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IMPLICATIONS OF REGOLITH THICKNESS IN APOLLO 16 LANDING SITE

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IMPLICATIONS OF REGOLITH THICKNESS

IN THE

APOLLO 16 LANDING SITE

by

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INTRODUCTION

Apollo 11 and 12 landing sites were on surfaces of basalt lava flows covered by regolith deposits that are the combined ejecta blankets of impact craters. They are typical of most maria terrains. For many areas in the maria it has been possible to use a Monte Carlo impact cratering model to compute regolith thickness distributions that are in agreement with regolith thickness distributions estimated from the morphology of small impact craters. When the calculated results agree with observed regolith thickness, it can be inferred that the regolith deposit in question was produced mainly by the impact process. This has obvious implications for interpretation of the geologic history of the area.

The purpose of this report is to determine the thickness of the regolith in the Apollo 16 landing site, to suggest certain areas where substrate samples may be obtained and to compare the results with predictions of regolith thickness calculated from the Monte Carlo impact cratering model. These comparisons will be used to offer several alternative interpretations of the recent geologic history of the landing site.

REGOLITH THICKNESS IN THE APOLLO 16 LANDING SITE

Methods of regolith thickness determinations yielding a detailed percentage distribution of lunar surface area with a given thickness (Oberbeck and Quaide, 1967 and Quaide and Oberbeck, 1968) cannot be applied in the study of the Apollo 16 landing site. These methods require the classification of large numbers of small normal, flat-bottomed, and concentric craters. The resolution of the Apollo 14 photographs covering the Apollo 16 landing site are not adequate to permit identification of small normal and flat-bottomed craters; nor are enough data available for accurate statistical analysis.

However, concentric craters can be identified and measured and the dimensions of these craters can be used to place limits on regolith thickness at the crater sites. Thus, regolith thickness measurements have been obtained from measurements of concentric craters near the three preliminary traverses. Experimental results given by Quaide and Oberbeck (1968), indicate that the thickness of the lunar regolith at the site of a lunar concentric crater is less than 0.125 D, where D is the crater rim crest diameter. These results have been confirmed independently from predictions of frequency distributions of other lunar crater types that were based on these laboratory results.

Apollo 14 photograph AS14-69-9520 showing the three preliminary traverses for the Apollo 16 mission is shown in Figure 1. Craters 2 through 8 have been identified from enlargements of this photograph as concentric craters containing central craters which usually are concentric to the outer craters. Crater 1 is probably a concentric crater but a distinct terrace cannot be identified because the center is small. However, there is an abrupt change in crater depth near the crater center and a bright ray surrounds the crater. Rays surrounding lunar craters of this size are caused by high concentrations of rocks that are derived from bedrock. Thus Crater 1 is also assumed to be a concentric crater.

Craters 1, 5, 6 and 8 are very near the paths of the proposed traverses. Their diameters are 25, 38, 51, and 46 meters, respectively. Therefore, the regolith thickness at the sites of Craters 1, 5, 6, and 8 is less than or equal to: 3.1 meters, 4.8 meters, 6.4 meters, and 5.7 meters, respectively. Craters 2, 3, 4, and 7 are further from the proposed traverses. The regolith thickness at these crater sites is less than 6.7, 6.4, 4.5, and 4.1 for Craters 2, 3, 4, and 7, respectively.

Based on these observations, regolith thickness appears to be less than 6.7 meters for most areas near and around the preliminary traverses. For all craters only an upper limit on regolith thickness can be calculated but the regolith could be much thinner than the indicated limit. Nevertheless, in order to locate that area with the thinnest probable regolith, that crater with the lowest limit of regolith thickness must be selected.

If only those craters identified as concentric craters are considered, Crater 7 must be selected as the site of thinnest probable regolith although the regolith thickness might be less at the sites of Craters 2 through 6. The regolith thickness at the site of Crater 7 is less than or equal to 4.1 meters. However, Crater 7 is almost 1 km distant from the southern arm of traverse 1. Regolith thickness at Crater 4 is less than or equal to 4.5 and it is only 450 meters west of the western arm of traverse II. Thus, it is suggested that a deep core be obtained at the site of Crater 4 on the second traverse and that the internal crater structure be documented photographically. This would require that the west arm of traverse II must be moved about 450 meters to the west in the vicinity of Crater 4.

If the regolith deposit is as thick as 4.5 meters at Crater 4, the bedrock will probably not be sampled by the deep core. Another opportunity for sampling bedrock is available on the third traverse. If astronaut observations of Crater 1 on traverse 3 reveal a bench or terrace on the walls of Crater 1, the regolith thickness adjacent to this crater will be less than 3.1 meters. Thus, bedrock sampling with a deep core would be highly probable adjacent to Crater 1.

IMPLICATIONS OF THIN REGOLITH DEPOSIT

In certain lunar maria areas, the regolith thickness distributions can be calculated from the total crater population. The greater the density of the crater population the greater is the thickness of the regolith. For example, Lunar Orbiter sites III P11, II P13b II P7b, V24 and Apollo 16 site have progressively higher populations of lunar craters. The estimated median regolith thickness for the first four of these lunar sites is 3.3, 4.5, 7, and 15 meters, respectively. However, the regolith thickness in the immediate area of the Apollo 16 landing site is less than 6.7 meters, less than what would be expected on the basis that its crater population is higher than crater populations in the other lunar sites.

The calculation of the regolith thickness distribution that would be produced if all craters in any of the lunar sites are impact craters is performed using a Monte Carlo cratering simulation model that has been developed to study lunar regolith evaluation. The results can be used to interpret the recent geologic history of the area studied. A brief description of the computer model will show the relationships between regolith growth and crater structure and other impact parameters.

MONTE CARLO IMPACT CRATERING MODEL

The computer simulation model generates craters and coordinates for craters using a random number generator. Craters are selected from cumulative distributions characteristic of craters that have been produced in a given lunar area. Averages of large numbers of crater counts and consideration of the destruction of very small craters by other craters, indicate that the cumulative number of craters per square kilometer that have been produced in these areas is proportional to the inverse 3.4 power of crater diameter given in meters. Figure 2 shows crater counts for the Lunar Orbiter III P11, II P13b, II 7b, and V24 sites and the Apollo 16 site superimposed on these hypothetical crater production curves. Solid lines of Figure 2 characterize values of K in crater distributions $N + K D^{-3.4}$ of: 2.5×10^7, 4.3×10^7, 7.0×10^7, 2.5×10^8 and 5.0×10^8. They adequately characterize the lunar data plotted as points on the same curve above certain minimum diameters that are different for each area. Below this diameter, it is assumed that the straight lines represent those craters actually produced and that the data points represent those craters surviving the obliteration brought about by other impacts.

After a given crater is selected from the crater production distribution it is assigned a random X, Y coordinate and the recorded thickness at that point in the computer grid array, the result of the combined ejecta of all previous craters, is determined. The crater diameter is then divided by the thickness and this determines whether the crater is normal flat-bottomed or concentric (Quaide and Oberbeck, 1968) or if it is formed entirely in hard rock. This, in turn, determines the amount of regolith material that is redistributed and the amount that is added to the regolith. For a crater of a given diameter these amounts depend on crater structure. Therefore, the amount of material added to the regolith by a crater of any given diameter is dependent on the particular history of cratering of all previous craters that have been produced by random impact. Thus, either a probabilistic calculation of regolith thickness or an actual simulation is required for a rigorous determination of the regolith thickness distribution that is associated with any given total crater population.

Figure 3 illustrates the effect of existing regolith thickness at the site of a crater on the growing regolith calculated by the Monte Carlo simulation model. Consider an initial uncratered lava flow surface. Craters C1, C3 and C5 are produced in the hard rock where there is no initial thickness (t_i) of debris. The volume of ejecta is computed by determining the volume of the crater according to a function determined from measurements of hard rock crater shapes. The volume determined is bulked by a factor derived from lunar sample measurements and is deposited about the crater. In Figure 3 it is shown as an annular blanket with uniform thickness and a radius equal to seven times the crater radius. The program permits distribution of the ejecta evenly, as shown, in an evenly decreasing pattern, or according to a negative power function. The extent of the ejecta throw-out can also be varied, but the value of 7r is a realistic measure determined from Lunar Orbiter photographs by measuring the radius of bright haloes around fresh craters and also by measuring the value of r at which craters with $D < 10$ m approach nominal mare concentrations.

Consider now crater C6, which is formed on the ejecta blanket of crater C5 and is of such a size that the crater is entirely in the debris layer ($D < 4t$). The volume is calculated according to a formula derived from measured shapes of normal lunar craters. The ejecta volume in this case is equal to the crater volume, since the debris layer has already been bulked. The ejecta is distributed according to the selected function. No new fragmented rock is added to the regolith from this crater.

Crater C4 happens to form where the regolith thickness, t_i, is greater than 9 DA, but less than 4 DA. According to laboratory experiments the geometry of the crater will be either that of a central-mound or flat-bottomed type. In this model study we lump both types into flat-bottomed geometry with a volume of the frustum of a cone. Again the volume of ejecta is equal to the crater volume. The ejecta is distributed according to the selected function. No new debris is added to the regolith.

Crater C2, on the other hand, was produced where the previously accumulated ejecta thickness, t_i, was less than 9 DA. According to laboratory experiments, the crater has concentric geometry and the ejecta will include portions from the already bulked regolith and portions from the substrate rock. The volume of preexisting debris ejected is the volume of the frustum of a cone. The volume of the substrate crater is a function of the diameter of the outer crater and the regolith thickness at the time of impact and is determined according to an expression derived from measurements made on Lunar Orbiter photographs. The volume of the substrate crater is bulked according to the appropriate bulking factor and is distributed about the concentric crater along with the ejecta from the surficial crater according to the selected function.

In the calculation, craters are entered and debris thickness is accumulated at 3×10^5 grid points in a typical grid array area of 260 square kilometers. With this array, it is possible to study an area of 260^2 km with sensitivity sufficient to collect debris from craters with diameters as small as 4.5 meters. Constants in the expression for t_e of Figure 3 are only valid for ejecta of uniform thickness and are shown only for illustration. All calculations of regolith thickness presented in this paper assume a more realistic conical ejecta shape. Thus, T_e varies as a function of distance from the source crater.

Monte Carlo calculations of regolith thickness distributions associated with four of the five lunar surface areas considered agree with estimated thickness distributions. Figure 1 shows total crater counts for Lunar Orbiter sites II-P11, II P-13b, IIP-7b and V-24 superimposed on the respective hypothetical production curves used in the Monte Carlo simulations. Figure 4 shows a comparison of the Monte Carlo calculations of regolith thickness (dashed lines) with the thickness distributions estimated from crater morphologies in each of the lunar areas (Oberbeck and Quaide, 1968).

There is good agreement between the calculated and estimated thickness distributions. This indicates that the regolith is of impact origin in these lunar areas because the calculated values assume an impact origin of all craters. That is, structures assumed to calculate regolith thickness are similar to those produced in the laboratory by hypervelocity impact.

A plot of calculated median thickness as a function of constants k in the production population of impact craters is shown in Figure 5. This curve can be used as a ready check on the origin of any lunar regolith deposit. Extrapolation of the data show that if all craters observed on the Cayley formation at the Apollo 16 landing site are impact craters the average regolith thickness should be 22 meters because the crater population is $N = 5.0 \times 10^{8} D^{-3.4}$.

Since the regolith thickness in the vicinity of all the preliminary traverses is less than 6.7 meters, it appears that either all observed craters are not impact craters or that some process has produced an indurated layer on top of the impact produced regolith without obliterating the underlying craters. Of the two possibilities the second is favored. If craters were of some origin other than impact they would probably be associated with volcanic terrains, flow surface structures should then be observed and at least some of the craters should appear fresh. Neither of these requirements is satisfied.

Most of the craters in the landing site are subdued. Therefore, it is suggested that most of the craters in the landing site are, in fact, of impact origin and that a deep regolith has been produced. However, it is further suggested that the regolith and impact craters have been mantled by a deposit that was indurated after deposition. This would produce the subdued appearance of the large craters and provide an indurated formation that could subsequently be modified by recent impact craters to produce a thinner regolith deposit.

If this interpretation is correct, the craters suggested for sampling bedrock might, in fact, sample a near surface indurated stratum rather than a substrate associated with the surface that existed before the production of the large craters. The hypothesized near surface stratum could be a welded ash deposit that may have originated from the volcanic terrain of the plateau to the south of the landing site.

CONCLUSIONS

Regolith thickness appears to be less than 6.7 meters in the vicinity of the three preliminary traverses. Crater 7 occupies the site with the lowest calculated limit of regolith thickness; it is 1 km from the nearest traverse. The next lowest calculated upper limit of regolith thickness is for the site of Crater 4 which is only about 450 meters from the traverse. If deep cores can be obtained at any place along the three traverses it should be obtained at the site of Crater 4. However, if the regolith thickness is as great as 4.5 meters at Crater 4, the deep core will probably not sample bedrock. In that case, a deep core should be obtained at the site of Crater 1 provided observation of the internal crater wall reveals a terrace. In that case regolith thickness near Crater 1 is less than 3.1 meters.

If the deep core can be obtained only near the landing site it should be obtained near Crater 5. Regolith thickness is less than 4.8 meters near Crater 5 and there is a fair chance of sampling bedrock. Photographic documentation of internal crater terraces should be obtained for all craters.

Perhaps all efforts to sample bedrock will fail due to operational constraints. If so, samples collected carefully from the rims of concentric Craters 1-8 will represent bedrock samples. These samples should be chipped from the largest rocks on the rims of the craters. The largest rocks surrounding concentric craters are produced from ejection of material from the central crater formed in the bedrock. However, much of the fine grained ejecta surrounding concentric craters was ejected from the preexisting regolith. The original site of crystallization of this material is unknown.

If samples are chipped from the largest rocks on the rims of the concentric craters, they would provide a good sample of geographic variation in properties of the bedrock. Craters 1, 3, 4, 5, 6, and 8 could be sampled in this manner because they are very close to the traverses. Total depth of concentric craters is about one-fourth the crater diameter. Thus, ejecta of Craters 1, 3, 4, 5, 6, and 8 probably sample bedrock material that was within 13 meters of the original upper surface of the indurated formation. Thus an opportunity exists for observing geographic variation in physical and chemical properties of the rock formation in this area. Finally, it is suggested that this near surface indurated formation may be a welded ash deposit that has mantled the large subdued impact craters in the area.

FIGURE CAPTIONS

Figure 1. Apollo 14 photograph AS14-69-9520 of three preliminary traverses of the Apollo 16 mission showing the location of concentric craters used to estimate regolith thickness.

Figure 2. Crater counts for Lunar Orbiter sites: III P11, II P13b, II P7b, V24, and Apollo 16 site superimposed on crater production curves used in Monte Carlo simulation of impact cratering.

Figure 3. Schematic of Monte Carlo cratering model showing the effect of regolith thickness on crater structure and on thickness of ejecta blanket, t_e.

Figure 4. Comparison of regolith thickness distributions calculated from Monte Carlo impact model with distributions estimated from morphology of small craters.

Figure 5. Median thickness of regolith calculated from Monte Carlo cratering model plotted as a function of K in crater production distributions: $N = KD^{-3.4}$.

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Quaide, W. L. and Oberbeck, V. R., 1968, Thickness Determination of the Lunar Surface Layer from Lunar Impact Craters. Journal of Geophys. Res. 73, 5247-5270.

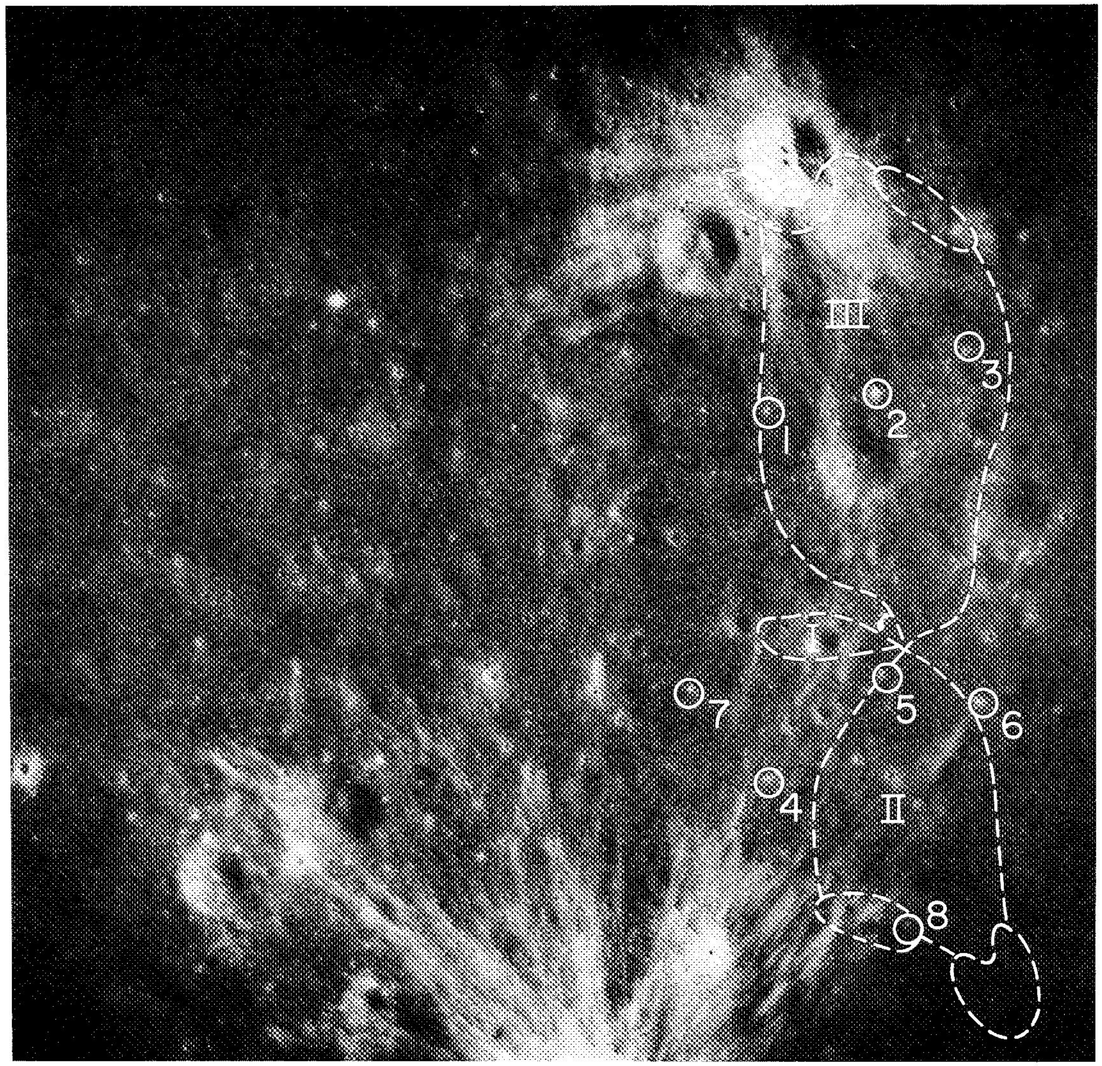


Figure 1.

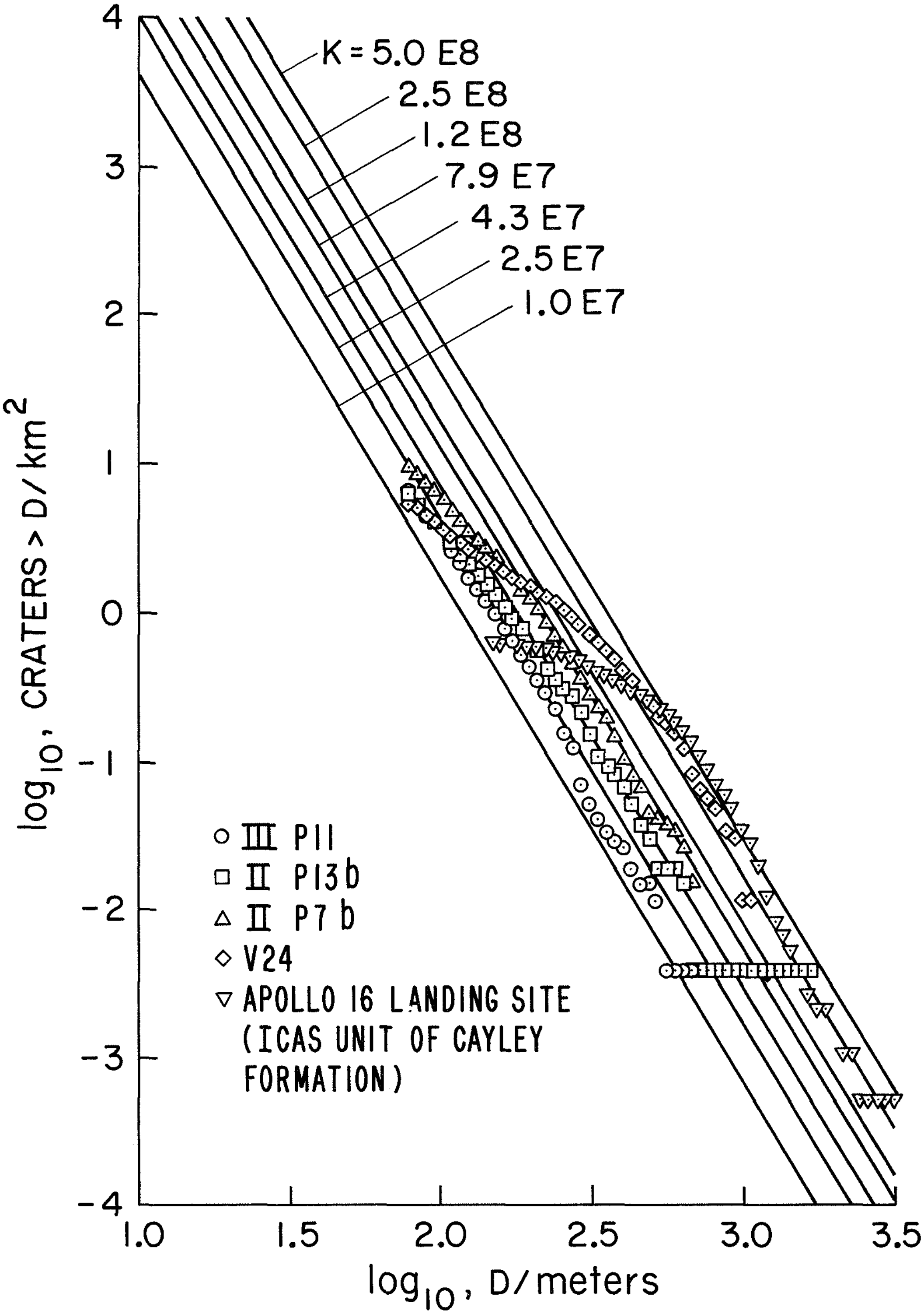
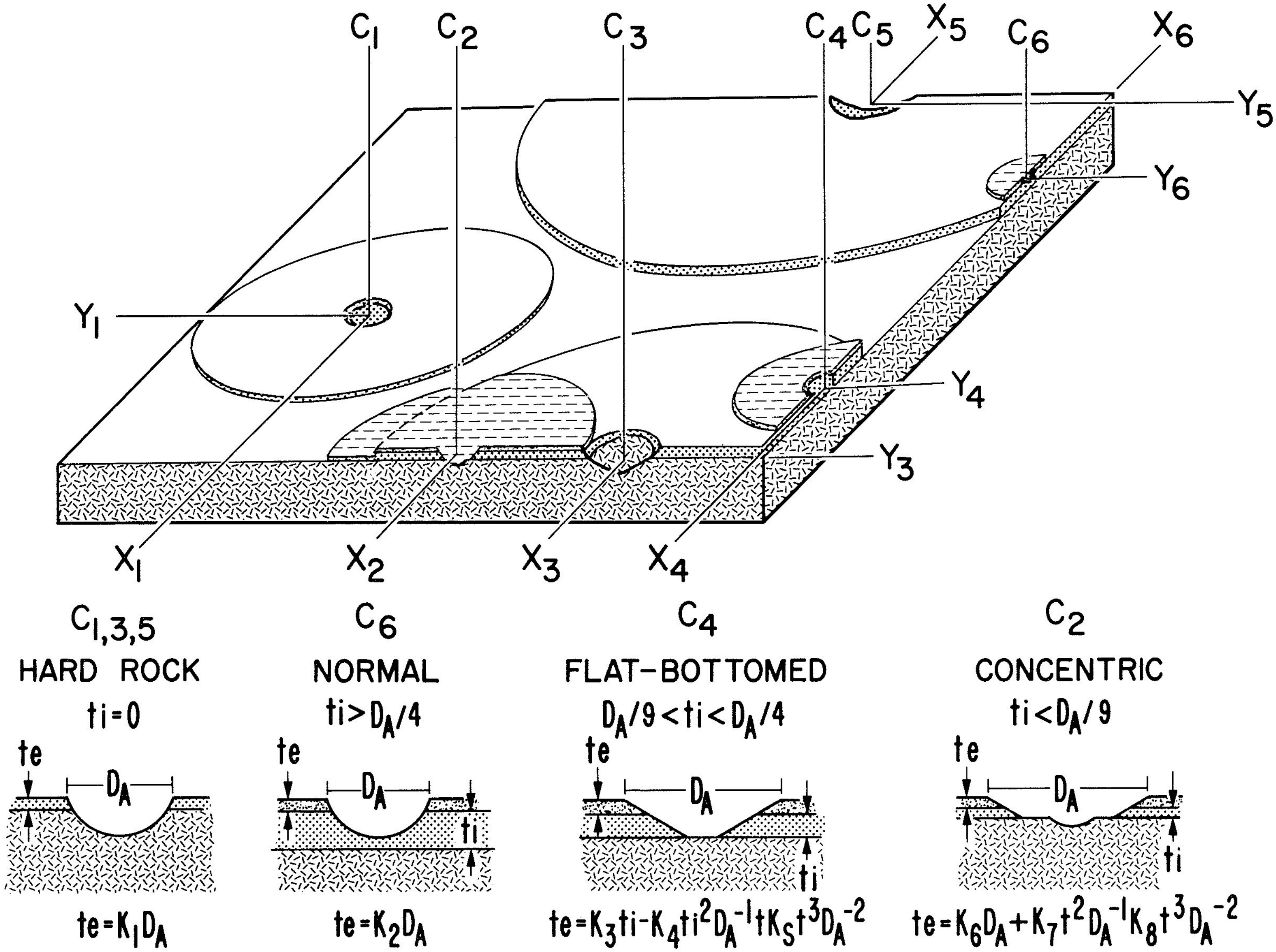

K = 5.0 E8
2.5 E8
1.2 E8
7.9 E7
4.3 E7
2.5 E7
1.0 E7
log10, CRATERS > D/km2
log10, D/meters
4
3
2
1
0
-1
-2
-3
-4
1.0
1.5
2.0
2.5
3.0
3.5
III P11
II P13b
II P7b
V24
APOLLO 16 LANDING SITE (ICAS UNIT OF CAYLEY FORMATION)

Figure 2.



C_1
C_2
C_3
C_4
C_5
X_5
C_6
X_6
Y_5
Y_6
Y_1
Y_4
Y_3
X_1
X_2
X_3
X_4
$C_{1,3,5}$
HARD ROCK
$ti=0$
te
D_A
$te=K_1D_A$
C_6
NORMAL
$ti>D_A/4$
te
D_A
ti
$te=K_2D_A$
C_4
FLAT-BOTTOMED
$D_A/9<ti<D_A/4$
te
D_A
ti
$te=K_3ti-K_4ti^2D_A^{-1}tK_St^3D_A^{-2}$
C_2
CONCENTRIC
$ti<D_A/9$
te
D_A
ti
$te=K_6D_A+K_7t^2D_A^{-1}K_8t^3D_A^{-2}$

Figure 3.

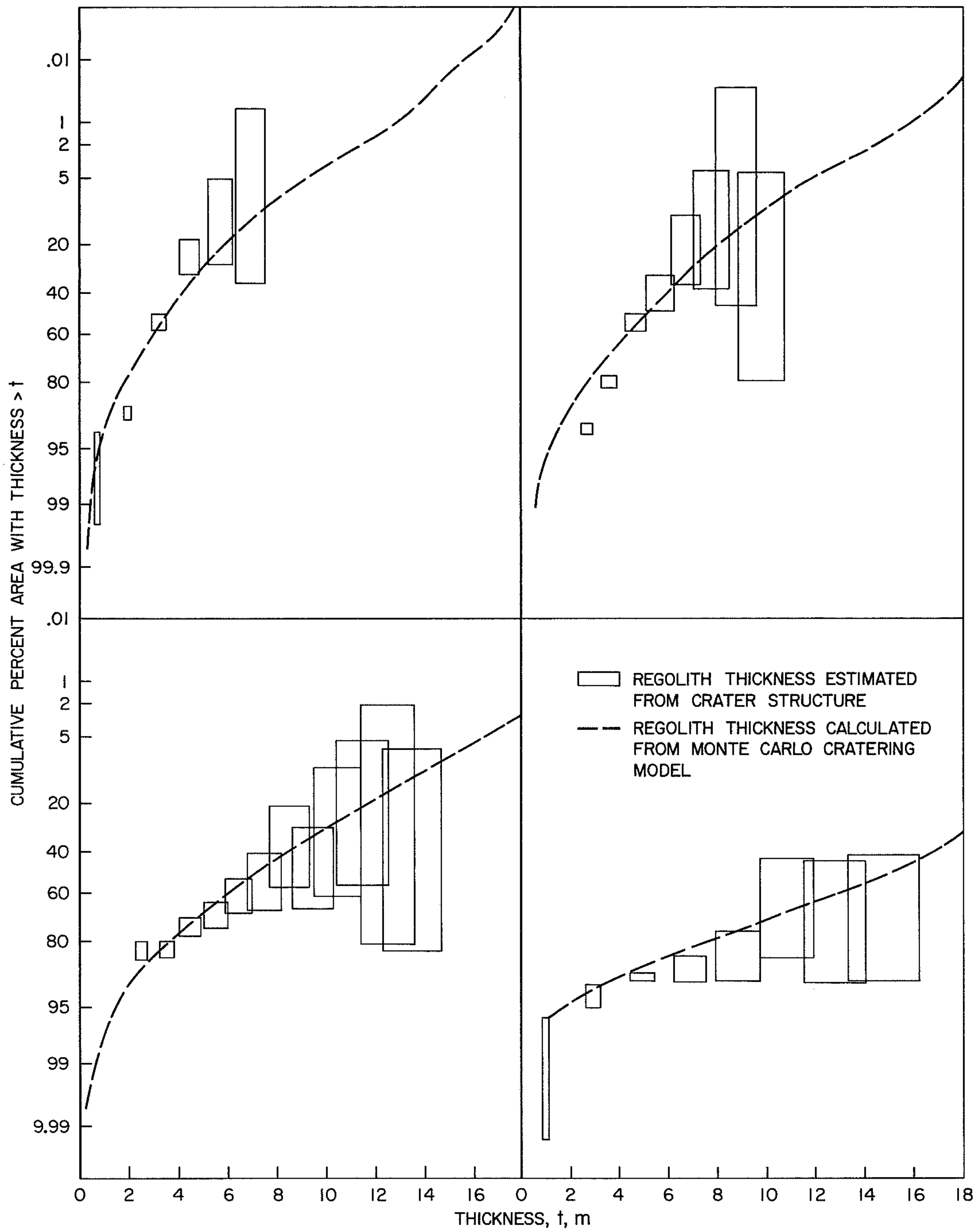

CUMULATIVE PERCENT AREA WITH THICKNESS > t
REGOLITH THICKNESS ESTIMATED FROM CRATER STRUCTURE
REGOLITH THICKNESS CALCULATED FROM MONTE CARLO CRATERING MODEL
THICKNESS, t, m

Figure 4.

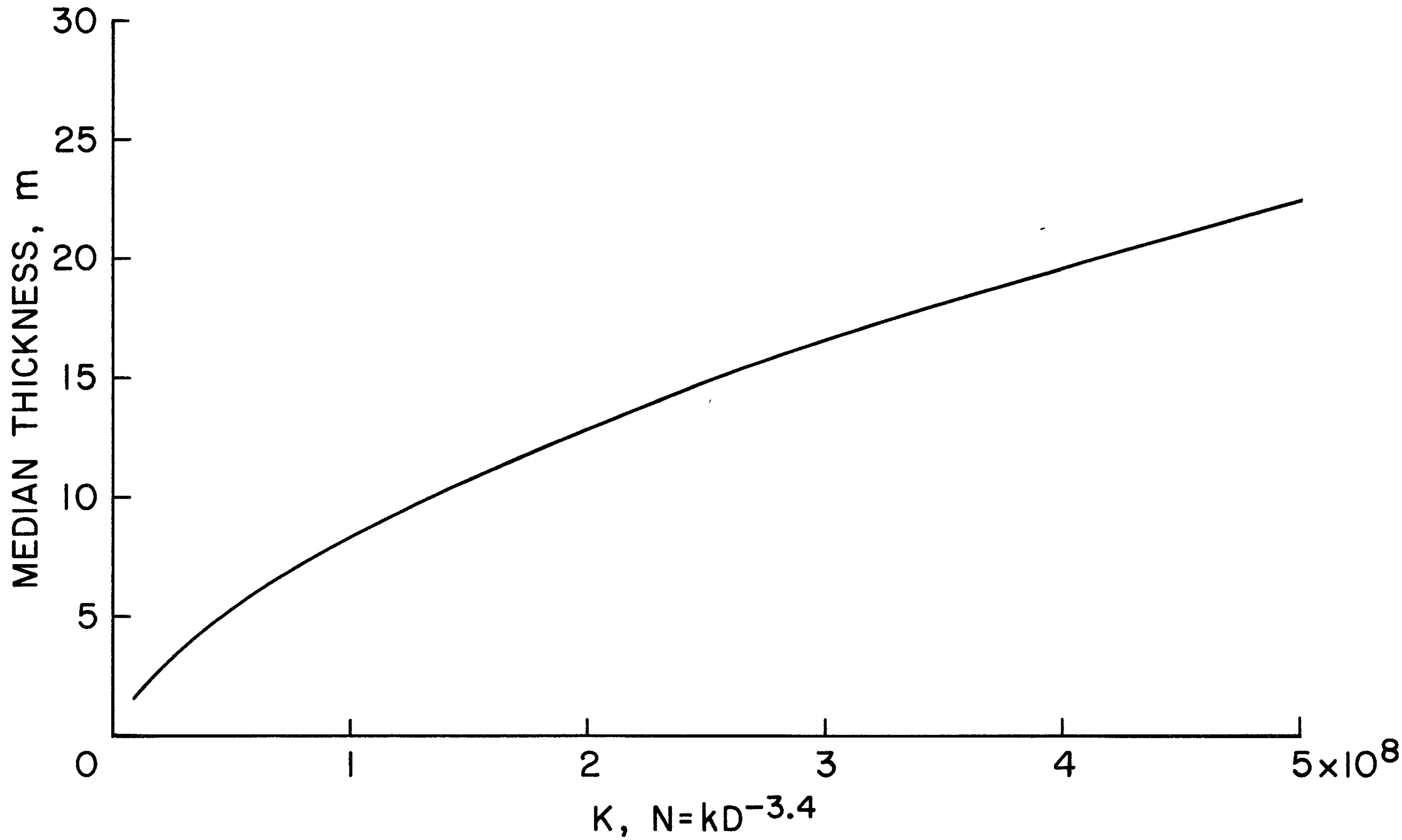


Figure 5.