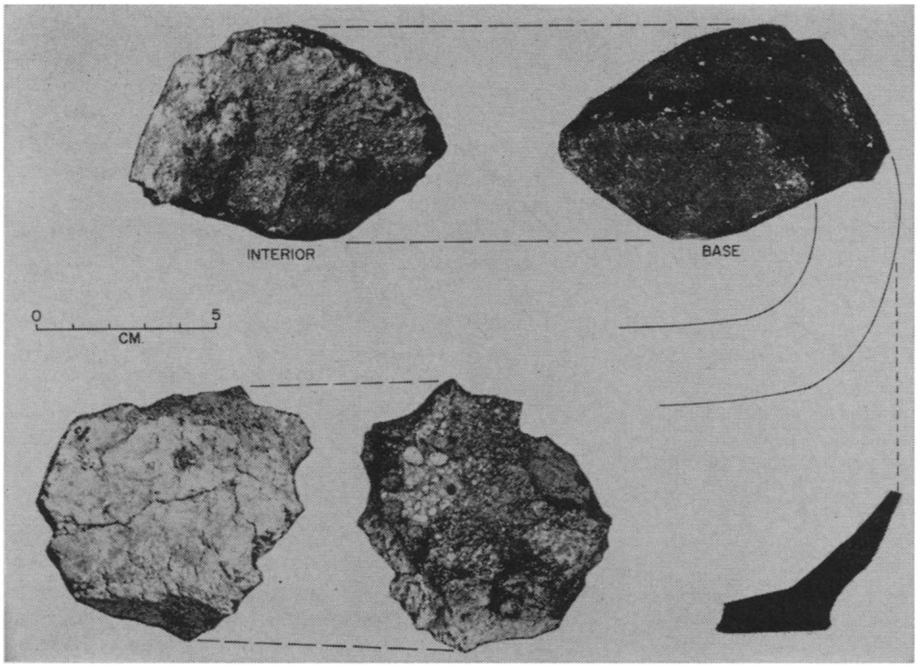

Fig. 1. Crucible fragments from Tal-i-Iblis level 1.

per would probably have reduced the crucible to a glass.

One must consider the possibility that the low melting point of the ceramic may be due to superficial deposits of water-soluble alkali. This seems unlikely because the base-exchange capacity of the clay should be relatively small (*10*), and the interior of the ceramic shard had the same melting point as the outer surface. The possibility that the copper stain and dross resulted from experiments directed toward the production of a blue-green glaze may be discounted for the following reasons: (i) the number of samples and the time span for their production (shards of this type were recovered from the first two levels of the mound); and (ii) the high degree of ceramic technology exhibited in well-made and highly fired shards from the same level.

On the basis of this evidence, it is reasonable that the crucible was used for the reduction of a copper ore. This work might be considered as support for the hypothesis that smelting antedated the melting of copper metal, as the smith did not employ a highly refactory ceramic for this process. The only ore samples found at this site have proved to be chalcocite, a sulfide ore that would require roasting. If this was the ore that was used in the 5th millenium, pyrometallurgy was well advanced at that time.

If, as Pittioni has cautiously suggested (*11*), the first use of smelting occurred in Anatolia (Catel Hüyük, level VI) not later than the 6th millenium, it would be reasonable to expect that the roasting and smelting of sulfide ores could have been accomplished by the end of the 5th millenium. Whereas more evidence concerning these events is necessary, the time scale for the development of metallurgy (*1*) will probably have to be extended.

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7 June 1966

Luna 9 Photographs: Evidence for a Fragmental Surface Layer

Abstract. *The morphological features of the lunar surface photographed by Luna 9 indicate a surficial layer of weakly cohesive to noncohesive fragmental material. Most of this material is finer than a centimeter and probably finer than a few millimeters, although objects of centimeter size and larger are plentiful.*

The pictures transmitted by Luna 9 have provided the first views of the fine-scale texture and structure of the lunar surface. Although the total areal coverage of the surface in these pictures is very small (and may be atypical of the moon in general), the photographs nevertheless contain a wealth of information that, when combined with results from studies of impact cratering in natural materials, furnishes the most definitive evidence to date of some of the important physical properties of the surficial layer of the moon. Because much of the cratering data is of recent acquisition, the full significance of the Luna 9 photographs has not been recognized by students of the subject either in this country or abroad (*1–5*). It is for this reason that this report was prepared.

Luna 9 landed along the extreme western margin of Oceanus Procellarum at selenographic coordinates reported to be 7°00'N and 64°33'W, as shown on the Aeronautical Chart and Information Center map of the Hevelius region (*6*). The site is approximately 90 km northeast of the center of the crater Cavalerius on a narrow tongue or strip of the mare surface that extends southward between hills of upland material. However, due to a 3 km-uncertainty in the precise impact point, one cannot be certain whether the surface in the photographs is upland or mare material.

Pictures have been examined from three separate panoramic scans of the lunar surface. One full panorama available for detailed study (apparently the last transmitted by Luna 9) includes about 280° of a complete scan. Due to an easterly tilt of the camera scan axis, the horizon is below the camera field of view in the remaining (westerly) 80° of the scan. Fragments of two earlier scans duplicating 160° of the panorama have also been examined. Because of the spacecraft movement, the camera position changed at least

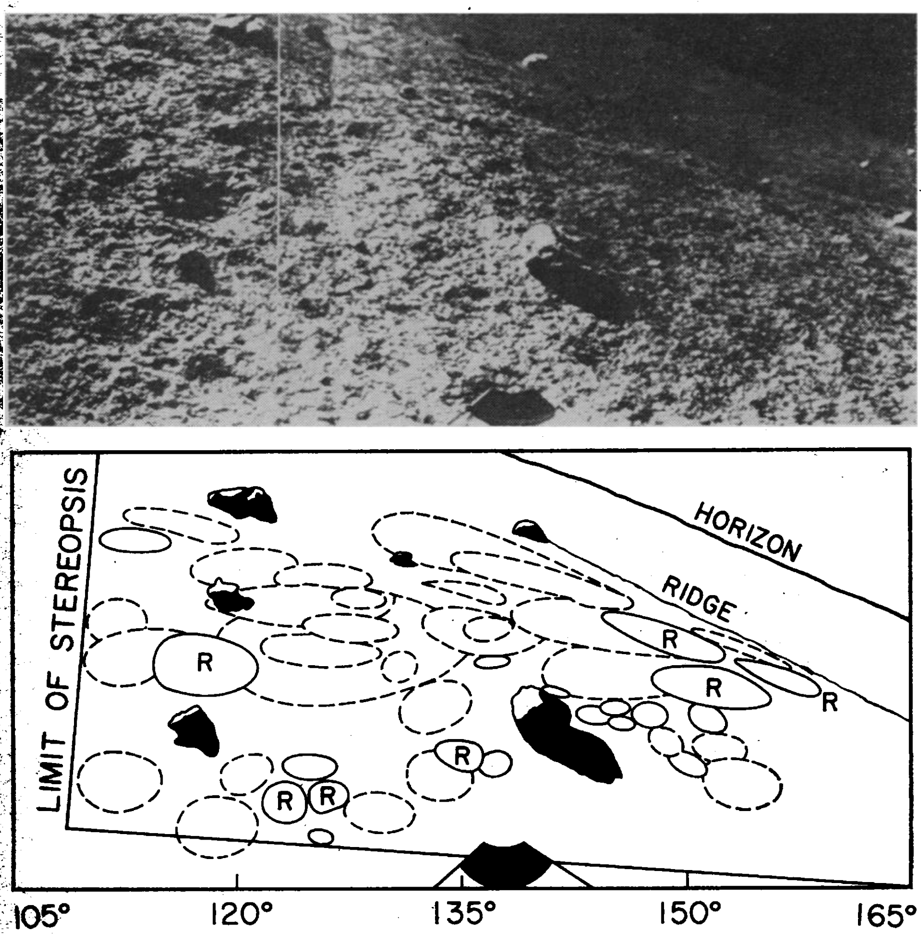

Fig. 1 (left). Portion of southeastern quadrant from Luna 9 scan with sketch of the foreground surface as interpreted from a stereoscopic image. Solid lines, well-defined craters; dashed lines, indistinct or uncertain craters. Rimmed craters, *R*.

once between each of the three scans. As a result of the movement, the photographs permit stereoscopic viewing of the lunar surface, so that the data content of the pictures is tremendously enhanced. Good stereopsis has been obtained for about 100° of the panoramic scan and it is excellent for a 60° segment in the immediate foreground that is southeast of the spacecraft. By making use of the reported height of the camera above the surface (60 cm) and its vertical field of view (30°), distances and sizes of nearby objects and features can be estimated with adequate accuracy for qualitative interpretations.

The stereoscopic views reveal an undulating surface that is littered with rocks and pocked with shallow depressions. Sizes of objects in the distant background have not been estimated due to uncertainties in the distances to the objects. The largest rocks in the near background, however, are estimated to be smaller than about 50 cm (Fig. 1). In the immediate vicinity of the spacecraft, the rocks range in size from approximately 15 cm to a few millimeters. Details finer than a few millimeters are beyond the limits of photographic resolution, but since the photographs show that frequency of occurrence for fragments increases with decreasing size, it is a reasonable supposition that fragments finer than millimeters exist and, indeed, are abundant.

The shallow depressions range in size from the lower limits of resolution to several meters and, perhaps, several tens of meters in diameter. They commonly overlap one another and seem to virtually saturate or blanket the entire visible surface. These depressions appear to be impact craters. It is significant that some of them have distinct, well-defined, raised rims. Rimmed craters with diameters from 10 to 100 centimeters are clearly evident in the

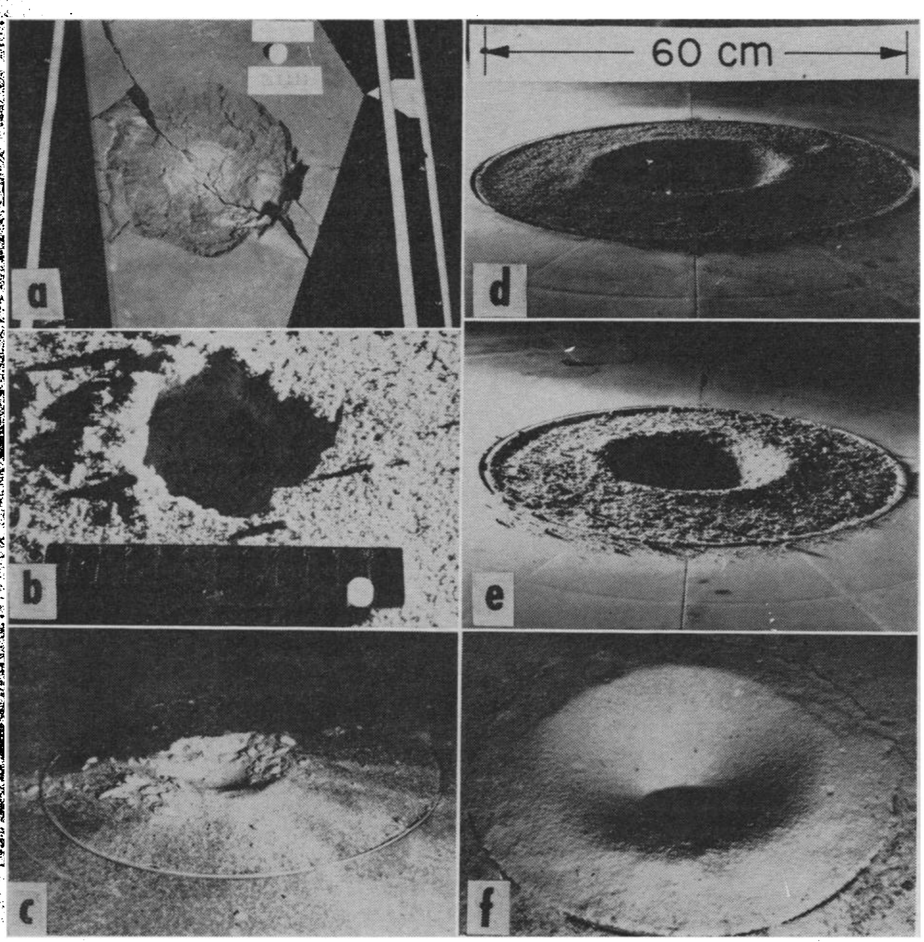

Fig. 2 (left). Typical impact craters formed in cohesive and noncohesive materials: (*a*) basalt (1 to 3 × 10^3 bars); (*b*) pumice (40 bars); (*c*) bonded quartz sand (1 bar); (*d*) basalt sand; (*e*) fine pumice sand; and (*f*) quartz sand. Values in parentheses are unconfined crushing strengths.

immediate vicinity of the spacecraft. The observations reported by Kuiper *et al.* (2) that craters shown in the Luna 9 photographs do not have rims are inaccurate. Rimless craters are, in fact, visible in the pictures, but they are accompanied by numerous rimmed craters as indicated in Fig. 1.

If the small craters are of impact origin, which is very probable, the presence of raised rims can be explained only by the existence of a surficial layer of granular material that is noncohesive or, in the extreme limit, weakly cohesive. Results from extensive laboratory cratering studies (7), which have produced impact craters up to 50 cm in diameter, indicate that cohesiveness precludes the formation of raised rims on such small-scale features. Figure 2 shows some representative laboratory impact craters that have been formed in a variety of target materials. As illustrated by craters in basalt, pumice, and weakly bonded quartz sand (Fig. 2, *a*, *b*, and *c*), strength or any degree of cohesiveness eliminates the formation of raised rims. On the other hand, craters formed in unbonded particulate material such as basalt fragments, pumice dust, and quartz sand (Fig. 2, *d*, *e*, and *f*) consistently display elevated rims. It has been found, moreover, that rim heights vary systematically with crater diameter for a variety of fine-grained target materials (Fig. 3), and that the rims and craters lose their identity and continuity if the particle size exceeds the nominal rim dimension (Fig. 4, *a*, *b*, and *c*). The presence of well-defined rims around craters as small as 10 cm in diameter, therefore, is indicative that the features were formed in noncohesive to weakly cohesive fragmental material that for the most part is of millimeter dimensions or finer. The depth of this noncohesive fragmental layer in the immediate foreground of the photographs cannot be less than the depth of the largest well-formed craters. Such a criterion leads to a minimum depth of about 20 cm for this layer, but it may be much deeper.

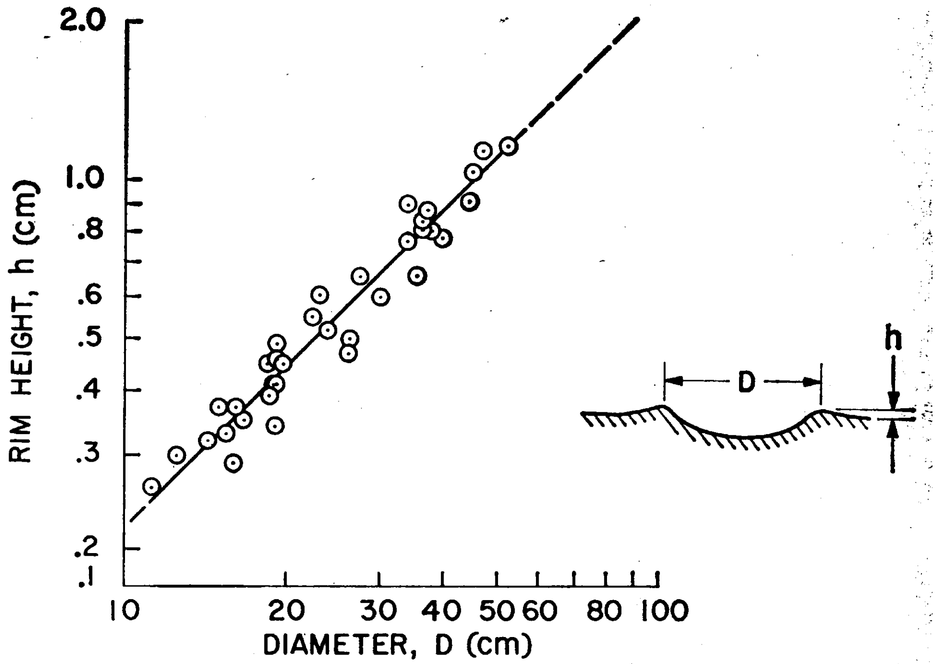

Fig. 3. Rim height as a function of diameter for craters formed in a variety of weakly to noncohesive fragmental materials.

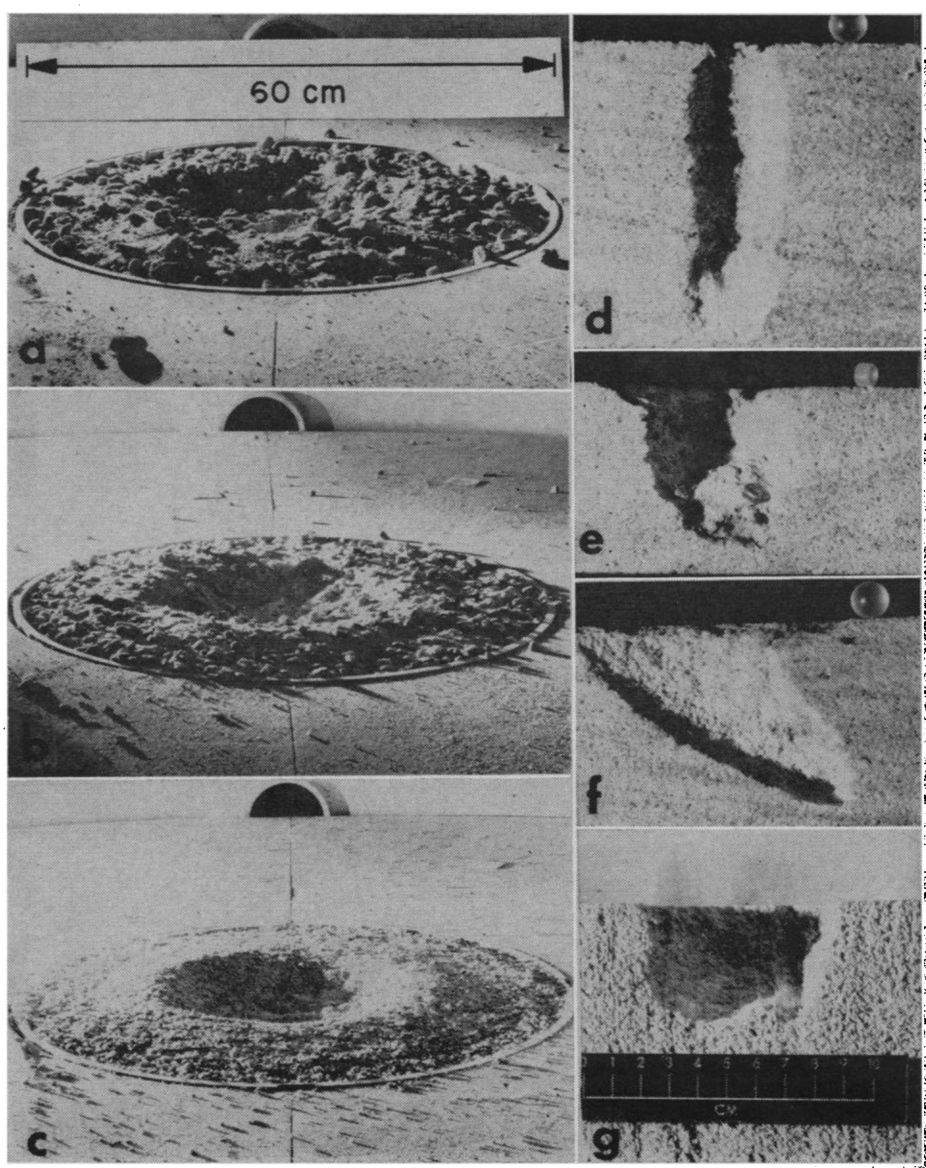

Fig. 4 (right). Craters formed in aggregate media composed of equal parts (by volume) of fine pumice sand and pumice fragments with dimensions of (*a*) 2 cm, (*b*) 1 cm, and (*c*) 3 mm. Sectioned craters in pumice blocks formed by impact at: 90° (normal) incidence for (*d*) 0.6 km/sec and (*e*) 6.5 km/sec; 30° incidence for (*f*) 0.6 km/sec and (*g*) 6.5 km/sec.

The preceding data and interpretation of Luna 9 pictures are in direct contradiction to the observations and analyses of other investigators (*2–4*). For example, Kuiper *et al.* (*2*) maintain that the surface has a "continuing solid structure" and, further, "is neither dust or loose scoria or debris, but hard cohesive though clearly very vesicular rock." This interpretation of the surface is nearly identical to those previously published by Kuiper in his analysis of Ranger 7, 8, and 9 photographs (*1*).

It seems unlikely, however, that the physical properties of the lunar surface are everywhere the same when surface morphology on all scales suggest inhomogeneity. The tremedous morphologic difference of maria and highlands. differences within maria and highland provinces themselves, differences on the fine scales observed in Ranger photographs, and even differences in maria colorations as pointed out by Kuiper (*1*) suggest that structural and stratigraphic differences should be expected. Since it is uncertain whether the panoramic views of Luna 9 are mare or highland type scenes, similarity of interpretation for all four photographic missions does not seem realistic.

Many interpretations (*2–4*) have stressed that the surface shown by Luna 9 is cohesive, highly vesiclular igneous rock. It must be emphasized that in addition to the strong evidence supplied by raised rims and the general morphology of the craters, there are no small craters in the photographs that even faintly resemble the laboratory impact craters that have been produced in blocks of porous cohesive materials. Although the detailed morphology of such craters is somewhat dependent on impact velocity and projectile density, their general appearance is a steep-walled cavity or cylindrical tube (Fig. 4 *d*, *e*, *f*, and *g*). Moreover, it is important to point out that the highly vesicular properties attributed to the surface material are an interpretative and not a demonstrative result. Individual fragments present on the lunar surface may well be vesicular, but there is no evidence in the photographs that permits a generalization regarding the degree of vesiculation. Furthermore, straight lineations that are observable in the Luna 9 photographs do not appear to be fronts of volcanic flows as suggested by Fielder (*4*). The linear structures are mostly parallel or subparallel to the horizon and are seen to be the crests of ridges when viewed stereoscopically. Such crests would appear as straight lines when viewed from low angles, regardless of their sinuous forms in plan view.

The lunar surface shown in the Luna 9 photographs is entirely consistent with cosmic impact processes. A continuum of crater geometries should be expected and is in fact to be seen in the stereoscopic scenes. Only the youngest craters have rims, since the very process that produces the newer craters would destroy and obliterate the older features. Not only is there a hierarchy of geometric forms but there is also an intricate record of superposition of craters, both of which clearly indicate an age sequence. Such overlapping of craters is consistent with repetitive impacts reworking the surficial layer many times over and providing a comminution process for reducing the surface material to fine clastic debris (*8*). Such clastic debris, together with small pits formed by micrometeorites, could readily produce the centimeter-scale surface texture and roughness that is shown in the photographs.

Although there is evidence in the photographs indicating that impact fragmentation and modification have taken place, there is no indication of the degree to which the surface has been modified. New surfaces have presumably been formed on the moon at different times. Such new surfaces may have been composed of hard rocks such as lava flows, or fragmental rocks such as large impact ejecta blankets or fragmental volcanic deposits. If the region viewed by Luna 9 had such a new surface of hard rock at any time in the past, it must have been extensively modified by impact fragmentation. On the other hand, if such a new surface were fragmental in nature, there is no indication of the extent to which it has been modified.

It is unfortunate that the precise landing site of Luna 9 is unknown, since the larger features visible on the Luna 9 photographs throw no further light on the possible origins of the rocks and surface material. Large craters are observable in the distant background and may well be of impact origin. However, the general morphology is not simple crater and plain. The topography contains ridges and valleys with craters dotting the surface. Such hill and valley topography could have been produced by volcanic activity. It is also characteristic of an impact ejecta blanket.

In conclusion, the surface viewed by Luna 9 consists of a noncohesive to weakly cohesive, poorly sorted fragmental material of unknown source, with the bulk of the fragments having sizes less than a centimeter and probably less than a few millimeters. The minimum depth of this fragmental layer is approximately 20 cm, but it may be much deeper. It is certainly not a vesicular cohesive rock surface with a continuous solid structure.

Note added in proof: The morphological features and the physical properties deduced for the surface material at the Luna 9 landing site are remarkably similar to those that have been subsequently revealed for the landing site of Surveyor I on Oceanus Procellarum (*9*). Although the observed similarities cannot be generalized into placing Luna 9 on a mare surface, the similarities do emphasize that crater geometry is a valuable criterion for identifying certain physical properties of the surface materials (*7*, *10*).

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