LAVA TUBE FORMATION — THE MAKINGS OF A CONTROVERSY
Findings from Studies on the Bandera Lava Field, New Mexico

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(Much of the data mentioned in this paper can be reviewed at length in the author's thesis, available as mentioned in his list of references, and in: Hatheway, Allen W. and Herring, Alika K. 1970. Bandera Lava Tubes of New Mexico, and Lunar Implications. University of Arizona Lunar and Planetary Laboratory Communications #152, Vol. 8, part 4, pp. 298-327.)

Observations made on active (mainly Hawaiian) and older lava fields (such as the Bandera of New Mexico, Fig. s 4-1 through 4-4) have brought attention to the fact that there may be two primary modes of lava tube formation. Conjecture as to these modes of formation stems directly from the earliest description of lava tube formation (Wentworth and MacDonald, 1953) which is opposed by a theory of formation set forth by Ollier and Brown (1965). This second work also sets out the first succinct description of fluid lava as a habitat for forming lava tubes.

Since the only observations of lava tubes made while the process of formation is active are those supporting the Wentworth and MacDonald view, many investigators hold resistance to the concept of a "mobile cylinder" (Hatheway, 1971) as an extension of the Ollier-Brown work.

Wentworth and MacDonald, followed by several others, have actually seen lava tubes forming from open channels. The mode of formation is simply one of development of a solidified crust, while fluid flow continues beneath. Greeley has noted, in several publications, that his field observations tend to support this theory and that tubes so formed tend to migrate laterally and vertically, in sections over limited distances.

While the circumstances surrounding formation of tubes from open channels are fairly simple, those responsible for tube development through mobile cylinders are more complex. In 1936, R. L. Nichols proposed that lava flows move forward as a series of flow units. Ollier and Brown (1965) clarified this concept with the added observation that the flow units are separated into flow layers formed in shear, along planes of variable viscosity.

That differentiation by flow layering does exist has been noted by Lutton, Girucky, and Hunt (1967), in which the flow layers were actually observed to constitute a relict internal cylindrical flow structure within a single 61-m thick lava flow.

The crux of the problem of defining mode of lava tube formation lies in the question of the existance of an open channel for distances of up to 35km (the longest distance yet reported for a single lava tube; Undara Crater tube, Queensland, White, 1965, fig. 2, plate 2). Will the roof-forming process produce a buried tube of this length?

As proposed by Hatheway (1971), a modified Ollier-Brown theory seems to adequately explain the occurrence of the longer lava tubes (one km - plus). Although long lava tubes have not been observed while forming, this theory is proposed to encompass all of the natural pocesses necessary to produce the tubes; with all of their distinct features.

It is a well known fact that lava flows extend themselves by flow units, and from within these, by smaller tongues of lava issuing forth from ruptures at the toes of flow units. The ruptures occur when the hydrostatic head of the fluid interior exceeds the tensile strength of the cooling basalt at the toe. Since tensile strength decreases markedly with temperature (Hatheway, 1971), this level of hydrostatic stress is rather easily attained. As soon as the break forms, the configuration of fluid flow soon stabilizes into a circular cross-section of equal shear stress between the evacuating lava and the less-viscous host lava.

Now, with the development of a semi-stabilized supply source of more fluid lava just up-gradient from the toe, a mobile cylinder, or supply conduit, filled with fluid lava must be present to continue to supply the effluent tongue. The theory proposed here holds that this mobile cylinder naturally propagates in an up-hill direction, following the position of maximum gradient for the flow unit (actually observed from lava tube traces on the Bandera flows). This generation of fluid supply volume continues until the modile cylinder reaches the source area, or vent. At this time the cylinder ceases to grow in length and merely snakes its way down through its own conduit until, like a subway train, it has completely left the conduit (or enclosing sheath) and has spilled out at the toe of the flow.

The result is an evacuated conduit....a tube formerly occupied by the mobile cylinder of fluid lava.

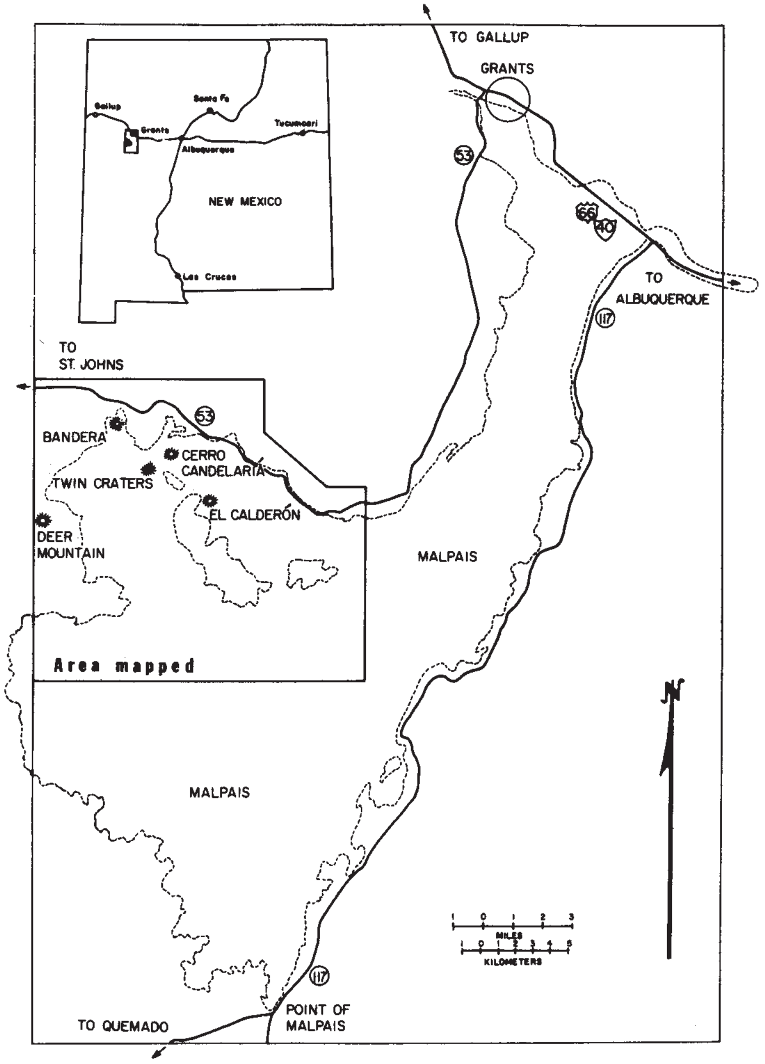


Figure 4-1: Index map to the Bandera lava field. Basalts of Pleistocene and Holocene age are outlined by the dashed line; they overlie in part older volcanics. (Ariz.fig.2)

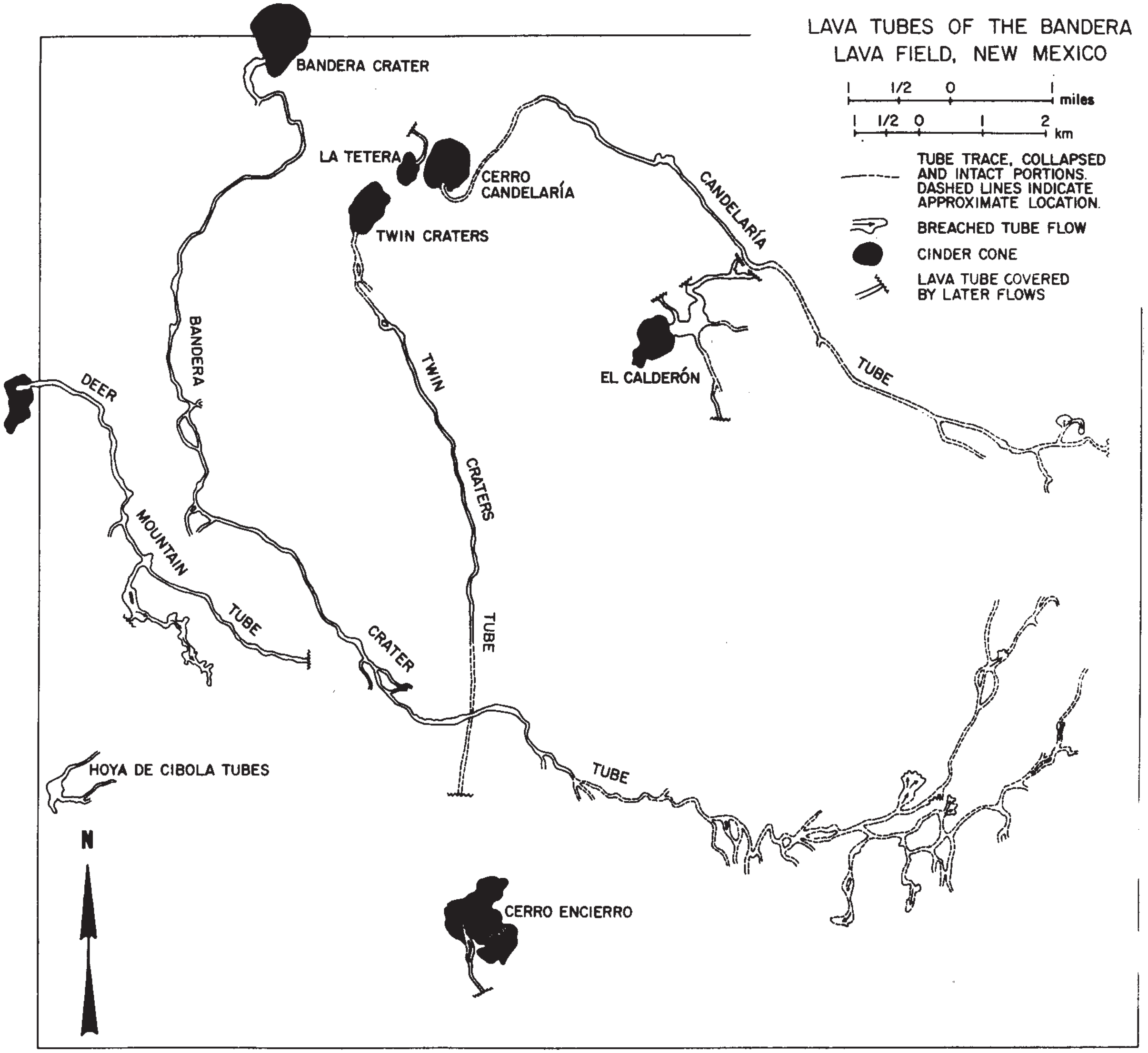


Figure 4-3: Lava tube systems of the Bandera lava field. (Ariz.fig.11)

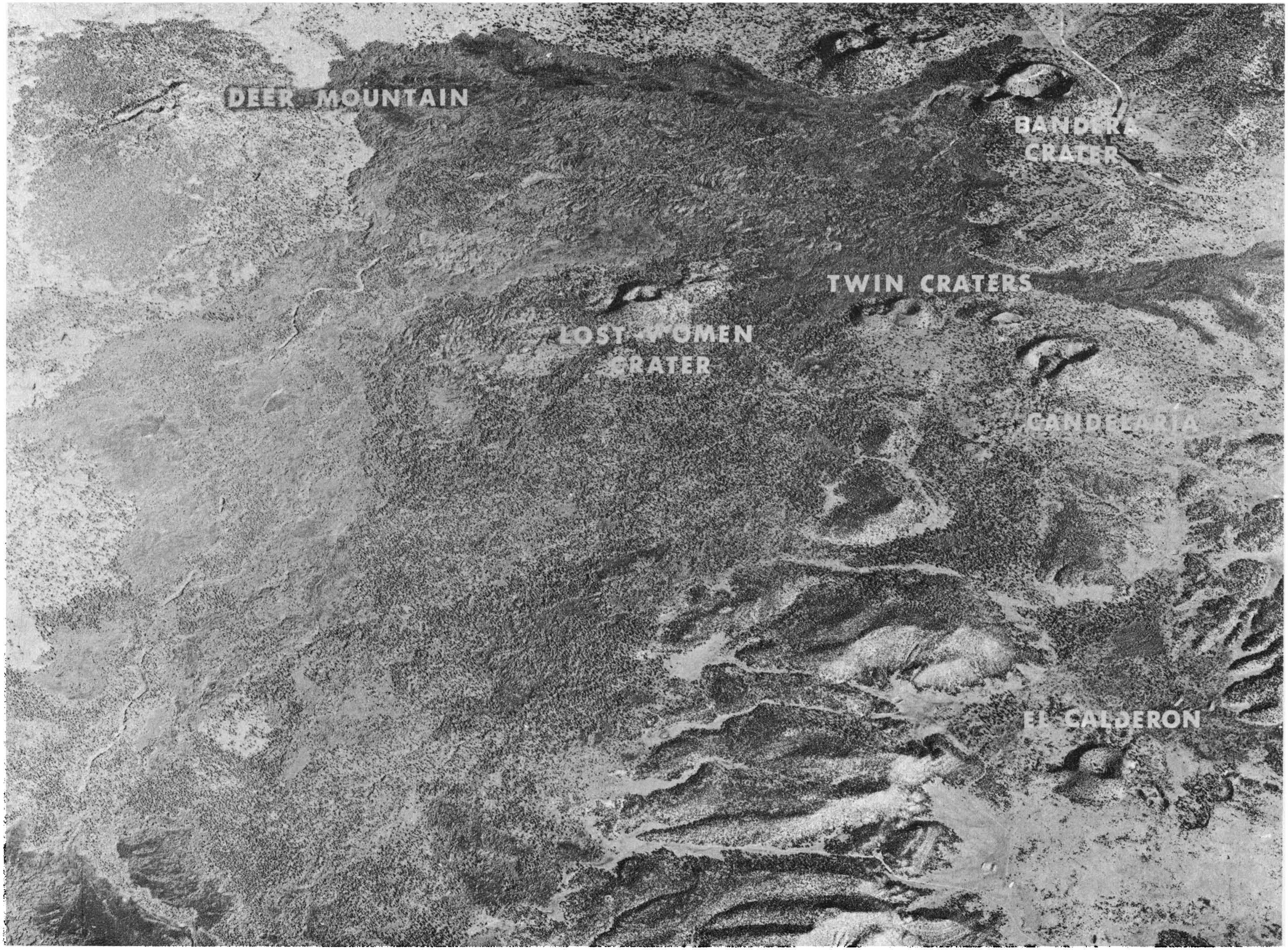


Figure 4-2

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).

Measurements of Sinuous Bends

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.

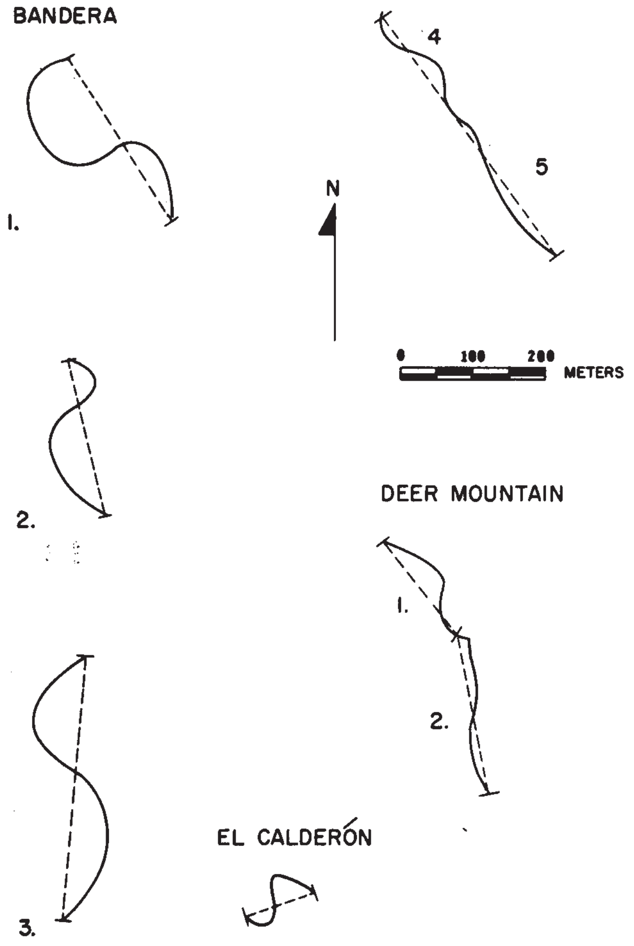


Figure 4-5: Traces of the more sinuous portions of several of the Bandera lava tubes. The bends are easily described by wave length and amplitude. The bends are analogous in many respects to lunar rilles. (Ariz.fig.14, incl.Table I)

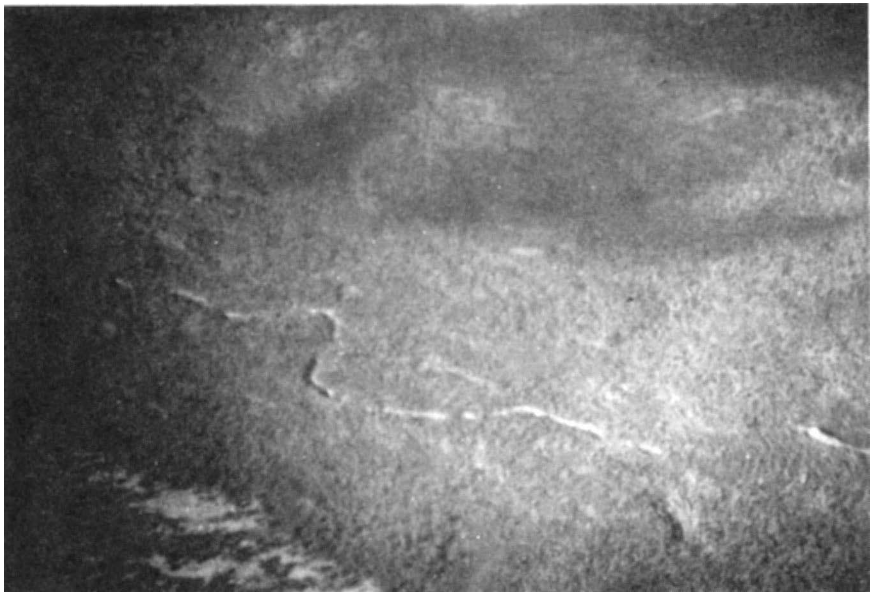


Figure 4-4: Aerial view of sinuous segment of Bandera Crater tube, showing segmental collapses. Halliday photo.

Figure 4-6: Sinuous bends along the lava tube issuing from El Calderon Crater. Four distinct tubes (1 thru 4) branch from the subsidence pit (P). Collapse of tube number 4 is evidenced by S (straight-sided collapse pits) and T (tensile failure producing a hole in the roof of the tube). (Ariz.fig.7-R)

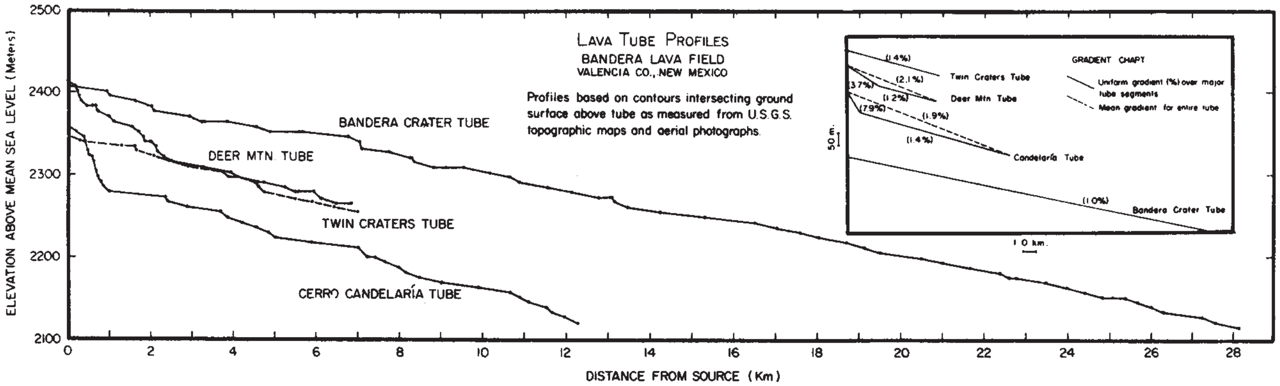
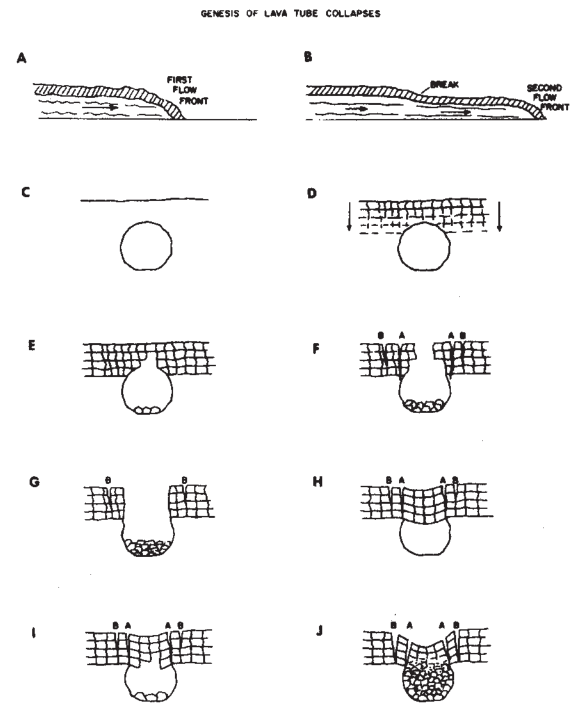


Figure 4-7: Gradient profiles of the Bandera lava tubes. (Ariz.fig.15)

Features observed on the Bandera and other basaltic lava fields of requisite chemistry and flow gradients, strongly suggest that most of the present-day collapse damage came about immediately after formation of the tubes (within a matter of weeks), before the host rocks cooled and became sufficiently strong to resist the shear and tensile components of gravity forces surrounding the lava tubes. Perhaps some of the damage was hastened by seismic tremors likely to have accompanied the eruptions.

At the present, data collected from numerous sites of lava tubes strongly suggest that these features occur only in alkali and high-alumina basalts and over flow gradients ranging upward from $4^{o}31'$, but no less than $0^{o}35'$ (Fig. 4-7). Characteristically the basalt associated with tubes and depressions is crystal-damaged and porphyritic; the barren host rock of nearby flow units devoid of depressions are finer grained and less damaged.

Velocity distribution in a newly formed lava tube (while occupied with full flow - or that of a mobile cylinder) equalizes shear forces around a circular section. Bends probably begin wher-



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.

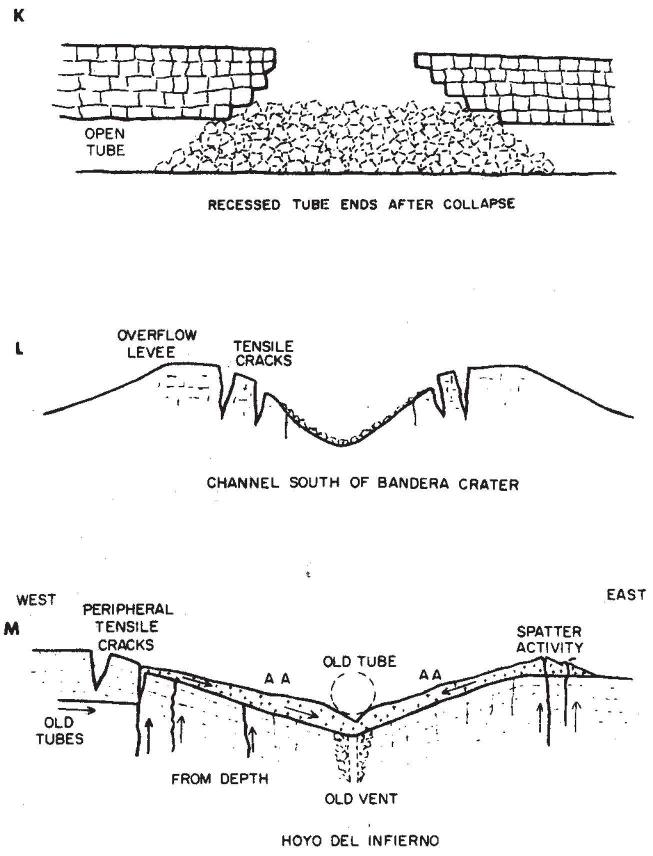
C. Evacuation of lava creates a mobile cylinder of lava shearing a contact with the surrounding, more viscous lavas.

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.)

Figure 4-8: Genesis of lava tube collapse. Ariz.fig. 16)

ever anomalously large pockets of equally viscous lava exist. As the pocket is mobilized in flow, continued flow erodes the section preferentially.

Young's modulus decreases radically with increasing temperature. The stability of a newly-formed lava tube depends upon its ability to resist the tensile and shear components of body forces surrounding the tube. Data were curve-fit and used in a thermoelastic stress analysis program.

Workers such as Murase have observed that lavas maintain an essentially linear structure elasticity for short periods of time at high temperatures. The thermoelastic stress analysis assumed linearity of elastic properties over the short time periods utilized in the analysis.

Typical shear surfaces formed by body stresses surrounding lava tubes were observed on the Amboy lava field of California and the McCartys flow of the Bandera lava field. There is a clear-cut transition between the tensile breaks of cooler origin near the surface, and shear at a depth of about one meter. Changes in surface character denote the temperature-dependent nature of tensile and shear failures in hot lava.

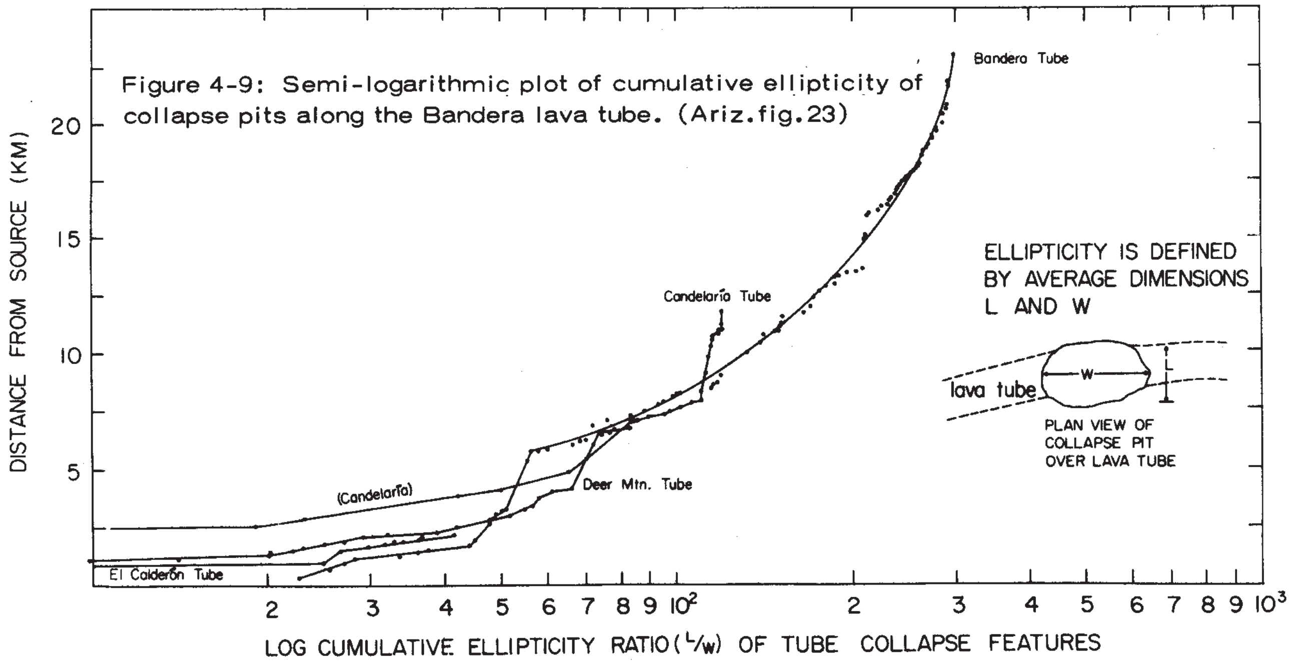


Figure 4-9: Semi-logarithmic plot of cumulative ellipticity of collapse pits along the Bandera lava tube. (Ariz.fig.23)

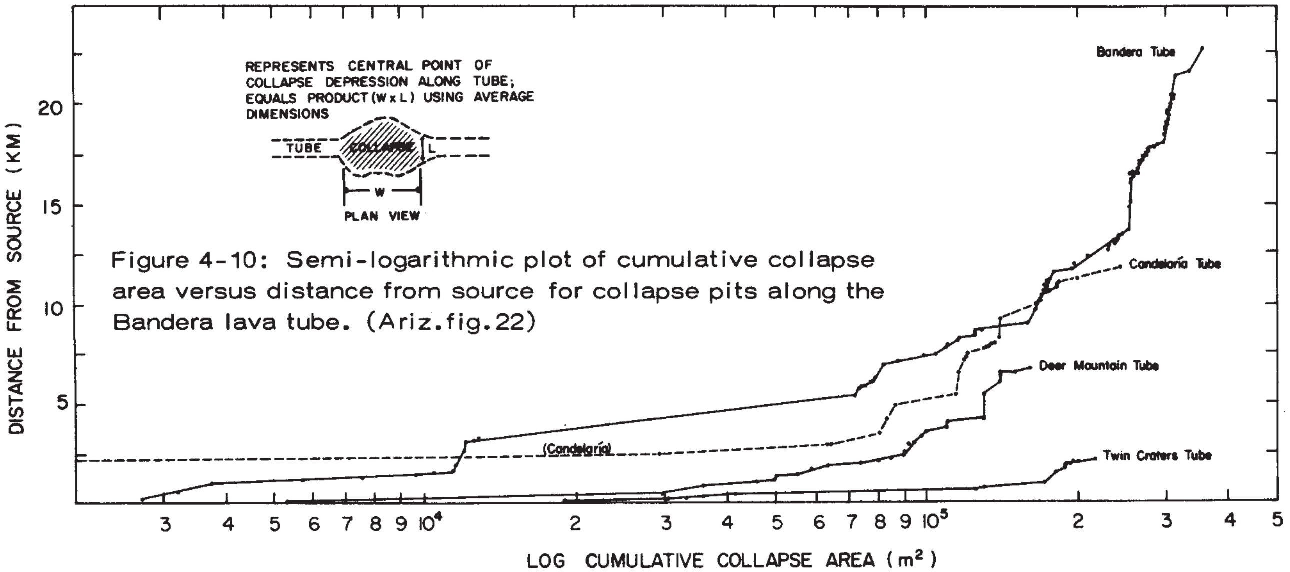


Figure 4-10: Semi-logarithmic plot of cumulative collapse area versus distance from source for collapse pits along the Bandera lava tube. (Ariz.fig.22)

Thermoelastic stress analysis showed that preferential shear and tensile failure occur just outside the periphery of the tube, from roughly the horizontal centerline upward into the lower half of the upper quadrants. Profiles vary considerably along short reaches of many lava tubes. Such variations attest to plastic deformation short of elastic failure, closely following formation of the lava tube.

Wide tensile fractures, extending three to five meters in depth, parallel the collapse features overlying many lava tubes (Fig.4-8). One nearly continuous fracture circumscribes each collapse in the McCartys basalt, Bandera lava field. Concentrations of tensile and shear stress in the host basalt immediately surrounding the tube result in a failure of the basalt, which is weak by virtue of its temperature, and formation of collapse depressions aligned along the trace of individual lava tubes. Detailed topographic mapping of a single collapse depression formed over a lava tube in the McCartys basalt showed a complex arrangement of peripheral tensile fractures denoting that the basalt failed in tension at the surface. Regardless of length of tube, the ellipticity (or length to width ratio) of collapsed segments of lava tubes remains fairly similar (Fig.4-9). The cumulative collapse area of pits along lava tubes shows the general effect of a thinning flow unit thickness as distance from source increases (Fig. 4-10).

Stratigraphic relationships and detailed lava-tube mapping at several locations in California and New Mexico have failed to substantiate that the longer tubes were formed in the alternative channel-and-fill mode.

Two theories thus have appeared which propose to account for the origin of lava tubes. The first of these, by Wentworth and MacDonald (1953) has been cited frequently in the past few years by several workers in lava tube research. The Wentworth-MacDonald theory is held by Hatheway (1971b) to constitute a valid explanation for formation of lava tubes less than about one kilometer in length. The theory calls for roofing by spatter and agglutination from lava flowing in open channels.

For the longer lava tubes, a compatible theory was developed by Ollier and Brown (1965) from basic observations of Nichols (1936). This concept has been modified to suit close field observations (Hatheway, 1971) and is herein proposed as a likely mode of formation for almost all lava tubes greater than about one kilometer in length.

The importance of a discussion of the two theories is that field observations of active basaltic eruptions, and those made on quiescent Holocene lava fields, suggest that the two theories are quite compatible; each explaining tube formation under a respective length criterion.

HATHEWAY, A.W. (1971a) Some physical considerations of lava tube formation (abs.): Geol. Soc. America, Cordilleran Sec., 67th Annual Meeting Prog., p. 134.

______ (1971b) Lava Tubes and Collapse Depressions: Unpbl. PhD Dissertation, Univ. Ariz., 353 p., available from Univ. Microfilms, Ann Arbor, Mich., as no. 71-25, 127.

LUTTON, R.J., GIRUCKY, F.E. and HUNT, R.W. (1967) Project Pre-Schooner; Geologic and engineering properties investigations: U.S. Army Corps of Engineers, Final Rept. PNE 505F (AD 657-638).

NICHOLS, R.L. (1936) Flow-units in basalt: Jour. Geology, v. 44, p. 617-630.

OLLIER, C.D. and BROWN, M.C. (1965) Lava caves of Victoria (Australia): Bull. volcanol., v. 28, p. 215-229.

WENTWORTH, C.K., and MacDonald, G.A. (1953) Structures and forms of basaltic rocks in Hawaii: U.S. Geol. Survey Bull. 994, 98p.

WHITE, D.A. (1965) The geology of the Georgetown/Clarke River area, Queensland: Comm. of Australia, Dept. Natl. Devl., Bur. Mineral Res., Geology and Geophysics Bull., 71, 165p.

GEOLOGY OF LAVA TUBES IN LAVA BEDS NATIONAL MONUMENT, CALIFORNIA

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READ IN ABSTRACT

Lava-tube systems in Lava Beds National Monument are among several that occur in young basalt flows which flank the Medicine Lake Highlands volcano. Mammoth Crater was the source for one tube system (including Heppe, Sentinel, and Dragonhead caves). This system includes both a major tributary and numerous distributary tubes. The large tributary (now collapsed) formed where lava ponded to one side of the main tube before draining it into subsurface. More typically the main channel fed numerous distributary conduits. Complexly branching distributary tubes at the monument headquarters are unusually well drained, evidently the result of a high gradient. The main channel in this area of high gradient (Crystal and Sentinel Caves) is narrow and deep and evidently carried a high rate of flow as suggested by evidence of high-velocity gas streaming above the lava river. Modoc Crater was the source of another lava large tube, whose uncollapsed segments include Bearpaw, Skull, Frozen River, Fossil, and Fern caves. This was a single channel throughout most of its 15-km length. Unusual features of this tube are a low gradient (less than 0.3° at the downstream end), and a series of collapsed blisters that form non-explosive craters with high outward-toppled rims. Like the Mammoth Crater tube, this tube generally is deeper than wide, is multistoried, has a thick roof, and is enclosed in several flow units. These complexities, which are typical of large tubes, originated by such mechanisms as successive lava overflow and levee building before the roof completely formed, non-uniform accretion on the tube walls, and local erosion into underlying materials. Except for small features in the tube lining, most layering exposed by tube collapse is believed to represent superposed flow units and not shear layers within the flow.