Dietz, R. S. (1962). Sudbury Structure as an Astrobleme (Abstract). Transactions of the American Geophysical Union, V-43, pp. 445-446.

Dobar, W. I. (1965). Behavior of Lava on the Lunar Surface. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 495-515.

__________ (1966). Simulated Basalt and Granite Magma Upwelled in Vacuum. Icarus, V-5, pp. 399-405.

Dobar, W. I., Tiffany, O. L., and Gnaedingre, J. P. (1964). Simulated Extrusive Magma Solidification in Vacuum. Icarus, V-3, pp. 323-331.

Dobrin, M. B. (1960). Introduction to Geophysical Prospecting. McGraw-Hill. 446 pp. New York.

Elston, W. E. (1965). Rhyolite Ash-Flow Plateaus, Ring-Dike Complexes, Calderas, Lopoliths, and Moon Craters. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 817-842.

Fielder G. (1961). Structure of the Moon's Surface. Pergamon Press. 266 pp. New York.

__________ (1965). Lunar Geology. Dufour. 184 p. Chester Springs, Pa.

Garland, G. D. (1965) The Earth's Shape and Gravity. Pergamon Press. 183 pp. New York.

Gilvarry, J. J. (1969A). Nature of the Lunar Mascons. Nature, V-221, pp. 732-736.

Gilvarry, J. J. (1969B). Mensuration and Isostasy of Lunar Mascons and Maria. Nature, V-223, pp. 255-258.

Girdler, R. W. (1963). Geophysical Evidence on the Nature of Magmas and Intrusion Associated With Rift Valleys. Bulletin Volcanologique, V-26, pp. 37-47.

Glasstone, S. (1965). Sourcebook on the Space Sciences. Van Nostrand. 937 p. Princeton.

Gold, T. (1966). The Moon's Surface. In The Nature of the Lunar Surface, Ed. Hess, W. N. et al, pp. 107-121. The Johns Hopkins Press. Baltimore.

Grant, F. S. and West, G. F. (1965). Interpretation Theory in Applied Geophysics. McGraw-Hill. 583 pp. New York.

Green, J. (1963). The Geology of the Lunar Base. Annals of the New York Academy of Sciences, V-105, Article 9, pp. 489-626.

__________ (1965A). Hookes and Spurrs in Selenology. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 373-402.

__________ (1965B). Tidal and Gravity Effects Intensifying Lunar Defluidization and Volcanism. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 403-469.

Greenwood, R. and Lynch, V. (1959). Geology and Gravimetry of the Mustang Hill Laccolith, Uvalde Co., Texas. Geological Society of America Bulletin, V-70, pp. 807-826.

Heiland, C. A. (1940). Geophysical Exploration. New York. Prentice-Hall. 1913 pp.

Hess, H. M. (1955). Serpentines, Orogeny, and Epeirogeny. In Crust of the Earth, Ed. Poldervaart, A. (Geologica Society of America Special Paper 62), pp. 391-407. New York.

__________ (1962). History of Ocean Basins. In Petrologic Studies, Ed. Engel, A., et al, pp. 599-620, pub. Geological Society of America, New York.

Hubbert, M. K. (1948). Line-Integral Method of Computing Gravity. Geophysics, V-13, pp. 215-225.

Innes, M. J. S. (1961). The Use of Gravity Methods to Study the Underground Structure and Impact Energy of Meteorite Craters. Journal of Geophysical Research, V-66, #7, pp. 2225-2239.

__________ (1964). Recent Advances in Meteorite Crater Research at the Dominion Observatory, Ottawa, Canada. Meteoritics, V-2, pp. 219-241.

Innes, M. J. S., Pearson, W. J., and Geuer, J. W. (1964). The Deep Bay Crater. Publications of the Dominion Observatory, Ottawa, V-31, #2, pp. 19-51.

Kane, M. F. and Shoemaker, E. M. (1969). Analysis of Gravitational Anomalies of the Moon (Abstract). American Geophysical Union Fiftieth Annual Meeting, Washington, D. C., p. 125.

Kopal, Z. (1962). Topography of the Moon. In Physics and Astronomy of the Moon, Ed. Kopal, Z. Academic Press, pp. 231-282. New York.

__________ (1966). An Introduction to the Study of the Moon. Reidel Publishing Co. 464 pp. Dordrecht, Holland.

Kuiper, G. P. (1966). The Moon and the Planet Mars. In Advances in Earth Science, Ed. Hurley, P., pp. 21-70. The M.I.T. Press. Cambridge.

Lingenfelter, R. E., Peale, S. J., and Schubert, G. (1968). Lunar Rivers. Science, V-161, pp. 266-269.

Lowman, P. D., Jr. (1963). The Relation of Tektites to Lunar Igneous Activity. Icarus, V-2, pp. 35-48.

__________ (1965). Magnetic Reconnaissance of Sierra Madera, Texas, and Nearby Igneous Intrusions. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 1182-1197.

MacDonald, G. J. F. (1961). Interior of the Moon. Science, V-133, pp. 1045-1050.

MacRae, D. A. (1965). Icy-Conglomerate Moon. Sky and Telescope, V-29, pp. 143-144.

Malahoff, A. (1969). Gravity Anomalies Over Volcanic Regions. In The Earth's Crust and Upper Mantle (Geophysical Monograph 13), Ed. Hart. American Geophysical Union, pp. 364-379.

McCall, G. J. M. (1963). Classification of Calderas: 'Krakatoan' and 'Glencoe' Types. Nature, V-197, pp. 136-138.

__________ (1965). The Caldera Analogy in Selenology. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 843-875.

Moore, P. and Cattermole, P. J. (1967). The Craters of the Moon. Lutterworth Press. 160 p. London.

Muller, P. M. and Sjogren, W. L. (1968). Mascons: Lunar Mass Concentrations. Science, V-161, pp. 680-684.

Murata, K. J. and Richter, D. H. (1961). Magmatic Differentiation in the Uwekahuna Laccolith, Kilauea Caldera, Hawaii. Journal of Petrology, V-2, pp. 424-437.

Nettleton, L. L. (1942). Gravity and Magnetic Calculations. Geophysics, V-7, pp. 293-310.

O'Keefe, J. A. (1968). Isostasy on the Moon. Science, V-162, pp. 1405-1406.

O'Keefe, J. A. and Cameron, W. S. (1962). Evidence From the Moon's Surface Features for the Production of Lunar Granites. Icarus, V-1, pp. 271-285.

Ollier, C. D. and Brown, M. C. (1965). Lava Caves of Victoria. Bulletin Volcanologique, V-28, Series 2, pp. 215-229.

Pike, R. J. (1967). Schroeter's Rule and the Modification of Lunar Crater Impact Morphology. Journal of Geophysical Research, V-72, #8, pp. 2099-2105.

__________ (1968). Meteoritic Origin and Consequent Endogenic Modification of Large Lunar Craters. Doctoral Dissertation, Dept. of Geology, University of Michigan.

Quaide, W. (1965). Rilles, Ridges, and Domes -- Clues to Maria History. Icarus, V-4, pp. 374-389.

Quaide, W., Gault, D. E., and Schmidt, R. A. (1965). Gravitative Effects on Lunar Impact Structures. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 563-572.

Ronca, L. B. (1965). A Geological Model of Mare Humorum. Icarus, V-4, pp. 390-395.

__________ (1966). Meteoritic Impact and Volcanism. Icarus, V-5, pp. 515-520.

Salisbury, J. W. (1961). The Origin of Lunar Domes. Astrophysical Journal, V-134, pp. 126-129.

Shoemaker, E. M. (1962). Interpretation of Lunar Craters. In Physics and Astronomy of the Moon, Ed. Kopal, Z. Academic Press, pp. 231-282. New York.

__________ (1963). Impact Mechanics at Meteor Crater, Arizona. In The Solar System, Ed. Middlehurst and Kuiper, V-4, pp. 301-336. U. of Chicago Press. Chicago.

__________ (1966). Preliminary Analysis of the Fine Structure of the Lunar Surface in Mare Cognitum. In The Nature of the Lunar Surface, Ed. Hess, W. et al. The Johns Hopkins Press, pp. 23-77. Baltimore.

Short, N. M. (1966). Shock Processes in Geology. Journal of Geological Education, V-14, #4, pp. 149-166.

Stipe, J. G. (1968). Iron Meteorites as Mascons. Science, V-162, pp. 1402-1403.

Turkevich, A. L., Patterson, J. H., and Franzgrote, E. J. (1967). Chemical Analysis of the Moon at the Surveyor V Landing Site. Science, V-158, pp. 635-637.

__________ (1968). Chemical Analysis of the Moon at the Surveyor VI Landing Site: Preliminary Results. Science, V-160, pp. 1108-1110.

Urey, H. C., Elsasser, W. M., and Rochester, M. G. (1959). Note on the Internal Structure of the Moon. Astrophysical Journal, V-129, pp. 842-848.

Walter, L. S. (1965). Lunar Differentiation Processes. Annals of the New York Academy of Sciences, V-123, Article 2, pp. 470-480.

Watts, R. N., Jr. (1970). Findings From a Sample of Lunar Material. Sky and Telescope, V-39, pp. 144-147.

Williams, H. (1941). Calderas and Their Origin. Publications of the Geological Society of the University of California, V-25, #6, pp. 239-346.

Wise, D. U. and Yates, M. T. (1969). Mascons As Structural Relief on a Lunar Moho. (Abstract) American Geophysical Union Fiftieth Annual Meeting, Washington, D. C., p. 125.

Yokoyama, I. (1961). Gravity Survey on the Aira Caldera, Kyusyu, Japan. Nature, V-191, pp. 966-967.

__________ (1963). Structure of Caldera and Gravity Anomaly. Bulletin Volcanologique, V-26, pp. 67-72.

__________ (1966). Crustal Structures That Produce Eruptions of Welded Tuff and Formation of Calderas. Bulletin Volcanologique, V-29, Series 2, pp. 51-60.