MOON: 'GHOST' CRATERS FORMED DURING MARE FILLING*

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Abstract This paper discusses formation of 'pathological' cases of crater morphology due to interaction of craters with molten lavas. Terrestrial observations of such a process are discussed. In lunar maria, a number of small impact craters ($D < 10$ km) may have been covered by thin layers of fluid lavas, or formed in molten lava. Some specific lunar examples are discussed, including unusual shallow rings resembling experimental craters deformed by isostatic filling.

1. Cratering During the Mare Epoch

'Ghost' craters – classically defined as shallow rings visible only under low lighting – and certain other features observed on Orbiter photographs suggest that some lunar craters were deformed by interaction with molten lavas. Many of these are impact features flooded by lava, but Guest and Fielder (1968) and Strom (1971) have demonstrated that many 'ghost' craters are volcanic in nature and occur particularly in association with mare wrinkle ridges. Recent terrestrial observations, to be discussed here, support the view that a range of 'pathological' crater morphologies results from interaction of molten lavas with pre-existing impact on volcanic craters, and that certain peculiar lunar structures can be so explained.

The probability of such interaction can be indicated as follows. The Apollo-dated rock samples returned from the Moon show that the range of dates from oldest lunar maria (represented by Mare Tranquillitatis) to one of the younger maria (represented by Oceanus Procellarum) ranges from about 3.8 to about 3.2 b. y. ago, an interval of about 6×10^8 yr (Papanastassiou and Wasserburg, 1971). Baldwin (1971), Hartmann (1971), and Shoemaker (1970) have shown that the cratering rate during this interval was on the order of 20 times the presently observed rate, and still greater in pre-mare time. The present rate of formation of craters of widely different sizes can be estimated by combining the known rate of formation of larger lunar craters ($D > 2$ km), based on Apollo dates, with the general distribution law of smaller meteoritic masses given by Vedder (1966): $\log I = -0.5 - \log m$ where I is impacts of mass m per km^2 per year. This law has an accuracy of about an order of magnitude. To represent a pre-mare

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flux 250 times greater, we must multiply Vedder's law by factor of $10^{2.4}$, giving $\log I_p = 1.9 - \log m$. These two curves are plotted in Figure 1. The cratering rate which applied during the emplacement of the maria lies between these two curves.

Astronaut observations and Earth-based analyses show that the lunar maria are successive layers of lava flows, ranging up to tens of meters in thickness. Studies of mare fine structure such as flow boundaries (Whitaker, 1972), ridge extrusions (Strom, 1971), and crater erosion (Soderblom and Lebofsky, 1972) show that emplacement of mare lavas occurred not in a single magmatic spasm, but was episodic. Seismic studies suggest basalt-like fill in typical mare-filled basins down to a depth of 20–25 km, and surveys show 'Archimedian' craters on surfaces about 3 km below the present mare surface. If we assume that the flows average 10 m in thickness, then we would have a total of 300 to 2500 flows and a mean separation time of 0.2 to 2×10^6 yr. As shown by geological experience (for example, the cooling of fiilled craters in Hawaii) and by

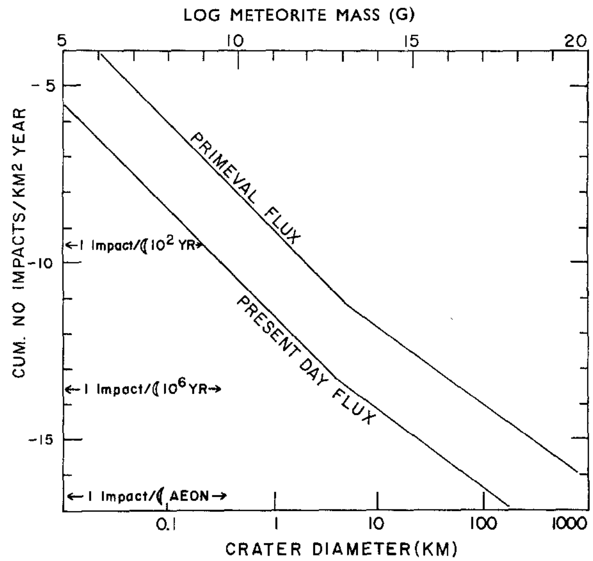


Fig. 1. Cratering rates applicable during formation of lunar maria. Lower curve gives the present-day cratering rate and the upper curve gives a cratering rate applicable about 4 aeons ago. Cratering rates during the formation of lunar maria lay between the two curves.

theoretical calculations (Ingersoll *et al.*, 1954), the time required to cool a slab of lava 10 m thick from the molten to the solid state is only on the order of a few years. Figure 1 indicates the size of the largest impact craters formed on the entire Moon during intervals of 10^6 and 10^2 yr; impact craters formed in molten cooling lava would probably be smaller than a few hundred meters in size unless long-lived, thick, local deposits of molten lava were abundant, while impact craters subsequently flooded by a single later lava flow could range up to 10 km in size, and craters covered by multiple flows could be many times larger (note that *mare* lavas cover only about 15% of the entire Moon).

This generalized overview of cratering during the mare-forming epoch suggests the approximate size ranges of unique structures that should result from impact cratering events in molten lava or on one of the penultimate lava flows. Such unusual features can only add to the range of complex, endogenic circular features found on the Moon, such as those described by Strom (1971). Furthermore, many volcanic features, as well as impact features, must have been deformed by mare flooding.

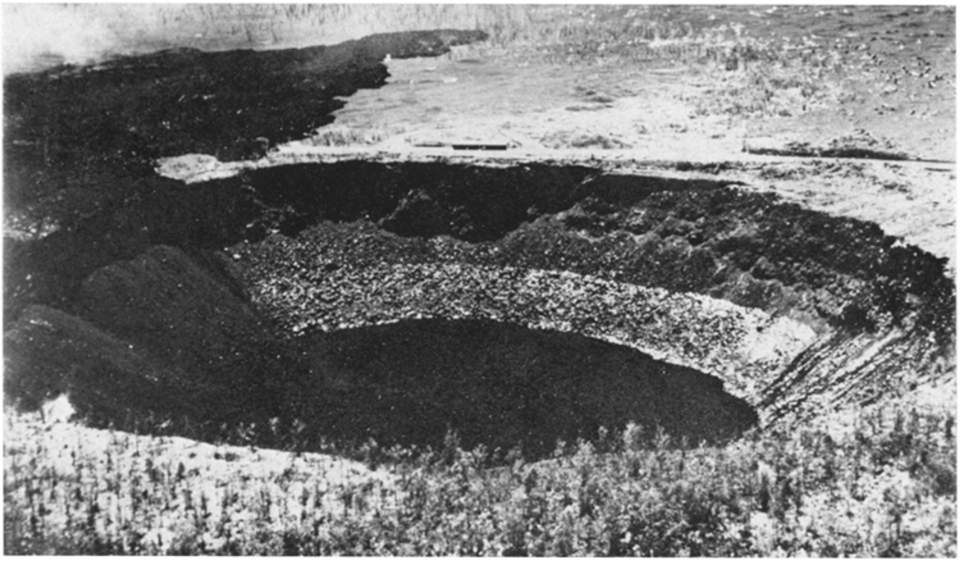
2. Terrestrial Example: Flooding of Alae Crater, Hawaii

Although lava covering as the cause of lunar 'ghost' craters has long been suggested, an eruption on the flank of Kilauea Volcano, Hawaii, in 1969–1972, afforded an opportunity to observe directly the kinds of structures produced when a crater-form depression is inundated by lava flows. Alae crater is one of about 12 collapse pits (Figure 2) on the east rift zone of Kilauea Volcano. Prior to the 1969 eruption, it was elongated in outline, 450 by 650 m across, and 165 m deep. Its floor was lava-covered as the result of brief eruption in 1965. Figure 2 shows not only Alae crater, which will be discussed further below, but also the nearby Aloi crater during its partial flooding in 1969.

An eruption of basaltic lava began in May 1969, along a fissure about 300 m *outside* the rim of Alae crater (Swanson *et al.*, 1971). Lava poured into the crater, filling it by October 10, 1969 (Swanson and Peterson, 1972) and forming a crust elevated several meters above the pre-eruption rim. Ten days later, a lava tube formed when a channel of lava overflowing the rim crusted over. Details of lava tube formation during this eruption have been discussed by Greeley (1971), Cruikshank and Wood (1972), and Swanson (1972). The tube carried a small volume of lava out of the filled crater reservoir to a position about 2.5 km downslope where it discharged as a surface flow. Nine days later the tube closed, trapping the remaining lava in the crater. Between October 1969 and August 1970, the lava in the filled crater was thickened by addition of further surface flows from the growing Mauna Ulu shield, which had built up over the original eruption site. Still more lava was fed into Alae beneath the lava crust by tube flows from a vent in the flank of Mauna Ulu, causing the crust to inflate. In early August 1970, the surface of Alae crater stood 24 m higher than the pre-eruption rim.

On August 8, 1970 the October lava tube reopened and began to drain lava from the upper portion of the filled reservoir. A subsidence bowl 13 m deep developed in the crust over the crater between August 8 and 13 as lava was withdrawn through the tube (Figures 3 and 4). Geological details of the evolution of Alae crater are given in a paper by Swanson and Peterson (1972).

The eruption at Mauna Ulu resumed in early February 1972, discharging lava through a major lava tube onto the depressed surface over Alae crater, where it formed a deep pond. Nearly continuous spattering at the margins of the pond rapidly built a spatter rampart thus restraining the liquid in the pond. The appearance of Alae crater in this condition strongly resembled that of the Halemaumau lava lake in Kilauea Caldera in the early part of this century (MacDonald and Abbott, 1970, p. 42).



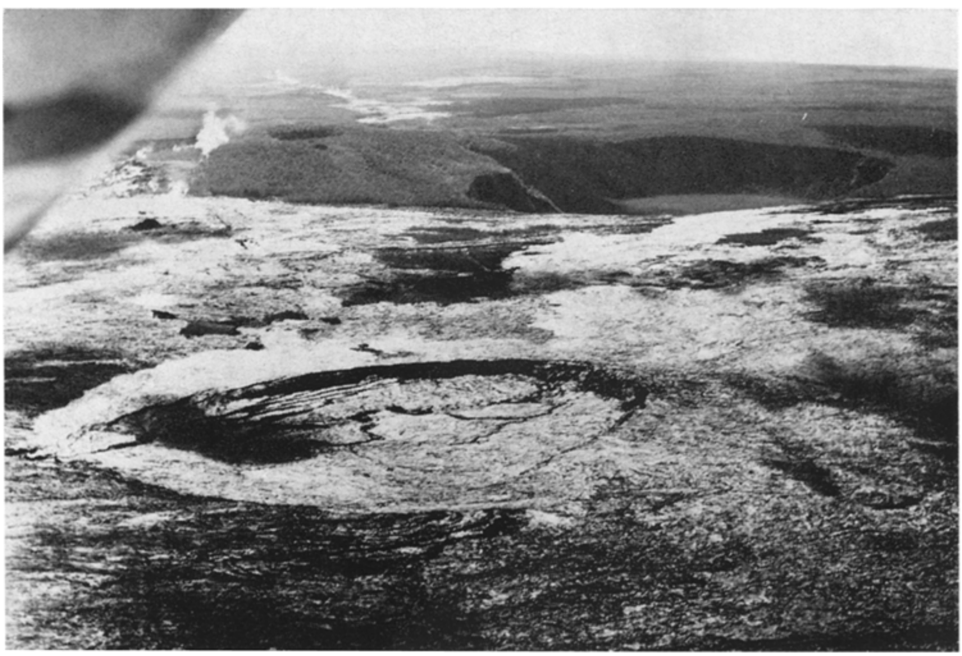


Fig. 2. (A) Typical Hawaiian pit crater (Aloi) during flooding by lava flows. Photograph by D. Swanson (September 24, 1969). (B) Alae crater, Hawaii after flooding by lava flows in 1969 and 1970. Compare with Figure 3. Photograph by C. A. Wood (August 1971).

As short flows of lava poured through numerous short-lived breaches in the levee, a broad lava shield was quickly built up, maintaining the rimmed active lava lake at the summit. This level of activity persisted through mid-July 1972 when this paper was completed. The evidence suggests that *thin* flows covering craters produce complex structure preserving evidence of the underlaying crater.

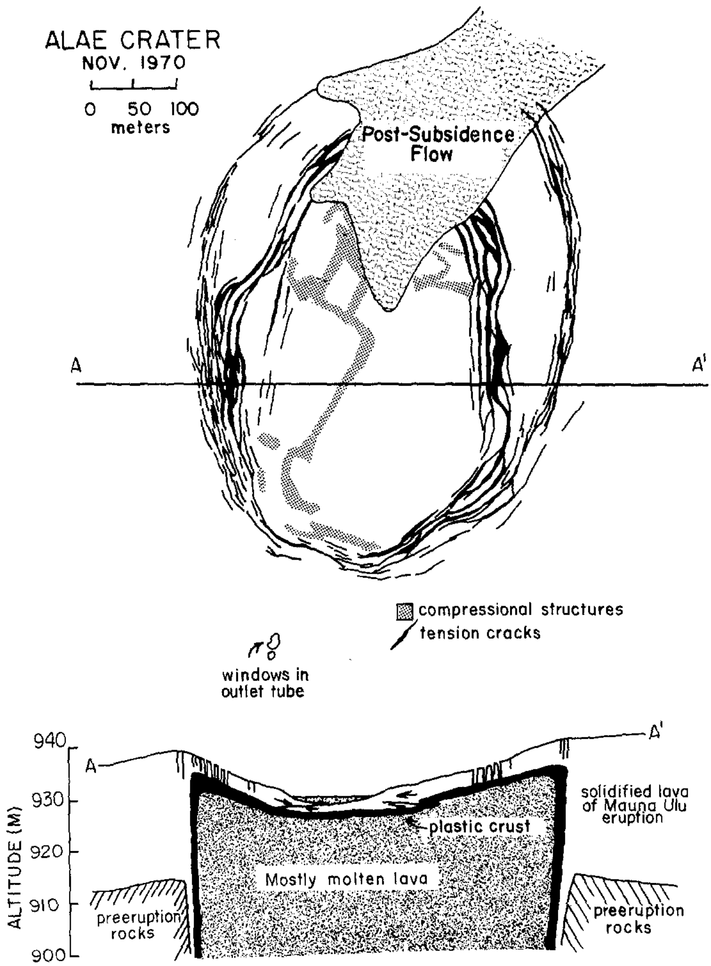


Fig. 3. Plan and cross-section of Alae crater showing fracturing and faulting produced during subsidence of floor. Modified from Swanson and Peterson (1972).

3. Lunar Examples of Flooded Craters

We now consider the evolution of lunar craters affected by lava flows of *external* origin (in contrast to well-known examples of internally flooded craters such as Plato and Archimedes). The fact that Alae crater was originally a *volcanic pit crater* is of little significance; a meteoritic crater in the same place would have behaved in a similar way, with the possible exception that all lavas might have entered from the surface. Had Alae been a meteoritic crater, its appearance after being covered by a 24-m veneer of new lava would be that of a shallow volcanic crater. The original depth-to-diameter ratio of Alae in early 1969 was 1:3; by January 1972, it was very shallow, being 1:12. Similarly the ratio for 'flooded' or 'ghost' craters on the Moon is smaller than for fresh craters.

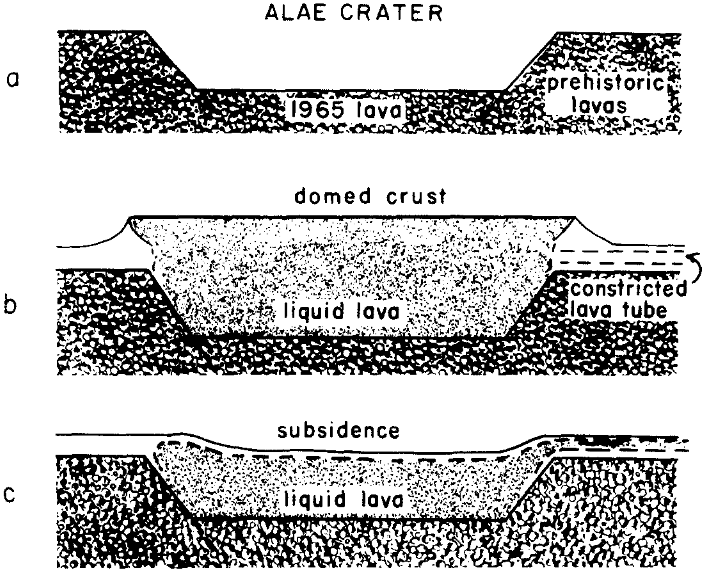


Fig. 4. Schematic cross-sections through Alae crater showing evolution during filling by lava flows. The development of the crater is shown prior to the resumption of activity in February 1972.

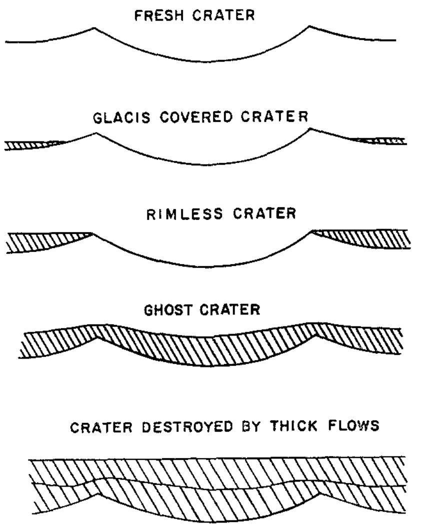


Fig. 5. Hypothetical stages in the filling of a lunar crater by lava flows.

A new, thin lava flow over previously cratered surfaces will bury fine ejecta structure around a given crater (Figure 5). If thick enough, the lava will rise up around the crater's glacis, reducing the elevation difference between the crater rim and the surroundings. Thicker flows could produce a rimless crater. Finally a flow or series of flows might be sufficiently thick to overflow a rim and fill the crater. As lava solidifies, its volume is reduced by about 10% or more, depending on the lava petrology, and the draped lava reveals pre-existing topography with reduced elevation differences. Additional flows could obliterate craters. Figure 6 shows what appears to be a typical crater (A) half covered by a mare ridge-like flow. The flooded wall of the crater has been 'aged' or muted.

Fig. 6. Lava flooding of lunar craters. The left wall of crater A is partially covered by flows. Framelet width 2.3 km (Orbiter III – 132M)

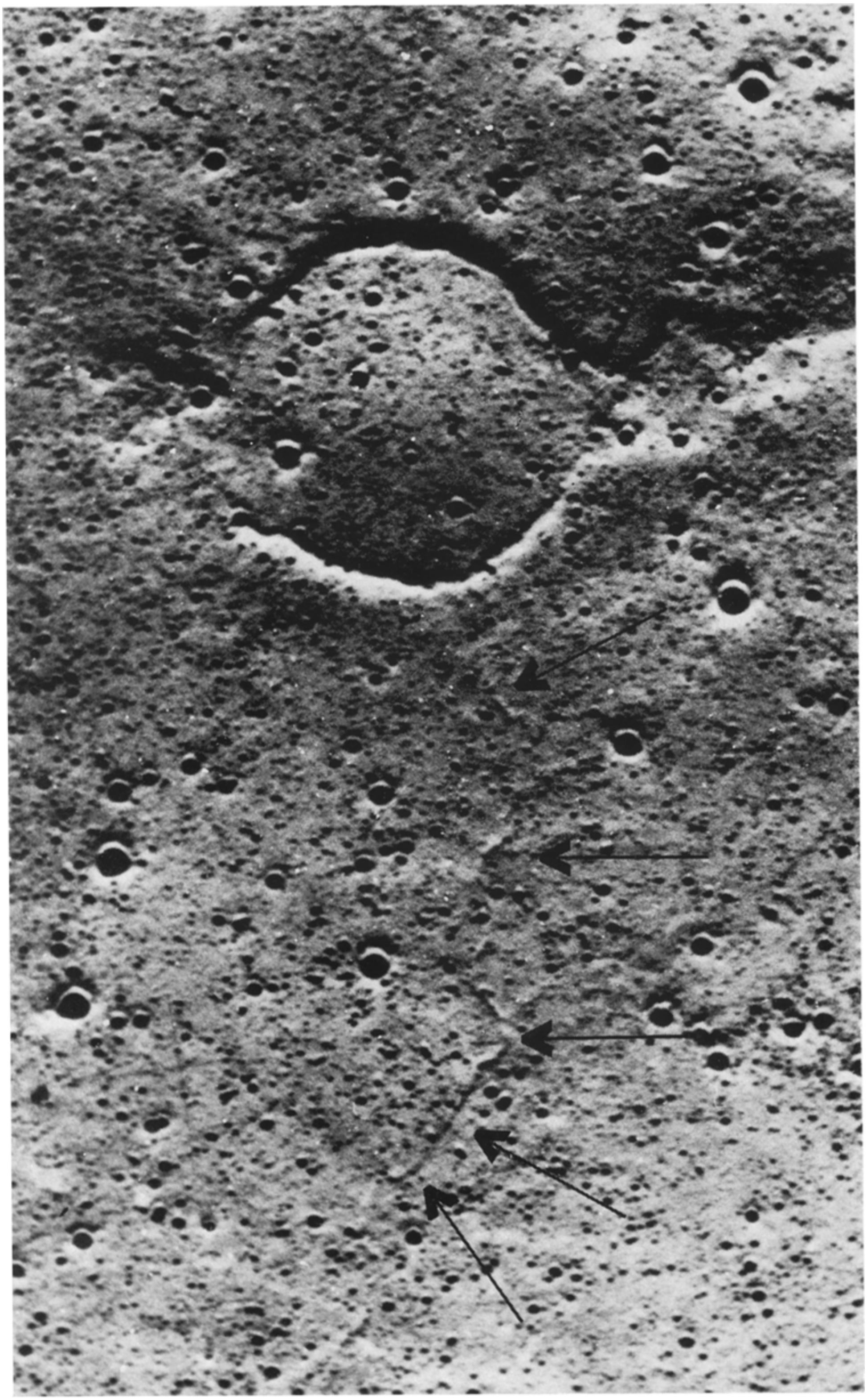


Fig. 7. Alae-like lunar crater and possible drainage tube or sinuous rille (arrows) in Oceanus Procellarum (60°W, 29°N). The large crater is about 7 km in diameter; the rille extends about 3 times the length shown here. (Apollo 15–M3–2489).

The Alae mechanism of drainage through lava tubes may have a lunar analog in a peculiar low-rimmed, 7-km crater in western Oceanus Procellarum (Figure 7). This crater is similar to a number of Strom's (1971) volcanic rings, and is the source of a narrow, discontinuous rille which is probably a collapsed lava tube that drained lava from the crater. This collapsed tube is among the very few known lunar rilles that originate at a crater wall; most begin in irregular depressions on the maria. The width of this rille is about 150 m and its length is about 70 km. The origin and detailed

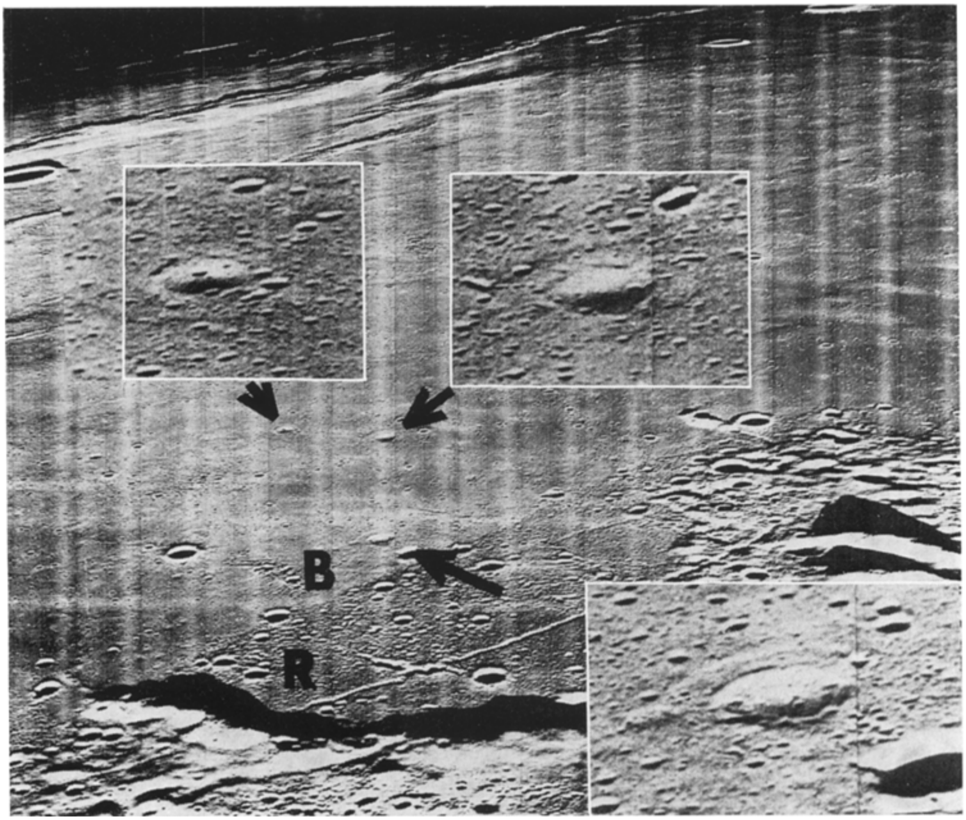


Fig. 8. Two flow units in Oceanus Procellarum (41° W, 2° N): a reddish older unit R and a bluish, younger unit B. Several indicated features (~ 1.4 km diameter) on unit B may be examples of craters formed originally in R and subsequently flooded by B. (Orbiter III – 161M). North to the left.

development of the crater at the head of the rille is not certain, but it served as either the primary lava source or as a lava reservoir, as at Alae, for a period sufficient to form the lava tube that later collapsed to produce the rille. Terrestrial lava tubes can form in a few hours and remain active for several months.

Finally, we take note of an interesting region in Oceanus Procellarum, southwest of Encke. Figure 8 is an oblique photograph of the region showing an upland region in the foreground and two mare units beyond. Color-enhanced photographs by Whitaker

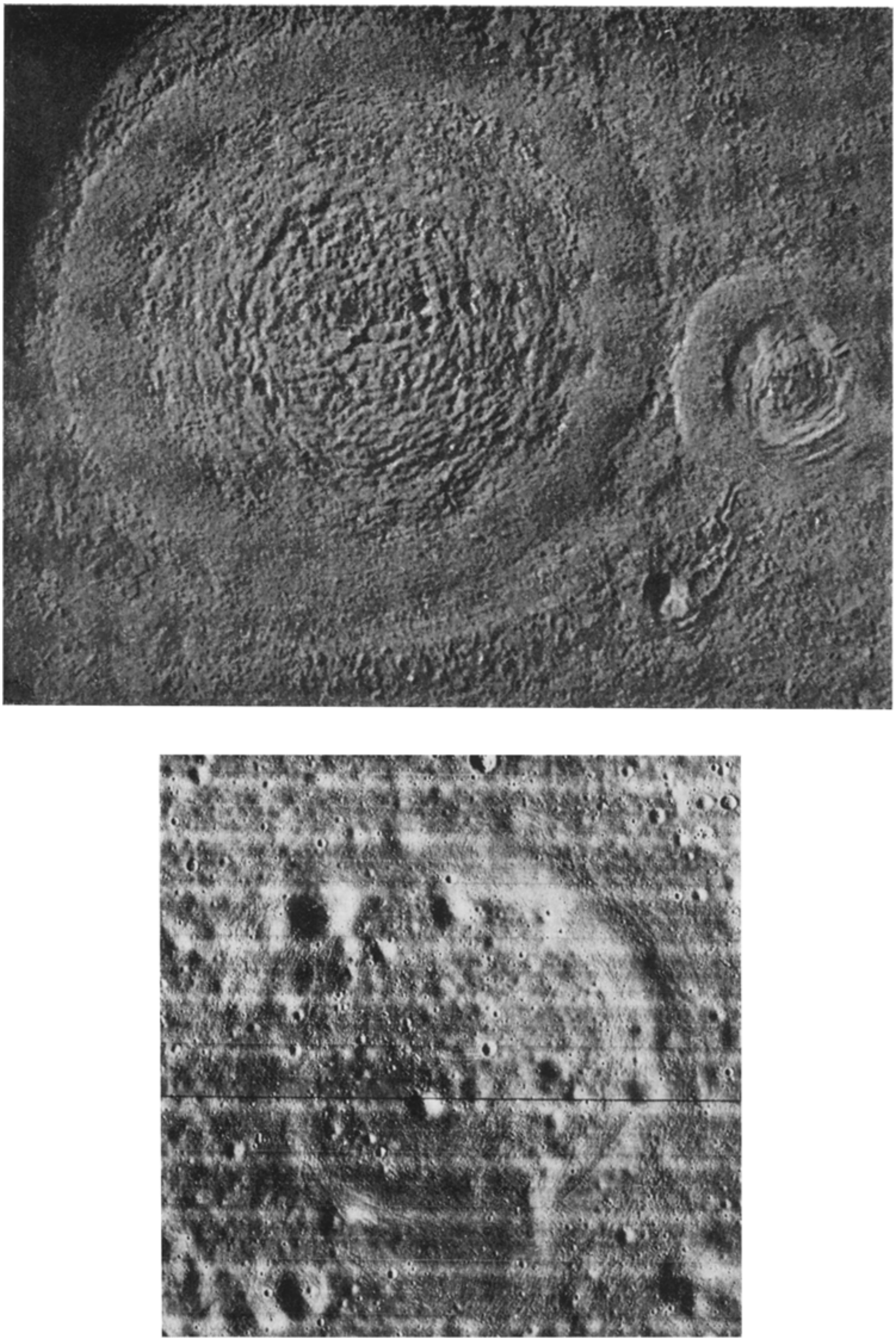


Fig. 9. Comparison of isostatically adjusted crater 10 cm in diameter formed in asphalt (Scott, 1967) (top) with one of several 'ghost' craters in unit B of Figure 7 (bottom) Illumination from the left for both photos.

(personal communication) show that unit R is red-hued, while B is distinctly bluer. Frequently at such contacts, the reddish unit is older as is confirmed in this case; crater counts yield a crater density on unit R three to seven times higher than on unit B.

Three peculiar soft craters lie on unit B (arrows). They are about 1.4 km in diameter and are distinguished by smooth, generally crater-free rims which are only slightly elevated above the surroundings. These craters are good candidates for craters formed on an early unit (R) and deformed by later lava flows (B). Further, their morphology is in excellent agreement with that of experimental, isostatically-filled craters produced by Scott (1967) and illustrated in Figure 9. The fact that three relatively large craters in a local region all have this rather unique appearance suggests that they are not cases of impacts into plastic lava, since three large impacts during the brief existence of molten lava in a local region would be improbable. On the other hand a precise matching of the conditions in Scott's experiment would require the interpretation that the craters formed by impact in a medium capable of isostatic deformation such as a lava plain with a subsurface concentration of magma. Alternatively the features may be the result of viscous deformation in a flow or series of flows that covered the region to a depth sufficient to obliterate pre-existing small craters, but thin enough to leave a fossil imprint of the three 1.4 km craters, similar to the process described for Alae crater. The absence of sharp extrusive features and the similarity to Scott's model argue against a purely volcanic origin for these craters, although it is difficult to rule out the possibility of a ring-dike intrusion which might have deformed the surface in a way crudely analogous to the final stages of Scott's experiment.

While we cannot conclusively establish the origin of these very 'soft' rings, we do point out that they are a class of unusual features hitherto unrecognized in the literature, different from the more common and bolder 'ghost' craters, but possibly end members in a spectrum related to deformation by lava.

4. Conclusion and Unresolved Problems

By consideration of a documented terrestrial case and of specific lunar examples we find support for the long-standing supposition that 'ghost' craters on the moon are accounted for by interactions of fluid mare lava flows with pre-existing craters of both impact and volcanic origin, as well as by endogenic volcanic ring complexes. It is to be expected that a wide range of morphologies, some unfamiliar, may be so produced. Even some 'soft' and rimless craters, widely considered to be of internal origin, may simply have been impact craters covered or flooded to their crests by lava flows.

This conclusion makes even more pressing the need to explain another lunar observation that has been largely ignored in recent literature: the lunar mare material not only has covered features with minor relief, but also has apparently had an extraordinary capacity to destroy selectively pre-existing major relief, particularly when in contact with terra materials. Many cases are known where crater walls have been destroyed apparently by contact with lunar lava. The missing walls of Fracastorius and Sinus Iridum are examples of many missing or heavily damaged crater walls.

Such walls have *not* been merely covered; rather they appear to have been breached. undermined, or collapsed. In many cases tectonic fractures may have been utilized, Sinuosities and partial under-cutting in many small lunar rilles suggest lava cutting, although it should be noted that flow channels normally develop by construction of levees rather than be erosion. All such observations suggest that the lunar mare lavas had great erosive power when acting on lunar materials. In contrast, terrestrial lava flows can be diverted by small hills which may be left isolated in the final frozen flow. It is known from Apollo data that lunar lavas were of high temperature and were unusually fluid by terrestrial standards, but this alone does not account for their erosive ability.

A possible solution to this problem is that the extreme erosive ability was caused not by only the properties of the lava, but by the properties of the lunar surface layer. The pre-mare surface probably consisted of approximately 2 km of regolith (Short and Forman, 1972) which, though unconsolidated by water-cementing (common terrestrially, MacDonald, 1972), may have been a welded microbreccia (as at the Apollo 16 site). An additional factor may be extreme tectonic fracturing of the surface, either due to pre-mare activity (e.g., the radial fracturing around basins or the global grid system). or due to tectonic activity during lava eruption. These factors may have made terra materials and crater rims much more subject to lava erosion than coherent crystalline rocks or terrestrial surfaces.

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References

Baldwin, R. B.: 1971, *Icarus* **14**, 36.
Cruikshank, D. P. and Wood, C. A.: 1972, *The Moon* **3**, 412.
Greeley, R.: 1971, *Modern Geology* **2**, 207.
Guest, J. E. and Fielder, G.: 1968, *Planetary Space Sci.* **16**, 665.
Hartmann, W. K.: 1970, *Icarus* **13**, 299.
Hatheway, A. W. and Herring, A. K.: 1970, *Comm. Lunar Planetary Lab.* **8**, 299.
Ingersoll, L. R., Zobel, O. J., and Ingersoll, A. C.: 1954, *Heat Conduction*, Madison, Univ. Wisconsin Press.
MacDonald, G. A.: 1972, *Volcanoes*, Englewood Cliffs, Prentice-Hall.
MacDonald, G. A. and Abbot, A. T.: 1970, *Volcanoes in the Sea*, Honolulu, Univ. of Hawaii Press.
Papanastassiou, D. A. and Wasserburg, G. J.: 1971, *Earth Planetary Sci. Letters* **11**, 37.
Scott, R. F.: 1967, *Icarus* **7**, 139.

Shoemaker, E.: 1970, 'Origin of Fragmental Debris on the Lunar Surface and the History of Bombardment of the Moon', presented at I Seminario de Geologia Lunar, Universidad de Barcelona, May 1970 (revised January 1971).
Short, N. M. and Forman, M. L.: 1972, *Modern Geology* **3**, 69.
Soderblom, L. A. and Lebofsky, L. A.: 1972, *J. Geophys. Res.* **77**, 279.
Strom, R. G.: 1971, *Modern Geology* **2**, 133.
Swanson, D. A.: 1972, 'Pahoehoe flows from the Mauna Ulu eruption, Hawaii', (in press).
Swanson, D. A., Jackson, D. B., Duffield, W. A., and Peterson, D. W.: 1971, *Geotimes* **16** (5), 12.
Swanson, D. A. and Peterson, D. W.: 1972, 'Partial Draining and Crustal Subsidence of Alae Lava Lake', U.S. Geol. Survey Prof. Paper (in press).
Vedder, J. F.: 1966, *Space Sci. Rev.* **6**, 365.
Whitaker, E. A.: 1972, *The Moon* **4**, 348.