in such a country to the economic activity existing in developed countries.

Incidentally, my planning office has just finished a feasibility study for an area in the Amazon Basin where 500 families may be settled in 14,400 hectares (1 hectare = 10,000 square meters), with a loan of \$16,000 (United States dollars) per family extending over a 10-year period. After 10 years each family will have paid the loan, earned \$44,000, and will continue to earn \$10,000 per year.

In consequence, one question remains open: Shall underdeveloped countries appeal to birth control, an issue greatly discussed in the United States (*2*), or shall they make every effort possible to increase the numerator of the income-per-head ratio, as they seek an internal market for their products, thus embarking in another kind of economic development? In economics, the benefit of the individual does not always mean the benefit of the community, and so a true answer may only be found by an accurate analysis of each area and not through hypothetical generalizations of economic-demographic models taken from developed areas.

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References

1. S. Enke, *Science* **164**, 798 (1969).
2. J. Blake, *ibid.*, p. 522.

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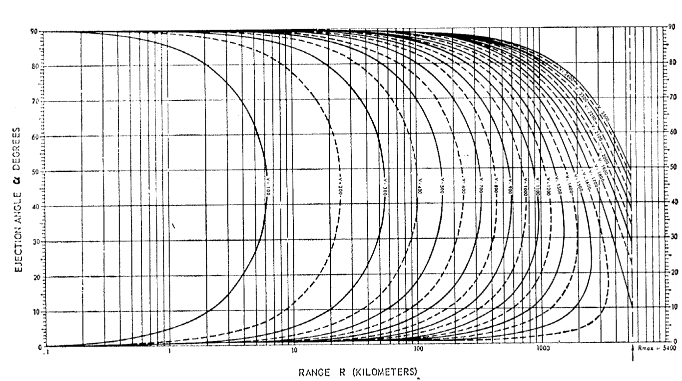
Origin of Glass Deposits in Lunar Craters

The mechanism of solar flash heating (*1*) for creating a glaze within small lunar craterlets in the Apollo 11 landing site is geologically unusual. A temperature rise in the shallow craterlets in question, if sufficient to have glazed their interiors by solar flash, would produce even greater thermal effects in larger and deeper lunar craters and fractures. Moreover, this effect should be latitude-dependent since the sun does not deviate much (1°35′) from the lunar equator. Perhaps proponents of "instant flash" would speculate that lava flow patterns and rounded central mountains in lunar calderas are melted by such flares. I have argued that over 95 percent of the major lunar surface features are purely volcanic and not in any way external in origin. Lava flow patterns in many lunar craters indicate intermittent internal activity. Examples are Tycho (*2*) and Copernicus. Moreover, there is no latitude dependence on melt phenomena in lunar craters. There are objections to the temperature increase in the craterlets causing internal glazing. In the first place, the temperature increase of about 100°K from center to rim by solar concentration of heat cited by Buhl *et al.* (*3*) refers to hemispherical craters of millimeter size. The craterlets discussed by Gold are much larger (20 cm to 1.5 m) and much shallower (< 20 degrees internal slope angle). Buhl *et al.* state (*3*, p. 5294) ". . . [lunar] craters larger than 1 mm in diameter are shallower . . . [than those less than 1 mm]." Diameter-depth ratios for lunar craters over a few millimeters in diameter and under about 3 m in diameter are far greater than 2. The diameter-depth ratio of the craterlet in which Surveyor 3 landed is greater than 15; and the one that Surveyor 5 landed in is greater than 45. Heat would not significantly concentrate in such shallow depressions. Can the suggestion of internal glazing be honored without data on the diameter-depth ratios of the craterlets in question? Glazing should be correlatable with this ratio as well as the latitude of the craterlet.

Let us assume that a 100°K temperature increase is achieved in the



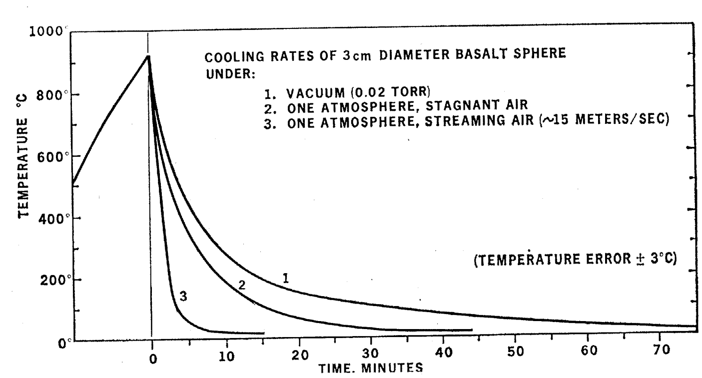


Fig. 1 (top left). Volcanic bomb impact craterlets in the Batur caldera, Bali, Indonesia. Diameter of craterlet in foreground is 1.8 m. Fig. 2 (bottom left). Range curves for lunar ejecta. Fig. 3 (bottom right). Cooling rates of a 3-cm basalt sphere in air and vacuum.

craterlets showing glazing. Then the temperature of the instant flash must have been very specific and within a small temperature range. The melting temperature of basalt is about 1425°K. To melt the craterlet interior and not the edges would require an instant flash temperature on the lunar surface of about 1325°K if a temperature concentration effect produces a 100°K temperature differential in hemispherical craters. This temperature would just glaze the craterlet interior but not the edges. A flare of 1225°K would not produce any effect, and one at 1425°K would glaze both rim and interior.

A more geologically realistic mechanism for producing glassy objects in lunar craterlets is by the impact of volcanic bombs which would produce the craterlets at relatively low velocities. In 1964, I suggested that the Ranger 7 craterlets were in part formed by the impact of volcanic bombs (*4*). In spite of the excellent treatment of the problem by Hartmann (*5*), I am unable to distinguish volcanic bomb impact craters from low velocity secondary craterlets produced by debris from primary impact craters. Volcanic bomb impact craters, although rapidly erased by erosion on the earth, are present around every modern volcanic eruptive center. For example, Fig. 1 shows such a craterlet produced in basaltic ash by a basaltic volcanic bomb on the northeast flank of the central volcano in the Batur caldera in Bali. Other volcanic bomb impact craters are in the background. Decker and Hadikusumo have discussed and photographed volcanic bombs and blocks emitted by eruptions at Krakatoa (*6*), Minakami those of Asama in Japan (*7*), and Wentworth at Keanakakoi in Hawaii (*8*).

From the equation (*9*) $R = 2r_0 \tan^{-1}[(\sin\alpha\cos\alpha)/gr_0/V^2 - \cos^2\alpha)]$ where R is range, r_0 is lunar radius, α is ejection angle, V is initial velocity, and g is lunar acceleration; a series of curves can be obtained (Fig. 2) to show distances that objects can be thrown on the moon by volcanic or impact processes. Using an initial velocity of 600 m/sec as the maximum for a volcanic eruption, one can see that the maximum distance a volcanic bomb can be thrown on the moon is 225 km at an angle of about 45°. This is in contrast with the 8 km or so for distances that volcanic bombs and blocks can be thrown on the earth (as at Bandaisan in Japan). The maximum travel times at optimum ejection angles for a bomb thrown these distances is 6 minutes for a lunar bomb and 13 seconds for a terrestrial one.

The cooling rate by conduction is much slower in a vacuum than in air. The contrast is even more extreme by comparing the cooling time in vacuum versus that in moving air. Figure 3 shows the cooling rates for a basalt sphere 3 cm in diameter (i) in vacuum (0.02 torr), (ii) in air at ambient temperature and pressure, and (iii) in an air stream (with a flow rate of about 15 m/sec) at ambient temperature and pressure. Obviously, radiative cooling would be greater than conduction in the 1300° to 600°C temperature interval. However, the formation of a cooled solid skin of basalt even at 1000°C on a volcanic bomb would serve as a thermal insulator as the temperature drops. The conductivity of basalt is very low (*10*), and a thin crust on a lunar volcanic bomb would preserve a molten interior for a longer period of time than a terrestrial equivalent. Not only would the conduction into vacuum be low but the conduction of heat through the crust of the bomb from the interior would also be low. Rapid heat conduction from the crust of the bomb to the lunar surface could only take place as long as 6 minutes after eruption.

The cooling rate of the center of the basalt sphere in an air stream at 300°C, for example, is three times faster than in a vacuum of 0.02 torr. With an increase of ratio of volume to surface area, the effect would be enhanced so that a large (> 10 cm) bomb with a molten interior and a thin chilled crust could impact within 225 km of a vent (to form an impact crater), burst, splatter, and chill to glass by conduction to the lunar surface. Not all bombs would do this and not all ejecta are bombs. They may be solid blocks.

For a given range, lunar volcanic bombs could be six times heavier than those of the earth, given equivalent volcanic energies. The maximum thermal energy of the Bezymianny eruption in 1956 was 10^{25} ergs according to Gorshkov (*11*). Many large lunar craterlets may be volcanic (volcanic bomb impacts, maars, ebullition craters, lava sinks). Of course, meteoroid impact must occur. Inspection of Fig. 2 shows that the secondary particles emitted from a single meteoroid impacting the moon can be "broadcast" at the optimum ejection angle of 13° to a maximum of 5400 km at an initial velocity of 1600 m/sec. Certainly the effects of such primary impacts (as trivial as I assume them to be for producing the major lunar surface features) will be much more widely dispersed on the moon than volcanic debris on a source for source basis.

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References and Notes

1. T. Gold, *Science* **165**, 1345 (1969).
2. R. Strom and G. Fielder, *Nature* **217**, 611 (1968).
3. D. Buhl, W. J. Welch, D. G. Rea, *J. Geophys. Res.* **73**, 5281 (1968).
4. J. Green, Fifth Conference on Problems of Planetology, Leningrad (1965); *Ann. N.Y. Acad. Sci.* **123**, 999 (1965).
5. W. K. Hartmann, *Icarus* **7**, **66** (1967).
6. R. Decker and D. Hadikusumo, *J. Geophys. Res.* **66**, 3497 (1961).
7. T. Minakami, *Earthquake Res. Inst.* **20**, 65 (1942).
8. C. K. Wentworth, *Pac. Sci.* **11**, 363 (1957).
9. F. E. Wright, *Annu. Rep. Smithsonian Inst.* **1935**, 169 (1935).
10. Thermal conductivities of nonvesicular basalt conducted by R. K. Stephens of the Livermore Radiation Laboratory are (cal sec^{-1} cm^{-1} $°C^{-1}$ $\times$ 10^{-3}) 3.0, at 20°C; 3.5, at 200°C; 4.0, at 400°C; 4.8, at 700°C (extrapolated). For a discussion of thermal conductivity in vesicular basalt, refer to J. Green, Air Force Cambridge Research Laboratories, Final Report, AFCRL-65-596, 30 September 1965, sec. 5.
11. G. Gorshkov, *Bull. Volcanol.* **20**, 77 (1959).
12. J. Osgood provided laboratory assistance and D. Stogryn assisted with the computations.

23 October 1969

Gold's hypothesis (*1*) on the source of lunar glazing is not consistent with what is known concerning the melting kinetics of plagioclase feldspars, which are primary minerals in basalt. The melting rates of plagioclase feldspars in general and of albite in particular are not governed by heat flow effects but rather by diffusion or viscosity effects (*2–4*). Albite is the plagioclase feldspar with the lowest melting point (~ 1395°K). Superheating of albite by as much as 100°K has been observed (*2, 3*). Greater superheatings have been observed for other silicate materials (*4*). At approximately 1400°K albite melt has a viscosity of 10^7 poises and a melting rate of approximately 1 μm/hr. Albite melting rates are expected to increase in proportion to superheating. Even at 1500°K, therefore, the melting rate of albite is expected to be less than 100 μm/hr.

Plagioclase feldspars higher in calcium (for example, labradorite) form less viscous melts than albite but have proportionally higher solidus temperatures ($\sim 1600°K$ for labradorite). The melting of such feldspars is faster than that of albite; however, melting is expected to be governed by diffusion or viscosity effects rather than by heat flow. Impurities in naturally occurring basalt also should increase their melting rates, but not to the point where melting will be governed by heat flow. Estimates of melting rates based on heat flow will be high by orders of magnitude.

The observation of "droplets [which] appear to have run down on an inclined surface for a few millimeters and congealed there," mentioned by Gold (*1*), is an interesting one. Such an effect can occur in "flash heating" if particles of a material with a melting temperature much below that of the aggregate occur on its surface. In this instance the chemical composition of such droplets should be different from that of the unmelted aggregate. Except for this particular case the observation of such droplets is not consistent with the hypothesis that melting occurred in situ. No material known exhibits a melt which does not wet its crystalline substrate. It is improbable that a portion of a melt will increase its total surface free energy by forming spheres which roll from the melt.

The various glazing effects and the presence of glassy spheres on the lunar surface are consistent with the hypothesis that both the spheres and the glaze are deposited on impact of relatively fluid molten material.

The question of whether the glazing of lunar soil occurred by melting in situ or by the splattering of molten rock should be resolved by the chemical analysis, including spectrographic impurity analysis, of the glaze, some droplets, and their substrate soil. If the composition of the droplets is that of a material whose melting temperature is well below that of the substrate, "flash heating" in situ is indicated. If the droplets have a composition similar to that of the aggregate, splashing by agitation of the melt is indicated. Likewise, if the glaze composition is not that which is obtained by melting its substrate soil (allowing for compositional differences at different places in the soil), it can be concluded that melting did not occur by radiation heating in situ.

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References

1. T. Gold, *Science* **165**, 1345 (1969).
2. A. L. Day and E. T. Allen, *Carnegie Inst. Wash. Publ.*, 31 (1905).
3. E. D. Dietz, "A Study of Superheating of an Albite Feldspar," thesis, Ohio State University (1965).
4. D. R. Uhlmann in *Kinetics of Reactions in Ionic Systems: Materials Science Research* (Plenum Press, New York, 1969), vol. 4, chap. 9.

27 October 1969

Gold (*1*) has suggested an explanation for certain glass deposits shown in close-up stereo photographs of the lunar surface at Tranquillity Base. After briefly describing the glass, Gold gives a thorough discussion of several hypotheses for the formation of deposits. We now describe the photographs of the glass deposits in greater detail, show comparable features from the returned lunar samples, and offer support for a hypothesis of formation not considered by Gold.

During the exploration of the lunar surface, the Apollo 11 crew observed deposits of glass which are described by Armstrong (*2*) as resembling big balls of solder, which had hit the surface in a fluid state and splattered out flat on the bottom, with rounded edges and an irregular upper surface. Armstrong states that the glass appeared to have a metallic luster with multicolored reflections. The glass was observed only in clusters of three to ten separate splashes near the center of small (about 1 m in diameter) impact craters. The splash deposits are reported to range in size from 1 to 10 cm in diameter. Some of the 1-m craters did not have obvious glass deposits.

Figure 1 shows a close-up photograph of one of the glass deposits described by Armstrong. The glass coats moderately indurated rock composed of the lunar soil. The indurated material has planar structure, and is distinct in texture from the loose to granularly aggregated material which partially covers the indurated material and the glass deposits. The indurated material was probably lithified by the shock wave of the impact explosion which excavated the crater. The surface modeling of the indurated material was also produced by the impact explosion. The glass coats the prominent portions of the crater bottom.

Study of the stereo photographs and returned lunar samples indicates that the rocks are locally covered with glass coatings of less than a square millimeter to 18 cm². These coatings have an irregular upper surface produced by the topography of the underlying rock and by broken and unbroken bubbles in the glass coating. Some of the larger glass deposits on rocks appear to be produced by the flattening and coalescence of several molten droplets. The glass-rock boundary is sharp, and the Lunar Sample Preliminary Examination Team (*3*) reported no obvious melting effects on the mineralogy or texture of the coated rock. Thin streamers and droplet trains radiate from the glass patches.

There is also a type of small (up to 1 cm in diameter in the lunar samples) glass deposit that resembles a pancake. This material has a smooth undulating upper surface, rounded edges, and a botryoidal, irregular bottom to which grains of soil are sintered. In the close-up lunar surface photographs (Fig. 2), pancake-glass deposits are seen to rest

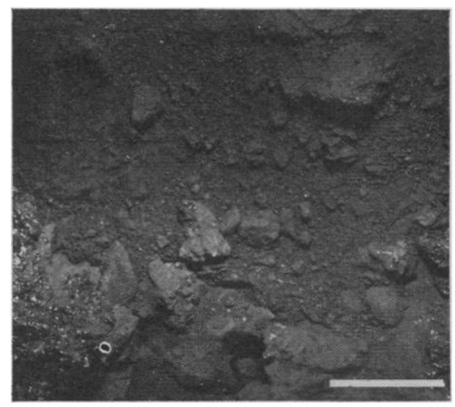

Fig. 1. Bottom of small lunar crater showing glass splatter on indurated lunar soil. Note also the glass spherule near the center top portion of the photograph. Scale, 2 cm.

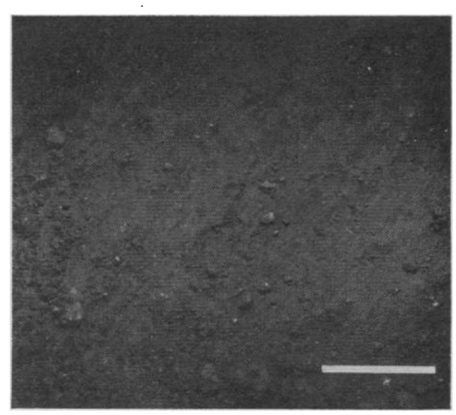

Fig. 2. Small pancake-glass deposit on undisturbed lunar surface material (upper left quarter of photograph). Note also the numerous glass spherules and the pronounced vertical planar structure of the undisturbed material. The loosely aggregated material on the surface was probably kicked into the field of view by the astronaut at the base of the camera. Scale, 2 cm.

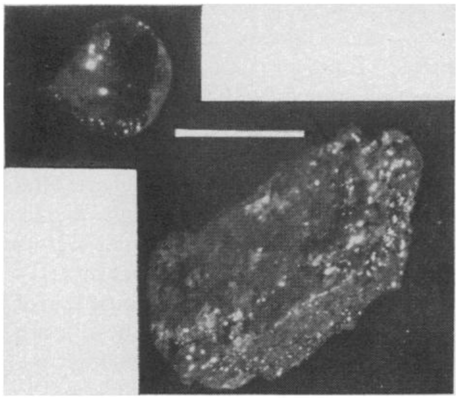

Fig. 3. Broken glass sphere (lower right) and small glass-coated rock (upper left) from returned lunar sample. Scale, 1 cm.

on undisturbed soil away from craters.

Numerous glass spheres and aggregates of glass spheres are shown by the close-up photographs. The returned sample contains many such glass spheres, which range in size from 10 mm to less than 10 μm. The glass is colorless to brown, red, green, yellow, and black. Many large spheres are dulled by surface irregularities and by dust which is sintered to the glass, and many spheres are partly hollow, containing one or more vesicles. One broken (10 mm in diameter) sphere shown in Fig. 3 (*4*) has a large central vesicle with smooth inner walls 1 to 1.5 mm thick, which contain abundant 0.1- to 0.2-mm vesicles. Most of the smaller spheres are solid glass; some have a small vesicle either in the center or slightly off center. Some ovoid and dumbbell shapes are present. Angular, blocky glass fragments are also present and exhibit the same variety of colors that the spheres exhibit. Figure 3 also shows a rock that has a glass coating which wraps around all sides, except the central portion of one of the large flat sides. For additional data on lunar glass and for a photograph of glass spheres in the lunar sample see (*3*).

Although the astronauts did not observe glass deposits outside the small craters, nevertheless glass spheres, pancakes, and rock coatings are visible in close-up photographs taken near the lunar module, which was positioned away from the small craters. Also, all these features are a part of the returned sample collected away from the small craters in which glass was described.

The glass spheres, pancakes, and rock coatings appear to be rock and lunar surface material fused by meteorite-impact explosions that excavated the craters in which the largest amount of the glass has been observed. The material under and around the crater was probably indurated by the shock wave from the explosion. The glass deposited as fallback from the explosion and therefore coats the prominent features of the indurated crater bottom. Loose material thrown out by the explosion covers crater walls and rims and slumps into craters, tending to cover the glass deposits. Many of the larger craters may have glass deposits entirely covered by slump or ejecta from nearby later impacts. The smaller and more scattered deposits of glass away from the craters were probably thrown out from these and other craters. Some small rocks became either partly or entirely glass-coated while in the explosion plumes above craters.

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References and Notes

1. T. Gold, *Science* **165**, 1345 (1969).
2. NASA, *Apollo 11 Photographic and Scientific Debriefing*; Open file Report (Manned Spacecraft Center, Houston, 1969, 149 pp.)
3. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
4. This photograph, which is a portion of NASA S-69-47074, the other photographs of returned lunar samples made during the preliminary examination period, and the lunar close-up photographs are available from the NASA Manned Spacecraft Center.

20 November 1969

The case for solar flash heating for some of the melted features in lunar craters that I have discussed is not very strong. However, it was stated there that the discussion was only to cover the case of surface glazing found in very specific places difficult to account for by other processes. Glass, in general, in the lunar soil can be easily explained in terms of impact phenomena; however, glass in the centers of craters, as described by the Apollo 11 and 12 astronauts and photographed with the close-up camera on the Apollo 11 mission, cannot be thought of as part of a general distribution, for it is evidently strongly concentrated in these particular places. It could perhaps be understood in terms of impacts causing the craters, as suggested by Greenwood and Heiken, but not by material falling in at random. However, if craters are caused by the same phenomenon as that which causes the glazing, such as the falling back of glass onto the crater bottom, several other remarkable conclusions follow. First, the glass must have been propelled with a remarkably low velocity so as to fall back just to the center of each small crater. Yet the process of liquefaction by shock will provide the material with a velocity which would raise it, in general, some hundreds of kilometers above the surface. To fall back where the material is now lying, it cannot have been lifted more than a few meters.

Second, the conclusion that the glass was formed at the time of formation of the craters in which it is now found implies that these great craters have suffered no significant modification since their formation. Yet it was in a substantial portion of the craters of the 2- to 4-foot diameter (0.6 to 1.2 m) range that the phenomenon was seen, in both the Apollo 11 and 12 missions. We have therefore to suppose that perhaps a half or quarter of craters of this size range were formed at such a time that subsequent erosion or impact modification did not even change the top few micrometers of the surface so as to destroy the glass or to cover it over. This would be exceedingly unlikely with the meteorite size distribution which is generally considered valid and with which only an extremely small proportion of craters in the 2- to 4-foot size range at any time would be free from surface degradation.

Thus, in detail, each explanation offered for the phenomenon seems unsatisfactory. It was this that prompted me to propose the solar flash heating, where the phenomenon could be understood, although not without invoking some events for which there is no other evidence.

The discussion of the glass-forming process by radiative heating does not change these conclusions in any material way. If heated sufficiently, all rocks will melt, and we can now determine experimentally by means of the lunar material what the intensity and duration of a flash would need to be to produce the observed effect. It is true that the concentration of heat in smaller craters would have been even greater, since they often have steeper sides—but then the objects so melted would also be smaller and might have been covered over sooner or escaped detection.

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