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OPTICAL PROPERTIES OF APOLLO 12 MOON SAMPLES

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ABSTRACT

The photometric phase function, color, normal albedo, polarimetric phase function, and spectrophotometry of the Apollo 12 soil are presented. In general, the optical properties of the Apollo 12 soil are very similar to those of the Apollo 11 soil and of lunar mare surfaces in general. Significant differences are that the Apollo 12 soil is 20 per cent brighter and considerably redder than the Apollo 11 soil. These may be explained by the presence of material comprising a ray of the crater Copernicus.

INTRODUCTION

During the past year, several papers on the optical properties of Apollo 11 lunar samples have appeared in the literature. There has been considerable overlap in coverage, with emphasis placed on the spectrophotometry of rocks and fines and on the photometric and polarimetric phase functions of the fines. The agreement among various experimenters has been generally good, with the result that the optical properties of the Apollo 11 fines are similar to those for a several km^2 area of Mare Tranquillitatis surrounding the landing site [Adams and McCord, 1970; O'Leary and Briggs, 1970].

Nevertheless, there remains some significant discrepancies between various experiments, particularly in their interpretation. It is not our purpose here to present a discourse on conflicting interpretations; only after much further study, maybe never, will a coherent story arise regarding the optical properties of the lunar surface.

In this paper, we present in detail the optical properties of the Apollo 12 samples and compare them to Apollo 11 samples and to the Moon as a whole. This work is an extention of similar studies performed on Apollo 11 samples [O'Leary and Briggs, 1970]. We have attempted to vary as many parameters as is reasonably possible in order to simulate the undisturbed lunar surface. Only then is it possible to make inferences regarding (1) the correlation between samples with large lunar reflectivities at 0.56μ wavelength of the Apollo 12 and Apollo 11 powders with a "mean moon" curve taken from Hapke [1968] and normalized to the normal albedo of the Apollo 11 site [Wildey and Pohn, 1969]. Both samples were prepared by gradually dropping the fines from a height of about 2 centimeters onto a sample tray. While the photometric curves of the two samples have similar shapes, the Apollo 12 soil is noticeably the brighter. For a given phase angle, the Apollo 12 soil is about 20 per cent brighter than the Apollo 11 soil, suggesting that an appreciable quantity of ray material is mixed in with the Apollo 12 mare material.

For $\epsilon = 60^{\circ}$, the photometric functions of the soils are flatter at large phase angles than is the moon. This effect can probably be attributed to large scale roughness of the lunar surface as will be discussed later in this paper.

Figure 2 gives reflectivity measurements for Apollo 12 soil in three colors. Extrapolation to zero phase angle results in the normal albedoes given in Table 1. Laboratory determinations of the color index, B-V, as a function of phase angle are plotted in Figure 1, along with the earthbased observations of Gehrels, Coffeen and Owings [1964] corrected for a solar B-V of 0.63. The Apollo 12 soil is redder than both the Apollo 11 soil and the mean value of the moon, and shows greater reddening with phase angle than Apollo 11 soil. Both samples show a minimum in B-V at $\sim 5^{\circ}$ phase angle, implying a steeper opposition effect at longer wavelengths than at shorter wavelengths. Unfortunately, information about the normal albedo and phase function of the Apollo 12 site from remote sensing are not available, so a detailed quantitative comparison between soil and site is not available. However, Mitchell and Pellicori [1970] have observed a 80 km-diameter region in Oceanus Procellarum about 225 km from the Apollo 12 landing site. Corrected for the solar B-V, their B-V value for the region is 0.14 at 90° phase angle, which is considerably bluer than the Apollo 12 soil and bluer than any of 17 other lunar regions sampled. Again, this suggests that ray material from Copernicus, which is much redder than mare regions [Coyne, 1965], is mixed in with the Apollo 12 soil.

The polarization dependence on phase angle for the Apollo 12 soil is very similar to that of the moon as a whole [Hapke, 1968] as shown in Figure 3. However, both samples have their peaks in polarization occurring at somewhat greater phase angles than does the moon [Pellicori, 1969]. The maximum polarization of the Apollo 12 sample is in good agreement with earthbased observations while that of Apollo 11 is anomalously high. Figure 4 gives phase dependence of polarization for the Apollo 12 soil in three colors, again in good agreement with the earth-based studies of mare regions by Pellicori [1969].

A study of the optical behavior for three degrees of compaction resulted in the curves of Figures 5 and 6. A process of roughening the soil surface by raking with the point of a needle gave the "fluffed" state [Hapke, 1968; Hapke et al, 1970a and b]. Lightly tamping the sample with a flat surface of stainless steel approximately 1 cm in diameter produced a smooth, level state of compaction labeled "packed". The "dropped" state was obtained by gradually dropping the powder as were the samples for the previously presented curves.

The "packed" curves are significantly different from both states of lesser compaction and from earthbased observations of the moon, in that they show a broad specular peak in reflectivity and excessive polarization at large phase angles. The range in normal albedoes of the various states was found to be similar to that reported for the Apollo 11 soil by Hapke et al [1970a and b]. The "packed" and "fluffed" curves of reflectivity and polarization bound the "dropped" curves, with the "fluffed" sample showing slightly lower reflectivites and lower polarizations than the "dropped" sample. Comparison of these samples with lunar surface photographs immediately rule out the "packed" state as a natural state of the lunar material. On the other hand, the "fluffed" state appears to have an unnatural roughness which is unlikely (though not impossible) to occur on the lunar surface. From examination of photographs, the true answer seems to lie between the "dropped" and "fluffed" states, with a tendency toward the dropped state. It is fortunate that the optical properties of both dropped and fluffed samples are similar, and that different fluffings and droppings produce results which repeat quite faithfully.

It is now possible to examine certain discrepancies between Apollo 11 results with the benefit of our study of the Apollo 12 soil. First, Hapke et al [1970b] have suggested that the relative flatness of the phase function of the lunar soil with respect to the Moon as a whole (e.g., see Fig. 1 $\epsilon = 60^{\circ}$) would tend to disappear if the sample is raked and fluffed. However, in Figure 5 we see that fluffing the soil affects the slope of the phase function only slightly, and it appears unlikely that varying the compaction is sufficient to produce the required match. It is more probably that large-scale roughness, e.g., mountain and rock shadows, account for the steeper phase curve for the moon as a whole.

The anomalously high polarization of our Apollo 11 soil (Fig. 3) is difficult to explain, because similar measurements by Geake et al [1970] do not show the anomaly. It is possible that our sample may have compacted too much from its dropping or that there was an inadvertant selective sifting in particle size. We did not observe a similar anomaly with the Apollo 12 soil, so it is unlikely that our previous measurements suffered from systematic instrumental errors. Moreover, the Apollo 11 polarization anomaly repeated for successive droppings suggesting that the effect is real. We are presently investigating possible sources of error attributable to sample preparation, but are meanwhile forced to conclude that our Apollo 11 soil exhibited anomalously high polarizations.

Finally, the normal albedo of our Apollo 11 soil sample was considerably lower than that measured on the Apollo 11 soil by Hapke et al [1970a and b], but in good agreement with that obtained from Apollo photography of a several km^2 area surrounding Tranquillity Base [Wildey and Pohn, 1969]. It is unlikely that the state of compaction or particle size selection are sufficient to explain the discrepancy. Hapke et al [1970b] suggested that the Apollo 11 soil was not typical of the Tranquillity site, an explanation which is not required for our results. In fact, the albedo of our Apollo 11 sample integrated over a hemisphere was somewhat lower than that of the lunar surface surrounding Tranquillity Base [O'Leary and Briggs, 1970]. At that time we suggested that the subsurface soil of the sample was slightly darker than the surface soil, in agreement with Surveyor results [Jaffee et al, 1968; Shoemaker et al, 1969] and consistent with the concept of ultraviolet bleaching of the lunar surface by the sun [Cohen and Hapke, 1968].

Figure 7 shows the diffuse reflectances of Apollo 12 soil and rocks from 0.4μ to 1.8μ wavelength as measured by a Cary 14 spectrophotometer with an integrating sphere. Spectrophotometry of the rock required that two chips (12022,88 and 12022,89) from the same rock be measured together because of their small size relative to the slit length. Included in Figure 7 are the curves determined previously [O'Leary and Briggs, 1970] for the Apollo 11 samples. The Apollo 12 soil shows a curve of steadily increasing albedo toward longer wave lengths, a behavior exhibited by the Apollo 11 material and by the moon as a whole. The albedo of the Apollo 12 soil is higher than that of Apollo 11, as in the case of the phase function observations. The particular rock samples investigated had a broad absorption band centered at about 0.9μ; the soil also shows a weak band near this wavelength. Observations of the Apollo 12 landing site coupled with the calibration work of McCord and Johnson [1970] yield a spectrophotometric curve from 0.4 to 1.1μ which is similar in slope to that of the Apollo 12 soil. Similar conclusions may be drawn for the spectrophotometric results of Apollo 12 as those for Apollo 11 [Adams and Jones, 1970; Hapke et al, 1970a and b; O'Leary and Briggs, 1970; Adams and McCord, 1970].

CONCLUSION

There appear to be no major differences between the optical properties of lunar soil returned from the Apollo 11 and 12 missions and those of the lunar mare surfaces. Some differences do arise in albedo, color and polarization, but they can probably be attributed to differences in properties of the surface and subsurface soil, and in an unknown blend of mare and upland material. The proper degree of compaction of the lunar surface can be reasonably reconstructed in the laboratory without introducing major changes in optical properties.

A few discrepancies still exist between various experimenters. More experiments on the Apollo 11 and 12 samples, as well as experiments to be performed on samples returned from future sites, will most likely resolve these conflicts.

ACKNOWLEDGEMENT

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Table 1

Normal Albedoes of the Lunar Powder Samples.

	Blue	Green	Red
Filter Wavelength (μ)	0.44	0.56	0.65
Normal Albedo, Apollo 12 ($\pm$ .003)	0.094	0.122	0.136
Normal Albedo, Apollo 11 ($\pm$ .003)	0.083	0.102	0.115

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FIGURE CAPTIONS

Figure 1. The reflectivity of Apollo 11 and 12 lunar soil samples versus phase angle at 0.56μ wavelength and for viewing angles $\epsilon = 0^{\circ}$ and 60°. (Top) Color index B-V of the powder samples versus phase angle for $\epsilon = 0^{\circ}$. Also plotted are the reddening function of the entire moon and several values for a region of Mare Tranquillitatis as determined by Gehrels _et al_ [1964] and corrected for a solar B-V of 0.63.

Figure 2. The reflectivity of the Apollo soil versus phase angle at three wavelengths and for viewing angles $\epsilon = 0^{\circ}$ and 60°.

Figure 3. The polarization of Apollo 11 and 12 lunar soils versus phase angle at 0.56μ wavelength and viewing angles $\epsilon = 0^{\circ}$ and 60°.

Figure 4. The polarization of the Apollo 12 soil versus phase angle at three wavelengths and viewing angles $\epsilon = 0^{\circ}$ and $\epsilon = 60^{\circ}$.

Figure 5. The reflectivity of the Apollo 12 soil versus phase angle at 0.56μ wavelength and viewing angles $\epsilon = 0^{\circ}$ and 60° for three degrees of compaction.

Figure 6. The polarization of the Apollo 12 soil versus phase angle at 0.56μ wavelength and viewing angles $\epsilon = 0^{\circ}$ and 60° for three degrees of compaction.

Figure 7. Diffuse reflectance versus wavelength of the Apollo 11 and 12 lunar samples.

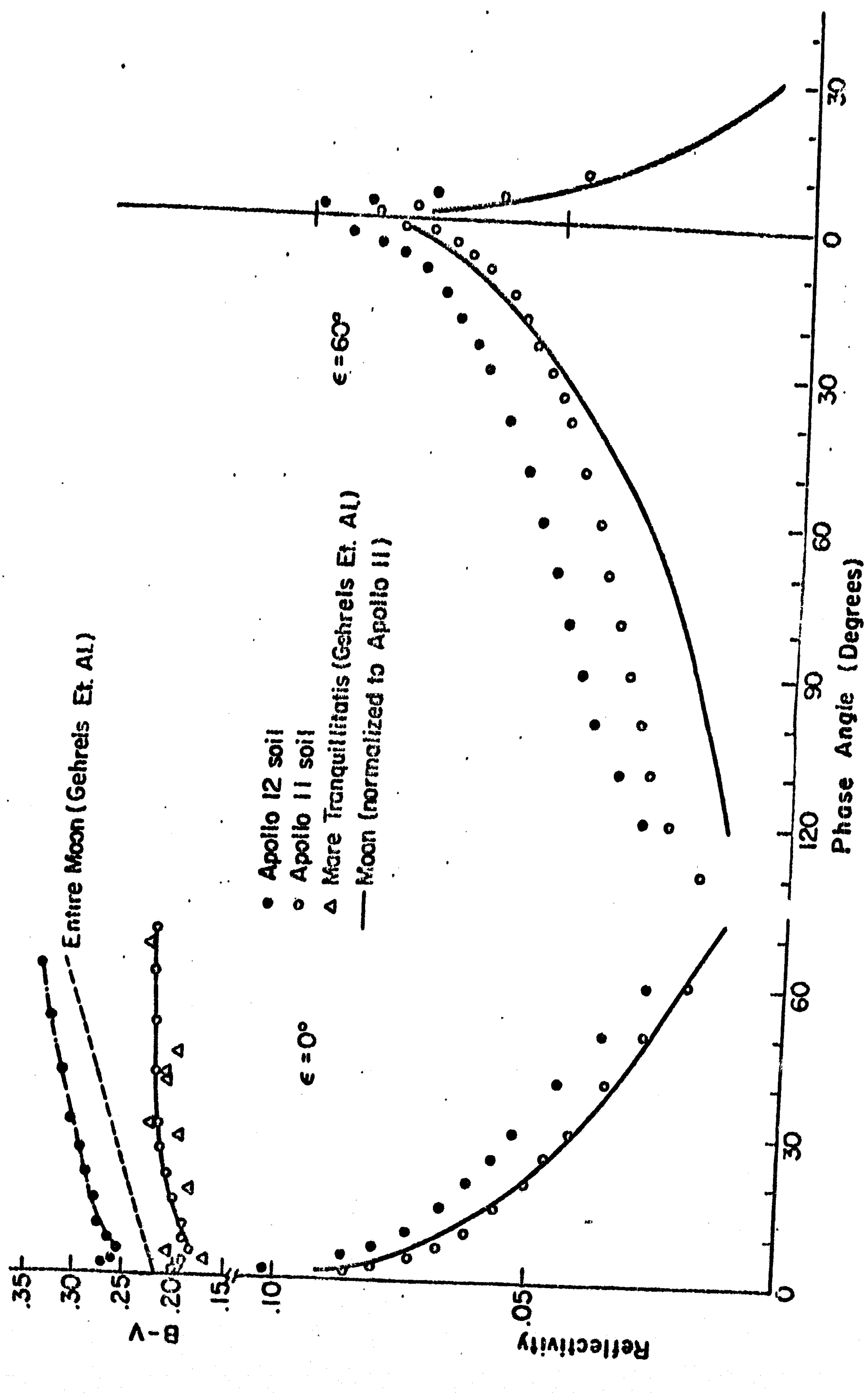
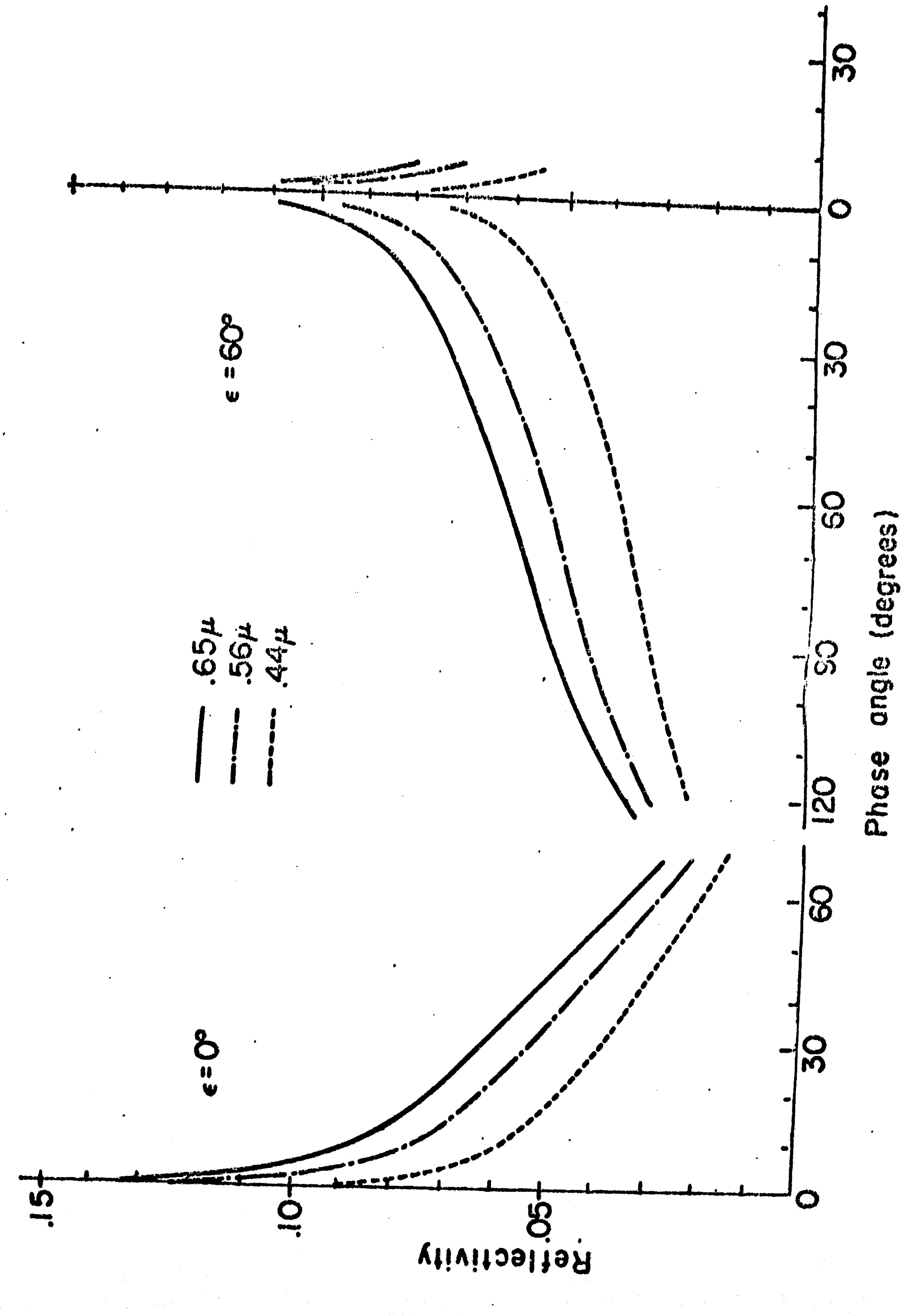
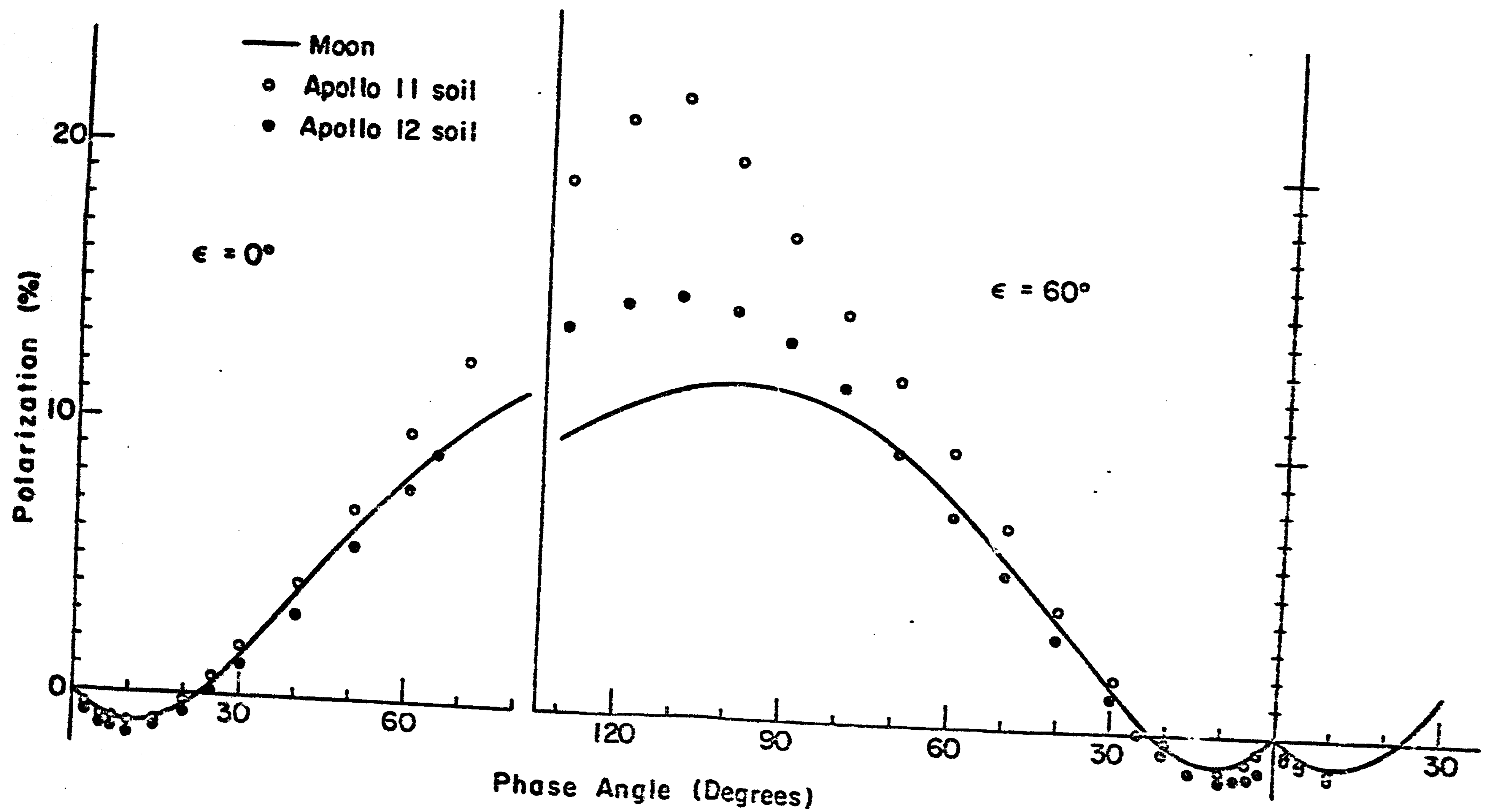

Entire Moon (Gehrels Et. Al)
Apollo 12 soil
Apollo 11 soil
Mare Tranquillitatis (Gehrels Et. Al)
Moon (normalized to Apollo 11)
ε = 0°
ε = 60°
B-V
Reflectivity
Phase Angle (Degrees)
.35
.30
.25
.20
.15
.10
.05
0
30
60
90
120

Figure I.



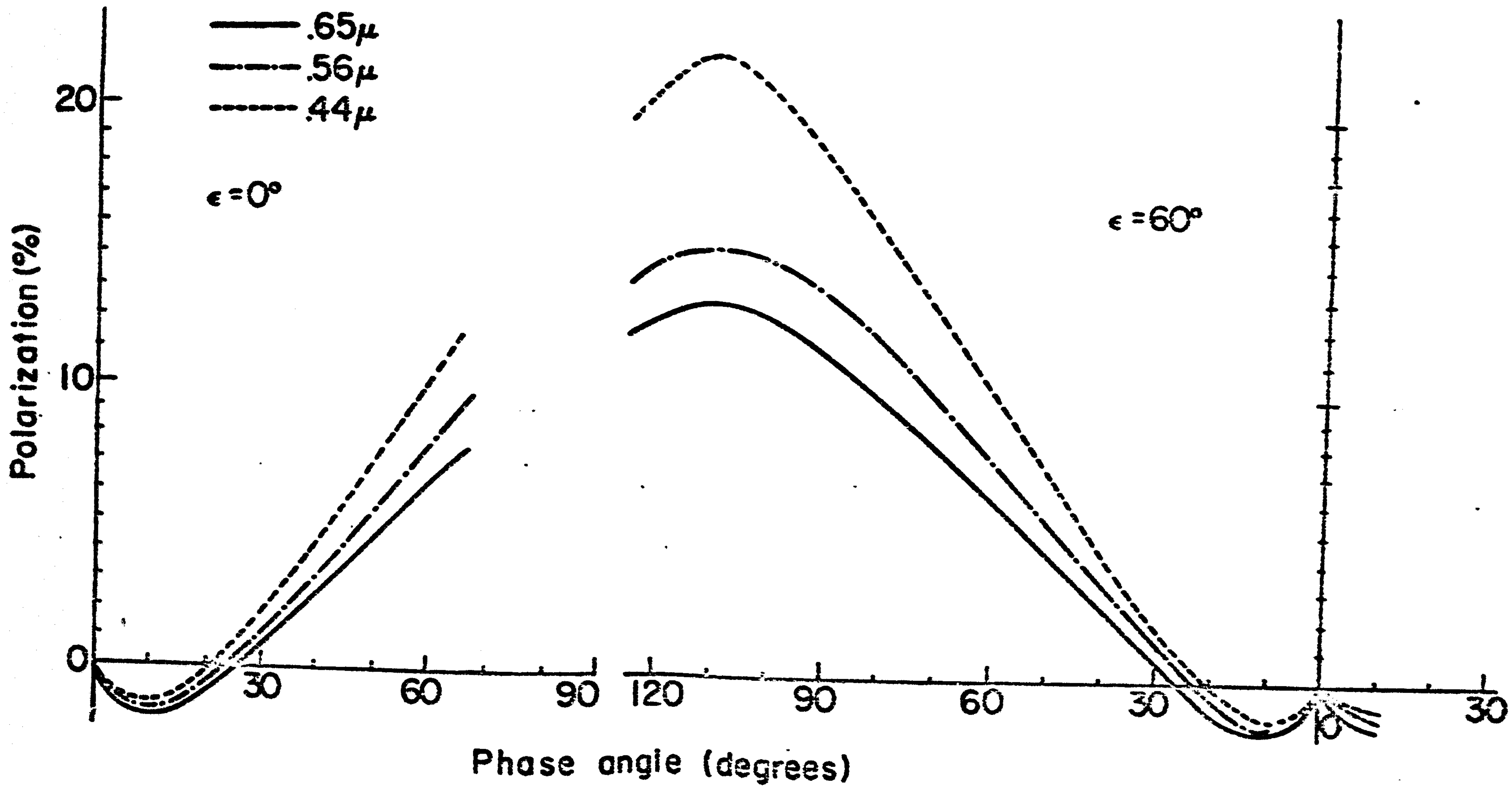
Reflectivity
.15
.10
.05
0
Phase angle (degrees)
0
30
60
120
90
60
30
0
30
ε = 0°
ε = 60°
.65μ
.56μ
.44μ

Figure 2.



Moon
Apollo 11 soil
Apollo 12 soil
Polarization (%)
0
10
20
$\epsilon = 0°$
$\epsilon = 60°$
30
60
120
90
60
30
30
Phase Angle (Degrees)

Figure 3



.65μ
.56μ
.44μ
ε=0°
ε=60°
Polarization (%)
Phase angle (degrees)
0
10
20
30
60
90
120
90
60
30
10
30

Figure 4.

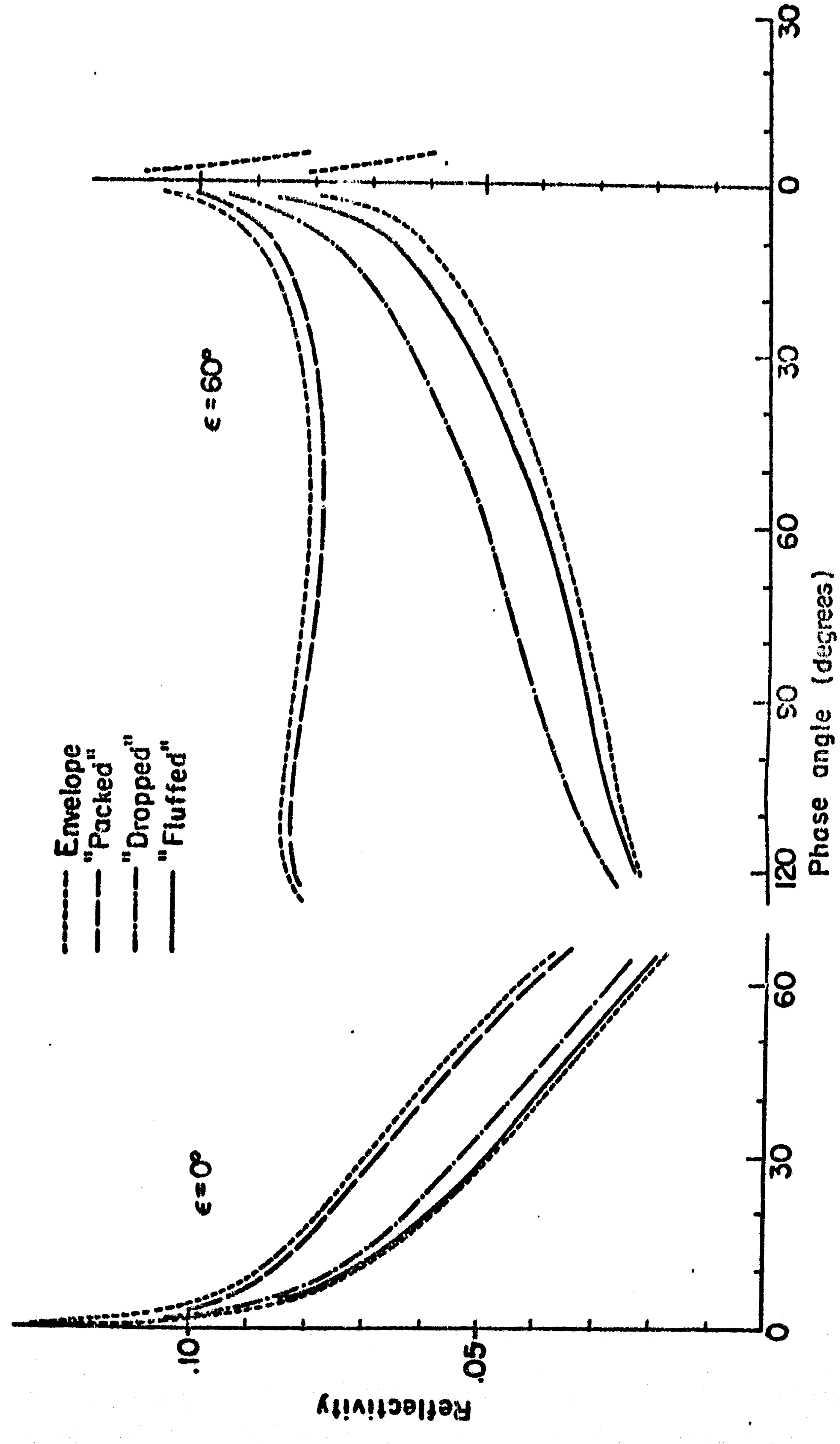
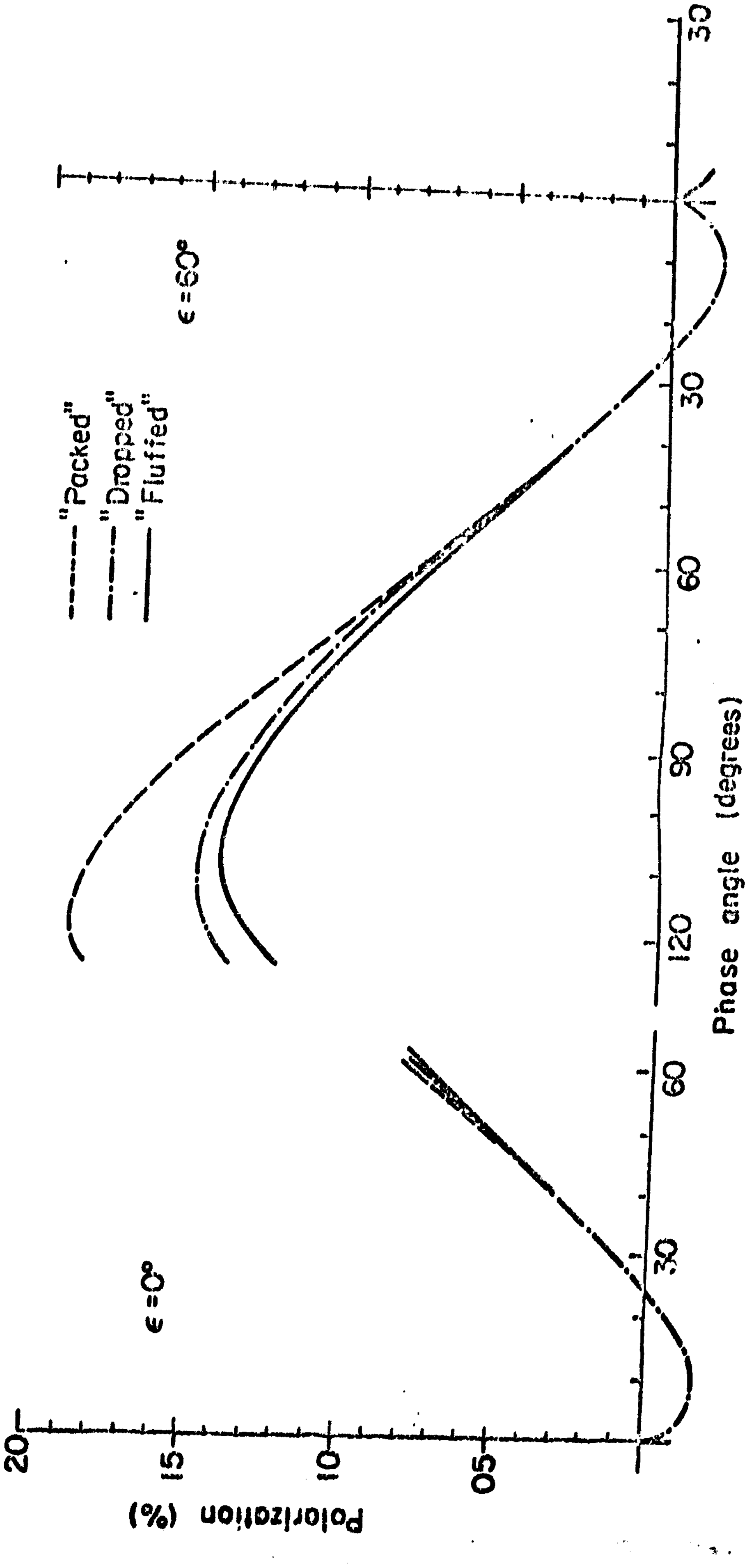

Envelope
"Packed"
"Dropped"
"Fluffed"
ε=0°
ε=60°
Reflectivity
.10
.05
0
30
60
90
120
Phase angle (degrees)

Figure 5


Polarization (%)
20
15
10
05
ε=0°
ε=60°
"Packed"
"Dropped"
"Fluffed"
30
60
30
60
90
120
30
Phase angle (degrees)

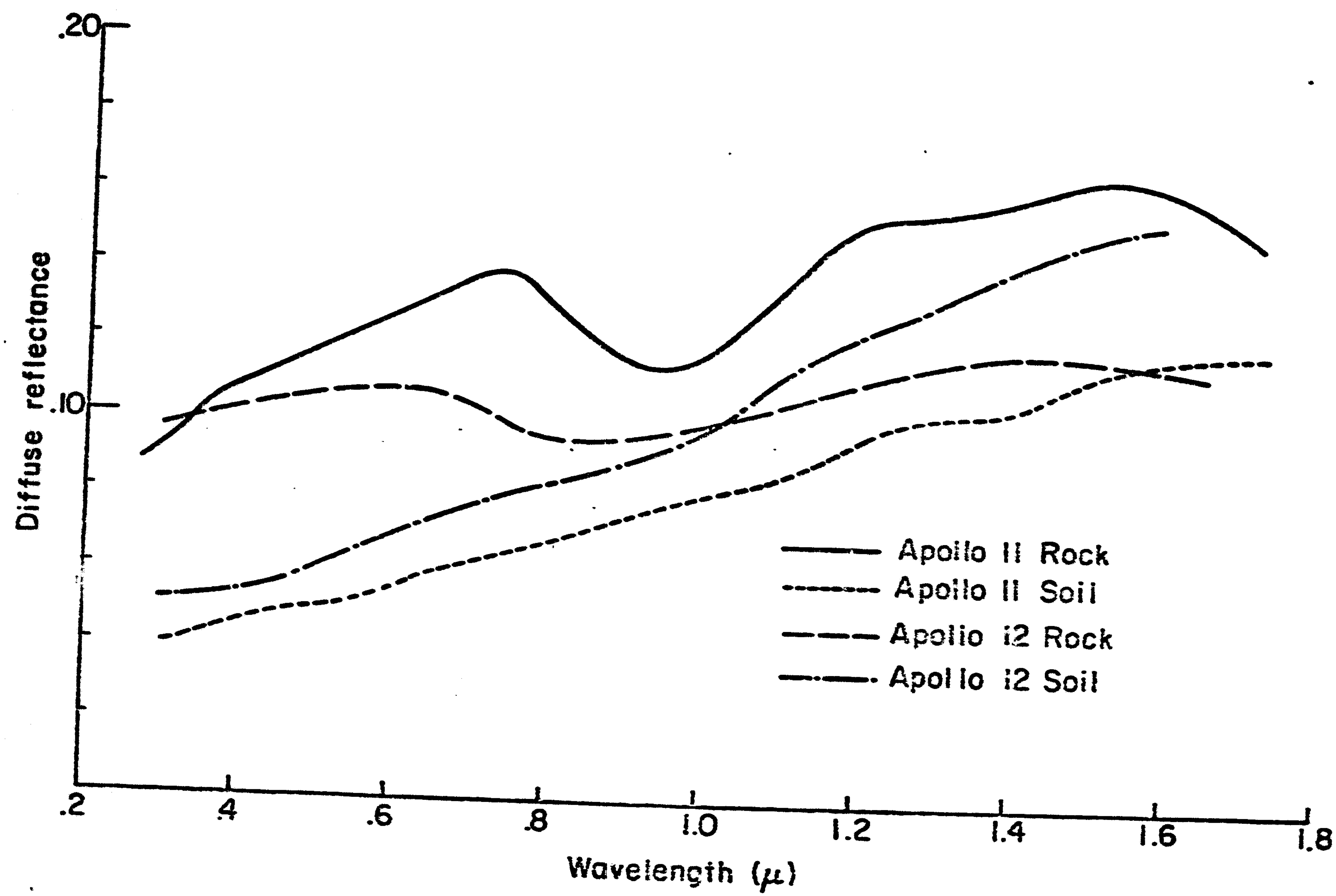

.20
.10
Diffuse reflectance
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
Wavelength (μ)
Apollo 11 Rock
Apollo 11 Soil
Apollo 12 Rock
Apollo 12 Soil

Figure 7