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MICROMETEORITE CRATERS AND  
RELATED FEATURES ON LUNAR ROCK  
SURFACES\*

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ABSTRACT:

Craters in the .4 to 10 mm size class were observed on six Apollo 12 whole rock surfaces (12017, 12021, 12038, 12047, 12051 and 12073). Craters on crystalline surfaces are characterized by a central, glass-lined cavity, a concentric zone of shock fractured, high albedo material and a concentric spallation area. The crater geometries observed are similar to craters produced in the laboratory with projectile velocities exceeding 10 Km/sec. The high projectile velocities required and the presence of a distinct demarcation line between cratered and uncratered surfaces on individual rocks indicate that most of the microcraters are produced by primary cosmic particles. These discrete impact events account for most of the erosion and fragmentation of lunar surface rocks.

## INTRODUCTION

This report summarizes results of a binocular microscopic study of almost 4000 microcraters and other related features on six whole lunar rocks collected during the Apollo 12 lunar landing mission (1). Both fine grained (12038, 12047) and coarse grained (12017, 12021, 12051) crystalline rocks were examined as well as one breccia (12073). It is the objective of this paper to present a detailed description of the crater morphologies and related features and discuss their significance (2).

## CRATER DIMENSIONS:

The structural elements used to describe the shapes of microcraters are illustrated and defined in Figures 1, 2a, and 2b. The halo is mostly absent on breccia surfaces.

It is important to note that the recognition of a spall area in this crater size range is consistent with descriptions of lunar microcraters in the 5 to 100 micron size class (3) as well as craters produced in the laboratory (4). The spall area is readily observed for about 15% of all craters. In none of the observed craters could the prior existence of a spall zone be excluded.

The size-frequency distribution of pit diameters is illustrated in Figure 3. The number of pits indicated for the smallest size classes is not necessarily representative of the actual population, because smaller pits become increasingly difficult to recognize. Craters of larger diameters than those observed cannot be expected

on rocks of the sizes investigated, as such crater producing events would completely rupture the rock (5).

The relations of pit-, halo- and spall diameter are illustrated in Figure 4. The ratios of halo/pit and spall/pit vary considerably, however they cluster around values of 2.2 and 4.5 respectively. Variations in these ratios are probably caused by relative abundances of target minerals, differences in impact velocities, the intensity of fracturing of the rock surface due to previous microcraters as well as measuring inaccuracies. Completely fresh pits show diameter/depth ratios from 2 to 5.

#### DETAILED MORPHOLOGY:

CENTRAL PIT: Not all pits are perfectly circular. The pit outlines may be irregular and jagged. In fine grained crystalline rocks and the breccia, the pits are in general more circular than in coarse crystalline rocks. Non-circularity of the pit is probably caused by different mechanical properties of the component minerals; shock impedance, strength anisotropies etc. exert control over the propagating shock front and thus over the melting and excavation process. This was especially illustrated by a few oval shaped pits which were formed in plagioclase bordered by pyroxene laths.

Perfectly fresh pits show smooth, well rounded lips of shock-melted glass. The lip is highly irregular in circularity and surface relief. Some have tear-drop shaped promontories. Raised lips are

common. Occasionally the glass has flowed onto the halo area without forming a distinct lip.

In some cases the glass lined pit is elevated with respect to its surrounding halo. It appears to sit on a pedestal or stylus and forms a positive topographic feature. Frequently fresh pits exhibiting well preserved lips and spall zones are associated with large pedestals. In two instances it could be observed that small glass droplets, undoubtedly originating from the pit, were visible in the excavated zone around the stylus. The freshness of the craters and the presence of glass droplets appear to be inconsistent with post cratering erosion processes and suggest that the removal of material leading to the formation of pedestals occurs during the crater forming event. Moreover large stylus pits are formed predominantly in previously shocked surfaces where mass removal was facilitated by existing microfractures.

Rock 12038 was studied in detail to investigate the origin of the glass which lines the central pit. Most glass linings display under high magnification a variety of colors corresponding to the mineral phases with which they were in contact. The glasses are produced in situ. Feldspar results in clear glass, pyroxene and olivine in honey-brown to dark brown colors and ilmenite in pitch black glass. In about 30% of the investigated pits the vari-colored glasses correspond proportionally to the mineral phases present. Another 60% of the pit linings correspond to the target minerals,

however they do not match precisely the target proportions. About 10% of the glass linings display colors which are either grossly out of proportion with respect to target minerals or have no relation at all to them; these glasses mostly were of dark shades, possibly suggesting the admixture of iron bearing projectile material. However, the majority of all glass coatings are shock melted glasses derived from the target materials.

HALO: All glass lined pits on crystalline rocks displayed a concentric zone of shock-fractured minerals. A gradual transition between highly fractured and unaffected rock was observed. Halos are less evident on breccias and glass coated surfaces. Though the depth of halos could rarely be measured, it is reasonable to consider this microfractured material to occupy a roughly hemispherical volume surrounding the pit. On densely cratered surfaces halo material surrounding closely spaced impact pits forms a continuous microfractured surface. This surface is noticeably lighter in color and gives the rock a shocked appearance, though the depth of the shocked material is generally less than 1 mm. Halos produced in plagioclase are most noticeable and aid most in the recognition of small impact craters in crystalline rocks.

SPALL ZONE: Craters which display pronounced spall areas are mostly fresh, i.e. display smooth crater lips. About 15% of all pits observed were surrounded by an easily identifiable spall area. Thus

fresh microcraters in the .1 to 1 mm range have compatible geometries to micron-sized craters in the Apollo 11 fines (3) and to those produced in laboratory studies (4). The correlation between erosional state of pit and presence of a spall zone strongly suggest that all craters were originally surrounded by a spall zone. The spallation is caused by the interaction of shock waves with the free surface of the rock. The ubiquitous presence of spallation processes must be accounted for in evaluating erosion rates on lunar surface materials.

CRATERS ON GLASS SURFACES: Rocks 12073 and 12017 display surfaces partially covered with a thin, coherent coating of dark brown glass. Small craters on these glass coatings in the .1 to .4 mm diameter size class have a central glass lined pit, a pronounced spall zone and a less prominent halo zone. They have in addition a distinct rim surrounding the pit, a feature which was never observed on crystalline rocks. Projectiles of sufficient energy were able to penetrate through the thin glass coatings to form a glass lined pit in the crystalline substrate and to cause a large amount of glass coating to spall. Spall zones in such a target configuration are particularly evident. Pit/spall-diameter ratios of 1:6 and larger were commonly observed.

#### FEATURES RELATED TO METEORITE IMPACT:

LARGE GLASS COATINGS: As mentioned above, rocks 12073 and 12071 displayed large surfaces ( $\approx 5 \text{ cm}^2$  and  $7 \text{ cm}^2$ ) which were partially

coated by glass. The thinness (50 to 200 $\mu$ ) in comparison with the lateral distribution, the smoothness of the glass surface and gradual pinching out at the contact with the crystalline surface (associated with glass drops) indicate a highly fluid state during deposition of the glass. The melt also "flowed" around corners of the rocks. Surface tension upon cooling was such that the glass contracted, leaving "windows" open through which the substrate is visible. Well defined schlieren were observed on glass 12017.

Rock 12017 was broken off on one side allowing a detailed study of the contact between glass and crystalline substrate. All along the exposed contact the crystalline material was shocked fractured, i.e. resembled halo material unequivocally associated with the glass deposition.

The presence of schlieren and shocked substrate suggest that the glass is of shock origin and impacted in a liquid state at high velocity. No observations are available to be able to distinguish between whether the collision with the rock occurred in flight or while the rock was resting on the lunar surface. The coatings could also be part of shock melted material originally lining the walls of a larger scale impact. The astronauts observed glass coated rocks sitting in or around meter-sized craters (1).

ROPY GLASS SPLASHES: Some glass splashes differ from the above mentioned glass coatings not only by a hummocky, highly irregular



surface but especially in size. They are commonly .3 to 1 mm in diameter. Quite frequently the surface has a dusty appearance. In general, they have highly irregular outlines. Ropy glass splashes are easily mistaken to be the bottom segment of a highly eroded central pit because they also have associated halo material. However the haloed zone is a seam .1 to .2 mm wide, irrespective of absolute size of the splash. The color of the ropy glass is of dark brown to black. It is unrelated to target composition. Ropy splashes are positive features with respect to the surrounding surface relief indicating deposition of material rather than removal. Although ropy splashes can occur on all cratered rock surfaces, they are concentrated in areas where other evidence points towards a contact with the surface of the lunar soil.

We interpret these ropy splashes as ejecta of cratering events happening in the lunar soil next to the rock. They possibly are materials excavated during "jetting" (6) and are thrown against the rock at velocities high enough to cause intense microfracturing.

WELDED DUST: Patches of non transparent, glass material of rough relief and "dusty" appearance were observed. The underlying rock is unshocked. The surface relief, dark color and concentration about the soil line lead to the conclusion that these patches are similar to ropy splashes in origin. Their masses and/or velocities were not sufficient to shock fracture <sup>the</sup> substrate. Thus welded dust is inter-

puted to be a thin spray of molten secondary ejecta mixed with unmelted lunar dust.

**THIN FILM COATING:** In contrast to the non transparent "welded dust", patches of extremely thin ( $>10\mu$ ) glass coatings were observed which were transparent. They are similar in occurrence and size to welded dust. Coated areas are darker than freshly broken crystalline surfaces. This coating is probably also related to secondary ejecta representing an extremely thin version of welded dust or possibly condensed silicate vapor. Consequently, "ropy splashes", "welded dust" and "thin film coating" may be genetically closely related.

#### DISCUSSION AND CONCLUSIONS:

Detailed stereoscopic microscope investigations demonstrated that lunar microcraters on crystalline surfaces larger than .4 mm are characterized by a central, glass lined pit, a lightened zone of shock fractured minerals and a spall area roughly 4.5 times as large as the central pit.

The presence of a glass-lined pit indicates impact velocities in excess of 10 Km/sec. (4). Ejecta during "jetting" of a large scale impact event may well reach absolute velocities of 20 Km/sec. (6). However relative velocities of fine grained particles within any given impact plume in excess of 10 Km/sec. are difficult to justify from considerations of cratering mechanics. Consequently, we believe that more than 95% of all cratering phenomena observed are due to primary flux of cosmic particles.

This hypothesis is further supported by the fact that rocks 12051, 12038 and 12021 have sharp demarcation lines between heavily cratered and completely uncratered surfaces. One can argue that uncratered areas are freshly broken surfaces not yet exposed to the bombardment of secondary projectiles. If this were the case the demarcation between cratered and uncratered areas would be formed by the rock geometry, i.e. the demarcation line would be associated with sharp edges and corners. The demarcation line in all 3 examples however runs across relatively flat surfaces, irrespective of rock geometry. It can be traced over the whole circumference of the rock and it is a plane rather than a line which separates cratered and uncratered surfaces. Such a distribution of cratered and uncratered areas is incompatible with in-flight collisions of secondary ejecta. Consequently, we conclude that the uncratered part of the rock was buried in the lunar regolith and the cratered areas were exposed to the bombardment of primary micrometeorites.

Only about 5% of all phenomena observed can be attributed to genuine secondary impacts. Such phenomena are glass coatings, ropy glass splashes, welded dust and thin film coating. The impact velocities of glass coatings and ropy glass splashes were such that they shock fractured the target materials. Occasionally cone shaped depressions without any melting phenomena, however sometimes associated with halo material as well as individual haloed patches are considered

to be genuine secondary craters. For all these secondary phenomena, 2-3 Km/sec can be conservatively estimated as maximum impact velocity.

The presence of a spall zone is important in evaluating cosmic "erosion" due to micrometeorite bombardment. The dominant erosion process on the scale observed is by far the catastrophic<sup>c</sup> rupture of rock surfaces due to discrete microcratering events. Individual events responsible for partial or complete destruction of craters are frequently observed. Overlapping spall zones are common. Discrete segments of pit walls are broken off, indicating a catastrophic rupture rather than gradual removal. In large diameter spall zones, the presence of halo material outside the central halo zone demonstrates the catastrophic removal of entire craters. The great abundance of these features indicates that erosion of lunar rock surfaces is dominated by high velocity, high energy impacts.

Moreover the extremely shiny surfaces of glass coatings demonstrate that mass removal by low energy projectiles does not exist on a significant scale. Similar observations were made on large single crystal faces as well as on the glass linings of central pits. If such a "sandblasting" effect of secondary projectiles were of importance, some of the glass coatings, single crystal faces or glass linings would be exposed to the surface long enough to be densely pitted, chipped and frosted. This was extremely rarely observed. Consequently, the state of preservation of glass and crystal surfaces supports the

view that "sandblasting" is of little importance for erosion processes on the lunar surface. Cosmic erosion on the scale observed appears to be dominated by catastrophic rupture and destruction due to discrete micrometeorite impacts.

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7. We acknowledge the hospitality of the Lunar Science Institute which is administered by the Universities Space Research Association under NASA grant NSR-09-012-071. We appreciate the cooperation of curator D. H. Anderson and other staff members of the Lunar Receiving Laboratory. J. F. Vedder, NASA-Ames allowed us to quote his unpublished results on high speed microparticle cratering.

FIGURE CAPTIONS:

- Fig. 1: Schematic cross section through microcrater. (Definitions: "pit": glass lined cavity in the center of overall crater, "pit-depth": distance from glass rim (fresh or broken) to bottom of pit, "halo": part of the spall area characterized by different albedo due to shock induced microfracturing, "spall": concentric area around pit which was removed due to shock wave interaction with the free surface).
- Fig. 2a: Microcrater displaying central pit, halo zone and spall zone on crystalline rock 12047.
- 2b: Microcrater displaying central pit and spallation zone on breccia 12073. (Breccia surfaces do not display prominent halo zones).
- Fig. 3: Size-frequency histogram of measured pit diameters (3813 counts).
- Fig. 4: Relation of pit ( $D_p$ ), Halo ( $D_h$ ) and Spall ( $D_s$ ) diameters versus count frequencies.

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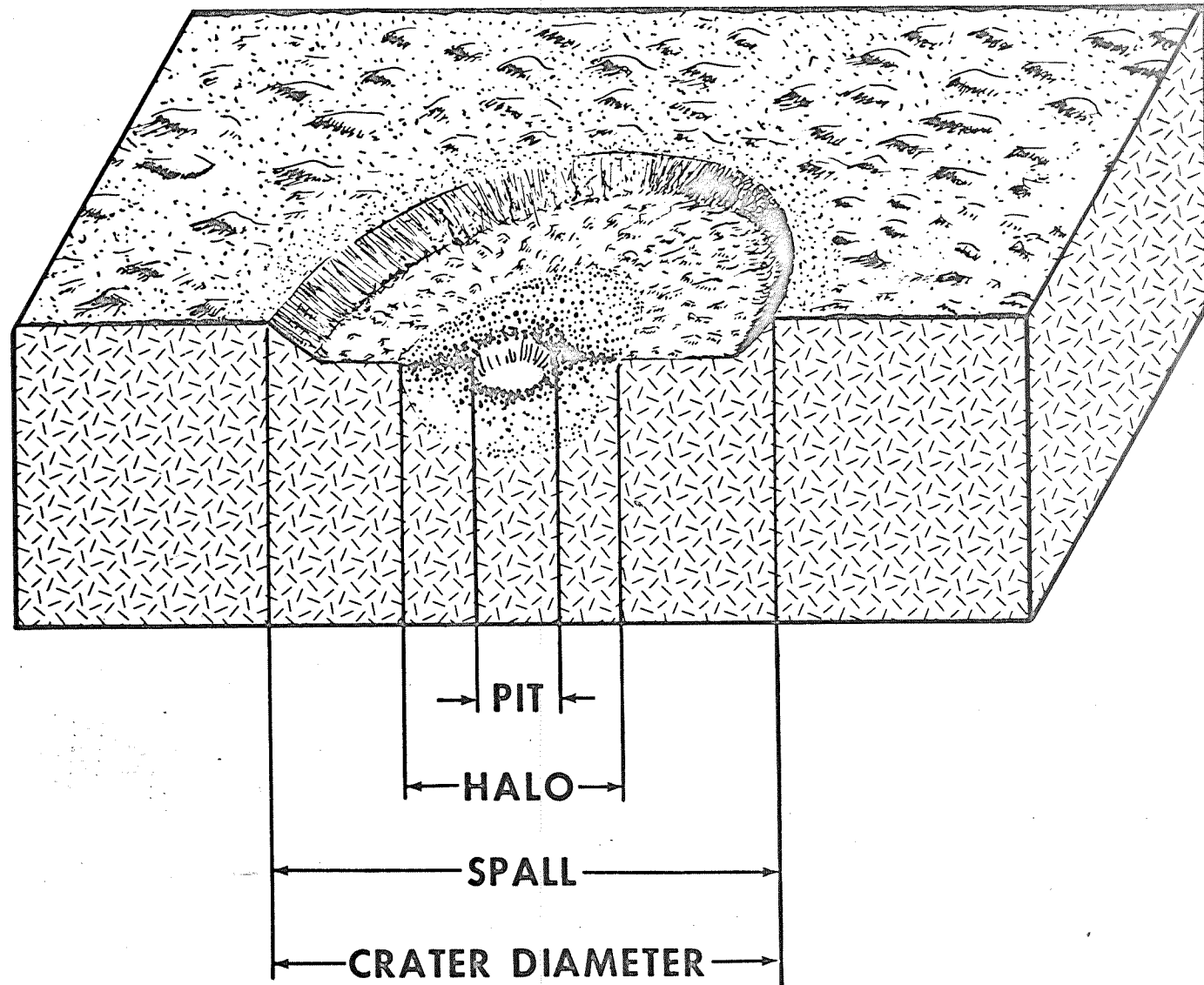
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# SCHEMATIC OF MICROCRATER



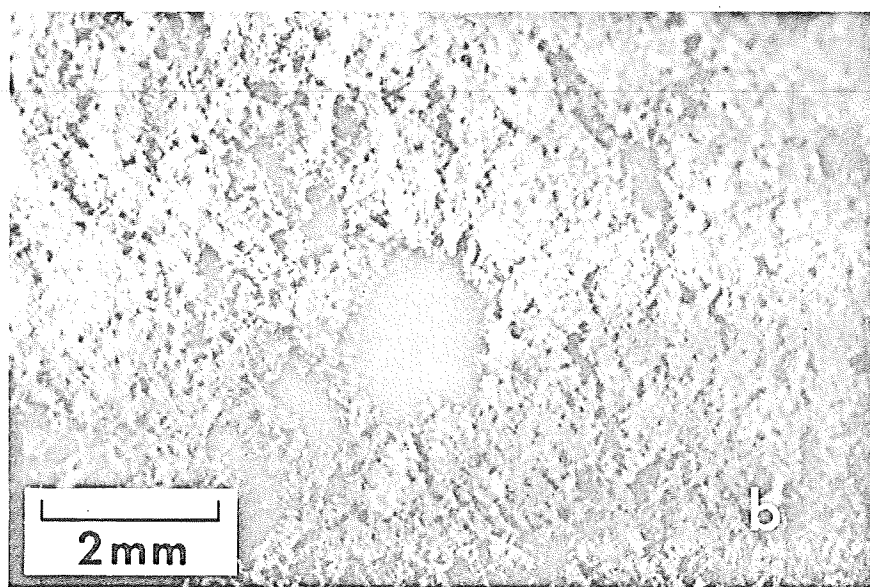
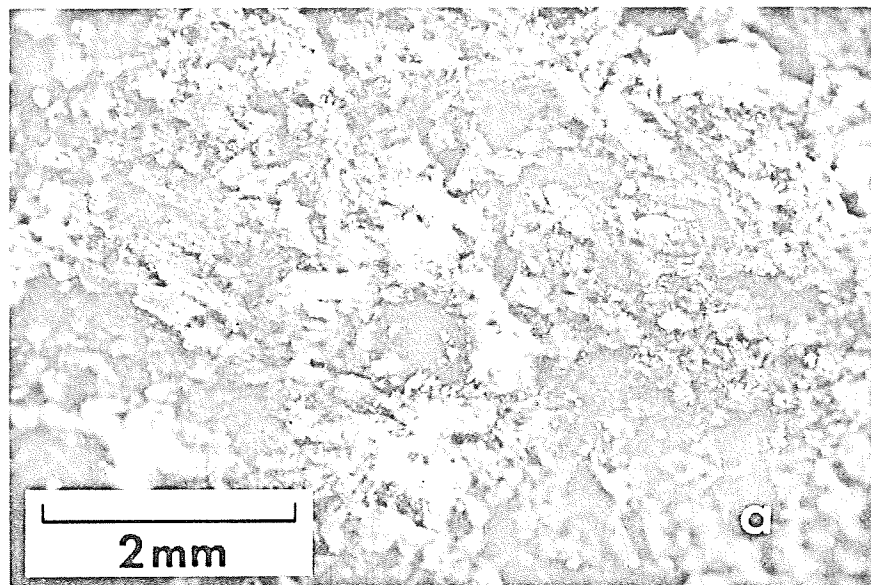


Fig. 2

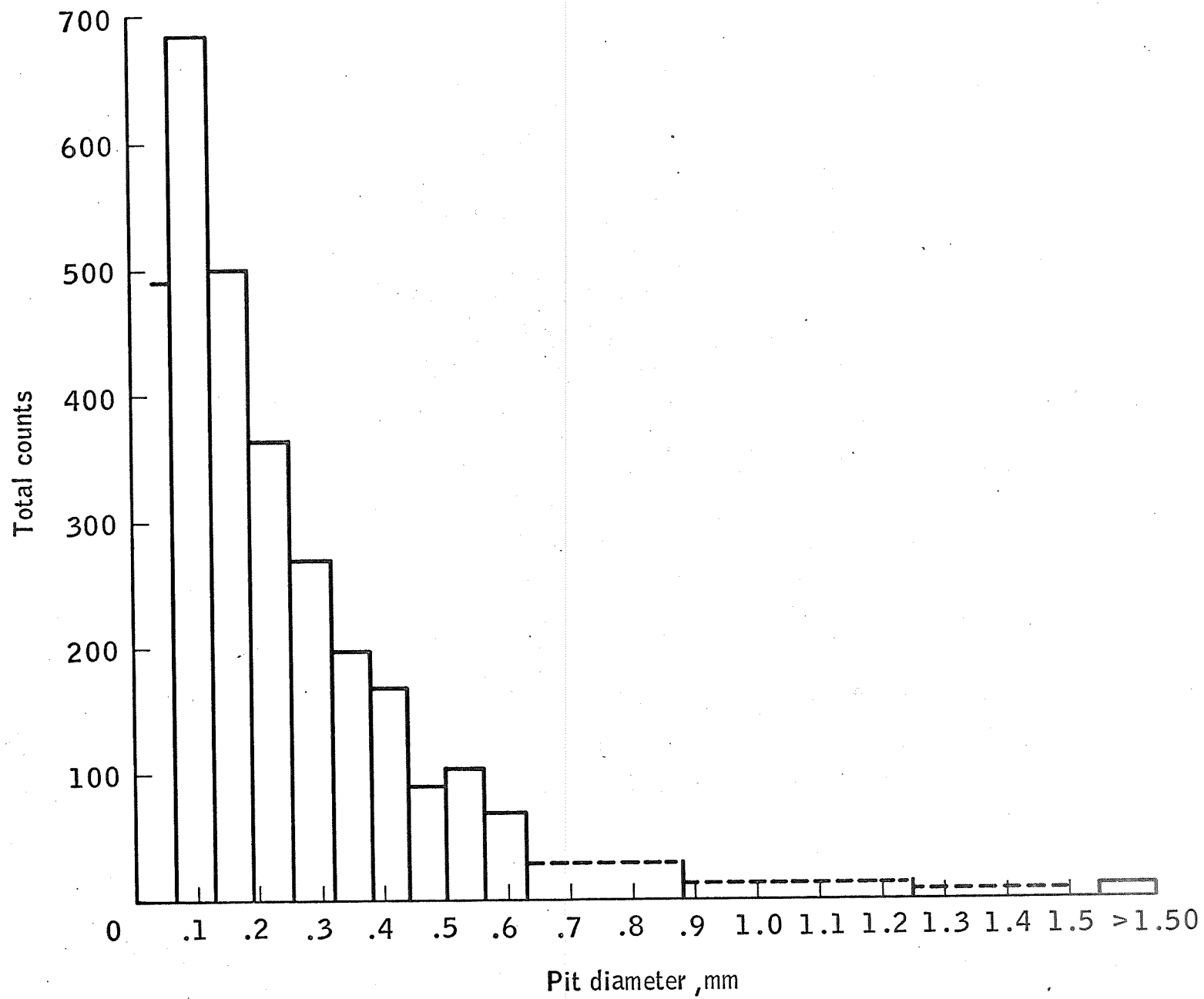


Fig. 3

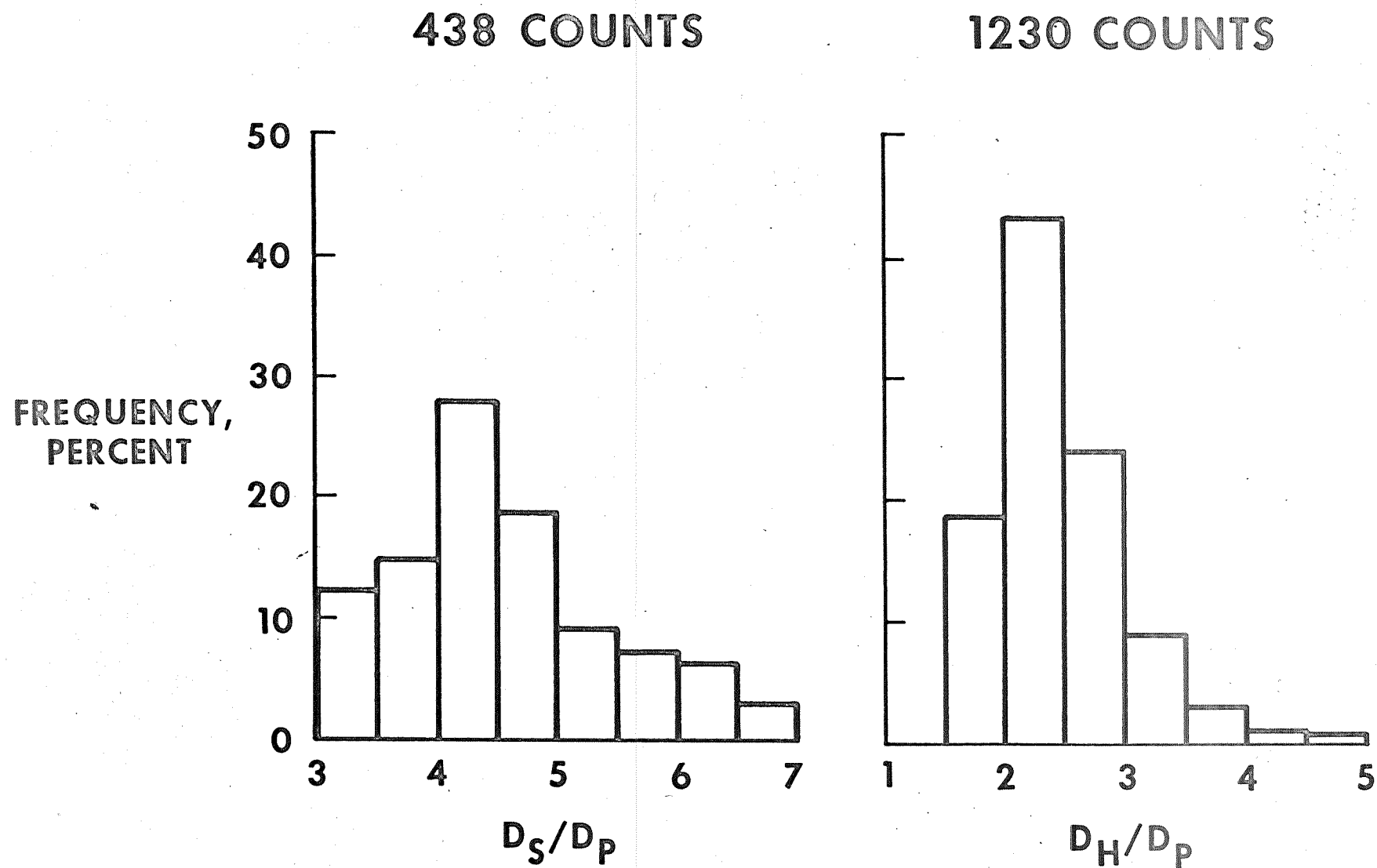


Fig. 4