Reports

Apollo 11 Observations of a Remarkable Glazing Phenomenon on the Lunar Surface

Abstract. *Some glazing is apparently due to radiation heating; it suggests a giant solar outburst in geologically recent times.*

The Apollo 11 mission carried a close-up stereo camera with which the astronauts took 17 pictures. Each is of an area 7.6 by 7.6 cm, seen with a resolution of approximately 80 μm. There are many details in these pictures that were not known previously or that could not be seen with similar definition by the astronauts Armstrong and Aldrin in their visual inspection of the lunar surface. One of those is outstanding in being wholly unexpected and possibly of consequence not only to lunar geology but also to aspects of the study of the sun, the earth, and other bodies of the solar system.

The observation is that of glossy surfaces, in appearance a glass of color similar to the surrounding powdery medium, lying in very particular positions. Small craters which are plentiful on the lunar surface—20 cm to 1.5 m in diameter—frequently have some clumps of the lunar soil or rough spots of the surface texture concentrated toward their center. They give the appearance of having been swept in at a time later than the formation of the crater. Some of these little lumps appear to have just their top surfaces glazed. The glassy patches that can be seen on the photographs range in size from ½ mm to about 1 cm.

The glazed areas are clearly concentrated toward the top surfaces of protuberances, although they exist also on some sides. Points and edges appear to be strongly favored for the glazing process. In some cases, droplets appear to have run down an inclined surface for a few millimeters and congealed there.

The astronauts' information was that similar things were seen in many small craters, many more than the eight instances of which we have photographs. They were not able at the time to pick up any of the objects for the sample return. They did not see a single glazed piece in any different geometrical position other than near the center of a small crater. They were not able to handle any of the objects, and thus have no direct observation as to the thickness of the glass. Since they only saw them from eye-height looking down at the ground in front of them, their visual acuity would be considerably less than that of the camera; they could therefore not supplement the detailed information contained in the pictures.

Several theories of the origin of this phenomenon have to be discussed.

1) *An effect connected with the rocket exhaust of the descent stage.* It might be thought that in the last phases of the landing process the rocket flame melted some lunar material and that this was blasted over the surrounding terrain. While at first this hypothesis seems very attractive, when pursued in more detail it runs into difficulties. These difficulties are concerned with the regional distribution of the objects and also with the detailed geometrical relationships in the places where they are seen.

The astronauts noticed these objects first in a region ahead and to one side of the landing approach path, about 15 m from the spacecraft. The pattern of disturbance caused by the rocket could be seen to extend hardly beyond the footpads of the spacecraft. The inspection of the approach path and the region directly underneath the nozzle of the rocket showed the ground disturbed there, but no evidence of any melting was seen. It seems most unlikely that, if melting occurred, all molten material was blasted away, without leaving a higher concentration near the source.

No explanation can be found as to how material so flung out would end up concentrated in little clumpings in the bottoms of small craters without there being also some on the flat surface or in much shallower depressions. The material could not be thought to be propelled by gas drag and slid over the surface, to land perhaps in sheltered holes, since the forces of the rocket gas drag are quite inadequate at a distance of more than a meter or so from the rocket. This is substantiated by the fact that the radially streaked pattern of the ground radiating out from underneath the spacecraft disappears at a distance of between 3 and 4.5 m. No glassy objects could have been dragged over the surface by this stream at a distance of 15 m; if they had been flung that far, they would be lying essentially where they landed, and no reason is then seen for the specific distribution that was found.

The glassy objects were, by the astronauts' descriptions and substantiated by the pictures, usually found in a tight clumping, and the pictures indicate in several cases a definite common azimuth dependence of the effect among the members of any one group. (There is no record of the azimuth position of the camera, so different groups cannot be compared with each other; but the camera was generally held facing nearly vertically downward. The astronauts were not aware of any azimuth effect, nor could they have been expected to see it, since it becomes evident only from a careful study of the high-resolution pictures.) It thus seems extremely improbable that any effect of the rocket exhaust can be held responsible for the phenomenon.

2) *Splashing of liquid drops from a larger impact elsewhere.* Many of the same objections can be raised again here. Such droplets could not have landed in preferential places. On impact, with the velocities necessary from a source more than a meter or so away, they would have toppled and destroyed many of the frail structures that they hit, and thus the geometrical relationships would have been lost.

3) *The objects are common in the ground, where they were distributed after being created by shock heating or volcanism. Erosion has exposed some of them.* The fact that the objects are found in the bottoms of little craters argues against slow erosion exposing them, for these craters are filled up and not

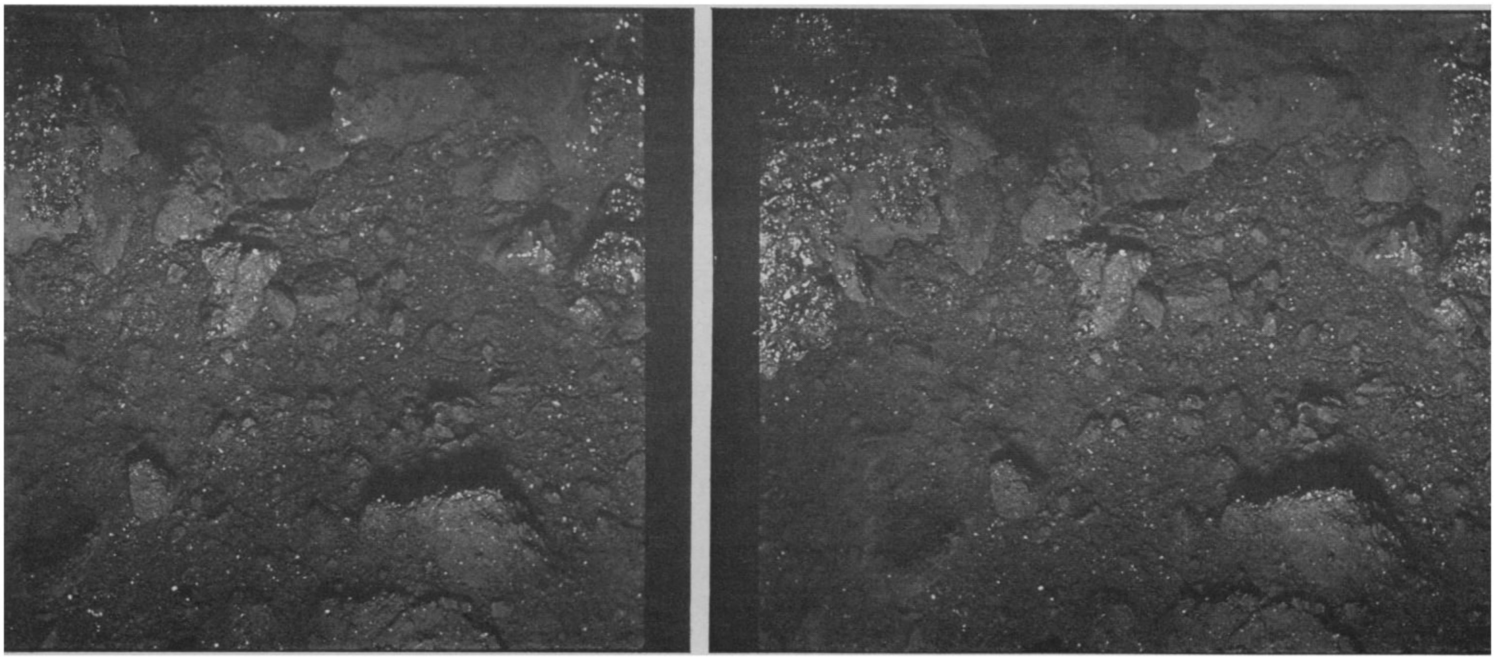

Fig. 1. Area 7.6 by 7.6 cm. A large area of glazing is seen in the upper left region, both on the horizontal and on the sloping surfaces of the protuberance. Some glazing is also seen on the upper right object, with edges and points particularly affected. In the lower part of the picture a small glossy bead is seen poised on a narrow pedestal. (The detail in the color stereo transparencies far exceeds that which can be reproduced in the present prints.) See cover for an enlargement.

emptied out by the lunar surface transportation processes. There are many cases of a clearly visible outline of the glazing, which show shapes characteristic of viscous flow defining that outline. One is thus not dealing with entirely glazed objects of which only a certain fraction is cleaned off and exposed; rather one is dealing with objects that are covered with a glaze mainly on top.

Small glassy spheres had been reported to be common in the lunar soil, and many are indeed also seen on the pictures. Their origin may be understood merely as a consequence of meteoritic impact melting and freezing during the ballistic trajectory of the ejected material. If the ground has been plowed over many times by impacts, as suggested by the topography of the moon, a substantial admixture of spheres and other shapes resulting from only partial melting must indeed be expected in the ground. The glazed surfaces discussed here appear not to be of this character. Fragments of them

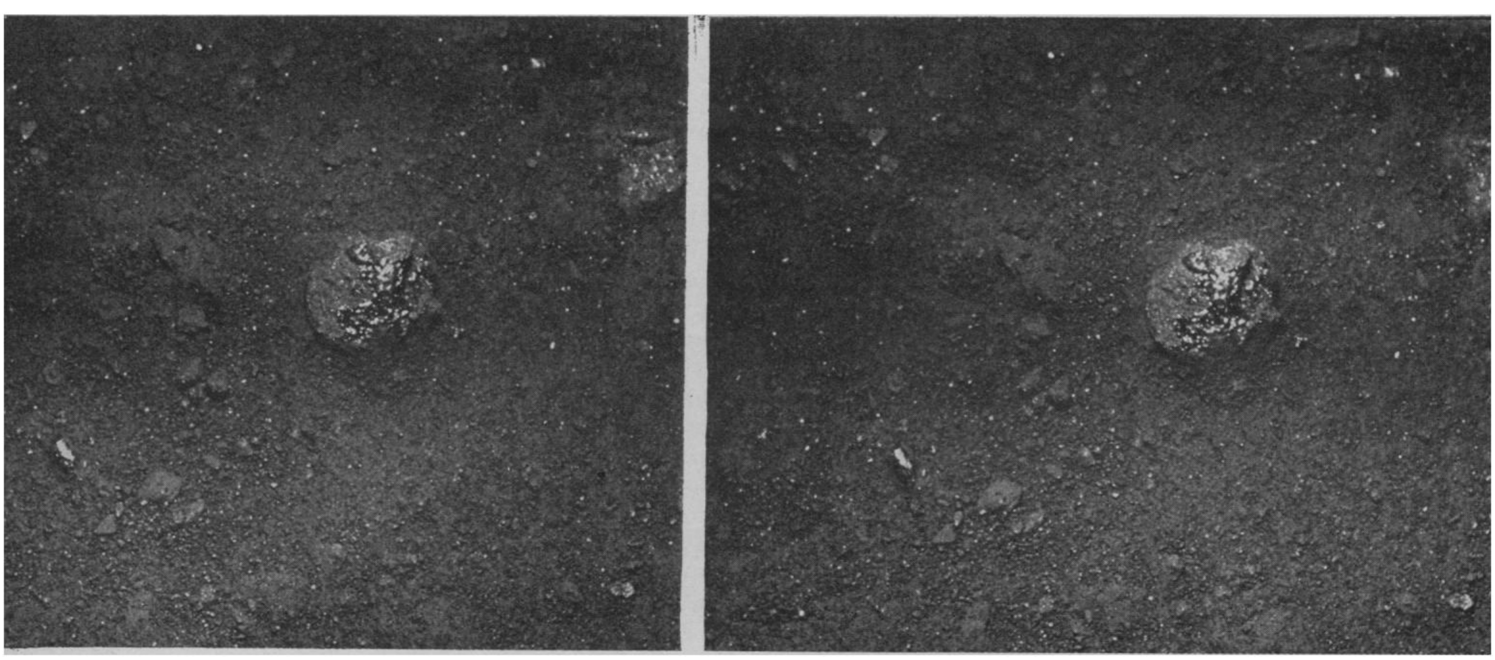

Fig. 2. Area 5.1 by 4.1 cm. A small lump of lunar soil with a glazed top, and a smaller glazed piece to the left. The larger object shows no change of color or texture compared with the surrounding ground, known to be soft, fine-grained soil, except for the glaze mark.

may also appear in the lunar soil, and those would be expected to be thin pieces, shiny on one side, and rough with embedded soil on the other.

4) *They are objects created by the impact that made the little craters in which they are now found.* This seems impossible in view of the fact that they are frequently quite frail structures, apparently only made of the powdery material, and they could not have survived and remained there in definite geometrical positions, when an explosive force excavated the crater. Whereas in a hard rock a glazed coating may remain lining the impact pit, this is very unlikely in a soft soil. All material exposed to enough heat to cause melting would be exposed also to aerodynamic forces large enough to be expelled. Any glass made by a strong pressure wave in the ground and subsequently exposed would not have glossy surfaces except as a result of fracture. The shapes seen are in most cases clearly the result of a surface viscous flow and not of a fracture.

5) *Radiation heating.* An intense source of radiative heating could account for all the facts now known. The wavelength of this radiation could be anywhere in the electromagnetic spectrum between the far ultraviolet and the far infrared. For radiative heating from a small angular source in the sky the bottoms of craters are substantially favored. The equilibrium temperature in a given radiation field is likely to be between 10 and 20 percent in absolute temperature above that of flat ground. [This problem has been discussed in some detail by Buhl, Welch, and Rea (*1*).] The reason for that is, of course, the diminution of the solid angle subtended by the cold sky for a particle in a hollow compared with one on flat ground. There is thus an intensity range where radiation heating will cause melting only in the bottoms of craters. The positioning of the objects can be understood in these terms.

No significant mechanical forces would be involved, and frail structures could suffer melting of their upper surface without being deranged. One protuberance, for example, shows no change in color or texture from the surrounding medium known to be soft powder. Yet it has a large patch of glazed material over the top of it (Fig. 2). If the source of the heating were not directly overhead, there could be a common azimuthal preference for the melted surfaces.

Protuberances rather than flat ground, and sharp points and edges, would be favored for melting if the heat source existed for a short time only. The reason for this is that heat conduction will carry away less heat from such positions, which would reach the temperature corresponding to the local radiative equilibrium sooner than that of the flat surfaces. The observations do demonstrate such an effect. Similarly, the apparently thin coating of glaze seen in many of the pictures indicates a short duration for the period of the radiative heating. With the approximately known rate of heat transfer in the lunar material, one may estimate that the duration of the heating phase was between 10 and 100 seconds.

Among the interpretations discussed here, only radiative heating seems to be able to account for the major observational data; and it accounts well for both the distribution over the ground and the detailed geometrical arrangements in which the glazing is found, for it is in just those places where the temperature would be expected to be at a maximum. We must therefore seek clues as to the nature of such a flash of radiation.

The time of occurrence of the flash heating would have to have been sufficiently recent for micrometeorites not to have destroyed the glaze, and for the mechanisms that redistribute the lunar soil not to have blanketed the objects. Estimates of the micrometeorite rate at the present time vary considerably, but it seems very unlikely that the glaze could be maintained on the surface for as much as 100,000 years and probably not for more than 30,000. The event in question would thus have to have taken place within this geologically very recent past. Several possibilities have to be discussed.

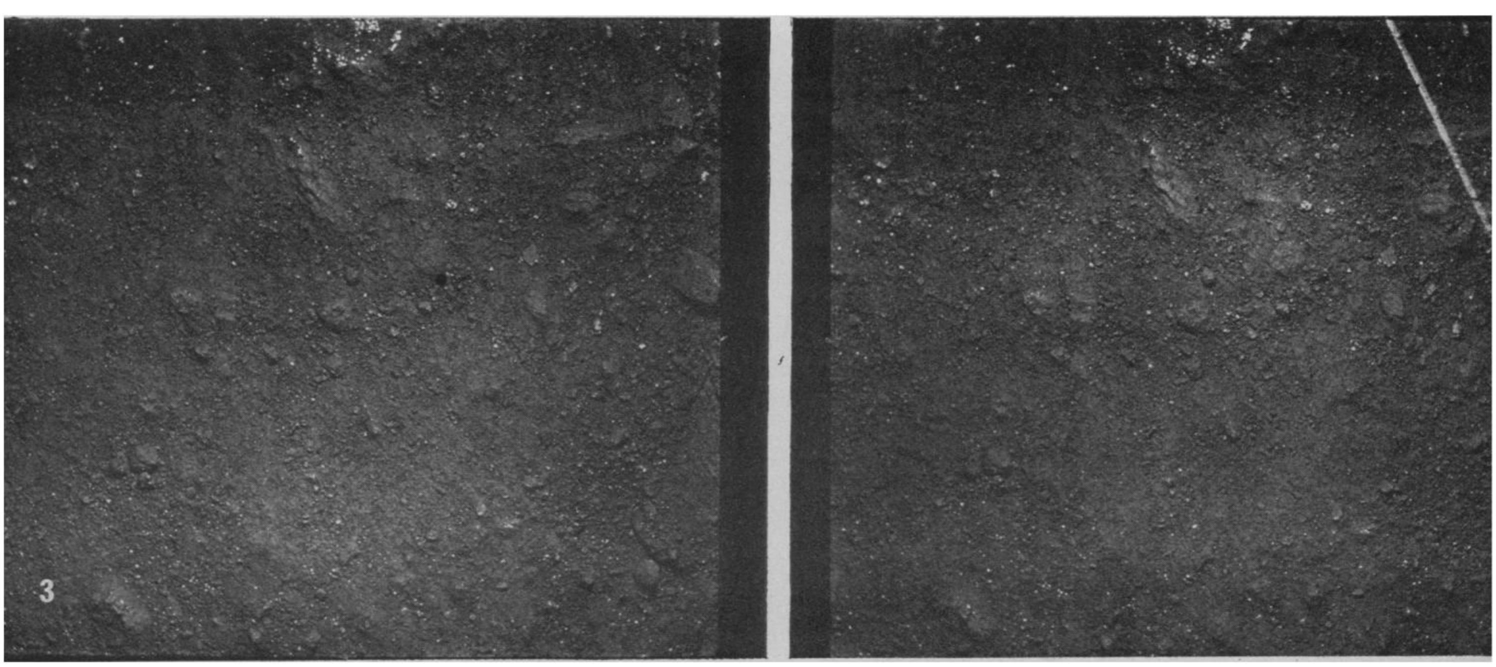

Fig. 3. Area 7.6 by 7 cm. This is the bottom of a crater and the affected area is close to the upper edge of the frame (and presumably beyond). Here glazing is seen in a very regular fashion, with the edges and points that face upward and out in a direction to the upper left consistently affected. The stereo view is required to observe the directional effect.

The first possibility is that there was an impact fireball on the moon. A large impact would no doubt generate intense radiation from the explosive gas cloud. This radiation will, however, be largely screened from reaching areas outside the crater made by the impact, and it seems unlikely that high radiation intensities would extend over regions beyond those swept over by the explosive action or by the expelled material. Craters would be particularly unfavorable locations for such a source of heat, rather than be highly favored as the observations show.

The second possibility is that there was an impact fireball on the earth. Although very large impacts may have taken place on the earth within geologic time, and may indeed be responsible for some of the widespread falls of tektites, no really major event is thought to have occurred within the sufficiently recent past. The energy released in an impact on the earth of a 1-km meteorite at a velocity of 20 km/sec is of the order of 3×10^{27} ergs and, if it were all converted into radiation, would only deposit on the order of 4×10^5 erg/cm^2 on the lunar surface. The value required to cause the observed effect is of the order of 3×10^9 erg/cm^2. No fireball of adequate intensity seems to have existed on the earth within the last hundred thousand years.

The third possibility is a flash from the sun.

One can calculate the increase in the solar emission that would be required to cause melting in favorable places on the lunar surface. The normal noontime temperature on the lunar equator is approximately 394°K. The analysis of Buhl *et al.* (*1*) shows that the absolute temperature in the bottom of a hemispherical crater must be expected to rise about 11 percent above that of the surroundings. The normal noontime temperature would thus be 437°K in such locations. If f is the factor by which the solar luminosity is increased, we require that

$$f = (T_m/T_0)^4$$

where T_m is the melting temperature and T_0 the normal temperature in the same location. If we adopt a melting temperature of the lunar surface material of 1400°K, a figure appropriate for basalt, the value of f would be 106. The temperature of the flat ground in the same radiation field would then be 1260°K. (For a brief flash the fact that a crater bottom started out 40 degrees hotter would further increase the margin between melting there and elsewhere.)

The flash heating, if it originated from the sun, which was overhead at the time in the lunar region in question, thus requires that the sun's luminosity flared up for a period of between 10 and 100 seconds to a luminosity of more than 100 times its present value. What could be the origin of such a flare-up?

Solar flares, as they are known at the present time, only reach a total energy output of less than 10^{33} ergs. The quantity we are discussing here is at least 4×10^{36} ergs for an isotropic source, or 2×10^{36} ergs for a localized source on the sun that radiates into a hemisphere only. While it cannot be ruled out completely that flares of such an intensity could occur, we have no evidence in this regard, although some earlier speculations exist (*2*).

The phenomenon may not be in the nature of a flare, but in the nature of a very minor nova-like outburst of the sun. The nova phenomenon among the stars is not understood, but it is normally concerned with a different class of star, and the intensity of the outburst to 100 times the luminosity, for a period of only tens of seconds, every few tens of thousands of years would be a phenomenon that would not have been recognized astronomically among stars of the solar type. One can therefore not completely rule out the possibility that stars that are like the sun do have occasional instabilities of internal origin, but very much weaker than the novae.

The infall into the sun of a comet or asteroid is another possibility (suggested to me by F. Hoyle). An object falling into the sun at the velocity of escape would have to have a mass of 3×10^{21} g for the kinetic energy to be sufficient to generate the flash. This would put the object into the class of asteroids or very large cometary cores.

For the infalling energy to be converted into radiation in its entirety, it would be necessary that the object break up in the solar atmosphere and that no substantial pieces remain intact at the level of the photosphere. Tidal disruption and violent heating could perhaps be invoked to break up a cometary body more readily than an asteroidal one. Also, comets have been known to approach the sun very closely in historical times, and the statistical evidence would be that many have hit the sun in a period of 30,000 years. The mass required of 3×10^{21} g is above that which has been guessed at for presently known comets. An icy cometary core would have to have a radius of approximately 100 km, while some comets now known may have cores as large as 50 km (F. Whipple, private communication). The suggestion that the flash was due to an infalling comet seems to merit further attention.

If such a flash occurred on the sun within geologically recent times, there are many other consequences that may perhaps be recognized on the earth or other planets. If the flash occurred as a result of an infalling object, or of a superflare, or of an internal outburst that exposed subphotospheric material, its spectrum would be mainly in the ultraviolet. So far as the earth is concerned, the total extra heat delivered would be mainly spread in the atmosphere and does not cause a substantial rise in the temperature of the lower atmosphere. The heat delivered to the ground is not likely to have been enough to cause any permanent effects. Nevertheless, there may be effects in the geologic record that can be attributed to such an event. The upper atmosphere of the earth and of Venus, and the entire atmosphere of Mars, would, however, have been seriously affected. On the earth, the ratio of He^3 and He^4 in the outer atmosphere suggests that there is no substantial preferential loss by slow evaporation of He^3 (*3*). If the outer atmosphere were entirely swept away by such outbursts, then the present ratio, which implies an absence of a preferential thermal evaporation at normal temperatures of He^3, would be more readily understood. The apparent absence of nitrogen on Mars, as reported from the data of the Mariner 6 and 7 flights, could also be understood if the entire atmosphere had been swept away and, in the short time since, if it had been replenished only from the constituents frozen out on the pole cap, which may be CO_2, but not nitrogen (this suggestion is due to C. Sagan).

Flash heating on the surface of Mercury would have been much more intense, and if made of lunar-type rock, almost an entire hemisphere would have been glazed. We do not know the surface material, nor the effects of erosion and solar irradiation on Mercury, and the absence now of a glazed hemisphere could be understood as due to a different material or a faster destruction of glass on Mercury than on the moon.

No doubt many more facts will come to light concerning the lunar surface, and perhaps this phenomenon as well, in the analysis of the lunar samples brought back by Apollo 11. A rapid publication of these findings was nevertheless indicated by the urgency to make the best possible scientific preparations for the next Apollo flights. A more complete review of this and other information contained in the close-up pictures will be published later.

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References and Notes

1. D. Buhl, W. J. Welch, D. G. Rea, *J. Geophys. Res.* **73**, 5281 (1968).
2. T. Gold, in *Semaine d'Etude sur le Problème du Rayonnement Cosmique dans l'Espace Interplanétaire* (Pontificiae Academiae Scientiarum Scripta Varia, Vatican, Italy, 1963), pp. 159–174.
3. G. J. F. MacDonald, *Rev. Geophys.* **1**, 305 (1963); W. I. Axford, *J. Geophys. Res.* **73**, 6855 (1968).
4. I am indebted to the National Aeronautics and Space Administration for arranging for the construction and deployment of the close-up camera; to E. Purcell, E. Land, J. Baker, R. Scott, and F. Pearce for their contributions in outlining and guiding this camera project; to Eastman Kodak for the design and fabrication of the instrument; and chiefly to Mr. N. Armstrong for his successful use of it, and his excellent descriptions of all relevant lunar surface observations made by himself and Mr. E. Aldrin. Work on the lunar close-up camera and the analysis of photographs obtained with it is supported at Cornell under NASA contract No. NAS9-9017. I thank F. Hoyle, F. L. Whipple, G. J. F. MacDonald, and S. Soter for helpful discussions.

19 August 1969

Bed Forms in Base-Surge Deposits: Lunar Implications

Abstract. *Undulating dunelike deposits of surface debris, widespread over parts of the lunar landscape, are similar in form but greater in size than base-surge deposits found in many maar volcanoes and tuff rings on Earth. The bed forms of base-surge deposits develop by the interaction of the bed materials with those in the current passing overhead. Therefore the "patterned ground" produced differs from that formed by ballistic fallout.*

As pointed out by Moore (*1*) explosive events such as shallow phreatic volcanic eruptions, large chemical or nuclear explosions, or hypervelocity impacts may give rise to turbulent debris-laden density flows somewhat similar in flow behavior to nuées ardentes. The density flows, known as base surges, expand radially outward from the base of a vertically rising explosion or eruption column and sweep laterally across the underlying surface at high velocities. Because base surges can develop by such diverse processes, it seems reasonable that they may have been important in dispersing and depositing debris on the lunar surface, irrespective of the kind of cratering mechanisms. Accordingly, the characteristics of base-surge deposits are of concern to lunar explorers. They must be considered in any interpretation of the origin of lunar fragmental debris, estimates on the thickness of the deposits, and the "mirroring" of buried structures within the underlying basement.

Although direct observational data of base-surge deposits on Earth are few, the surface configurations (bed forms) of layers which were shaped during such deposition appear to be of two kinds; low-amplitude bed waves with long axes approximately perpendicular to current directions, and planar, rather featureless surfaces. However, the distinction between these different bed forms becomes increasingly difficult as the wavelength of the undulation increases. For example, the surface of a low-amplitude, long wavelength bed form would appear to be planar when viewed up close, but may easily be recognized as part of a wave when viewed from a greater distance (compare different layers in Figs. 1 and 2).

Although maximum velocities of base surges are several times greater than those of water flowing in alluvial channels, base surges do develop bed forms similar in shape to those developed by debris-laden streams (*2*). Thus, we use similar terms. Low-amplitude bed waves with stoss- and leeside slopes inclined at angles less than the angle of repose are antidunes or sinusoidal waves; relatively flat, featureless surfaces are referred to as plane bed forms. With concurrent deposition and migration of bed forms, accompanied by changes in velocity of the current overhead, depositional sequences containing a succession of low-angle antidune foreset and backset cross laminae will be interspersed with plane beds and with dunelike bed forms of different wavelength (Figs. 1 and 3).

Base surges from the 1965 phreatic volcanic eruption of Taal Volcano, Philippines, deposited dunelike forms with wavelengths which progressively decrease from 19 m close to the eruption center to about 4 m at 2.5 km distant (*1*). This reflects the reduction in velocity. Internal structures show cross-bedding caused by wavelike transfer of debris in the current direction. Dunelike forms were also deposited by a base surge which developed from the 100-kiloton underground thermonuclear Sedan test of 6 July 1962.

Recently, it was suggested (*3*) that the uppermost layer of sand around Meteor Crater, Arizona, was deposited from a "dense suspension" during crater evisceration, rather than by later reworking of airfall debris. The sand layer exhibits sedimentary structures resembling water-laid deposits.

Bedding characteristics of base-surge deposits may be studied in the rim ejecta of volcanoes built mostly by phreatic eruptions. Of particular importance are partially dissected maar volcanoes; geologic evidence shows that nearly all maar volcanoes formed in environments where surface or subsurface water had access to the volcanic vents. The rim ejecta of most maars, especially those with broad, low ramparts which surround shallow, wide craters, have bed forms indicating emplacement by surge-flow processes (Fig. 3). Directional features around the craters show that the depositing currents spread out radially from the vents at high velocity.

Sedimentary structures in maar ramparts, such as those at Zuni Salt Lake, New Mexico (*4*), Salt Lake Craters, Hawaii, Cerro Colorado, Sonora, and the Macdoel, California, tuff rings (Fig. 3), exhibit broad undulations instead of uniform primary dips. We conclude that such low-amplitude structures, preserving the form of broad waves, were developed by base-surge flow. Wavelengths may attain many meters, or be only a fraction of a meter.

On vertical exposures cut radially into maar rims, large-scale undulations are not easily discernable. Instead, the conspicuous structures consist of dozens of thin-bedded or laminated tuff and lapilli-tuff layers, some of which show low-angle foreset and backset cross laminae. Thus these deposits pre-