

TERRESTRIAL ANALOGS TO LUNAR DIMPLE (DRAINAGE) CRATERS

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Abstract. In addition to modes of formation offered by previous investigators, terrestrial drainage craters formed over lava tubes in Oregon are presented as analogs to lunar drainage craters. Craters associated with lava tubes result from: (1) drainage of surface material through roof fractures; (2) plastic collapse of the partially cooled lava tube roof; and (3) drainage of surface material into roof collapses. The former two categories result in shallow, often elongate craters; the latter category forms classic 'dimple' shaped craters. Elongate dimple craters formed over volcanic fissures in southern Idaho are also discussed and presented in support of one mode of formation proposed by previous investigators for lunar drainage craters.

Movement of surface material toward the orifice is initiated on Earth largely by wind and water; in lunar conditions, initial movement is attributed to micro- and macro-meteoritic bombardment, seismic disturbances generated by internal and external processes, and by thermal creep.

1. Introduction

Dimple (and drainage) craters were discovered by the investigators of the Lunar Ranger missions. The craters are characterized by their morphology and small diameter, and are thought by many investigators to result from drainage of fragmental surface material into subsurface cavities, or withdrawal (drainage) of magma from beneath cooled lava crusts to form collapse depressions. Several other hypotheses have, however, been proposed to explain their mode of formation, and drainage is thought to occur into several types of cavities. Some of the ideas are rather speculative and are not based on laboratory or field observations of possible analogs; these ideas are reviewed and the results of recent field investigations are discussed. Two types of terrestrial features are presented as possible analogs to lunar dimple craters.

2. Lunar Dimple and Drainage Craters

The term *drainage crater* is applied to craters thought to result from drainage of fragmental material into subsurface cavities, or drainage of molten magma from beneath partially cooled lava crusts. *Dimple crater* is a special type of drainage crater with a dimple-shaped morphology. Drainage craters are distinguished from other lunar craters by: (1) lack of raised rim; (2) convex slopes; (3) small diameter (usually 200 m or less); (4) often elongate form in planimetric view; (5) association often with similar craters in crater chains (some crater chains are aligned with regional structural trends);

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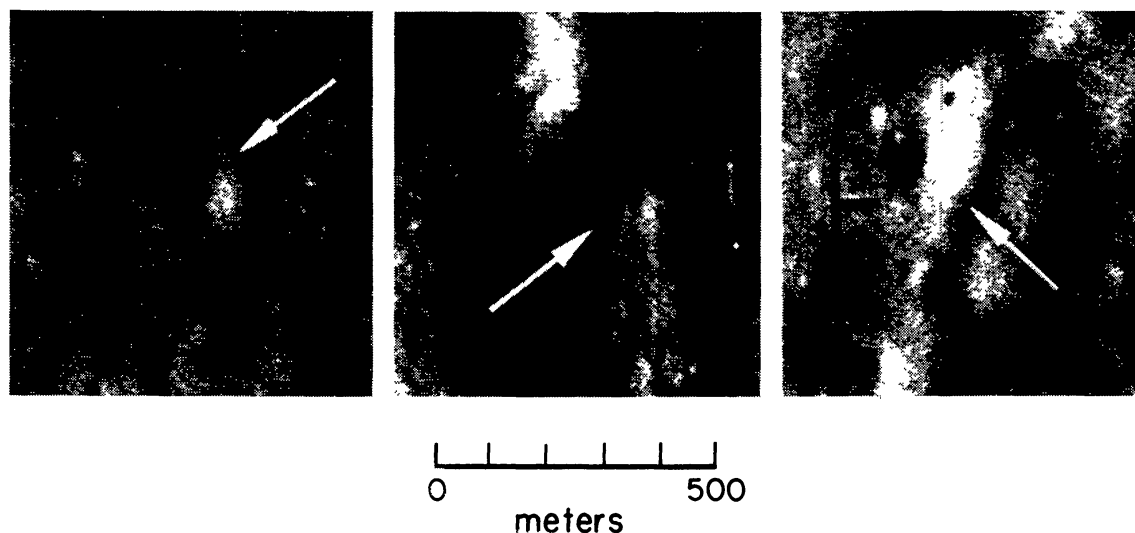


Fig. 1. Dimple craters (white arrows) defined by Urey (1965, p. 139) on Ranger VII photograph No. 199 (A-camera).

and (6) steeper slopes toward the center than near the periphery (dimple crater *sensu stricto*).

Urey (1965, p. 143), in discussing the results of Ranger VII, described some craters (Figure 1) in Mare Cognitum as 'dimple' features and offered explanations for possible origin. The craters could result from slumping of surface material into a crevasse; lack of distinct funnel-shaped form was attributed to fragmental cohesive (sticky) material being moved into the crevasse by micrometeorite or small macrometeorite bombardment, rather than free flow. Under bombardment, some material would be sprayed on the slopes; if a hole exists at the bottom of the crater, such 'spray-back' would not take place and the slope would steepen. As an alternative mechanism, Urey (1965, pp. 143–144) suggested that dimple craters may form around chunks of solid material in the fragmental surface layer. Under micrometeorite bombardment, etc., the solid chunk would eventually be depressed with smaller fragments distributed around the chunk. This mechanism would explain large rocks found in some dimple craters, but would not necessarily explain the linear disposition of the craters.

Shoemaker (1966, p. 252) described several small aligned lunar craters as probably resulting from local drainage of weakly cohesive fragmental material into underlying fissures. In discussing the Surveyor V results, Shoemaker (1967, p. 41) described many craters within view of the spacecraft as drainage features (Figure 2), including the 9×12 m crater on which Surveyor V landed. Although the craters lack the characteristic funnel-shaped profile, they are rimless, aligned along an inferred fissure, and some are elongate.

McCauley (1966, pp. 313–319) made a photogeologic map for the floor of lunar crater Alphonsus and distinguished 'funnel crater material'. The unit was characterized by small, rimless craters, generally less than 200 m in diameter, which he attributed to drainage of loosely compacted surface material into fissures and cavities.

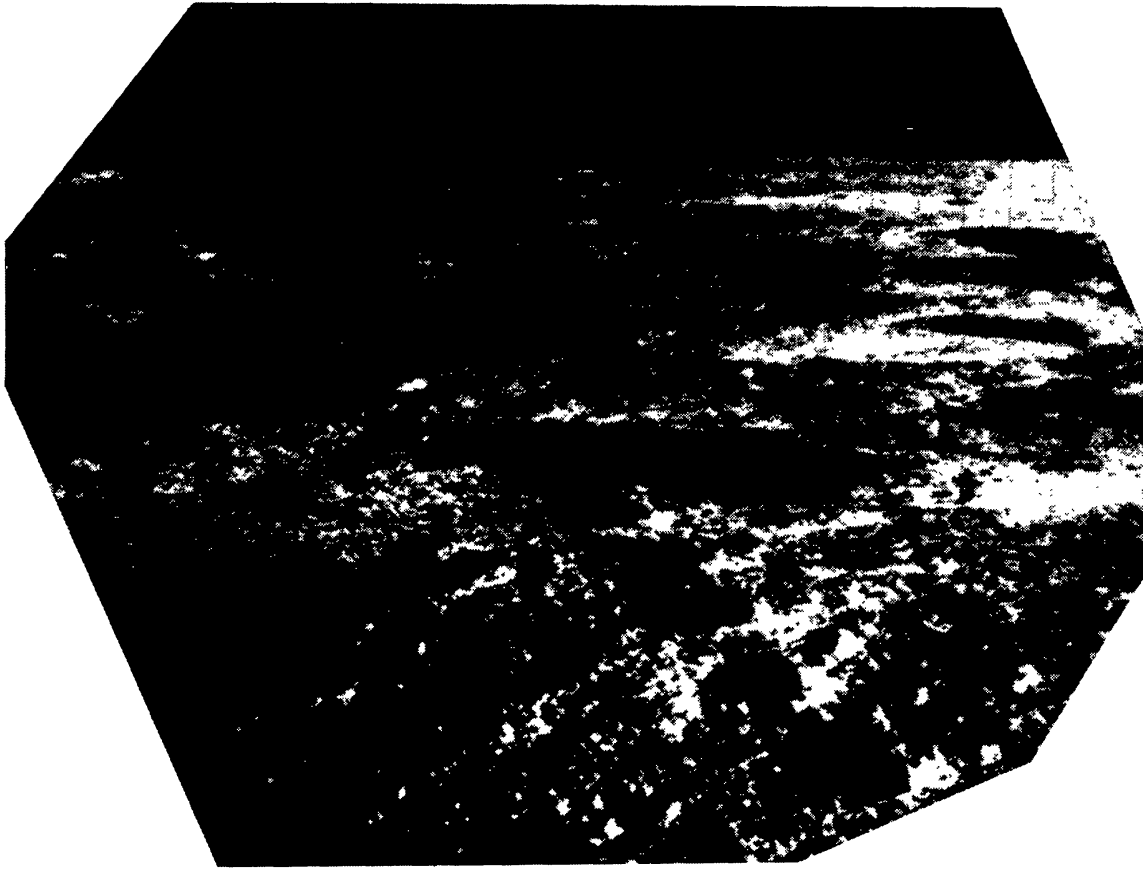


Fig. 2. Wide-angle picture taken from Surveyor V (Day 266, 11:26:28 GMT); Shoemaker (1967, p. 16) identified the chain of small craters (20–40 cm in diameter) as resulting from drainage into an underlying fissure or parallel fissure.

Schmidt (1966, pp. 326–335), in discussing the geology of part of Mare Tranquillitatis from Ranger VIII photographs, distinguished funnel craters and dimple craters by the wall slope and regularity of rim. He defined funnel craters as steep (greater than 15°), circular, and without raised rims. Dimple craters were defined with slopes ranging from less than 15° to greater than 15° and with poorly defined rims. Both forms, as well as some linear depressions, were attributed to drainage of finely divided solids through orifices. Schmidt (1966, p. 331) also suggested that funnel craters might result from upward discharge of material through the mare surface.

Kuiper, first in analyzing Ranger VII results (1965, p. 11, 50–54), and later Rangers VIII and IX results (Kuiper *et al.*, 1966, p. 35–245), discussed shallow lunar depressions and dimple craters. Several possible modes of formation were proposed: withdrawal, relocation, or local drainage of magma from beneath the surface crust layer into lower subsurface vesicular layers; volumetric decrease of subsurface material upon cooling and solidification; escape of gases; and roof cave-in of hollow lava chambers. Lack of straight conical sections on slopes of lunar dimple craters was attributed to cave-in rather than drainage and suggested to Kuiper (1965, p. 11) that the thickness of loose surface material is inappreciable. Several lunar dimple craters photographed by

Ranger VIII were described and illustrated as having a central break, or cave, and were offered as evidence of partial roof collapse over lava chambers. Large shallow depressions were attributed to complete collapse of lava chambers resulting from withdrawal of magma. Examples of this type collapse were cited and illustrated from lava flows in New Mexico.

There is general agreement that some lunar craters result from the drainage of surface fragmental material into subsurface cavities, and that craters so formed can be recognized by the criteria listed earlier. Some authors believe that some depressions and dimple craters result from collapse of lava chambers and that there is not necessarily movement of fragmental material.

Volcanic features involved in the formation of drainage craters can be divided into two groups: primary and secondary. Primary features are formed while the lava is molten or plastic. Advancing lava flows, particularly the smooth, pahoehoe type lavas, are often momentarily halted and form lava pools or lakes; a crust of variable thickness usually forms over the dammed flow. A resurgence of lava from the source, or a weakness at the flow front, permits the flow to break out of the pool and the magma drains from beneath the crust. The partly cooled crust is plastically deformed, creating numerous depressions of the type described by Kuiper.

Secondary volcanic features that may lead to drainage craters are formed after the lava has solidified. They include fissures, fractures, and fractures associated with crustal chambers and blisters. Material deposited over the surface containing both primary and secondary features may then 'drain' into the subsurface cavities or fissures. Such material can be subsequent lava flows, ash deposits and other pyroclastics, and weathering products derived from the initial lava flow.

3. Lava Tubes and Drainage Crater Formation

In addition to the volcanic structures discussed above, it is proposed that lava tubes, features common in many basaltic lava flows, can have both primary and secondary structures leading to drainage crater formation and collapse depressions.

The geology and morphology of lava tubes are relatively unknown and the mechanics of lava tube formation have not been studied in detail. Macdonald (1953), Ollier and Brown (1965), and Skeats and James (1937) have made contributions toward understanding lava tubes. They form only in pahoehoe basalt, a material characterized by smooth, ropy surfaces and distinguished from aa lava as being richer in gases and more fluid. Pahoehoe often grades into aa, apparently as cooling and degassing (hence greater viscosity) occurs. As the advancing basalt flow cools and forms a solid crust, flow continues beneath the crust and is eventually restricted to tubular conduits (early-stage lava tubes). The advancing flow is supplied by distributary conduits termed 'feeder tubes' which may remain open or become plugged. Often the roof has not cooled to a sufficient thickness to support the weight of the crust and as the fluid lava drains from the tube, the plastic roof sags into the void. This may occur along much of the tube's length or may take place at intervals, leaving lava bridges between

the collapse depressions. The result is a series of shallow, elongate depressions, all approximately the same dimension (determined by the size of the lava tube). Some shallow drainage crater chains may be explained by this mechanism.

Subsequent surges of lava can enlarge the conduit by remelting the cooled basalt. Drainage of the lava and cooling of the conduit results in formation of the lava tube. As the lava tube cools, joints and fractures often develop in the basalt containing the tube. Many fractures reach the surface through the roof and can serve as orifices for the drainage of surface material into the lava tube. Often, very small segments of the roof collapse forming features termed by 'spelunkers' as *skylights*. Skylights serve as excellent orifices in the formation of drainage craters and such features may represent the lunar dimple crater 'caves' described by Kuiper *et al.* (1966, p. 92). Lava tubes range in size from a few inches in diameter and a few feet long to nearly a hundred feet wide and many miles long. The tubes are geologically short-lived; they may collapse by interior spallation of the roof or they may fill with detritus.

The possible existence of lava tubes on the Moon was discussed earlier (Oberbeck *et al.*, 1969). Morphologic similarities of collapsed terrestrial lava tubes and some lunar sinuous rilles, lunar scaling considerations, and probable basaltic composition for parts of lunar mare areas (Turkevich *et al.*, 1968) were offered as evidence.

4. Field Observations and Comparison with Lunar Features

Several lava tubes and lava tube systems were examined in Central Oregon, southeast of Bend (Figure 3). Many tubes are radial to Newberry Caldera and formed in Recent basalt flows erupted from the parasitic cones on the caldera flanks. The geology and morphology of lava tubes of the region will be the subject of another paper. Three lava tubes (Boyd Cave Lava Tube, Horse Cave Lava Tube System, and Wind Cave of the Arnold Lava Tube System) illustrate primary and secondary drainage features which may be analogous to lunar features.

Volcanic structures in the Snake River Plains, Idaho, were also studied for possible lunar analogs and, here, a rift zone was found to be significant in the formation of drainage craters.

A. BOYD CAVE LAVA TUBE

Boyd Cave is about 7 miles southeast of Bend, Oregon (Figure 3) in Deschutes National Forest (NW 1/4, Sec. 8, T. 19S., R. 13E.). The main segment of the cave is 1990 feet long and has an average height of 11 feet and a maximum width of 33 feet (Figure 4A). The source of the flow containing the lava tube is not known; the general downslope trend of the tube, however, is north and the source may be associated with one of the parasitic cinder cones a few miles to the south. Overall slope of the tube is rather gentle, about one foot per 50 feet.

Entrance to the tube is gained through a small roof collapse (skylight) approximately 10 feet in diameter. The tube extends 73 feet upslope from the entrance and is blocked by sand and partial collapse of the roof. Sand covers the floor 80 feet downslope from

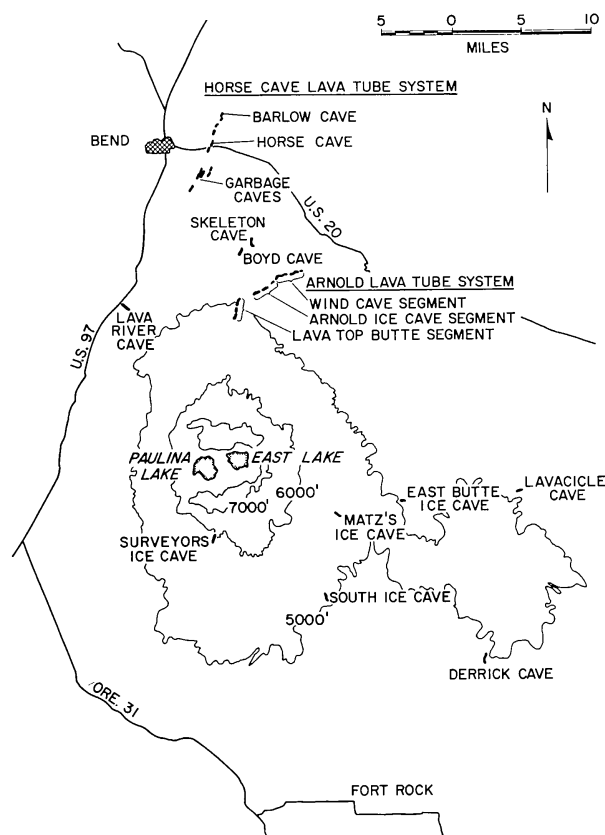


Fig. 3. Newberry Caldera, Oregon, and associated lava tube systems. Paulina Lake and East Lake are in the approximate center of the caldera; lava tubes are radial to the caldera; only the known major lava tubes are shown.

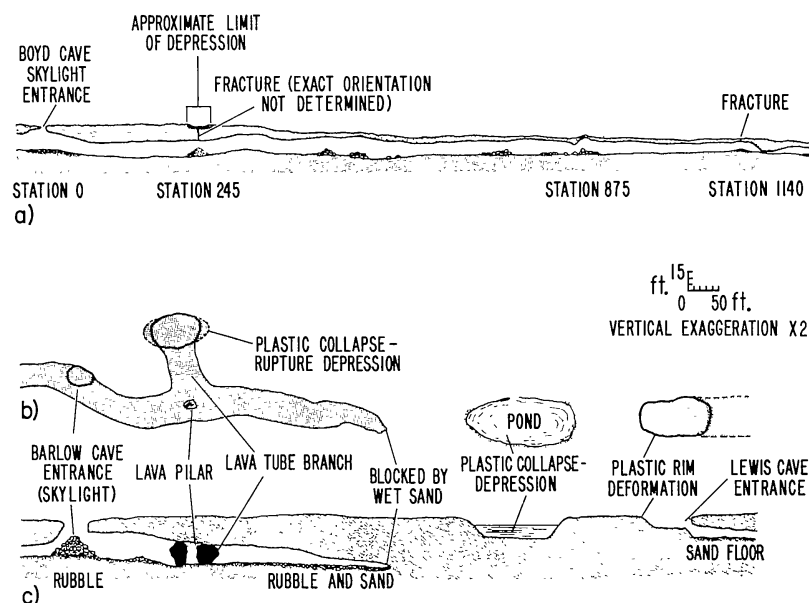


Fig. 4. (a) Longitudinal cross-section of Boyd Cave Lava Tube. – (b) Planimetric view of Barlow Cave Segment (Horse Cave Lava Tube System), dashed line indicates subsurface traverse of lava tube. – (c) Same lava tube, longitudinal cross section.

the entrance. At a station 245 feet from the entrance is a large pile of sand, 30 feet long, 14 feet wide, and 8 feet high, amounting to approximately 950 cubic feet (Figure 5). The sand (fine sand to silt size particles) has entered through a roof fracture which extends across the tube and is, in places, an inch wide. A surface traverse of the tube revealed a very shallow depression over the exact location of the sand pile in the tube (as determined by both traverse and by sound transmitted from the depression to a listener stationed in the tube). The surface depression is 22 feet long, 16 feet wide, and about 1 foot deep at the center; roof thickness of the tube is about 10–12 feet.



Fig. 5. Boyd Cave Lava Tube, Oregon; Station 245, sand and other detritus which has drained into tube. White arrows indicate roof fracture; view down tube slope.

Volume of the depression is about $\frac{1}{3}$ that of the sand pile and it is assumed that the depression is filling in by wind and water transport. Depth of sand in the depression is about 14 inches; depth of the sand in areas to both sides of the tube is 24–30 inches.

For the next 620 feet the floor is covered with a small aa basalt flow formed subsequently to formation of the tube. At a station 1140 feet from the entrance is a similar fracture perpendicular to the tube axis, extending across both walls and across the ceiling through which sand from the surface is flowing (Figure 6). Figure 4A is a longitudinal cross-section of part of the tube; roof thickness over the tube is less than 3 feet. Sand covers the floor for the next 360 feet and because there is little sand on the floor upslope from the fracture-vent, it is assumed that this sand has entered the tube through the fracture and washed downslope by water entering the tube. The amount of sand in the tube is in this section estimated to be 1400 cubic feet.

The point on the ground above the fracture was located by surface traverse and the area examined. Although no crater or depression was found, there is a large sandy area about 40 feet in diameter that is without vegetation. It is the only bare ground



Fig. 6. Boyd Cave Lava Tube, Oregon; Station 1140, two conical sand piles resulting from material entering tube through roof fracture, view up tube slope.

in the general vicinity and it may represent an area in which the surface sand is moving by soil creep, thus not allowing propagation of vegetation. Deposition is apparently sufficient to fill in and obliterate potential depressions.

The longitudinal section of the lava tube (Figure 4A) shows the roof is quite thin in many places. Some sections of the roof, even those as thick as 6 feet, have live roots exposed in the ceiling. The roots follow fractures and in weathering probably enlarge the fractures. This does not, however, exclude the possibility of fractures of sufficient size to permit drainage of surface fragments into the tube. Very young lava tubes in areas devoid of vegetation were examined in the Snake River Plains, Idaho, and roof fractures of the size observed in Boyd Cave were found.

If lunar lava tubes form similarly to terrestrial lava tubes, they may be expected to have roof fractures formed during cooling and from impact. The impact-generated lunar surfaces produces a fragmental layer of variable thickness (Quaide and Oberbeck, 1968). It is reasonable to assume that some lunar craters have formed by drainage through fractures into lunar lava tubes. Crater size would be determined by thickness of the fragmental layer and dimensions of the fracture and lava tube. Movement of material may be initiated by micro- and macro-meteoritic bombardment, seismic disturbances and thermal creep. A series of fractures along the tube could result in a chain of drainage craters of approximately the same size and morphology. Planimetric outline of the crater would be either round or elongate parallel to the fracture (perpendicular to the axis of the tube).

Like the shallow depression formed over Boyd Cave Lava Tube, lunar drainage craters formed through fractures may be shallow and lack the typical 'dimple' profile if the rate of drainage is slow. The shallow round-bottomed crater shown in Figure 2,

and suggested by Shoemaker to be a drainage feature, may have formed by this mechanism.

B. HORSE CAVE LAVA TUBE SYSTEM

Horse Cave Lava Tube System is a complex network of anastomosing lava tubes southeast and east of Bend, Oregon, trending north-northwest from NE 1/4, Sec. 15, T. 18S., R. 12E., to NE 1/4, Sec. 19, T. 17S., R. 13E. (Figure 3). One of the main segments of the system is composed of elements extending from Horse Cave (NW 1/4, Sec. 25, T. 17S., R. 12E.) to Barlow Cave (NE 1/4, NW 1/4, Sec. 19, T. 17S., R. 13E.) west of Bend Municipal Airport. Several sections along the tube have collapsed roofs which form shallow, elongate depressions. Of significance is the collapse of the roof before the flow had cooled completely and while the lava was plastic as indicated by the inward drape of the lava sheets over the rims of several depressions. Figure 7

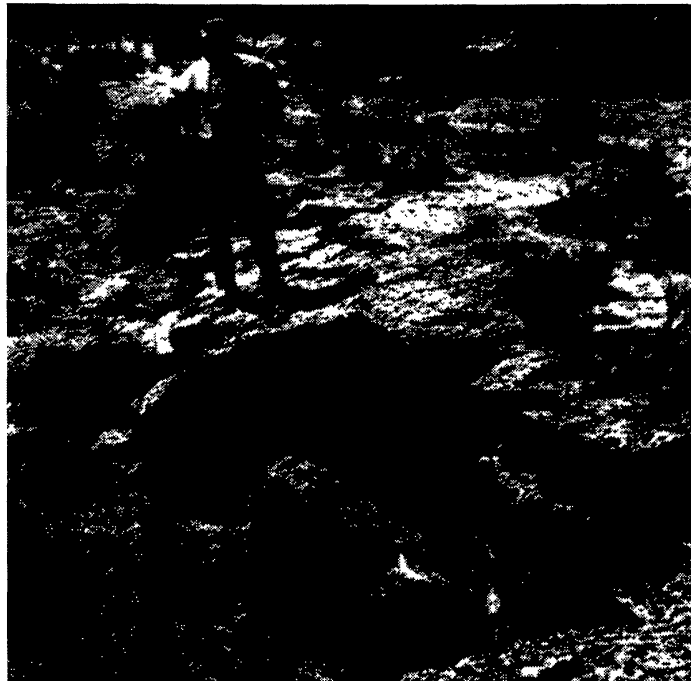


Fig. 7. Horse Cave Lava Tube System, Oregon; near Barlow Cave entrance. Plastic deformation of roof segment on one edge of elongate depression.

illustrates plastic surface deformation of the roof over a lava tube branch near Barlow Cave entrance. Relationship of the branch to the main tube element is shown in Figure 4B. In most cases, the lava sheet ruptured before draping to the bottom of the tube. The rupture forms a low (often less than one foot high), wide entrance to uncollapsed parts of the lava tube. Sand and fragmental lava cover the floor of most depressions and this material frequently drains into the uncollapsed lava tube.

Some depressions result from plastic collapse of the lava, but probably without rupture. These depressions are relatively impervious and form small ponds during

the wet season. Surface and subsurface traverses of the area show the lava tube (Figure 4C) leads toward one pond and ends within about 120 feet of the pond. The tube end (Figure 4C) is blocked by wet sand. Apparently there are fractures in the lava which permit some drainage of both sand and water into the tube.

Roofs of some lunar lava tubes may also collapse during drainage of molten basalt from the tube to form depressions. Unlike drainage craters formed over roof fractures, many lava tube collapse depressions are elongate parallel to the tube axis. Thus, the lunar counterparts would be shallow, situated with similar craters in chains, and elongate parallel to the crater chain.

C. WIND CAVE LAVA TUBE

Wind Cave Lava Tube is part of the Arnold Lava Tube System (Figure 3) and is entered by a large collapse in SW 1/4, SW 1/4, Sec. 14, T. 19S., R. 13E. Approximately 450 feet downslope from the entrance is a small roof collapse (skylight) 10 feet in diameter. Drainage of sand and detritus through the skylight has resulted in a crater 93×84 feet (short distance parallel with axis of lava tube). Configuration of the crater is classic dimple-shaped, with convex rims, steepening slope to center, and lack of raised rim (Figures 8 and 9). The crater is about 8 feet deep to the skylight where the slope steepens sharply to the ceiling of the lava tube. The material draining into the lava tube is primarily sand but also includes small basalt blocks which have weathered free from the crater slopes.

Some lunar dimple craters may form over skylight entrances to lava tubes. Skylights are usually sufficiently large to permit rapid drainage of loose material to form a



Fig. 8. Wind Cave Lava Tube, Oregon. 'Dimple' crater resulting from drainage of sand and basalt fragments through roof break-down (skylight) into lava tube. The Forest Service (Deschutes National Forest) has placed a safety fence around the skylight. The skylight is named 'Darkhole' on the United States Geological Survey $7\frac{1}{2}'$ Unedited Advance Topographic Sheet *Kelsey Butte, Oregon*.

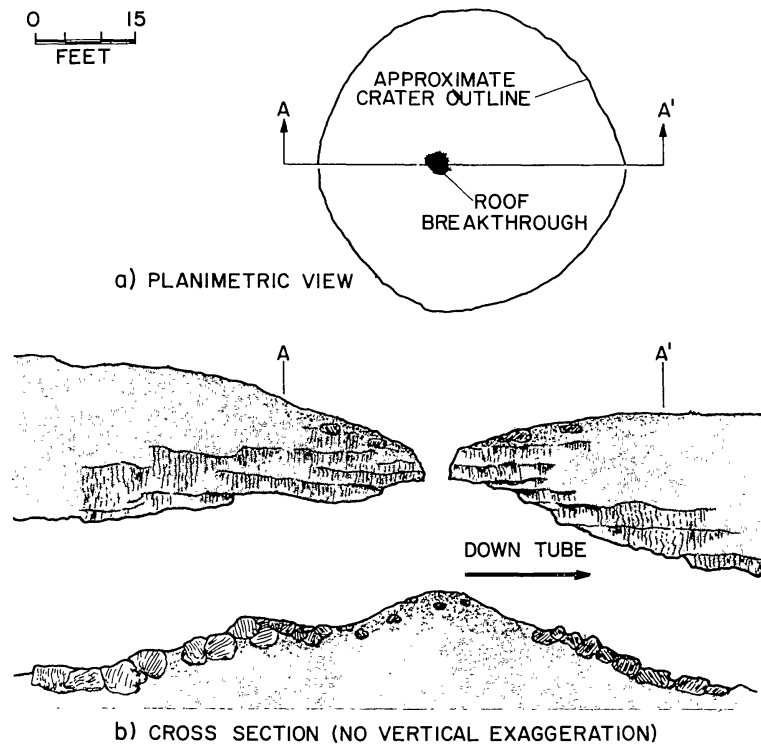


Fig. 9. Wind Cave Lava Tube, Oregon. (a) Planimetric view of approximate crater outline and skylight entrance to lava tube. – (b) Cross-section along tube axis showing 'dimple' crater profile and roof thickness over lava tube.

dimple shaped crater, unlike the small roof fractures which lead to round-floored craters. Because the orifice is generally circular, the crater develops concentrically about the orifice and is also circular. The lunar dimple crater described by Kuiper *et al.* (1966) in Range VIII photographs (last frames of P₃ and P₄ cameras) as having a central cave may have formed by collapse into a lunar lava tube. If so, the central cave could be a skylight entrance to a lava tube. A series of skylight roof collapses would result in a dimple crater chain which would follow the meandering course of the lava tube. The craters may be of variable size according to the size of the skylight orifice.

D. KING'S BOWL LAVA FIELD, IDAHO

This area is centered 20 air miles northwest of American Falls, Idaho, in the Snake River Plains. Recent lava flows have emanated from a major north–south trending rift; Printz (in print) speculated that the rift could be traced through a series of en echelon fractures to the north-northwest to connect with the Great Rift of Craters of the Moon National Monument. King's Bowl Lava Field is at the south end of the rift zone, and is characterized by fresh spatter cones along the rift, pahoehoe lava flows, and squeeze-ups; the youngest lava flow has been dated by Carbon 14 method at 2070 ± 130 years (J. Papadakis, personal communication). Two fissure zones parallel the rift and, as shown by superposition of the lava flow, were formed prior to eruption

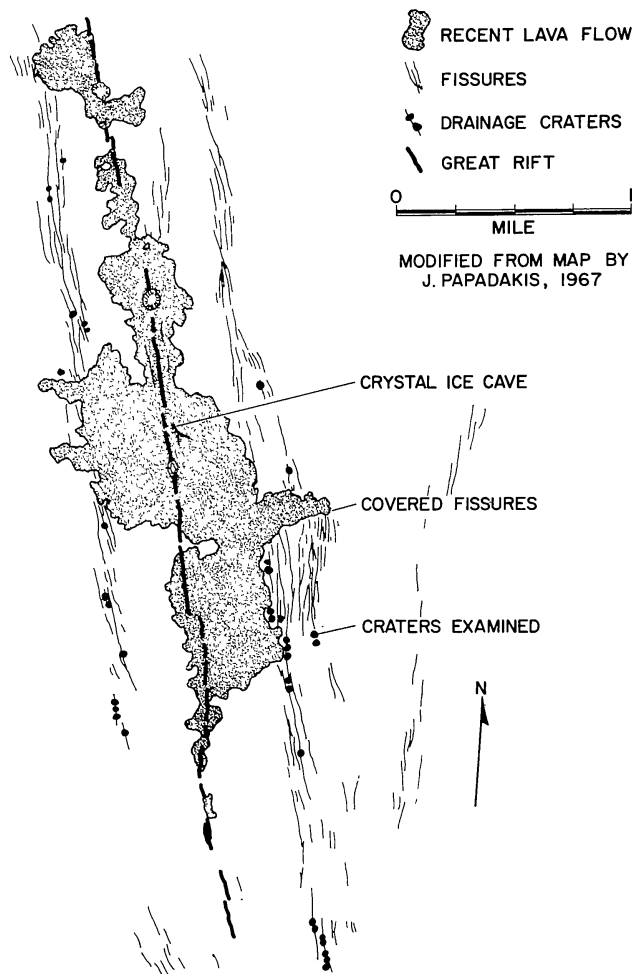


Fig. 10. King's Bowl, Lava Field, Idaho. Recent lava flow (stippled pattern) is superposed over sets of fissure containing dimple-shaped drainage craters.

of the King's Bowl Lava Flow (Figure 10). The older basalt containing the fissures is mantled with soil composed of fine sand to silt size particles (thickness ranges from less than 1 inch to 18 inches) which supports growth of sage brush. Aerial photographs show several dozen craters along many of the fissures (Figure 11). The craters are all approximately the same size, elongate, and are commonly in crater chains. Two craters were measured and examined on the ground and were found to result from drainage of fragmental surface material into the fissure. Their form (Figure 12, 13, 14) is that of a typical elongate drainage crater: lack of raised rim, convex upslopes, and steepening slope toward the orifice. The craters are not always symmetrical about the center; this may be due, in part, to configuration of the orifice and nature of the material in the bank of the crater. Eccentricity of the northern crater illustrated in Figure 14 results from the basalt outcrop on the western slope preventing crater enlargement in that direction. Figures 12, 13 and 14 show the craters and their relation to the fissure over which they have formed.

Urey (1965), Shoemaker (1966), McCauley (1966), Schmidt (1966), Kuiper (1965), and others suggested that lunar drainage craters, particularly the dimple type, may



Fig. 11. King's Bowl Lava Field, Idaho; vertical aerial photograph of dimple-shaped drainage craters (white arrows) formed over north-south trending fissures. NASA-Ames aerial photograph 10-17-68 (878 2-14).

form by drainage into crevasses, fractures, or fissures. The examples pictured here confirm the fact that dimple-shaped craters can form over volcanic fissures. As shown in Figure 11, the crater chains are aligned with the regional structural trend; the same relationship was noted by the investigators of the *Ranger* missions for some lunar crater chains.

Unlike lava tube dimple craters, craters developed over fissures would tend to be elongate with uniform widths and in straight crater chains.

5. Concluding Remarks

Some lunar craters may result from drainage of fragmental surface materials into subsurface cavities, or through roof collapse of lava tubes and chambers by drainage of magma beneath the semimolten, plastic crust. Fragmental surface materials probably consist mostly of impact generated fragments but may also include fine pyroclastics. Movement of material toward the orifice can be initiated by micro- and macro-meteoritic bombardment, seismic disturbances generated by internal and external processes, and by thermal creep.

Figure 15 summarizes the categories of lunar and terrestrial drainage craters dis-

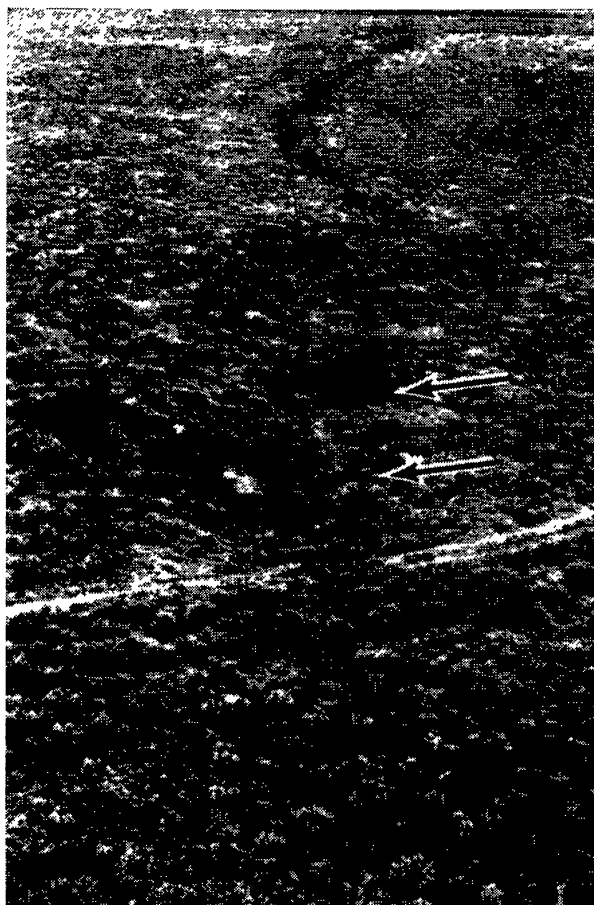


Fig. 12. King's Bowl Lava Field, Idaho; aerial oblique view of dimple-shaped drainage craters (arrows) and the fissure over which the craters have formed. View toward north.

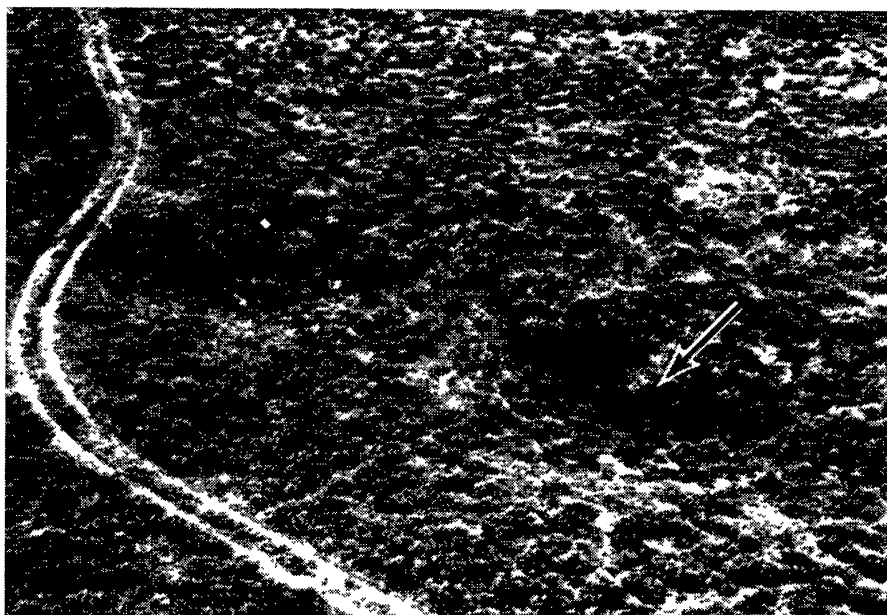


Fig. 13. Detail of craters shown in Figure 12; view to southwest. Basalt outcrop in north crater is indicated by white arrow.

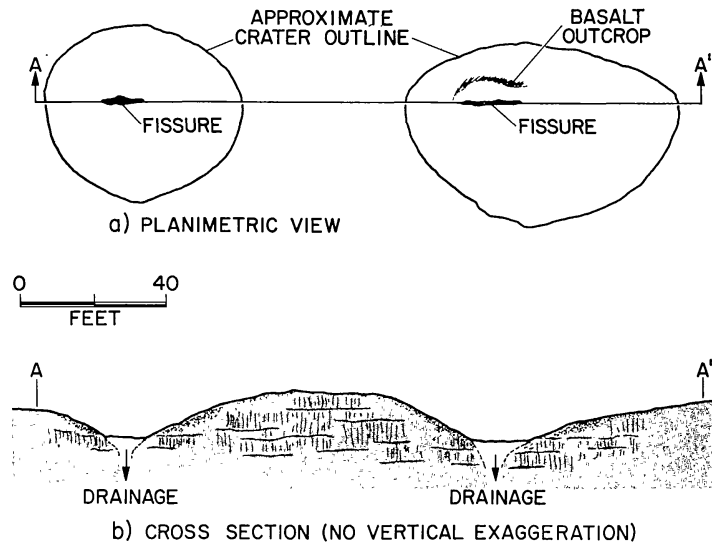


Fig. 14. King's Bowl Lava Field, Idaho; dimple-shaped drainage craters formed over fissures. (a) planimetric view with approximate crater outline – (b) cross-sectional view taken along fissure.

	OUTLINE	CONFIGURATION	MODE OF FORMATION
DIMPLE FORM	ELONGATE		DRAINAGE INTO FISSURE
	ROUND		DRAINAGE INTO FISSURE
			DRAINAGE INTO SKYLIGHT ROOF COLLAPSE OVER LAVA TUBE
ROUND BOTTOM	ELONGATE		PLASTIC ROOF COLLAPSE OVER LAVA TUBE RESULTING FROM MAGMA WITHDRAWAL
			DRAINAGE INTO ROOF FRACTURES OVER LAVA TUBES

Fig. 15.

cussed here. Those forming over small orifices and those resulting from plastic roof collapse are generally shallow and round-bottomed without a central 'dimple' depression. Drainage craters formed over lava tube roof fractures are elongate perpendicular to the axis of the tube. Those formed by plastic roof collapse may be elongate parallel to the lava tube axis. Both forms may be in meandering crater chains, following the axis of the tube. Dimple craters are special types of drainage craters, and form when drainage is more rapid than infill, which permits a steepening of crater slope toward the orifice. These may form by drainage of material through orifices over lava tubes and volcanic fissures.

In closing, it is emphasized that while the terrestrial analogs discussed here appear to account for the origin of some lunar drainage and dimple craters, other possible modes of formation are not excluded.

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