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EXPERIMENTAL STUDIES ON THE FORMATION OF LUNAR SURFACE FEATURES BY GAS EMISSION--A PRELIMINARY REPORT

by

S. A. Schumm

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EXPERIMENTAL STUDIES ON THE FORMATION OF LUNAR SURFACE FEATURES BY GAS EMISSION--A PRELIMINARY REPORT

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INTRODUCTION

Many features of the lunar surface are clearly of endogenetic origin. Among these, the sinuous rille is of particular interest. Straight rilles resemble graben--terrestrial geologic features--but sinuous rilles are not quite like any described feature of the Earth's surface. In the absence of an indisputable terrestrial analog whose origin is understood, the problem of how sinuous rilles form has prompted numerous diverse theories (e.g., Cameron, 1964; Quaide, 1965, Kuiper, Strom, and Le Poole, 1966) but remains unresolved.

The search for answers to this problem has only lately been taken up in the laboratory. This report describes a series of experiments primarily aimed at demonstrating that some lunar sinuous rilles could have formed as a result of fluidization of loose surficial materials by gases vented from lunar crustal fractures. The work was performed at the Engineering Research Center of Colorado State University in Fort Collins, as part of the U.S. Geological Survey's program of lunar investigations sponsored by the National Aeronautics and Space Administration, under Contract No. R-66.

EQUIPMENT AND PROCEDURES

Procedures varied for each series of experiments; the details of each are described with the results. Preliminary experiments were performed in the Department of Physiology and Biophysics hypo-hyperbaric chamber at both 8 mm of pressure and normal atmospheric pressure. As the results were not significantly different, subsequent experiments (those described in this report) were conducted at normal atmospheric pressure.

A flume 2.4 meters long, 30 cm wide, and 27 cm deep was constructed, and a trough (air chamber) 5 cm wide and 2.5 cm deep was built into the floor of the flume. One end of the trough was completely sealed; at the other end a vent was cut to permit entry of compressed air. The trough was roofed with a strip of masonite. Holes and slots of different sizes were cut in this roof to form various patterns of vents. A mixture of 2 parts medium sand, 2 parts very fine sand, and 1 part 200-mesh marble dust was poured into the flume, covering the air chamber with a layer of predetermined thickness. The cohesion imparted by the marble dust permitted steep walls and rims to form but did not prevent fluidization of the material.

When using granular materials in a model study, it is frequently not possible to scale down the size of the material to that which is dimensionally correct for replication of the prototype because such fine material is very cohesive. Hydraulic engineers often utilize sediment obtained from the channel of the river that is to be modeled with the realization that the model will not be dimensionally correct. The model, therefore, is considered to be a small stream from which data can be obtained that may apply to the prototype. The application of the experimental results reported herein to lunar problems is based on the same assumption; that is, the very small features developed during these experiments may have formed in a manner similar to larger lunar features that they resemble.

The flow of compressed air entering the gas chamber was regulated by a valve, and a pressure gage and flow meter were connected to the pipe through which compressed air moved into the flume. During these experiments, the flow meter was not used because numerous small leaks occurred along the sides of the flume. The leaks, although preventing collection of meaningful data on flow rates, did not interfere with development of the experimental features. Compressed air was released from a high-pressure line into the gas chamber at pressures ranging from 20 to 60 psi, but, as the valve was opened very slowly, during each experiment, venting of gas through the granular material occurred at much lower pressures. Therefore, it is not possible to relate the morphology of the features that developed in the granular material to gas pressure or flow rate.

EXPERIMENTAL SERIES 1

The purpose of the first series of experiments was to determine how variations in the thickness of materials would affect the morphology of the features produced. The sand and dust mixture was poured into the flume, and air was forced into the material through a 1.6 mm circular vent cut into the air chamber roof. In the first experiment, a 1.3 cm layer was used. The thickness of the layer was increased each time by either 1.3 or 2.5 cm, so that in the seventh experiment the layer was 12.7 cm thick.

The first three experiments, in which layers 1.3, 2.5, and 3.8 cm thick were used, produced steep-sided explosion craters, shaped like inverted cones. As thickness was increased, crater depths and diameters also increased, at a steady rate (fig. 1). Beginning with the fourth experiment, however, the relationships of thickness to crater depths and diameters changed markedly (fig. 1): depths decreased to 2.5 cm and remained there, and the rate of increase of crater diameters diminished. As a result, crater morphologies changed. Experiments 4 through 7 produced relatively wide, shallow, flat-floored craters, in contrast with the steep-sided craters of experiments 1 through 3. In layers thicker than 3.8 cm, the volume of ejected material was similar to that in the 3.8 cm layer, but the material remaining in the craters became fluidized and tended to spread out rather than to form the steep walls that characterized craters in the three thinner layers.

To summarize, craters were formed by explosion in thin layers, and by a combination of explosion and fluidization in thicker layers. Therefore, these results suggest that pneumatic crater-forming processes are influenced by the thickness of the materials

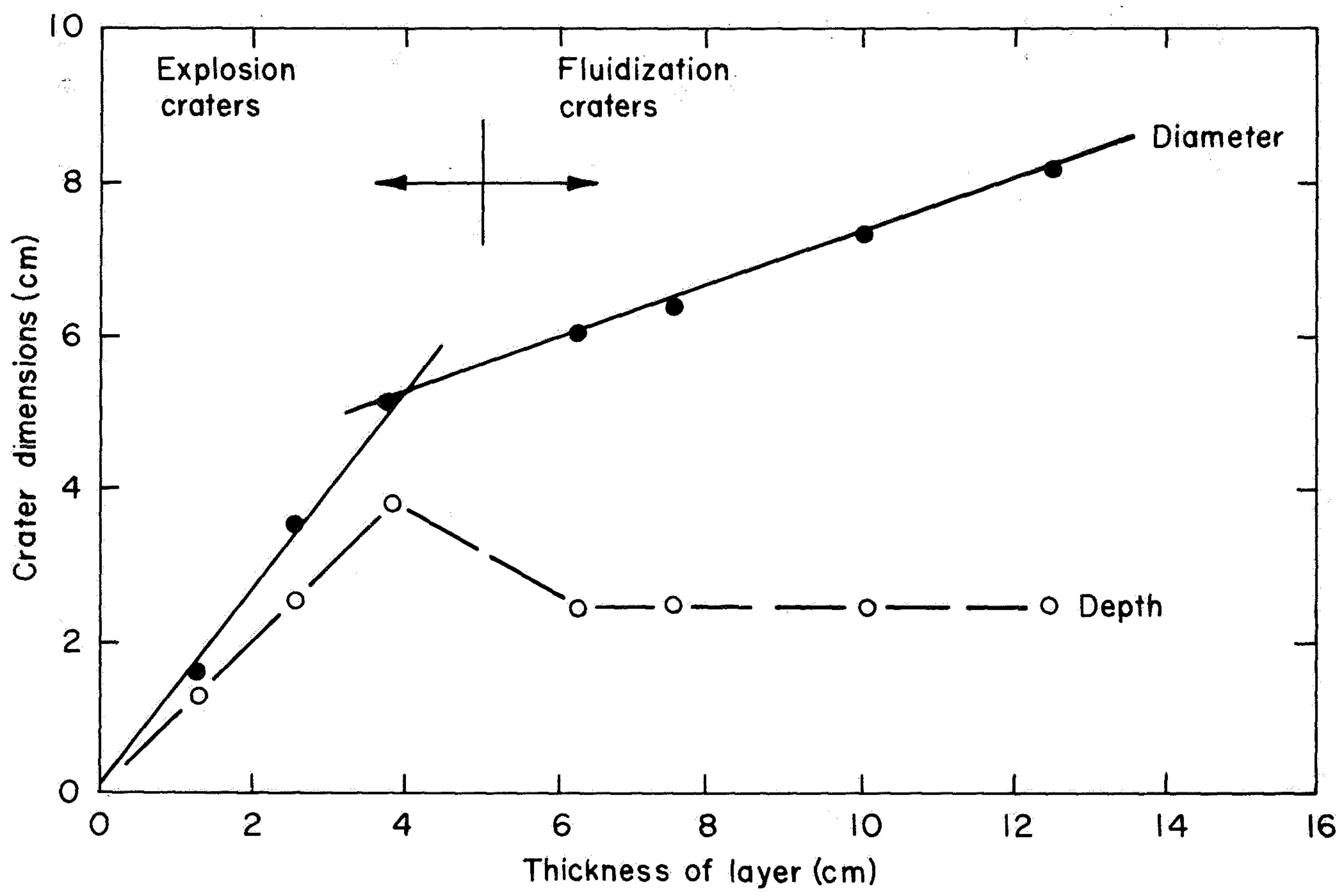


Figure 1.--Graph of relations between thickness of layers and dimensions of craters in experimental series 1.

in which they operate, and that craters of the same age formed in materials of different thickness may display significant morphological differences.

EXPERIMENTAL SERIES 2

The second series comprised five experiments to determine the effects of vent shape and thickness of materials on crater morphology. First, the roof of the air chamber was vented by a line of 1.6 mm holes at 2.5 cm intervals, which were covered with a 1.3 cm layer of the sand and dust mixture. Air was released slowly into the chamber until a series of funnel-shaped explosion craters had formed over all but one of the vents (fig. 2a).

This procedure was repeated using a 2.5 cm thick layer of material; this time, both explosion and fluidization craters formed (fig. 2b). Most of these craters were markedly less circular than the ones formed in the preceding experiment. Many were roughly square in outline and were separated from adjacent craters by nearly straight walls. These departures from circularity were due to mutual interference during development of adjacent craters.

For the third experiment, a 3.8 cm thick layer was used. The same procedure was followed, and this time the craters that formed were all of the fluidization type (fig. 2c). Crater pairs commonly coalesced to form large ellipsoidal craters with low central ridges transverse to the major crater axes. Adjacent craters that had not coalesced were separated from each other by a straight rim, as in the preceding experiment. Where one vent was more active than its neighbor, the straight rim was displaced toward the less active one.

The fourth experiment involved a change in the vent pattern of the air chamber roof. Slots were cut connecting every other pair of holes (i.e., 2d and 3d, 4th and 5th, etc.) so that a line of 2.5 cm long slots each 2.5 cm apart was produced. A 1.3 cm

Figure 2.--Craters formed during experimental series 2.

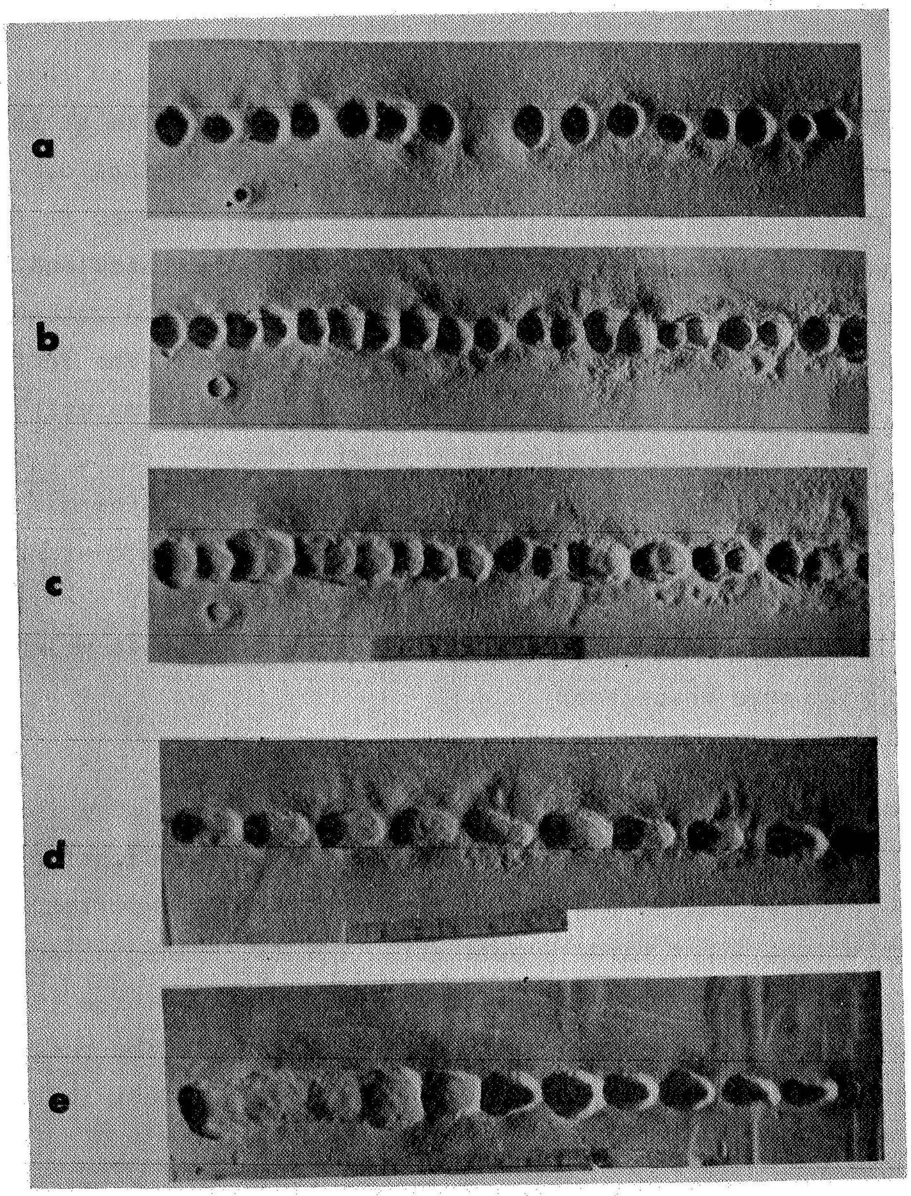
a. Circular vents 1.6 mm diameter, 2.5 cm apart, layer 1.3 cm thick; all explosion craters. Air chamber roof exposed in most craters. (Small crater at lower left was formed by air leak at edge of chamber.

b. Vents same as in a, layer 2.5 cm thick; some explosion craters, some fluidization craters.

c. Vents same as in a and b, layer 3.8 cm thick; all fluidization craters, several crater pairs coalescing, separated by low straight septum.

d. Slot vents 1.6 mm wide, 2.5 cm long, 2.5 cm apart, layer 1.3 cm thick, elliptical craters.

e. Vents same as in d, layer ranged in depth from 5 cm at left to 7 mm at right; explosion craters formed in thin material, fluidization trough formed in thick material. Deepest crater formed at head of fluidization trough (extreme left).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thickness of sand and dust was laid down and the procedure of the three preceding experiments was repeated. Under these conditions, a series of elliptical craters formed (fig. 2d).

The final experiment of the series was set up to investigate what sort of craters would form if air was vented through the slotted roof into a layer of gradational (rather than uniform) thickness. Accordingly, the materials were laid down so that they sloped from a thickness of 5 cm at one end to 7 mm at the other end. The craters produced on this sloping surface are shown in figure 2e. Elliptical explosion craters formed at the shallow end. Craters increased in size toward the thick end, and in the thickest material, at the left end, a fluidization trough formed owing to coalescence of four craters. The left end of this trough is deepest because some fluidized material flowed downslope (right) toward the lower craters.

These experiments demonstrated that where the thickness of materials reaches a critical value, craters that form over closely spaced vents in the materials will coalesce and, if the vent shape is linear, will form a channel-like depression in which material will move downslope.

EXPERIMENTAL SERIES 3

The purpose of the third series of experiments, five in all, was to further investigate the development of a fluidization trough, such as had been produced in the preceding experiment. In each of the first three experiments of this series, a layer of material, wedge-shaped in profile, was emplaced over a straight line of 1.6 mm circular vents spaced 2.5 cm apart. The range in thickness of the material was as follows (left to right in fig. 3):

2.5 cm to 7 mm--1st expt., fig. 3a
3.8 cm to 7 mm--2d expt., fig. 3b
5.0 cm to 7 mm--3d expt., fig. 3c

Compressed air was released into the material, as in series 2. The results were comparable to those obtained before. Explosion craters formed in the thinnest material, whereas fluidization craters formed in the moderately thick and thickest material. In the latter, they coalesced to form a linear trough, which was deepest at its head (fig. 3c). Of particular interest was the gradation in height of the pair of parallel linear rims, or levees, that bounded both sides of this trough. They were very low at the head of the trough but gradually increased in height downslope and were highest at a point a little more than half the distance from the left end to the right. This progressive buildup of rim material suggests that as material migrated downslope toward the lower craters it was also being ejected from the trough.

The last two experiments of this series were set up to simulate the effects that gases would produce if vented along a fracture at the base of a fault scarp. A 1.3 cm layer of material was laid down, and a board was set vertically in it, adjacent to the row of 1.6 mm circular vents. This time, the release of compressed air produced a line of semicircular craters (fig. 3d). This procedure was repeated using a 2.5 cm layer of material, and some of the semicircular craters that formed this time coalesced into large, semi-elliptical craters (fig. 3e).

EXPERIMENTAL SERIES 4

The next series of experiments utilized slot-shaped, rather than circular, vents and was designed to further investigate the effects of vent shape and thickness of material on crater morphology. Four 1.6 mm wide slots spaced 2.5 cm apart were cut in the air chamber roof along a straight line through the circular vents of experiment 3. From left to right, their lengths were as follows: 15 cm, 20 cm, 2.5 cm, and 15 cm.

A 1.3 cm thickness of material was laid down, and air was vented very slowly into it. Four elongate troughs formed (fig. 4a); scalloped edges reflected irregularities in rate of airflow, especially at the position of circular vents now connected by the slots. This procedure, repeated with a 3.8 cm thickness of material, produced a series of wider troughs that nearly coalesced to form one long trough (fig. 4b).

Figure 3.--Craters and troughs formed during experimental series 3. Vents are circular, 1.6 mm diameter, 2.5 cm apart in a straight line.

a. Layer ranged in thickness from 2.5 cm at left to 7 mm at right; mostly explosion craters, some fluidization craters in thick material at left.

b. Layer ranged in thickness from 3.8 cm at left to 7 mm at right; explosion craters in thin material at right, fluidization trough in thick material at left.

c. Layer ranged in thickness from 5 cm at left to 7 mm at right; fluidized material migrated down trough from left to right and deepest crater at head of trough had only a very low rim.

d. and e. Vertical board placed adjacent to same row of vents; d--layer 1.3 cm thick; e--layer 2.5 cm thick; semicircular craters formed adjacent to board and some coalesced in (e) to form semi-elliptical craters.

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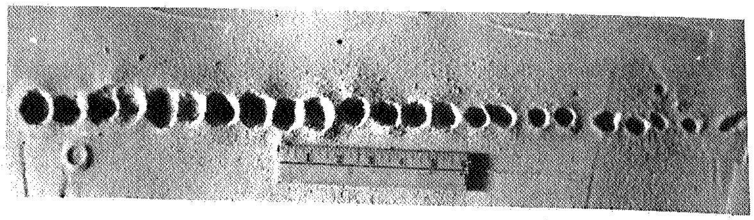

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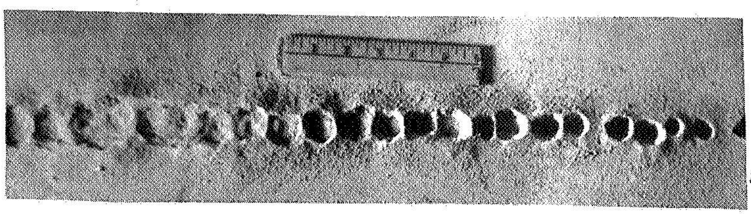

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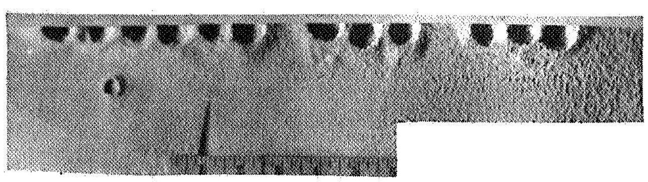

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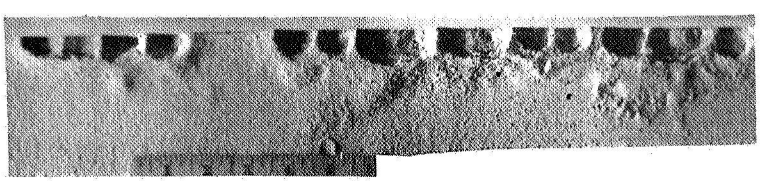
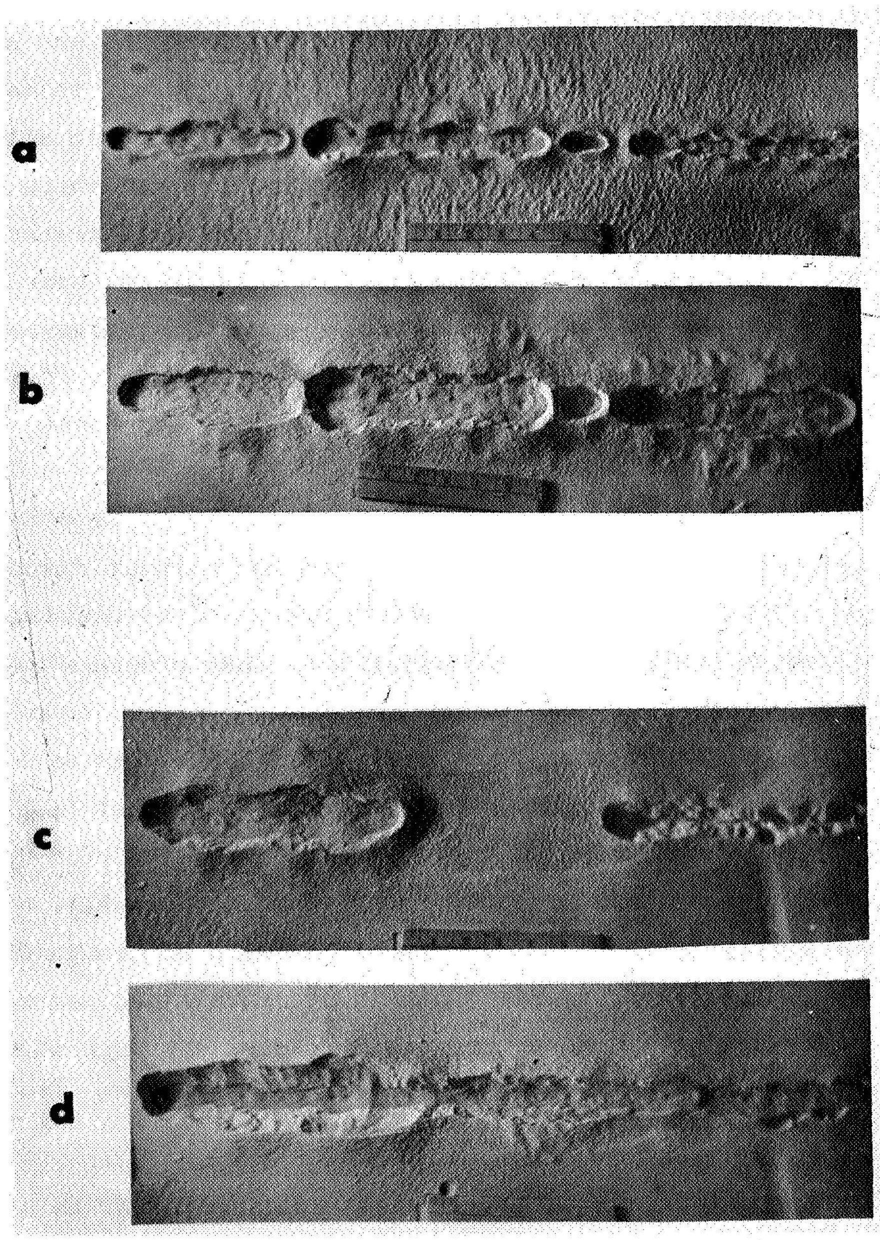


Figure 4.--Troughs formed in experimental series 4. Vents in a and b were 1.6 mm wide slots in a straight line, 2.5 cm apart. Slot lengths, from left to right were 15 cm, 20 cm, 2.5 cm, and 15 cm.

a. Layer 1.3 cm thick, troughs showed pattern of vent slots. Irregular margins of troughs caused by irregular venting of gas.

b. Layer 3.8 cm thick; wider troughs formed which almost coalesce.

c. and d. Development of trough above single 0.6 meter-long slot in wedge-shaped layer which ranged in thickness from 6.4 cm at left to 1 cm at right. Initial breakout occurred in this case at both ends simultaneously, and two troughs grew by lateral erosion (c) until they coalesced; fluidized material then moved downslope from the wide end at left and almost filled the narrow end at right (d).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The next step was to change the vent pattern from a series of slots of different lengths to one long (0.6 m) slot. In order to avoid formation of irregular margins (fig. 4a, b) the roof of the air chamber was replaced and a smooth slot was cut to permit essentially uniform venting of gas along the length of the slot. A wedge-shaped layer of material, 6.4 cm thick at one end and 1 cm at the other, was laid down over this vent and air released into it. This procedure was repeated several times; in all but one instance, air first broke the surface at the end where the material was thinnest. The left wall of the initial crater then migrated upslope until a 0.6 m-long trough had formed over the vent. In the one instance that deviated from this sequence of development, venting began simultaneously at both ends (fig. 4c), and subsequent lateral migration of trough walls continued until the two troughs coalseced (fig. 4d).

The right-hand half of the trough in figure 4d is essentially an explosion feature; it is shallower and has a lower rim than the left-hand half. The latter, which developed by fluidization rather than explosion, is bordered by rims that progressively rise in height toward the right, owing to downslope migration of fluidized material from the left end of the trough (compare with third expt. of series 3--fig. 3c). When the two troughs met (fig. 4d), much of the fluidized material from one (the left) flowed into and almost filled the lower end of the other (the right).

The photographs demonstrate the dependence of trough dimensions on thickness of material. As in previous experiments, downslope migration of fluidized material produced a trough with a deep up-slope end and a shallow terminus.

EXPERIMENTAL SERIES 5

The purpose of the next series of experiments was to simulate the effects that would be produced in loose material by venting gas through a sinuous fracture. Accordingly, a sinuous line of closely spaced 1.6 mm holes was drilled into the air chamber roof. When air was vented into a 7 mm thickness of material, a line of tiny explosion craters formed that exactly duplicated the arrangement of the underlying vents (fig. 5a). However, in a thicker layer of material (2.5 cm), venting produced a rimmed sinuous trough (fig. 5b), which was much less angular than the line of craters in the thinner layer.

Next, the vents were covered with a wedge-shaped layer, 5 cm thick at one end and 7 mm at the other. Venting produced a sinuous channel with a very high rim at the downslope end (fig. 5c). As in the previous experiments with material of gradational thickness, downslope movement and ejection of fluidized material produced rims that gradually rise in height toward the terminus of the trough. In addition, a well-defined circular depression formed at the head of the trough.

These results suggest two conclusions: (1) Gas vented from sinuous fractures can produce sinuous surface features, and (2) the thicker the material overlying the fracture, the smoother the bends of the trough that may form.

EXPERIMENTAL SERIES 6

The final series of experiments was devoted to investigating the effects of discontinuities in vent patterns on features produced by venting gas through several different types of loose materials. Vent patterns were designed with a view toward simulating the offset linear and en echelon fracture patterns that form by operation of natural geologic processes.

Six linear slots were cut in the air chamber roof. Figure 6a gives a general idea of the lengths and arrangement of the slots, and the illustration caption lists exact lengths and order or arrangement. The vents were covered with a 4.4 cm layer, and compressed air was released into the material. The craters that formed over the two short slots farthest to the right coalesced (fig. 6a), but nothing resembling a sinuous channel formed, even during several reiterations of this procedure.

The procedures followed in the next experiments marked a departure from those used earlier: layers of three different

Figure 5.--Sinuous troughs formed during experimental series 5.

a. Layer 7 mm thick, tiny explosive craters showed angular pattern of 1.6 mm-diameter vents used in this series (a, b, and c).

b. Layer 2.5 cm thick; trough pattern was sinuous rather than angular.

c. Layer ranged in thickness from 5 cm on the left to 7 mm on the right; gently curving trough formed in thicker material, and fluidized material flowed downslope to right. Deepest crater with low rim was at upslope end, at left, as in other flow experiments; very high rim developed around crater at downslope end, at right, owing to ejection of material flowing to this end of trough. Note formation of several small craters along axis of trough during final stages of experiment as gas pressure dropped.

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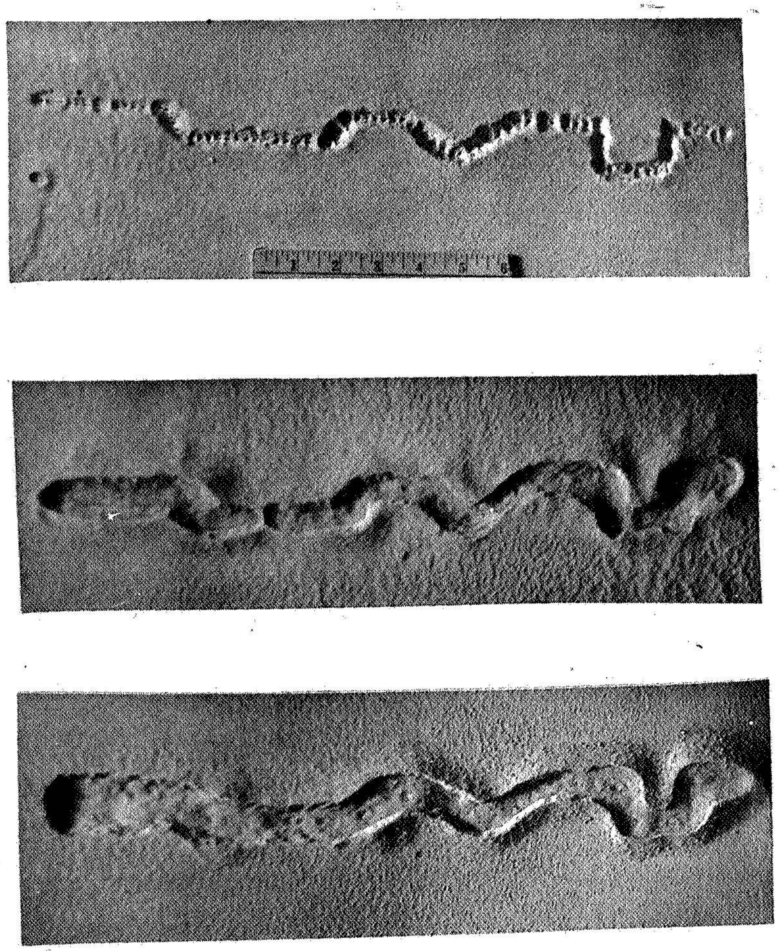


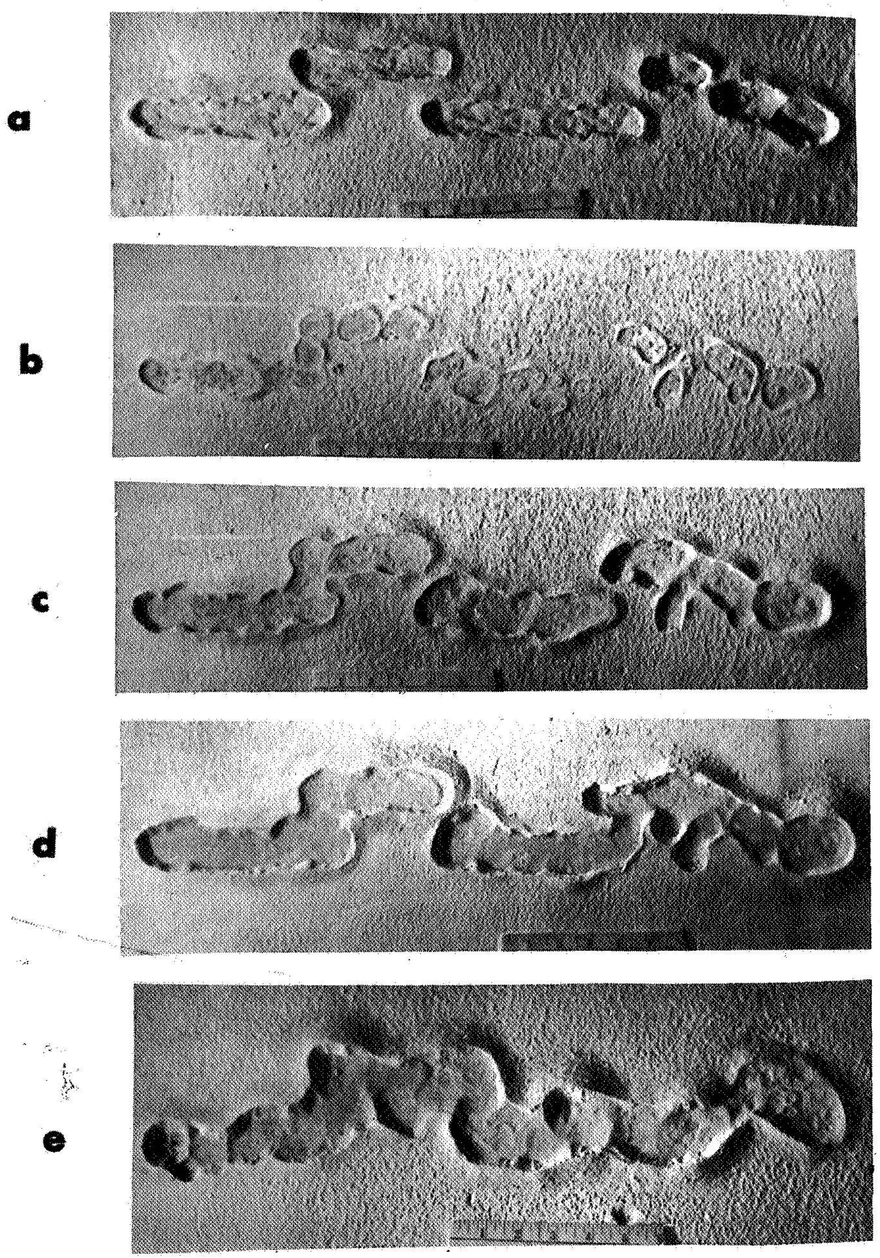
Figure 6.--Troughs formed above discontinuous, offset vent slots during experimental series 6. Slot pattern, from left is

1. 14 cm slot
2. 13 cm slot, 5 cm north of (above) first slot, ends overlapped 2.5 cm
3. 17 cm slot 5 cm south of (below) second slot, ends overlapped 2.5 cm
4. Three 3.8 cm slots en echelon, no overlap of ends, average separation between slots was 1.3 cm.

a. Depth of layer 4.4 cm; troughs duplicated slot pattern, but did not form sinuous trough.

b, c, d. Sequence of events in formation of sinuous trough with same slot pattern but with a 1.3 cm thick layer of pumice and gravel interposed between vents and 3.8 cm thick upper layer.

e. Conditions same as in b, c, and d, but flume tilted 3° to the right; fluidized material in sinuous trough moved downslope producing deep crater at head (extreme left) deep trough in upper (left) end, and shallow, partly-filled trough at lower (right) end.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materials were employed, in addition to the sand and dust mixture. In earlier experiments, preceding those described in this report, a layer of coarse material had been emplaced over vents, and this in turn was covered with the sand and dust mixture. The purpose of this procedure was to simulate a zone of shattered material associated with a fault and to observe the effects of dispersal of gas through this zone. A series of crater clusters that did not conform to the vent pattern was produced as a result.

In order to further explore the effects of gas dispersal through a simulated zone of shattered material, a straight slit 0.6 m long was cut into the air chamber roof and covered with a 2.5 cm thick layer of 1-mm plastic spheres, which in turn was covered with a 2 cm layer of the sand and dust mixture. Gas dispersed through the layer of spheres and formed the fluidization-crater clusters shown in figure 7a.

In another experiment, the same vent was covered with a 1.3 cm layer of 5-mm pumice fragments, which in turn was covered with a 1.3 cm layer of 3-mm gravel and a 1.3 cm layer of the sand and dust mixture. Dispersal of gas through the layers of coarse material again produced fluidization-crater clusters and isolated explosion craters that did not conform to the vent pattern (fig. 7b).

Next, the air chamber roof, vented as in the first experiment of this series (fig. 6a), was covered with a 1.3 cm layer of the pumice and gravel and, over that, a 3.8 cm layer of the sand and dust mixture. The sequence of events that took place upon release of compressed air is shown in figures 6b and 6e. First (fig. 6b), fluidization-crater clusters formed in a pattern similar to that of the vents. These then coalesced to form fluidization throughs with irregular margins and rims that varied in height (fig. 6c). With further enlargement, the troughs coalesced into two long irregular troughs (fig. 6d). However, it was not until the flume was tilted 3° to the right that fluidized material moved downslope and a continuous sinuous channel formed, deep

a

b

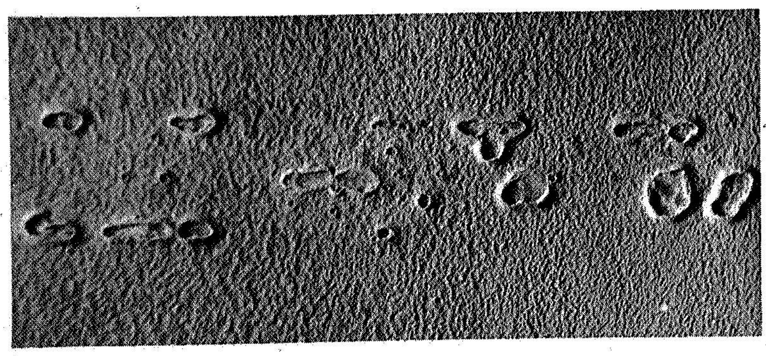

Figure 7.--Crater clusters formed in experimental series 6 over a straight vent.

a. Layer of 1-mm plastic spheres, 2.5 cm thick, interposed between slot and 2 cm-thick upper layer; dispersion of gas through spheres produced clusters of fluidized craters.

b. Layer of 5-mm pumice fragments 1.3 cm thick, overlain by 1.3 cm layer of 3-mm gravel, covered by layer of fine sand and dust 1.3 cm thick; dispersion of gas through layers interposed between slot and upper layer produced clusters of fluidization craters and isolated explosion craters.

at one end and shallow at the other (fig. 6e).

These results suggest that when gas is released from a group of discontinuous fractures and then disperses upward through a zone of shattered, coarse material, it can produce a continuous channel, sinuous in form, in the finer material of an uppermost surficial layer. The features produced during this last experiment are in several respects similar to some lunar sinuous rilles.

CONCLUSIONS

Gas emission can produce either explosion or fluidization craters in loose materials, depending upon the nature and thickness of the material. The surface forms produced in these experiments resemble several types of small- to moderate-sized lunar features. Chains and clusters of lunar craters, as well as parts of some sinuous rilles, may well have formed as a result of fluidization of fragmental surficial materials by gases vented from fractures in the lunar crust.

Additional experiments with a variety of materials and vent patterns should be conducted. Such experiments should be designed to provide data on flow rates and pressure drops associated with crater formation.

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