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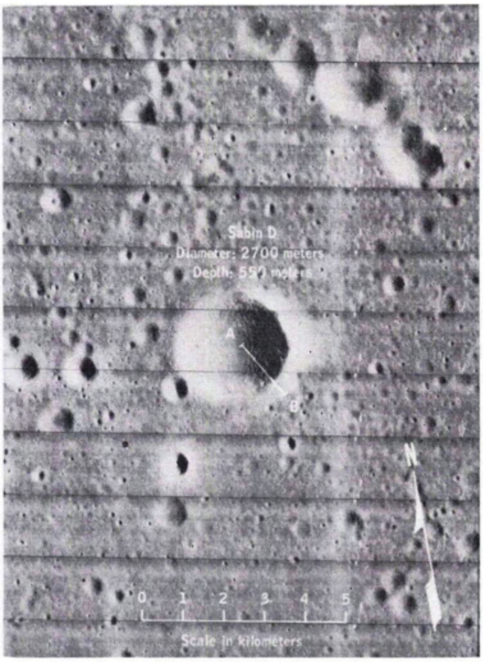

FRONTISPIECE. Medium-resolution Lunar Orbiter II photograph showing crater Sabine *D* and profile line *A–B*.

Lunar 'Rolling Stones'

Several of the boulders appeared to have rolled several hundred meters down the walls of craters.

(*Abstract on page 248*)

INTRODUCTION

DURING THE ANALYSIS OF Lunar Orbiter II photography at the Manned Spacecraft Center, Houston, Texas, observers noticed several large boulders which appeared to have moved or rolled over the lunar surface, leaving discernible tracks in the lunar surface material. Several of the boulders appeared to have rolled several hundred meters down the walls of craters. Other boulders appeared to have been ejected from nearby craters and to have rolled short distances down the outer rim before coming to rest. This paper presents a preliminary investigation of four of these *rolling stones*. The purpose of the investigation was to determine some of the physical characteristics of the boulders and the surfaces over which they moved. As all of the boulders studied were located in potential Apollo landing areas, it was felt that the information would be useful in evaluating these sites.

INVESTIGATION

GENERAL

Of the four boulders studied, two were located in Mare Tranquillitatis (23° E), one in Sinus Medii (1° W), and one in Oceanus

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* Submitted under the title "Preliminary Investigation of Several Lunar 'Rolling Stones' ". Messrs. Eggleston and Patteson are with the Lunar and Earth Sciences Division of NASA-Manned Spacecraft Center; Messrs. Throop and Arant are in the Surface Analysis Section, Mapping Sciences Laboratory of Lockheed Electronics Co.; and Mr. Spooner is in the Photometry Section of the latter organization.

TABLE 1. DESIGNATIONS AND LOCATIONS OF THE FOUR PHOTOGRAPHS OF BOULDERS THAT WERE STUDIED

Designation	*Longitude*	*Latitude*	*Orbiter Site*
A	23°39′ E	01°20′ N	II P6
B	01°18′ W	00°04′ N	II P8
C	19°10′ W	00°25′ S	II P11
D	24°50′ E	02°45′ N	II P5

Procellarum (19° W). Their designations and locations are as shown in Table 1.

BOULDER A

The boulder given the most extensive analysis was Boulder *A*. It is located within the crater Sabine *D* which is found in the southwest corner of Mare Tranquillitatis. The location of the crater and the area photographed as Orbiter Site II P6 are shown in Figure 1. The size and shape of the crater Sabine *D* were determined by measurements made on the Lunar Orbiter medium-resolution photograph shown as the Frontispiece. Stereoscopic measurements were taken of the path to determine the depth of the crater. The profile constructed from the measurements is shown in Figure 2. The crater was determined to be approximately 2700 meters in diameter and approximately 550 meters deep. The average slope of the crater wall along the path of the boulder is approximately 31 degrees. The boulder came to rest at a point where the angle of the slope becomes about 13 degrees and appears to be resting in a small crater.

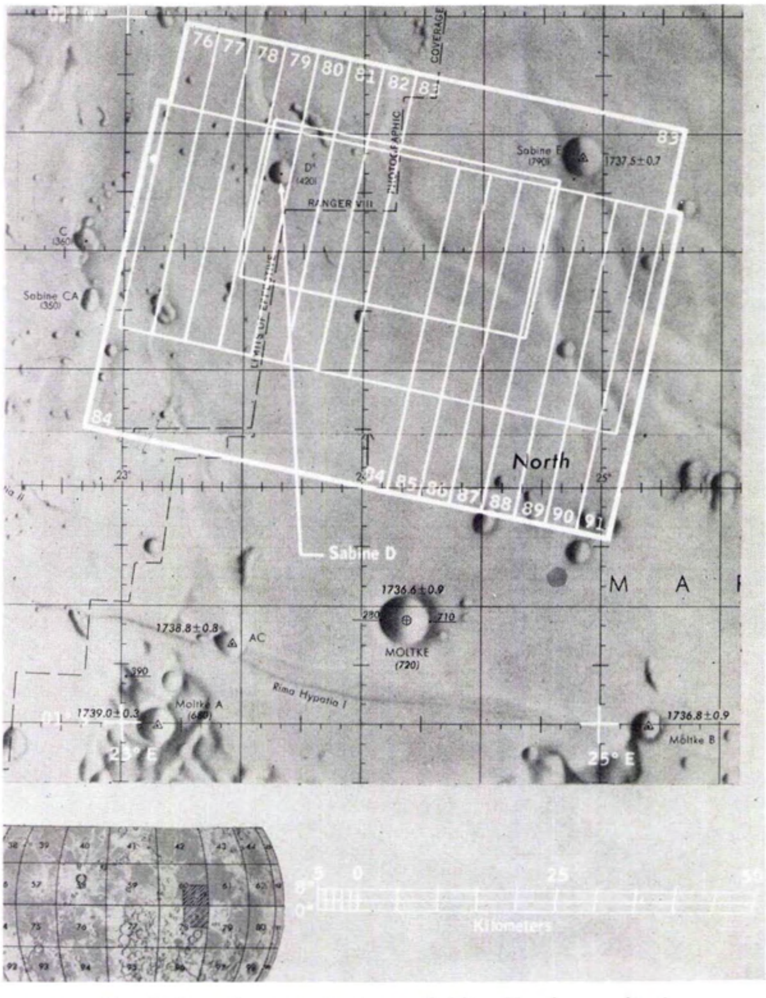

FIG. 1. Location map for Lunar Orbiter II primary site 6.

ABSTRACT: *High-resolution (1 meter) photographs obtained from Lunar Orbiter II showed four large boulders (larger than 5 meters in diameter) together with tracks which obviously indicate that rolling or sliding had taken place. Two (and possibly three) of these boulders reflected light characteristic of convex and glossy (spectral) surfaces. Parts of the craters appeared to be covered with compressible material which failed under the rolling pressure, but no "snowballing" occurred. Based on Surveyor I studies, one of the boulders would have a density between 1.3 and 2.3 grams per cubic centimeter.*

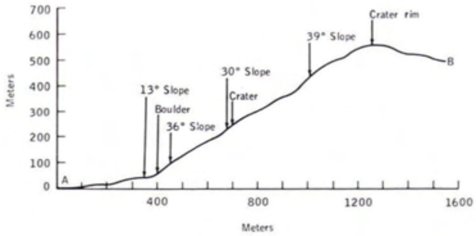

FIG. 2. Profile down wall of crater Sabine *D* along track of Boulder *A*.

The dimensions of the boulder and the track down the crater wall were measured on the Lunar Orbiter II high-resolution photography. A portion of frame number 79 showing the crater Sabine *D*, the boulder, and the track is shown in Figure 3. The measurements were taken directly from the photography and confirmed by microdensitometer measurements made with a Joyce-Loebl scanning microdensitometer. The isodensity map, from the microdensitometer scans of the high-resolution negative photograph, is shown in Figure 4. Using the methods indicated, the boulder was determined to be approximately 9 meters in diameter. The track was found to average 5 meters in width and was nearly uniform in width throughout its length. In addition, the boulder was determined to be nearly spherical in shape, a characteristic that was not observed on rocks nearby or on the crater rim.

The isodensity pattern of the illuminated portion of the boulder, as presented in Figure 4, has a greater area of density fall-off at the sunward edge of the boulder than can be explained by the combined effects of the frequency response of the photographic system and by the size of the scanning aperture used on the microdensitometer. The isodensity pattern of this boulder shows a definite symmetry in the light-reflection pattern with the brightest points near the center of the illuminated area. The normally used lunar photometric function would predict that the brightest points should be at the sunward edge of the boulder with a continuing light fall-off as the shadow area is approached. Further consideration of the isodensity pattern of the rock indicates that the observed pattern can be best explained by the assumption of a convex and glossy (specular) surface on the rock. The assumption of a retroreflecting or a diffuse reflectance characteristic would require a concave rock surface in the vicinity of the brightest area. It seems, therefore, that the boulder analyzed in Figure 4 is unusual inasmuch as it does not reflect light in the same way as most lunar material.

The physical dimensions of the boulder and the track, shown in Figure 4, were used in a graphic determination of the depth of the track which was found to be approximately 0.75 meter (Figure 5). An attempt was made to analyze the shape of the track depression at several positions along the path. However, no clearly defined shape could be consistently obtained. This interpretation of slopes de-

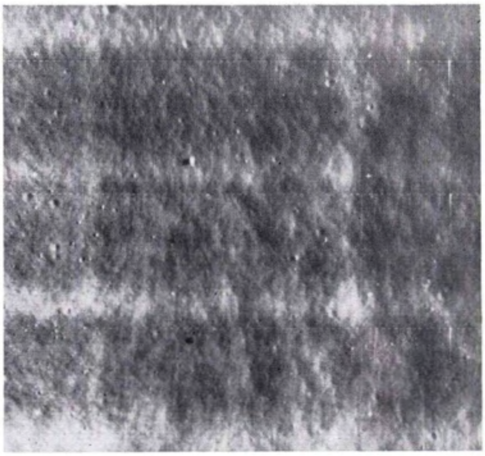

FIG. 3. Portion of photograph of crater Sabine *D* showing the boulder and the track.

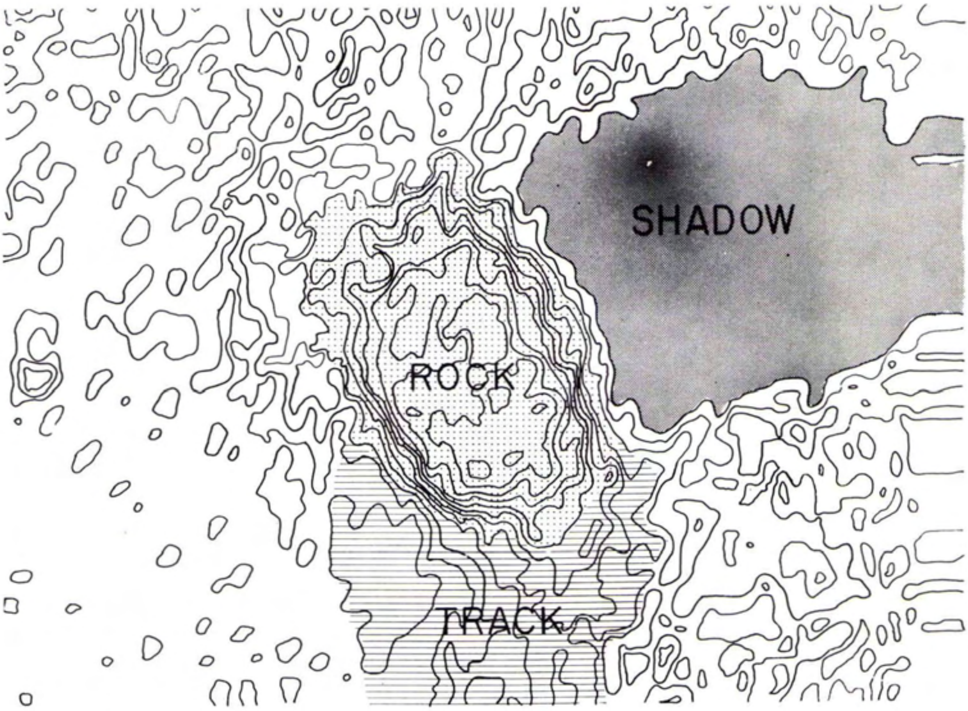

FIG. 4. Isodensity map of Boulder *A*, boulder shadow, and track from high-resolution photography.

pends on the photometric model used in combination with the isodensitometer measurements. It is believed that the photometric function of the compressed material in the track does not follow that which is normally measured from the lunar surface (retroreflecting). If this difference in photometric functions were the case, it might explain the difficulty in defining the shape of the track with respect to the adjoining lunar terrain.

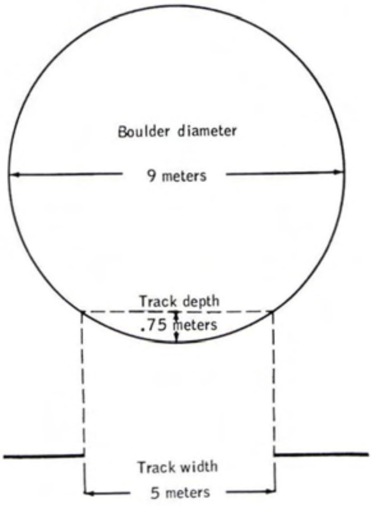

FIG. 5. Graphic determination of track depth.

These data were used to make some preliminary calculations to determine the approximate range of bearing strength of the crater-wall material. To simplify these calculations, the boulder and the track were considered in a static situation. If the surface area of the spherical segment of the boulder were considered to be flat (that is, the radius→∞), then the bearing strength so calculated would be conservative. However, the contact of the rolling stone with the surface was transient, and the depression made by the rolling stone is probably less than would be made by a static stone. These two effects should tend to oppose one another.

The volume of a spherical boulder 9 meters in diameter is 382 cubic meters. The mass of the boulder over a density range which would include possible rock types that might be encountered on the lunar surface is shown in Figure 6. The graph covers the range of densities from 0 to 3 grams per cubic centimeter. The surface of the spherical segment of the boulder in static contact with the lunar surface is 21.2 square meters. The ratio of

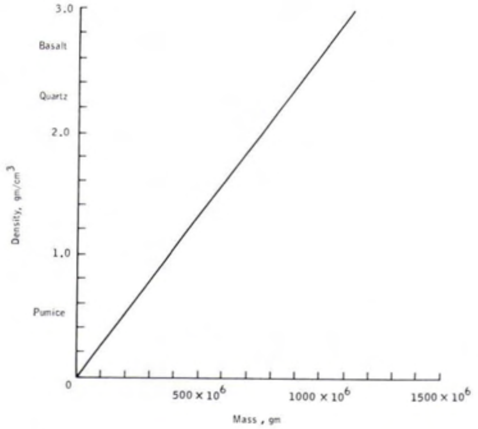

FIG. 6. Density versus mass for a range of possible lunar rock types.

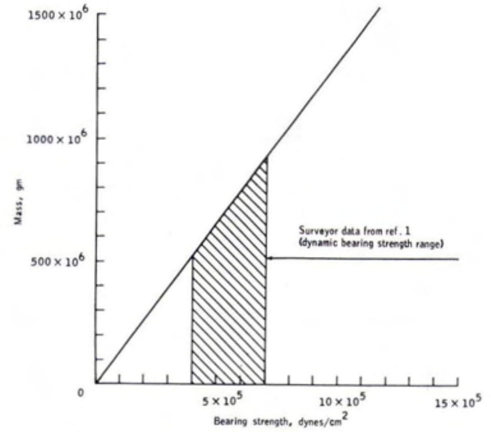

FIG. 7. Mass versus bearing strength.

the range of possible masses computed to the area results in a range of possible bearing strengths for the crater-wall material. A graph of mass versus bearing strength is shown in Figure 7.

The only direct measurement of the bearing strength of the lunar surface was obtained from Surveyor I and from two Russian *soft-landed* Lunik spacecraft. According to Reference 1, at the impact point and under the impact conditions of Surveyor I, the lunar surface did create a maximum dynamic resistance of 4×10^5 to 7×10^5 dynes per square centimeter (6 to 10 psi). This statement is taken to mean that the dynamic bearing strength of the surface at the Surveyor I touchdown point is at least equal to or greater than 4×10^5 dynes per square centimeter. Reference 1 also states that the static bearing capacity and other soil properties that would produce such a dynamic effect have not been conclusively determined. However, in Reference 2, it is stated that, if the material is homogeneous and similar to that observed at the surface to a depth of 1 foot or 30 centimeters, the preliminary analysis indicates that the soil has a static bearing capacity at the scale of the Surveyor I footpad of about 3×10^5 dynes per square centimeter, or 5 pounds per square inch.

The area in which Surveyor I landed and the area in which the rolling stone is located are separated by 60 degrees in lunar longitude. However, if the rolling stone were interacted with lunar material having a bearing strength similar to that experienced by Surveyor I, then the boulder would have a uniform density between 1.3 and 2.3 grams per cubic centimeter.

BOULDER B

A second boulder, Boulder *B*, located in Sinus Medii, was analyzed because its presence was unique to the general area and because of its unusual reflective characteristics. Although numerous boulder-strewn craters were found in both eastern and western mare areas, few boulders large enough to be analyzed were found in Sinus Medii. This boulder was determined to be approximately 7 meters in diameter and was located on the wall of the crater (shown but not named on ACIC lunar maps) approximately 1,300 meters in diameter. A photograph of the area, showing the location of the stone in the crater, is given in Figure 8. The track of the stone extends to the edge of the photograph, and its full length could not be determined. An enlargement of the same photograph is shown in Figure 9. The photograph has been inverted so that north is toward the bottom

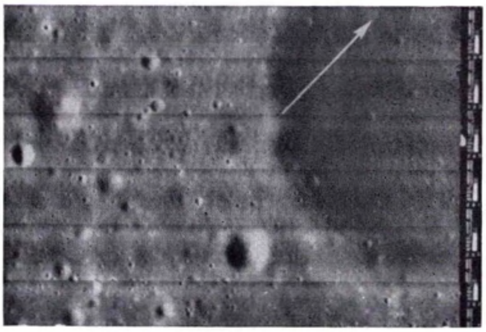

FIG. 8. Photograph of Boulder *B* and its track located in the southern wall of a crater in Sinus Medii.

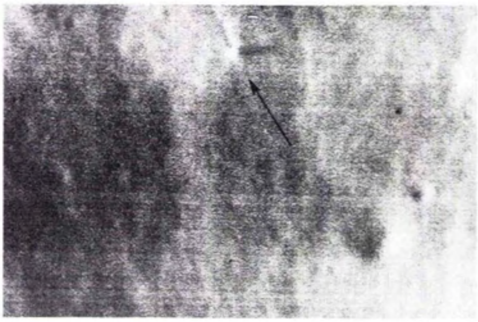

FIG. 9. Enlarged photograph showing boulder *B* and its track.

of the figure and the sun toward the left (east) at an elevation of 27.8 degrees.

The boulder shown in Figure 9 seems to exhibit a *glossy* reflective pattern. This pattern is apparent in the isodensity contours shown in Figure 10. For the measurements, the aperture of the isodensitometer was purposely made large to emphasize the general light-reflective pattern of the boulder. The pattern, as measured, clearly shows that the brightest points are centrally located well in from the visible edges of the boulder and not near the sunward edge. If the boulder had exhibited the normal lunar backscattering reflective characteristics, the brightest points would have been found along the sunward edge. Such a characteristic is illustrated in the following section with the discussion of Boulder *C*.

BOULDER C

The third boulder analyzed, Boulder *C*, was found in the ejecta blanket of a crater located on the eastern edge of Oceanus Procellarum and about 10 degrees due south of the large crater Copernicus. The small crater, shown in Figure 11, was measured to be 375 meters in diameter and was surrounded by a large number of boulders extending out to distances of about one-crater-diameter in all directions. Close examination of this ejecta material revealed several boulders which had left short tracks in the lunar surface before coming to rest. One such boulder is marked on Figure 11 with an arrow, and an enlargement is shown in Figure 12. In both Figures 11 and 12, north is toward the top of the figure.

The boulder shown in Figure 12 was measured to be approximately 9 meters across, but does not appear to be spherical; the shadow of this boulder indicates an irregular shape. The sun angle above the local horizontal at the time of the photograph was 29.0 degrees. The two sharp black lines in the middle and top of Figure 12 are scratches on the film and not a part of the lunar scene. However, a number of small boulders and rubble, down to a few meters in diameter, can be observed in this enlargement.

FIG. 10. Isodensity map of Boulder *B* as determined from Lunar Orbiter II photography.

A measurement of the reflective properties of this boulder is given by the isodensity pattern presented in Figure 13. Unlike that obtained for Boulders *A* and *B*, the pattern exhibits the usual lunar backscatter characteristics. The brightest part of the rock was found along the leading edge toward the sun. In addition, a strong similarity exists between the light-reflective pattern from the top of rock and that from the surrounding terrain. This could indicate that both have at least a thin covering of the same material or that the boulder is *instant rock*, formed from lunar surface material during the explosive process. The latter assumption is less favored because of the relatively large size of the boulder, its relative distance from the crater, and the indication from the track that it had rolled a short distance after impact with the surface.

BOULDER D

The fourth boulder analyzed, Boulder *D*, was chosen because it left a clearly defined and unusual *skipping* track. Like Boulder *A*, this boulder seemed to have been dislodged from the wall of the crater and to have rolled, bounced, or skipped down the inside slope. Both Boulders *A* and *D* are located within the same general area, about 40 kilometers apart.

The boulder and track were located on the southwest wall of the crater shown in Figure 14. An enlargement of the boulder and its

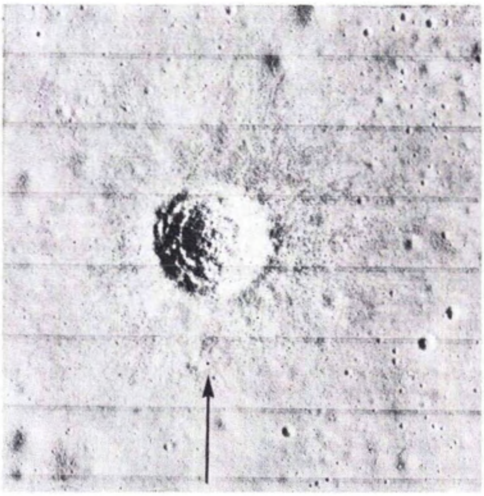

FIG. 11. Photograph of a crater and its ejecta located on the eastern edge of Oceanus Procellarum. Boulder *C* is indicated by arrow to the north–northeast of the crater.

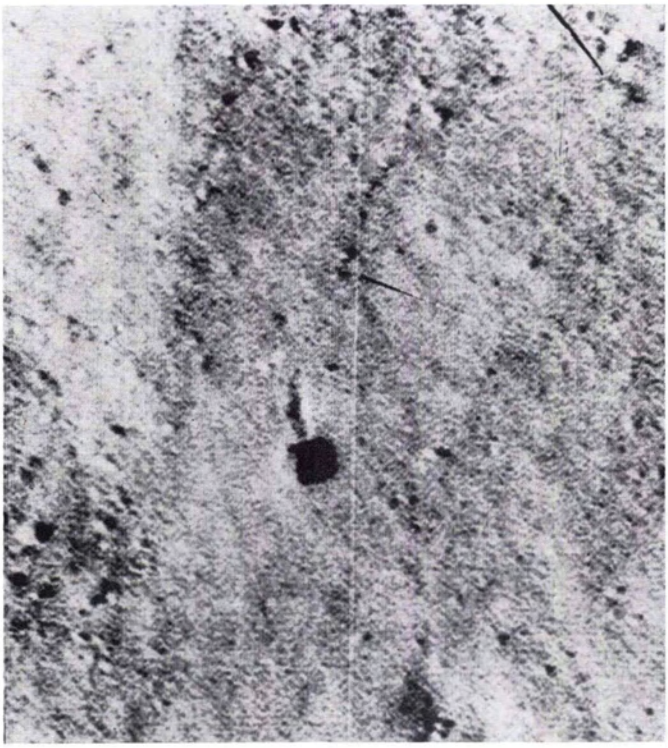

FIG. 12. Enlarged photograph of Boulder *C* and its track.

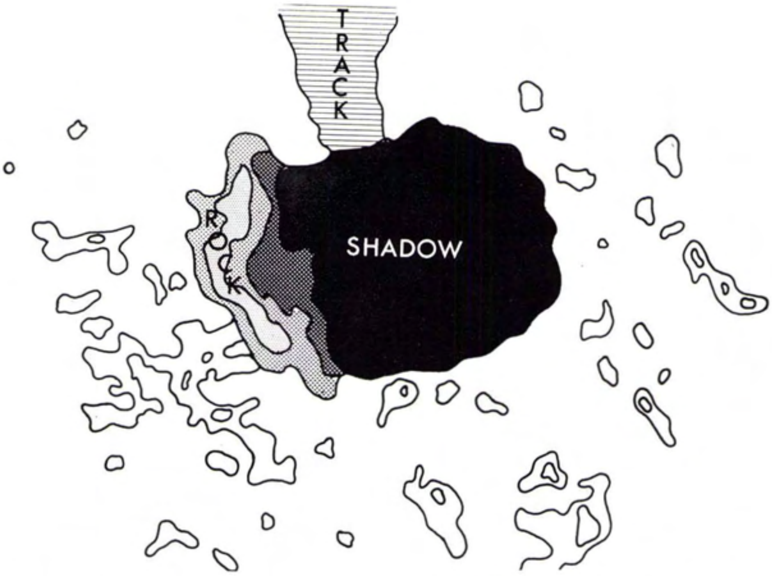

FIG. 13. Isodensity map of Boulder *C* as determined from Lunar Orbiter II photography.

track is shown in Figure 15. The boulder appeared to be nearly spherical and was measured to be about 5 meters in diameter. The path was irregular; it was measured to be from 1 to 3 meters in width. The sun elevation at the time of the photograph was 21.7 degrees above the horizon.

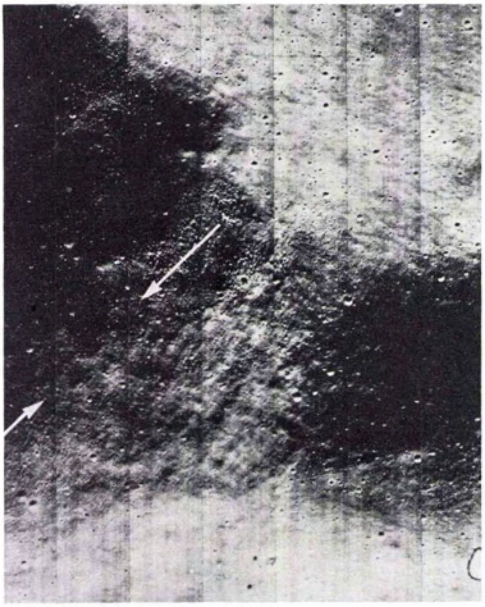

FIG. 14. Photograph of Boulder *D* and its track located in the southwest wall of a crater in Mare Tranquillitatis.

As the boulder did not roll to the apparent low point of the crater, measurements were made to determine the terrain slope along the path followed by the boulder. The results are shown in Figures 16, 17, and 18.

Figure 16 locates the profiles, measured by photometric techniques, from the apparent low point (C_o) of the crater along four rays which cut across the path of the boulder, *A* to *B*. The results are shown in Figure 17 for each of the four profiles. Points *A*, *D*, *E*, and *F* are the intersections of profile rays with the track of the boulder. The profile along the track of the boulder is shown in Figure 18. Note that the relative change in the vertical and horizontal distance has been plotted. Figure 18 shows that the boulder rolled about 360 meters in horizontal distance and about 130 meters vertically. The average slope was thus about 20.5 degrees. Examination of the profiles in Figures 17 and 18 indicates that the boulder followed the path of the largest relative slope and came to rest on a near-horizontal shelf or plateau. It is rather interesting to note from the photograph in Figure 15 that several smaller boulders can be observed in or along the path of Boulder *D* and that Boulder *D* apparently struck a larger boulder about 30 meters before coming to rest. The larger boulder appears to be partially buried in the surface. As in the case of Boulder *A*, no cause for the movement of Boulder *D* can be observed from the photograph. In both cases, the track originated

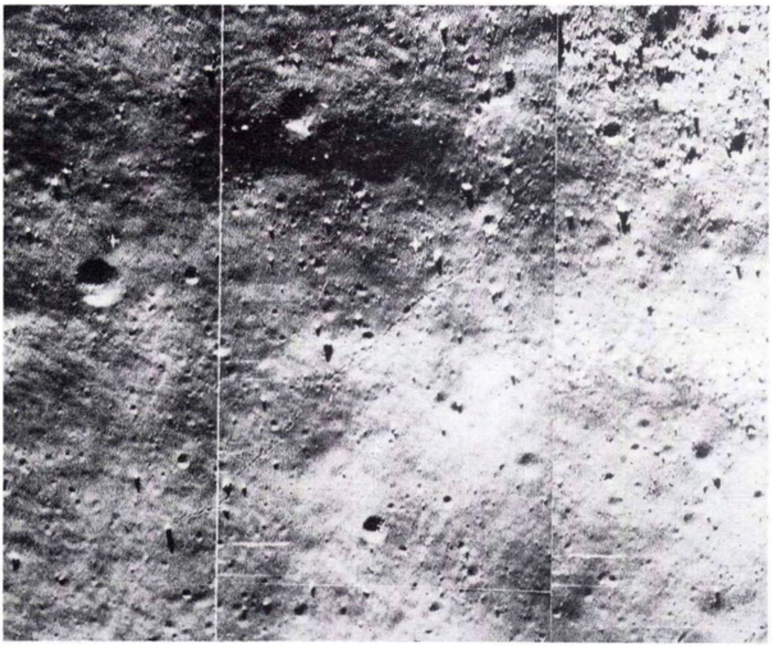

FIG. 15. Enlarged photograph showing Boulder *D* and its track.

from a cluster of large boulders near the rim of a crater.

An isodensity map of the boulder, the track, and the shadow is shown in Figure 19. While this pattern shows much similarity to that of the glossy Boulders *A* and *B*, an analysis of a more detailed microdensitometer pattern of this boulder indicated that in this case the noise (disturbances) from the Lunar Orbiter transmission system was too great to say conclusively that this boulder exhibited a glossy reflective surface characteristic.

CONCLUSIONS

Through the use of the high-resolution (1 meter) photographs of the lunar surface ob-

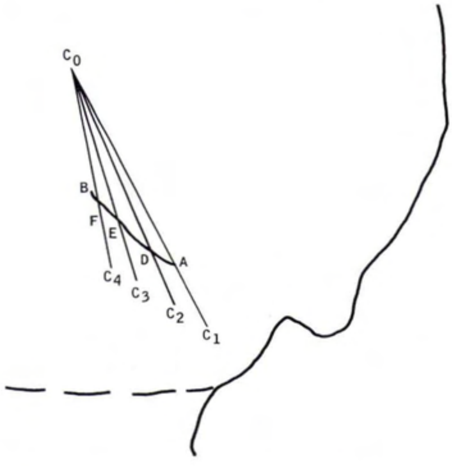

FIG. 16. Profiles measured across track *A–B* of Boulder *D*. Point C_0 is apparent low point of crater.

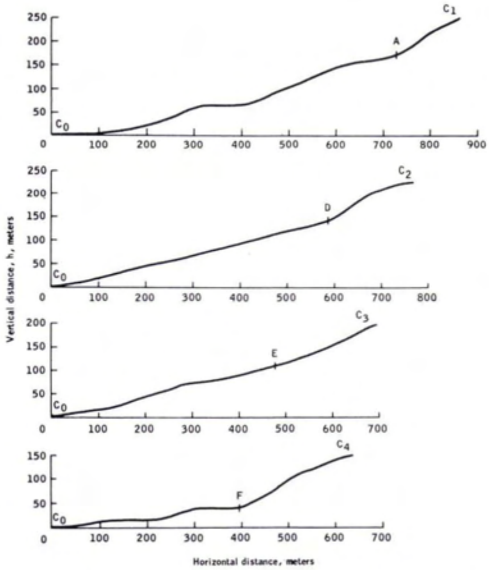

FIG. 17. Profiles across path of Boulder *D*.

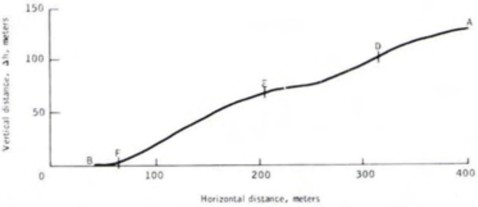

FIG. 18. Profile of terrain along track of Boulder *D*. Track started at *A* and ended at *B*.

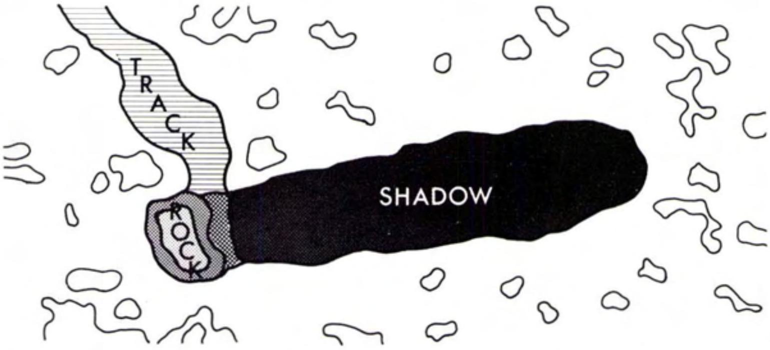

FIG. 19. Isodensity map of Boulder *D* as determined from Lunar Orbiter II photography.

tained from the Lunar Orbiter spacecraft, a general study was made of boulders lying on the lunar surface. Four of the larger boulders (with diameters >5 meters), which were distinctive because of the presence of tracks in the lunar surface, were given a more detailed analysis. From this study and analysis, several conclusions may be drawn.

- Large, cohesive, and near-spherical boulders exist on the lunar surface.
- At least a few lunar boulders have moved or have been moved recently enough so that their tracks have not been obliterated by lunar erosion processes.
- As determined by microdensitometer measurements, two (and possibly three) of these boulders reflected light in a pattern characteristic of convex and glossy (specular) surfaces.
- The interior walls and exterior slopes of lunar craters appeared to be covered with a compressible material which failed under the pressure of the boulders as they moved over the surface. There was no *snowballing* or buildup of lunar material in front of the boulders.
- It was not possible to determine uniquely the mass and density of the boulders or the bearing strength of the lunar surface material from the photographic data. However, if the lunar surface had a bearing strength similar to that experienced by Surveyor I, then one of the boulders analyzed would have a density of between 1.3 and 2.3 grams per cubic centimeter.

Many new and unusual features are to be found on the lunar surface, some of which will be amenable to limited analysis. The rolling stones are examples of such features. As knowledge of the lunar surface increases, it is expected that these isolated and limited analyses will more closely fit together.

REFERENCES

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2. *Surveyor I, A Preliminary Report*, NASA SP-126 (1966).