No. 152 BANDERA LAVA TUBES OF NEW MEXICO, AND LUNAR IMPLICATIONS

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ABSTRACT

Olivine basalts, which erupted over the past million years on the North Plains of Valencia County, New Mexico, exhibit lava-tube systems. These fluid-transport tunnels are near-circular in cross section and lead downslope from volcanic cinder cones over mean gradients of from 0° 35′ to 1° 12′ for distances up to 28.6 km. The tubes may either be straight or sinuous, and are sometimes modified by overflow features, spatter-cones, and several types of collapse structures and subsidence pits. They appear genetically related to sinuous rilles on the lunar surface. A large-scale map is appended.

1. *Lunar Analogs*

This study was undertaken at the request of Dr. G. P. Kuiper and Mr. R. G. Strom, whose interpretation of aerial photographs of the Bandera volcanic field revealed a number of similarities between the lava tubes and lunar rilles and other features, first reported by Kuiper, Strom and LePoole (1966, p. 199–210).

This paper considers the morphology and origin of the Bandera lava tubes. These represent the best-preserved and most concentrated group of tubes yet described.

Terrestrial lava tubes bear a striking morphological resemblance to certain lunar features. Figs. 1A and 1B are *Orbiter V* views of lunar features that appear to be complexes of collapsed lava tubes; alternate intact and collapsed segments are present. Other sinuous rilles appear to be drainage channels often originating at small craters (probably volcanic), exhibiting varying degrees of sinuousity, sometimes bifurcating in the downslope direction, occasionally rejoining; and tending to narrow toward the terminus. Examples are the Marius Rille, Schröter's Valley, and the several rilles near Prinz.

It is not simple to predict the effects of the lesser lunar gravity, or to suggest an appropriate scaling factor for analogous lunar features. While the terrestrial lava tubes appear to be similar to the lunar features shown in Figs. 1A and 1B, they obviously are not as large in width, length, and depth as the rilles near Prinz or as Schröter's Valley. For many of the smaller rilles, the geometry of the Bandera tubes is comparable.

The literature on terrestrial vulcanology indicates that lava tubes occur, almost without exception, in olivine basalts. This general composition agrees with the chemical analyses of the lunar maria determined from the *Surveyor* alpha-scattering experiments and *Apollo* samples.

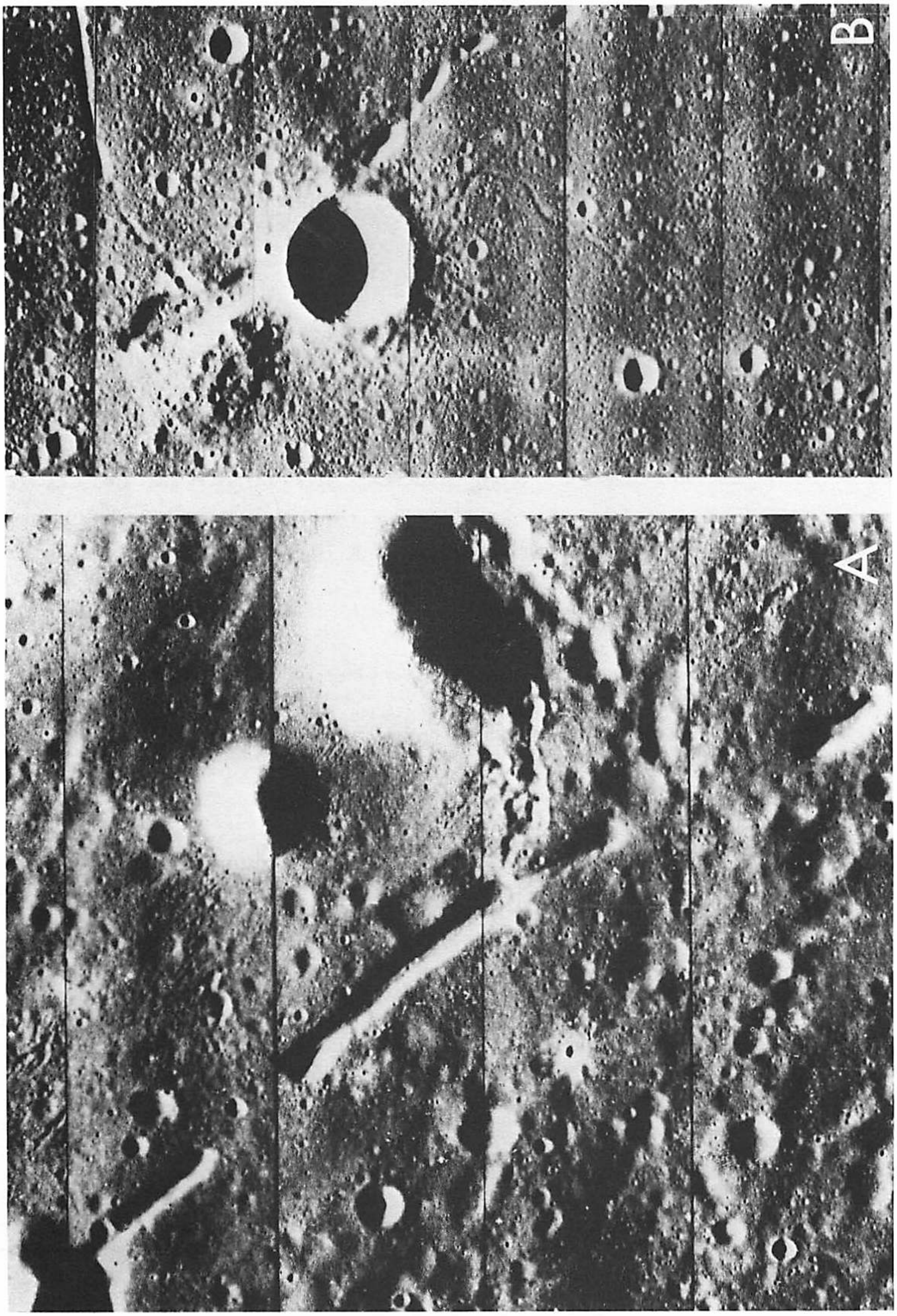

Fig. 1 *Orbiter* views of probable lunar lava tubes exhibiting series of collapse pits separated by intact segments. A. Near the Prinz rille system, at 41°50′ W, 27° 40′ N (*Orbiter V*, Frame M-190). B. In Marius Hills, at 57°05′ W, 11°40′ N (*Orbiter V*, Frame M-210).

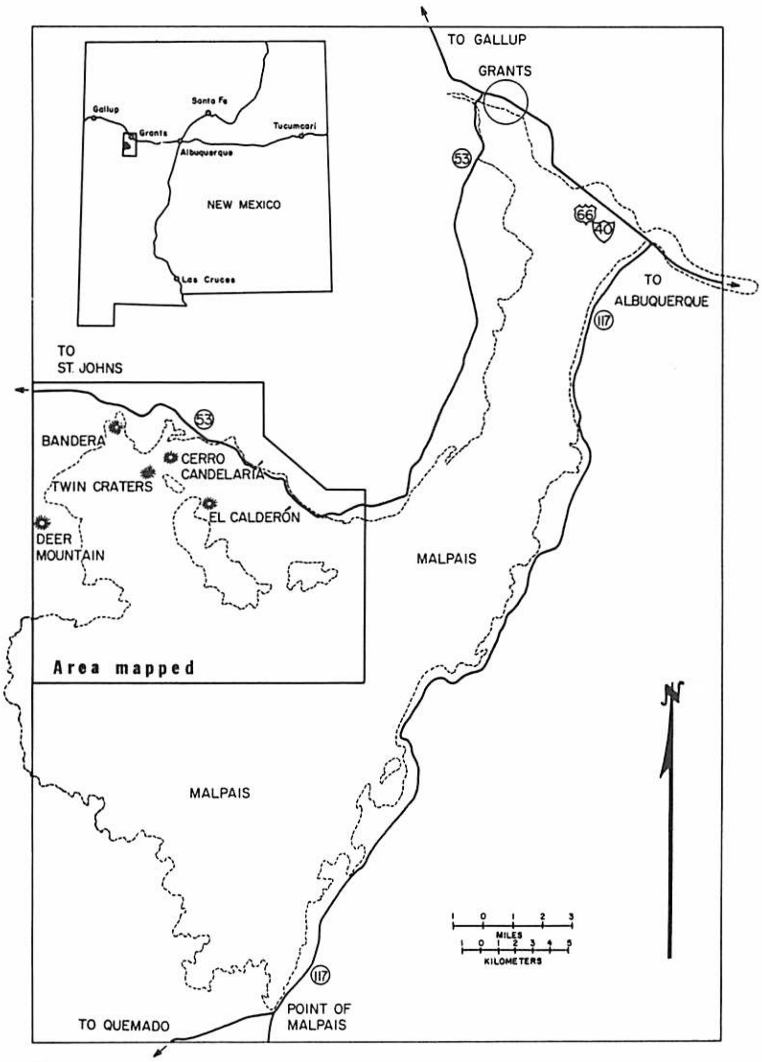

Fig. 2 Index map to the Bandera lava field. Basalts of Pleistocene and Holocene age are outlined by the dashed line; they overlie in part older volcanics.

2. *Geologic Setting*

The Bandera lava field (heretofore unnamed) lies on the Continental Divide in a sparsely settled area of Valencia County, SW of Grants, New Mexico (Fig. 2). We have named the field after the largest and youngest of the volcanic cinder cones situated in the northwest corner. The rim of this cone, Bandera Crater, is 2700 m above sea level, while the southernmost extension of the lava field, at Point of Malpais, is at 2160 m. The extreme northeastern terminus of the flow, at McCartys, is at an elevation of about 1880 m. Lava flows of Pleistocene and younger age are outlined on Fig. 2 and comprise an area of about 640 km^2.

A geologic map covering about 290 km^2, which includes the lava tubes, is appended. It shows a series of 11 distinct basaltic formations which have erupted on a much older terrain of sandstone and granite. With the exception of the State Geologic Map of New Mexico (Dane and Bachman, 1965), no prior geologic work has been performed in the area studied. However, Nichols (1936, 1939, 1946) and Thaden, *et al.* (1967) investigated some aspects of the McCartys flows along the eastern flank of the lava field.

The surfaces of the lava flows are mainly pahoehoe, except for some distinct flows which are made up of aa and block lava. The aa lava generally resulted from local eruptions along fissures and at spatter-cones, many of which appear to be associated with faulting. The lava tubes occur exclusively under pahoehoe surfaces, although in some instances they have been covered by later aa flows.

Fig. 3R La Verruga, a cluster of 4 spatter-cones, the largest of which is about 5 m high. These vents are surrounded by later aa flows, some of which issued from fissures near the cones. Stereoscopic view obtained with Fig. 3L (left) looseleaf.

The Bandera lava field has definite structural trends indicated by the locations of cinder cones and orientation of lineations observable on aerial photographs. The cones are aligned at about N40°E and closely parallel a prominent lineation trend of about N30°E. These lineations are probably sub-surface fractures and have two preferred orientations: N30°E and N50°W. The lineations are shown as faults on the Map. No vertical displacements along the lineations were observed.

A fault graben may lie between El Calderón crater and the ash-mantled hill E of Bandera Crater. The sandstone ridges in this area are about 65 m lower than the main ridge line of the Cerritos de Jaspe.

Vertical displacement is not apparent in the lava units within the graben, suggesting that formation of the graben predated the volcanic activity.

a. Spatter-cones. Numerous spatter-cones dot the northwest quarter of the geologic map (Map, Figs. 3–4). These vents are 5 to 10 m in height, and formed mainly along the fault lines. The cones form kipukas (islands surrounded by younger lavas) in larger expanses of aa basalt.

A mound of platy black olivine basalt (Fig. 5) measuring about 10 m in diameter is associated with one of the spatter-cones lining the Bandera Crater lava tube, at a point about 250 m S of Hoyo del Infierno.

In this section the basalt shows a subtrachytic texture in which plagio-clase microlites occur in sub-parallel laminae. Magnetite makes up about 20% of the rock and accounts for a slight magnetic response to a large magnet. All of the spatter-cones appear to be the result of fairly late eruptions along faults and this platy basalt is probably differentiated from the underlying magma.

b. Pre-lava rocks. Little Hole-in-the-Wall and the Cerritos de Jaspe are monoclines of Permian sandstone of the Yeso, Abo, and Glorieta formations (Dane and Bachman, 1965). These ridges strike about N40°W and dip moderately to the southwest. Several low hills of sandstone occur in the area W of Cerro Encierro. These hills do not appear on the Geologic Map of New Mexico (1965), but appear to belong to the same general series of Permian rocks.

Granites bound the lava field to the N and do not

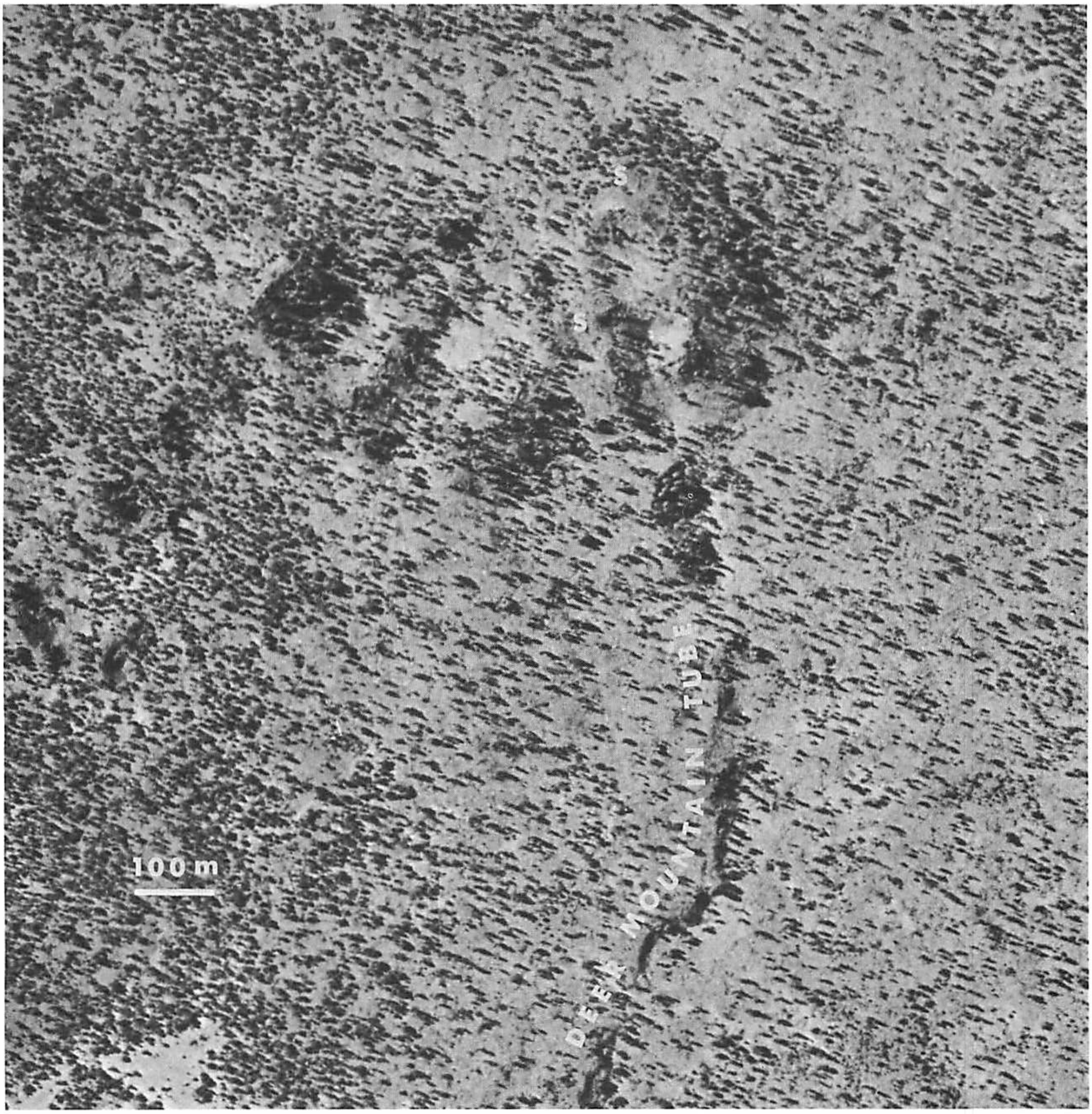

Fig. 4R Summit of Deer Mountain. Three lava tubes originate within a complex of explosively-modified cinder cones. Spatter-cones line the rims of some of the cones (s). (North is to the right; photos courtesy U.S. Forest Service.) (Stereo with Fig. 4L looseleaf.)

Fig. 5 Magnetite-rich platy basalt extruded along a tensile fracture associated with the Bandera Crater lava tube (Fieldbook gives scale).

directly influence the configuration of the flows other than providing the north face of the valley through which the Cerro Candelaría and El Calderón basalts flowed.

3. *The Lava Flows*

The 11 basaltic formations shown on the geologic map (and named here for the first time) were subdivided on the basis of their stratigraphic positions and on the character of their surfaces (freshness, relative relief, albedo, vegetative cover and soil regolith). These formations are described here, from the oldest to the most recent.

a. *Cerro Encierro flows.* Many fault lines are observed as linears on the surface of the flow (Map), and a single lava tube of about 0.5 km of exposed length runs S from the crater. The uppermost segment of this tube is covered by a layer of ash and it is also buried along its lower extremities by the younger Hoya de Cibola basalts. More than 180 m of Tertiary basalts lie beneath the Cerro Encierro lavas.*

b. *Cerro Bandera flows.* The soil on the Cerro Bandera flow places this activity in the period of vulcanism associated with craters and volcanoes of Tertiary age which lie further to the S and W. This area may have also contained many lava tubes, as indicated by the well-eroded remnant channel descending from the east side of Cerro Arizona, about 3 km W of the mapped area. This completely-collapsed tube is overlain by the Western Flows of the Bandera Crater formation N of Deer Mountain at the western edge of our Map.

c. *Deer Mountain flows.* Deer Mountain is a shield volcano 3 km in diameter. The last activity produced a series of explosively-altered cinder cones on the summit, from which radial flows spread to the E and S (Fig. 4). The eastern flow appears the most recent and was of sufficient thickness to permit the formation of a lava tube.

The Deer Mountain tube is exposed for 7 km, but is buried to the E by the lavas from Bandera Crater. About 3.3 km from the top of the mountain, the overall tube gradient decreases abruptly from 2° 08′ (3.7%) to 0° 41′ (1.2%). At this point, a broad mound containing a central crater measuring 100 m in diameter formed over the tube. We named the mound El Carbunculó because of its distinctive appearance from the air (Fig. 6). Two subsidiary tubes join at El Carbunculó.

A breached flow from the Deer Mountain lava tube occurred NW of El Carbunculó and resulted in the formation of a series of at least five distinct flow surges, augmented by intermittent eruptions from a small vent shown on the map at a point of 0.85 km SW of El Carbunculó.

d. *Hoya de Cibola flows.* A broad, dome-like highland surrounds several vents to the S of Deer Mountain. These vents lie near Hoya de Cibola, a large subsidence feature probably genetically related to the two large pits found along the Bandera Crater lava tube. The origin of these pits is probably similar to that suggested by Anderson (1941, p. 391) for Giant Crater, located in the basalts of the Medicine Lake Highland of northern California. Anderson describes Giant Crater as "somewhat circular in outline with a diameter of an eighth-mile." The precipitous sides and a vertically-walled pipe in its bottom led Anderson to conclude that magmatic stoping or fairly rapid withdrawal of magma from beneath the area had caused the collapse.

A lava tube 1 km in length enters the Cibola Pit from the S and the probable extension of this tube leaves the pit from the N. It appears that this pair represents the original lava tube, although a collapsed lava tube is exposed high on the eastern escarpment of the pit and traverses the eastern slope. The juncture of this collapsed tube with Cibola Pit is radial. We were unable to study Cibola Pit in detail and are uncertain as to the place of this tube in the history of Hoya de Cibola.

e. *Twin Craters flows.* The oldest exposed basalt flows associated with the newer cinder cones are those which flowed from Twin Craters (Map).

The one lava tube mapped here is believed to extend nearly 9 km but is exposed only 7 km. The tube is nearly straight and branches were found in only two locations. The tube apparently runs upslope as far as Twin Craters. Open collapse pits along the tube are rare, as most failures are plastic, with a gradual surficial sag over the tube line. A rather constant gradient of 0° 48′ (1.4%) was measured.

One of the four separate flow units appears to be the result of flow out of the ruptured lava tube. Some of these outcrops are not connected with the visible trace of the tube but may have come from breached subsidiary tubes.

f. *Lost Women Crater flows.* The area surrounding Lost Women Crater and its subsidiary cones at Cerrillo del Fuego contains the greatest concentration of vents involved with pyroclastic activity. These cones have been extensively modified by explosive

* Mr. Robert Lee, foreman of the York Ranch, reports that this depth of basalt was penerated during the drilling of East Well, located in Sec. 2, T7N, R11W.

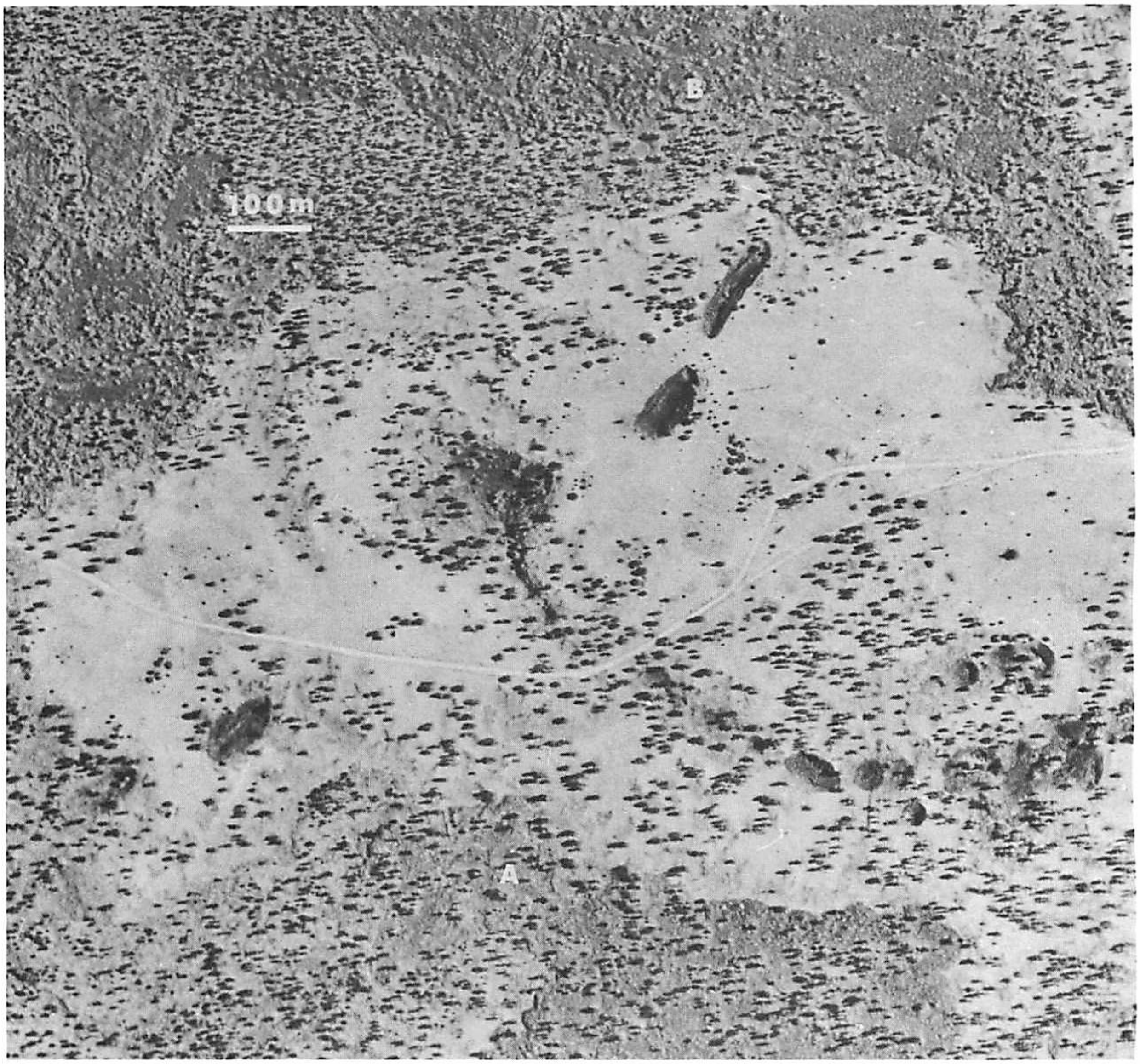

Fig. 6R El Carbunculó spatter mound, lying at the confluence of 2 branches of the Deer Mountain lava tube. The pit crater in El Carbunculó was probably a vent for minor fissure eruptions. Breached flows (A) from the lava tube can be seen below the spatter mound. Basalts from Bandera Crater (B) cover the tube to the E. (North is to the left; photos courtesy of U.S.F.S.) (Stereo with Fig. 6L looseleaf.)

activity and now appear as notched or breached conelets. The craters were formed over an existing flow, now covered on all sides by younger basalts. Minor lava eruptions then issued from fissure vents situated about 1 km S of Lost Women Crater. These later basalts were confined to topographic depressions in the earlier Lost Women flows. Lava tubes did not develop, probably because of a small supply of lava, extremely rough terrain, and the factors favoring production of aa.

g. El Calderón flows. A collapse pit (P), 305 m by 200 m, formed in the central area of a system of lava tubes (Fig. 7). This tube system contains various types of collapse features. An open channel filled with rubble lies N of the pit (Fig. 8) and progresses into alternating intact and collapsed portions of the lava tube. Sections of the former are semicircular. Collapses occurred primarily in three forms: straight-sided open channels, shorter pits (S in Fig. 7) which are often oval in plan, and circular holes in the roofs (T in Fig. 7) of otherwise intact tubes.

The main tube is now covered by the Candelaría basalts to the NE. The exposed segments adjacent

Fig. 7R Lava-tube complex at El Calderón. Three lava tubes emerging from the crater enter the subsidence pit (P) and then branch into 4 distinct tubes (1–4). The largest tube is a totally-collapsed open channel, with 2 very tight sinuous bends (arrows). Further to the E along this tube, alternate types of collapse occur: straightsided pits (S), and a small, circular, tensile failure producing a hole in the roof of the tube (T). (Photo courtesy U.S. Air Force.) (Stereo with Fig. 7L looseleaf.)

to the crater are sinuous (Fig. 7). As the tube leaves the crater, it apparently branches into three separate tubes which rejoin S of the collapse pit (P) less than 400 m away. A small branch tube also leaves the collapse pit to the SE.

Late flows near El Calderon consist of mixed pahoehoe and aa, erupted along a NW-trending fault intersecting the crater. A patch of aa about 1 km W of the crater center was probably the last flow from this fissure. Spatter-cones are numerous W of the crater and the area is transected by several faults.

h. *Cerro Candelaría flows.* The earlier lavas which erupted from Cerro Candelaría and La Tetera must have had high viscosity, or were erupted in a series of shortlived surges, for the terrain surrounding these vents has the highest slope in the entire lava field. These lavas moved only a few kilometers. Of the five flows associated with these craters, three appear to constitute the base upon which Cerro Candelaría (a cinder cone) and La Tetera (a block lava dome) were formed. A fourth flow unit, SE of Twin Craters, may have issued along a fault.

Capping this domal surface of basalt, the final surges of lava from both La Tetera and Cerro Candelaría flowed for more than 12 km in the valley along Highway 53.

Lava tubes are associated with both craters but the Candelaría tube is the more prominent. The upslope connection between the lava tube and Cerro Candelaría is obscure and the tube may end at the upper point shown on our Map. This point is at the break in slope from 4° 31′ (7.9%) to 0° 48′ (1.4%). The Candelaría tube is now a collapsed channel with overflow levees (Fig. 9), suggesting that a conduit from Cerro Candelaría may have fed the tube some time after it formed.

i. Monte Peñascoso flow. A fissure eruption paralleled Monte Peñascoso, a small sandstone ridge 1.2 km S of Highway 53, and covered the Candelaría tube 12.3 km from its source. The eruption was largely aa and completely surrounds the sandstone hill.

j. *Bandera Crater flows.* Bandera Crater is a cinder-mantled basaltic volcano whose rock walls

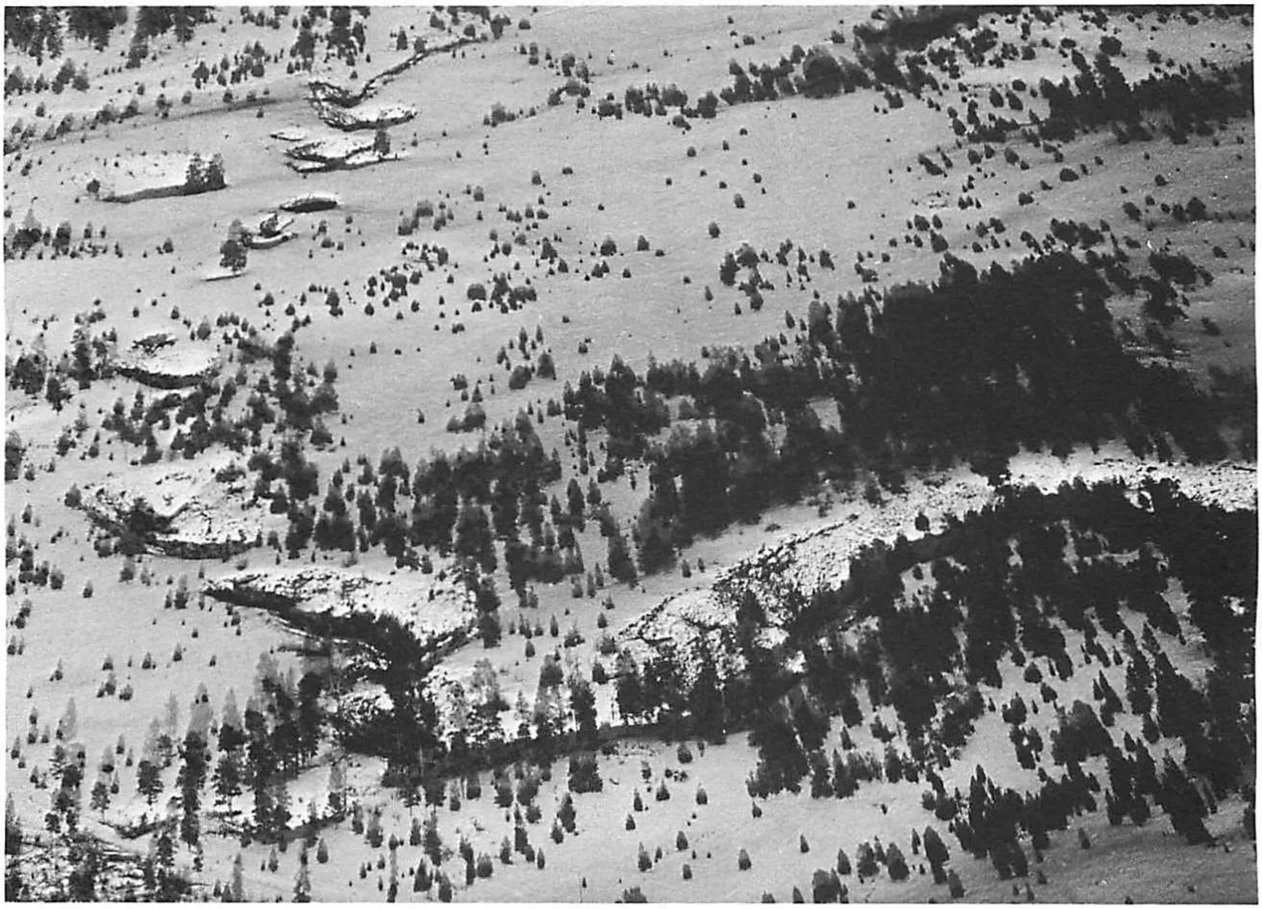

Fig. 8 Low oblique aerial view of the El Calderón lava tube. The sinuous bend on the tube nearest the viewer was measured in Fig. 14. Note the development of a V-shaped channel as rock has sloughed into the channel from the tensile fractures bordering the tube. (Road in lower left is 3 m wide.)

are exposed in a breached conical interior. The breach appears to have been formed by the extrusion of the massive flows which now contain the Bandera lava tube. Internal collapse has enlarged the interior of the cone, and the floor of the lava tube channel is now about 110 m above the crater floor. No evidence of explosive or pyroclastic activity is found on the surface of the flows S of the crater, but a thick blanket of ash covers the sandstone hills to the N and E.

The sequence of events for Bandera Crater is suggested as follows:

1) extrusion of the Central flows (aa)
2) spatter-cone activity
3) extrusion of the Western and Eastern flows (mainly aa)
4) increased spatter-cone activity
5) formation of Bandera Crater
6) development of the Ice Caves exogenous dome
7) breaching of Bandera Crater
8) ash falls
9) eruption of thick pahoehoe flows in which the lava tubes formed
10) recession in the throat of the volcano
11) eruption of local aa flows from fissures on the northern and central portions of the flows.

The broad expanse of pahoehoe lava lying N of Hole-in-theWall was the first in a series of three massive flows, shown on the Map as the Central, Eastern and Western flows. The maximum extent for these flows was more than 30 km. Three other flows from the crater have surfaces of aa and block lava. Two of these extend only about 5.5 km from the crater, but the third is exposed for about 7 km. *The aa surfaces have distinctly lower albedo than the pahoehoe.*

A vent may underlie an exogenous dome S of Bandera Crater near Ice Caves. This low dome is

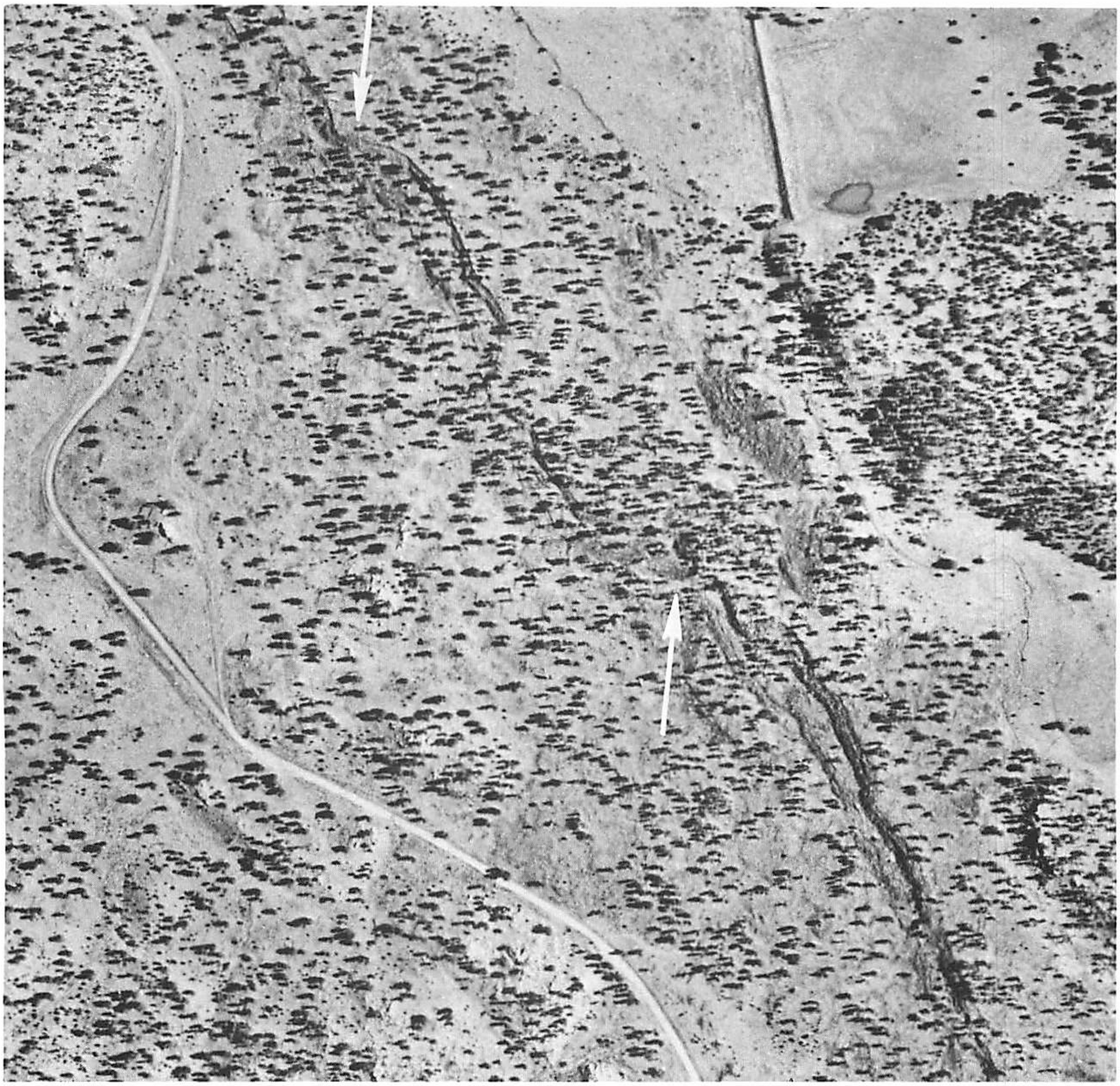

Fig. 9R Portion of the Cerro Candelaría lava tube which has collapsed into an open channel with low levees. The absence of side flows indicates that collapse was gradual enough to permit the removal of stoped roof blocks before they could constitute a hindrance to flow within the tube. Arrows indicate abrupt changes in direction. The earthen drainage berm in the upper right is 230 m long. (Photos courtesy of U.S.F.S.) (Stereo with Fig. 9L looseleaf.)

not connected with any of the flows from the crater, and was probably the result of lavas issuing from a vent located at the intersection of faults.

With the exception of the Bandera Crater lava tube, all of the tubes in the lava field appear to have formed in single flow units. The Bandera Crater tube was traced for 28.5 km downstream from the crater and *is common to three distinct flow units,* suggesting a more complicated origin. We have considered three hypotheses for this origin:

(1) The lavas from Bandera Crater progressed as a series of succeeding flow units in which each new unit was formed by a rupture in the flow front of the preceding unit. The unit most distant from the source would then be the youngest. This is the method of progression of most lava flows. A tube formed in each successive flow could be fed by the tube in the preceding unit. (However, the large amount of lava in the lower unit of the Bandera Crater flows suggests that it originated as a separate flow, instead of as a flow unit issuing from an earlier flow).

(2) The lavas issued from Bandera Crater in three massive surges, the first of which was the greatest and reached the area N of Hole-in-the-Wall. The second and third surges occurred soon thereafter, possibly within a matter of days, and did not reach as far as the first. As the second and third surges occurred the first continued to move forward, partially in response to the hydrostatic pressure of the new overriding lavas. Ruptures in the flow fronts of this first unit initiated flow through the tubes. Flow through interconnecting tubes would continue as long as the source continued to supply lava to the system. When the later surges ceased the main tube would be emptied by continued drainage at the lower end. The process was complicated by the tube's failure as shown by the channel at Pie de Pájaro, which appears to have distributed the later flows over much of the first surge.

(3) The second, or intermediate flow crossed the surface of the first and changed the position of its lava tube. Above Pie de Pájaro we are probably observing the original tube.*

Spatter-cones abound on the Bandera Crater flows between Deer Mountain and Bandera Crater. They usually occur as kipukas and most of them developed after the Central flows were erupted, but they antedate the Western and Eastern flows. The spatter-cone complex at La Verruga formed on an aa surface and was not surrounded later by such a flow (Fig. 3).

k. *McCartys flows.* R. E. Nichols' studies of the Bandera lava field, referred to above (the only previous work), were limited to the most recent activity. He named the McCartys flows, running in the valley of the Rio San Jose near Grants and McCartys, and on this basis was the first to describe collapse depressions.† He postulated a theory for their formation which remains essentially valid today.

A much wider area of the McCartys flows was investigated by Kuiper *et al.* (1966) and Kuiper (1966) in connection with the NASA *Ranger* program, and numerous illustrations of collapse depressions in this and several other flows were reproduced. The depressions are nearly circular pits, formed by the collapse of small lava tubes at isolated locations when fluid basalt drained through breaches in the fronts of thin flows. Collapse of these tunnels is similar to that occurring along the large lava tubes described above.

The McCartys flows are predominately pahoehoe but are randomly spotted with aa surfaces over their 31 km length. The flows form the E edge of the Bandera lava field and overlie, in turn, the Cerro Encierro, Cerro Candelaría, Monte Peñascoso and Bandera Crater basalts. The source area is in the vicinity of Section 28, T7N, R11W, where a vent now occupied by a mount of block lava is situated about 6.5 km S of the mapped area. Much of the lava was released along fissures, not from the main vent.

McCartys basalt is distinguished from Bandera Crater basalt by increased crystallinity of the matrix, and the absence of very fine plagioclase microlites. In thin section, the McCartys specimens exhibit intergranular or intersertal textures with 15 to 40% olivine. The higher olivine content is often marked by glomeroporphyritic sequestering of phenocrysts. At one location, undamaged plagioclase laths had formed in the interspace between fragments of fractured and dislocated olivine crystals.

High-temperature relatively-disordered plagioclase occurs in two size ranges: phenocrysts averag-

* We thank Dr. B. Nordlie of the Geology Department at the University of Arizona for suggesting this possibility.

† Skeats and James (1937) studied basaltic barrier forms in the lavas of western Victoria; their description of origin of the features is identical to that of Nichols. The Australian lavas are older and the collapse depressions are not as common or as well developed.

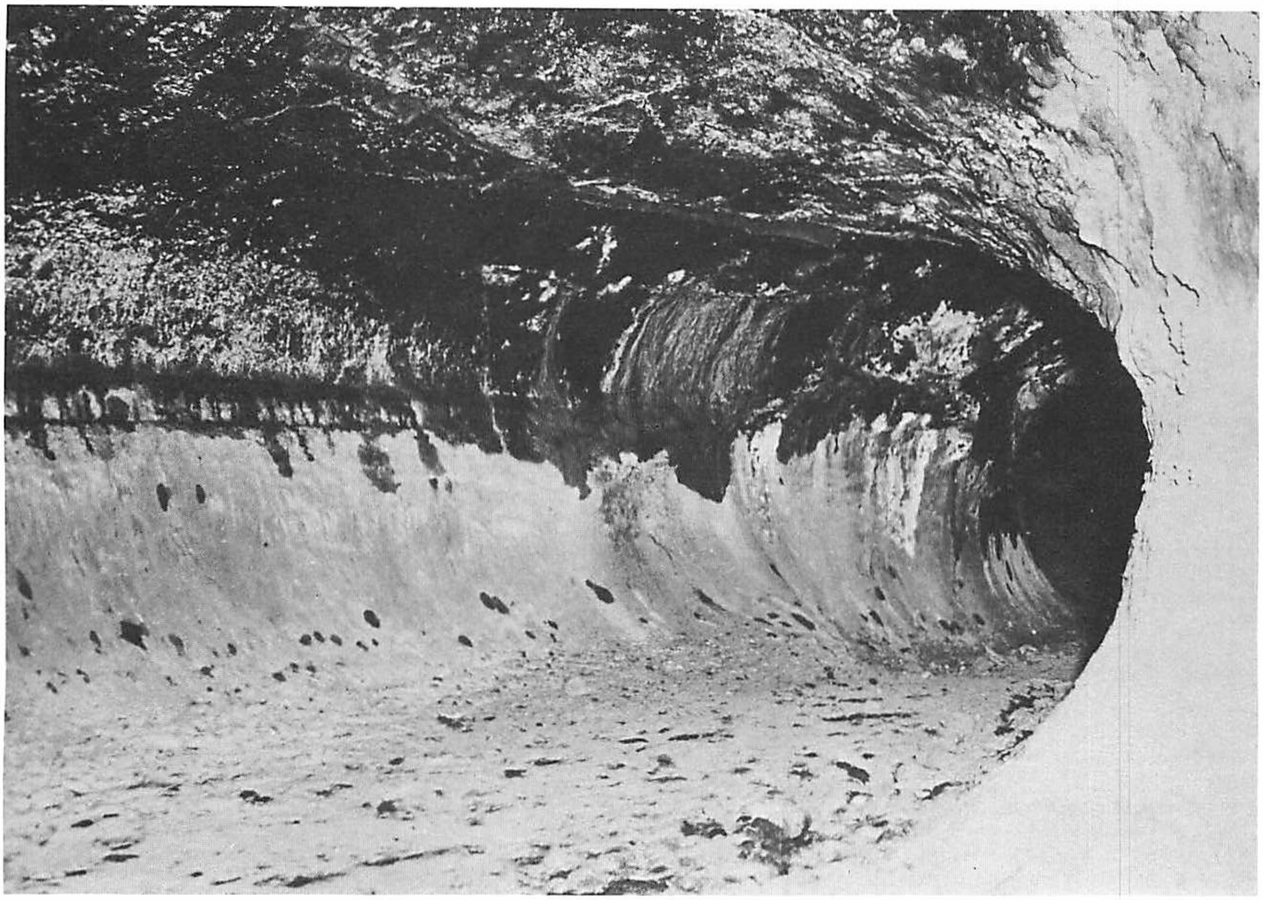

Fig. 10 Valentine Cave, Lava Beds National Monument, California. A typical lava tube, of circular cross section, formed in olivine basalt. A flow line is seen on the opposite wall and a partial filling remains solidified as the floor. Tube height is about 2 m. (Photography by National Park Service, 1966.)

ing about 0.2 mm in length; and those averaging about 0.6 mm in length, although sometimes as long as 1.5 mm.

Recently, Renault (1968) has undertaken a chemical and petrographic study of the Holocene basalts of New Mexico and has furnished the following X-ray fluorescence analysis for a specimen of the McCartys basalt taken in the vicinity of Section 15, T9N, R10W, NE of the mapped area. We believe that this analysis is probably representative of most of the olivine basalts of the Bandera lava field.

SiO_2 .. 49.93%	FeO 9.25%	Na_2O .. 2.89%
TiO_2 .. 1.38	MnO 0.17	K_2O 0.75
Al_2O_3 16.62	MgO 8.45	P_2O_5 .... 0.25
Fe_2O_3 1.54	CaO 8.90	

Although the McCartys basalt is of the type in which lava tubes form, tubes appear absent from the McCartys flows. Instead, collapse depressions have formed. The reason may be that the gradients were too slight to allow complete evacuation of tunnels. We found that the gradient at the crest of the McCartys flows between Interstate 40, E of Grants, and the top of the vent, in Sec. 28, has a mean slope of 0° 21′, lower than any value found among the Bandera flows where tubes abound.

4. *The Lava Tubes*

Lava tubes begin as fluid transport conduits providing a connection from the source to the frontal (lower-elevation) portions. The tubes are found to have nearly circular cross sections in which newer lava may or may not have flowed after the original drainage. The circular shape of the interior of such a tube is illustrated in Fig. 10.

Eight distinct tube systems were mapped in the Bandera lava field (Fig. 11). Groups of tubes as extensive as these are not common but smaller systems have been reported at several locations in the western United States, Alaska, Hawaii, Australia, Iceland, and in East Africa. The only two recorded observations of lava-tube formation are cited by Wentworth and MacDonald (1953, p. 45), in which H. T. Stearns in 1935 and G. A. MacDonald in 1942 observed the development of small lava distributory tubes on Mauna Loa.

a. *Mechanism of tube formation.* Two modes of

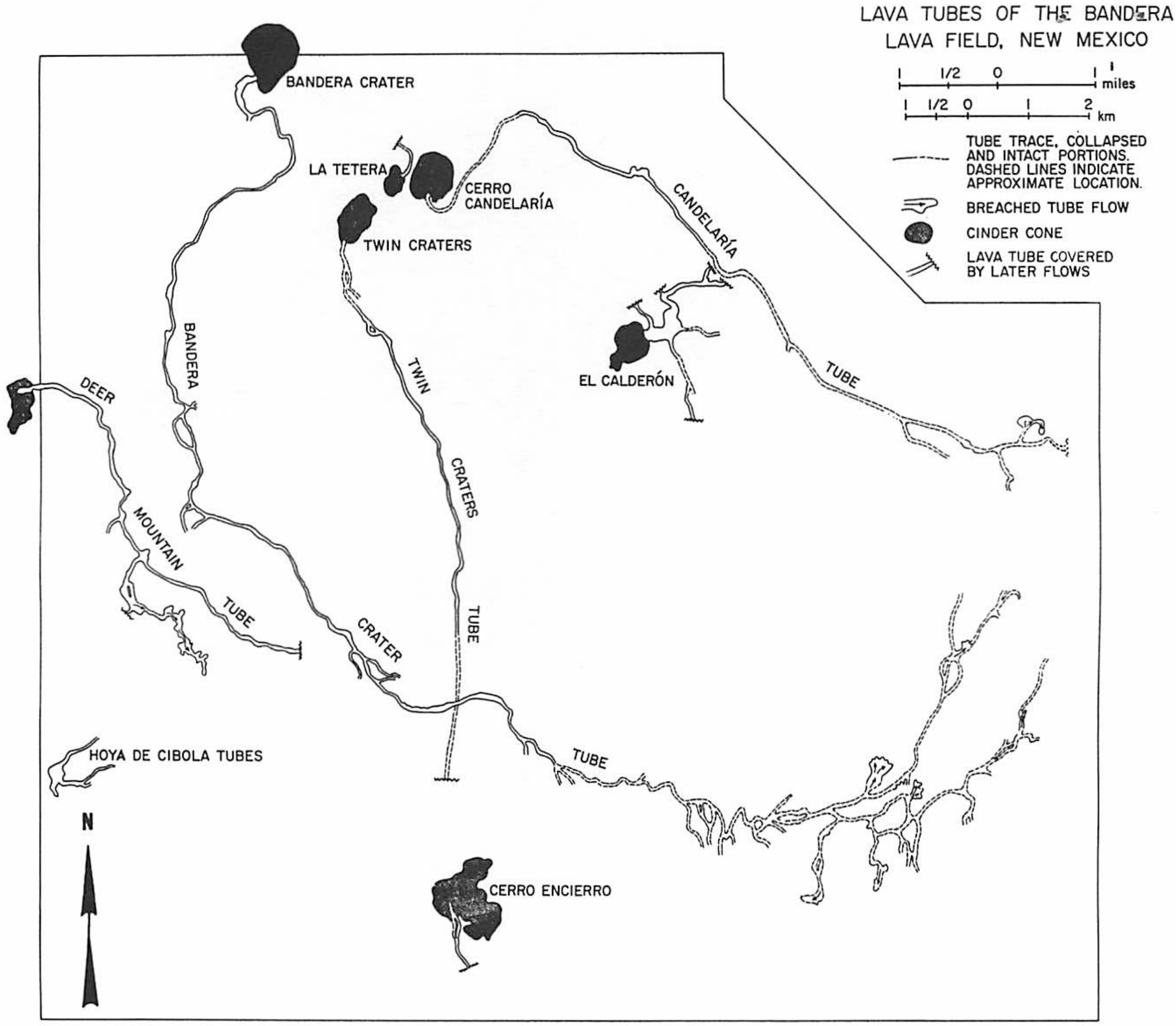

Fig. 11 The lava tube systems of the Bandera lava field.

lava-tube formation satisfy two distinct sets of circumstances. Wentworth and MacDonald (1953) described an open lava channel developing a crust while flow continues beneath. This creates a circular tube which may remain intact after drainage of the lava. Such tubes have been reported to range from decimeters to more than 6 m in diameter. The process involves continuous movement of lava from higher to lower elevations and may apply only to tubes of a few hundred m in length.

A second mode has been proposed by Ollier and Brown (1965). We have modified it slightly and believe that it now adequately explains the formation of very long tube systems (28 km in the Bandera Lava field). Ollier and Brown concluded that the process observed by MacDonald for the formation of a roof over the Mauna Lao channels inadequately explains the larger tubes. They note that the walls of lava tubes in the Western District of the State of Victoria, Australia, always exhibit a succession of flow layers. These layers could have formed through shear between horizontal layers of fluid lava possessing different viscosities from differential cooling. The layered effect was probably enhanced as horizontal and vertical cooling joints were formed (Fig. 12).

The Ollier-Brown explanation calls for the formation of cylindrical bodies of more fluid lava within the larger moving mass of basalt. These conduits are believed to be normally rather narrow, though they could sometimes coalesce into larger fluid bodies. The hydrostatic pressure of the molten rock against the solidifying flow front finally exceeds the tensile strength of the cooling rock, allowing streams of fluid lava to form extensions of the flow front. These new flow units are supplied by lava moving out of the conduits. As long as the supply is sufficient to replace the lava pouring out of the rupture, a mobile cylinder is present. When the supply ceases, the cylinder drains to form the open tube. We believe this explanation also applies to the formation of the very long tubes of the Bandera field.

Lava tubes remaining entirely filled upon solidification have been reported by Wentworth and MacDonald (1953) in Hawaii, by Waters (1960) in the Tertiary basalts of the Columbia River Plateau, and by Ollier and Brown (1965, Plate II) in olivine basalt at Byaduk, Victoria.

b. *Hydrodynamic considerations.* The parameters governing formation of lava tubes are not fully known. The hydrostatic pressure (P) exerted by the mobile cylinder is proportional to the elevation difference, $\triangle h$, between source and flow front: $P = \rho\triangle h$, in which ρ is the density of the fluid lava. This, of course, neglects friction, and thus gives a gross upper limit to the pressure. If $\rho = 2.63$ gm/cm^3,* the maximum hydrostatic pressure developed prior to formation of the open tube would be 78 kg/cm^2 for $\rho\triangle h = 296$ m as found for the full length (28.6 km) of the tube. This would be more than sufficient to produce rupture of the face of the flow. Tensile strength of fresh, unweathered basalt, free from structural discontinuities, is commonly about 10% of its uniaxial *compressive* strength of 1,500-3,000 kg/cm^2 (Deere and Miller, 1966); Farmer (1968, p. 57) reports *tensile* strengths of 100-300 kg/cm^2. These values are for room temperature, and since rock strength diminishes with increasing temperature, a pressure of 78 kg/cm^2 is expected to produce tensile failure of cooling basalt, especially at the front of the flow where jointing and fracturing by contraction occur. (In fact, secondary flow units are observed in basaltic flows stemming from primary units with $\triangle h \sim$ 20-30 meters.)

c. *Contrast with fluvial systems.* Although lava tubes may develop sinuous bends analogous to meanders in streams, they are not otherwise comparable. River meanders are the result of a stream bed attaining near-equilibrium conditions over parts of varying gradients. During the approach to equilibrium, the stream develops a series of sine curves as the gradients are reduced through channel lengthening. The position of the stream bed and the rate of development are governed by velocity and discharge, as well as by variations in rock hardness.

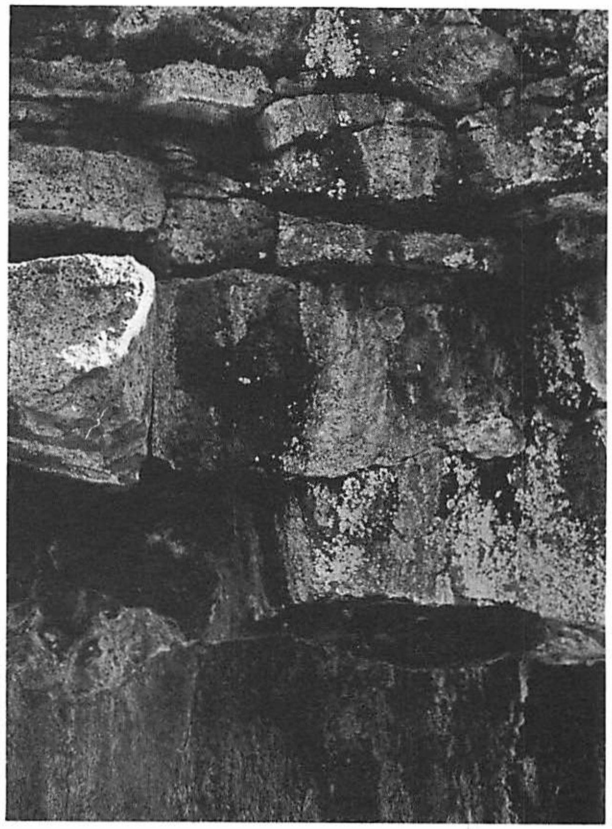

Fig. 12 A series of flow layers exposed in the wall of a collapsed segment of the Bandera Crater lava tube. The central layer is 0.5 m thick and shows the characteristic features of a flow layer: definite upper and lower contacts, greater vesicularity at the top, vertical columnar jointing, and gas pocket partings in the horizontal plane.

Meanders apply to *open channel systems*, and require long periods of time to form.

By contrast, lava tubes appear to form rather rapidly from a conduit located to ensure *maximum gradient for the flow.* The conduit as such has a relatively short life, and the complicating effects active in stream morphology are absent. Lava tube morphology on a grand scale largely follows the *topography* on which the flow progresses though it will be affected by the quantity of lavas flowing through the conduit (as well as its velocity which in turn depends on both topography and quantity).

d. *Sinuous bends in lava tubes.* Somewhat irregular sinuous bends developed at various locations along three of the Bandera lava tubes (Fig. 13). Although we propose a different origin, we have employed Leopold, Wolman, and Miller's (1964, p. 295) description of river meanders. Our data appear in Table I; the individual sinuous bends are illustrated to scale in Fig. 14. Though lava-tube bends are normally formed around topographic

* Taken from Skinner (1966, p. 93) for basalt at 1250°C. In the temperature range of free flowing basalt (900–1200°C) the density will not vary appreciably for uniform chemistry and volatile content.

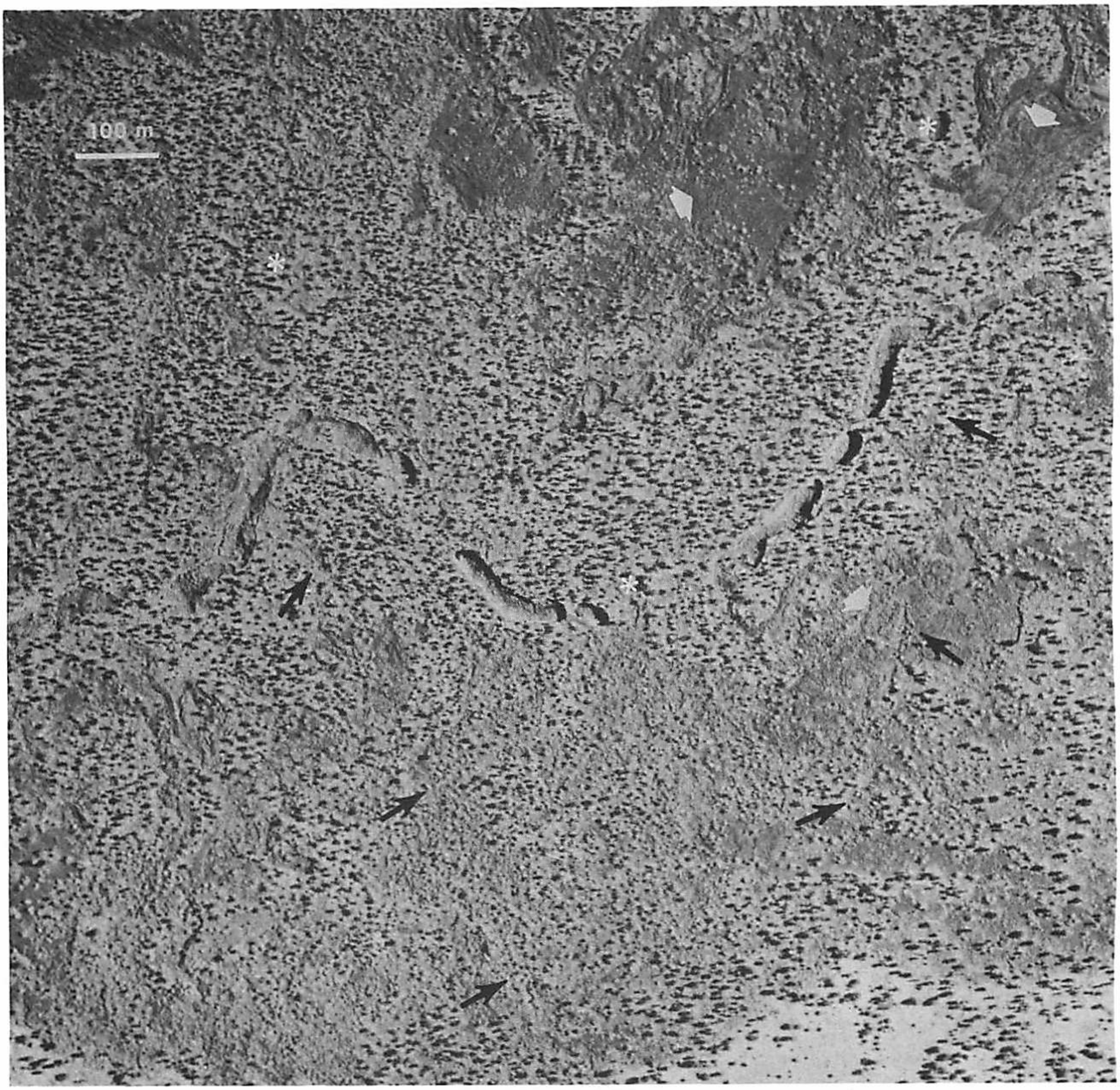

Fig. 13R Sinuous bends along the Bandera Crater lava tube. Compare with Fig. 1A-1B which show lunar rilles with alternate intact and collapsed segments. Asterisks mark the positions of chimney vents along the tubes. Large patches of aa (white arrows) issued from the tubes and from fissures. Two fault linears are indicated by black arrows. (North is to the left; photos courtesy U.S.F.S.) (Stereo with Fig. 13L looseleaf.)

TABLE I
MEASUREMENTS OF SINUOUS BENDS
(See Fig. 14)

LAVA TUBE	D	λ	α	MRC	W
Bandera Crater					
site 1	0.0 — 1.7 km	1100 m	444 m	323 and 418 m	19 — 34 m
site 2	7.3 — 8.5	817	514	114 and 400	19 — 42
site 3	7.5 — 9.2	1480	42	247 and 418	27 — 49
site 4	12.5 — 13.0	475	104	171 and 323	57 — 60
site 5	13.0 — 14.4	1000	114	266 and 400	23 — 30
Deer Mountain					
site 1	1.0 — 1.4 km	684 m	228 m	76 and 532 m	19 — 49 m
site 2	1.7 — 2.9	874	133	360 and 400	15 — 60
El Calderón					
site 1	1.2 — 1.8 km	420 m	236 m	91 and 130 m	45 — 78 m

D = distance from source.
λ = mean length of bend.
α = amplitude of bend, as measured above and below the length line (Fig. 14).
MRC = mean radius of curvature.
W = channel width range for the bend.

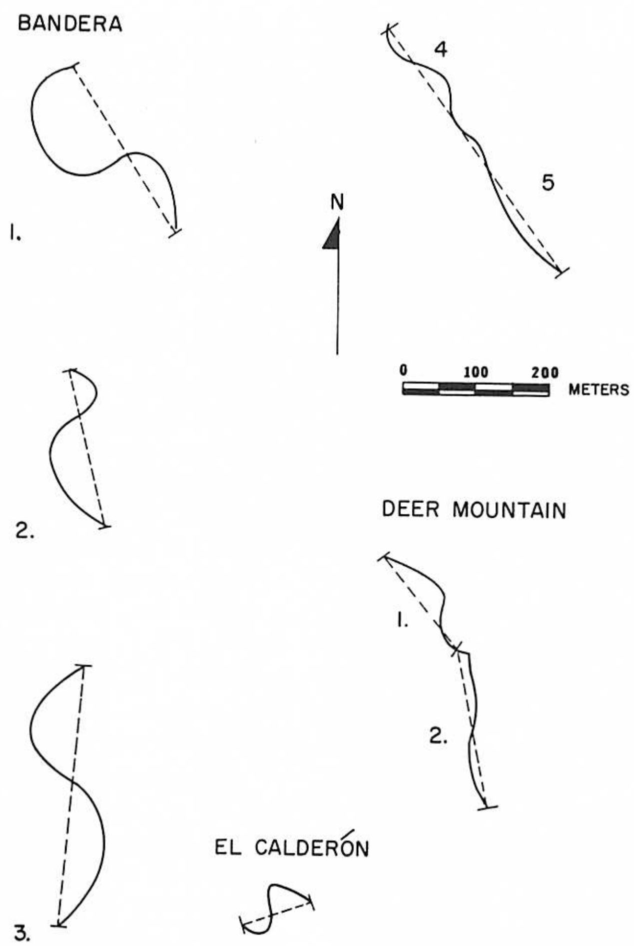

Fig. 14 Sinuous bends along the Bandera lava tubes. The dashed lines are the mean lengths listed in Table I.

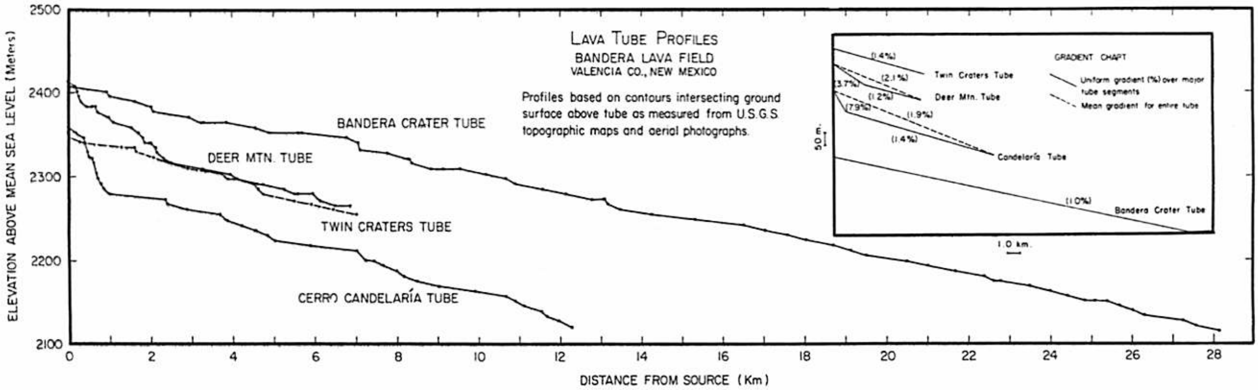

Fig. 15 Gradient profiles of the Bandera lava tubes.

irregularities in the path of the flow, some bends may result from the juncture of two adjacent tubes. Portions of each of the two tubes may remain intact and not be visible at the surface; and the bend is created by the combined collapse of portions of both tubes.

e. *Importance of pahoehoe lava.* The formation of any one lava tube depends upon the chemistry, temperature, and volumes of lava, as well as the underlying topography. Lava tubes almost always form in olivine basalt, and usually only in pahoehoe. To our knowledge, the only location at which *collapse depressions* have formed in aa is on the Carrizozo lava field of Lincoln Co., New Mexico, but there pahoehoe underlies the aa (Kuiper *et al.*, 1966, Figs. 36-44).

The question remains as to which parameters control the production of either pahoehoe or aa. Washington (1923) considered that pahoehoe crystallized largely after surface exposure and that latent heat of crystallization helped to maintain fluidity. Emerson (1926, p. 109) studied the problem in detail and was unable to detect any crystal differences in thin sections of pahoehoe and aa. Emerson agreed with Washington that viscosity may be dependent upon the degree of crystallization attained in the magma at the time of its extrusion. MacDonald (1953) made the important observation that pahoehoe and aa can usually be differentiated *only at the ground surface and that below this level the structure and texture of the rock types seem identical.*

It is also well known that pahoehoe flows often become aa flows farther away from the source (Jones, 1943; MacDonald, 1953). Viscosity must therefore be the primary parameter accounting for the surficial lava type.

We have noted that aa lavas also spread from fissures on the surface of the flow (Figs. 24 & 26, below) as well as from breaches in the Bandera Crater tube. Similar aa units are found as breached flows in the Twin Craters and Hoya de Cibola lava tubes. Due to their original high viscosities, these lavas did not spread as widely as the pahoehoe.

Both aa and pahoehoe lavas are present on the Bandera lava field. Some flows in the Bandera Crater basalts are entirely aa, while *the lava tubes are formed entirely under pahoehoe surfaces.* Although Renault's chemical analyses are not yet available,* we assume that chemical and temperature differentiations of the lavas at the source and within the flows do affect the production of pahoehoe vs. aa lavas. MacDonald (1953) concluded that aa formation is aided by loss of dissolved gas and a greater degree of crystallization at the time of extrusion. This may be the case especially for aa flows stemming from ruptures in lava tubes.

f. *Gradient of lava tubes.* The authors determined gradients for longitudinal profiles of the lava tubes from published and manuscript U.S. Geological Survey 7½ minute topographic quadrangle maps (Fig. 15). The tubes were carefully mapped on the quadrangles from aerial photographs and elevations derived for various points where the tubes are exposed. The profiles are remarkably constant over distances of hundreds of m to several km. Appreciable changes in gradient occur only at points where the *underlying* topography changes slope.

The single mean gradients of 0° 35′ to 0° 48′ for Bandera and Twin Craters tubes are more meaningful than the two mean gradients for the Deer Mountain and Cerro Candelaría tubes which were

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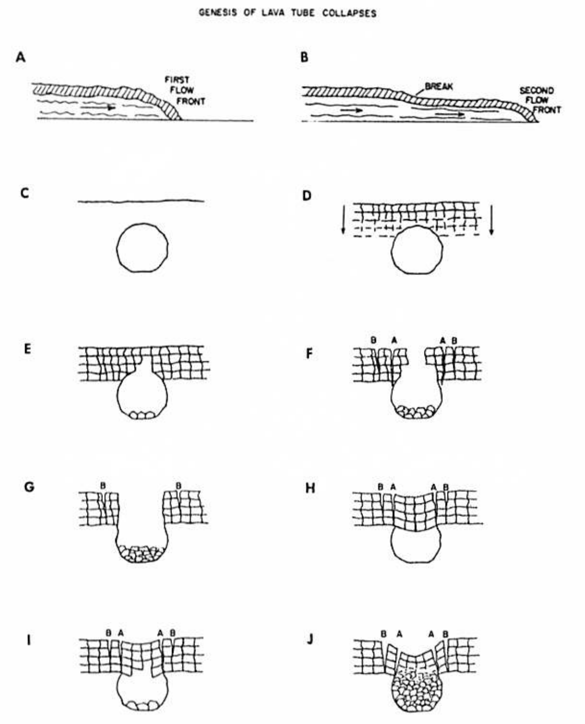
* Dr. J. R. Renault, of the New Mexico Bureau of Mines and Mineral Resources, Socorro, has undertaken a chemical and petrographic study of the Holocene basalts of New Mexico. He has collected representative samples from the Bandera lava field and provided us with an analysis of the McCartys basalt (Sec. 4).

influenced by slope changes and which also have buried extremities. These two tube systems would probably approach the lower limit of 0° 35′ if the gradients were known for their complete extents. The derived gradients are tabulated in Table II, to which may be added the McCartys flow, which lacks tubes, with only 0° 21′. This suggests *a lower limit for tube formation* of about one half degree.

g. *Mechanism of tube collapse.* We believe that tube failure began almost immediately after formation and that portions of the tubes underwent complete collapse in periods as short as a few weeks. Some small surficial flows may have come from breaks in the tubes (e.g. the aa flows of the Bandera Crater tube), but these did not constrain the flow while the tubes were active.

A sequence of formation and collapse of the lava tubes is depicted diagrammatically in Fig. 16



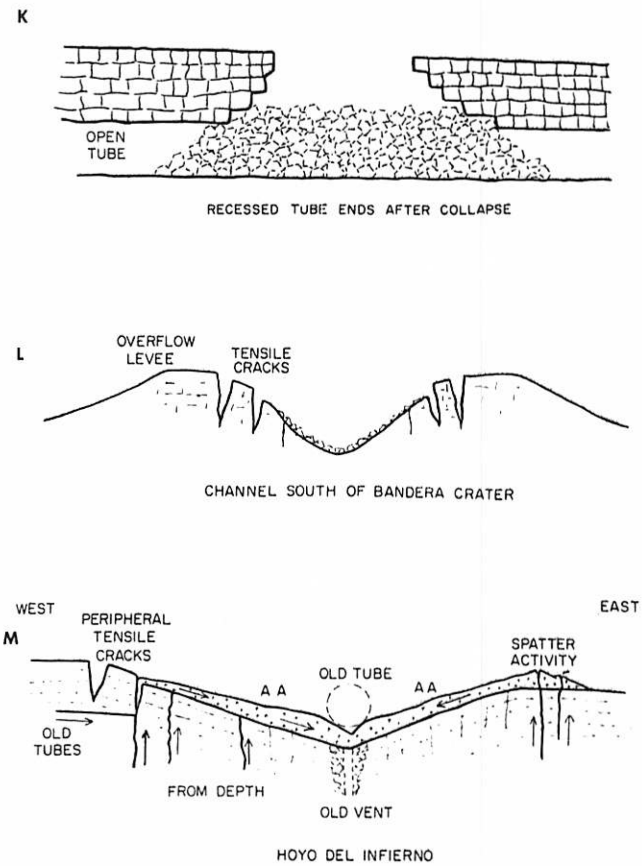


Fig. 16 A. As the flow advances, the outer surface cools and solidifies, while the interior portions remain molten and fluid.

B. Hydrostatic pressure forces the molten interior against the immobile crust at the flow front, forming new flow units and draining lava from the interior.

C. Evacuation of lava creates a mobile cylinder of lava shearing a contact with the surrounding, more viscous lavas.

D. Differential cooling generates vertical joints which intersect the horizontal planes formed by laminar flow within the massive lava flow.

E. Joint cracks moving from the surface downward reach the upper surface of the tube and when contraction in the horizontal direction is sufficient, blocks begin to spall from the roof of the tube. Some plastic deformation may also occur along the upper interior surface of the tube. Shear planes may develop along the lower interior surface in areas in which heat dissipation has occurred to a lesser degree and where the rock may still be plastic.

F. Primary (A) and secondary (B) tensile fractures form in the roof arch and begin to outline a peripheral failure of the tube.

G. Final failure occurs along primary tensile fractures and the cycle is complete. The process may be assisted by seismic activity of a volcanic nature.

H. OR: Plastic deflection of the roof area results in deformation of the tube cross section.

I. Spalling then occurs.

J. The tube is filled with rubble and tilted slabs of basalt. In some instances this rubble fills the collapse pit to a point above the original roof line and the lava tube is made inaccessible.

K. Cave-like recesses found at the ends of many collapse pits along the lava tubes.

L. Diagrammatic cross-section of the channel on the Bandera Crater lava tube S of the crater. (See also Fig. 17.)

M. Diagrammatic cross-section of the Hoyo del Infierno subsidence pit. The interior of the pit is now largely covered with aa lava extruded through fissure vents and tensile cracks onto a surface of tilted pahoehoe slabs. (See also Figs. 25A and B.)

TABLE II
LAVA TUBE GRADIENTS

Tube	Upper Segment		Lower Segment		Mean Gradient	
	Deg.	Percent	Deg.	Percent	Deg.	Percent
Bandera Crater					0°35′	1.0
Cerro Candelaría	4°31′	7.9	0°48′	1.4	1°05′	1.9
Deer Mountain	2°08′	3.7	0°41′	1.2	1°12′	2.1
Twin Craters					0°48′	1.4

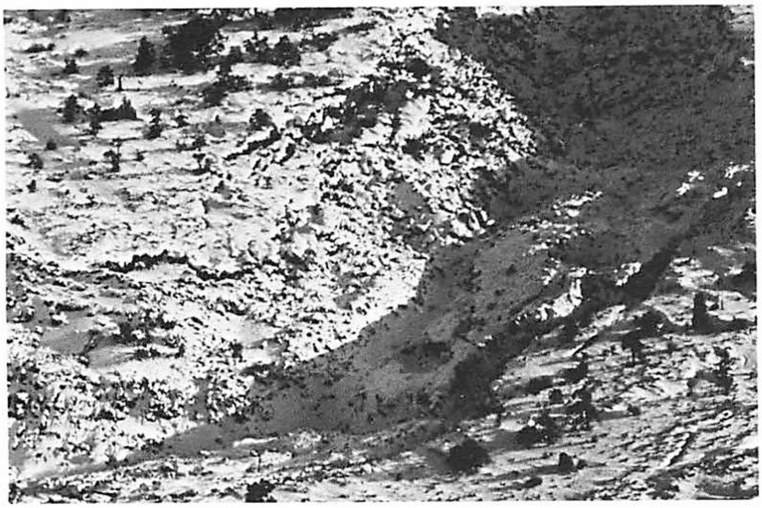


Fig. 17 Aerial view of the open channel about 0.5 km S of Bandera Crater. The rubble-filled channel is about 20 m deep and 150 m wide between the parallel tensile fractures along its upper flanks.

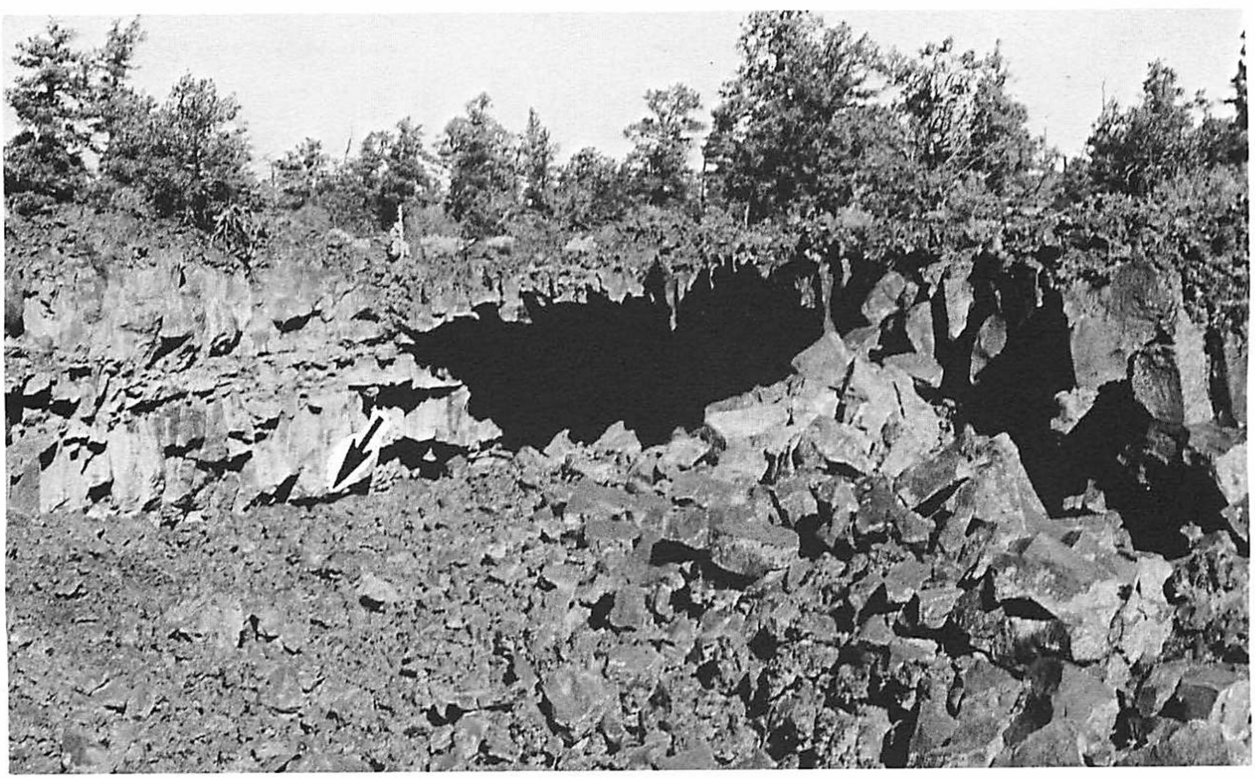


Fig. 18R Large straight-sided collapse pit on the Bandera Crater tube about 0.95 km S of the La Verruga spatter-cones. Scale is given by a 2-m range board placed above an aa mantle averaging about 0.5 m in thickness. The arrow denotes the approximate position of the original tube roof, lying at a depth of about 6 m in dense basalt. The tube is not exposed and the loose blocks filling the depression have broken exclusively along columnar joints. (Stereo with Fig. 18L looseleaf.)

A-J. The wider collapse features such as the channel just below Bandera Crater (Figs. 16L and 17) and at El Embudito were probably formed by continuous open-channel flow following the initial local collapse. The large subsidence pits along the Bandera Crater and Hoya de Cibola lava tubes may have resulted from the local collapse of a group of parallel tubes. Some of the collapse rubble may have been removed through inactive vents (Fig. 16M). General subsidence of the roof may have been further assisted by magma withdrawal.

Collapsed lava tubes are usually straight-sided, partially filled with rubble (Figs. 17, 18), with arches of stable basalt at the ends. Exposed tube openings are not commonly found, even though the depressions often have cave-like recesses at their ends (Figs. 16K, 19).

Most collapse pits along the tubes are ringed by concentric tension fractures (Fig. 20). The interior fractures are between slabs of lava which have tilted inward, but there is usually one prominent boundary fracture which is wider, deeper, and more nearly continuous than those nearer the pit.

A chain of collapse features along a lava tube provides a definite trace (e.g. Fig. 13). Steep-walled depressions and wide collapse channels with tension fractures appear along with intact portions of the tube and thin arches or bridges across the tube. The original tube width may be enlarged considerably in collapse (Fig. 17) if the host rock is plastic or if the tube remains filled with lava long enough for plastic deformation to develop in the wall rock. After initial stoping has caused roof collapse, large blocks of wall rock may slump downward as the tensile fractures develop into near surfaces at depth, especially if the rock is still slightly plastic (Fig. 17). A long portion of this channel-type collapse occurs in the upper part of the Candelaría lava tube (Fig. 9). Fig. 9 also shows that changes in tube direction can be abrupt.

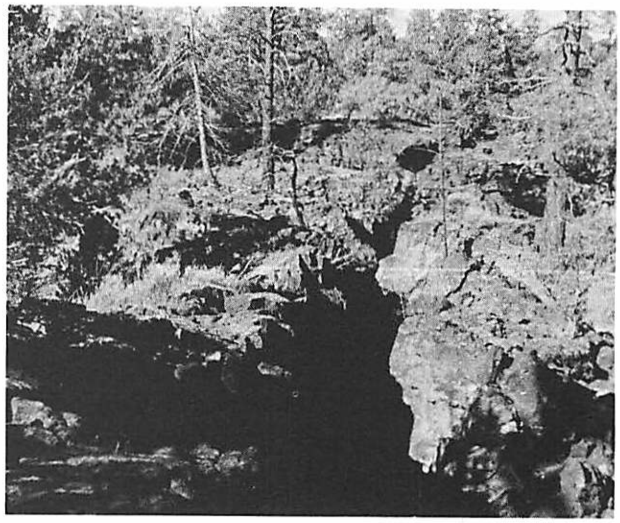


Fig. 20 Tension fracture typical of those found paralleling most collapse pits. The cracks lies about 10 m from the walls of the pit, is about 2 m wide, and is open to about 10 m. A thin mantle of aa overlies the pahoehoe.

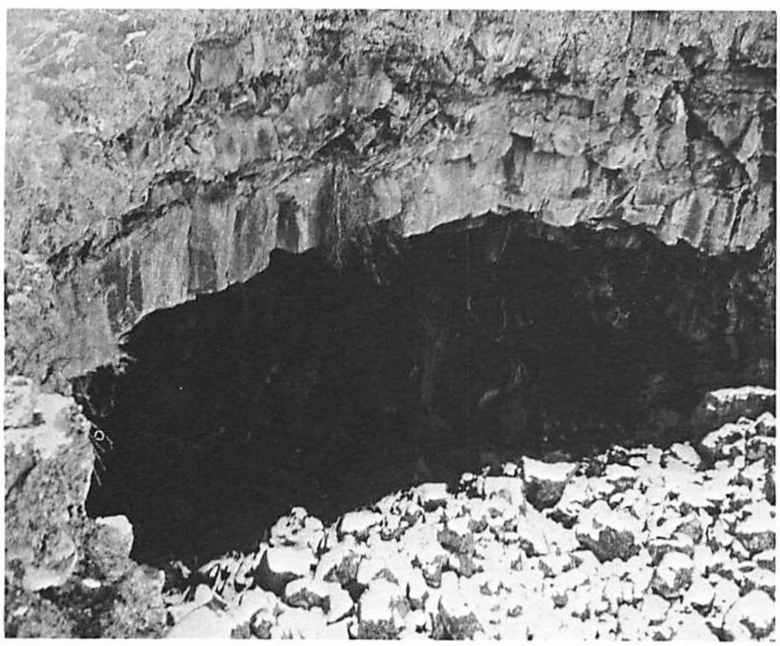


Fig. 19 Cave-like recess lying at the end of a collapse depression on the Bandera Crater tube. The original lava tube roof was located at a depth of about 6 m, or slightly below the surface of basalt blocks seen on the floor of the depression. Flow layers in the roof arch are about 1 m thick.

Many combinations of plastic and elastic failure can be observed along the Bandera lava tubes. One such combination is illustrated in Fig. 21, in which a plastically-deformed tube roof (center) is covered by a younger pahoehoe flow from spatter-cones.

Measurements were made of the dimensions of tube collapse features using steroscope and hand comparator. The error of measurement is estimated to be 3%. Figs. 22 and 23 present the data for collapse features on the four larger tube systems.

Fig. 22 plots the cumulative area of collapse against the distance from the source (observed or postulated). Discontinuities represent local conditions such as tube collapse due to faults or local vents. Fig. 22 shows moderate increase in the cumulative collapse area for $D < 5$ km, whereas at greater distances the increase is larger. This reflects increased tendency for collapse at greater distances from the source where the flows are thinner.

The Deer Mountain lava tube has anomalously large collapse pits in the first few km of its extent (Map, Fig. 4). The tube was formed on a gradient of as much as 2° along its upper extent, which would have resulted in increased flow velocity and the formation of a large tube close to the surface. The tube may have been further enlarged and weakened by erosion and melting due to a continuous flow within the tube, resulting in breaches which now appear as surficial flows S of El Carbunculó (indicated by arrows on the Map). The cumulative collapse area of the Deer Mountain lava tube increases at a higher rate than of the other three tubes, whose

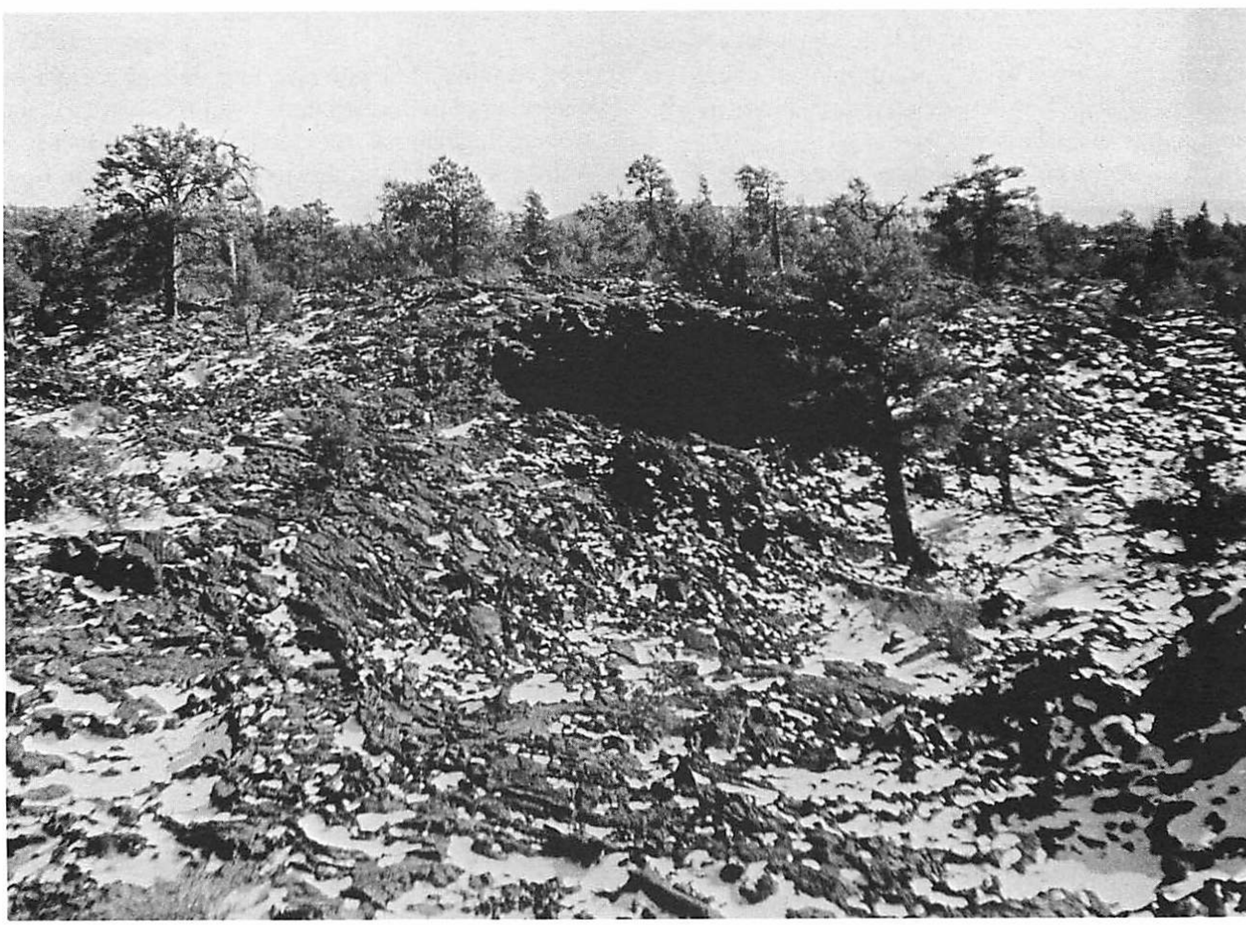


Fig. 21R Two-stage collapse of the Bandera Crater lava tube. Pahoehoe units from vents near the crater (about 0.4 km to the left) flowed into a plastically-deformed tube segment and were followed by the formation of a stope or chimney in the central middleground. (Stereo with Fig. 21L looseleaf.)

gradients are lower. This increased fraction of collapse suggests successive surges of lava within the tube.

The cumulative collapse area curve for the Bandera Crater lava tube shows a steep increase beyond 13 km. This trend is to be expected with distance, but it is also noted that it is not present in the other tubes, apparently because their total lengths are not exposed.

The *ellipticity of collapse features* was determined by the ratio of lengths versus widths of the pits. These data are collected in Fig. 23 where some

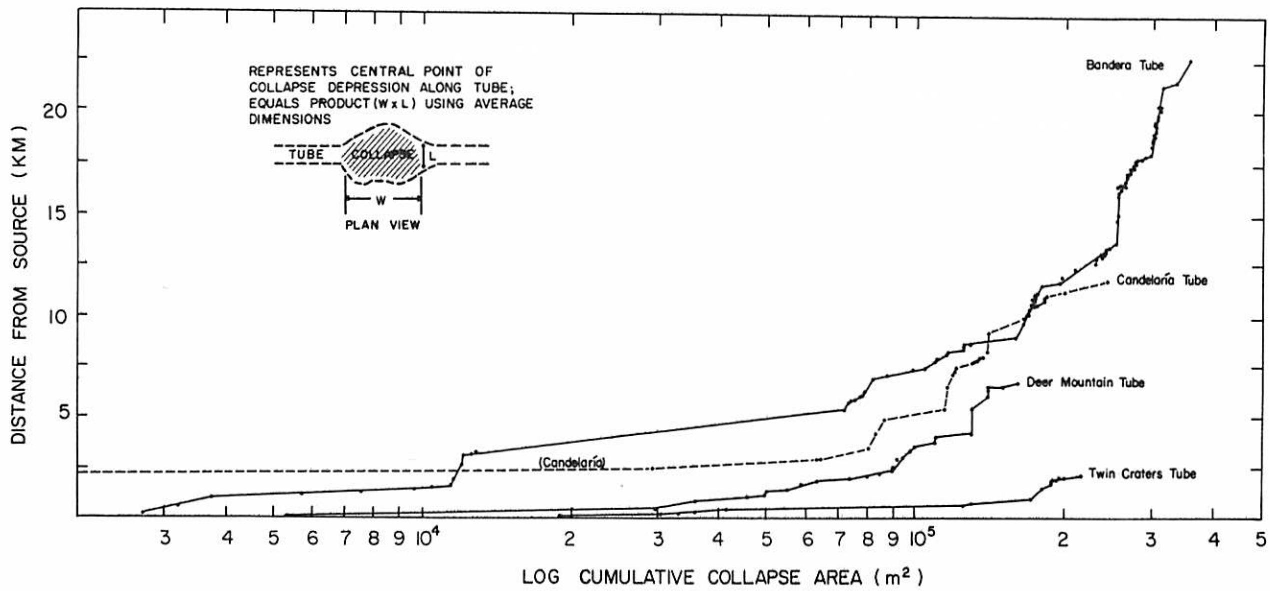


Fig. 22 Semi-logarithmic plot of cumulative collapse area versus distance from source for collapse pits along the Bandera lava tubes.

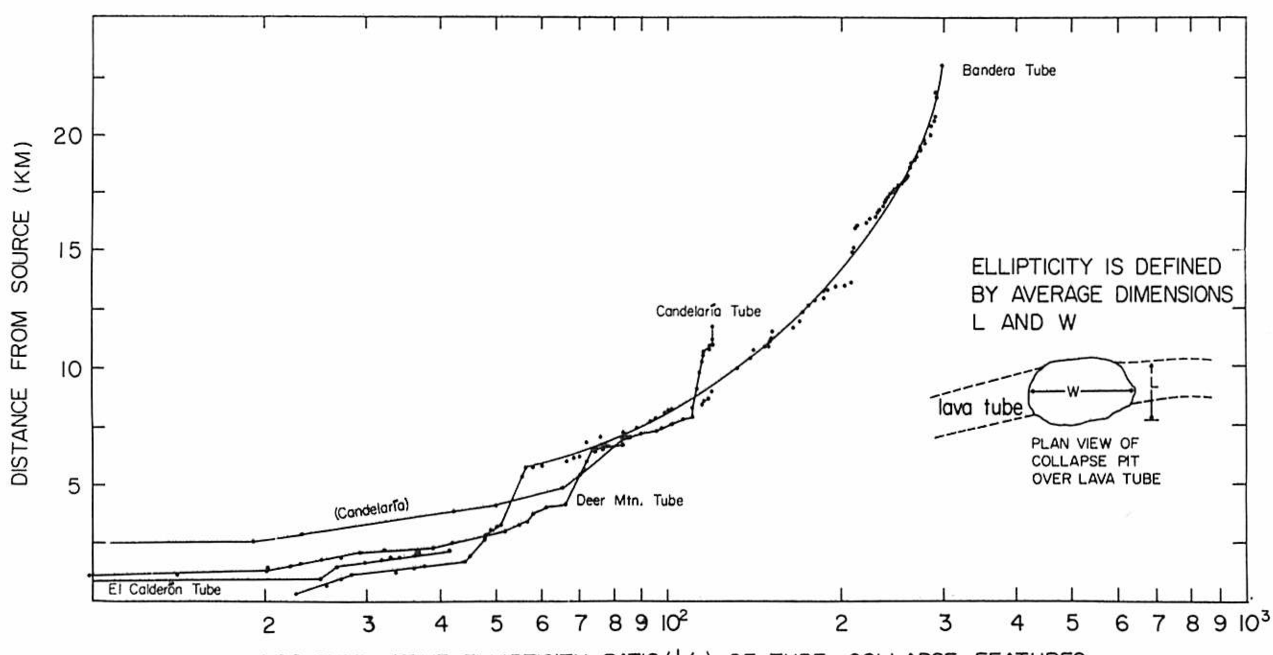


Fig. 23 Semi-logarithmic plot of cumulative ellipticity of collapse pits along the Bandera lava tubes.

discontinuities are caused by open channels along the tubes. The ratio, length to width, increases in the lower reaches of the tubes at D > 3-5 km, suggesting a correlation between ellipticity and tube depth. The greater the depth, the more stable a tube becomes with regard to both normal and shear forces. This stability may be adversely affected by faults or seismic activity. The intersections of tubes with faults generally occur at points of collapse. The original thickness of the roof of the Bandera Crater tube appears to have been 6-15 m; but this has been reduced to 1-2 m by spallation from the roof. To this thickness must be added the thin aa or pahoehoe flows that originated from nearby spatter-cones or from fissures in the lava tube itself (often < 1 m thick).

h. *The subsidence pits.* Hoyo del Infierno and Hoyo de Diablo are the sites of local widening and

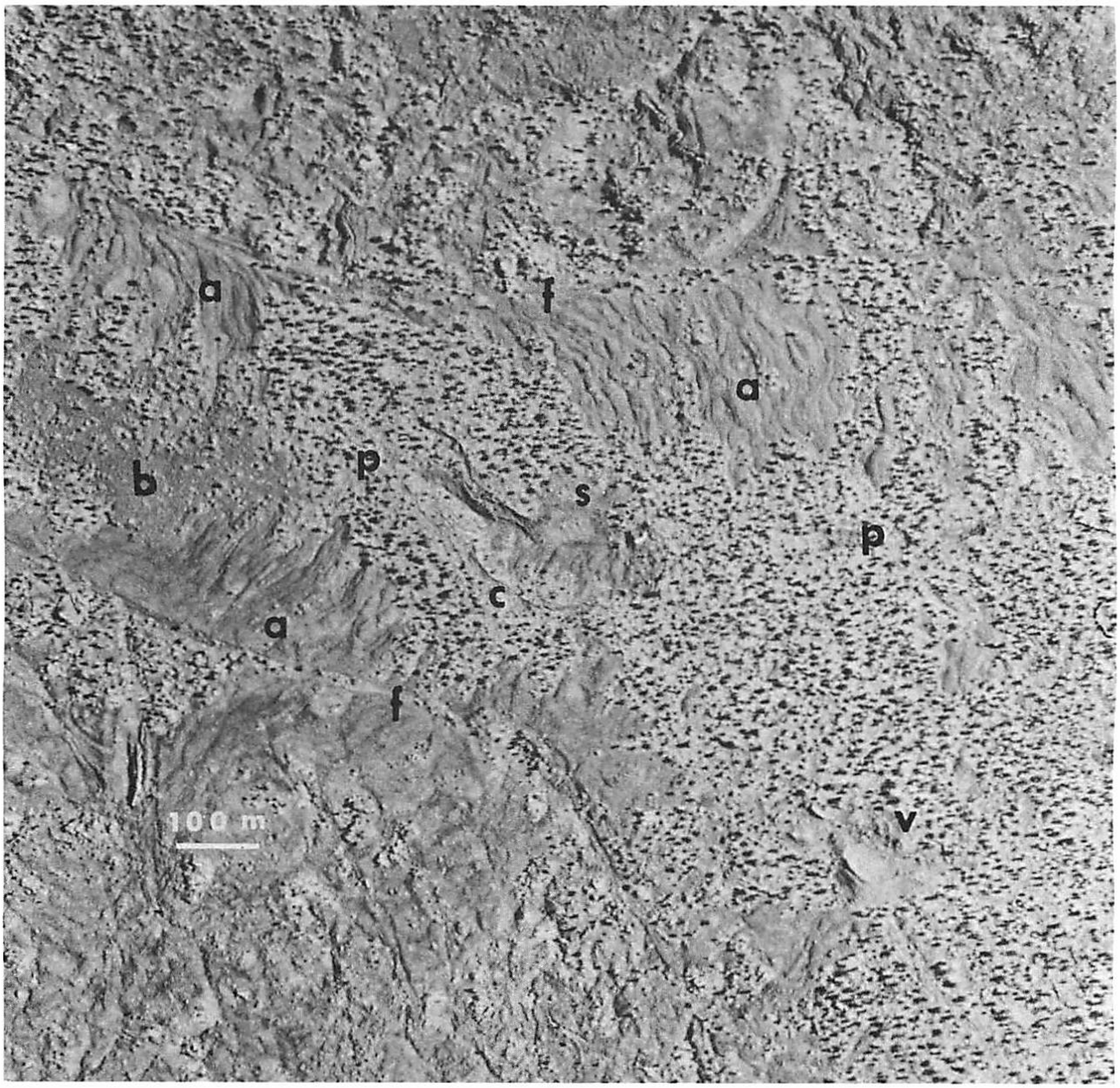
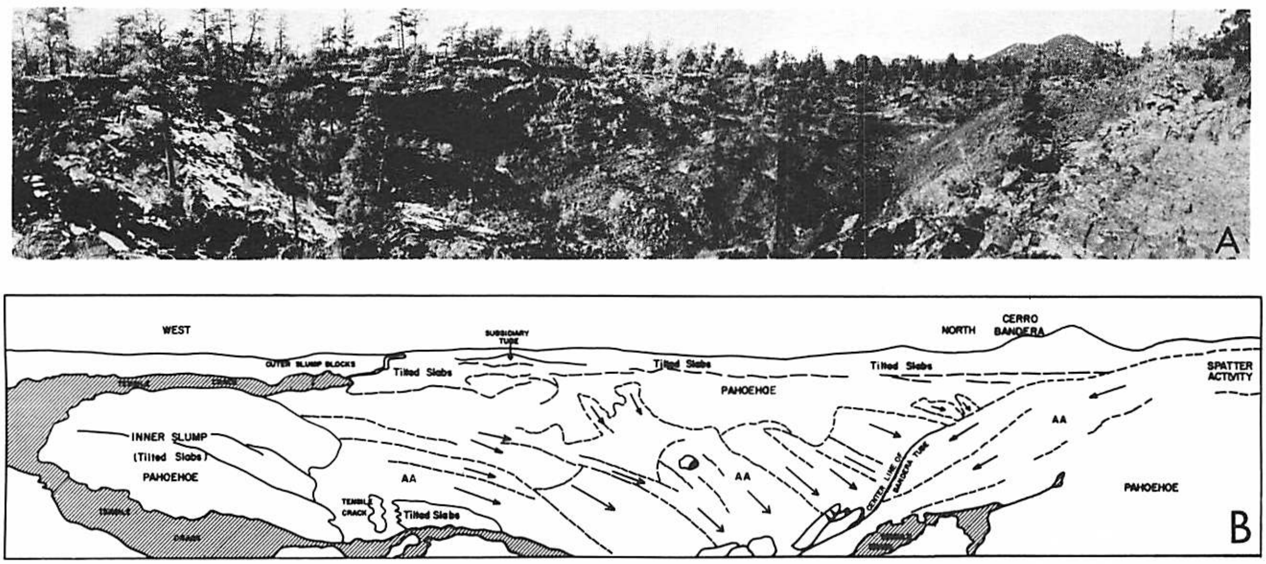


Fig. 24R Area surrounding Hoyo del Infierno. The subsidence pit terminates in a string of ordinary lava-tube collapse pits (p), is outlined by peripheral tension cracks (c), and is modified by aa flows (a) and later spatter activity (s). Localized eruptions have occurred at spatter-cone complexes such as La Verruga (v) and along fissures (f) and from breaches in the lava tube (b). (North is to the left; photos courtesy of U.S.F.S.) (Stereo with Fig. 24L looseleaf.)



Figs. 25A and B A. Panorama of the Hoyo del Infierno subsidence pit. B. Explanatory sketch showing features of the subsidence pit.

deepening of the Bandera Crater lava tube. The depth and width of the first are about 20 and 150 m, respectively, indicating that it was not formed entirely by tube collapse. The considerable depth suggests that some of the interior material may have been removed by local vents (cf Fig. 16M). The unusually large width may have resulted from the coalescing and subsequent collapse of parallel tubes. Numerous fissure eruptions of aa partially obscure the course of the tube. Fig. 24 presents an aerial view of the area. A panoramic view of the pit and explanation are given in Figs. 25 A and B.

The axis of the pit connects with the collapsed lava tube at either end. As seen in Fig. 24, the pit is surrounded by peripheral tension fractures except in a portion of the east flank which is now covered by spatter-cones. This spatter activity has superseded the aa eruptions stemming from fissures on the flanks of the pit. The distinctive appearance of the aa tongue is shown in Fig. 26.

Hoyo del Diablo, also along the Bandera Crater lava tube, resembles Hoyo del Infierno. Another large subsidence pit, reproduced in stereo by Kuiper *et al.* (1966, p. 117), about 520 m long, 180 m wide, and 36 m deep, is located on the Hoya de Cibola lava tube, south of Deer Mountain (Sec. 3). Collapse features of this magnitude are not common.

i. *Other features.* Additional modifications have resulted from the overflow of collapsed tubes. This occurred at several locations, e.g. the channel S of Bandera Crater, a location further S and E at El Embudito, at Pie de Pájaro, and along the upper portion of the Cerro Candelaría tube (Fig. 9). Collapse was gradual and interior flow probably removed the rubble. Later surges in the flow topped the banks alongside.

Local chimney venting was found at several places along the Bandera Crater lava tube (Map). The vent shown in Fig. 27 is a small spatter-cone with a partially collapsed throat which has a lining of remelted basalt, produced by release of burning gases.

Lava tube tributaries are fairly common. The central tube occupies the crestline of the flow and branches may join at various angles. These branches were contemporaneous conduits and open tubes were formed by the drainage of their fluid contents through ruptures along the flanks of the main flow. There is no indication that the tubes cross paths. The lower extremities of some tube systems may be extremely complex.

The terminal area of the Bandera Crater tube was mapped largely from aerial photographs (Map), and is made up of many subsidiary tubes which formed in thin units near the margin of the flows. As breaks occurred at many places around the flank of the flow, these evacuating tubes joined with the central tube at its location along the crestline of

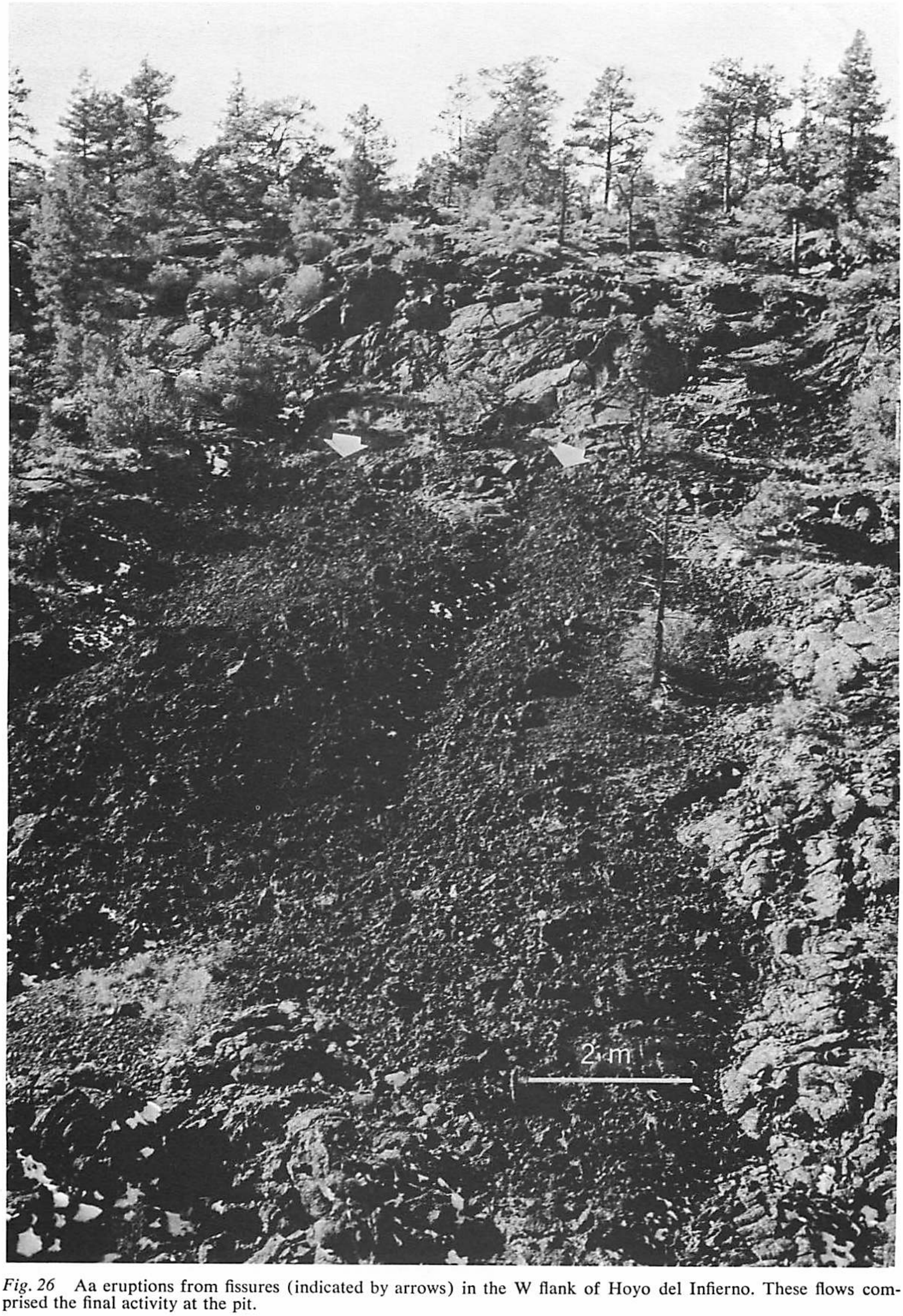


Fig. 26 Aa eruptions from fissures (indicated by arrows) in the W flank of Hoyo del Infierno. These flows comprised the final activity at the pit.

Fig. 27 Throat of partially collapsed chimney vent viewed from rim of the surrounding spatter-cone. The cave below was formed by the collapse of the lava tube which is now filled with rubble. The facade over the vent is a skin of remelted basalt produced by exit of burning gases.

the flow. Several examples of breached flow from the tubes in this area indicate that the lava tube was acting as a supply conduit at the time of collapse.

5. *Conclusions*

The lava tubes of the Bandera field formed in olivine basalts over gradients as small as 0° 35′, at locations where large amounts of lava flowed unimpeded over distances of 7–28 km. Tubes of comparable length did not form in the olivine basalts of the McCartys flow, but collapse depressions are abundant there. The mean gradient of the McCartys flow is 0° 21′, which suggests that the range of minimum gradients responsible for the production of long tubes in olivine basalts may lie between 0° 21′ and 0° 35′. Sinuous bends of varying regularity along some of the tubes probably formed when thicker portions of the flows moved around local irregularities or obstructions.

The lava tubes studied on the Bandera lava field all appear to have been formed by the development of mobile cylinders of lava in a cooler, more viscous host rock. These cylinders transported fluid lavas to the toe of the flow as long as the source provided a continuous supply. When this ceased, the tube probably drained rapidly. Collapse began shortly after formation of the tubes and continued with time. Later failure was mainly in the form of sloughing from the walls of the collapsed tubes. Much of this early and later collapse was brought about by faulting. In some instances, the totally-collapsed portions of the tubes have U-shaped cross sections and appear to resemble certain lunar rilles. A detailed comparison with lunar rilles awaits a closer mapping of representative cases.

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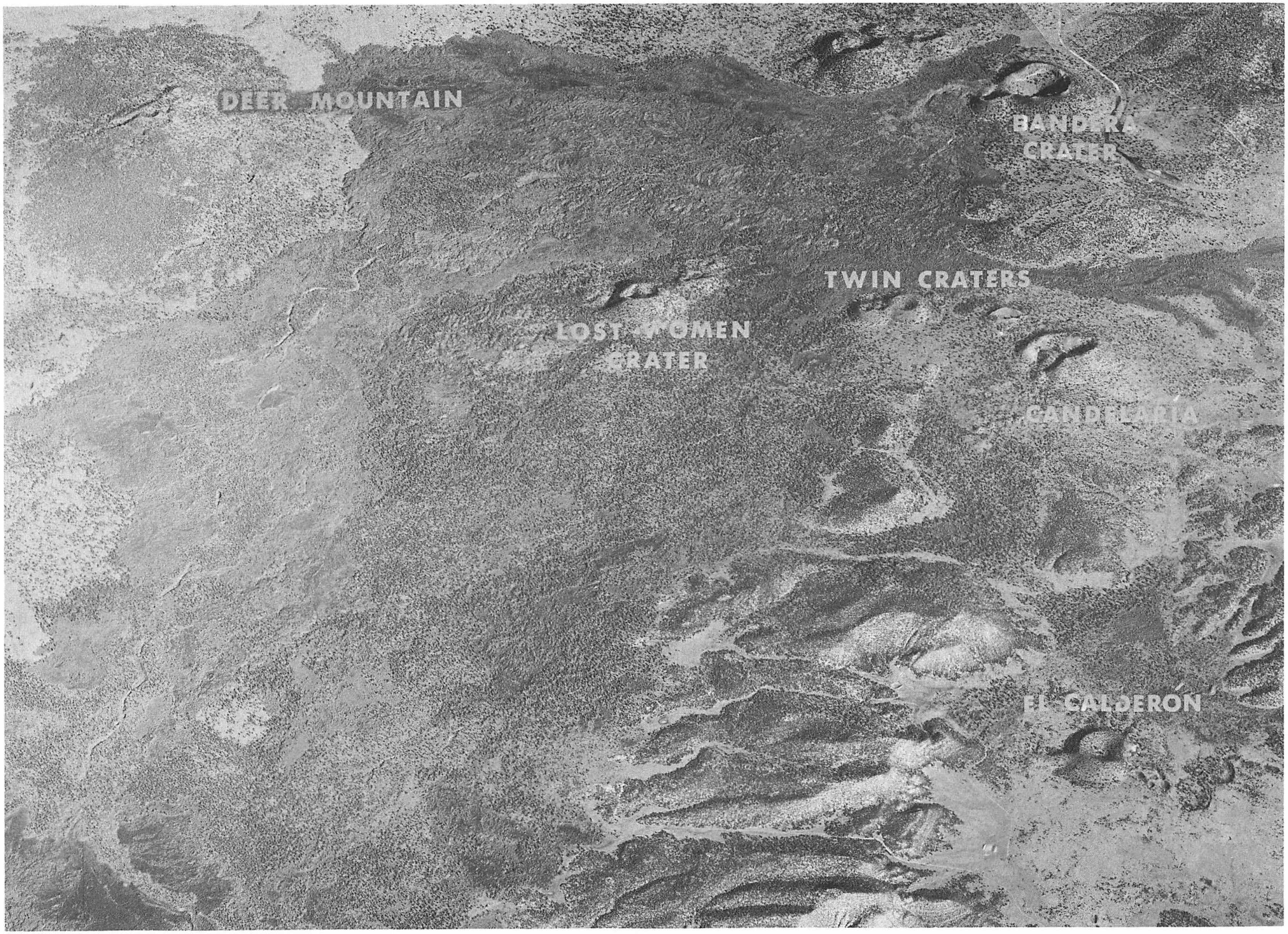

Low oblique aerial photograph of the Bandera lava field showing principal craters and collapsed lava tubes. The view is to the NW with foreground about 8 km across. (U.S. Govt. Photo, 1965).

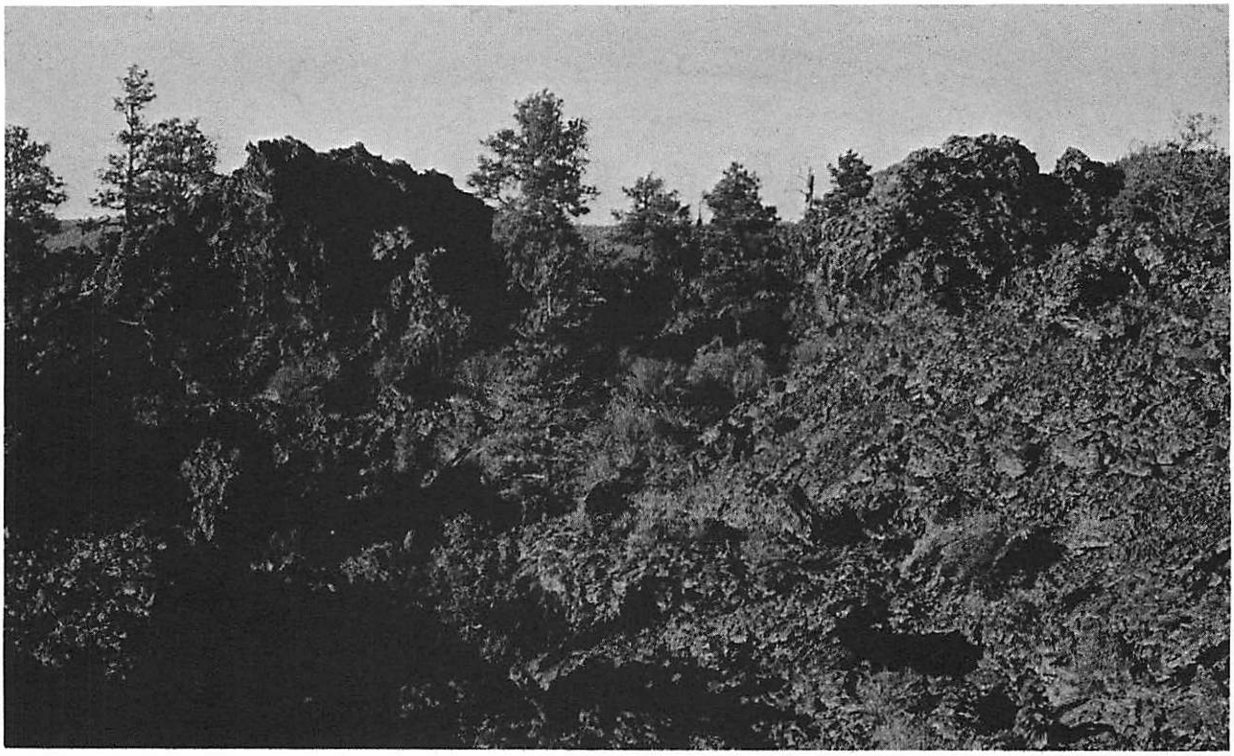

Fig. 3L

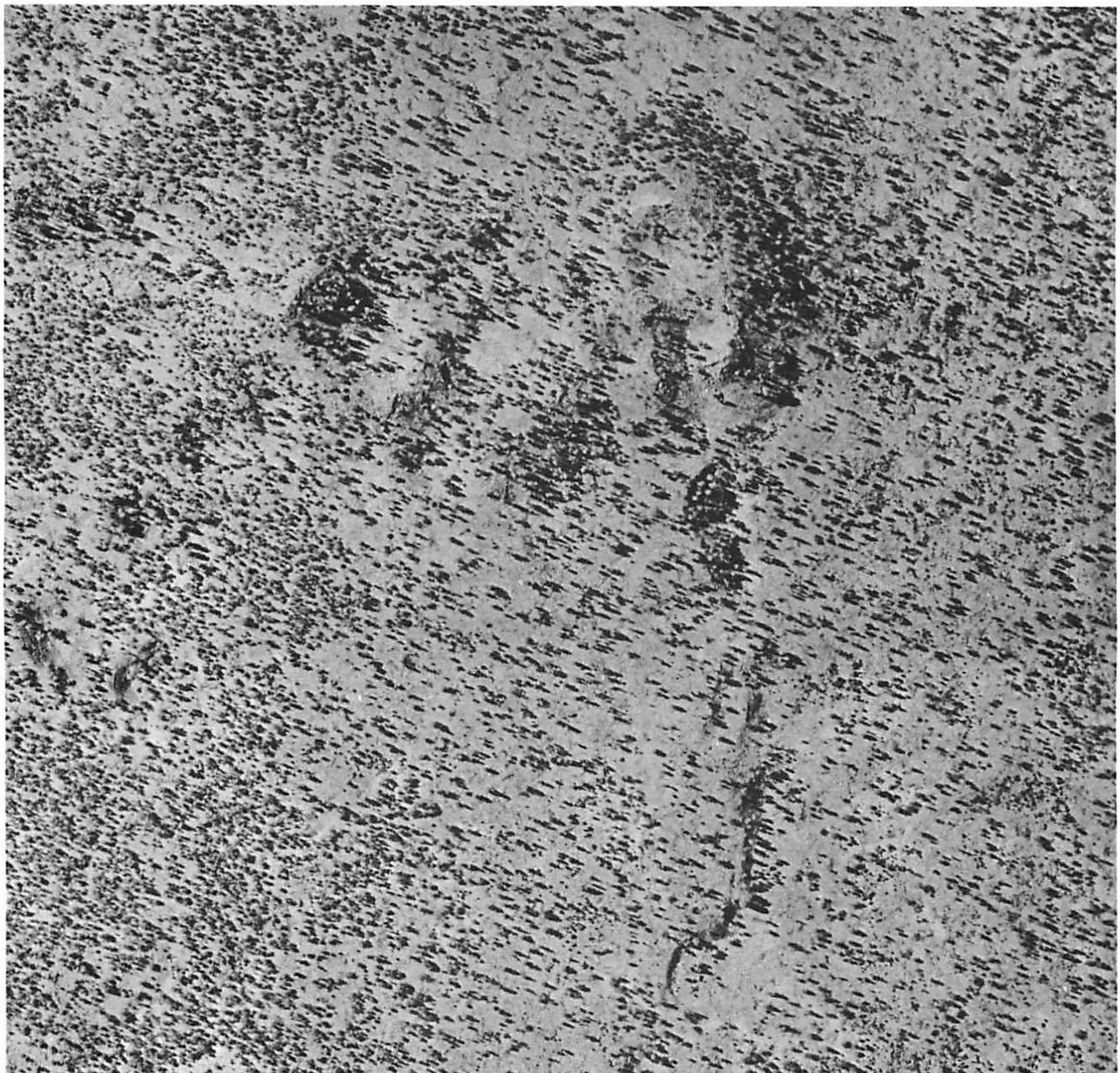

Fig. 4L

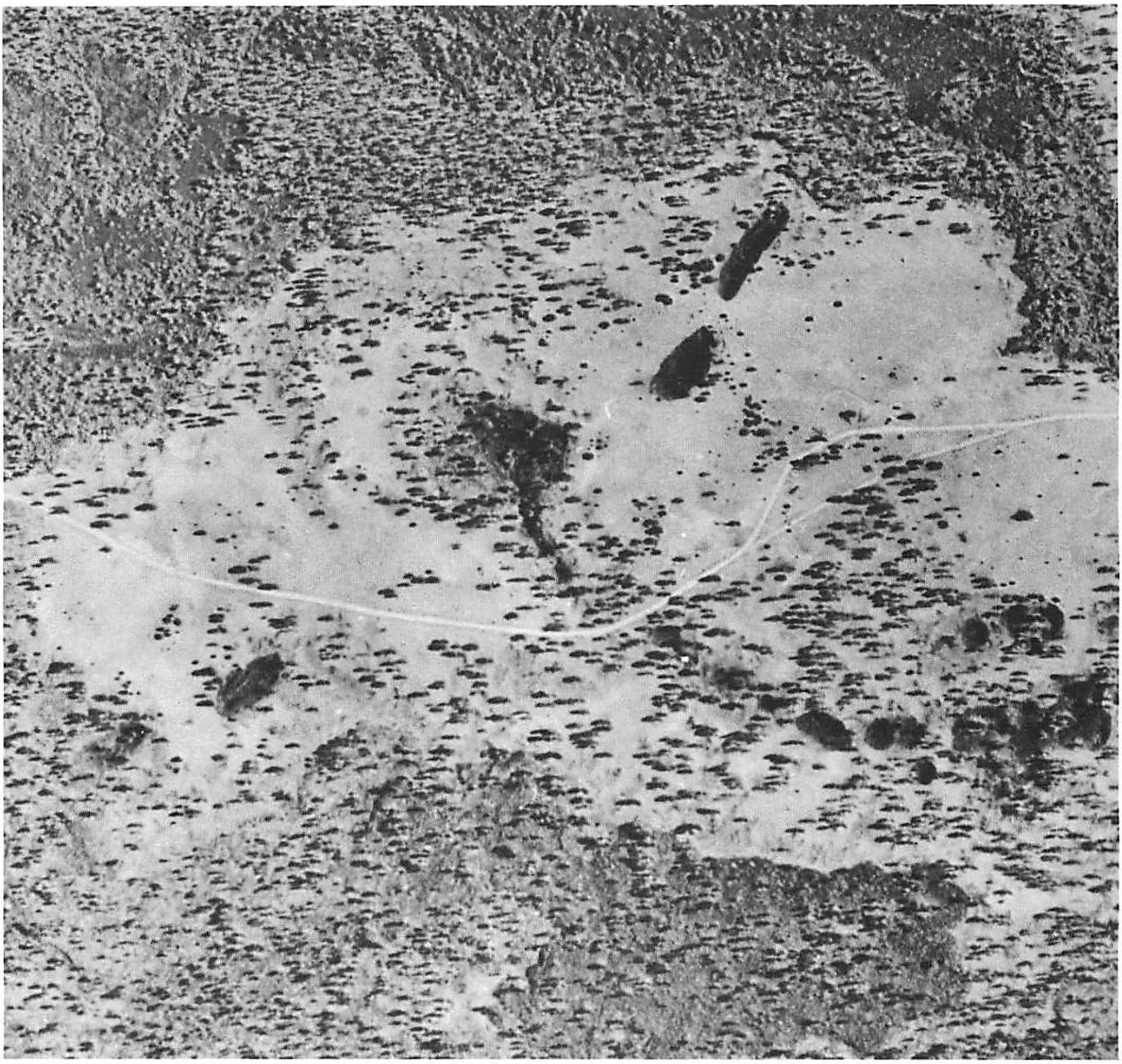

Fig. 6L

Fig. 7L

Fig. 9L

Fig. 13L

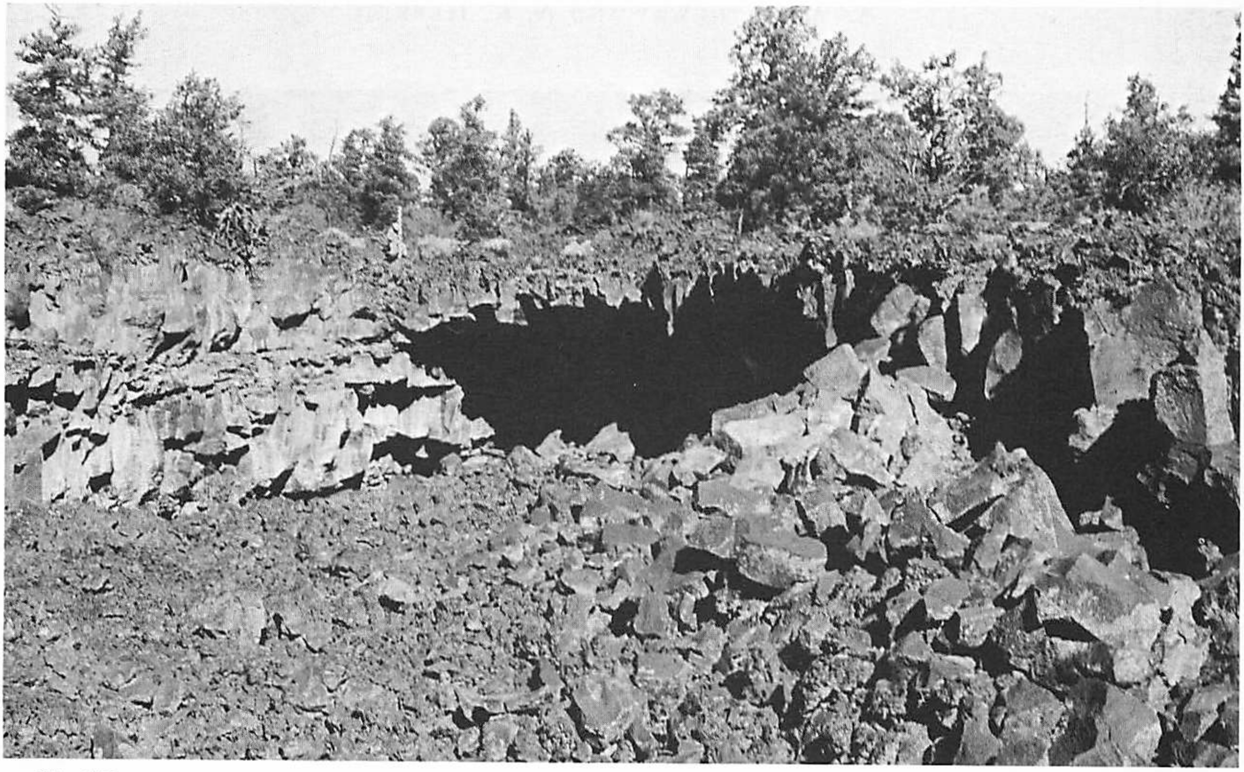
Fig. 18L


Fig. 21L

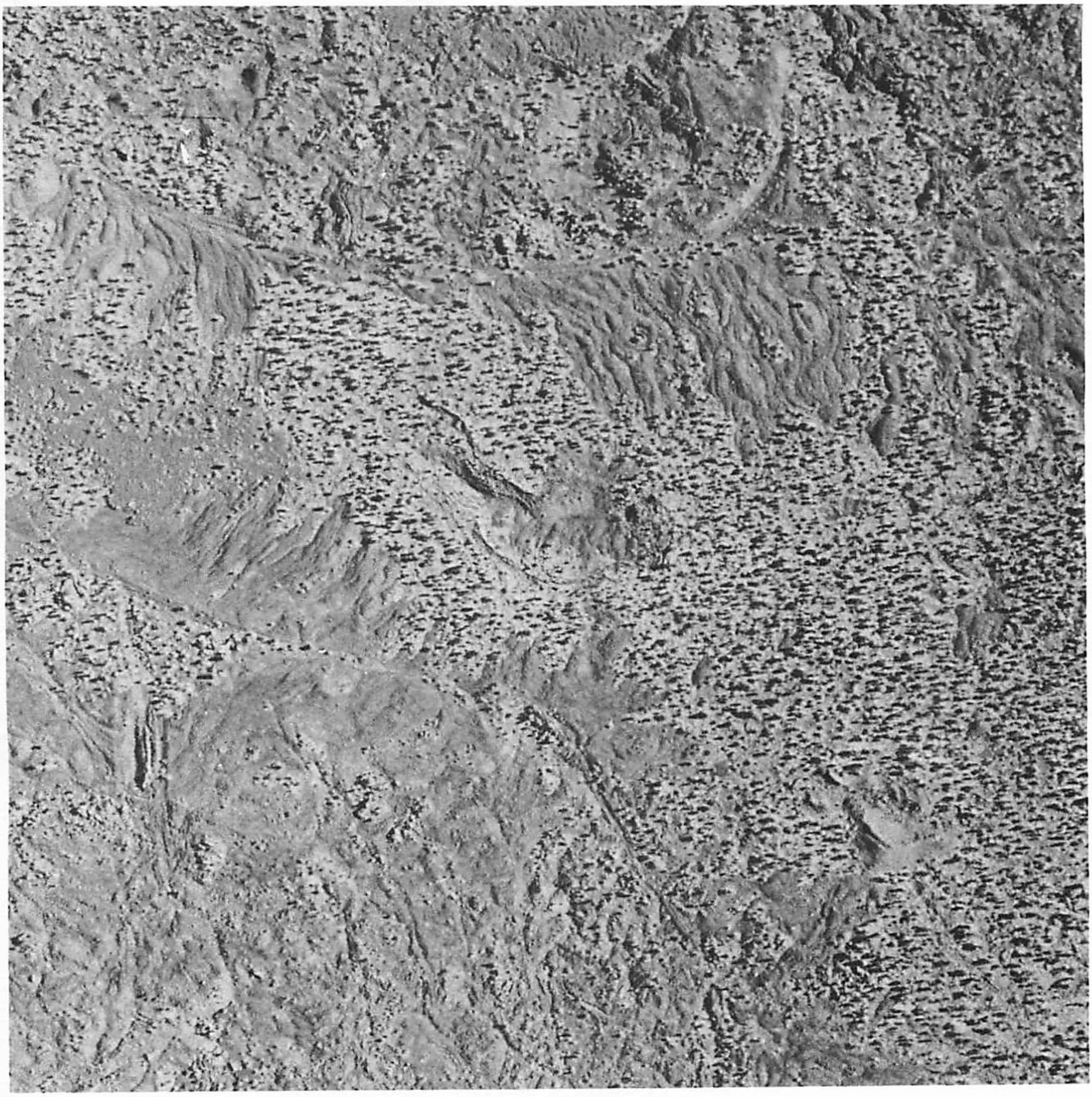

Fig. 24L