References and Notes

1. F. P. Shepard, *Bull. Geol. Soc. Am.* **60**, 1597 (1949).
2. T. K. Chamberlain, thesis, Univ. of Calif., Scripps Inst. Oceanog. (1960); R. F. Dill, thesis, Univ. of Calif., Scripps Inst. Oceanog. (1964).
3. D. L. Inman, *Beach Erosion Board Tech. Mem.* **100** (1957).

4. Support for this research came from the Office of Naval Research. Expert piloting by A. Falco and A. Laban contributed immeasurably to the success of the operations.

12 May 1964

Ranger Moon Pictures: Implications

Prior to the Ranger pictures the information about the small-scale structure of the lunar surface had been limited to that obtainable by telescope and radar observations. Earthbound telescope observations had given information down to a scale of about 1 km, and had clearly shown that craters existed in all stages of "freshness." Craters that would be judged old by the criterion of overlap by others, were generally seen to be smoother, less high for a given diameter, and often had a rather smooth interior. Young craters had apparently sharp rims and steep, rugged features. From the consistency of this effect it had been concluded that there was an active erosion process continuously degrading the features of the moon much as erosion alters the surface of the earth. This posed the question of a mechanism for transportation in the absence of agencies that erode on earth. The required rates are of course very low compared with terrestrial ones; removal of 1 micron per year from high ground and deposition on low would suffice to create the observed effects in all of geologic time. This could still lead to deposits 4 km deep. It is very difficult to judge such very slight processes in unusual conditions. However no processes could be envisioned that would transport large pieces of rock except the impact explosions. Those, however, convert much material into fine powder, and even with their action one could not contemplate a large fraction of the deposit on low ground being in any state other than dust. However the rates that could be ascribed to this process are too low in view of the number of small craters seen, and an additional process is required. Several processes can be suggested that may be effective in transporting material downhill, but only if it is in finely divided form. This was the origin of the suggestion that rock dust was the major constituent of the lunar surface, and that low regions had accumulations of it down to the depth of the original features, judged in some cases to be 2 or 3 km.

The fact that deposits of dust may be kilometers deep must not be taken to mean that the material maintains the consistency of a fine powder at great depths, no more than it does on the earth. Sediments originally made of fine particles may be in various stages of cementation. The agencies causing cementation of sediments on the earth are mostly different from those that could be active on the moon. There vacuum welding may be very important, especially for particles that are pressed together for such long periods of time that solid-state diffusion is a significant effect. Close to the surface, effects of sputtering and of evaporation and condensation can also assist in cementing grains together. The discussion of the mechanical properties of such sediments is clearly very important for future exploration of the moon, and measurements of these must receive a high priority in future missions to the moon. But it is important to keep separate the discussion of the origin of the material and its present mechanical properties—a point which has been confused in the literature and in popular writings where it has often been implied that if the low ground is filled with dust sediment then it will be loose and soft to some great depth. This is no more a direct implication there than it would be in the Mississippi basin. Nevertheless, such an origin raises the question of the bearing strength of the surface for exploration purposes, while an igneous origin would have implied almost inevitably an adequate strength.

Erosion and a sedimentary origin for the *mare* material was also implied by a different observation. Almost without exception craters that fell partly on highland and partly on *mare* ground had the *mare* portion much more heavily eroded, and often it had disappeared altogether. Thus *mare* material appeared generally more susceptible to erosion, and therefore, most likely, it was not as solid a material as much or all of the highlands. One is there concerned with thicknesses up to 3 km, and the argument is independent of thin layers that may influence the radio, thermal, or optical properties of the surface.

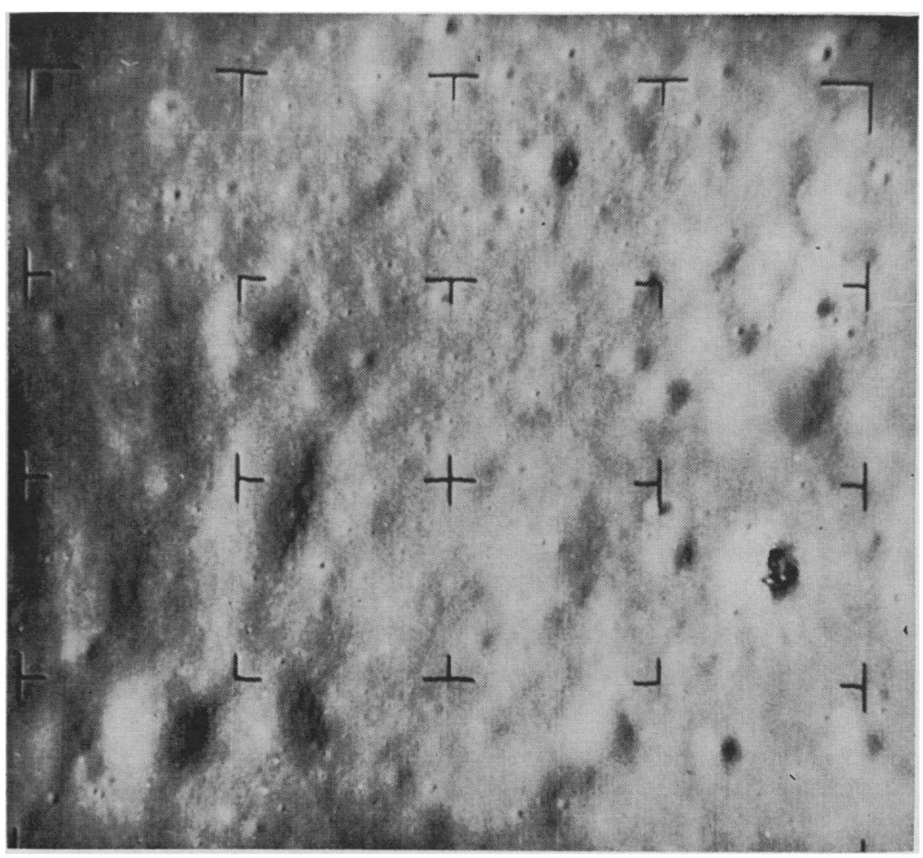

Fig. 1. High definition Ranger picture [scale, 1⅔ mile (2.6 km) on a side], showing many gently rounded craters in otherwise featureless terrain. Note the resolution of the photograph by means of the few small sharp-featured craters.

On a much smaller scale the radar evidence had demonstrated that the lunar ground was remarkably smooth on the scale of the wavelengths used when these were longer than about 3 cm (*1, 2*). For shorter wavelengths the radar scatter assumed the character appropriate to a rough surface, demonstrating that irregularities of that size cover most of the surface. At a 70-cm wavelength, where the most detailed observations were made, most of the ground appears smooth, and the proportion of ground covered with irregularities on that scale has been estimated, by an argument that required certain additional but plausible assumptions, to be approximately 5 percent (*3*).

This had implied that there was something other than solid rock at least in the first few meters of depth, for it seemed inconceivable that such a smooth rock surface could be generated or maintained in the presence of primary and secondary bombardment with meteorites. The smoothing over common to all the small impact craters except the most recent ones has been attributed to erosion. Uneroded craters larger than about 1 m across, and rough enough to scatter diffusely, would need to occupy about 5 percent of the ground, on the assumption that no other types of rough features are common.

The excellent Ranger pictures have completely confirmed these points. First, it is striking that in the entire interval of size or resolution from 300 m—the best visual telescope resolution—to 0.9 m, the highest Ranger resolution, there is no widespread new type of lunar feature to be seen. Round craters seem still the predominant surface irregularity. There is nothing that could be regarded as a sign of lava flow; there are no boulder fields or rock surfaces of angular shapes except in very small areas. The ground is not covered with the cracks or faults commonly occurring on all rock surfaces on the earth. By comparison with any terrestrial rock desert the ground is very featureless. Figures 1 and 2 give a comparison of the lunar ground with a terrestrial volcanic region. A sand desert would provide a better approximation except that rounded crater shapes are substituted for the usual shapes that result from wind and water erosion.

A few features other than craters are seen—gentle ridges and some unevenness on the nearly flat ground—but though very interesting, these features are certainly very minor in the sense of the area covered by them. Since there is no new type of widespread feature that might have invalidated the interpretation of the radar results, the pictures with a definition of a meter or so and the interpretations placed on the 70-cm radar measurements had to be in close agreement. This is indeed the case, and the excellence of the agreement will increase the reliance on radar data in the future. Most of the ground appears smooth or appears to have only very rounded craters that would not diffuse 70-cm waves. A small percentage of the ground is covered with sharp-edged steep-sided craters that certainly will diffuse 70-cm waves. The differentiation into two types of ground rather than a continuous spectrum of irregularity had been suggested by the radar observation of signal strength against range, which showed an abrupt change of gradient. One can now see that this is indeed merely the differentiation seen on high definition pictures between "new" craters and all the rest.

The Ranger pictures leave no doubt that erosion is a major effect in shaping the surface. No effect could be suggested for making so great a number of shallow and gently rounded crater profiles other than starting with steep, sharp-edged craters like the "new" ones seen, and letting erosion degrade them. For craters a few meters or tens of meters across, the erosion process must be very fast compared to the geological time scale, if the same process is to have had the discernible effects on craters tens of kilometers in size in the age of the moon. Erosion rates of the order of 1 micron per year, as needed for the explanation of the large

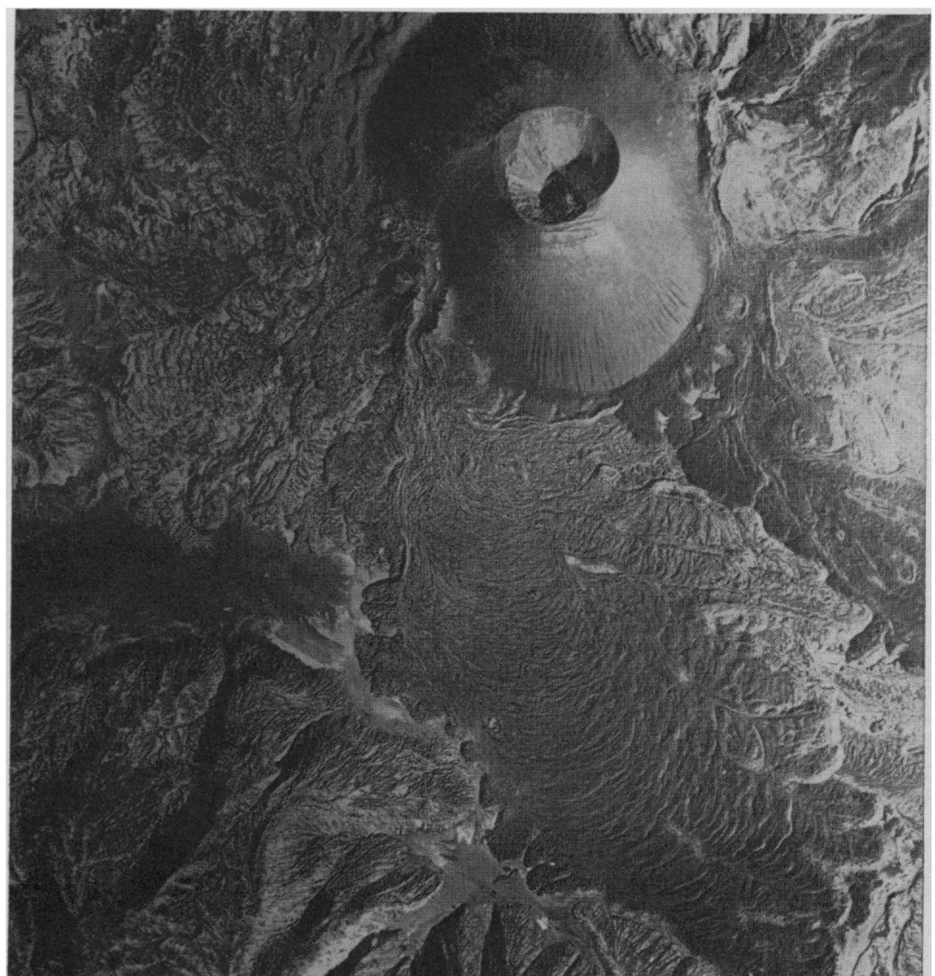

Fig. 2. Paricutin lava flow in Mexico [scale, 0.87 mile (1.4 km) on a side]. This picture is included, arbitrarily chosen from a multitude of possible ones, to show the degree of roughness and flow features which are always characteristic of extensive lava fields. Individual flow fields vary greatly from each other, and no picture could be regarded as representative. But, unless the field has been covered by a thick blanket of overlying deposit, many features connected with the flow and freezing of the lava are usually in evidence. In contrast there are no such features seen on the Ranger pictures of the moon.

features, would destroy a 10-m crater that is initially 3 m deep in about 3 million years. On the assumption that the erosion rate slows up when all gradients have become low, such a crater would still remain visible for a longer period, but it would appear as a shallow crater with rounded profile.

It is not our purpose to discuss possible mechanisms for erosion, but only to discuss the evidence for its occurrence. However, since one is not inclined to accept even the strongest evidence when it points towards an inconceivable occurrence, it should be mentioned that we can see no reason to discard the suggestion of dust transportation downhill by the combined action of micrometeorites liberating particles from their surface adhesion and electrostatic effects opposing their immediate return to the surface. With this combination there would then be a tendency for grains to glide for some way, greatly enhancing the effective downhill creep beyond that which mere statistics of repeated random scattering would achieve (*4*).

It appears then that a few percent, perhaps 5, of the moon's surface has been covered with craters larger than 1 m in, say, 3 million years. From this, one may derive an order of magnitude of meteoritic infall rate, but not without an assumption regarding the surface structure and thus of the size of meteorite required for the formation of a crater of given size. In a loosely cemented dust surface of much less than the compact density, craters will be much larger for a given size of meteorite than they would be in solid rock. This difference will be largest for very small craters where structural strength rather than gravity determines the size, while for very large craters the difference will be reduced to that resulting from the density factor alone.

The fact that crater formation proceeds more readily than in solid rock is also displayed by the appearance of the multitude of small secondary craters seen in the Ranger pictures. There it is certain that impact speeds are low, well below lunar orbital speed. Nevertheless most of these are also circular or only slightly deformed. This must mean that the energy liberated even at speeds of less than 1 km per second is still enough to excavate a crater that is very large compared to the projectile. In rock or any firm material this would not be the case, and the craters would mostly appear as imprints of the shapes of the projectiles or scars torn by them. In softer materials the effects of any liberation of gas at impact would be more significant. More information about these effects could be obtained by attempting to create the general appearance of lunar secondary craters by means of various projectiles shot into different terrestrial surfaces.

The Ranger pictures thus appear to show mostly a uniform, fine-grained material of low structural strength near the surface and in the first few meters below the surface. They show no hint of any transition to a different material below, such as a change in the appearance of deeper craters or an occasional outcrop of something looking like rock. It is therefore most likely that one is seeing the same type of material at all the depths excavated by the craters, but very probably in progressively greater compaction and cementation at the greater depths.

The Ranger pictures have clearly strengthened the case for dust being the main constituent of the lunar lowlands by not showing any rock formations. There is no case for discussion of a two-layer model. What structural strength can be attributed to dust sedimentation at various depths cannot be judged very well until impact probe experiments have been carried out; but without any clear signs of firm rock the pictures must lead to more concern about sinkage on impact or dust blowing in rocket exhausts in future operations on the lunar surface.

T. GOLD

Center for Radiophysics and Space Research, Cornell University, Ithaca, New York

References and Notes

1. J. V. Evans, in *Physics and Astronomy of the Moon*, Z. Kopal, Ed. (Academic Press, New York, 1962), p. 429; G. Pettengill and J. Henry, in *The Moon*, Z. Kopal and Z. K. Mikhailov, Eds., (Academic Press, New York, 1962), p. 519.
3. T. Gold, Center for Radiophysics and Space Research, Cornell University, report No. 156 and paper presented at the American Geophysical Union meeting, April 1964.
4. ———, in *The Moon*, Z. Kopal and Z. K. Mikhailov, Eds. (Academic Press, New York, 1962), p. 433.
5. Supported by NASA grant NSG-382.

17 August 1964

Plutonium Dioxide: Preparation of Single Crystals

Abstract. *Well-formed single crystals of plutonium dioxide were precipitated from a silicate glass and examined as an inclusion in a glass fiber drawn from the parent material. Excellent atomic scattering factors for* Pu^{+4} *may be obtained with these specimens.*

Single crystals are desirable for precise crystallographic studies. The usual technique for the preparation of single crystals from a fused sample is not readily adaptable to the isolation of plutonium dioxide because this oxide loses oxygen rapidly below its melting point (2400°C), whether in an inert atmosphere or under reduced pressure (*1*).

We prepared well formed single crystals of this compound by the unique method of precipitation from a silicate glass. Our co-workers (*2*) at Mound Laboratory determined that up to 20 percent plutonium dioxide could be dissolved in a simple silicate glass composed of 70 percent SiO_2 and 30 percent Na_2O by weight.

To form the single crystals we dissolved plutonium dioxide in excess of 20 percent by weight, in the simple sodium silicate glass. The molten glass containing the dissolved plutonium dioxide was rapidly cooled by pouring the melt on a steel plate. This cooling process resulted in the formation of homogeneous green glass beads. Although the glass was supersaturated with plutonium dioxide, it did not devitrify on cooling. We placed the plutonium-bearing glass beads in a platinum-rhodium bushing to draw glass fibers by the monofilament process. When we heated the bushing to 1300°C, plutonium dioxide crystals precipitated in the molten glass. As the glass fibers were drawn from the bushing, the crystals emerged completely encased in the fibers.

The crystal habit was that of hoppered cubes with perfect edges, some of which were up to 60 microns long. The crystals in the glass fibers were mounted for characterization by single-crystal x-ray diffraction techniques. We took a set of $MoK\alpha$ precession and $CuK\alpha$ Weissenberg photographs of a specimen with a 30-micron edge (Fig. 1). Analysis of the photographs revealed that the hoppered cube was a monocrystal and that the internal ordering was generally good. The back reflection pattern indicated only slight evidence of imperfections. The crystal was face-centered cubic, and its unit