Central Peaks in Lunar Craters

by

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Presented in Partial Fulfillment of

Requirements for the Degree of

Master of Science

The University of Arizona

April 1972

Accepted

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Introduction:

In 1609 Galileo directed his first crude telescope toward the surface of the moon and found it to be pockmarked with craters. Today a good pair of binoculars will afford the observer a much better view of our satellite than Galileo could have ever hoped for, but the amount of insight gained as to the nature of the craters will be little increased from that of an observer of the seventeenth century. In the past one hundred years large telescopes have brought the lunar surface close enough to allow mapping of many of the large-scale features, but distance and the blurring effect of the earth's atmosphere limited the amount of sound geologic information available. In the early 1960's the five Lunar Orbiter missions provided astrogeologists with thousands of photographs of the surface of the moon at resolutions far better than anything available from the ground. Since 1969 the Apollo missions have again increased our potential for understanding the moon with high-resolution photography from lunar orbit and "ground-truth" from several locations.

With all of this new data, it must be conceded that certain aspects of the lunar craters are still debated, particularly the nature of the central peaks rising from the floors of many craters. Small telescopes will show many of these features, and the increased resolving power of some of the largest instruments can begin to show morphologic features on some of the more massive peaks. No detailed observations of central peaks were possible, however, prior to the

time of the Orbiter missions. It is somewhat surprising, therefore, that the literature contains no analysis of the central peak problem subsequent to the availability of the Orbiter photography. The present investigation utilizes the Orbiter material, as well as other data returned during the past decade of lunar research, in an attempt to answer the question of the nature of the lunar central peaks.

Possible explanations:

Over the years many explanations of the origin of central peaks have appeared in the literature of geology and astronomy. Growing realization of the complexity of the geology of the moon argues against advocating any one process to the exclusion of all others. The moon seems quite capable of having supported a great variety of events and processes during its long history. Based generally on terrestrial analogues, the processes called upon to account for central peak formation fall into three broad categories: Impact processes, volcanic processes, and others.

Astrogeologists are in general agreement that the majority of lunar craters were formed by hypervelocity impacts of bodies from space. Terrestrial impact craters and manmade explosion craters often exhibit central uplifts, and several explanations have been advanced. In the formation of craters, especially large ones, a great amount of material is rapidly removed, and the crater floor might be expected to rise in response to this sudden loss of overburden. This is known as isostatic compensation (Baldwin,

1971, Pike, 1967). On the other hand, in a hypervelocity impact event a tremendous compressional wave is produced. When this wave interacts with a free surface, such as the ground surface or the surface of the impacting body, a rarefaction wave is generated which travels in the opposite direction. It is this rarefaction wave which excavates the crater and this wave has also been credited with forming the central uplift (Milton, et. al., 1972). It has been suggested that the compressional wave could be reflected off a layer at depth, such as the earth's Mohorovičić Discontinuity, and return to the crater with sufficient energy to push up the floor of the crater into a central peak (Dence, 1964). A mechanism has also been proposed whereby material in the walls of the crater moves downward and toward the center along paraboloid slip surfaces, resulting in an uplift at the center (Dence, 1968).

Another school of thought has long held that central peaks, especially those observed to have small pits in their summits, are actually volcanic. Many early observers, such as the Earl of Rosse (Lovell, 1970), believed that the entire crater was volcanic in nature, with the central peak either forming the crater walls or arising later, in the manner of Wizard Island at Crater Lake. Others have shown that, while the crater-forming process may be impact, the central peak could theoretically be a subsequent volcanic manifestation, resulting either from impact-melting of the target material or eruption of molten material from below, triggered by the impact (Carr, 1964). Terrestrial cases of impact-induced melting apparently do occur, as studies of some of the ancient impact craters on the

Canadian Shield indicate (Beals and Halliday, 1965).

Two other explanations for central peaks have been suggested, which may reasonably be discarded as being inapplicable, at least to the moon. It has been mentioned (Cordell, et. al., 1971) that central peaks may be pingos; small hills formed when ground water freezes and pushes up the overlying rocks and soil. The evidence from the lunar samples to date shows that there is essentially no free water on the lunar surface or in the rocks, and that the rocks crystallized from an anhydrous magma (Mason and Melson, 1970). The Apollo 14 Active Seismic Experiment (the thumper) indicated that no recognizable amounts of water, either liquid water or ice, exist beneath the Fra Mauro landing site. (Kovak, 1972). Lunar scientists are in general agreement that this result may be extended to the rest of the lunar surface, since any near-surface water would have been lost long ago to the vacuum of space. It should be noted, however, that the Apollo 17 astronauts will conduct experiments capable of detecting underground ice or water if it does occur on the moon. ("Aviation Week", 1972). The other suggestion is that central peaks may be the remains of the impacting bodies themselves, assumed to be iron meteorites. (Öpik, 1971). Our present understanding of the dynamics of impact events (Shoemaker, 1963) suggests that the impacting body should be pulverized and in large part melted or vaporized by the explosion. This must have been the case for terrestrial craters, such as Meteor Crater and the Odessa Craters, known to have been formed by iron meteorites. The Apollo samples have contained only microscopic particles of meteoritic

iron in the soil (Mason and Melson, 1970). Furthermore, the high-resolution Orbiter and Apollo photographs of several large central peaks show that they resemble terrestrial mountain masses much more than the broken fragments of large iron meteorites (see Addendum).

Description of Present Study:

This investigation is a statistical and morphologic study of the central peaks in craters on the lunar front side, using orbital and earth-based photography. The area covered is a section of the lunar surface within 45 degrees of the center of the front face. This comprises about 15% of the lunar surface, or approximately $5.6 \times 10^6 \text{ km}^2$. This area was chosen for study because of the availability of supporting data and because, near the lunar limb, distortion renders earth-based photographs of little value.

The high-resolution photographs taken by Lunar Orbiter IV were examined, and for each crater with a detectable central peak the following information was recorded:

- (A) Photograph number.
- (B) Crater designation: in accord with the Lunar and Planetary Laboratory designation from "The System of Lunar Craters" (Arthur, et. al., 1963, 1964, 1965, 1966).
- (C) Shadow length: where detectable peak shadow fell on crater floor - units of 1/20 inch, $\pm$ 1/100 inch accuracy.
- (D) Peak area: tracing of peak area measured with a compensating polar planimeter - units of cm^2 , $\pm$ 0.2 cm^2 accuracy.
- (E) Trend: direction of elongation of peak or line of peaks -

units of degrees, measured clockwise from long axis of photograph and later converted to true azimuth (IAU convention, north up, east to the right when the moon is viewed with the naked eye).

(F) Location of peak: direction of center of area of most massive feature, from center of crater - units of degrees.

(G) Displacement of peak: location of center of area of most massive feature in per cent of crater rim radius, from center of crater - increments of 10%.

(H) Albedo of crater rim, peak and floor: estimated from large-scale full moon photographs in the "Consolidated Lunar Atlas" (Kuiper, et. al., 1967). Ten point albedo scale, calibrated for each photograph; 10 = brightest feature on photograph, 5 = average brightness of the highlands, 1 = darkest feature on the photograph - $\pm$ one albedo unit accuracy (estimated).

(I) Peak morphology: three digits giving information concerning small, medium and massive central peaks -

none
single
multiple
ridge,
arc
combinations of the above

One digit describing dominant morphologic feature of the peak -

none
summit pit
massive central uplift
flows associated with summit pit
lava lakes on crater floor associated with peak
slump from walls associated with peak
crater associated with a rille
peak parallel to nearby linear feature
peak parallel to peak in a nearby crater of similar apparent age
textured crater floor

One digit giving crater location -

mare
 highlands
 pre-mare crater later flooded by mare (mare embayment)
 crater associated with mare wrinkle ridge
 uncertain cases

This data was transferred to punched cards and statistical evaluations were carried out using the IBM 83 Card Sorter and the CDC 6400 Computer of the University of Arizona Computer Center. Measurements of peak height and area were converted to kilometers and km^2 , respectively, and trend and location measurements were converted to true degrees using a computer program devised by the author employing photograph parameters supplied by the Boeing Company, builder of the Lunar Orbiter spacecraft (NASA, 1968). This program involved the simplifying assumption that the spacecraft was directly over the crater when the photograph was taken. The major error introduced by this assumption was in the computation of peak heights, where a probable error on the order of 0.1 km was introduced. This error is small because Orbiter IV high-resolution photographs cover a narrow band on the lunar surface from almost directly overhead. Combined with the error involved in the initial measurement of peak heights, the accuracy of the final result is estimated to be around ± 0.2 km, as compared with accuracies in crater depth on the order of ± 0.03 km for the revised "System of Lunar Craters" (computer mathematics supplied by D.W.G. Arthur, in press). Since the only use made in this investigation of peak height involved graphical analysis and calculation of average slopes these errors are not considered critical.

In addition to data collected by the author, additional data

from the revised "System of Lunar Craters" (in preparation; see Wood (1972)) were graciously made available to the author by the staff of the Lunar and Planetary Laboratory. These data included crater depth, diameter, floor diameter/rim diameter ratio, relative crater age and information on crater morphology. All of the above data were derived from the same set of Orbiter IV photographs used by the author.

Data for the present statistical studies were taken only from the high-resolution Orbiter IV photographs in order to avoid any selection effects on data quality introduced by using higher-resolution photographs of specific craters. In some cases this may have had the undesirable effect of degrading the available information about a specific feature, due to shadow positions or photographic defects. However, the author feels that the overall trends of the statistics should not be changed by this effect.

Morphologic studies of individual craters of interest were pursued using photographs from all five Lunar Orbiter missions, plus Apollo and earth-based photographs.

Previous statistical studies:

The most recent analysis of the statistics of lunar central peaks is that of Wood (1968). His data were derived from "The System of Lunar Craters" and therefore were based on photographs taken from earth, but the findings still appear to be valid. Wood's major results are summarized in his abstract: "Only about 3% of all catalogued craters (diameter greater than 3.5 km) have peaks; this value is much smaller than has been previously reported (due to

selection effects of previous authors). However, the percentage of craters with observed central peaks increases markedly with size and approaches 100% for undamaged craters of diameter 70 km and larger. Young (undamaged) craters have peaks more frequently than older craters." His data also suggested to Wood that "peak age is highly correlated with crater age."

Present results:

Statistical Analysis

Analysis of the trends of the central peaks indicates that, of 580 central-peaked craters, the peaks of 381, or 66%, showed no trend. For the remaining 199 the orientations of the trends are not random, but exhibit distinct preferred directions, as shown in Figure 1. Figures 2 and 3 show the orientations of peaks in the mare and highland regions respectively. The mare sample is small, so the overall statistics are controlled by the highland orientations. The mare surface is considerably younger than that of the highlands, and the single preferred direction, toward the northwest, may be indicative of a different class of impacting bodies in later lunar history, or perhaps a planet-wide stress field that changed with time.

The relation of central peak trends to this proposed stress field may be seen by comparing these figures with Figures 1 and 2 of Strom (1964). In Strom's analysis of lunar lineaments he concluded that the preferred orientations of lineaments reflect some sort of strain on the body of the moon, and concluded further that for "the majority of central peaks exhibiting linear structures ... their configuration has been influenced by the regional fracture

Figure 1.

Figure 2.

Figure 3.

TRENDS-HIGHLANDS (True Azimuths)

patterns." Figure 1 of this paper exhibits the trends to the north, northeast and northwest found by Strom. Differences between this figure and those of Strom are partially due to the fact that the latter were taken from limited areas of the lunar surface, and partly to the fact that in the present investigation all directions are true azimuths, while Strom's figures showed apparent azimuth as viewed in orthographic projection.

The results of the study of peak displacements is shown in Figure 4. Of the 580 craters 285, or 49%, had their peaks located at or distributed symmetrically about the center of the crater. The other 51% showed peak displacement from the center of the crater in a specific direction. The statistics of these directions will be dealt with in the next section.

As Figure 4 shows, for the symmetrically-located central peaks the strong tendency is for the center of area of the peak to be at or near the center of the crater - an actual "central" peak. However, for the asymmetrically-located peaks the majority of craters have peaks located between 20% and 40% of the rim radius from the center. This result is in contrast with most terrestrial impact and explosion craters, where the uplift is usually centered at or near the geometrical center of the crater. Possible explanations will be discussed below.

For the 295 craters with asymmetrically-located central peaks the azimuths of the peaks were tabulated and are presented graphically in Figure 5. It can be observed that the distribution of azimuths is not random, but shows a decided east-west tendency. Comparison with Figure 1 and Strom's (1964) Figures 1 and 2 shows that this

Figure 4.

ALL PEAKS

Figure 5.

LOCATION - ALL PEAKS (True Azimuths)

pattern of azimuth distribution is quite different from either, and another mechanism besides the crustal fracture pattern is probably controlling peak displacement. Possible explanations will be discussed below.

For the analysis of albedoes the craters with massive central peaks were chosen, based on the fact that it is often difficult to distinguish small peaks from crater floors on full-moon photographs. The number of craters with massive peaks is 145, or 25 % of the total.

No accurate comparison of albedo data for different craters can be made using the full-moon prints from the "Consolidated Lunar Atlas" due to the photographic dodging technique employed to increase print contrast. For this reason only albedo differences were considered.

The craters with massive central peaks were divided into groups according to rim albedo, and the distribution of peak albedoes was investigated for each group. For each crater, rim albedo was subtracted from peak albedo and the results for all groups were combined. These combined results are shown in Figure 6. Overall the peak albedo for the majority of craters is equal to or slightly less than the rim albedo. To the extent that lower albedo can be correlated with increasing age this finding supports the hypothesis that central peaks form concurrently with or soon after their craters. However, the albedo similarities may also be interpreted as the results of later slumping of material from the peak and wall slopes, and therefore be unrelated to either peak or crater age.

Figure 6.

Central peak data from the present investigation were compared with data from the revised "System of Lunar Craters". Complete data were available for the northeast, northwest and southwest quadrants (quadrants A, B and C), for all craters larger than 7 km in diameter and for some smaller. Revised data for the southeast quadrant (quadrant D) were not available, and the information from "The System of Lunar Craters" (including all craters larger than 3.5 km in diameter) had to be used. For quadrants A, B and C the data used included crater depth and diameter, floor/rim (diameter) ratio, relative crater age (1 represents new craters, 5 represents old ruined craters) and crater type information. For quadrant D the available information included only crater diameter and relative age.

For statistical studies involving heights and areas of central peaks the set of 145 massive peaks was used, since the small amount of information on sizes of medium and small peaks was approaching the limits of accuracy. The area of each massive peak was plotted against its crater's depth/diameter ratio for the 28 craters for which this information was available. No correlation was evident. Similarly, peak height was plotted against the depth/diameter ratio for 20 craters, and again there was no obvious trend. Since both crater age and degree of flooding affect all of these parameters the lack of trends was not unexpected.

Central peak area and height were plotted against crater floor/rim ratio, again with inconclusive results. In this case the samples were larger, with 51 points for the area plot and 31 points for the height plot. It was noted that values of the floor/rim ratio greater

than 0.75 generally correspond to old or flooded craters, but the peak statistics showed no meaningful trend with crater age or condition. The lack of any strong relationship between the floor/rim ratio and peak height or area tends to argue against any mechanism which would require that the size of the central peak should be related in a simple way to the size of the crater or the energy involved in crater production.

Crater depth was plotted against peak height for 20 craters, and again the results were inconclusive. In this case, as discussed above, both crater age and degree of flooding tend to affect both of these parameters, but probably to differing degrees. However, even for fresh, unflooded craters no trend was apparent.

In an attempt to eliminate the effect of flooding a new parameter was introduced. This was the difference between crater depth and peak height, or the elevation difference between the top of the peak and the crater rim. This parameter was plotted against crater diameter, which will also be unaffected by flooding, and a possible negative correlation was observed in the case of young craters. This indicates that, for larger craters, the peak rises closer to the level of the rim. However, it must be noted that at least one peak which fits this trend is of probable volcanic origin. With only twenty points in the sample and a large scatter the meaning of this result is not clear.

The only really definite correlation between peak and crater parameters is between log peak area and log crater diameter. This is shown in Figure 7, for 123 data points. The meaning of this correlation is somewhat questionable, however. Figure 8 shows the

Figure 7.

Figure 8.

same parameters plotted for 36 of these peaks which show summit pits, flows or other features thought to indicate volcanism. The general trend seems to be the same as that for the larger sample.

Figures 9 and 10 show the relationship between log crater diameter and log crater depth for young (age 1 and 2) craters. Figure 9 contains data for 25 craters with massive central peaks, while Figure 10 shows data for all craters with central peaks of any size for which these data were available. Note that this included only quadrants A, B and C. On each figure the straight line is the depth/diameter relationship found by Baldwin (1963) and the curved line is the author's interpretation of this relationship using data from the revised "System of Lunar Craters". In almost all cases the discrepancy between the two relationships is due to the increased depth calculated for craters measured from the Orbiter photographs. The Lunar and Planetary Laboratory curve is probably the more accurate, based on the quality of images from Orbiter photography versus even the best earth-based material, but only absolute depth measurements, such as those provided by the Apollo laser altimeter experiments, will finally resolve the discrepancy. Assuming the accuracy of the LPL data (from which both the general curve and the central peak data were derived), it should be noted that the points for craters with central peaks lie near the curve for all craters, but generally on the side indicative of lesser depth for a given diameter than the mean. If this effect is real it would indicate a tendency for the crater floor to rise in cases where central peaks are produced, though whether this could be explained by some rebound mechanism or by

Figure 9.

Figure 10.

volcanic tumescence remains to be seen.

Morphologic Analysis

In general the 145 "massive" central peaks identified in this study are so identified because they exhibit definite morphologic characteristics at the scale of the Orbiter IV photographs (80 - 90 meters). The medium and small peaks are almost always seen merely as featureless hills (see Addendum, however). The one-digit classification of the dominant morphologic characteristic of each peak has been discussed above. This scheme may appear to contain a bias in favor of a volcanic hypothesis of peak formation, but this is only because volcanic features may be observed at the resolution of the Orbiter IV photographs. Features characteristic of a rebound origin have never been defined in the literature, and the present study yielded no clear-cut examples of characteristics obviously indicative of rebound.

Morphologies of massive central peaks were first investigated by dividing the sample into mare craters (17) and highland craters (113), the remaining 15 craters being pre-mare, associated with a mare wrinkle ridge, or undefinable. For both mare and highland craters all parameters measured were tabulated and compared. The only notable differences concerned medium-sized peaks, albedo and peak location. Of the mare craters 65% have medium-sized peaks, while only 42% of the highland craters do. Occurrence of small and massive peaks was similar for both surfaces. No explanation is immediately obvious, but the small size of the mare sample makes great emphasis on this result unwise. The rims, peaks and floors

of mare craters tend to be brighter than those of highland craters. This may be explained by the relative youth of the mare surfaces compared to the highlands. Comparison of albedo with relative age indicates that most craters darken as they become older. Mare craters are also noteworthy in that they have asymmetrically-located peaks only 18% of the time, while they occur in 58% of all highland craters. If this effect is real it would seem to call for some difference in the mode of formation of central peaks on these two surfaces.

Many authors have pointed to the summit pits on some central peaks as evidence of volcanic origin for these peaks (Moore, 1953). Of the 145 massive central peaks 34, or 23%, showed summit pits. In addition 1% exhibited flows on the floor of the crater associated with the central peak and 2% showed flows on the peak originating from the summit pit. Thus, at Orbiter IV resolution, 26% of the massive central peaks showed features mentioned in the literature as being indicative of volcanism.

The analysis of peak trends presented above indicates that central peaks may be useful indicators of the local fracture pattern in the vicinity of the crater. In addition, of the massive central peaks 3% were distinctly parallel to linear features in the immediate vicinity of the crater. In three other cases craters were observed wherein the central peak was parallel to the peak of a nearby crater of similar apparent age. This could be indicative of multiple cratering events in which the trends of the peaks were influenced by the fracture system formed between the two craters.

In 6% of the cases of massive central peaks the morphology

and albedo observations indicate that the peak may have been formed as the result of slumping of material from the crater walls (see Cannon (1970) for a discussion of slumping mechanisms). Other examples of dominant peak morphology noted in this study occurred in less than 1% of the cases, and are not considered here.

In an effort to further test the feasibility of a volcanic hypothesis those peaks observed to have volcanic characteristics were studied as a group. The first question was whether or not the summit pits could reasonably be expected to have been formed simply by random impact on the summits of pre-existing peaks. Baldwin, in a pre-Orbiter analysis of this problem (Baldwin, 1949), estimated that the average density of impact craters of a size to form a summit pit visible from earth is about one crater per 86 km^2 . In a more accurate analysis of highland crater density Hartmann and Yale (1968) indicated that one 2 km crater per 100 km^2 and one 1 km crater per 13 km^2 represents a maximum applicable density. The total area of massive central peaks measured in this survey is 2766 km^2 . The fact that a summit pit as defined here must be found at or very near to the actual summit of the central peak serves to reduce this available area by at least a factor of ten. Thus, even for the maximum density of Hartmann and Yale, only 21 summit pits of a diameter of 1 km should be expected, based on this rough analysis. The fact that 37 summit pits were observed and more may have been masked by shadows and photograph defects indicates that volcanic process may indeed be responsible for producing these features in many cases.

For craters with single massive peaks the mean slope angle

of the peaks was computed. Only peaks with areas over 15 km^2 were considered, since below that size the measurements began to approach the size of the probable errors. For 12 peaks with indications of volcanism the mean slope angle is 15° . For 23 peaks with no volcanic indications the mean slope is 13.5° . In no case does the slope of a peak exceed 28° . In studies of the effects of the lunar vacuum and gravity on the characteristics of small particles Halajian (1964) found that the expected lunar angle of repose should be somewhat steeper than the approximately 35° angle found on earth. This indicates, at least, that the central peaks are not composed of small fragmental material. The extremely low viscosity of the mare basalts (Murose and McBirney, 1970) suggests that, if lunar volcanoes are built up from flows, their slopes could be quite shallow.

Several central peaks which show definite signs of volcanic origin are discussed in the Addendum. The best available photographic evidence points to volcanic activity on some central peaks, and nothing in this investigation precludes that possibility.

Discussion:

The various theories of the origin of central peaks can now be examined in terms of the data of the present investigation and other recent findings. The volcanic hypothesis will be considered first.

Today the moon is considered to be essentially a dead world. The three passive seismic experiments set up by the Apollo astronauts reveal a level of seismic activity about one millionth that of the

earth (Hammond, 1972). Small tremors have been recorded periodically, however, from depths to 800 km, or nearly 40% of the distance to the moon's center (Page, 1972b). These results indicate that the moon has a strong, solid outer layer, not presently undergoing significant internal activity such as that associated with terrestrial volcanism. The youngest solidification age so far reported for the lunar rocks is 3.1 billion years. Based on this evidence the moon is thought to be essentially dead, and recent volcanic activity on a large scale may be ruled out (Hammond, 1972).

There is ample evidence, however, that volcanism has played a major role in early lunar history. The mare are almost certainly composed of basalt flows. Sinuous rilles, such as Hadley, are probably the results of processes connected with volcanism (Page, 1972a). Orbiter and Apollo photography yields numerous examples of features which would unquestionably be called volcanic if observed on earth (see Addendum, also Hartmann and Harris, 1968).

The generally-accepted relationship between crater depth and diameter, for almost all lunar craters as well as terrestrial impact and explosion craters, is a fairly strong argument against a volcanic origin for any large number of the lunar craters. Terrestrial volcanoes exhibit a great variety of shapes and sizes, with crater depth and diameter depending more on immediate eruption history than on initial formation conditions. The plot of depth versus diameter for craters with central peaks shows a similar trend to that for all lunar craters, casting doubt on any theory which would call for all craters with central peaks to be of volcanic origin. An origin due to explosive volcanism, however, is certainly

not ruled out for certain craters, and the search for photographic parameters which can be used to distinguish between volcanic and impact craters continues.

Earlier in the discussion results were quoted which indicate little or no correlation between massive central peak dimensions and dimensions of the associated craters. The only clear correlation found was between peak area and crater diameter, but this probably cannot be used to support either general hypothesis of peak formation to the exclusion of the other. In the case of impact-induced volcanism, for example, the event that produced the larger crater could be assumed to have had a greater effect in triggering the volcanic activity, and thus lead to the production of a larger peak. Arguments could similarly be advanced relating crater energies, diameters and peak sizes.

The general conformity of the orientations of central peaks to the lunar grid, thought to be associated with a planet-wide system of fractures and zones of weakness, could be used as persuasive evidence that central peaks are similar to fissure eruptions, such as those displayed in Arizona's San Francisco Peaks. On the other hand, theoretical and observational work on perturbations of symmetric rebound structures by local fracture systems remains to be done.

The seeming preference of asymmetrically-located peaks for displacements in easterly or westerly directions probably cannot be accounted for in terms of pre-existing fractures. One alternative suggestion is that peak displacement is indicative of the direction from which the impacting body struck the lunar surface. Baldwin (1963) suggested that, for objects traveling near the plane of the

ecliptic, the horizontal velocity component with respect to the lunar surface would be generally east-west. Orbital theory and observations of meteor trails lead to questions about this assumption. However, the nature and orbital characteristics of the bodies which formed the lunar craters are still highly speculative. Elston's (1970) analysis of the lunar grid notes an east-west trend in the alignment of intersecting craters which is absent from the trends of other features. Elston suggests a planet-wide east-west tension, but the ecliptic-motion hypothesis might also account for the observations. Chapman and Fielder (1964) examined earth-based photographs and found peak displacements favoring the northeast-southwest directions. They concluded that peak formation could not be related to impact, and advocated a volcanic origin for most peaks. The Chapman and Fielder investigation employed 81 craters, with azimuths plotted in $22\frac{1}{2}^{\circ}$ increments. The present investigation used 295 craters, with 10° increments. As Figure 5 shows, some preference for northeast-southwest displacements may exist, along with a strong east-west preference as predicted by the direction-of-impact hypothesis. This problem demands a great deal more theoretical work.

The comparative albedoes of the crater rims and peaks may be noteworthy. Figure 6 indicates that, for most craters with massive central peaks the crater rims are as bright as, or slightly brighter than, the peaks. This is probably indicative of similarities of material and slope. For the two craters, Plinius and Lansberg, with apparently volcanic peaks, however, the peaks are two albedo units brighter than their respective crater rims. This may be indicative of volcanic activity occurring long after the crater was formed,

or it may be characteristic of the albedo of the material from which the peak was built. In either case it must be noted that the albedoes for these two craters are highly anomalous.

The low average slope of the massive central peaks (13° - 15°) may be an indication of the nature of the material making up the peaks or of the range of slopes stable under lunar erosive forces, or a combination of the two. The slope angles for Plinius and Lansberg are 7° (minimum) and 15° , respectively.

The coincidence was noted between average slopes for peaks with and without summit pits. Coincidences between these two groups show up in most of the other comparisons of the data also. Indicative of this similarity are Figures 7 and 8, which show that peaks with summit pits cannot be distinguished from those without pits on plots of peak area versus crater diameter. The same holds true for the other relationships studied. Whether this is due to inadequate data, coincidence, or a single origin for most peaks awaits further study.

If volcanic activity is to be accepted as a possible cause of lunar central peaks some interaction between impact and volcanism must be demonstrated. Several such mechanisms have been discussed in the literature. If the material at a depth of several kilometers was once near the melting point of its temperature-pressure curve an increase in temperature or a decrease in pressure could bring it to the point of fusion, and this could lead to volcanic activity. The pressure drop might be caused by mechanical unloading as the cratering event excavated several kilometers of overburden. However, the magnitude of this effect is thought to be small in comparison with others (Carr, 1964). Another possibility is that the breccia

zone known to form beneath impact craters could extend down to the region of incipient melting, lowering the pressure (Ronca, 1966). A heat source is provided by the zone of impact-melted material immediately below the crater floor (Beals and Halliday, 1965). Finally, the breccia zone will act as a thermal insulator, and in an area of high temperature gradient this might have the effect of raising the temperature at depth above the melting point (Carr, 1964). The high heat flow measured at the Apollo 15 landing site (Hammond, 1972) may indicate the existence of such local hot spots where conditions would be favorable to the production of impact-induced volcanism. The rather attractive notion of a pre-existing layer of molten material at a depth of a few kilometers is probably incorrect, however. The high relief, several kilometers in many cases, maintained by many craters with central peaks over long periods of lunar history (Copernicus is around one billion years old (Page, 1972a)) would have been lost if a molten layer had existed near the surface through much of their history. Also, the seismic experiments on the lunar surface indicate layer boundaries only at depths of 25 and 65 km (Hammond, 1972), which is thought to be too deep to be influenced by any but the largest cratering events (Ronca, 1966).

As discussed above, four mechanisms for the formation of central peaks have been advanced which are related to impact. The first is isostatic compensation (Baldwin, 1971). The prediction is that, with time, the crater floor will rise and the rim will sink until the entire structure approaches the original ground level (Danes, 1970 and Pike, 1967). The effect is well-

demonstrated in model studies using materials such as asphalt (Scott, 1967). Moreover, with increasing crater age the depth/diameter ratio does show a marked decrease, at least to the point that class 4 and 5 crater rims become so degraded that shadow measurements of depth are impossible. Lunar erosion processes, however, also act to decrease total crater relief, so the effect cannot be entirely attributed to isostasy. Whether isostatic rebound is responsible for central peaks is also open to question. Small craters (under 10 km in diameter) sometimes show floors which appear to arch up, but the central peaks for large craters are almost always small in relation to the floor area and rise abruptly from generally smooth floors. The model studies also predict a degree of circular symmetry not reflected in the lunar peak data. Finally, gravity data from tracking of the low (14 km) orbits of the Apollo 14 Lunar Module indicates that the observed negative gravity anomalies over several large craters can be completely explained by visible mass defect, without resorting to any isostatic rebound (results based on crater depths from ACIC charts, which often give incorrect depth values) (Sjogren, et. al., 1972).

The theory of shock waves being reflected from layer boundaries at depth and returning to the crater with sufficient energy to produce a central peak (Dence, 1964) must be viewed with skepticism both for the earth and the moon. The only possible reflecting layers would be the earth's Mohorovičić Discontinuity, at a depth of 40 km under the continents, and the lunar 25 km layer discussed above. Both of these layers seem far too deep, given the fact that shock wave energies decay as the fourth power of

distance (Chabai and Hankins, 1960). Moreover, for a spherical shock front, only a tiny fraction of the reflected energy will return to the crater; the rest will reach the surface outside the crater rim. Finally, studies of the underlying geology of central uplifts in terrestrial craters such as Sierra Madera (Howard and Offield, 1968) and Gosses Bluff (Milton, et. al., 1972) show that only the uppermost layers of strata were deformed to produce the peak, while underlying strata maintained their original positions. Apparently the formation of a central peak by rebound is a near-surface phenomenon.

The theory that some central peaks are formed by the slumping of wall material and slippage of material along surfaces dipping toward the center of the crater has several advocates (Dence, 1968). The present investigation noted a few craters wherein the material of the central peak seemed to be at least partially derived from the walls. Most large peaks, however, stand alone without any visible communication with the crater walls. There is seldom any surface indication of movement of material below the crater floor toward the center. This mechanism also seems to imply a degree of circular symmetry at least on the order of that of the crater. This is not the case for the central peaks in lunar craters, as the statistics on peak location demonstrate.

The final mechanism, involving a rarefaction wave creating a central uplift at the instant of crater formation, seems to have more to recommend it (Milton, et. al., 1972; Mutch, 1970; Beals, et. al., 1963; Shoemaker, 1963). In nuclear and chemical explosion

craters where central uplifts are produced these are produced at the instant of explosion. It was noted that surface explosions are much more effective in producing peaks than underground blasts (Mutch, 1970). On the moon the determination of the equivalent "explosion" depth for an impact is almost impossible at the present time. For terrestrial craters the orientation of shatter cones can be used to give such an indication (Beals and Halliday, 1967 and Dietz, 1963), and the fact that the Apollo 16 astronauts found a shatter cone in a lunar crater suggests that someday this technique may be used on the moon. As mentioned above, the upper strata beneath a crater are moved inward and upward to produce the central uplift, indicating that the energy for peak formation comes from above, not below, the crater floor. This sort of mechanism, wherein the formation of the central uplift is directly and immediately connected with the cratering event, is compatible with indications that the peak and crater are essentially the same age, and may be related, through the direction of impact, to peak offset.

Objections to this mechanism may be found in a comparison of lunar and terrestrial central uplifts. Although statistics on size and location of uplifts in terrestrial craters do not appear in the literature, analysis of maps of individual craters gives the general impression that these features are almost always well-centered and generally larger with respect to the crater dimensions than their lunar counterparts (Dence, et. al., 1968; Roddy, 1968; Dence, 1964). The size difference may be accounted for by the extensive vertical erosion all of these terrestrial craters have suffered; often only

strata from far below the original cratered surface remains. The orientation problem persists without solution, however. About one lunar crater in three has an asymmetrically-located peak, and of these the majority of peaks are located 20% - 40% of the rim radius from the crater center. The direction-of-impact hypothesis should also apply to terrestrial craters, but this does not seem to be the case in the admittedly small number of craters extensively studied and mapped. Finally, the question of distribution of peak orientations remains. Only one third of the massive central peaks are reasonably circular in plan view. The rest show asymmetries of form and obvious elongation. As discussed above, rebound theory may be able to explain this in terms of impact onto a surface with a pre-existing fracture pattern, but the theoretical work which would prove it remains to be done.

The final important question to be answered by any theory which relates peak formation to impact is: why do some craters have peaks and others not? Wood (1968) indicated that most craters over 70 km in diameter have peaks, but some of the older large craters do not. Moreover, some younger craters of medium size have no peaks, as in the case of a large group of craters in the 40 km range in the southern highlands. There does not seem to be a definite minimum energy, as judged from crater diameter, above which central peak formation invariably sets in, and the indications are that somewhat different mechanisms may be operating at different diameters. The problem of why large basins have no central peaks was noted by Hartmann and Wood (1971), who observed that, in the largest craters and the smaller multi-ringed basins a transition takes place from

central peaks to peak rings for basin (crater) diameters in the range 140 - 175 km. Many problems persist, however, regarding the presence of central peaks in some craters and the absence of peaks in nearby craters of similar age and size.

Conclusion:

The two theories of central peak formation found to be most likely are impact-induced volcanism and rebound involving immediate production of the central peak during the cratering event. For craters without obvious volcanic manifestations the statistics of this study show no means of distinguishing between these two mechanisms. Photographic evidence for the probable volcanic nature of several peaks is presented in the Addendum.

Addendum: Evidence for volcanic central peaks

Several lunar central peaks exhibit direct or indirect evidence of volcanic origin. Among those showing indirect indications is the peak of the farside crater Tsiolkovsky, shown in Plate 1 as seen by the Apollo 15 crew. While no summit pit or flows are apparent, lines of dark material may be seen in the vicinity of the crest of the highest peak which may be indicative of the final stages of eruption. The floor of the crater is flooded with lava, and the peak complex rises abruptly from the flat floor, with no connection to the crater walls. There is no evidence of isostatic uplift of the floor since it was flooded.

Plate 2 shows the crater Copernicus, thought to be nearly one billion years old on the basis of samples of ray material returned by the Apollo 14 astronauts. This crater contains peaks of all three sizes, massive, medium and small. The floor is covered with a lava flow. Note the small peak indicated by the arrow. Plate 3 is a high-resolution Lunar Orbiter V photograph of this small peak, which reveals it to be a cinder cone, about 1 km in diameter, with blocky ejecta issuing from the vent.

Plate 4 is an Orbiter IV photograph of the 40 km crater Plinius. A flow of bright material can be traced from the summit pit down the right side of the peak. The peak of this crater is considerably brighter than the rim, which is not the case for the great majority of lunar craters.

A similar 40 km crater, Lansberg, is shown in the next three plates. Again a large flow can be traced from the summit pit to the crater floor, where it arcs in an anti-clockwise direction.

Plate 7 shows the peak and flow from the side, as seen by the Apollo 14 astronauts. The peak resembles a breached volcanic cone or possibly an elongated cone which arose along a fissure. This peak is also considerably brighter than the crater rim.

Plates 8 and 9 show the farside crater Icarus, the only relatively fresh crater known whose peak is as high or higher than the crater rim. A peak this high cannot be formed by isostatic rebound, where the center of the crater will only rise to the approximate level of the pre-impact surface, nor could it be formed by gravity sliding of material from the walls. Several craters of similar size and apparent age to Icarus are visible on Plate 8, but none has so massive a peak, indicating that not all of these peaks were formed by impact. There is some evidence for a small summit pit and flows on the floor of Icarus, but the available photography is not adequate to allow unambiguous identification of volcanic features. At the request of R.G. Strom this crater was photographed on the Apollo 16 mission, and the Command Module pilot reported that the peak definitely rises above the crater rim.

Apollo 15

AS15 91 12383

Central Peak of Tsiolkovsky

Lunar Orbiter IV 121-H2

Copernicus

Lunar Orbiter V 154-H1

Cinder cone on floor of Copernicus

Lunar Orbiter IV 85-H2

Plinius

Lunar Orbiter IV 125-H3

Lansberg

Apollo 14

AS14 70 9825

Lansberg

Apollo 14 AS14 70 9835

Lansberg

Lunar Orbiter II 33-M

Icarus

Apollo 11

AS11 44 6606

Icarus

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