N73-30804

NASA TM X- 62,302

NASA TECHNICAL MEMORANDUM

NASA TM X-62,302

CASE FILE COPY

EMPLACEMENT OF THE CAYLEY FORMATION

Verne R. Oberbeck, Friedrich Hörz, Robert H. Morrison and William L. Quaide

Ames Research Center
Moffett Field, CA 94035
and
Lyndon B. Johnson Space Center
Houston, TX 77058

September 1973

EMPLACEMENT OF THE CAYLEY FORMATION

Verne R. Oberbeck[1]

Friedrich Hörz[2]

Robert H. Morrison[1]

William L. Quaide[1]

[1]Space Science Division
Ames Research Center, NASA, Moffett Field CA 94035

and

[2]Planetary and Earth Sciences Division
Lyndon B. Johnson Space Center, NASA, Houston TX 77058

Abstract

Analysis of the effects of ejection of materials from large lunar craters, photogeologic evidence, remote measurements of surface chemistry and petrology of lunar samples are synthesized and result in a new hypothesis for emplacement of the Cayley Formation. Previous theories for emplacement of the Cayley are volcanic ash emplacement and emplacement as ejecta from multiringed basins.

Calculations presented in this paper show that materials ejected beyond the continuous deposits of large lunar craters produce secondary impact craters that excavate and deposit masses of local material equal to multiples of the crater ejecta deposited at the same place. It is shown that the main influence of a large cratering event on terrain at distances greater than 50 km from large lunar craters is one of cratering and deposition of local material by secondary craters rather than deposition of ejecta from the large crater.

Large numbers of secondary craters have been observed in and around the Cayley Formation and many examples of these are presented in this paper. Evidence of significant lateral transport of highland debris by ejection of material from secondary craters and by landslides triggered by secondary impact is presented. Other proposed mechanisms for emplacement of the Cayley Formation are discussed and implications regarding the origin of material in the continuous aprons surrounding large lunar craters is considered.

1. Introduction

Interpretation of the nature and origin of the Cayley Formation at the Apollo 16 landing site is critical to understanding the geologic history of the Moon. It and other smooth plain materials are widespread and common in local depressions of most of the lunar highlands. Cayley plains were originally included in the Fra Mauro Formation by Eggleton and Marshall (1962) because the hummocky Fra Mauro Formation, exposed continuously southward from the Carpathian Mountains, becomes gradually smoother and seems to grade into what is now known as the Cayley Formation. Wilhelms (1965) removed the smooth flat part without hummocks from the Fra Mauro Formation and named it the Cayley Formation. Moreover, he noted that the outer contact of the smoothest facies of the Fra Mauro, next to the newly defined smoother Cayley Formation, was very difficult to locate; maps of the Julius Caesar (Morris and Wilhelms, 1967), and Mare Vaporium quadrangle (Wilhelms, 1968) show many of the contacts between the smooth Fra Mauro and Cayley as questionable.

Wilhelms (1965) noted that local sharp contacts of the Cayley Formation with adjacent rugged terrain suggest a considerable thickness of material that is sharply localized (Fig. 1). This, together with the common mantled appearance of the surface of Cayley Formation, as deduced from muted forms of craters and other features, led to the conclusion that the formation might have been produced by volcanic ash flows (Wilhelms, 1965). >Fig. 1

Volcanic concepts prevailed throughout the Apollo 16 premission interpretations, though many additional observations and interpretational details were added (Milton, 1972; Elston _et al._, 1972; Wilhelms and McCauley, 1971;

and Trask and McCauley, 1972). However, the impact generated breccias returned during the Apollo 16 mission did not verify the volcanic nature of the Cayley Formation, at least at this particular locality. Analysis of the stratigraphy of North Ray crater and the block distribution at the landing site (Ulrich, 1973) have yielded a model for the local stratification. A 50 m thick layer of light colored, friable feldspathic impact breccias overlies more coherent, glass-rich dark matrix impact breccias, containing, as inclusions, rocks of metaclastic and igneous appearance. However, there is no clear evidence for distinctive stratigraphic units of significant lateral and vertical extent and significant physical differences as determined by the active seismic experiment (Kovach _et al._, 1973). At the Apollo 16 landing site the impact generated breccias extend to depths below 200 m; but the nature of the underlying basement is unknown. Petrographic analysis of the materials returned from many locations in the Apollo 16 Cayley plains reveals that there is an exceptional variety of breccia types, metaclastic and crystalline rocks (LSPET, 1973; Warner _et al._, 1973; Wilshire _et al._, 1973; Walker _et al._, 1973; Bence _et al._, 1973; and others). All investigators emphasize that the highly complex multiple breccias imply multiple impact events. Elevated temperatures either short of melting or with various degrees of partial melting are implied; the thermal energy necessary for the observed metamorphism has probably been delivered by meteorite impact. Except for some crushed anorthosites, all returned rocks show evidence for multiple brecciation. A variety of absolute formation ages for Apollo 16 rocks are available (Tera _et al._, 1973; Husain and Schaeffer, 1973; Compston _et al._, 1973). The bulk of formation ages clusters between 3.8 and 4.1 x 10^9 years. This implies that discrete thermal (impact) events spanned the period 3.8 to 4.1 x 10^9 years.

Study of the magnetic properties of Apollo 16 rocks revealed that all rocks have very high metallic iron content (Pearce et al., 1973). In comparison with mare basalts and various regolith materials such concentrations are interpreted to reflect severe thermal metamorphism in a highly reduced environment at temperatures above 770°C, the Curie point of Fe°. Thus, post-mission analyses reveal that the Apollo 16 Cayley Formation is made up of a sequence of impact generated breccias exhibiting a history of either complex, multistage mechanical mixing or severe thermal metamorphism compatible only with shock induced temperatures above 800°C.

Any interpretation of emplacement of the Cayley Formation at its present sites must therefore involve an impact mechanism that allows for exposure of the samples to impact of extra lunar bodies before emplacement at the present locations. Consequently, Chao et al. (1973), Hodges et al. (1973) and Eggleton and Schaber (1972) have proposed various mechanisms for emplacement of the formation from one or two distant impact basins. All mechanisms proposed have the commonality that the materials of the Cayley Formation are considered to consist of the ejecta of one or two large multiringed impact basins that has been transported to the present site of the Cayley Formation either as ejecta or as fluidized debris. However, if the emplacement of the Cayley Formation is related in origin to formation of these large basins then the Cayley Formation must have been emplaced mainly by secondary craters of these events rather than by direct transport of basin ejecta for hundreds of kilometers.

Results of laboratory simulation of lunar secondary craters coupled with computational results and observations of lunar secondary craters to be presented in this paper compel this conclusion. The combined evidence shows that material ejected from large lunar craters at radial distances greater than 50 km produce well formed secondary craters that excavate and deposit much larger amounts of local material than the mass of material ejected and deposited from the distant primary crater.

Thus, our new hypothesis for emplacement of the Cayley Formation is that many highland craters and multiringed basins formed by impact and ejected material to great distances on the Moon. This material impacted over a long period of time on the highlands terrain and produced craters that ejected and deposited masses of material hundreds of times greater than that deposited from the primary crater. The main effect of these impacting fragments from distant highlands and multiringed basins was one of erosion of material from high elevations and deposition of this material in local depressions in the highlands and floors of ancient centers and of reworking level areas. An effective means for spreading the eroded materials out to large level plains was the formation of efficient landslides and ejection of material from many secondary craters over a long period of time.

Evidence will be presented in this paper to show that material ejected from huge lunar craters like Copernicus have in fact produced secondary craters, and the nature and distribution of these craters will be illustrated as they are central to our new hypothesis. Results of experiments simulating secondary craters and a calculation of the amount of material that is excavated and deposited by secondary craters, as opposed to that of the primary crater ejecta, are also presented. In addition examples of large secondary craters in the Apollo 16 site and other areas of Cayley Formation are presented to illustrate their presence, and remote measurements of surface chemistry are shown to be consistent with the hypothesis that secondary craters have eroded highly shocked material from the highlands and deposited it in depressions to form the Cayley Formation.

2. Effects of Ejection of Material From Large Lunar Impact Craters

A. LUNAR SECONDARY CRATERS

Figure 2 shows a photomosaic of the lunar crater Copernicus and the surrounding terrain. The appearance of the ray system is striking. It extends for hundreds of kilometers from the parent crater. A recent study indicates that these rays are due to concentrations of innumerable small secondary and tertiary craters of Copernicus formed when material ejected from Copernicus impacted the lunar surface (Oberbeck, 1971). Some large secondaries of Copernicus can also be seen in Figure 2. They radiate from Copernicus in chains and are sometimes found in the bright rays. Some are found as close as 50 km from the rim of Copernicus. Apparently material thrown this far from lunar primary craters has produced secondary craters, rather than continuous deposits of ejecta from the primary crater. Figure 3a shows a typical secondary crater cluster, produced by material ejected from Copernicus; the craters are all subdued, compared with primary craters of the

>Fig. 2

>Fig. 3a

same size. Those farthest from Copernicus are more subdued than those nearest Copernicus. Moreover, those at the edge of a cluster are typically more well-defined than those at the center. Figure 3b shows a secondary cluster that was probably produced by material ejected from Aristarchus Crater. Those at the western edge of the chain are more defined as a group than those farthest from Aristarchus. The V shaped ridges radiating from the crater chain are components of the lunar herringbone pattern (Oberbeck and Morrison, 1973a, b). Because of the youthful appearance of the parent craters, these examples must represent some of the freshest secondary craters on the Moon. Clusters similar to these occur in great numbers around fresh, large lunar impact craters. One should expect secondaries from older primary craters to be even more subdued and difficult to observe. >Fig. 3b

Based on laboratory simulations of secondary craters, the subdued nature of secondary craters is thought to be the result of simultaneous impact of fragments ejected from the parent crater at nearly the same time. Figure 3c shows a plot of the ratio of h_D, the depth of the downrange crater, to h_U, the depth of the uprange crater for crater pairs produced by simultaneous impact of two lexan projectiles of equal masses (0.43 grams) into quartz sand at impact velocities and impact angles suitable for simulation of many lunar secondary craters (Oberbeck and Morrison, 1973a). As impact angle, θ, measured from the normal increases, the ratio h_D/h_U decreases because the downrange crater becomes progressively more subdued (shallower). Figure 3d shows two of the closely spaced craters (experiment 1018) produced simultaneously by projectiles impacting at velocity equal to 0.78 km/sec and impact angle equal >Fig. 3c >Fig. 3d to 75°. Their shadow patterns and their profiles (Fig. 3e) show that the >Fig. 3e downrange crater is subdued most because ejecta from the growing uprange crater partially fills the downrange crater. This probably explains the observation that lunar secondaries of a chain or cluster that are farthest from the parent crater are also the shallowest.

Secondary craters on highland terrain are even more subdued and in many cases are difficult to observe. Figure 4a shows a large group of subdued >Fig. 4a Copernican secondaries superimposed on Delisle α, a high ridge northeast of Aristarchus. The crater field contains well-defined, though subdued craters on each side of Delisle α, but not on the rugged positive relief. Figure 4b >Fig. 4b shows a secondary crater chain that crosses a mare ridge. The group of craters indicated by the arrow nearest the ridge is almost completely filled, presumably by material dislodged from the ridge during impact. Thus, development of observable secondary craters on positive rugged topographic features with steep slopes seems to be very poor because the slope materials are less stable and tend to slide downhill; this in turn causes materials uphill from the craters to also become unstable and to slide downhill, thereby obliterating the freshly produced crater.

In summary, large secondary craters of Copernicus are numerous and they are present as close as 50 km from the rim of Copernicus. They are subdued even when young and they are not well expressed on rugged terrain. Secondary craters can also be observed at distances only 40 km from the rims of Kepler and Aristarchus craters. No secondary craters are observed on the continuous ejecta blanket of these large craters because later arriving material swamps and fills the early craters. In any event for those materials thrown beyond the continuous ejecta blanket (40-50 km), the material impacts at sufficient velocity to produce discrete craters rather than continuous deposits of primary crater ejecta.

B. MASS EJECTED FROM SECONDARY CRATERS

Recent laboratory simulations of secondary craters of Copernicus indicate that the material that formed these secondaries impacted at angles exceeding 60° measured from the normal (Oberbeck and Morrison, 1973a). Moreover, the results of Shoemaker (1962) indicate a narrow range of impact angles, from 68° to 76°, for fragments that were ejected from Copernicus and that formed the satellitic craters. To simulate these craters and thus determine the mass ejected from the craters relative to that of the impacting fragments, lexan projectiles were fired into quartz sand targets at impact angles (measured from the normal) of 60° and 75°. Two orthogonal profiles of each crater permitted a calculation of crater volume and, therefore, mass ejected from each crater. The ratio, μ, of this mass to projectile mass is plotted in Figure 5 as a function of the range, R_S, calculated from the projectile velocity and impact angle by using Equation (2) of Oberbeck and Morrison (1973a). The figure shows that the data for each impact angle can be described by an empirical equation of the form > Fig. 5

$$\mu = K \; R_S^{\,a} \tag{1}$$

where K and a are constants. For both impact angles the value of a is 1/3, whereas the values of K are 0.58 and 0.39 for 60° and 75°, respectively.

The data are consistent with lunar observations that material thrown only 50 km on the Moon produced well developed secondary craters. Moreover, if the data for 75° can be extrapolated as shown by the dashed line in the figure, the mass ejected and deposited locally by secondary craters at ranges from 50 km to 2000 km varies from 142 to 490 times that deposited locally from the primary crater. Their values are substantially smaller than values varying from about 1,340 to 2,034, calculated for the artificial lunar impact craters produced by Rangers 7, 8, and 9 using the data of Whitaker (1972). These spacecraft impacted the Moon at velocities ranging from 2.62 km/sec to 2.67 km/sec, just above the velocity range for fragments that produced secondary craters. However, the data of Figure 5 and the Ranger data are all consistent with the conclusion of Oberbeck (1971) that "ray material at great distance from the source crater must not have been excavated from the distant crater because any material from such a crater must have been shattered on impact and diluted by the ejecta from the crater it produces." Thus, both lunar observations and laboratory simulations offer convincing evidence that the effect of material ejected from a large crater on terrain located at distances greater than 50 km from the crater has been one of production of secondary craters, rather than deposition of material, and that this crater production is a powerful erosive mechanism.

The degree to which production of secondary craters has played a role in the formation of the Cayley deposits is indicated by calculations of the cumulative mass excavated from these craters and deposited locally as opposed to the total mass ejected from the primary crater and deposited locally. These calculations were made by using an expression for the cumulative mass derived in the following manner. First, it is assumed that the areal density, δ, of the material that was ejected from the primary crater and that impacted the lunar surface varies with radial distance, R, from the crater according to the following equation

$$\delta = C\, R^{-b}, \tag{2}$$

where C and b are constants. This equation is that given in Carlson and Roberts (1963) for the ejecta mass distribution around terrestrial explosion craters. The mass of this material ejected from the primary crater is, therefore,

$$dm_P = 2\pi\ \delta\ RdR, \tag{3}$$

which becomes, upon substitution of Equation (2),

$$dm_P = 2\pi\ CR^{1-b}dR. \tag{4}$$

However, impact of this material produced numerous secondary craters that ejected material of total mass

$$dm_S = \frac{dm_S}{dm_P}\ dm_P = \mu\ dm_P. \tag{5}$$

Substitution of Equations (1) and (4) into Equation (5) yields

$$dm_S = 2\pi \; KC \; R_S{}^a R^{1-b} dR. \tag{6}$$

If R_E is the radial distance at which material was ejected from the primary crater, then

$$R_S = R - R_E. \tag{7}$$

Therefore,

$$dm_S = 2\pi \; KC (R - R_E)^a R^{1-b} dR. \tag{8}$$

Integrating Equation (8) one obtains the following equation for the cumulative mass ejected from the secondary craters at radial distances greater than or equal to R:

$$m_{SC} = 2\pi \; KC \int_R^{R_m} (R - R_E)^a R^{1-b} dR. \tag{9}$$

Here, R_m is the maximum radial distance to which ejecta is thrown. However, the total mass of material that was ejected from the primary crater and that impacted the lunar surface is obtained by integrating Equation (4) as follows:

$$m_{PT} = 2\pi C \int_{R_o}^{R_m} R^{1-b} dR. \tag{10}$$

Upon integration, this equation becomes

$$m_{PT} = 2\pi C\ (1/R_o{}^{b-2} - 1/R_m{}^{b-2})/(b-2). \tag{11}$$

Dividing Equation (9) by Equation (11) gives the ratio of cumulative mass ejected from the secondary craters to total mass ejected from the primary crater as follows:

$$m_{SC}/m_{PT} = K(b-2)\int_{R}^{R_m}(1-R_E/R)^a R^{1+a-b}dR/(1/R_o{}^{b-2} - 1/R_m{}^{b-2}). \tag{12}$$

Assuming that $R_E \approx R_o/2$ and evaluating the integral in terms of a binomial series, one obtains to a good approximation that

$$\begin{aligned} m_{SC}/m_{PT} = K(b-2)R_o{}^a \Big\{ & \left[(R_o/R)^{b-a-2} - (R_o/R_m)^{b-a-2}\right]/(b-a-2) \\ & -a\left[(R_o/R)^{b-a-1} - (R_o/R_m)^{b-a-1}\right]/\left[2(b-a-1)\right] \\ & -a(1-a)\left[(R_o/R)^{b-a} - (R_o/R_m)^{b-a}\right]/\left[8(b-a)\right] \\ & -a(1-a)(2-a)\left[(R_o/R)^{b-a+1} - (R_o/R_m)^{b-a+1}\right]/ \\ & \left[48(b-a+1)\right] \Big\} \Big/ \left[1-(R_o/R_m)^{b-2}\right]. \end{aligned} \tag{13}$$

Values of the ratio m_{SC}/m_{PT} were calculated for various crater sizes by using Equation (13). In these calculations, an ejection angle and, therefore, impact angle of 75° was assumed, which is consistent with the results of Shoemaker (1962) and Oberbeck and Morrison (1973a). In addition, the extrapolation of Figure 5 was assumed to apply. Thus, values of 39.0 and 1/3

were used for K and α, respectively. Furthermore, the upper limit of integration, R_m, was assumed in each case to be equal to the radius of the ray pattern observed on lunar photographs, measurements of which are given in Figure 44 of Baldwin (1963) as a function of crater size. The values used are probably smaller than the radii of the actual ray patterns since ejected material is probably thrown farther than is apparent on the photographs. However, use of these values leads to smaller values for the ratio m_{SC}/m_{PT} than what may actually prevail, and the values thus obtained are therefore conservative. Although values for b from 3.7 to 4.5 have been reported (Carlson and Roberts, 1963, and Marcus, 1968) for crater Teapot Ess, a shallow depth of burst terrestrial explosion crater which has been used previously as a model for impact crater events (Shoemaker, 1963), a value of 5 was used in the calculation to again yield conservative answers. For each crater size the values of the ratio m_{SC}/m_{PT} were calculated only for radii greater than either the observed radial limit of the continuous ejecta blanket, as given in Figure 6, or the radial distance for onset of cratering, whichever is largest. >Fig. 6
A distance of 50 km from each crater rim, rather than 40 km, was chosen for the onset of cratering to again obtain conservative values for the ratio m_{SC}/m_{PT}.

The results of the calculations for the ratio m_{SC}/m_{PT} are given in Figure
Fig. 7a< 7a. For comparison, values are plotted in Figure 7b for the ratio of the >Fig. 7b
cumulative mass m_{PC} of material ejected from the primary crater that impacted the lunar surface at radial distances equal to or greater than R to the total mass m_{PT} ejected from the crater. This ratio was calculated by using the

values stated previously for b and R_m in the equation

$$m_{PC}/m_{PT} = \left[(R_m/R)^{b-2}-1\right]/\left[(R_m/R_o)^{b-2}-1\right], \qquad (14)$$

which can be derived by integrating Equation (4) between the limits of R and R_m and dividing the resultant equation by Equation (11). Figure 7a shows that for all primary crater sizes considered, the cumulative mass ejected by all secondary craters in the satellitic crater field varies from about six to over ten times the total mass ejected from the primary crater. In addition, comparison of Figure 7a with Figure 7b shows that beyond any given radius, the cumulative mass ejected by secondary craters exceeds the cumulative mass deposited by the primary crater by two orders of magnitude, which compares with the values of μ given in Figure 5. Therefore, although the values of the ratio m_{SC}/m_{PT} appear at first glance to be very large, they can be shown to be not unreasonable since their approximate order of magnitude can be obtained simply by assuming that the ratio μ is constant with R and equal only to 100, a very conservative value, and by multiplying this value times the values of the ratio m_{PC}/m_{PT} at corresponding radii.

Data of Figure 7a shows that if it is necessary to relate the Cayley deposits genetically to large impact events (Chao et al., 1973; Hodges et al., 1973) then the Cayley deposits could not consist mainly of material from the distant basins. Indeed, the figure indicates that in the lunar surface area between 1600 km from the center of Imbrium (R_o = 335 km), the approximate radial distance of the Cayley Formation at the Apollo 16 landing site, and 4,020 km from the center of Imbrium, secondary craters have ejected a cumulative mass of over four times the total mass of material ejected from Imbrium. More importantly, Figures 5 and 7a show that any fragments from Imbrium that impacted near the Apollo 16 site would have produced secondary craters, rather than deposits, and that these secondary craters would have ejected and deposited a total mass of local material about 440 times that of the Imbrium fragments. Therefore, the Cayley deposits must consist mostly of material ejected and deposited locally from secondary craters. The figure shows also that the many smaller highland craters surrounding the Apollo 16 site must also have contributed substantially, over a long period of time, to the Cayley deposits. Acting as a powerful erosional and depositional agent, secondary craters have played an important role in producing the Cayley Formation.

The following section demonstrates that secondary craters have contributed to the accumulation of the Cayley Formation in the Apollo 16 landing site and other areas by also shedding materials from higher elevations in the highlands into depressions.

3. Secondary Craters on the Cayley Formation

An example of a large depression containing Cayley Formation (Fig. 8) is Ptolemaeus crater. The longest secondary crater chain is that chain cutting across the highlands and floor of Ptolemaeus and extending into Alphonsus crater. Figure 8a shows ridges (indicated by arrows) associated with this subdued chain, supporting the hypothesis that it is a huge secondary crater

> Fig. 8

> Fig.8a

chain (Oberbeck and Morrison, 1973a). The secondaries are well defined on the floors of Ptolemaeus and Alphonsus, but where they cross the highlands between these two craters, they are not, presumably because the rugged terrain is less stable after impact. This secondary chain is viewed as the most recent secondary chain of this size that has eroded material from the highlands and the rim of Ptolemaeus and that could have deposited material over a large area of the floor of Ptolemaeus, thereby adding material to the Cayley Formation. Thus, many large highland craters intermediate in age between the ancient crater Ptolemaeus and the unidentified younger crater that produced the very fresh secondary crater chain (Fig. 8a) must have produced countless secondary crater chains and clusters on highland terrain and on the crater floor. These would have transported material from the highlands to the crater floor and reworked the crater floor material. The material eroded from the highs pooled in the depressions to form the Cayley Formation. There are numerous additional crater chains and clusters on the floor of Ptolemaeus. This supports the view that the surrounding highlands were also exposed to secondary cratering. For example, Fig. 8b shows a crater chain that is older than the one shown in Fig. > Fig. 8b
8a but younger than the very subdued crater chain shown in Fig. 8c. Figure > Fig. 8c
Fig. 8d< 8d shows one large fresh crater cluster and a small cluster of very subdued craters. These are only a few of the many subdued crater chains and clusters that have been observed on the surface of the Cayley Formation in this area.

Examples of secondary craters can also be given for the Apollo 16 landing site and its surroundings, where many additional subdued craters can be identified as members of chains and clusters. One fresh crater chain (Fig.

Fig.9a< 9a) is certainly of secondary impact origin because it has a herringbone ridge component. More eroded chains and clusters are also visible. An example of a very large fresh subdued crater chain in the crater Dolland C is

Fig.9b< shown in Fig. 9b. A still more subdued crater chain is shown in Fig. 9c. It > Fig.9c

is noteworthy that members of any given chain or cluster typically display the same state of preservation and that this pattern is different for other chains or clusters. Such characteristics are compatible with an origin by secondary impact cratering because members of a given chain or cluster were formed nearly simultaneously, but adjacent chains or clusters were produced by ejecta from different primary craters that impacted at distinctly different times. Thus, it is concluded that the crater chains illustrated in Figures 8 and 9 are of secondary impact origin and that many similar chains and clusters have the same origin.

Fig.10a< Figure 10a shows a photograph of the Davy crater chain that occurs partially on the floor of Davy Y crater in the Cayley Formation and partly on the rim of Davy Y crater and the adjacent highland. Until recently this crater chain was thought to be of volcanic origin (Mutch, 1972). Like the Cayley Formation it occurs in the floor of Davy Y crater. Recent Apollo 16 high resolution panoramic photographs revealed the presence of ridges that radiated from the intersection of craters of the crater chains (Fig. 10a) and it has been concluded that these are probably secondary impact craters of

Fig.10b< a large lunar crater (Oberbeck and Morrison, 1973b). The insert in Figure 10b shows the area at the base of the Davy Y crater wall where it can be seen that the craters nearest the wall have been filled (arrow) presumably by material from the highlands that has been dislodged by secondary fragments that have impacted there and has been moved downslope to fill the craters. This is strong evidence for addition of material from the highlands to the Cayley Formation as a result of secondary impact cratering.

The subdued crater chains and clusters on the Cayley Formation surrounding the Apollo 16 landing site and on the floors and walls of Ptolemaeus and Davy Y craters and the surrounding highlands are secondary craters. It is reasonable that these areas would have received massive bombardment of simultaneously impacting clusters and chains of secondary fragments because there are so many primary highland and maria craters and large multiringed basins surrounding the Cayley patches. The absence of obviously fresh well-formed secondaries around any of these lunar highland craters suggests that the subdued crater chains and clusters so typical of the Cayley Formation must be considered as prime candidates for secondaries of the highland craters and multiringed basin.

Since such craters must have been produced at velocities less than lunar escape velocity, they would have ejected material at lower velocities but at velocities that are sufficient to propel materials on the Moon to distances measured in kilometers but insufficient to produce well-formed craters even in relatively loose regolith materials. Evidence for this are V shaped ridges greater than 8 km in length that are associated with secondary craters (Guest and Murray, 1971). The process can produce subdued crater fields of reworked breccias, even in flat areas, by simultaneous impact on a previously cratered surface. However, massive secondary cratering can transport large quantities of highland material over considerably larger lateral distances by formation of highly efficient landslides.

Howard (1973) has examined the process of lunar avalanche formation and offers convincing evidence that lunar landslides are of the highly efficient type on the Moon. He illustrated some landslides on the interior walls of craters that were triggered by secondary impacts. We have also observed examples of landslides triggered by secondary impacts. A landslide triggered by the secondary fragments impacting on a ridge is shown by the insert in Fig. 4c < Figure 4c. Based on stereoscopic observations, the area mapped as C defines the thickest part of the landslide. The area D is thought to contain landslide material also since there appears to be a thin deposit here and the frequency of small craters is much less than on adjacent terrain. Areas A and B mark the positions of thick deposits that could be either landslide debris or secondary crater ejecta deposits. The largest lunar landslide discovered to date is shown in Figure 11A. It extends 5 km from the base of > Fig.11A the massif. Howard (1973) noted, but did not specify, the nature of evidence for triggering of this landslide by secondary cratering. We believe it was triggered by impact of the fragments that produced the secondary craters at Fig.11B < the top of the massif (Fig. 11B).

In summary, because of the subdued character, even when fresh, and because of their still poorer development in rugged highland terrain, the influence of secondary craters has been greatly underestimated. The immense volume of material excavated and redistributed by secondary craters represents a powerful erosion and depositional mechanism that must have contributed significantly to the evolution of the lunar surface, in particular to the highland terrains that are exposed longest to the primary meteoroid bombardment.

If many of the highland craters are correctly mapped as preImbrium then secondaries of Imbrium could have contributed to the Cayley Formation on the floors of these craters. However, many of the highland and mare craters are postImbrium and so must also have contributed to production of the Cayley Formation. Thus, Cayley-type deposits must have been emplaced over a long period of time from preImbrium to postImbrium time.

4. Remote Measurement of the Cayley Formation

A variety of remote measurements of the physical and chemical properties of the Cayley Formation strongly support the conclusion that it was emplaced by small cratering events that could be mainly secondary craters. The albedo measurements of Pohn and Wildey (1970) indicate that the albedo value at different localities in the Cayley is rather variable. Yet the absolute albedo of individual Cayley occurrences is similar to the local highlands terrain.

Telescopic spectral reflectivity work in the wavelengths .3 to 1.1 μm (Adams and McCord, 1972; McCord _et al._, 1972a,b) show that lunar highland materials are diagnostically different from mare surface. Within highland areas, differences are subtle if present at all. Such differences are best explained by various ratios of glass to crystalline materials thought to reflect an aging effect due to continuous meteoroid bombardment. The Cayley Formation does not possess any diagnostic spectral characteristic, yet on a local scale it seems indistinguishable from its surroundings.

Infrared data taken during lunar eclipse reveal that the lunar surface exhibits a considerable degree of thermal heterogeneity (Shorthill *et al.*, 1972). Again, mare are different from highlands, and within the highlands the Cayley Formation does not differ from its surroundings. Radar backscatter experiments at 3.8, 70, and 800 cm wavelengths also show that there is no diagnostic property for Cayley (Thompson, 1973; Thompson *et al.*, 1973). The Cayley Formation blends into its surroundings with respect to topographic features as large as 10 meters.

Significant data for the interpretation of the Cayley Formation may be present in geochemical investigations along the lunar ground tracks of the Apollo 15 and 16 Command Modules. The Gamma Ray Spectrometer results (Metzger *et al.*, 1973) and those of the X-ray spectrometer (Adler *et al.*, 1973)
Fig. 12 < are illustrated in Figures 12 and 13, respectively. The fractional surface >Fig. 13
area per resolution cell of the above experiments was determined with a planimeter using the geological map by Wilhelms and McCauley (1971) as a basis. Neither of the experiments reveal any diagnostic criteria for the Cayley Formation. The data obtained while flying over the mapped Cayley localities (see Figs. 12 and 13) demonstrate instead that the chemical makeup of the Cayley may be different from locality to locality and--most importantly--that although one patch of Cayley material may differ from another patch, most have close affinities to the nearby highland terrain.

Inspection of Figure 12 shows that resolution cells with equal areas of Cayley Formation often exhibit different gamma ray counts, but adjacent resolution cells containing different proportions of Cayley Formation often exhibit similar gamma ray counts. Although the X-ray spectrometer data plotted in

Fig. 13 < Figure 13 do not show it, Adler's tabulated results (Adler, 1973) show similar Al/Si and Mg/Si ratios for the Cayley Formation in Ptolemaeus crater and for the highlands east and west of Ptolemaeus.

Using laboratory studies of the magnetic properties of lunar rocks, Strangway et al. (1973) interpret the orbital subsatellite magnetic results (Coleman et al., 1972) to be due most likely to Cayley-type breccias similar to the Apollo 16 materials. Apparently, basins that formed magnetic anomalies are filled with breccias. Interestingly, the largest magnetic anomaly, the crater Van de Graaf, happens to be mapped as Cayley.

In summary, the remote sensing studies reveal that the mapped Cayley occurrences have close affinities to their surrounding terrain. Moreover, they are in all likelihood made of breccias. The fact that they blend in with the local highland terrain suggests that small craters have indeed transported previously brecciated material of the highlands into depressions and thus formed the Cayley.

5. Discussion

The historical association of the Cayley Formation with the Imbrium Basin and its presence between large highland craters and on the floors of ancient craters at considerable distances from other younger basins and craters suggest that it is genetically related to the large craters and basins. Evidence is offered that secondary craters of these basins and craters have transported materials of local highs into local depressions. It is suggested that this is the dominant emplacement mechanism for the Cayley plains, a conclusion which rests on a number of independent observations and calculations:

(a) Material ejected beyond the continuous ejecta blanket of primary impact craters has produced secondary craters. For the craters Kepler, Copernicus and Aristarchus this cratering regime starts at least at a distance of 50 km from the rim of the parent crater.

(b) Calculations based on cratering experiments indicate that these secondary craters have ejected material equal to multiples of primary crater ejecta mass. Thus it must be recognized that material ejected from large craters and basins in ballistic trajectories could not have produced continuous primary crater ejecta deposits at the Apollo 16 landing site, but instead must have produced large secondary crater ejecta deposits.

(c) Large subdued crater chains have been observed on the Cayley Formation and other smooth plains and examples have been illustrated in this paper. Their different ages indicate that they represent a powerful erosive mechanism that has acted over a long period of time.

(d) The subdued appearance of the Cayley Formation can be explained by the fact that simultaneous secondary impact produces such an appearance.

(e) A variety of remote sensing measurements suggests that the Cayley Formation is indeed locally derived because it is similar to the surrounding highland terrain. Erosion of highland terrain by small craters would produce these relationships.

(f) Sample analyses reveal compelling evidence that the Apollo 16 Cayley materials were exposed to multiple impact cratering.

Cumulatively, these results are incompatible with one large scale depositional event but compatible with a local origin of the Cayley Formation. The continuous bombardment of the highlands by meteoroids occurred and the associated secondary fragments shed materials from the intercrater highland terrain and deposited it into local depressions. The Cayley plains are viewed as very large mass wasting and secondary ejecta deposits.

Soderblom (1970) and Soderblom and Boyce (1972) have treated the effects of mass wasting. Their calculations and observations indicate that a crater 600 m in diameter would have filled since formation of the Cayley plains (3.7×10^9 years) and that craters in the 1500-1800 m diameter range would have been leveled off since deposition of the Fra Mauro Formation (3.8×10^9 years). These craters have depths of 200-300 m and thus filling to such depths implies considerable mass wasting of material as a result of primary craters, in addition to secondary craters. We believe secondary craters were more important because of our calculations of the mass ejected and deposited by lunar secondaries relative to that deposited by primaries and because subdued secondary craters seem to dominate the Cayley Formation surfaces. This subduing characteristic of the Cayley Formation is therefore not due to a mantling effect by deposition of distant crater or basin ejecta but to the smoothing effects that are so characteristic of simultaneous secondary impact cratering. When craters are produced at nearly the same time on the Moon (Fig. 3a) and in the laboratory (Fig. 3d), the ejecta of one crater typically fills the other which is being formed at nearly the same time. This produces a smoothing of the craters.

While the secondary craters have been of most importance for emplacement of the Cayley Formation we believe a completely different process has produced the shock damage exhibited by the samples. The severe thermal effects observed in the Apollo 16 breccias must all have been produced by primary meteorite impact, barring other energy sources but impact. The thermal metamorphism observed could not have been produced by secondary impacts because these impact velocities will not result in shock pressures of sufficient amplitude to cause partial or complete melting based on equation of state work by Ahrens et al. (1973) and others. Thus, the shock damage and thermal metamorphism exhibited by the Cayley materials were produced by primary craters. The ubiquity of multiple brecciation of the Apollo 16 samples is strong evidence of formation by multiple primary impact because investigations of terrestrial impact structures and their ejecta deposits (Engelhardt, 1971; Dence, 1971; Kieffer, 1971; and Chao, 1972) as well as small scale crater experiments and consideration of energy partition during the impact process (Gault and Heitowit, 1963) indicate that molten and highly shocked materials only make up about ten percent of the ejecta mass for a single crater event. Thus multiple impacts are necessary to account for the petrographic features exhibited by

Apollo 16 samples (see also Chao et al. 1973; Dence and Plant, 1972; Short and Forman, 1972).

The local source of the multiple breccias probably consists of the combined ejecta of a large number of fairly small primary highland craters because only these would be near enough to the Cayley Formation to permit deposition of most of their ejecta without reexcavating large amounts of material by formation of secondary craters that do not enrich the ejecta with breccias. This suggests that the sources were initially enriched in breccias and were nearby and emplaced at their present sites by secondary craters.

In summary the new hypothesis suggests that all or most of the petrographic features of Cayley materials were produced by multiple primary impact in the highlands; these enriched breccias were shed from highs into depressions in the highlands by innumerable secondary craters that must have accompanied formation of each primary crater. Secondary craters were probably more important in eroding the highlands because they eject more material than the primary craters.

The existing current published hypotheses for emplacement of the Cayley Formation involve deposition of ejecta from multiringed basins even though the basins are hundreds of kilometers from the supposed sites of deposition. For example Chao et al. (1973) hypothesize that material was ejected from Orientale basin in ballistic trajectories and was deposited as a unit thousands of kilometers away at the Apollo 16 site. Hodges et al. (1973) have also hypothesized that the Cayley Formation resulted from material ejected from one or more impact basins in ballistic trajectories and deposited at hundreds of km away. These mechanisms are improbable in our view because we have shown that material ejected to these distances produces craters that eject and deposit much more local material than was added by the secondary fragments. Although some of the Apollo 16 material may have been derived from the Orientale or Imbium basin, it must be recognized that the debris consists mostly of secondary crater ejecta.

The main argument that has been presented to attribute the formation of the Cayley plains to the Orientale cratering event is the seemingly contemporaneous deposition of the Cayley and Hevelius Formations, the latter being unequivocally associated with mare Orientale (Soderblom and Boyce, 1972; Chao et al., 1973). A problem concerning the contemporaneity of Cayley plains arises from the specific crater dating technique used (Soderblom, 1970; Soderblom and Boyce, 1972). This technique is applicable only to strata which are at least as thick as the depth of the craters used in the age determinations. For the particular Orientale hypothesis (Chao et al., 1973), measurements of age are based on use of craters 800-1200 m in diameter. In order that craters can be used with confidence to date a surface the formation should be at least as thick as the depth of the craters so that there is reason to believe the crater was formed after emplacement of the formation. The 800-1200 m diameter craters would be 200-300 meters deep. Volumetric considerations preclude that the entire lunar globe is covered by Orientale ejecta this deep. Even in view of the above authors the postulated Orientale deposit does not exceed a few tens of meters and it was not demonstrated that the dated craters formed after deposition of this layer. Thus, the equivalent age of the Cayley plains and formation of mare Orientale is not accepted here.

Another current hypothesis for the formation of the Cayley Formation involves a quasi-fluid ejection regime. It is considered in this hypothesis that the smooth plains materials were emplaced in a hypothesized fluid ejection regime originating during the Imbrium basin formation to account for the morphologic difference between the thick ejecta of the Fra Mauro Formation and the smooth, level Cayley Formation (Eggleton and Schaber, 1972). The fluidizing medium is considered to be vaporized target and projectile material, and the masses mobilized are considered to have been deposited after the thick bulk ejecta. Whether such a process exists or whether the postulated time sequence for deposition of the units is realistic should probably await further theoretical and experimental verification. However, even this theory acknowledges that most of the mass ejected from large multiringed basins like Imbrium is transported in ballistic trajectories to produce formations like the Fra Mauro Formation (Eggleton and Schaber, 1972). Thus only a small fraction of crater ejecta must have been transported in the hypothesized quasi-fluid regime beyond the thick ejecta. Our results (Figs. 5 and 7a) show that a mass of material approximately 10 times the primary crater mass is deposited by secondary craters formed outside the thick ejecta. Thus, it would appear that any basin or crater ejecta that may have been deposited in these areas by the hypothetical quasi-fluid regime must be very small compared to the local deposits emplaced by secondary craters.

Concepts developed in this paper for understanding the effects of ejection of material from lunar craters and basins on terrain at great distances from the basins or craters can also be applied to interpretation of origin of the material in the aprons surrounding these basins and craters. Materials of aprons surrounding large basins have been interpreted as ejecta from the basins (Eggleton and Schaber, 1972). However, these deposits extend for hundreds of kilometers from the basins and craters. Our results (Fig. 5) indicate that material thrown from basins or craters to these ranges would excavate great quantities of local material in addition to depositing material from the central crater or basin. Thus, these aprons do not contain only basin or crater ejecta as has been traditionally assumed. Investigations of the Ries crater, (Hüttner, 1969) show that the Ries apron contains large amounts of marley sand mixed with crater ejecta on the periphery of the apron. This material was not ejected from the crater site because the formation is not present within the area of the crater. It must have been mixed with basin ejecta as a result of secondary cratering. Thus considerable care must be used in associating crater apron materials with crater ejecta. For example, the Apollo 14 Fra Mauro samples must contain some local material in addition to material ejected from Imbrium basin. Additional work is required for full understanding of the ejection and depositional processes associated with large scale lunar impacts.

References

Adams, J. B. and McCord, T.B.: 1972, "Electronic Spectra of Pyroxenes and Interpretation of Telescopic Spectral Reflectivity Curves of the Moon", Proc. Third Lunar Sci. Conf. 3, MIT Press, 3021-3034.

Adler, I., Trombka, J. I., Schmadebeck, R., Lowman, P., Blodget, H., Yin, L., Eller, E., Podwysocki, M., Weidner, J. R., Bickel, A. L., Lum, R. K. L., Gerard, J., Gorenstein, P., Bjorkholm, P., and Harris, B.: 1973, "Results of the Apollo 15 and 16 X-Ray Experiment", Proc. Fourth Lunar Sci. Conf., in press.

Ahrens, T. J., O'Keefe, J. D., and Gibbons, R. V.: 1973, "Shock Compression of a Crystallized Breccia from Apollo 15", Lunar Science-IV (abstract) 18-20.

Baldwin, R. B.: 1963, The Measure of the Moon, Univ., of the Chicago Press, Chicago, U.S.A.

Bence, A. E., Papike, J. J., Sueno, S., and Delano, J. W.: 1973, "Pyroxene Poikiloblastic Rocks from Apollo 16", Lunar Science-IV (abstract) 60-62.

Carlson, R. H. and Roberts, W. A.: 1963, "Mass Distribution and Throwout Studies", Project Sedan, PNI-217F, The Boeing Co., Seattle WA., U.S.A.

Chao, E. C. T.: 1972, "Geologic Implications of the Apollo 14 Fra Mauro Breccias and Comparison with Ejecta from the Ries Crater, Germany", Jour. Research U.S. Geol. Survey 1, 1-18.

Chao, E. C. T., Soderblom, L. A., Boyce, J. M., Wilhelms, D. E., and Hodges, C. A.: 1973, "Lunar Light Plains Deposits (Cayley Formation) - A Reinterpretation of Origin", Lunar Science-IV (abstract) 127-128.

Coleman, P. J., Schubert, G., Russel, C. T., and Sharp, L. R.: 1972, The Moon 4, 419-429.

Compston, W., Vernon, M. J., Chappell, B. W., and Freeman, R.: 1973,"Rb-Sr Model Ages and Chemical Composition of Nine Apollo 16 Soils", Lunar Science-IV (abstract) 158.

Dence, M. R.: 1971, "Impact Melts", J. Geophys. Res. 76, 5552-5565.

Dence, M. R. and Plant, A. G.: 1972, "Analysis of Fra Mauro Samples and the Origin of the Imbrium Basin", Proc. Third Lunar Sci. Conf. 1, MIT Press, 379-399.

Eggleton, R. E. and Marshall, C. H.: 1962, "Notes on the Apenninian Series and Pre-Imbrium Stratigraphy in the Vicinity of Mare Humorum and Mare Nubium", in Astrogeolog. Studies Annual Progr. Rep., 1961, U. S. Geol. Survey, 132-137.

Eggleton, R. E. and Schaber, G. G.: 1972, "Cayley Formation Interpreted as Basin Ejecta", NASA SP-315, 29-7 through 29-16.

Elston, D. P., Boudette, E. L., Schafer, J. P., Muehlberger, W. R., and Sevier, J. R.: 1972, Apollo 16 Field Trips", Geotimes 17, 27-30.

Engelhardt, W. V.: 1971, "Detrital Impact Formations", J. Geophys. Res. 76, 5566-5574.

Gault, D. E. and Heitowit, E. D.: 1963, "The Partition of Energy for Hypervelocity Impact Craters Formed in Rock", Sixth Hypervelocity Impact Symposium, Cleveland, Ohio.

Guest, J. E. and Murray, J. B.: 1971, The Moon 3, 326-336.

Hodges, C. A., Muehlberger, W. R., and Ulrich, G. E.: 1973, "Geologic Setting of Apollo 16", Proc. Fourth Lunar Sci. Conf., in press.

Howard, K. A.: 1973, "Avalanche Mode of Motion: Implications from Lunar Examples", Science 180, 1052-1055.

Husain, L. and Schaeffer, O. A.: 1973, "$^{40}Ar-^{39}Ar$ Crystallization Ages and $^{38}Ar-^{37}Ar$ Cosmic Ray Exposure Ages of Samples from the Vicinity of the Apollo 16 Landing Site", Lunar Science-IV (abstract) 406-408.

Hüttner, R.: 1969, "Bunte Trümmermassen und Suevit", Geologica Bavarica 61, 142-200.

Kieffer, S. W.: 1971, "Shock Metamorphism of the Coconino Sandstone at Meteor Crater, Arizona", J. Geophys. Res. 76, 5449-5473.

Kovach, R. L., Watkins, J. S., Nur, A., and Talwani, P.: 1973, "The Properties of the Shallow Lunar Crust: An Overview from Apollo 14, 16 and 17", Lunar Science-IV (abstract) 444-445.

LSPET (Lunar Sample Preliminary Examination Team): 1973, "Preliminary Examination of Lunar Samples from Apollo 16", Science 179, 23-34.

Marcus, A.H.: 1968, "Covariance Function of Elevations on a Cratered Planetary Surface", Part II TR-68-3405, Bellcom Inc.

McCord, T. B., Charette, M. P., Johnson, T. V., Lebofsky, L. A., and Pieters, C.: 1972a, "Lunar Spectral Types", J. Geophys. Res. 77, 1349-1359.

McCord, T. B., Charette, M. P., Johnson, T. V., Lebofsky, L. A., and Pieters, C.: 1972b, "Spectrophotometry (.3 to 1.1μm) of Visited and Proposed Apollo Lunar Landing Sites", The Moon 5, 52-89.

Metzger, A. E., Trombka, J. I., Arnold, J. R., Reedy, R. C., and Peterson, L. E.: 1973, "Some Correlations Between Measurements by the Apollo Gamma Ray Spectrometer and Other Lunar Observations", Proc. Fourth Lunar Sci. Conf., in press.

Milton, D. J.: 1972, "Geologic Map of the Descartes Region of the Moon," Apollo 16 Premission Map, U. S. Geol. Survey Misc. Geol. Inv. Map I-748.

Morris, E. C. and Wilhelms, D. E.: 1967, "Geologic Map of the Julius Caesar Quadrangle of the Moon," I-510, (LAC 60), U.S. Geological Survey, Washington DC, U.S.A.

Mutch, T.A.: 1972, Geology of the Moon, Princeton Univ. Press, Princeton NJ, U.S.A.

Oberbeck, V.R.: 1971, "A Mechanism for the Production of Lunar Crater Rays", The Moon Vol. 2, 263-278.

Oberbeck, V. R. and Morrison, R.H.: 1973a, "Laboratory Simulation of the Herringbone Pattern Associated with Lunar Secondary Craters", The Moon, in press.

Oberbeck, V.R. and Morrison, R.H.: 1973b, "On the Formation of the Lunar Herringbone Pattern", Proc. Fourth Lunar Sci. Conf., in press.

Pearce, G. W., Gose, W. A., and Strangway, D. W.: 1973, "Magnetic Studies on Apollo 15 and 16 Lunar Samples", Proc. Fourth Lunar Sci. Conf., in press.

Pohn, H. A. and Wildey, R. L.: 1970, "A Photoelectric-Photographic Study of the Normal Albedo of the Moon", U.S. Geolog. Survey Prof. Paper 599-E.

Shoemaker, E. M.: 1962, "Interpretation of Lunar Craters", in Physics and Astronomy of the Moon, Kopal ed., Academic Press, New York NY, U.S.A., 283-359.

Shoemaker, E. M.: 1963, "Impact Mechanics at Meteor Crater, Arizona", in The Moon, Meteorites and Comets, B. M. Middlehurst and G. P. Kuiper, eds., p. 301, Univ. of Chicago Press.

Short, N. M. and Forman, M. L.: 1972, "Thickness of Impact Crater Ejecta on the Lunar Surface", Modern Geology 3, 69-91.

Shorthill, R. W., Thompson, T. W., and Zisk, S. H.: 1972, "Infrared and Radar Maps of the Lunar Equatorial Region", The Moon 4, 442-446.

Soderblom, L. A.: 1970, "A Model for Small Impact Erosion Applied to the Lunar Surface", J. Geophys. Res. 75, 2655-2661.

Soderblom, L. A. and Boyce, J. M.: 1972, "Relative Ages of Some Nearside and Farside Terra Plains Based on Apollo 16 Metric Photography", NASA SP-315, 29-3 through 29-6.

Strangway, D.W., Gose, W. A., Pearce, G. W., and McConnell, R. K.: 1973, "Lunar Magnetic Anomalies and the Cayley Formation", Nature, in press.

Tera, F., Papanastassiou, D. A., and Wasserburg, G. J.: 1973, "A Lunar Cataclysm at 3.85 AE and the Structure of the Lunar Crust", Lunar Science-IV (abstract) 723-725.

Thompson, T. W.: 1973, "Atlas of Lunar Radar Maps at 70 cm Wavelength", The Moon, in press.

Thompson, T. W., Masursky, H., Shorthill, R. W., Zisk, S. H., and Tyler, G. L.: 1973, "A Comparison of Infrared, Radar and Geologic Mapping of Lunar Craters", Icarus, in press.

Trask, N. J. and McCauley, J. F.: 1972, "Differentiation and Volcanism in the Lunar Highlands: Photogeologic Evidence and Apollo 16 Implications", Earth. Planet. Sci. Letters 14, 201-206.

Ulrich, G. E.: 1973, "A Geologic Model for North Ray Crater and Stratigraphic Implications for the Descartes Region", Proc. Fourth Lunar Sci. Conf., in press.

Walker, D., Longhi, J., and Hays, J. F.: 1973, "Petrology of Apollo 16 Meta-igneous Rocks", Lunar Science-IV (abstract) 752-754.

Warner, J. L., Simonds, C. H., and Phinney, W. C.: 1973, "Apollo 16 Rocks: Classification and Petrogenetic Model", Proc. Fourth Lunar Sci. Conf., in press.

Wilhelms, D. E.: 1965, "Fra Mauro and Cayley Formations in the Mare Vaporum and Julius Caesar Quadrangles", in Part A of Astrogeological Studies Annual Progress Report, 1964-65, U.S. Geolog. Survey, 13-28.

Wilhelms, D. E.: 1968, "Geologic Map of The Mare Vaporum Quadrangle of the Moon", I 548 (LAC59), U. S. Geological Survey, Washington DC, U.S.A.

Wilhelms, D. E. and McCauley, J. F.: 1971, "Geologic Map of the Near Side of the Moon", U.S. Geol. Survey Misc. Geol. Inv. Map I-703.

Wilshire, H. G., Stuart-Alexander, D. E., and Jackson, E. D.: 1973, "Apollo 16 Rocks: Petrology and Classification", J. Geophys. Res. 78, 2379-2392.

Whitaker, Ewen A.: 1972, "Artificial Lunar Impact Craters: Four New Identifications", Part I Apollo 16 Preliminary Science Report, NASA SP-315, 29-39.

Figure Captions

1. The distribution of the Cayley Formation on the lunar frontside according to Wilhelms and McCauley (1971). Note that Cayley predominantly occurs in topographic lows, e.g., old craters, etc.

2. Photomosaic of lunar crater Copernicus and associated ray pattern and secondary craters.

3. a. Cluster of subdued secondary craters of Copernicus, located at 39°20′W, 28°15′N, approximately 151 km northeast of the center of Prinz Crater.

   b. Secondary craters of the crater Aristarchus, located at 27°0′W, 26°0′N, approximately 100 km northeast of the center of Euler Crater.

   c. Ratio of depth, h_D, of downrange crater to depth, h_U, of uprange crater for two craters produced simultaneously at various impact angles, θ.

   d. Photographs of two craters produced in experiment 1018.

   e. Profile along bilateral axis of symmetry for craters produced in experiment 1018.

4. a. Secondary craters that are visible on surface surrounding Delisle α but not on its high terrain.

   b. Secondary crater chain crossing a mare ridge located at 27°40′W, 20°40′N, approximately 90 km southeast of the center of Euler Crater.

   c. Map of landslide caused by secondary craters of Fig. 4b.

5. Ratio, μ, of mass ejected from crater to mass of projectile that produced crater plotted versus the range, R_S, that the projectile would have traveled on the Moon for two different impact angles.

6. Measured radius, R_{eb}, of continuous ejecta blanket for various large lunar craters and basins as a function of crater or basin radius, R_o. The radius of the inner ring of Imbrium is plotted.

7. a. Ratio of cumulative mass, m_{SC}, ejected by secondary craters at radial distances greater than R to total mass, m_{PT}, ejected from primary crater as a function of radial distance R for craters and basins of various radii, R_o.

   b. Ratio of cumulative mass, m_{PC}, that was ejected from primary crater and that impacted lunar surface at radial distances greater than R to total mass, m_{PT}, ejected from primary crater as a function of radial distance R for craters and basins of various radii, R_o.

8. Secondary crater chains and clusters in the Cayley Formation on the floor of Ptolemaeus Crater.

   a. Parts of lunar craters Ptolemaeus and Alphonsus and large secondary crater chain with associated V shaped ridges (indicated by arrows).

   b. Secondary crater chain older and more subdued than chain shown in Fig. 8a.

   c. Secondary crater chain older than chain shown in Fig. 8b.

   d. Secondary crater clusters (indicated by arrows) in two different stages of preservation.

9. Cayley Formation near the Apollo 16 landing site (marked as X).

   a. Relatively fresh secondary crater chain (indicated by arrow) of Theophilus Crater with V shaped ridges and very subdued cluster of secondary craters.

b. Large secondary crater chain in Dolland C Crater.

c. More subdued and older secondary crater chain.

10. a. Davy Crater chain crossing from floor of Davy Y crater into highland terrain.

b. Magnification of area outlined in Fig. 10a, showing partially filled craters.

11. Lunar surface area near the Apollo 17 landing site and landslide (A) caused by secondary craters (B).

12. Distribution and concentration of radioactive elemental species like Th, U, etc., according to Metzger et al. (1973). Superimposed numbers are the percent of surface area per resolution cell covered by Cayley as obtained by planimetry. Note that there is no correlation between radioactivity and Cayley coverage and that Cayley blends into its surroundings.

13. Mg/Si and Al/Si ratios along the Apollo 16 ground track according to Adler et al. (1973). Notice the lack of correlation with the Cayley Formation. Cayley has no distinct Mg/Si and/or Al/Si ratios; it blends into its surroundings.


N
MARE FRIGORIS
MARE IMBRIUM
MARE SERENITATIS
MARE CRISIUM
OCEANUS PROCELLARUM
MARE HUMORUM
MARE NECTARIS
W
E
S

Figure 1.

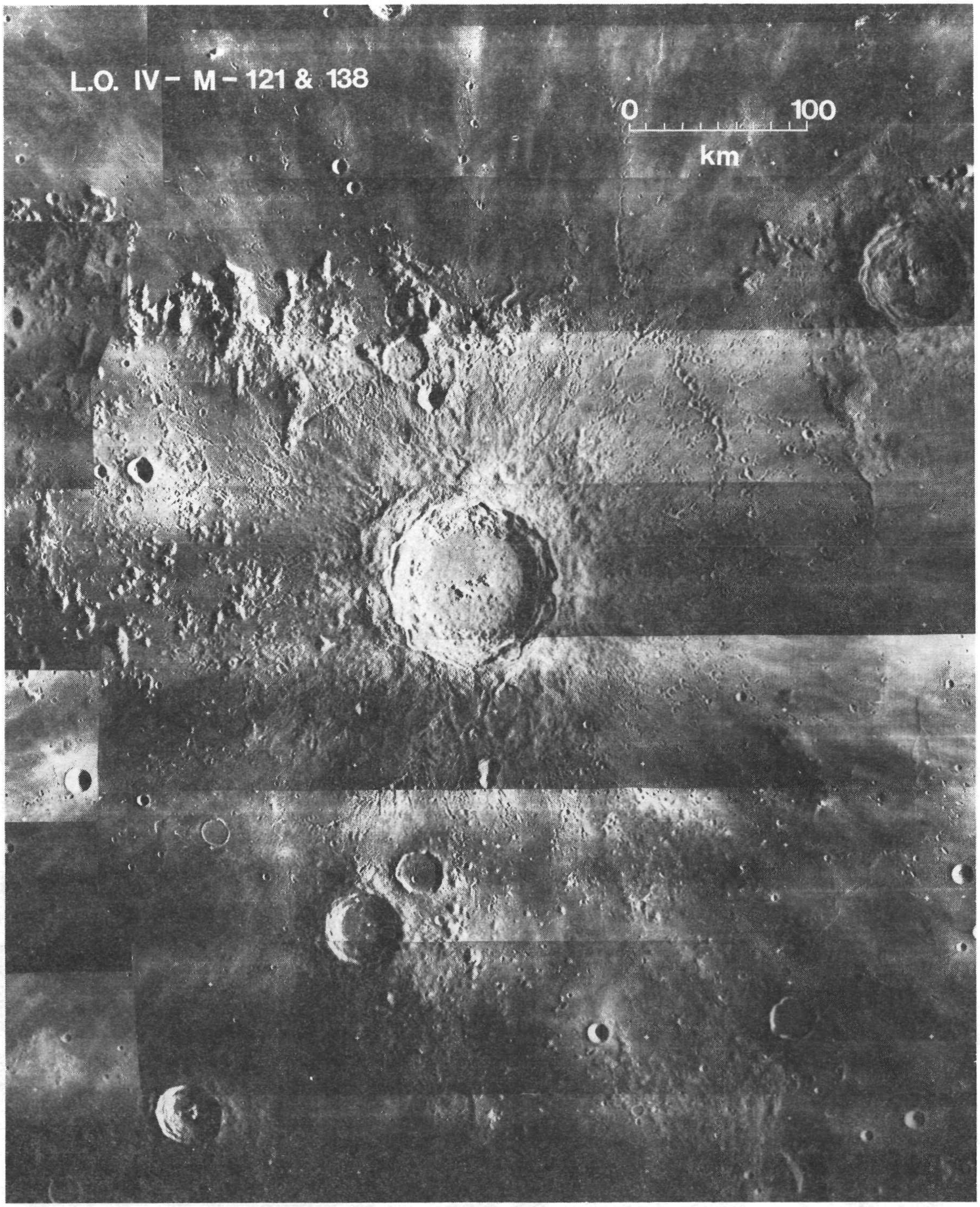
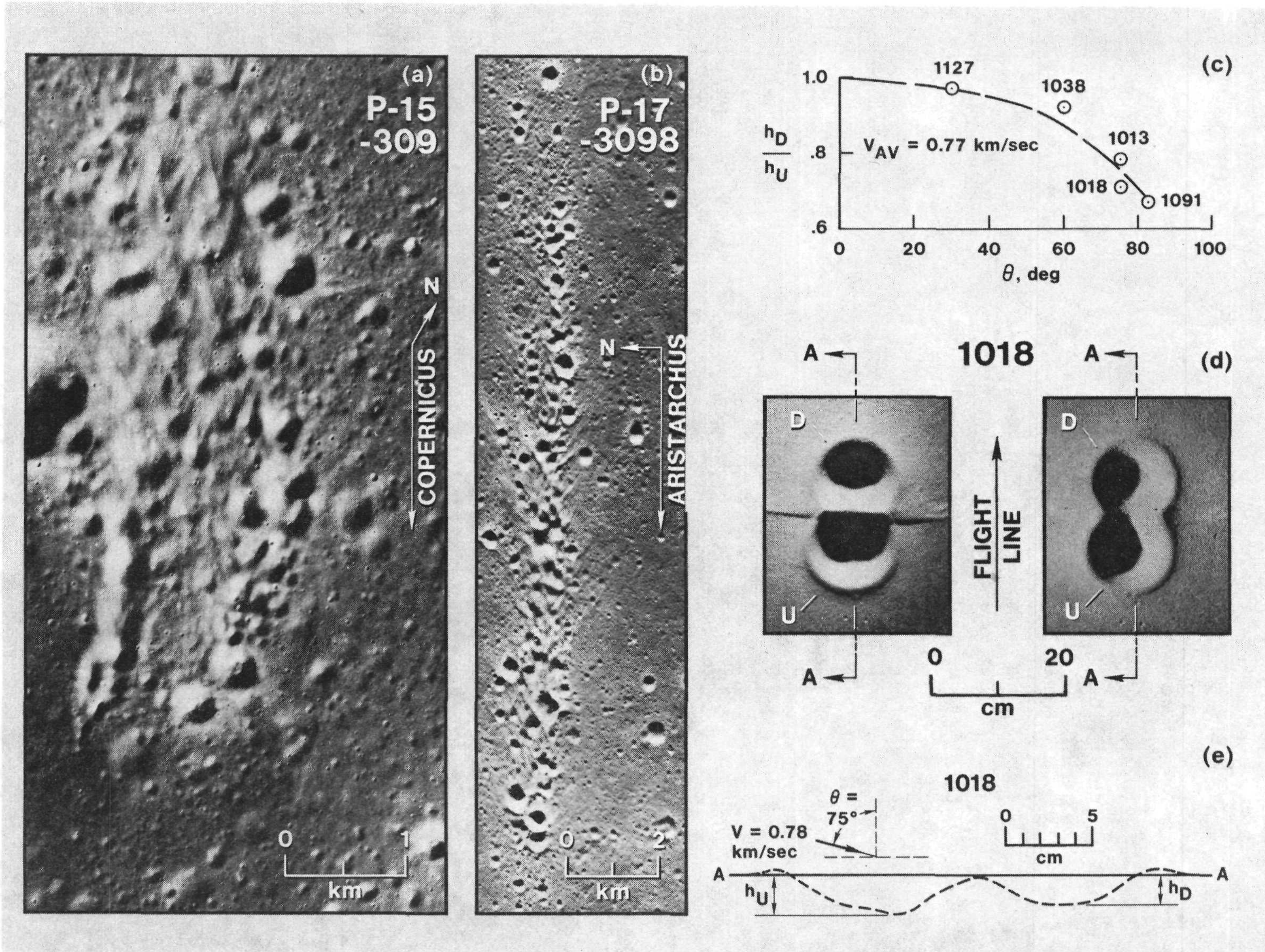


Figure 2.



(a)
P-15
-309
N
COPERNICUS
0
1
km
(b)
P-17
-3098
N
ARISTARCHUS
0
2
km
(c)
1.0
.8
.6
$\frac{h_D}{h_U}$
V_{AV} = 0.77 km/sec
1127
1038
1013
1018
1091
0
20
40
60
80
100
θ, deg
1018
(d)
A
D
U
FLIGHT LINE
0
20
cm
(e)
1018
θ = 75°
V = 0.78 km/sec
0
5
cm
h_U
h_D

Figure 3.

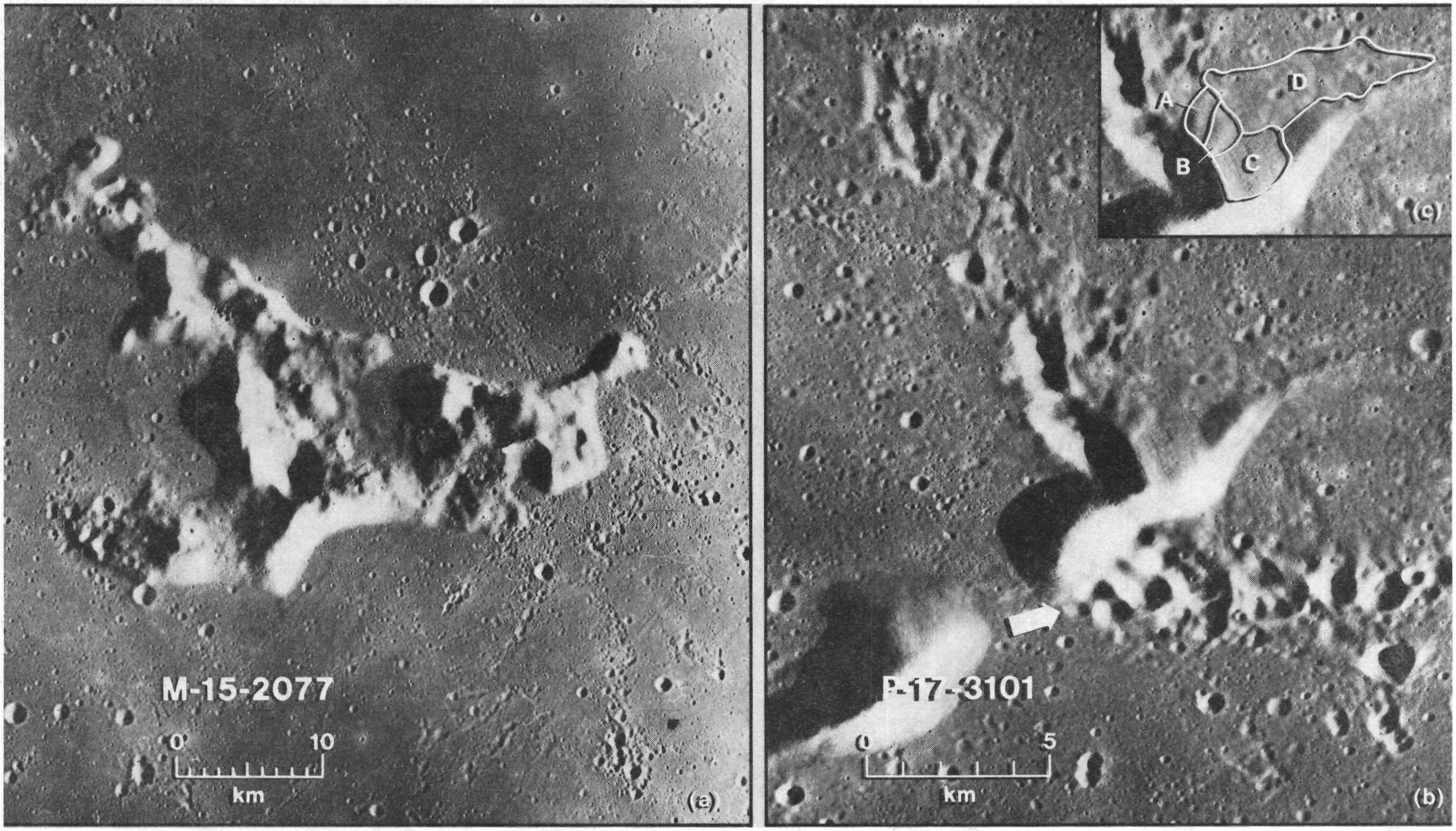


Figure 4.

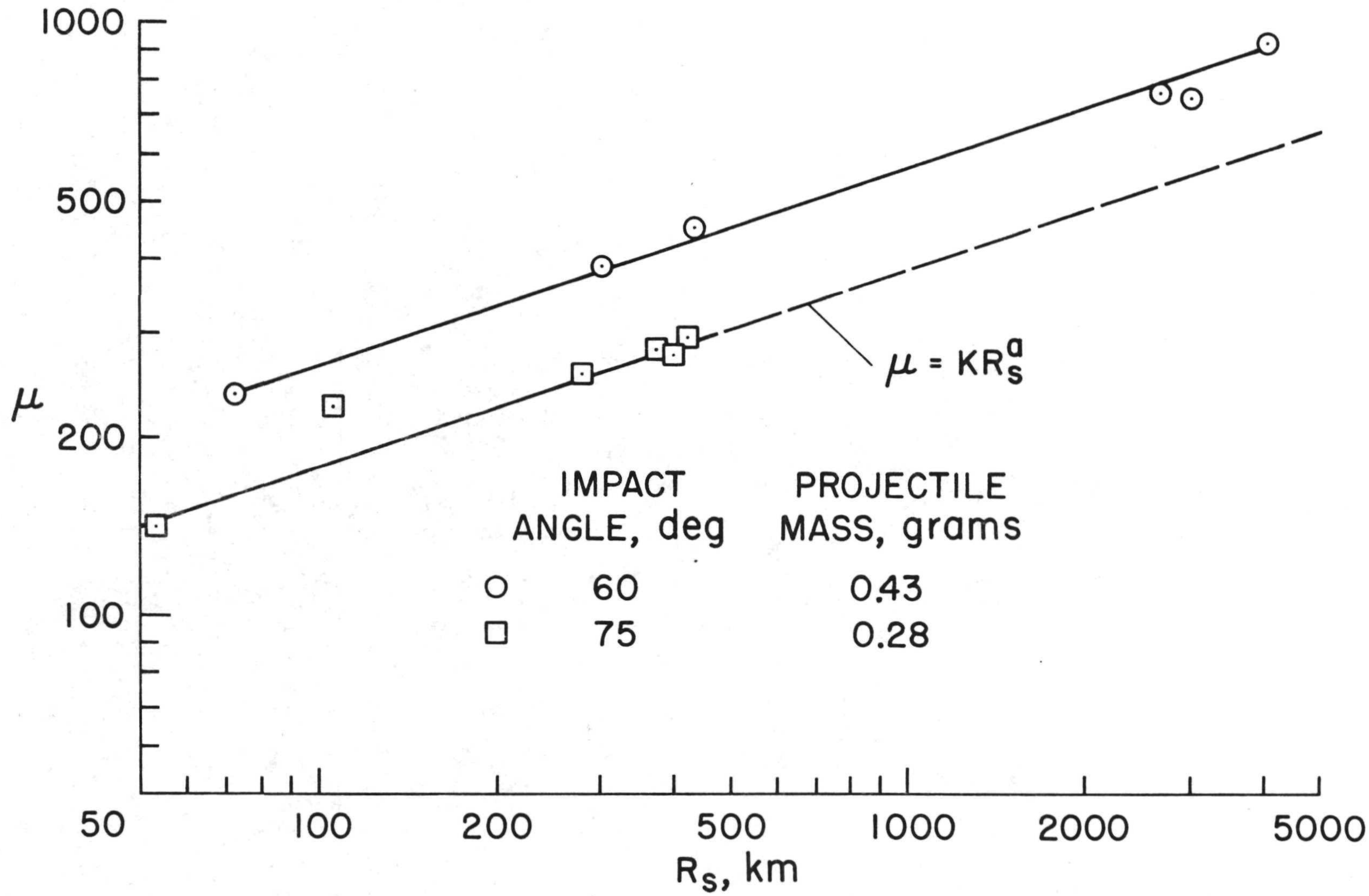

1000
500
200
100
50
μ
100
200
500
1000
2000
5000
R_s, km
$\mu = KR_s^a$
IMPACT ANGLE, deg
PROJECTILE MASS, grams
60
0.43
75
0.28

Figure 5.

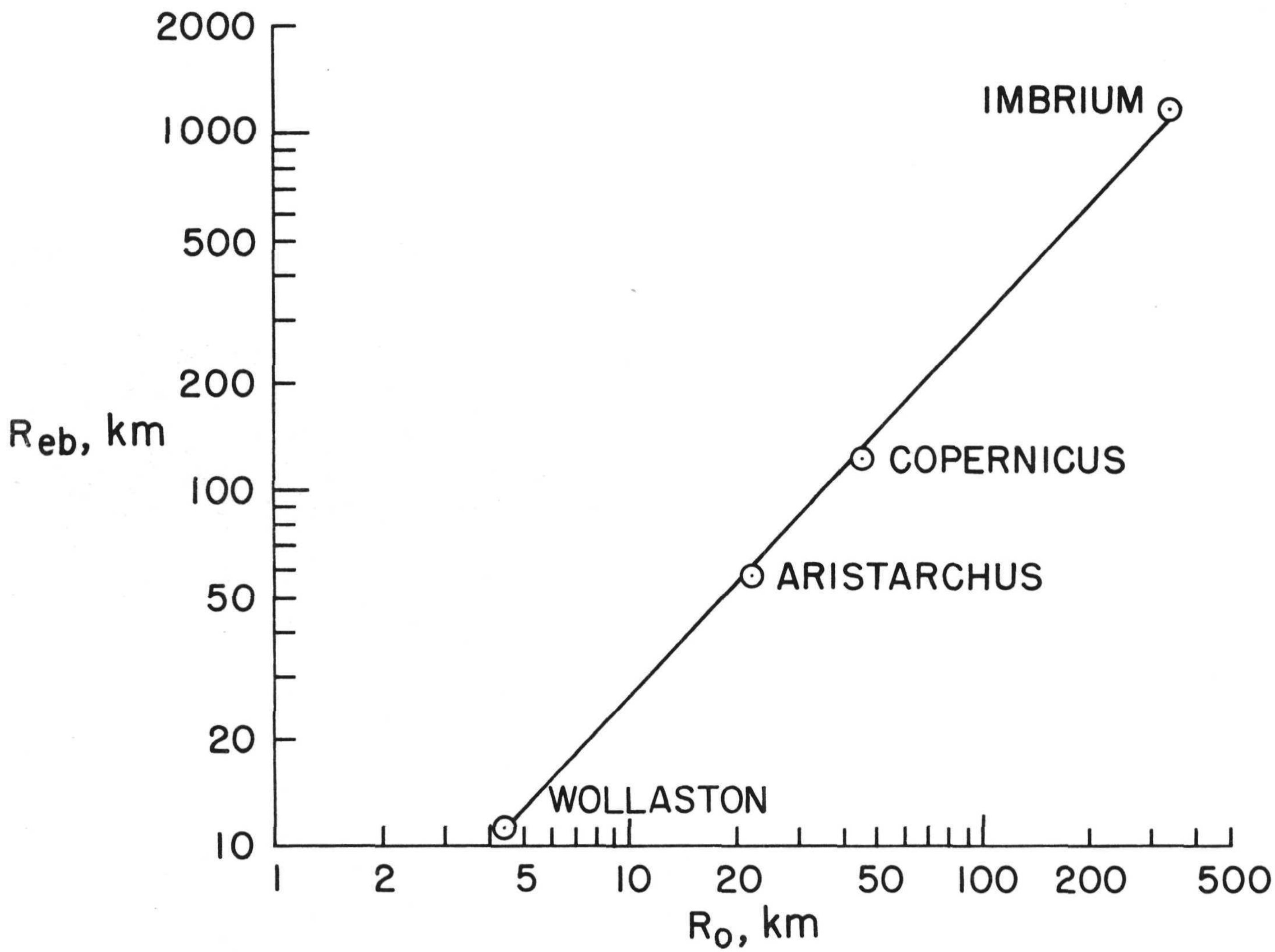

IMBRIUM
COPERNICUS
ARISTARCHUS
WOLLASTON
2000
1000
500
200
100
50
20
10
Reb, km
1
2
5
10
20
50
100
200
500
Ro, km

Figure 6.

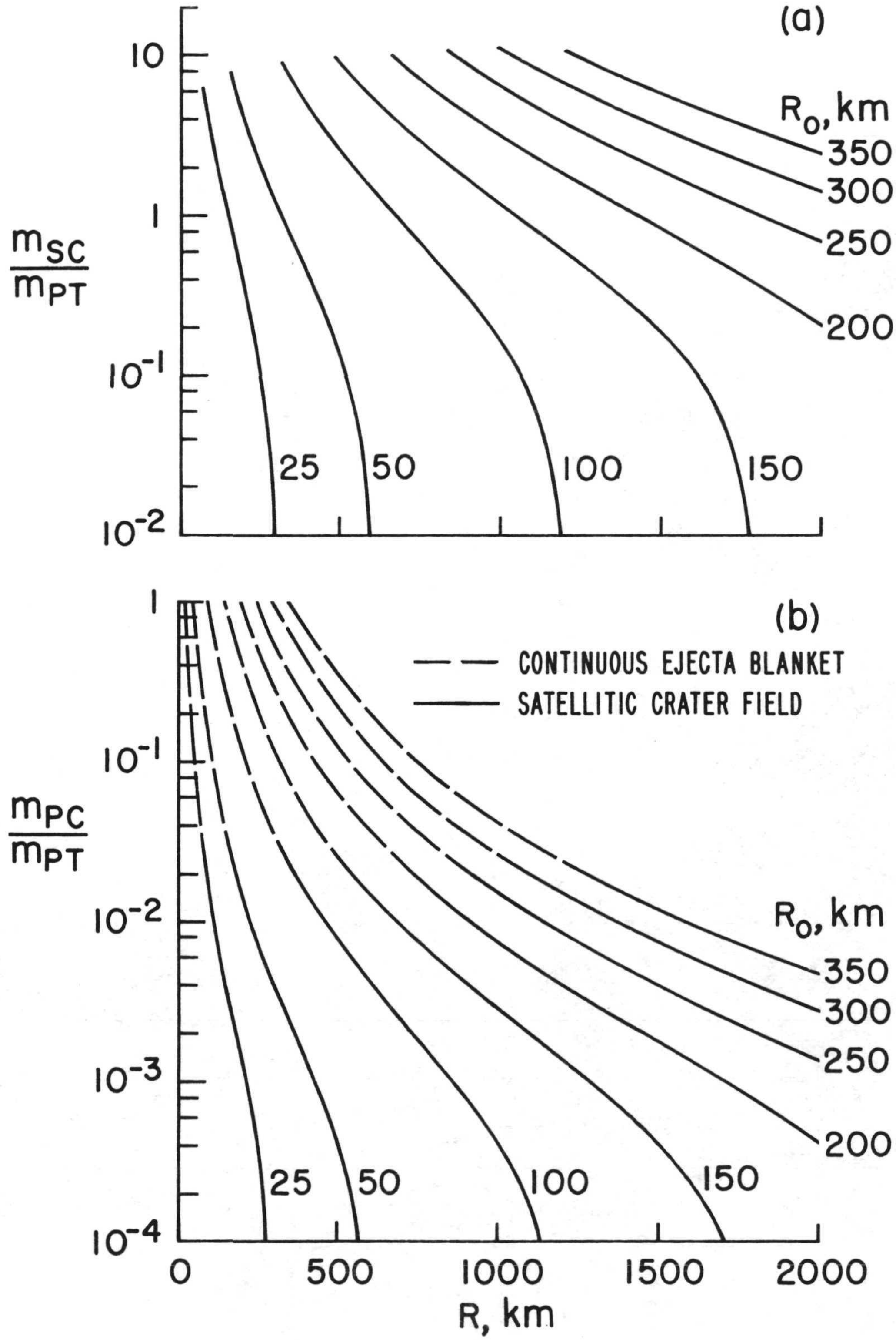

(a)
10
1
10^{-1}
10^{-2}
$\frac{m_{SC}}{m_{PT}}$
R_0, km
350
300
250
200
25
50
100
150
(b)
CONTINUOUS EJECTA BLANKET
SATELLITIC CRATER FIELD
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\frac{m_{PC}}{m_{PT}}$
R_0, km
350
300
250
200
25
50
100
150
0
500
1000
1500
2000
R, km

Figure 7.

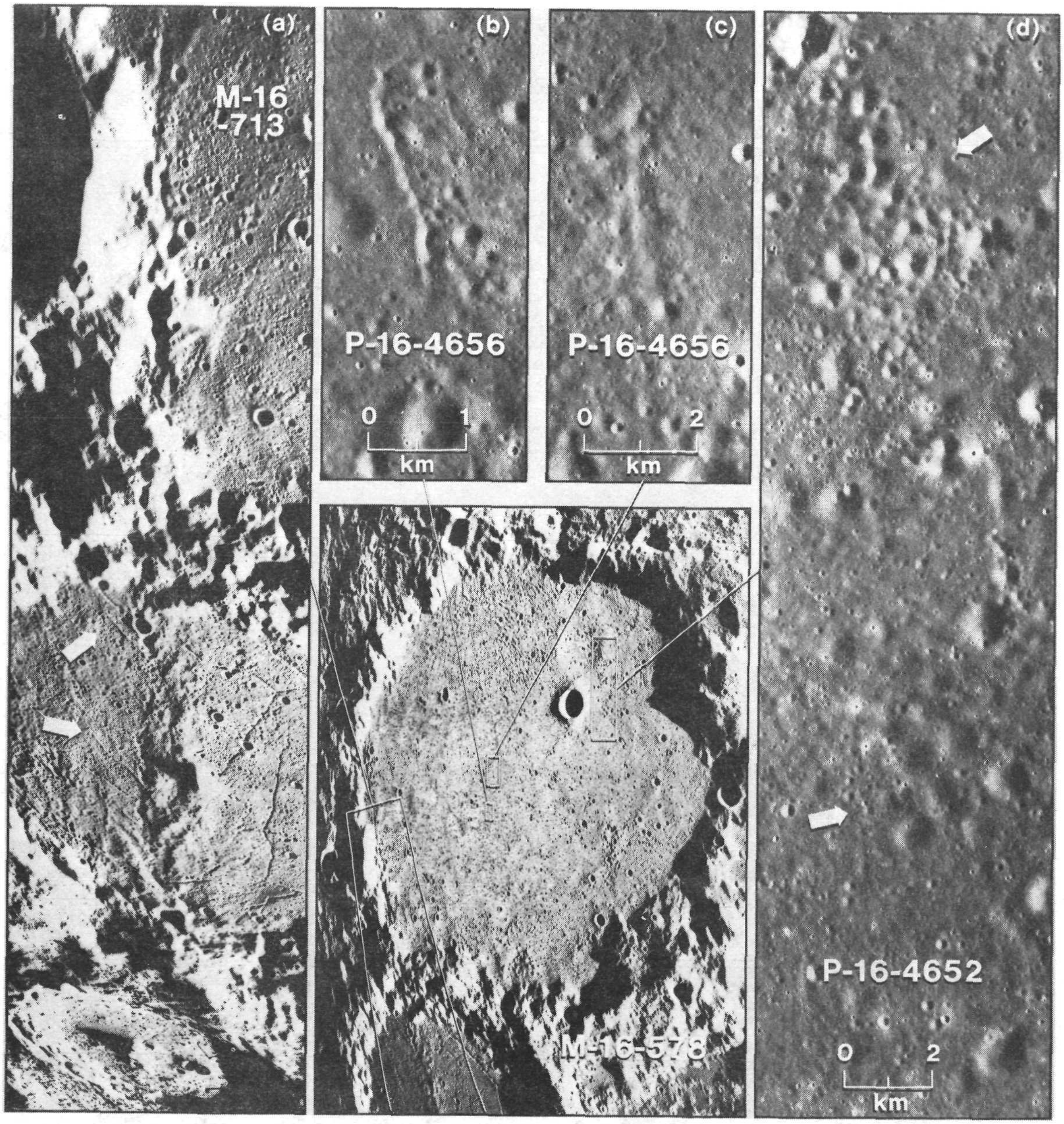


Figure 8.

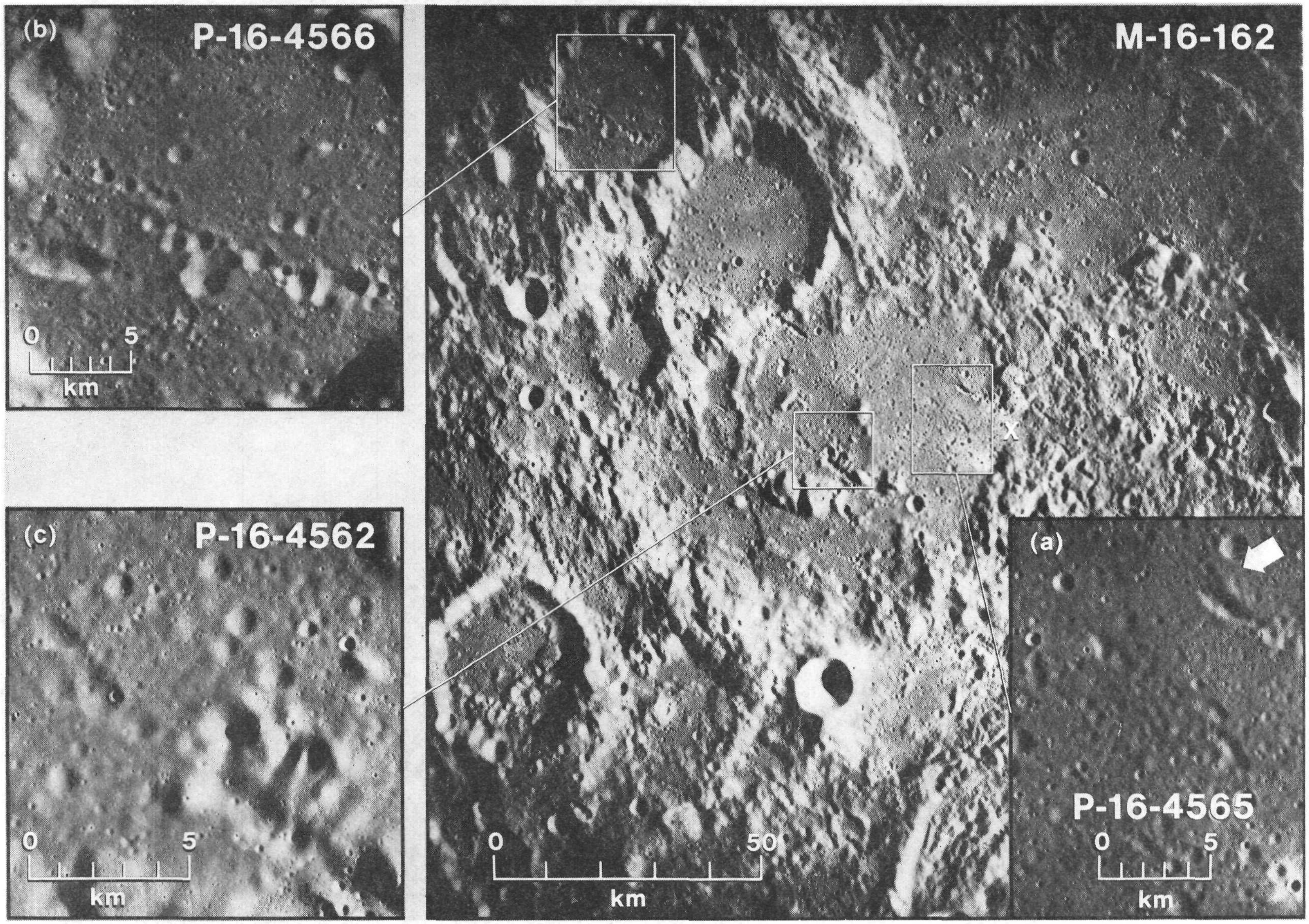


Figure 9.

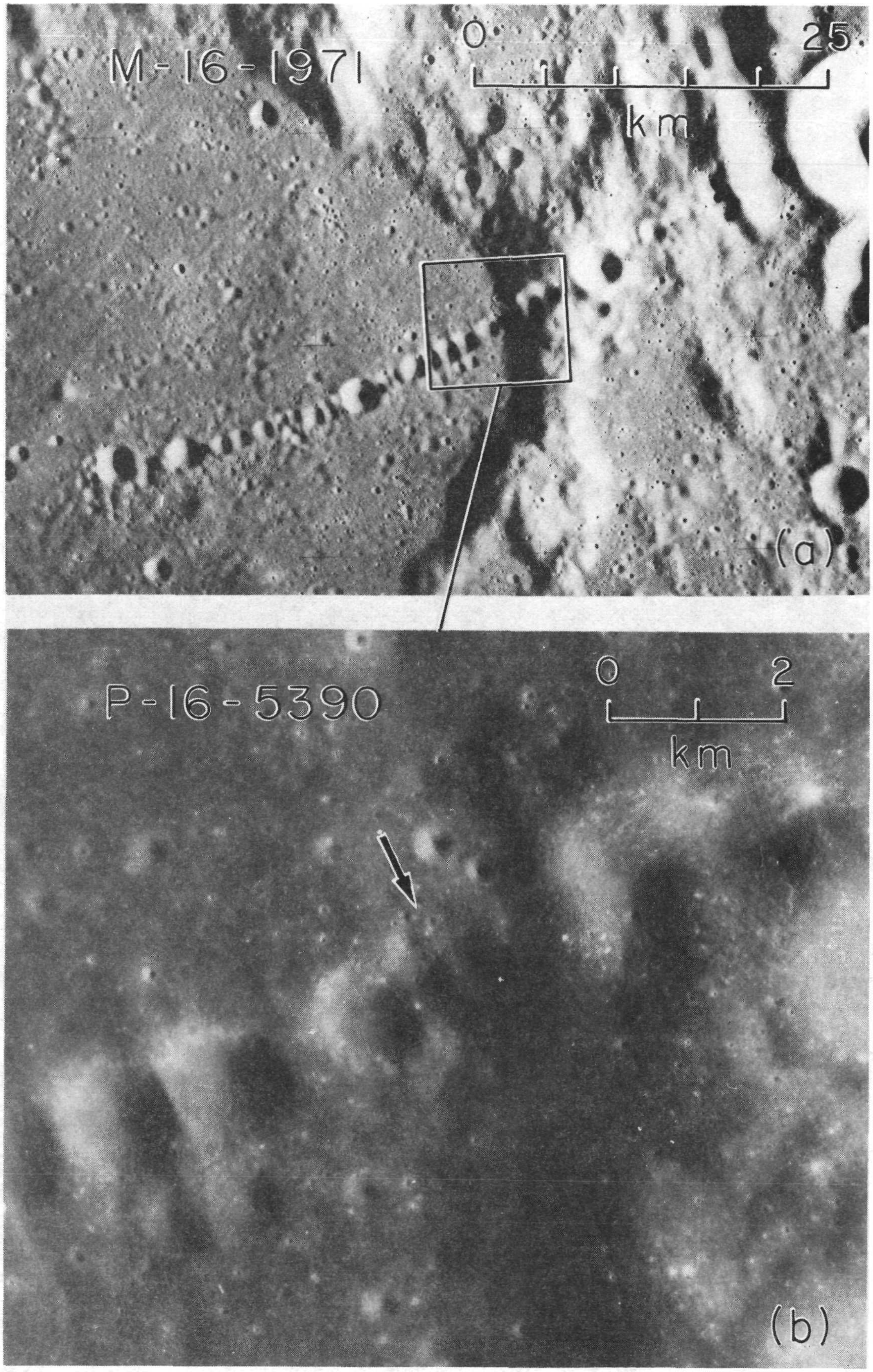


Figure 10.

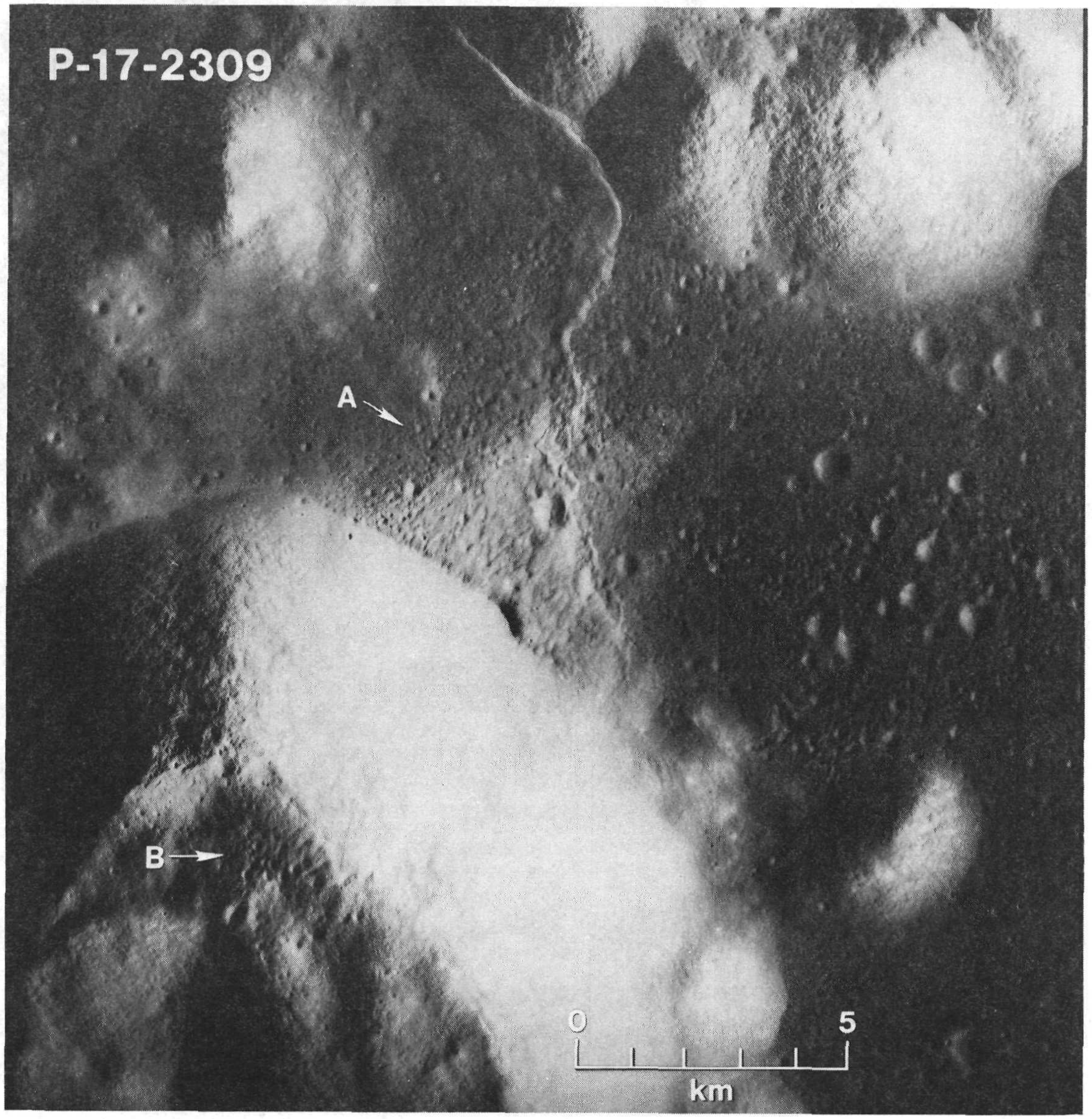
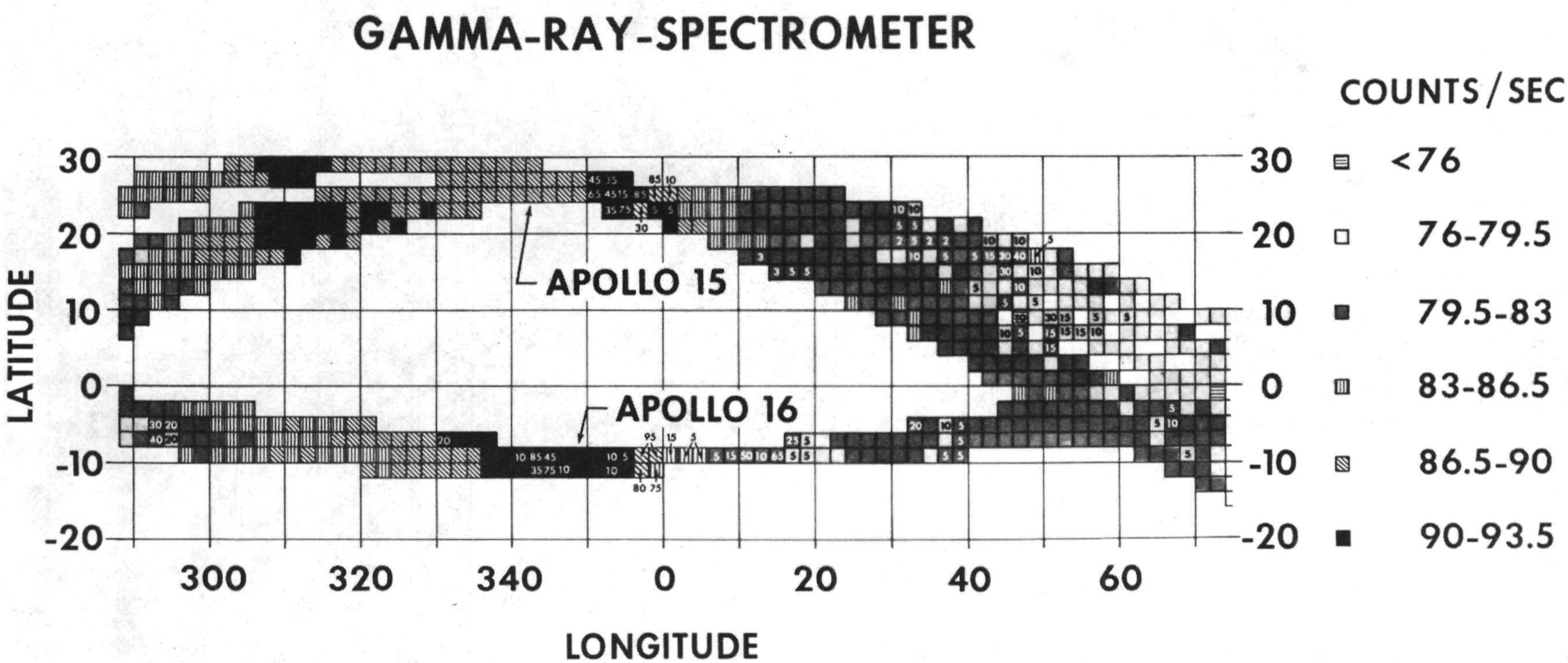
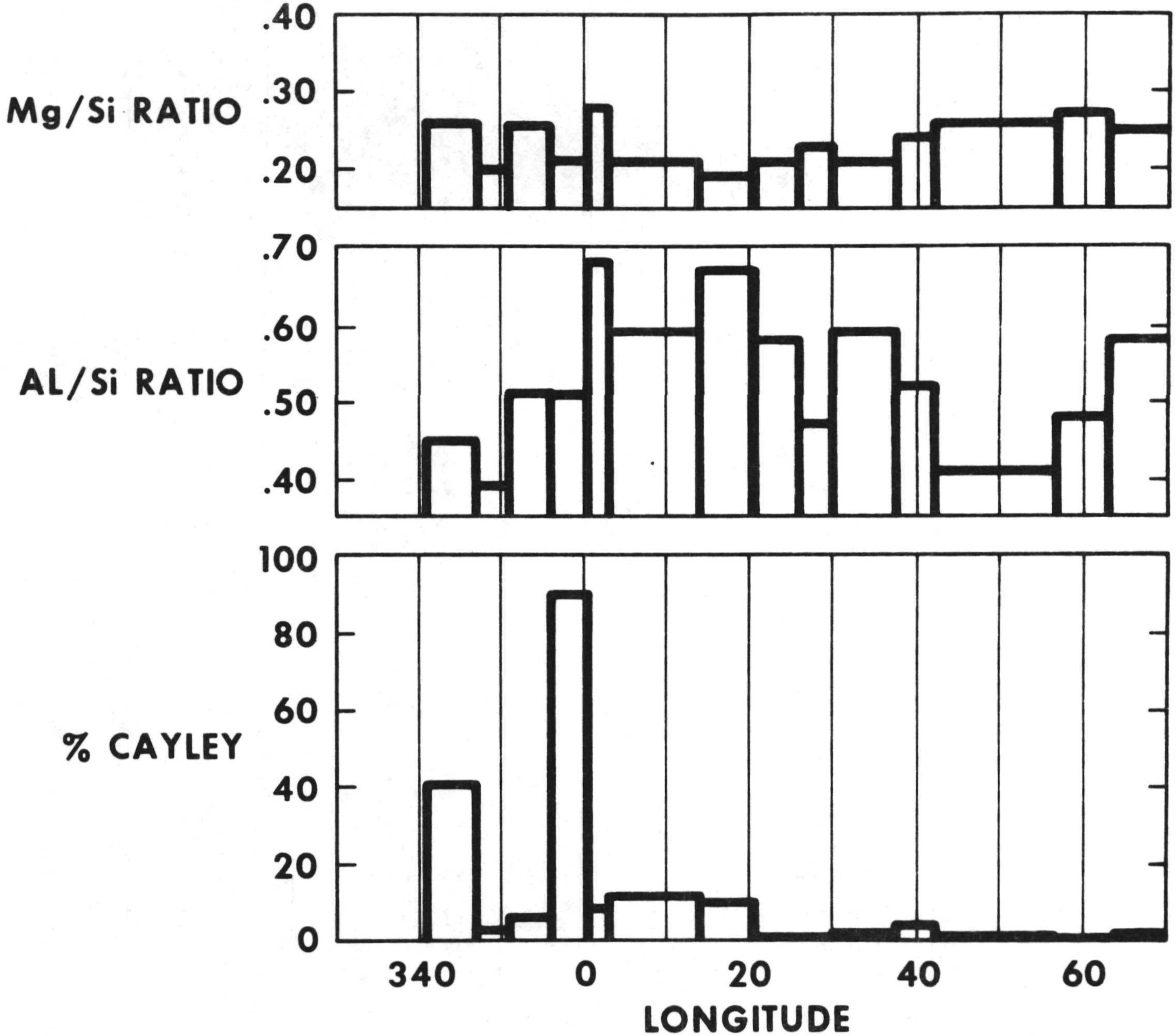


Figure 11.



GAMMA-RAY-SPECTROMETER
COUNTS / SEC
<76
76-79.5
79.5-83
83-86.5
86.5-90
90-93.5
APOLLO 15
APOLLO 16
LATITUDE
LONGITUDE

Figure 12.



Mg/Si RATIO
.40
.30
.20
AL/Si RATIO
.70
.60
.50
.40
% CAYLEY
100
80
60
40
20
0
340
0
20
40
60
LONGITUDE

Figure 13.