Selected CAVES AND LAVA-TUBE SYSTEMS *in and near* LAVA BEDS NATIONAL MONUMENT, CALIFORNIA

U.S. GEOLOGICAL SURVEY BULLETIN 1673

Lava cascade in Thunderbolt Distributary of Labyrinth Cave system.

SELECTED CAVES AND LAVA-TUBE SYSTEMS
IN AND NEAR LAVA BEDS
NATIONAL MONUMENT, CALIFORNIA

Frontispiece. Two visitors explore Valentine Cave, a well-preserved cave that is deservedly popular with Lava Beds National Monument visitors.

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By AARON C. WATERS, JULIE M. DONNELLY-NOLAN, and BRUCE W. ROGERS

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Many of the feature names used in this report and on the included maps were assigned by the authors. These names are not officially recognized or approved by the U.S. Board on Geographic Names and are thus considered informal.

Selected Caves and Lava-Tube Systems In and Near Lava Beds National Monument, California

By Aaron C. Waters, Julie M. Donnelly-Nolan, *and* Bruce W. Rogers

Introduction

Lava Beds National Monument (fig. 1) lies on the north slope of the huge Medicine Lake shield (fig. 2), a complex volcanic edifice of greater volume than the steep-sided Mount Shasta volcanic cone, which towers as a snowclad land mark 40 mi southwest of the monument (fig. 3).

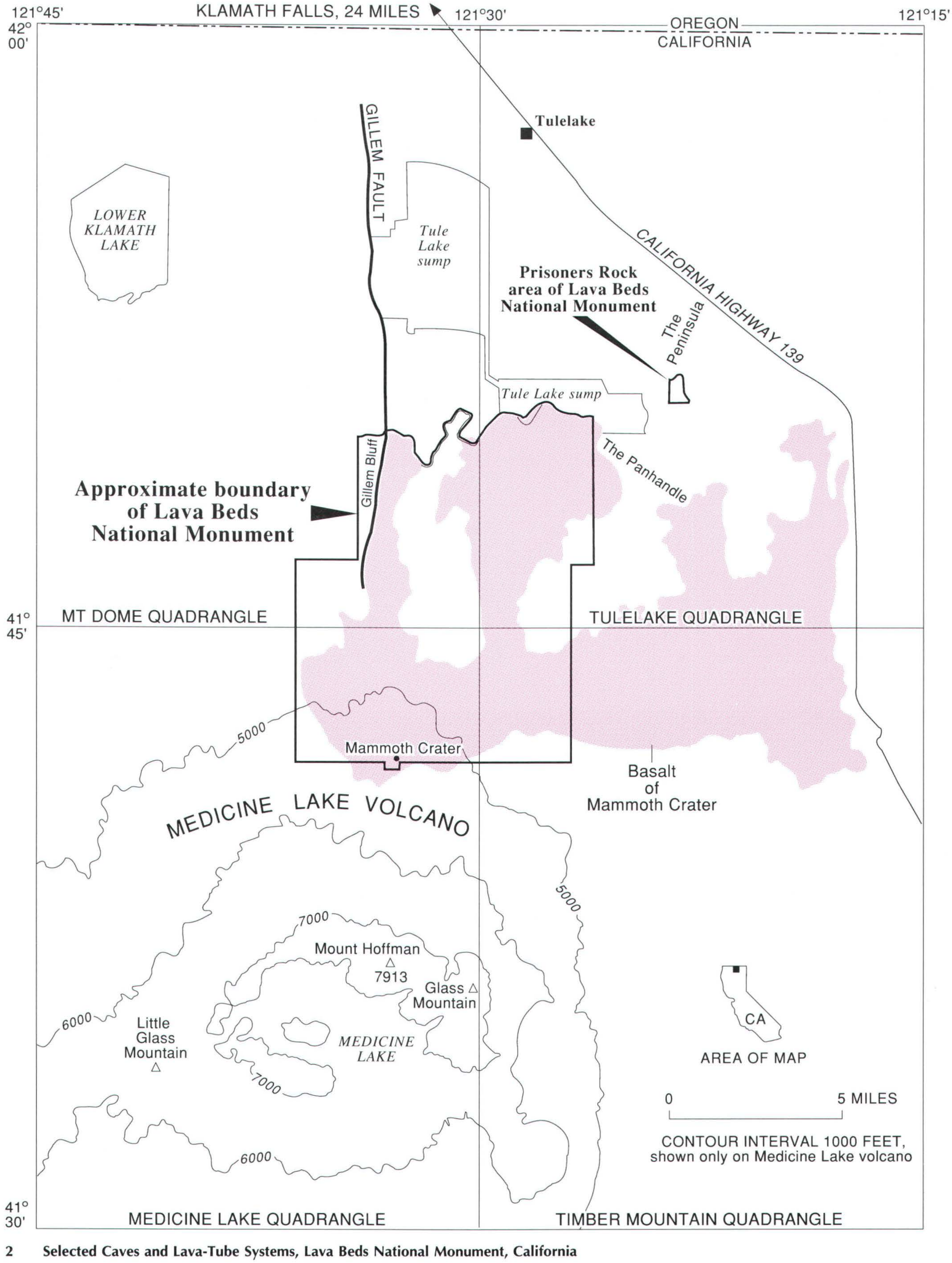
Much of the north and south flanks of the Medicine Lake shield were built from molten lava transmitted through lava tubes. These tubes formed beneath the congealing surface of basalt flows in somewhat the same way that a brook may continue to flow beneath a cover of its own winter ice. As molten lava emerges from a vent and flows downslope, congealing lava from the top and sides of the central channel often forms a bridge over the lava stream. The sticking together of bits of lava spatter and fragile lava crusts strengthens the bridge in the manner that thin crusts of floating ice raft together to cover a brook during early stages of a winter freeze. Eruption of basalt lava, however, is a much more violent and spasmodic process than the steady gathering of water that feeds a brook. If liquid lava stops rising from its source deep within the earth, the still-molten lava moving beneath the crusted-over top of a lava flow will continue to drain downhill and may ultimately leave an open lava-tube cave—often large enough for people to walk through. It is rare, however, to find such a simple scenario recorded intact among the hundreds of lava-tube caves in the monument. Even before the top and walls of a lava flow have time to cool during a pause in lava supply, a new and violent eruption of lava may refill the open tube, overflow its upper end, and spread a new lava flow beside or on top of the first flow. Even if the original tube is large enough to contain the renewed supply of lava, this tube must deliver the new lava beyond the end of its original flow and thus the lava field extends farther and farther downslope. If the gradient of flow flattens, the tube may subdivide into a number of smaller distributaries, which spread laterally over the more gently sloping ground.

Within Lava Beds National Monument, most lava tubes are found within the basalt of Mammoth Crater (figs. 1 and 4). Complicated and intertwining lava-tube systems originating from Mammoth Crater and other vents have built a broad fan of complexly interfingering lava flows that form the northeast perimeter of the Medicine Lake shield. Most of this lava was delivered through lava tubes. Some tubes conveyed lava underground 15–20 mi from their sources. Nevertheless, today one cannot walk for a distance of even 4 mi within any one lava tube. Large parts of the roofs of most lava tubes have fallen in, hiding the floor of the tube under huge piles of breakdown or angular broken rock, often stacked so tightly that access to both upstream and downstream portions of the tube is closed. In some places, however, collapse of the tube's roof has provided a large entrance into the lava tube through which one can walk with ease. In some collapse piles where access appears to be lacking, one can search the maze of tumbled blocks and perhaps find a crawlhole into a lava tube. Openings into caves may be detected by noticing the runways of small animals or testing the direction of air flow. On sparklingly clear, very cold winter days, openings into underground caverns will emit a white fog, just as one's exhaled breath does on such a day.

Holes in the landscape surface formed by failure of part of a lava tube's roof are called collapse pits, breakdowns, or more commonly, collapse trenches (see maps 2, 5, 10, and 20; plates 1, 2, 4, and 6). While walking across the relatively flat surface of the lava flows, you are seldom aware of their presence until a large and deep hole yawns at your feet. Some small breakdowns are dangerous death traps for animals. Unwary humans have met a similar fate (see map 12, pl. 4, and the "Skull Cave" section).

Once underground within a lava tube you may find your way impeded or blocked by a variety of features. Piles of loose rock that have peeled off the ceiling and walls of the tube may clutter the floor of the cave and slow your pace. Where no fallen blocks are present, the smooth to ropy (pahoehoe) surface of the lava on which you walk may change gradually to a very rough surface composed of bubble-filled loose blocks of a spiny (aa) lava. In some cases it may even completely block the cave entrance. The words pahoehoe and aa come from the Hawaiian language. Most lava tubes are found in pahoehoe lava (e.g. Greeley, 1971a; Harter, 1971), but occasionally they occur in aa lava (Guest and others, 1980).

Geologists recognize several varieties of pahoehoe (MacDonald, 1953; Wentworth and MacDonald, 1953). The smooth but thin and partly congealed skin on the surface of the molten lava may become wrinkled and twisted into


121°45'
KLAMATH FALLS, 24 MILES
121°30'
121°15'
42°
00'
OREGON
CALIFORNIA
Tulelake
GILLEM FAULT
LOWER
KLAMATH
LAKE
Tule
Lake
sump
CALIFORNIA HIGHWAY 139
Prisoners Rock
area of Lava Beds
National Monument
The
Peninsula
Tule Lake sump
The Panhandle
Gillem Bluff
Approximate boundary
of Lava Beds
National Monument
41°
45'
MT DOME QUADRANGLE
TULELAKE QUADRANGLE
5000
Mammoth Crater
Basalt
of
Mammoth Crater
MEDICINE LAKE VOLCANO
5000
7000
Mount Hoffman
7913
Glass
Mountain
6000
Little
Glass
Mountain
MEDICINE
LAKE
7000
CA
AREA OF MAP
0
5 MILES
CONTOUR INTERVAL 1000 FEET,
shown only on Medicine Lake volcano
6000
41°
30'
MEDICINE LAKE QUADRANGLE
TIMBER MOUNTAIN QUADRANGLE

small ridges that resemble ropes, as the hot and plastic crust is dragged along by molten lava beneath. These ropes in turn may be dragged and stretched out into attenuated lobate forms (fig. 5). Near the end of the period of consolidation some ropy pahoehoe may be cut by closely spaced vertical shears to form laminated or cauliflower pahoehoe.

Subtle transitional changes in a pahoehoe surface can be recognized where pahoehoe changes to aa downstream (Peterson and Tilling, 1980). The smooth to ropy forms begin to lose the glassy luster that formed as a thin skin of chilled basalt glass, and the small spherical bubbles confined beneath this glass skin increase in number, grow larger, and become visible on the surface as bumps and broken bulges of the glass crust. As the bubbles grow larger and more irregular in shape, many of them explode outward through the sticky glass crust, and with further movement this prickly surface breaks up into small discrete blocks, completing the transition to aa lava (fig. 6).

In lava tubes the transition from pahoehoe to aa is frequently found downstream from an area where molten lava was violently churned up while tumbling

◄

Figure 1. Index map showing Lava Beds National Monument, Medicine Lake volcano, and distribution of basalt of Mammoth Crater (shaded pattern), which is host to most of the lava-tube caves in the monument.

Figure 2. View of Medicine Lake shield volcano from northern edge of Lava Beds National Monument. Gillem Bluff to right. Field of view is about 15 mi across.

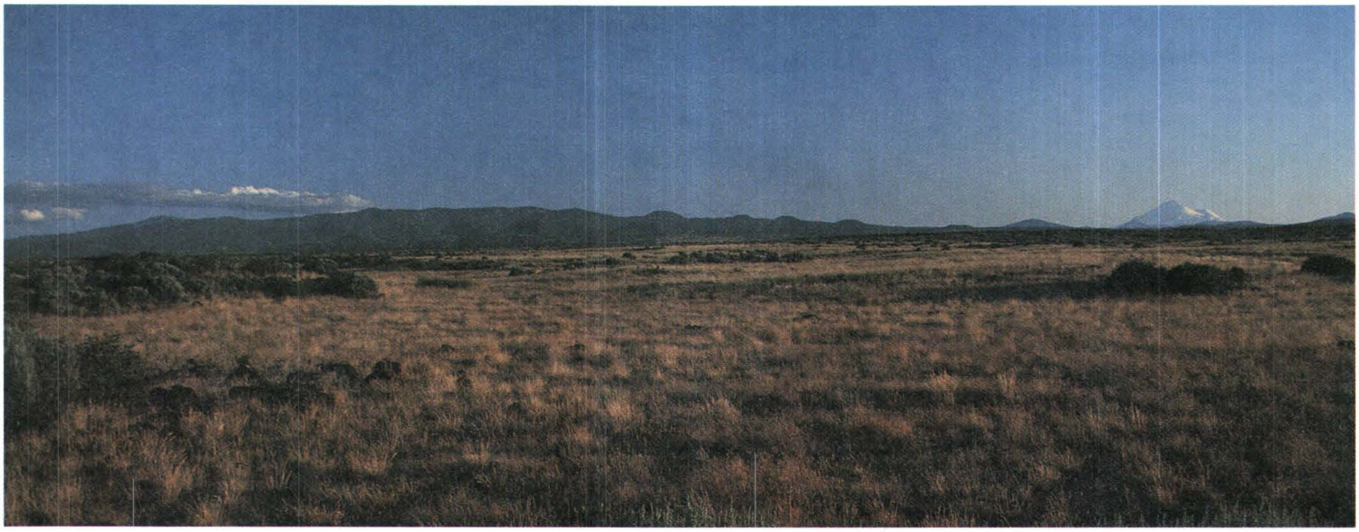
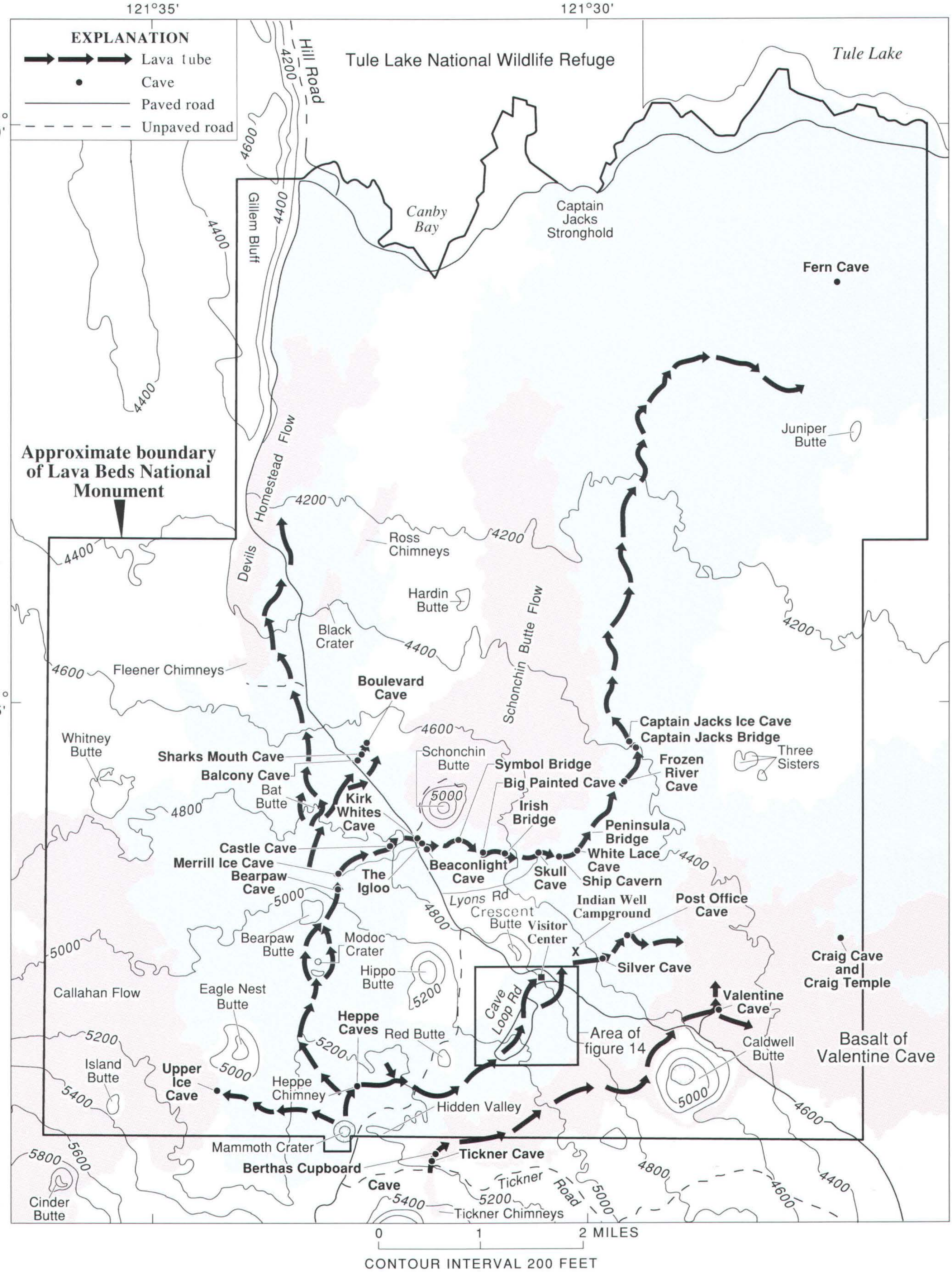


Figure 3. Late afternoon view across Lava Beds National Monument with upper part of Medicine Lake shield volcano on left skyline. Snowcapped Mount Shasta is about 40 mi distant on right skyline. View is southwestward.


121°35'
121°30'
41° 50'
41° 45'
EXPLANATION
Lava tube
Cave
Paved road
Unpaved road
Tule Lake National Wildlife Refuge
Tule Lake
Hill Road
Gillem Bluff
Canby Bay
Captain Jacks Stronghold
Fern Cave
Juniper Butte
Approximate boundary of Lava Beds National Monument
Devils Homestead Flow
Ross Chimneys
Hardin Butte
Schonchin Butte Flow
Black Crater
Fleener Chimneys
Boulevard Cave
Whitney Butte
Sharks Mouth Cave
Balcony Cave
Bat Butte
Kirk Whites Cave
Schonchin Butte
Symbol Bridge
Big Painted Cave
Irish Bridge
Captain Jacks Ice Cave
Captain Jacks Bridge
Frozen River Cave
Three Sisters
Peninsula Bridge
White Lace Cave
Ship Cavern
Skull Cave
Beaconlight Cave
Castle Cave
Merrill Ice Cave
Bearpaw Cave
The Igloo
Lyons Rd
Crescent Butte
Visitor Center
Indian Well Campground
Post Office Cave
Silver Cave
Craig Cave and Craig Temple
Bearpaw Butte
Modoc Crater
Hippo Butte
Callahan Flow
Eagle Nest Butte
Cave Loop Rd
Area of figure 14
Valentine Cave
Caldwell Butte
Basalt of Valentine Cave
Heppe Caves
Red Butte
Island Butte
Upper Ice Cave
Heppe Chimney
Hidden Valley
Mammoth Crater
Berthas Cupboard
Tickner Cave
Cave
Tickner Road
Tickner Chimneys
Cinder Butte
0 1 2 MILES
CONTOUR INTERVAL 200 FEET

over a lava fall or down a series of lava cascades.

Two additional varieties of pahoehoe are commonly recorded by observers of actively erupting flows in Hawaii but are more difficult to recognize in the congealed flows at Lava Beds National Monument. Pahoehoe toes from 1 to several feet in length may sprout forward all along the front of some advancing lava flows. In places the chief manner of forward movement is by the extending and overriding of successive pahoehoe toes. Shelly pahoehoe congeals where large hollow lava blisters 3 ft or more in diameter have formed beneath a thin crust of erupting volatile-rich lava. These large lava blisters flow out, flatten, and override one another. Fleener Chimneys, in the monument, erupted shelly pahoehoe as the last part of the eruption that produced the Devils Homestead flow. Much of this flow is aa (fig. 7), particularly farther from the vents at Fleener Chimneys.

The bubbles and blisters that form in molten lava are produced by release of water and other gases from the molten rock. When pressure is lowered by rise of molten liquid, called magma, to the surface, or by the turbulence of tumbling over a cascade, the lava may froth just as the dissolved carbon dioxide in beer will froth and form bubbles as you open the can and tumble the beer into a glass.

Not all collapses of lava-tube roofs took place after volcanism ceased. Many lava tubes contain easily decipherable records of breakdown that occurred when molten lava was flowing through a tube. Careful examination of the congealed surface of the last flow of lava down a tube is likely to reveal both small and large blocks of rock that tumbled from the roof of the cave and were then rafted downstream on the molten flood until it, in turn, congealed into rock. Large rafted blocks are shown on the maps of this report.

◄ **Figure 4.** Location map of Lava Beds National Monument showing major lava-tube systems, cave locations, and other selected features. Basalt of Mammoth Crater shown in blue. Other lava flows shown in red.

If a large segment of a tube roof collapses while the tube is still filled or half-filled with flowing lava, a number of events can occur that leave their record in the rocks to be examined long after volcanism ceased. If the tube is only half full of flowing lava, and the thickness of collapse debris is nearly equal to the

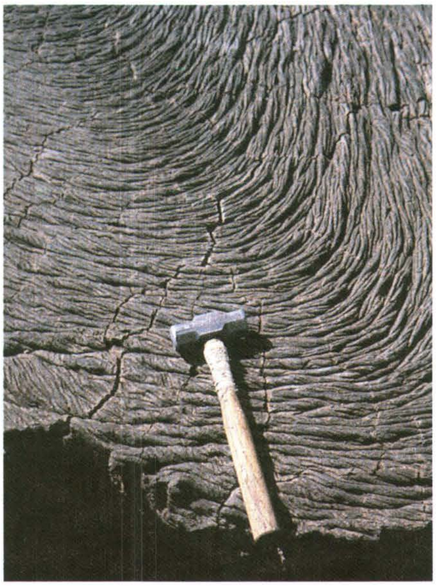


Figure 5. Ropy pahoehoe. A pasty red-hot rind of partly congealed magma at the surface of a lava flow was folded and twisted into rope-like ridges as it was dragged forward by the molten rock beneath. Chilled by air, the lava surface congealed into lustrous black glass. Near Giant Crater, south flank of Medicine Lake volcano (see fig. 1).

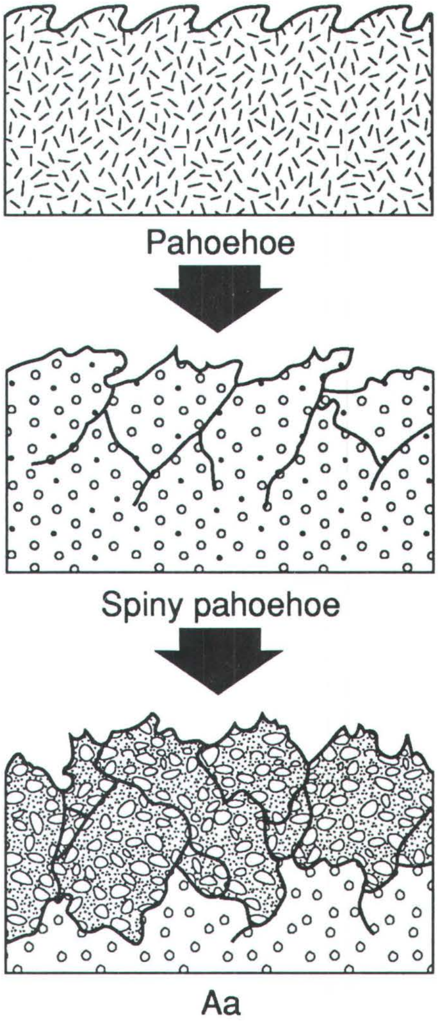


Figure 6. Increasing vesiculation and turbulence may cause a lava flow to change from pahoehoe to aa downstream.

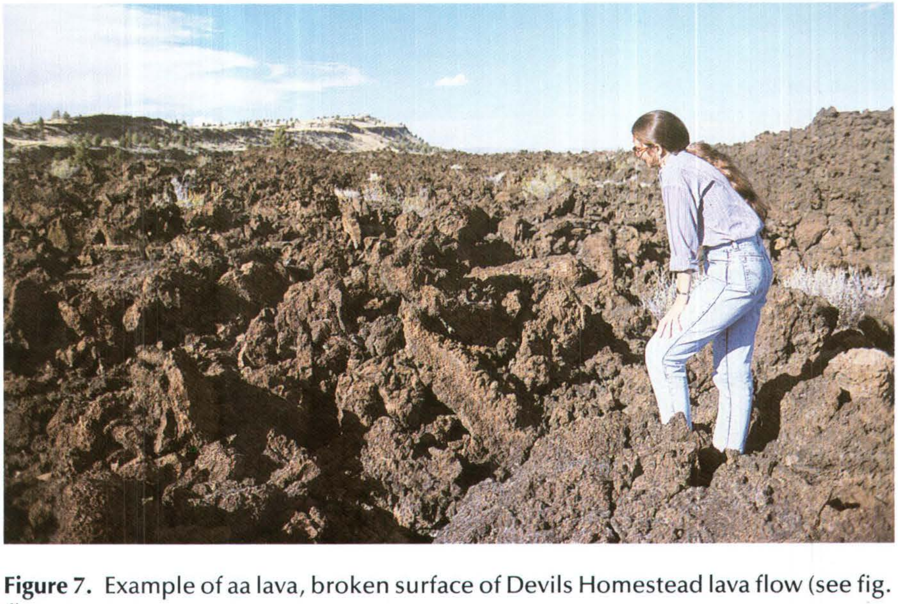


Figure 7. Example of aa lava, broken surface of Devils Homestead lava flow (see fig. 4).

flow, then the lava may pool behind the obstruction, flow over the tumbled blocks, and cascade off the downstream side. Alternately the molten lava may penetrate between the fallen blocks and buoy them up enough that with the additional hydraulic energy of lava ponding behind the obstruction, the flow is able to entrain and bulldoze enough of the obstruction for the lava river to restore its former gradient. Much of this buoyed material is deposited downstream in alcoves, where the tube widens, or on the inside of curves, where the stream velocity slackens. Examples of these features are well preserved in the central part of Valentine Cave (map 8, pl. 3), in parts of Tickner and Berthas Cupboard Caves (map 9, pl. 3), and in many other lava-tube caves.

When a roof collapse is so large that it effectively plugs a tube filled with flowing lava, the molten lava in the tube downstream from the obstruction flows on, leaving an open lava tube; however, minor leaks through or around the plug may continue to feed a small flow into the eviscerated tube below. Upstream from the plug the molten lava backs up and fills the tube to its roof. This process gradually increases the hydraulic pressure on all parts of the tube until a weak spot is opened, generally in the cave's roof. The lava then pours out of this hole and forms a new surface lava flow, which spreads downstream from the point of egress. As this flow advances downslope one or more lava tubes may develop within it. With further spreading and subdividing, one lobe may find a breakdown leading to an open tube below. Thus a part or all of the flow may be diverted, tumbling as a lava fall through this breakdown—perhaps into the same tube that was plugged by a breakdown upstream.

Studies of the many lava-tube caves in the monument also provide alternate interpretations of what has happened in places under essentially these same conditions. If the obstruction cannot be bulldozed away by the lava, the pressure of backed-up lava may also be relieved by the formation of a bypass around the obstruction. Such a bypass is very possible if the flowing lava remained hot beneath its already firmly congealed crust. The hotter liquid magma within the tube simply pushes the cooler, plastic material aside, and a bypass is formed around one side of the obstruction. In some tubes two bypasses may form, one on each side. Such a double bypass is present near the downstream end of Tickner Cave (map 9, pl. 3).

Relief of the pressure in a backed-up lava tube can also come from collapse of the floor of the filled lava tube downward into an underlying lava tube. In each of the three major lava-tube systems in the monument there are numerous examples where this has happened. If the lava in both tubes then drains out, the connector, as the underground collapse conduit is called, remains open and can provide access to a cave passage that might never have been discovered otherwise. Connectors, once formed, tend to persist. The Silver Connector, shown on map and section of Post Office Cave (map 15, pl. 5), passes through lava tubes at five different levels, but it is entirely underground—not a surface collapse. Flowage within connectors was not always down. Some of them transmitted lava from a lower ponded level to an upper open level, but the evidence for this is not likely to be discovered unless the plugged lower level also obtained release at some lower point to allow both it and the connector to drain. Otherwise the connector remains filled with congealed lava and so would remain unidentified or possibly be mistaken for the vent of a new volcano.

Indeed, open lava tubes, and open connectors of any kind between lava tubes, are unusual features. From the very nature of the way they develop, lava tubes cannot remain open unless the lava field forms over a topographic slope that affords sufficient gradient for lava to drain out of the tube after eruption ceases. Tubes cannot develop within lava that remains ponded until solidification. Furthermore, flowing lava, like water, spills into any opening available. So it is quite normal that a walk downstream within a lava-tube system will reveal that each lava tube and its distributaries are likely ponded to the roof with the final flow of lava that entered. You will first notice that lava on the floor of the cave begins to rise against the walls of the cave, and it acquires a smooth ponded surface with few of the usual pahoehoe ropes. The surface of the pond appears to rise downstream until it intersects the roof of the cave; actually, it remains level, whereas the ceiling and floor of the tube slope downstream. The lava that rose in the tube was pooled by an obstruction to this level, and congealed because it was unable to drain out.

From studying partly eroded shield volcanoes, geologists find that lava tubes containing a filling of congealed lava are much more abundant than open lava tubes. Open lava tubes will be more common among the youngest lava flows in a volcanic pile, for most older open lava tubes may have been filled with the lava from later eruptions. It has been estimated that only 10 to 20 percent of the lava tubes of a flow drain and remain accessible to an explorer. Nevertheless, because of the complexities of intermittent pauses and recurring floods of magma, combined with the interruption of flow in tubes by roof collapse, it is likely that a few lava tubes will remain open on the steeper flanks of a shield volcano, even if they are buried under hundreds of feet of new flows.

Some lava tubes receive fillings of material other than lava. Sand, gravel, or volcanic ash washed in by surface water may fill them. A rise in the water table after volcanism ceases may drown the underground passages. In the monument, large tubes that are 100 ft or more below the ground surface may be filled completely with ice, or else have their walls decorated by a frieze of large frost crystals interspersed with draperies of long icicles. Crystal Cave (map 18, pl. 6) is an outstanding example.

Intact parts of the ceiling in most caves show fine displays of lavacicles. As the name implies, they are like icicles but were formed as molten lava dripped from the roof of the cave. Undamaged parts of most tube walls show linings of dripstone (figs. 8 and 9). These capture the flow forms taken by congealing liquid lava as it splashed against or dripped off the walls of a tube when the lava surface quickly lowered in the tube.

Lavacicles can weld together into a dripstone drapery where lava drips slowly from an overhanging ledge.

Because of similarity with features found in limestone caves many authors use the name lava stalactite instead of lavacicle. The process of formation, however, is utterly different. Limestone cave stalactites are formed from material precipitated as a water solution degases and evaporates. Icicles and lavacicles are caused by the freezing of a liquid. Many stalactites in limestone caves have a companion stalagmite that grows up to meet them when water droplets falling from the tip of the stalactite degas and evaporate on the cave floor, leaving a deposit.

On the surface of some large rafted blocks, however, splatters of lava and pieces of plastically deformed lavacicles that tumbled onto the block as it traveled down the lava tube are likely to be present. Companion lava stalagmites (fig. 10) are sparse in lava tubes because drip from the tip of a lavacicle in most cases fell into the molten flood below. Where the floor had already solidified, stalagmites consisting of droplets of lava welded together are often present. Occasionally these display frozen rivulets of lava, which ran down their sides and partially smoothed their surfaces.

High-lava marks on the walls of a tube, like the high-water marks of a river in flood, record the position of lava at some former high stage in its flow. If lava remains constant for considerable time at one level high within a tube, the congealing of the lava surface inward from the walls may build a lava balcony; if ponding occurs lower on the walls (less than 3 ft), a lava bench may form. Most maps in this report show where balconies and benches are present. For excellent examples, see the maps of Silver (map 14, pl. 5), Tickner (map 9, pl. 3), Balcony (map 13, pl. 4), and Valentine (map 8, pl. 3) Caves.

In places, a flow that was building paired benches—one from each wall—may form a crust of congealed lava extending completely across the tube. If the still-molten lava flowing beneath this crust drains out later, a two-storied tube remains—an upper older story—beneath which a newer lower tube remains active. If the magma in the lower story then drains out, a tube-in-tube is formed. Another type of tube-in-tube forms when a small lobe of new lava invades an older and larger open lava tube and then drains out soon after a thin exterior crust has solidified. Even more interesting examples of stacked tube-in-tubes occur in places where small tubes, 3 to 7 ft in diameter, have been occupied by brief periodic surges of lava—a crust forms that encircles each new surge of lava, but if the flow is too small to fill the tube, this new crust develops some distance from the roof and upper walls, while firmly attached to the floor. Thus a few flow surges of diminishing size will produce tube-in-tubes stacked within one another that resemble nested concrete culverts of varying size. Examples may be seen in Tickner Cave, and at the downstream terminations of Arch and Silver Caves.

The formation of thin accretionary crusts of basalt magma at places where it comes in contact with air or with cold rock is responsible for many interesting minor features, both on the surface and within lava tubes. At first these crusts are plastic and mobile, and with added cooling they may be folded into many small lobes whose surfaces resemble sections of coiled ropes congealed into stone. Such accretionary lava crusts are visible in many lava tubes. Coatings of lavacicles on the roof of a cave may have peeled off and exposed another thin layer underneath, which also has lavacicles. Observe the dripstone on the wall of a cave over an area of several square meters, and you are almost sure to find

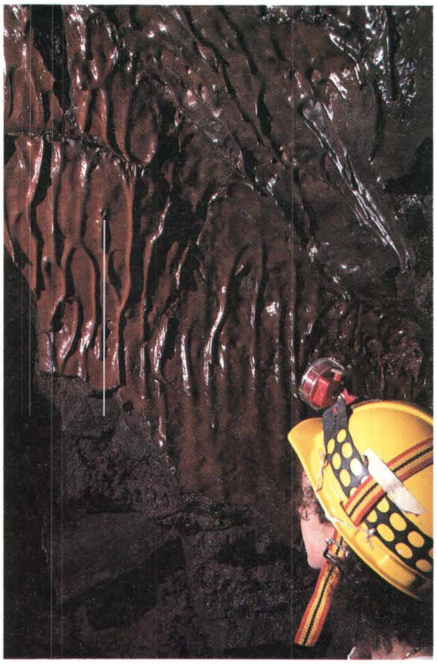


Figure 8. Lava dripstone trails down wall of Post Office Cave (see fig. 4 and map 15, pl. 5). Reddish color was produced by oxidation of hot lava surface.

Figure 9. Lava driblet on wall of Fern Cave (see fig. 4 and map 17, pl. 5). Pencil for scale.

Figure 10. Lava stalagmite formed by dripping of still-hot lava from ceiling of Post Office Cave (see fig. 4 and map 15, pl. 5) onto still-moving flow. The 2-ft-high stalagmite was apparently rafted downstream from the ceiling drip that formed it. Hammer for scale.

"pull outs" where the dripping plaster of this final coat sagged down or peeled away from the wall (fig. 11). Behind the pull out another layer of dripstone is exposed on the wall. Examine the cross-section edge of a large lava tube sliced by a major breakdown, and you will probably see layer after layer of accretionary lava plaster called linings welded together in the cross section of the tube. Every accretionary layer represents a separate volcanic surge followed by a period of quiescence. Most accretionary layers, as can be seen by their tight welding, resulted from small-scale fluctuations in the amount of magma coursing through the tube.

Instructive examples of the transitory skins that form on moving basalt lava are present in many of the 3-ft-high benches that border the walls of large-diameter (30–60 ft) cave passages such as in Craig and Valentine. In places where a falling roof block has sliced such a bench, vertical inward-sagging thin layers of basalt can be seen beneath the final coating of lava plaster covering the bench. Some of these layers exhibit torn, crumpled, and pulled-out edges, all of which indicate that their extensions were sheared off and distorted by the pull of the lava flowing beside them (fig. 12). A thin plastic layer of congealing basalt cannot remain arched over a cave of large dimensions, but it can be preserved in small tube-in-tubes, such as those in the Garden Bridges area. Generally, such skins of congealing lava are continuously rafted forward and simultaneously sag, shear, and pull loose along the walls of the cave. The result of these processes is precisely what can be seen within the broken benches of Valentine and Crystal Caves.

Exploring the Caves

For safety or conservation reasons certain caves may be closed to the public or have restricted access. As of April 1990, only Mushpot Cave is lighted, and two of the caves described in detail have restricted access: Crystal and Fern Caves. Always check in at the Visitor Center for information regarding cave access as well as safety and exploration guidelines before entering any cave in the monument.

Time did not permit preparation of geologic maps for all caves in the monument. We did, however, explore a large number of the known caves. Most caves in the wilderness area of the monument were rejected for mapping, not only because of their remoteness, but because most of the deep tubes have collapsed and only small remnants of little geologic interest remain. However, Craig Cave and Craig Temple, accessible only by an 11-mi drive over rough, unpaved roads or a 3-mi hike across rugged terrain, were mapped because of this lava tube's geologic importance and large size. Fortunately, the group of caves whose easily accessible entrances lie adjacent to Cave Loop Road (maps 1–7, pls. 1 and 2) provide excellent examples of nearly all features typical of lava-tube caves.

Cave Names

Nearly all caves and many other geographic features within Lava Beds National Monument were named by J.D. Howard, an early settler and guide whose chief avocation became the discovery, naming, and measuring of the caves. He also assisted in the building of wagon roads so others could visit these natural

Figure 11. Lava dripstone and "pull out" in wall of Mushpot Cave (see fig. 14 and map 1, pl. 1). Dark area in center is a pull out where pasty red-hot dripstone sloughed off the wall and oozed downward. Pencil for scale.

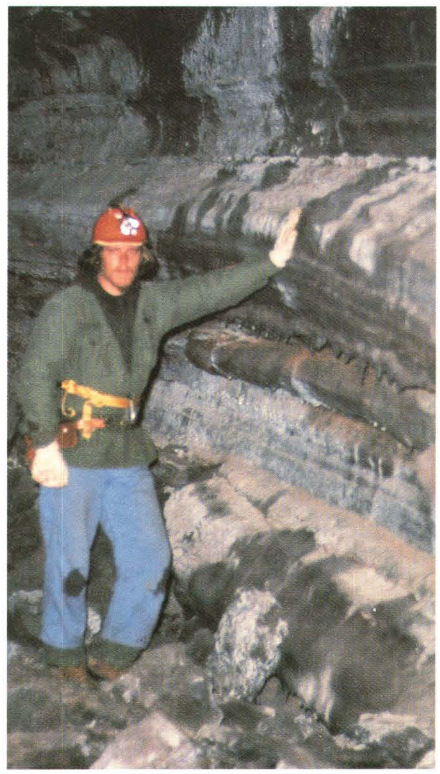


Figure 12. Broken, partly collapsed lava bench on wall of Crystal Cave (see fig. 14 and map 18, pl. 6).

wonders. From 1917 until about 1933 it appears that he spent almost all of his spare time searching for caves and generally exploring all parts of the northeastern one-third of the Medicine Lake shield. Howard was also a self-educated student of the classics, especially Greek and Roman history and mythology. This is evident in many of the names he used such as Catacombs Cave whose many side passages reminded him of the burial places of ancient Rome. Also, Cleopatras Grave, a coffin-shaped rafted block embedded in the pahoehoe floor of a lava tube in a distant part of Catacombs Cave reminded him of an Egyptian sarcophagus (fig. 13). After J.D. Howard's death, Ranger James R. Valentine compiled an interesting document from Howard's field notes and other written observations. It is on file at the monument.

In recognition of this area's spectacular natural features and because of the role they played in the Modoc Indian War of 1872–73 (Riddle, 1914, reprinted 1973; Murray, 1959; Thompson, 1971; Brown, 1970, p. 213–234; Waters, 1981), an area of 76 square mi was set aside by President Calvin Coolidge (Proclamation #1755) on November 21, 1925 as Lava Beds National Monument.

Cave Maps and Descriptions

Most of this report is devoted to the description of selected lava-tube caves in Lava Beds National Monument (herein, "monument" refers to the Lava Beds National Monument). The text for each map is headed with the number and title of the map. The order of presentation is related to the local geography. Caves with easily accessible entrances near Cave Loop Road (maps 1–7, pls. 1 and 2) are most frequently entered by park visitors, so they are described first. Consult the location map of the Cave Loop Road area (fig. 14) to find cave entrances and to understand how the lava-tube systems are related to each other.

Mushpot Cave (map 1, pl. 1) is lighted and contains an underground lecture facility and a trail. The entrance to Mushpot Cave is by a stair through a small hole in the cave's roof located within the parking lot at the Visitor Center. Mushpot, Lava Brook, Arch, and Indian Well, Doc Yock, and Stinking Caves are shown on map 1, plate 1, "Lava-Tube Caves of the Headquarters Area." Map 2, plate 1, "Labyrinth Cave System," continues map 1 to the south. It, too, contains several interconnected but separately named caves. Among its larger segments are Golden Dome, Labyrinth, Hopkins Chocolate, short openings within the Garden Bridges area, and Blue Grotto.

Catacombs Cave (map 3, pl. 1), Ovis Cave and Paradise Alleys (map 4, pl. 2), Natural Bridge area (map 5, pl. 2), Hercules Leg and Juniper Caves (map 6, pl. 2), and Sentinel Cave (map 7, pl. 2) complete the sequence of cave maps around Cave Loop Road. The map of the Natural Bridge area shows the large and spectacular collapse trenches that are one of the main visitor attractions of this particular area. Cave Loop Road changes direction by crossing over a large natural bridge between two of these breakdowns. Several small and short lava tubes, including Juniper Pole and Sunshine Caves, as well as short sections of the large feeder tubes beneath the Natural Bridge, are shown on map 5, plate 2.

Outside of the Cave Loop Road area are several caves easily reached by improved roads: Valentine Cave (map 8, pl. 3), Tickner and Berthas Cupboard Caves (map 9, pl. 3), Heppe Caves and the Mammoth Crater-Hidden Valley area (map 19, pl. 6), Merrill Ice and Bearpaw Caves (map 10, pl. 4), Kirk Whites, Beaconlight, and The Igloo Caves (map 11, pl. 4), Skull Cave (map 12, pl. 4), and Boulevard, Balcony, and Sharks Mouth Caves (map 13, pl. 4).

Silver Cave (map 14, pl. 5), Post Office Cave (map 15, pl. 5), Craig Cave (map 16, pl. 5), Crystal Cave (map 18, pl. 6), and Fern Cave (map 17, pl. 5) are in remote areas or are restricted to entrance only with permission, but these five are among the most interesting in the monument.

The above listing is by no means the order to follow in visiting the caves. A much more logical order for anyone who wants to visit three or four caves to get an overall view of lava tubes would be

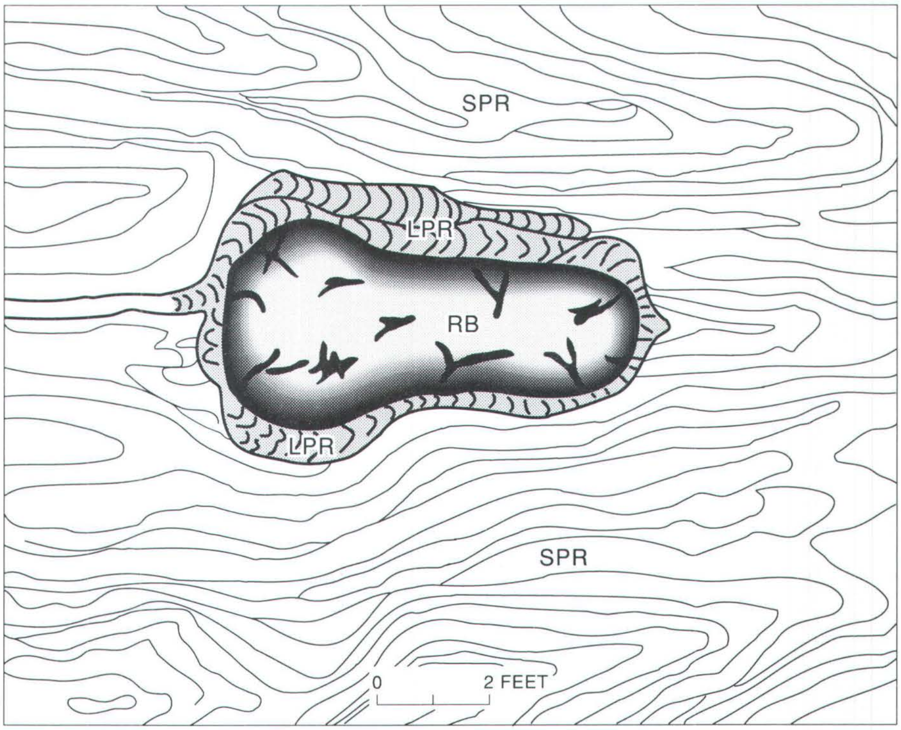


Figure 13. Sketch of rafted block (RB) framed by two large pahoehoe ropes (LPR) projects above a flow of intricately dragged out small pahoehoe ropes (SPR). Coffin-shaped block in Catacombs Cave (see fig. 14) is named Cleopatras Grave (map 3, pl. 1).

Mushpot, Catacombs, Ovis, and Merrill Ice or Skull. Those people with specific interests who may want to spend several days or weeks exploring the caves should first examine the maps and pick out the areas that seem of interest. Perhaps the following brief paragraphs may help to develop a plan that will save time and increase the enjoyment and productivity of your stay:

1. The novice to cave exploration should start with Mushpot and Lava Brook Caves to acquire confidence in traversing and understanding near-surface lava-tube systems. Catacombs is excellent for a followup, and so is Valentine. For examples of deep and large "feeder tubes" start with a small remnant such as Ovis, or Heppe, follow up with Craig, and then graduate by tracing the Cocoa Pipeline, if accessible, through its full length in Post Office Cave.
2. The geologist interested in the mechanics and hydraulics of lava-tube formation and development will find Post Office, Tickner, Berthas Cupboard, Crystal, Skull, Catacombs, and Valentine among the most instructive caves to study. For lava tubes that invaded cinder cones or other tuffaceous sediments see Skull, Crystal, Kirk Whites, Beaconlight, and some small but deep caves (unmapped) near Schonchin and Bearpaw Buttes (Castle and White Lace for example).
3. The student of ice formation within caves will find Crystal Cave of special interest. Access is limited (as of April 1990) to small groups by pre-

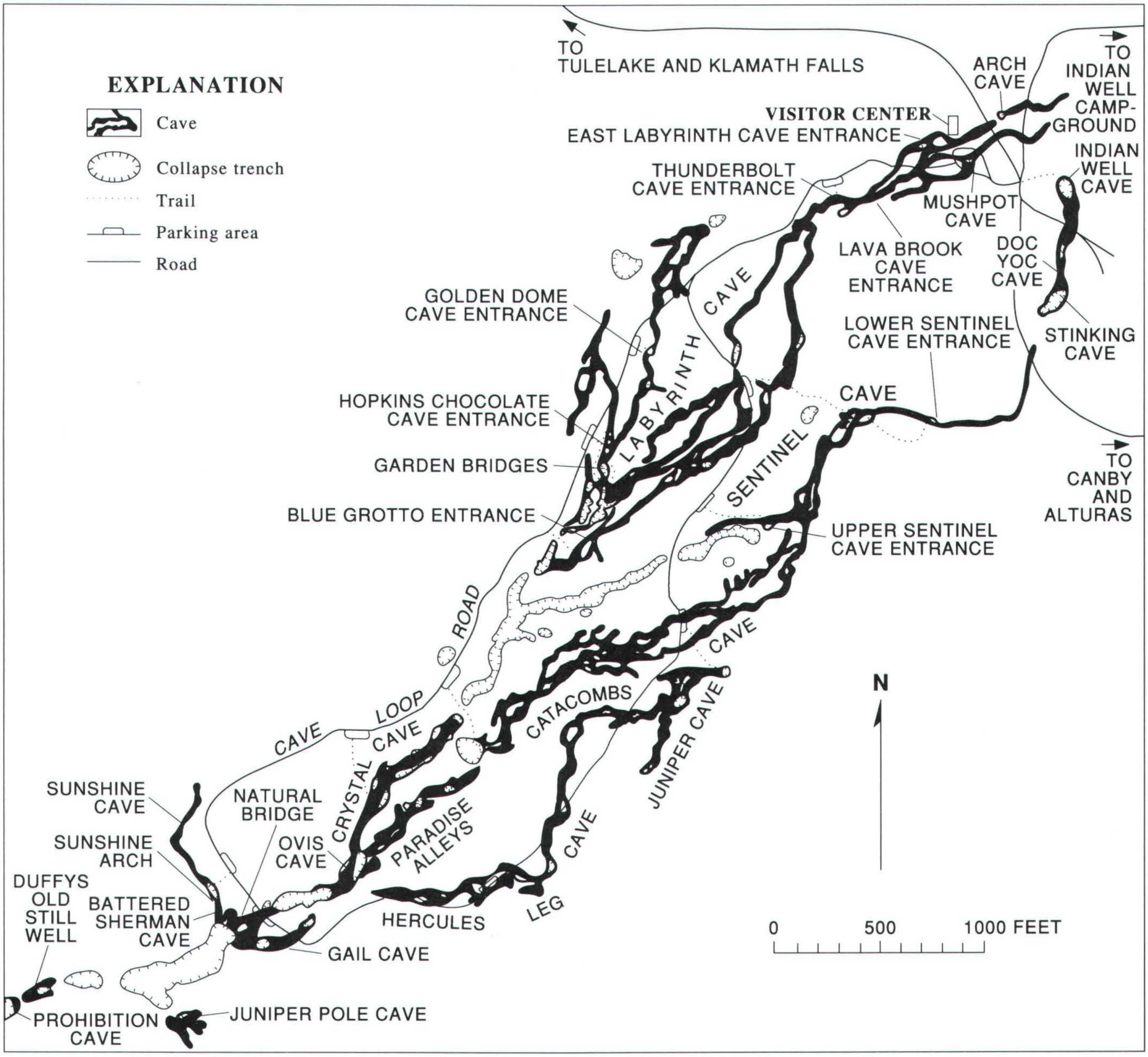


Figure 14. Location map of Cave Loop Road area showing lava-tube systems and cave entrance locations. Unlabeled roads in upper-right corner of map are shown in detail on map 1, pl. 1.

arrangement in wintertime only so as not to damage the fragile ice formations. Other caves that usually contain much smaller amounts of frost and ice are Skull, Merrill Ice, Captain Jacks Ice, Frozen River, Caldwell Ice, and Upper Ice Cave.

4. People interested in early Indian cultures will find the best displays of pictographs in Fern Cave. Other good localities are among the breakdowns between Skull and Merrill Ice Caves, especially near Symbol Bridge. Petroglyphs are well exposed in both Juniper Cave and in a separate and protected area of the monument at Prisoners Rock (fig. 15), northeast of the main area of the monument and 2.5 mi southwest of the town of Newell.
5. Those interested in the microclimate adaptations of plants will find the Garden Bridges, easily reached from Cave Loop Road, a rewarding area. The breakdowns and numerous short cave remnants within a small area provide variations from moist cool air at cave entrances to the dry sun-baked roof tops over caves. Examine the Natural Bridge area as well. Fern cave is named for the large population of ferns (rare in this desert region) that cover its entrance mound. The greenhouse-like atmosphere of this cave is in stark contrast with the dry air above ground. Fern Cave is kept locked, but tours can be arranged by contacting National Park Service personnel at the Visitor Center.

Each cave description herein should be read with the respective map unfolded beside it because most of the text material is tied directly to the map.

Preparation of the Maps

Planetable and alidade traverses were made in mapping the larger lava tubes, and a description of the procedure follows. A station is occupied, and a sight through the alidade is taken on a miner's lamp or flashlight placed at the next station. Distance between stations is measured with a stretched steel tape, and orientation at a new station is controlled by backsight to the former station. Position of the walls is obtained and plotted directly on the planetable sheet: an assistant walks beside the steel tape, carrying a lightweight stadia rod to measure the distance (horizontally at right angles to the tape) of all points where the wall of the cave changes direction. At each of these points he calls out the distance on the tape, and then the distance to the wall, to the person operating the planetable, who immediately scales off and plots this point on the planetable sheet. After both walls have been drawn, the positions of geologic features—such as balconies, skylights, breakdowns, rafted blocks, collapse piles—are plotted, using the stadia rod to measure their outlines with reference to the tape. The height of the ceiling above floor is determined at selected points with the stadia rod held vertically or if the roof is too low, with a folding rule. The heights of benches, balconies, lava cascades, and other salient features are obtained and plotted on the planetable sheet. Thus a rough draft of the map is prepared continuously as the traverse is extended.

Before a traverse of more than a few hundred yards was completed, we nearly always encountered passages too small for the planetable to be leveled on its tripod, or we had to extend the traverse through crawlholes along the side or roof of a cave. In such situations we used cloth tape and a Brunton compass (a compass with attached clinometer to measure angles) to extend the traverse until the planetable-alidade work could be resumed. At first we were concerned about the magnetic errors that might arise from using a Brunton in such close proximity to basalt lava. To our surprise, repeated checks showed that large magnetic deviations are not a problem in caves but are common when a Brunton is used on top of a prominent basalt outcrop. Apparently, this discrepancy is caused by lightning strikes on a surface outcrop of basalt that produce magnetic changes great enough to strongly affect the needle of a Brunton.

Acknowledgments

A project to map selected lava-tube caves within Lava Beds National Monument was initiated by Paul F. Haertel, former Superintendent of the monument, in 1974. At Haertel's request, Aaron

Figure 15. View northeast across Tule Lake to The Peninsula and Prisoners Rock where the Petroglyphs section of Lava Beds National Monument is located. Photograph taken from near Hospital Rock, in northeastern part of monument.

Waters agreed to do the cave mapping and to prepare a report on each major cave. In 1974 Eric Pittenger and William Ruddiman III from Oregon State University assisted in the fieldwork. Jamie Gardner and David Kimbrough from the University of California, Santa Cruz, joined William Ruddiman III and Waters during the 1975 field season. In 1976 Alison Till, also of U.C. Santa Cruz, and Waters returned for one month to complete some details of the underground mapping, and to map some of the important lines of surface breakdowns. The cave mapping was completed and mylar copies of all cave maps and descriptive reports were delivered to the National Park Service in 1977. Subsequent to this work, Julie Donnelly-Nolan began work in the monument in 1979, and that work resulted in a surface geologic map (Donnelly-Nolan and Champion, 1987). She updated the geologic interpretations in this book and added some figures and references. Where interpretations in this bulletin differ from those on the surface map, the interpretation is that of the first author in each case. Bruce Rogers redrafted and added to many of the maps and their descriptions and contributed new figures including many new photographs. Keith Howard reviewed the manuscript. James O. Sleznick, Superintendent of the monument from 1978 to 1986, encouraged publication of the cave maps and descriptions. Janet Sowers and other National Park Service personnel provided useful information.

CAVES EASILY ACCESSIBLE FROM CAVE LOOP ROAD

Lava-Tube Caves of the Headquarters Area

The Cave Loop Road area, south of the Headquarters building, is composed of many small and large lobes of lava, most of which subdivide downstream into new lobes. Many of these lobes contain from one to several small lava tubes, which also may bifurcate and spread out like the distributaries on a delta. Beneath this complex pile of overlapping lava lobes and lava tubes is a chain of large feeder tubes, which delivered molten lava from Mammoth Crater to this area and also far to the northeast. Figure 14 shows some of the complex relations in this set of tubes that originated at Mammoth Crater. Figure 4 shows that this is only part of a much larger array of lava tubes in the basalt of Mammoth Crater (Donnelly-Nolan and Champion, 1987).

Mushpot Cave

The entrance to Mushpot Cave is a hole in its roof, located in the parking lot that serves the Visitor Center and Headquarters building (map 1, pl. 1). This is the only cave in the monument that contains lights and interpretive signs, which point out geologic features. It is an excellent place to get acquainted with lava-tube caves. A staircase leads to the floor of the cave, and from this point one can traverse the main branch of Mushpot lava tube downstream (northeast) for 520 ft. Upstream the tube is blocked 25 ft south of the foot of the stair by a floor jam of broken and deformed lava blocks.

Downstream 65 ft from the entrance the main tube widens into a broad domelike area and is intersected on its southeast wall by another wide tube, which diverted part of the flow in Mushpot tube to the east. Only about 50 ft of the length of this east flowing tube is visible because both upstream and downstream it is filled to its roof with congealed lava. Yet another tube, a small tributary, spilled a thin flow of rough-surface pahoehoe into the main tube at a point low on the west wall 25 ft downstream from the foot of the stairway. This small tributary is accessible only by crawling for 180 ft, where further access upstream is blocked by a lava lobe that leaves just a 6-in. space between floor and roof.

Features Near Entrance

Upon entering Mushpot Cave pause about halfway down the staircase and look around. An open lava-tube cave extends downstream on the right and an alcove extends upstream on the left. Notice that the walls of this alcove are covered with lava dripstone—a thick plaster of sticky lava that oozed and dripped down the wall in thin lobes as the surface of molten lava lowered within the tube. Similar dripstone, somewhat obscured by lichens and dirt, extends to the top of the entrance pit on the east and south; the presence of this dripstone indicates that this entrance was a former skylight—a hole in the roof of the tube that was open to the sky while molten lava was in the tube. Most entrances to lava tubes are not former skylights; they have been opened by collapse of a part of the roof long after volcanism ceased. Actually, some collapse has occurred on the west side of this skylight. Note that this overhanging west edge is not covered with dripstone but instead was pared back by blocks that tumbled from it and were carried away in the molten flood. One large block that fell from this edge was too heavy for transport; it landed on the floor of the alcove at a point just upstream from the foot of the stairs. Examine its rounded top and sides and note that it is completely plastered over with a thin coating of lava which is smooth on the top and pulled into dripstone on the sides. After its tumble this block was completely immersed in the molten lava flowing down the tube.

Descend to the foot of the stairs and inspect the upstream end of the cave before starting on the trail downstream. Looking upstream from the base of the stairs, one of the first things you notice is the feature that gives the cave its name—a small rounded mound of smooth lava with a hole in its top (fig. 16). Sticky lava emerged from this hole, spread radially, and built up a low cone, in the same way boiling porridge spills from an overfilled pot. Peer into the hole at the top of this Mushpot bubble, and you can see at a depth of 2 ft a miniature tube inside the thin smooth lobe of yellowish lava, which floors this part of the chamber. The opening through which the lava porridge spilled out is a skylight on the top of this tiny tube-in-tube. The tube-in-tube developed as a later flow of lava flowed along the larger tube. The Mushpot bubble and the tiny tube-in-tube beneath it were produced by leakage through a lava jam that blocked the main tube. This trickle of smooth yellow lava can be followed down the floor of Mushpot tube, as a narrow lobe, to its terminus about 20 ft downstream from the stairway (west of the trail).

Crouch beside the Mushpot bubble so you have a clear view upstream (south) and you will see the lava jam blocking the tube (fig. 16). Filling a 3-ft space between floor and roof of the tube is a jumbled mass of frothy and distorted lava blocks—the crusted-over surface of a moving flow that broke and stuck, creating a constriction comparable to an ice jam in an Arctic river after the spring thaw. Note that the roof of the cave against which the lava has jammed is covered with lavacicles, some of which punctured the rising lava-jam blocks. Notice that these lavacicles embellish the roof of the cave not only here, but also above the Mushpot bubble and down the course of the Mushpot tube. The lava jam blocked the tube for only about 30 ft; the upstream area beyond this jam is in Lava Brook Cave (map 1, pl. 1).

High-Lava Marks

Another important feature well displayed in the area that contains Mushpot bubble is a high-lava mark, similar to that of a flood mark left by a river. One high-lava mark is present 20 in. above the floor on the east wall of the tube in the alcove containing the Mushpot bubble. It marks the maximum depth of lava before the jam blocked the tube. Note that the mark is plastered across the dripstone wall of this alcove. One small patch of dripstone at the south end merges with the high-lava mark, and one small tongue of dripstone that slid off the side of the fallen block at the stairs is younger. These small patches of dripstone may be from lava that splashed up onto the wall by violent emission of gasses ("fountaining") of the flow that produced the high-lava mark. Follow the high-lava mark downstream—it is not continuous because it is covered or removed in places by collapse or by human activities connected with trail construction. It slopes downstream, but at a lower gradient than the surface of the flow that now forms the floor of the tube. At the Mushpot the high-lava mark is 20 in. above the floor. Where the intersecting distributary tube takes off into the east wall 80 ft farther downstream, the high-lava mark is 6 ft above the floor and five other faint high-lava marks visible below it mark brief halts in the lowering of the lava flood. Three of the most conspicuous ones are present on the peninsula-like hump that flares out from the wall of the eastern distributary at the junction of the two tubes. Trace these high-lava marks back upstream toward the Mushpot and note that all converge southward. To the north, the top one rises to the roof of the tube; the trace of this high-lava mark indicates that below this point the Mushpot tube was completely filled with lava.

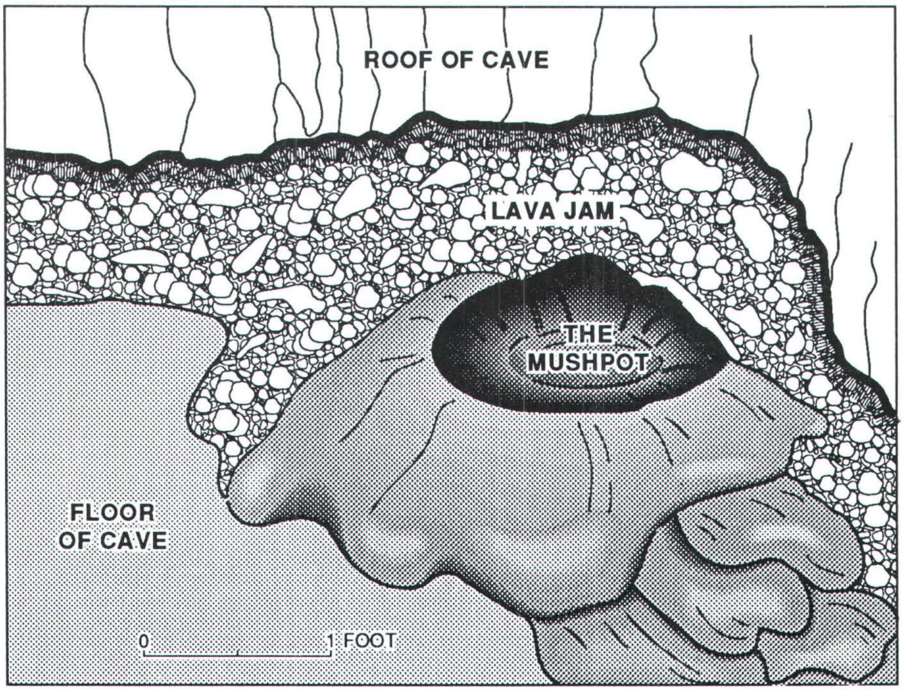


Figure 16. Drawing of Mushpot bubble, which was formed by overflow through tiny hole in small lava tube. The small lava tube was formed by trickle of lava that leaked through the floor jam of blocks which forms the upstream termination of Mushpot Cave (see map 1, pl. 1).

Eastern Distributary

The Mushpot tube is abnormally wide in the area where it is joined by its western tributary and its eastern lava-filled distributary (see map 1, pl. 1). Note also that the roof is abnormally high, 9–13 ft, over the eastern half of the tube in this area but is abnormally low (3–4 ft) in the western half of this wide tube, providing only crawlspace. Three pillars connect roof and floor in the western part. Directly across Mushpot tube from this area of pillars, the large distributary tube takes off into the eastern wall. It is larger than Mushpot tube but is filled almost to its roof with lava. Its roof is only 3 to 4 ft above its floor at the junction with Mushpot tube, but downstream 35 ft east of Mushpot tube the roof rises to a maximum height of 6 ft in a partly collapsed dome. The northern half of this dome was destroyed by a roof collapse before the final flow of lava occupied the tube. The swirling action of spiny pahoehoe against the collapse blocks left a high-lava mark 1–3 ft above the present tube floor. Collapse blocks above this high-lava mark are loose and were never covered by lava. East of the collapse pile the floor of congealed lava intersects the top of the tube in a wide arc, but at the northeast corner the pahoehoe surface swirls to the right, the tube steepens, narrows, and is closed shut in the top of a cascade of spiny pahoehoe.

From these relations, it seems apparent that the eastern distributary is a somewhat older and deeper tube than the higher Mushpot tube, which collapsed into the distributary in the general area where the Mushpot tube expands to 40 ft in width. The low roof over the west side of the Mushpot tube is, therefore, the continuation of the eastern distributary roof, upstream from the point where the two tubes merge. Lava from Mushpot tube filled the lower distributary tube to its roof, except for the low-ceiling area on the west side of the enlarged Mushpot tube and the 50 ft that the distributary tube extends to the east. Detailed evidence of exactly how the two tubes joined is obliterated by the deep lava fill in the lower tube, but enough of the roof remains to establish the overall relation of one tube to the other.

Western Tributary

The western tributary is a small tube, less than 6 ft wide and 3 ft high. It is floored by a small stream of spiny pahoehoe, in places only a few inches thick. In the upper part of the tube the lava flowed along an incline of 11° for 54 ft. A traverse up this tube is strictly a crawl; in only one spot, adjacent to the small pillar halfway along this passage, is it possible to stand upright. Access to Lava Brook Cave is blocked upstream by a passage less than 6 in. high, but this same point can be approached in the tube's continuation for 20 ft as a distributary from Lava Brook Cave.

Balconies and Skylights

Downstream along the Mushpot tube trail, beyond the complex area of tube junctions, are three features that interrupt the smooth contours of the cave's arched roof and walls.

The largest is a balcony located 130 ft downstream from the cave entrance. It hangs as a graceful semicircle 9–12 ft above the floor of the tube. The smooth upper surface of the balcony is plastered against the upstream half of a dome in the roof of the tube. It probably formed when a lava pool filled most of the tube completely but rose only part way to the top of the dome. Cooling lava at the top of the pool evidently attached to the tube walls and formed a narrow platform. Before thickening, the lava beneath the platform drained out of the tube and left the platform hanging at its present level. This crescentic balcony overlooks the underground lecture hall on the floor of the cave.

A second feature in the cave's roof is located another 160 ft farther downstream. It resembles part of a culvert from which the bottom half has been removed. This rounded ceiling channel can be followed for 35 ft along the top of the larger tube, until it turns into the south wall and is lost within a few feet under a plaster of dripstone. It definitely records the presence of a small open lava tube, only about 8 ft in diameter, whose floor collapsed into the large Mushpot tube below.

The third and highest feature is a niche in the south wall 17 ft above the tube floor. This niche is part of a high and narrow cupola in the tube's roof. It is located at the sharp bend 150 ft upstream from where the main tube is blocked by ponding of lava. The cupola and niche probably are a roofed-over skylight in the tube's ceiling. Its original walls are obscured by a plaster of dripstone. Many of the thin plates of lava that formed by the bridging of congealing lava in skylights—as observed on active lava tubes in Hawaii (Greeley, 1971b, 1972; Peterson and Swanson, 1974)—are clearly visible as horizontal ridges partly smoothed over by the dripstone plaster. Repeated freezing-over of the lava surging within this narrow skylight built a cover across a hole, which formerly opened to the surface. When the lava in Mushpot Cave withdrew to its present level, only a cupola and niche in the wall remained to indicate the position of the roofed-over skylight. Today an electric light illuminates the niche. Downstream from this point the trail ends. Though the ceiling is low, you can still crawl for another 100 ft by avoiding two areas of collapse blocks. The tube is closed by a lava filling to its roof.

Dripstone and Lavacicles

Both Mushpot and Lava Brook Caves provide such excellent examples of dripstone and lavacicles (such as those shown in figs. 8 and 9) that further descriptions and locations of these features are useful. Fine examples of lavacicles cover the large domes in the area where Mushpot tube widens at its junction with the eastern distributary. Excellent places to study them more closely at eye level can be found along the main tube roof throughout its length, except in areas of roof collapse. In these areas, many stages and changes in the development of the lavacicle and dripstone plaster are recorded. Many interesting patterns result from the response of molten lavas of varying viscosities to the pull of gravity. On steep and smooth walls, pull-out patches in the dripstone are common (fig. 11). Fine examples of such sloughing are present on the southeast Mushpot wall between the large balcony and the roofed-over skylight. Good examples of pull-out patches from a lavacicle-covered roof can be seen on the high domes in the tube junction area. Other interesting forms, better seen in Valentine and Post Office Caves, are near those high-lava marks where the moving lava dragged and distorted hot and sticky dripstone. In places the dripstone is sheared into narrow benches and strips or broken into foliated masses.

Caliche, False Gold, and Phosphorescent Deposits

Changes after solidification also produce interesting patterns superimposed upon the lavacicles and dripstone. Water from rain and melting snow seeps down into the caves and then may spread out, wetting the surface of the lavacicles and dripstone. Some of this water evaporates and leaves a thin coat of caliche (calcium carbonate plus minor amounts of other soluble salts and clay) as a white filigree-like tracery upon the dark lava surface beneath (fig. 17). Excellent examples of this lace-like natural ornamentation can be seen on both walls of Mushpot Cave between the large balcony and the roofed-over skylight. J.D. Howard gave the name "White Lace" to a cave with walls of this kind of caliche. If cave walls are completely covered with white caliche, they may show a silver or pale-blue sheen when wet. This phenomenon is the source of the names "Silver Cave" and "Blue Grotto."

In some areas (notably in parts of Catacombs, Labyrinth, and Valentine Caves) the caliche is pale buff or tan to chocolate brown instead of white because of a higher content of clay, soil humic acids, hydrous iron oxide stains washed in with the calcium carbonate, and the growth of "lava-tube slime" (bacteria and primitive fungi) on the moist walls. Water droplets on this fungi-rich caliche may glow like polished gold when a light is played upon them (fig. 18). This "false gold" is sometimes visible in wet areas of Mushpot Cave and is beautifully displayed on the moist roof and walls of Golden Dome, Hopkins Chocolate, and Valentine Caves.

Another uncommon but interesting secondary effect, visible in near-surface caves with wet floors, is a flickering greenish glow along the floor, which appears to change color and intensity as light is played upon it. This is phosphorescence derived from the decay of animal droppings on the cave floor, and it is occasionally seen in wet parts of Valentine Cave.

Lava Brook Cave

The entrance into Lava Brook Cave (map 1, pl. 1), like Mushpot's, appears to have been a skylight when the lava tube was active. The hole is so small that the two steep stairs built into it—one leading downstream, the other upstream—obscure the walls; however, some dripstone is visible and extends to the surface.

Three Junction Area

For the first 50 ft downstream from the entrance stair, Lava Brook is a small lava tube that is about 8 ft wide, 5–6 ft high, and cluttered with collapse blocks. It then makes an abrupt turn to the right (southeast). Its gradient steepens, and it throws off two small distributary tubes from its left side. The first one, located exactly at the bend, is a small crossover tube that leads to the entrance of East Labyrinth Cave (see map 1, pl. 1).

This crossover tube leaves Lava Brook by dropping abruptly in a 5-ft lava fall. The tube is so narrow and low that it requires stooping or crawling for much of its 125-ft length. In places it is so cluttered with collapse blocks that, except for another lava fall about midcourse, there is nothing to see except collapse features.

The second small distributary heads in the same direction from a point 10 ft farther down the Lava Brook tube. It also immediately drops in a 3-ft lava cascade. Ceiling heights are only 3–4 feet, but the tube is free of collapse blocks and displays fine examples of lavacicles, dripstone, and pahoehoe. After crawling for 32 ft, you will find this direction blocked by lava up to the roof, but the pahoehoe stream that formed the floor actually turns sharply to the left (north), drops abruptly 3–4 ft below its upstream floor, and resumes its course to the northeast. Further access is denied only a few feet beyond the northeast turn by the lava that rose to within 6 in. of the roof. By plotting this point on the maps we found that this tube is the upstream continuation of the tiny tube up which we had

Figure 17. White caliche deposit along crack in wall of Post Office Cave (see fig. 4 and map 15, pl. 5). This cave deposit was formed by evaporation of percolating surface water carrying calcium carbonate.

Figure 18. False gold cave deposits on wall of Golden Dome Cave (see fig. 14 and map 2, pl. 1). Deposit consists of thin coating of fungi-rich caliche. Field of view is 6 ft across.

crawled 180 ft from the Mushpot tube. Access is blocked for less than 20 ft between them.

Twin Pillars-Sleeping Beauty Area

Returning to the main Lava Brook tube and continuing downstream, we come to two small pillars, with a nest of intersecting benches and lava tubes around them. To understand this complicated area, carry the map and refer to it constantly while examining this part of the cave. The first feature to note downstream is a lava bench, 2 ft high, which begins on the left (north) wall 12 ft downstream from the head of the tiny tube described previously that leads from the Mushpot tube. Beyond this bench the left wall of the tube turns due east, whereas the opposite wall diverges southeast. The main lava channel follows the southeast trend and is bounded on its north side by the lava bench. The gradient steepens, and as the channel deepens the bench of its left side subdivides into two benches; the lower bench ultimately rose 4–5 ft above the floor of the tube downstream. Because of the divergence in direction of the tube's walls, the benches soon widen to a maximum of 18 ft. At the point of divergence, twin pillars connect both benches with the roof of the cave. The higher bench is attached to the north side of the smaller (northern) pillar, and the lower bench clings to the southwest side of the larger pillar. Between the two pillars is a deep cleft. An early rush of molten but viscous magma, which formed the higher bench named "Sleeping Beautys bier," rose in a standing wave 2 ft high and stuck in the upstream end of this cleft. It thus protected the deep cleft from further invasions of molten lava while the benches and channel were built. Moreover, a small tributary from the north was also spilling lava into the main Lava Brook tube just at the downstream edge of the pillars. As the lava from this tributary decreased in volume it carried away what may have been molten or sticky continuations of the benches downstream from the pillars. The same kind of action was probably occurring on the edges of the Lava Brook channel simultaneously. The lava from this tributary appears to have been fed from a tube-in-tube (now filled in), but the last lava emitted cascaded in a curving steep-gradient gutter, which today resembles a ramp making a left turn to join a freeway on a lower level. A further complication is that a much larger tributary joins the Lava Brook tube from the opposite (south) side at the same point. The pahoehoe floor of this tributary tube is at the level of the lower bench, so its mouth hangs 3 ft above the Lava Brook channel. The exact order in which these different benches, gutters, and channels were built is perplexing, but the order of their final abandonment by liquid lava can be worked out. Lava stopped flowing from the south tributary first, then from the main Lava Brook tube, and the final driblet down the tube was out of the curving lava gutter that drained the north tributary.

Mushpot-Lava Brook Floor Jam

Continue down from the Twin Pillars through the main Lava Brook tube on a traverse that runs slightly north of east for 110 ft to where a big tributary intersects this tube from the south. Along the first 80 ft of this traverse, Lava Brook is an ordinary clean tube exposing good lavacicles, dripstone, and a spiny pahoehoe floor. Two long remnants of the 3-ft bench cling to its south wall. About 80 ft below the Twin Pillars the roof of the cave begins to lower, and the lava on the floor pooled and broke up into blocks, which were heaved up in a semisolid state and deformed against one another. Another 5–10 ft farther, these broken and distorted blocks were raised in two giant steps by molten lava, and finally a little farther downstream the heaved blocks were rebroken and jammed tight against the roof. This is the opposite side of the lava jam just upstream from the Mushpot bubble. Access between the two caves is barred by the lava jam over a distance of approximately 30 ft (see map 1, pl. 1). Curiously, no clear evidence was seen that molten lava backed up high enough to fill the tube behind this dam. Apparently the floor jam did not form until the final stages of lava occupancy. The last of the molten lava trickled between the floor jam blocks and formed both the Mushpot bubble and the small lobe of yellowish lava that extends downstream from it.

South Tributary

On returning to the Lava Brook entrance, a side trip to the head of the south tributary is worthwhile, although for about half its length you will have to walk in a stooped position and crawl over the last few feet.

As previously noted, a step up a 2- to 3-ft scarp is required to enter this tube. One can then continue upstream in a particularly clean cave with a well-exposed ropy pahoehoe floor. At 120 ft the source of the lava that built this floor is evident. It is a thin flow that debouches from a gutter down the middle of the tube, leaving benches of older lava on either side. In another 60 ft the entire tube appears to end bluntly in a rock wall, beneath which the gutter disappears as a tube-in-tube. However, there is a narrow opening along the right (north) side of the cave, and by climbing up over a 5-ft lava fall, one can squeeze through and find that the tube opens up to its full width upstream at a level 5–7 ft higher. A small linear breakdown in the floor indicates that the gutter we followed to the lava fall continues beneath the higher level as a tube-in-tube. This upper tube is only 40 ft long. It ends in a wall from which several large blocks have tumbled, revealing an unusually clear example of a tube that had been open at one time but that is now completely plugged with lava. The tube received a tributary from the south, 10 ft downstream from this wall. Solidified lava chokes this tributary nearly to the roof, but by crawling into it and poking a stadia rod out as far as it would go, the shape outlined on the map was obtained. The direction of flow was noted from the pahoehoe ropes.

Lava Brook Cave Upstream from Entrance

The upstream part of Lava Brook Cave is an ordinary tube with a steeper gradient than most other tubes. Upstream

120 ft from the entrance a distributary takes off to the south but ends within 20 ft. Before it ends, however, a narrow gutter plunges beneath its floor, and because this place is only 20 ft from the upstream end of the south tributary tube (see map 1, pl. 1), it appears fairly certain that this is the same tube-in-tube, which broke out as a gutter on the floor of the south tributary just below the 5-ft lava fall.

Upstream 220 ft from the Lava Brook entrance, the Lava Brook tube merges with a collapsed section of the Thunderbolt Distributary. Instead of returning to the Lava Brook entrance from this tube junction, it is more interesting to complete a traverse by turning north and following the Thunderbolt tube downstream and exiting at the East Labyrinth entrance. This section of the Thunderbolt Distributary is known as the East Labyrinth Cave, and it is by far the most interesting part of this tube.

Area Near Thunderbolt Entrance

The area near Thunderbolt entrance (southwest corner, map 1, pl. 1) has undergone extensive roof unraveling. Daylight is visible through cracks and some small holes in the roof, which is barely 2 ft thick.

Thunderbolt Distributary (East Labyrinth Cave)

The junction of the Lava Brook tube and the Thunderbolt Distributary is approximately midway between the Lava Brook entrance and the Thunderbolt entrance. As you round the corner from Lava Brook Cave and start downstream into the Thunderbolt Distributary, this section of the tube is called East Labyrinth Cave. The last flow of lava to occupy this distributary went down the Lava Brook tube because the downstream continuation of the Thunderbolt Distributary was blocked by a widespread floor jam. You must pick your way over and around this large jam of disrupted floor blocks for 25 ft. At the downstream end of the jam the two obstructions that caused the lava to jam up are obvious. First, the main flow of lava collided at a 45° angle with and piled up against the east wall of the Thunderbolt tube. Second, the Thunderbolt tube narrows greatly here and opens downstream from this point as a gutter only 4–5 ft wide, with benches 4 ft high on either side. The last flood of lava was not able to turn sharply and pour through this narrow passage. It piled up into a jam of blocks, increased the obstruction, and forced all the late flow into Lava Brook tube.

Continuing downstream below this floor jam, we find that the gutter in Thunderbolt's continuation (East Labyrinth Cave) was roofed over as a tube-in-tube at one stage in its history, for a natural small bridge connects the two benches just downstream from the lava jam. In another 20 ft the gutter widens to 5 ft—the full width of the tube—and the benches are discontinuous from here downstream. One bench, on the southeast side, consists of a pile of roof-collapse blocks that were overridden and smoothed out along the tube by moving lava. Where the tube bends, the benches end, and the tube continues almost due north. Benches are absent here, and most of the cave's floor is cluttered with blocks that have tumbled from the roof after volcanism ceased.

Upstream 130 ft from the East Labyrinth entrance is a gutter with benches on either side called Jupiters Thunderbolt. It reappears in the middle of the tube, extends for 50 ft, then dives into the floor on the west wall to continue as a small open distributary branch at a slightly lower level. This distributary is too small to traverse without crawling. Rubble from collapse litters the next 100 ft of the main tube from this distributary junction northeast to the East Labyrinth entrance, where caving-in of the roof has breached the surface.

Downstream from East Labyrinth Entrance

The tube downstream from the East Labyrinth entrance splits into two branches around a pillar 100 ft long and 60 ft wide. Neither branch can be negotiated without a tight crawl, and when you can finally stand you are in a wet section of the cave that receives percolating wastewater from the facilities at the Headquarters building and the Visitor Center. Farther northeast the tube widens and exhibits interesting pillars and benches before ending in a lava seal 60 ft from Arch Cave.

Arch Cave

Arch Cave (map 1, pl. 1) is entered through a hole 7 ft wide but only 3 ft high. The cave is the eastern continuation of the East Labyrinth lava tube. It can be traversed for 335 ft and has some very interesting features that can only be reached by stooping or crawling through about half the length of the cave. After 100 ft of low-ceilinged passage you come to a floor jam of lava blocks tilted into an 8-ft lava cascade that leads into a room with a 13-ft ceiling. The cascade marks the place where this shallow, near-surface tube broke through its floor into a larger tube below. Within this room, a pool of lava 10 ft deep fluctuated up and down for some time as shown by high-lava marks on the walls. Marks are also on the walls of another 14-ft-high but smaller room 75 ft farther downstream. In this second room lava dripped down the side of the cave in three small lava cataracts (see map 1, pl. 1). This lava was funneled through cracks in the high-level bench as the lava surged up and down within the upper chamber.

Downstream from this second chamber the tube narrows markedly into a short crawl passage with a ceiling only 2–3 ft high. It then opens up into a "keyhole" passage. This narrow tall tube probably formed by the merging of two levels whose walls were later lined by successive layers of lava plaster. Many layers of this plaster pulled away from the walls while still sticky and coiled down the walls like a jelly roll. Others curled over and broke off or were slowly let down onto the floor in wavy and wrinkled masses as the lava flowed out from beneath them (see fig. 19 and the cross sections on map 1, pl. 1). This keyhole-shaped tube with its strange peeling and curling walls of lava plaster can be traversed for 80 ft. At its end the tube plunges steeply, apparently down a lava cataract, to where the curling masses of plaster clog its continuation completely.

Near-Surface Nature of the Headquarters and Labyrinth Area Tubes

From our investigations of these Headquarters area lava tubes, one conclusion needs to be emphasized: all of them described so far, with the possible exception of the eastern distributary of Mushpot Cave, are small near-surface tubes. If you compare map 1 and map 2 (pl. 1), it appears at first glance that all of the lava active in making the remarkably extensive bifurcating caves of the Labyrinth area was finally funneled downstream into the tiny single tube containing the Thunderbolt entrance. This interpretation is, of course, nonsense. What is missing in such an analysis is the fact that nearly all the tubes in both Labyrinth and Headquarters areas disappear downstream because lava filled to their roofs; thus, further tracing of them is impossible. Only the parts that have drained out after cessation of volcanism can be entered, mapped, and studied.

Unquestionably, deep beneath the Headquarters area are scores of tubes filled to their roofs with lava. One example we studied is the eastern distributary of Mushpot Cave, where 70 ft of the roof of a deeper, now-filled tube is visible. We also traced Mushpot, parts of Lava Brook, and Arch Caves downstream to where they are filled with congealed lava.

Well over 85 percent of the deep underground lava "plumbing" system in Lava Beds National Monument was filled with congealed lava and is therefore inaccessible. But accidents of various kinds have, in places, preserved short sections of intact lava tubes. Examples of large remnants in the monument are Crystal, Craig, and Post Office Caves. Indian Well (map 1, pl. 1) and Sentinel Caves (map 7, pl. 2) are easily accessible small remnants on a line upstream with Ovis Cave, Crystal Cave, and the deep tubes underlying Natural Bridge. Downstream their extension can be traced by breakdowns at the entrances into Post Office and Silver Caves and eastward to a possible junction with Craig Cave.

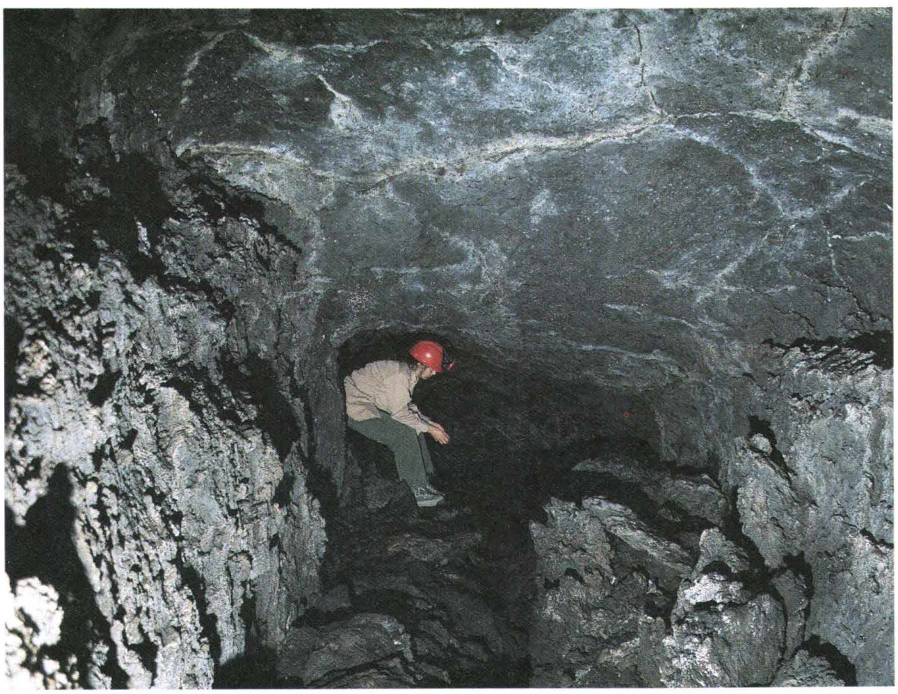


Figure 19. Interior of Arch Cave (see fig. 14 and map 1, pl 1) showing jagged benches and heaved and broken floor.

We now turn to a description of a much collapsed and battered small remnant of two large tubes within this long chain of breakdowns—Indian Well Cave.

Indian Well, Doc Yock, and Stinking Caves

Eastward approximately 450 ft from the Visitor Center, and across the main road at the head of a deep breakdown, is Indian Well Cave (see map 1, pl. 1). This cave is very different from the near-surface small-diameter caves described previously. J.D. Howard named the cave Indian Well because of the pool of water that develops in the deep central part of the cave after the spring runoff. The pool is not permanent; in many years the water is lost by evaporation or downward percolation within a few weeks to a month. Nevertheless, in this dry area of no surface streams, it has furnished a welcome supply of water to both animals and humans.

The entrance to Indian Well Cave is spectacular. At the south end of the breakdown a sliced-off section of the upper half of the lava tube rises over the pile of collapse rubble on the tube's floor in an impressive arch, 60 ft wide and 20 ft high. Continuing southward into the cave, the walls narrow until, 55 ft from the entrance, the cave is only 30 ft wide. It widens again where the west wall and part of the roof have slumped inward and dumped so much rubble into the cave that the trail must turn and hug the east wall to avoid it. Throughout the first 120 ft of the cave no original features (such as lavacicle roof, dripstone walls or pahoehoe floor) are preserved, except as broken fragments on the ends of fallen blocks. The floor is a hummocky blanket of collapse rubble, and both roof and walls show places where large blocks have tumbled to the floor. However, 125 ft from the entrance, an alcove extends into the east wall of the cave 10 ft above the rubble-covered floor. This remnant of lava bench is the only primary feature found in this part of the cave (fig. 20).

At the south edge of the alcove the rubble on the floor of the cave drops off abruptly to the south in a low scarp, which grades into a steep rubble slope. The trail negotiates this steep slope by stairs, which end on a platform built on the floor next to the pool basin for which the cave was named. The floor of this ephemeral pool is a smooth oval saucer 20 ft long and 15 ft wide. It is white from the caliche efflorescence precipitated by evaporating water. This deposit of calcium carbonate, along with clay washed down into this spot during the spring snowmelt, gives the bottom of the basin enough of an impermeable seal to hold water through part of the summer season.

The pool occupies only a small part of this deep central depression, which continues 60 ft farther south to where the floor rises abruptly in a steep rubble slope. How could this deep depression form at the bottom of a higher lava tube that transmitted molten lava to the north? Part of the answer becomes clear when we examine the pool basin in more detail. On the east, north, and on part of the northwestern margins of the pool is a rock lip overhanging the surface of the pool but no more than 4 ft above the bottom (see heavy dashed line on map 1, pl. 1). Apparently this is the roof of a second large tube, at a lower level. The deep depression in the central part of the upper tube was caused by its floor giving way and tumbling piecemeal through the roof of the tube below.

When did this collapse happen? Evidence is equivocal, but at least a part of the collapse occurred while the lower tube was filled or nearly filled with flowing lava. Many of the collapse blocks, and all of them in the immediate area of the present water pool, apparently were carried down the tube by this flowing lava. Supporting evidence is that the caliche and clay which helped form the basin of the water pool were not deposited on an irregular heap of large fallen blocks, but they were instead deposited on a relatively flat surface. The lateral extent of this flat surface and the lavacicle roof above it can be investigated by poking a long rod between roof and floor. In several places a 15-ft stadia rod can be extended all of its length. This must mean that the lower tube is now filled almost to its roof. The blocks, which poured through this hole in the roof when the collapse occurred, did not jam but were transported down the lower tube. They were later enveloped by the ponding lava, which nearly filled the tube when it cooled. Such relations are not unusual in lava-tube caves. Clearer evidence of such transport can be seen in Post Office, Catacombs, Valentine, Berthas Cupboard, and many other lava-tube caves.

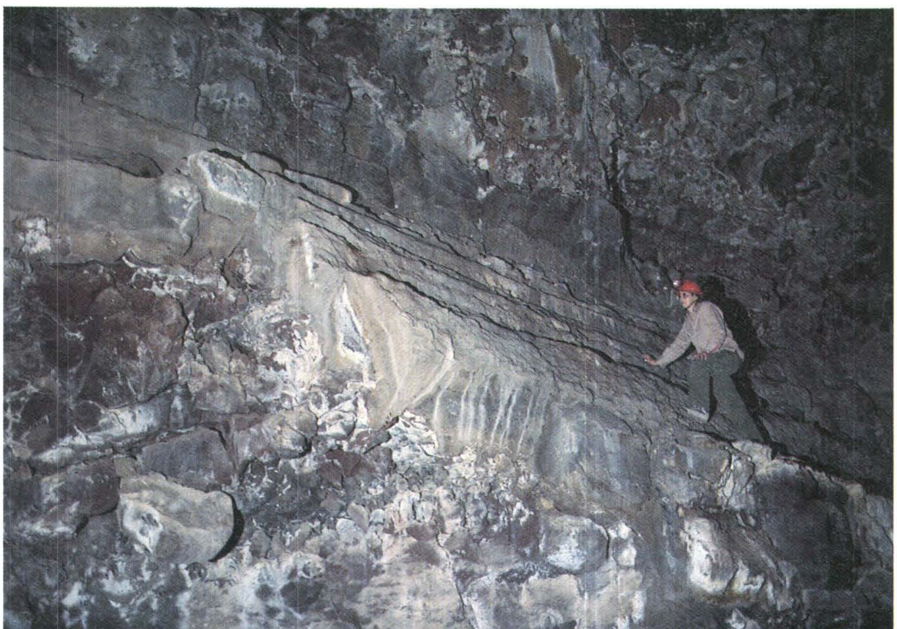


Figure 20. Much of original wall lining has collapsed but some remains on wall of Indian Well Cave (see fig. 14 and map 1, pl. 1).

The trail ends at the foot of the stairs, but the remaining 150 ft of accessible cave to the south is easily traversed if one does not mind climbing over large jumbled blocks. High on the west wall in this part of the cave are remnants of a balcony that runs along most of the wall, buried by slides near the middle and the south end.

At the south end of the cave the floor rises higher and higher until it ends in a clutter of huge blocks not far below the surface of the ground. A small dug-open crawlway serves as an egress out into the collapse fill at the north end of the Doc Yock-Stinking Cave breakdown.

In summary, Indian Well Cave is a 300-ft-long remnant of a part of two superposed large feeder tubes. Only the upper tube can be traversed. It has been so modified by rockfalls from its roof, slides through its west wall, and the collapse of 60 ft of its floor into the lower tube that almost nothing but collapse features are visible. A little of the intact roof of the lower cave can be seen in an overhang just above the floor of the water pool in the deepest part of the cave.

Doc Yock Cave is a continuation of the upper level of Indian Well Cave. As in Indian Well, the cave has undergone massive collapse with most of the resulting breakdown falling into the lower tube levels. A short intact segment of tube complete with several rafted blocks and a pahoehoe floor is present at the upper southern end of the cave. Judging from this intact segment of Doc Yock Cave, the original tube was 21 ft wide and probably in excess of 17 ft high.

Stinking Cave is a further extension of the Indian Well-Doc Yock Cave tube. In cross section the 128-ft-long cave is shaped like a tall rectangular canyon, with little collapse except at the ends. The northern end lies partly underneath Dock Yock Cave and probably represents a middle level in the tube system. It is closed by the deep collapse of the tube at the southern end of Indian Well. A short lower segment of passage just inside the entrance may represent a lower level of the tube. The southern entrance of Stinking Cave shows approximately how much the cave passage has collapsed laterally. The main tube is a fairly uniform 9 ft wide until it approaches the Stinking Cave collapse, where it flares to a width of 39 ft. Many thin linings of lava can be seen in the alcoves just inside the entrance arch; progressive collapse of these shells resulted in the very wide entrance arch.

Labyrinth Cave System

The line of collapse trenches (or breakdowns) along which Indian Well and Sentinel Cave lie intersects the Cave Loop Road area (fig. 14) at Natural Bridge and continues northeast past Ovis Cave for 2,100 ft. There, the tube that collapsed to form the collapse trenches divides into two major distributaries. Looking downstream, the one on the right appears to be the larger of the two. It extends northeast and is marked by an almost continuous line of collapse trenches for 1,250 ft. Farther northeast, a few large segments of its roof survive along a continuing line of trenches. Sentinel Cave, which consists of at least three partially collapsed feeder tubes stacked one on top of another, is a roofed-over section of this distributary system. Indian Well is the next cave that interrupts the line of breakdowns to the northeast.

The left and smaller distributary (which divides into the Labyrinth Cave system) takes off on a more northerly course. Unlike the Sentinel distributary, additional distributaries diverge from it. By the time this northern line of collapse trenches, natural bridges, and partly collapsed caves reaches the northern end of the Garden Bridges area 900 ft downstream from its junction with the Sentinel distributary, it has subdivided into six major distributaries. Most of these branches, however, maintain connections with their neighbors through secondary distributaries and crossovers (see fig. 14 and map 2, pl. 1).

Nearly all this network of lava tubes lies close to the surface and many roof collapse openings provide additional entrances. To the early explorers who lacked maps, these interconnected but outward-fanning underground passages seemed a complicated maze, although in reality they form an orderly distributary pattern. It is not surprising that the name "Labyrinth Caves" appears in the notes of J.D. Howard, who explored and measured the length of many Labyrinth passages between 1918 and 1933. Some of the Labyrinth System caves, however, were known to Native Americans and early settlers long before Howard's work. E.L. Hopkins explored Chocolate Cave in 1892 and named it for the chocolate-colored "mud," which coats roof and walls of parts of this cave during the period of snowmelt or after heavy rains. Other names in common use for parts of this system are Blue Grotto, Garden Bridges, Golden Dome, Hopkins Chocolate Cave (also called Hopkins Chocolate Cup), and Thunderbolt. Lava Brook, Mushpot, and Arch are the Labyrinth tubes that reach farthest northeast before filling with lava. These names and the features to which they apply are shown on figure 14 and maps 1 and 2 (pl. 1). The Garden Bridges is an area of collapse trenches and natural bridges from which the Hopkins Chocolate Cave and Golden Dome Distributaries split and fan out to the north. The true Labyrinth area lies east of Garden Bridges where the name Labyrinth is used in a more restricted sense for the maze of interconnected tubes on different levels. Finally, two very long distributaries (Thunderbolt and Labyrinth), which carried a small part of the reunited lava flood northeast into the Mushpot-Lava Brook-Arch Cave area, complete the Labyrinth distributary system.

The divergence of the main Labyrinth feeder into six large branches lies within an area only 650 ft long and 150 ft wide. From here the tubes fan out to the north and northeast (fig. 14). The tube in Arch Cave that is filled with lava (see northeast part of map 1, pl. 1) can be traced south and southwest through the Thunderbolt Distributary (map 2, pl. 1) and into the Labyrinth, a distance of more than 3,800 ft. Most tubes of the Labyrinth, however, are inaccessible due to lava filling and collapse over short distances.

Garden Bridges Area

The name "Garden Bridges" (map 2, pl. 1) is applied to the region characterized by many large oval breakdowns separated by natural bridges, within which the original Labyrinth parent tube subdivided into six main tubes and several minor ones (fig. 21). During the time since lava drained from these tubes, the weak roof above most of the junctions, as well as above wide parts of the tubes, has collapsed. The result is many large oval collapse pits between short stretches of lava tube forming natural bridges. At the ends of some collapse pits, debris has piled up to ground level. Between such pits natural bridges probably exist, but entrance to them is blocked by talus. Many, however, are open; a climb over a loose pile of talus will generally reveal an entrance to a short section of lava tube.

Geologically, most of these short sections show only a few primary features because their floors are littered with collapse blocks, and their roofs are scarred in places where blocks have fallen out.

To a biologist, however, the Garden Bridges area is of much more interest. The small caves under natural bridges, the loose piles of talus blocks, and the countless nooks and crannies in the cave roof and walls provide refuge for many mammals. Birds are abundant, and there is a greater variety of insects and arachnids here than in most areas of the monument. Lizards and snakes, too, are attracted to this area by the abundance of food.

Botanists, too, will find a wide variety of plant life. The large range of temperature and humidity, from the cool moist air of the caves to the burning heat and desiccation on top of the lava bridges, produces microclimates to which a surprising variety of plants has adapted.

Access to the Garden Bridges is from a parking lot off the Cave Loop Road, with signs marked for both Garden Bridges and Hopkins Chocolate Cave. The trail from the parking lot forks: the left (north) fork goes to a stairway that leads into Hopkins Chocolate lava tube; the right (south) branch continues on the surface for 200 ft and loops back to the parking lot on a different course. This trail affords excellent views of many of the natural bridges and good opportunities to observe the varied flora and fauna.

One geologic curiosity in the Garden Bridges area, a well-preserved tube-in-tube (fig. 22), is easily reached from this trail. The locality is inside the remnant of a near-surface cave 120 ft long that lies in the northwesternmost line of large collapse trenches within the Garden Bridges area (labeled "tube-in-tube" on left edge of map 2, pl. 1). After lava had congealed on the floor of this distributary, a new surge of lava spilled along a gutter-like trough near its west wall. After solidifying a few inches along its top, walls, and floor, molten lava remaining in the interior of the new lava flow drained out and left behind an open culvert-like tube-in-tube. Small collapses allow one to peer into the tube-in-tube and see that it has its own lavacicles and dripstone walls. Upstream and downstream continuations of both tubes are hidden under collapse debris.

Blue Grotto Area

The area from Blue Grotto to the large collapse pits west of the Blue Grotto entrance incorporates the southern part of the Garden Bridges (map 2, pl. 1). The Blue Grotto entrance heads the only developed access trail into the complicated and extensive cave system between Garden Bridges and the two southeastern distributaries. It also provides access to the easternmost distributaries and, of course, Blue Grotto. A sign and parking lot alongside the Cave Loop Road a short distance south of the Garden Bridges parking lot marks the beginning of a trail to the Blue Grotto entrance. Underground access is provided by a stairway in a deep collapse pit in the roof of this first distributary to leave the main Labyrinth feeder; this is the longest of the distributaries (Labyrinth Distributary, map 2, pl. 1).

Part of the distributary connects the Blue Grotto entrance staircase with the large collapse 110 ft upstream. This breakdown occurred at the junction where two distributaries separated and effectively blocked the upstream continuation of the distributary. Its position can be inferred from the map. It appears that the tube holding the Blue Grotto entrance departed from its northerly flowing companion in a lava cascade. Details are not clear at the head of the passage because rubble has spread into the cave from the

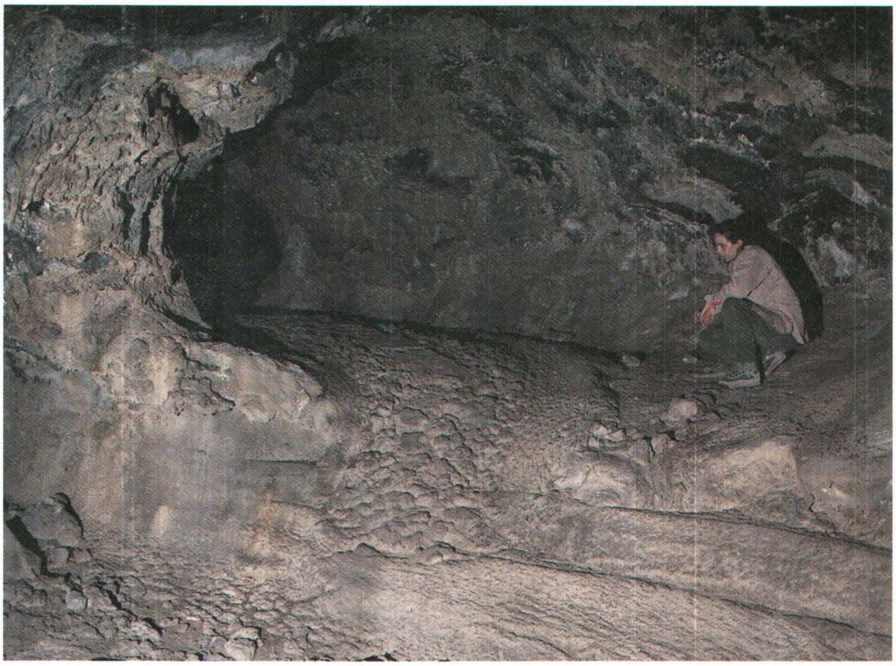


Figure 21. Lava flow cascade in smaller tube, Garden Bridges area of Labyrinth Cave (see fig. 14 and map 2, pl. 1).

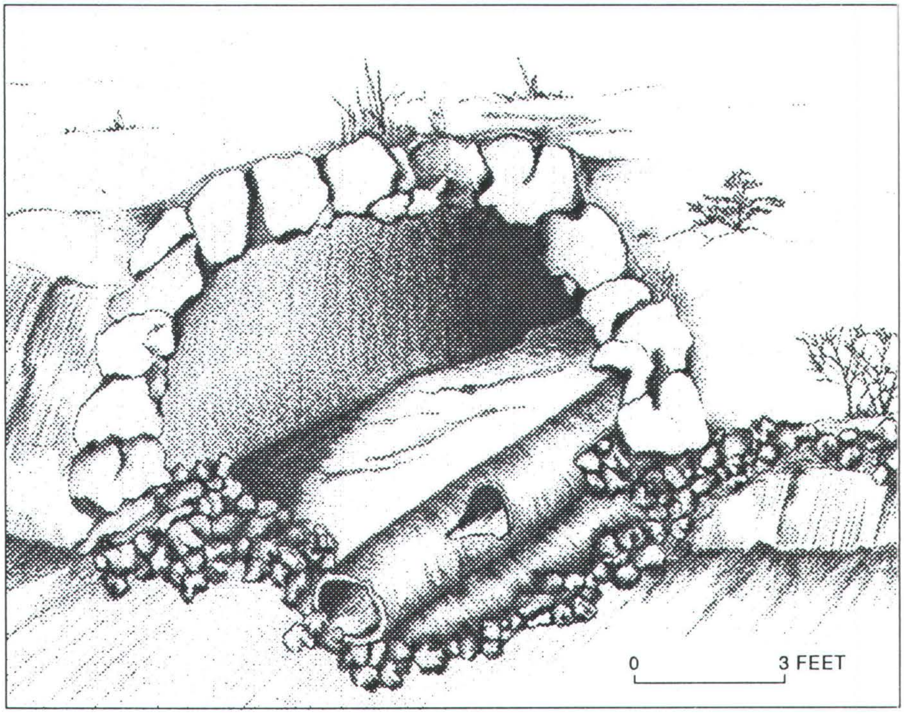


Figure 22. Sketch of tube-in-tube, Garden Bridges area (see map 2, pl. 1). After the larger tube drained, a new gush of molten lava built a small tube within the older, larger tube.

surface collapse and only one corner of the cascade is exposed (map 2, pl. 1, lower left corner). Downstream from the base of the lava cascade a floor jam of pahoehoe blocks spreads across the tube just upstream from the entrance stairway. Downstream from the entrance the tube widens greatly and spreads around two large pillars near its southeast wall. At the point where these lava streams reunite farther downstream another small oval collapse breaks through to the surface. Still farther downstream about 45 ft, the tube again forks. The right (northeast) branch is the continuation of the main tube; the smaller (north) branch, the Chiroptera Crossover, was left hanging 4 ft above the main tube's floor when both tubes drained. The north branch is a crossover to the Blue Grotto. At some time in its history the upper Blue Grotto tube broke through its floor into the crossover, leaving a hole 6 ft deep. The Blue Grotto derives its name from the pale-powder-blue to blue-gray color of its roof in a particular light. A thin coating of a mixture of caliche and clay left by rainwater, which seeps through the roof of the cave and evaporates, is the cause of this color.

One can climb out of the Blue Grotto tube through a surface collapse and continue along the surface via the Garden Bridges trail. Small tubes and lava blisters just below the surface are common to the north and west of this part of the Garden Bridges area; a few are large enough to show on the map. From the entrance to Hopkins Chocolate Cave, additional partly collapsed near-surface lava tubes and blisters are visible at the ground surface to the north and northeast.

Hopkins Chocolate Cave

This cave (map 2, pl. 1), discovered by E.L. Hopkins in 1892, is reached by a fork from the same trail that services the Garden Bridges area. E.L. Hopkins is credited with discovering the cave in 1892, although it may have been known previously to Native Americans. On some National Park Service maps the cave is designated as "Hopkins' Chocolate Cup." The name comes from the chocolate to yellow-brown mud, which drips through parts of the roof of the cave during the wet season.

The cave is entered by a stairway placed in a small circular roof collapse at the northwest end of the Garden Bridges area. At the base of the stairway the lava tube drops off to the northwest with a high downstream gradient, over lava cascades and falls, and joins a larger tube 380 ft downstream. Upstream from the entrance the tributary tube cannot be followed underground because of collapse pits at the north end of the Garden Bridges area. However, the distribution of these pits (see map 2, pl. 1) demonstrates that this tube and the tube that leads to Golden Dome are separate branches of one larger tube exposed only as a few natural bridges upstream from their junction. The point at which the Hopkins Chocolate tributary diverges from the Golden Dome tube is 150 ft upstream from the Hopkins Chocolate Cave entrance.

The relation of the large tube segment into which the tube containing the Hopkins Chocolate Cave debouches as a tributary to the rest of the Labyrinth Cave system is equivocal. This segment, called Hopkins Chocolate Cave Distributary on the accompanying map, extends approximately 650 ft to the north. Downstream it is filled with lava; upstream it is demolished by a surface collapse at a point only 120 ft northwest of the near-surface lava chamber that contains the tube-in-tube previously described as a geologic curiosity in the Garden Bridges area. Very likely there was an underground tube connection between these two points, although now it may be filled with lava. A collapse near this area could have blocked the flowing lava and dammed it to the roof of the large tube that contains the tube-in-tube. The small surface lava tubes and blisters that abound in this area probably broke out through cracks in the collapsing roof. Downstream from the inferred collapse, the Hopkins Chocolate Cave Distributary would have drained to where it could be replenished by lava from its tributary that contains the Hopkins Chocolate Cave entrance. The entrance tube is considered a crossover from the Golden Dome Cave Distributary into the Hopkins Chocolate Cave Distributary. Hopkins Chocolate Cave is a remnant of the northwesternmost large tube of all those in the Labyrinth system. Although we strongly favor this scenario, it has not been verified by leveling along floors throughout the Labyrinth distributaries.

Whatever the exact relations, the Hopkins Chocolate Cave Distributary has features of interest that are easily reached from the Hopkins Chocolate Cave entrance. In its lower part, downstream from the crossover (tributary) junction, wet patches on the roof and walls show excellent examples of the golden lava-tube slime for which Golden Dome Cave was named.

In the middle section of the Hopkins Chocolate Cave Distributary, the tube detours around one large and one small pillar. A floor jam of pahoehoe blocks is present above a constriction of the tube at the west tip of the upstream pillar. On the opposite side of this pillar the last trickle of lava ends in a lobe with a thin steep front.

The best development of the pale chocolate-colored mud is in the crossover, on and around the benches and small rounded pillar 175 ft downstream from the entrance.

Golden Dome Cave

Golden Dome is the name given to the arched roof of a large lava pool at the north end of the accessible part of the Golden Dome Cave Distributary (fig. 23 and map 2, pl. 1). The downstream end of this dome has collapsed and partly buried the pillar that helps to support the remainder of the dome. This collapse effectively blocks exploration of the tube farther downstream, but judging from the size of the tube and the width of the pools along it, only a small part of the total tube length is now exposed to view.

The Golden Dome generally has a small amount of water dripping from, or evaporating on, its ceiling. The water droplets on the roof glisten with a golden luster, as internal reflection within the drops enhances the golden brown color of the lava-tube slime-covered clay and caliche coatings on the lavacicles and dripstone.

A marked trail leads from the parking lot at the Cave Loop Road to the Golden Dome entrance at a point 700 ft upstream from the tube's termination in the Golden Dome and 630 ft downstream from where this distributary splits off from the Hopkins Chocolate Cave crossover. One can traverse only 545 ft upstream from the Golden Dome entrance because the final 85 ft to its junction with Hopkins Chocolate Cave Crossover has been obliterated by collapse.

The Golden Dome Cave Distributary contains excellent examples of a lavacicle-covered roof, dripstone walls, and pahoehoe floors. High-lava marks along the walls testify that at times the tube was not completely filled with lava. A few lava benches record periods when the lava remained at this level until considerable solidification from the walls had occurred. Other benches made partly of collapse breccia that was smoothed over and partly bulldozed away by moving lava are present on both sides of the north branch of the lava tube that enters the Golden Dome from the west. They record collapse of roofs during the time when lava was flowing in the cave, a common occurrence in lava tubes.

Over most of its accessible course the Golden Dome Cave Distributary proceeds northward by a series of cascades interspersed with lava pools. Several parts of the complex area around the two large pillars near the north end of the tube have large roof collapses. Those who wish to see the golden reflections in the water droplets will find the same features near the north end of Hopkins Chocolate Cave, where they can be reached by a shorter and easier traverse.

Labyrinth (Area East of Garden Bridges)

Three large distributaries take off to the northeast from the east side of the Garden Bridges area (map 2, pl. 1). For the first 1,000 ft each of them seems to wander aimlessly, encroaching on its neighbors through numerous crossovers, splits around large pillars, and additional subdivision into minor distributaries and

Figure 23. Interior of Golden Dome Cave (see fig. 14 and map 2, pl. 1) is covered by false gold cave deposits. Ceiling height is about 10 ft at highest point. National Park Service photograph.

dead-end passages on different vertical levels. This part of the tube system is truly a labyrinth, and the visitor who wants to explore it is advised to carry the accompanying map and keep track of his or her exact whereabouts by observing the map at each tube junction. The easiest approach to this interesting area is through the Blue Grotto entrance, but do not take the left (north) fork, which drops over a 4-ft scarp into the head of the crossover tube leading to the Blue Grotto. Instead, continue northeast down the main distributary tube. This northeast-trending tube runs in a relatively straight line with no embellishments except a former skylight and some lava benches along the walls until it reaches a large-scale breakdown. The trail partly avoids this breakdown by entering a small bypass tube on the left (west). It then enters a maze of intersecting and branching passages that offers a wide choice of where to go and what to see. This maze is the heart of the Labyrinth—a place of blind alleys, numerous lava falls and cascades with lava pools between, hanging balconies and side tubes, and a wide variety of narrow benches and pillars. Most of the tubes within this maze contain excellent lavacicles and dripstone walls, and many are embellished with the lace-like tracery of caliche, clay, and iron oxides deposited by rainwater, which seeped through the roof and precipitated on roof and walls. The floor features range from smooth to slightly ropy pahoehoe on the lava pools to large frothy pahoehoe ropes in tubes of moderate gradient. Rare spiny aa surfaces are present below some rapids and lava falls. The roofs of many larger tubes, especially at tube junctions, have been scarred by roof collapse and in a few places by breakdowns to the surface. Most of the more interesting features are shown on map 2, plate 1. Note the position of stairs or ladders constructed by the National Park Service to assist you over lava falls and other obstacles, and to help you get from one place of interest to another. Nearly all features typical of lava tubes are contained within this compact but diverse area.

This complex network of intertwining tubes appears to suddenly become more orderly approximately 1,050 ft downstream from the Blue Grotto trail entrance. Here the anastomosing pattern virtually ceases and the tubes recombine into two major outlets—the Thunderbolt and Labyrinth Distributaries.

Thunderbolt and Labyrinth Distributaries

The western Thunderbolt Distributary (map 2, pl. 1) is monotonous compared to the wild jumble from which it emerged upstream. It has high ceilings and is easy to traverse. Large parts of its interior are intact and preserve a good display of lavacicles, dripstone, and pahoehoe floors.

The eastern Labyrinth Distributary (map 2, pl. 1) is larger, but it is littered with far more collapse breccia. Beyond the Popcorn Chamber, the passage turns north, bends sharply northeast again and promptly subdivides, and finally reunites in a complicated fashion around a cluster of five pillars. An array of lava benches clings to the tube walls and to parts of the pillars. These benches record fluctuating levels of lava, some of which persisted long enough for considerable solidification before final withdrawal to the level of the present cave floor. Withdrawal must have been abrupt and complete, as indicated by steep 1- to 5-ft-high benches and narrow balconies that remain.

The Labyrinth Distributary lies close to the surface, and numerous roof collapses are found along it. Two major breakdowns reach the surface, and much of the tube floor is littered by blocks that fell from the roof and walls.

Beyond the Labyrinth area, both the Thunderbolt and the Labyrinth Distributaries bend left and trend almost due north (map 2, pl. 1). Although the course of each is sinuous in detail, they maintain a northerly direction for more than 1,100 ft. Then, 200 ft southwest of the Thunderbolt entrance both assume an approximate N. 45° E. direction. Whereas upstream from the Thunderbolt entrance the two distributaries unite in a single tube, below this entrance about 180 ft they split into the Lava Brook, East Labyrinth, and Mushpot Caves shown on map 1, plate 1.

Catacombs Cave

Catacombs Cave (map 3, pl. 1) is popular among monument visitors; J.D. Howard was the first to record notes on exploration of this complicated and interesting network of underground passages. Visitors who are unable or unwilling to venture far underground can find excellent lavacicles and dripstone exposed on the ceiling and walls of several branching passages within 200 ft of its entrance. These features, plus a floor of ropy pahoehoe, are nicely displayed in the small dead-end tube called The Bedroom, which is easily reached by a 150 ft traverse that takes two left turns and then two right turns from the entrance. Those who wish to spend more time underground and observe a wide variety of lava-tube features will enjoy the area around The Bathtub. It is reached by an easy traverse of nearly 720 ft down the main passage, where a short flight of stairs leads up to The Bathtub.

Adventurous persons who enjoy long crawls over rough-surfaced pahoehoe (fig. 24), while simultaneously trying to avoid the thrust of sharp lavacicles into their backs, will find their mettle tested by a long underground trip to Cleopatras Grave (fig. 13) via Howards Hole.

And finally, people interested in the hydraulics of a complicated near-surface lava-tube system will find the pattern of tubes, complicated breakdowns, lava falls, drains, and cascades near The Bathtub to be particularly interesting. Similar features, as well as balconies and rafted blocks, are found farther downstream near Howards Hole.

The overall length of the accessible area of the Catacombs system is 2,000 ft but rarely is it as wide as 250 ft. Yet, because of the abrupt turns, the interconnected passages, small complicated cascades, lava falls, interchanges that join passages together at different levels, and the numerous short distributaries that are nearly filled with lava, the total length of accessible passage is more than 7,500 ft. This very complicated system of irregularly branching tubes of different sizes, lengths, and trends (see map 3, pl. 1) makes Howard's name, the "Catacombs," particularly apt.

Most of the passages become inaccessible downstream because lava has ponded to within inches of their roofs, whereas some are inaccessible due to collapse. Therefore the above figure of over 7,500 ft represents only a part of the total tube system in operation during active volcanism.

Entrance to the Catacombs is on a well-marked trail that starts at the Catacombs parking lot beside Cave Loop Road. The trail leads east into and across a large collapse trench, which is a part of the line of major breakdowns coursing through the Cave Loop area. Beyond the climb out of the trench the trail continues east then southeast for 160 ft and then drops into the 140-ft-long and 120-ft-wide Catacombs Basin (map 3, pl. 1). The trail skirts an apron of collapse blocks for 80 ft and then turns due east and enters Catacombs Cave.

Former Lava Lake in Catacombs Basin

During part of the period of volcanism, Catacombs Basin was apparently filled by a lake of molten lava. This lake acted as a holding reservoir from which lava flowed into the Catacombs tubes. The lava came from the Paradise Alleys tubes, which branch from the main breakdown channel 650 ft farther upstream at the head of Ovis Cave (map 4, pl. 2). The Paradise Alleys-Catacombs lava-tube system formed a moderate-sized distributary system from this main feeder; the Labyrinth network of caves (map 2, pl. 1) was a larger distributary system on the opposite (northwest) side of the main feeder tube.

At times the volume of the lava in Catacombs Basin exceeded the capacity of the earliest Catacombs lava tubes to transmit lava as fast as it was supplied. Then the lava spilled over onto slightly older flows and, in parts of the area, welded to the flow beneath. Both the older and overlying younger flows developed lava tubes, and connectors certainly developed between tubes on different levels of approximately the same age.

During the waning stages of volcanism enough capacity had developed from increasing numbers of interconnected passages in the Catacombs system, and so the total volume of lava delivered into the holding reservoir could be transmitted. From then on the basin seldom overflowed. The very latest overspills from Catacombs Basin developed four short lava lobes, which are shown on the map. Two of them spread northwest and were later cut off and dropped into the deep collapse trench just south of Crystal Cave. Two of these four lobes had started to form lava tubes within them before they congealed.

With these generalized preliminary remarks to sharpen observation and perception, one can now proceed underground (with map!) and observe the details.

Features Between The Bedroom and The Bathtub

A curious feature of the Catacombs tube system is that it consists not of a single lava tube with neatly branching distributaries, but it instead consists of two, and in places three or more, parallel tubes at slightly different levels and with several interchanges between them. A network of three main tubes developed at the head of the Catacombs tubes long before the last overspills from the Catacombs Basin. Access by trail to the Catacombs is through the southeasternmost of these three tubes. At the Asparagus Patch, downstream 80 ft from the entrance, this tube turns abruptly to the north, and then, 50 ft farther downstream, it is joined by the middle tube of this threefold network. Upstream in this middle tube, one finds another crossover, some 30 ft long, connecting to a section of the third tube. From here, only 80 ft of this northwestern tube is accessible. Upstream it is cut off by collapse breccia along the north wall of the former lava lake. It ends in a curious dead-end feature named The Bedroom. This rectangular room has near-vertical walls completely sealed over with dripstone

Figure 24. Rough-surfaced flow almost filled the complex downstream part of Catacombs Cave (see fig. 14 and map 3, pl. 1), leaving only a low crawlspace for explorers. Note false gold cave deposits on lavacicle-studded ceiling.

and a roof covered with lavacicles (fig. 25). The northwest end of The Bedroom is a solid wall of dripstone—its appearance seems to negate the idea that this tube might once have extended farther in that direction. Yet, 45 ft northeast of this walled-in end of The Bedroom, a lava tube with exactly the same trend is present (map 3, pl. 1). Upstream, toward The Bedroom, this tube is filled to its roof with blocks of collapse breccia that are almost completely penetrated and sealed in by lava; downstream the tube is open with a floor of frothy pahoehoe in which are embedded many rafted blocks of collapse material. A little farther downstream this tube is again partly blocked by a more recent roof collapse, which occurred after volcanism had ceased and the tube had drained.

Downstream through this network of tubes is a point at the northeast end of Applegate Avenue where the three components of the tube system merge into one large tube 40 ft wide. In another 50 ft, however, this large tube, The Lower Chamber, turns sharply to the north and immediately spawns two branches from its east side. The two branches unite again downstream but continue to flow along near-parallel courses with occasional pillars such as the Wine Cask between them. Additional subdivision is present still farther downstream. By the time one reaches The Bathtub, a northeast-southwest section through The Bathtub Drain intersects seven tubes spread over an area 250 ft wide.

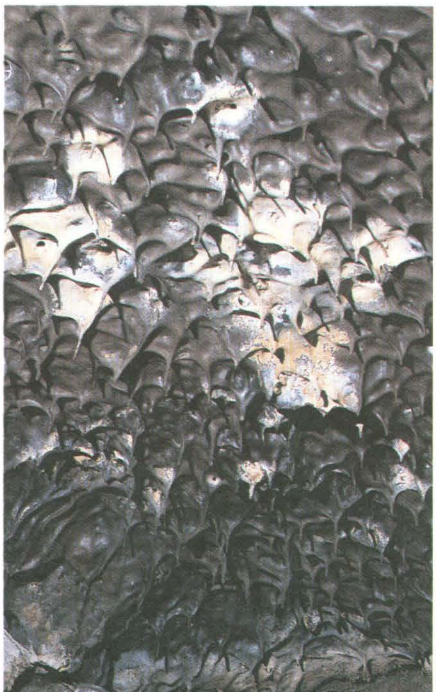


Figure 25. Shark-tooth-shaped lavacicles on ceiling of Catacombs Cave (see fig. 14 and map 3, pl. 1). End of flashlight at lower left for scale.

The branching tubes are typical of the kind that can develop in either a large, thick flow of basaltic lava or, more likely, a thick succession of flow units rapidly erupted over a sloping surface. A major eruption will build a large lobate ridge elongated downslope, which develops a thick crust by congealing of the lava on the top and sides of the flow. As lava is fed into the still molten interior of the flow, it begins to break out through cracks in the front and sides of the partly solidified flow, forming definite underground tubes filled with traveling lava. As lava continues to pour into and through these developing tubes, complicated anastomosing passages may result. Further complexity also results from distributary tubes that branch off from the central tube plexus toward the margins; these complications multiply if rapidly fed lobes pile up on one another and weld into flow units containing tubes at different levels.

The Bathtub Area

The Bathtub lies at the center of an area that is one of the most complicated and therefore interesting parts of Catacombs Cave (map 3, pl. 1). Within 80 ft of The Bathtub are five lava falls, three lava cascades, one vertical shaft through which lava tumbled, and over a dozen lava tubes of various sizes, several of which intertwine in a complex fashion.

To find The Bathtub, and The Bathtub Drain within it, follow the trail 720 ft downstream from the Catacombs entrance to the bottom of an 8-ft stairway. Climb these stairs to reach the surface of the lava that fills The Bathtub. It is a pool of congealed lava 75 ft long and 25 ft wide, evidently ponded after it had half-filled a large lava tube. The source of the lava, the cause of its ponding, and the places where it spilled out after overfilling The Bathtub are not immediately apparent but can be worked out on further examination. Walk northeast along the Boxing Glove Chamber (away from the stairs) and notice that the roof of the lava tube gets progressively lower, until, 120 ft from the stairs and around a gentle curve to the right, the ceiling of the tube comes down to and passes beneath the ponded lava. Note also that over the last few feet, the ponded lava is bowed up into pahoehoe ropes, showing that in this part of The Bathtub lava was creeping forward at a very slow rate downstream toward the place where the tube disappears beneath the lava fill. A tube as large as this could easily carry away the lava ponded in The Bathtub in a matter of minutes. Evidently the tube somewhere downstream was dammed, perhaps by a roof collapse, until the increasing hydraulic pressure and the lava's rise in elevation caused it to spill over into some nearby underground tube.

Return toward the stairs along the southeast wall of the Boxing Glove Chamber, and about halfway back notice a small tube, partly filled with lava, that exits The Bathtub eastward. Explore this tube and in less than 10 ft you find lava frozen as it spilled over a 9-ft fall into a much larger tube below. At the base of the fall the lava turned abruptly to the right (south) and tumbled into yet another tube 5–6 ft lower. By using the map or, by a tortuous crawl upstream, you will find that this tube passes directly underneath The Bathtub. Moreover, the tube connects directly with the lava in The Bathtub through a vertical hole that forms the lower part of the feature named The Bathtub Drain. This feature, however, is more easily studied from The Bathtub floor above than from its exit into the lower tube. The Bathtub Drain (fig. 26) is a funnel-like depression near the southwest end of The Bathtub. The upper part of the funnel walls reveals how the lava of The Boxing Glove Chamber floor cracked into crescent-shaped blocks and moved slowly down the vertical shaft of the funnel. The more liquid lava and loose blocks dropped through onto the tube floor below. Because of the almost perfect preservation of the cracked Boxing Glove Chamber floor on the upper funnel walls, we reason that The Bathtub Drain did not open until late in the history of The Bathtub after the floor and much of the interior lava was solid or pasty. When The Bathtub filled, most of the excess lava escaped through two other exits: one is the previously described small tube in the east wall; and the other is over a larger lava fall at the southwest end of The Bathtub where the ladder is located. This 8-ft lava fall dropped the lava into a large tube whose level is 5–6 ft above the floor of the tube under The Bathtub Drain (see map 3, pl. 1).

Where did the lava come from that entered The Bathtub and ponded within it? Its source was one of the network of tubes upstream to the southwest. The map pattern shows that the source tube is one of the several northeast-trending distributaries common to the Catacombs system. But where, exactly, is the upstream continuation of the Bathtub tube? Congealed lava at the southwest corner of The Bathtub (just southwest of the Pin Cushion, a large fallen block on the edge of the Bathtub Drain funnel) exhibits pahoehoe ropes indicating that this lava was flowing into The Bathtub through an almost completely filled tube. This tube cannot be examined farther upstream because of a clearance of only a few inches between fill and roof, but the top of this flow can be seen from the top of two lava cascades that pour out of the northwest wall of The Igloo, a tube that contains the stairway (map 3, pl. 1). One cascade is 15 ft and the other 50 ft upstream from the base of the stairway. Again, the clearance between ponded lava and ceiling as observed from the top of these cascades is in most places 1 ft or less, but by probing around with a stadia rod, we determined that the tube is at least 8 ft and in some places more than 20 ft wide. Perhaps at one time the tube continued upstream to a junction (now walled off) with the plexus of tubes 250 ft or more upstream. The elevation here is sufficient to have fed lava into The Bathtub.

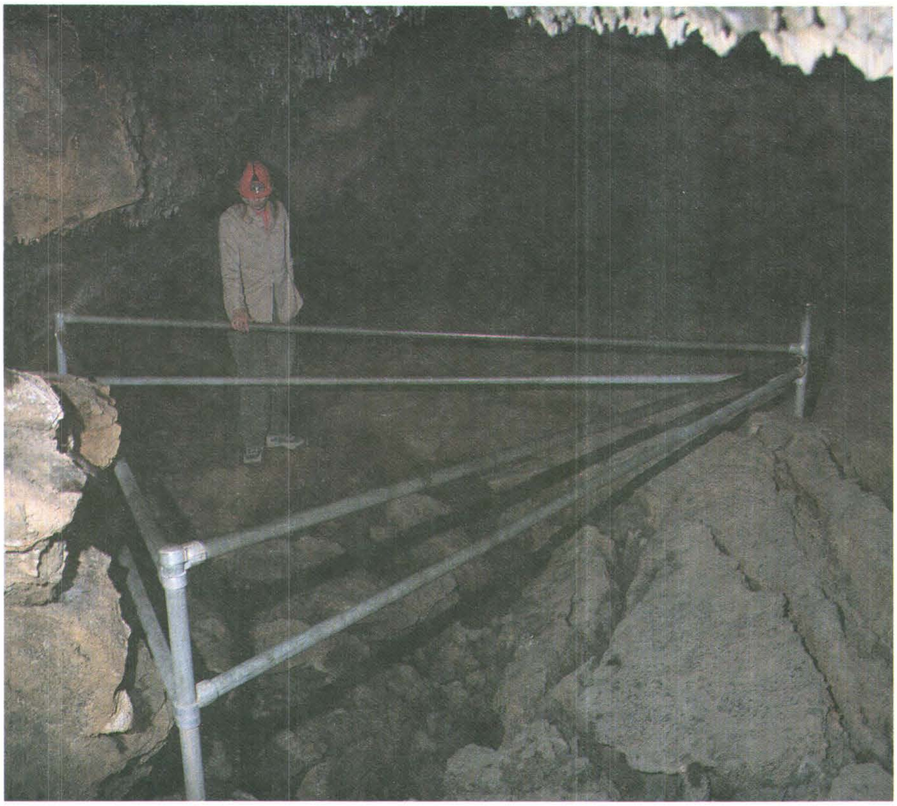


Figure 26. Protective fence prevents visitors from stumbling into The Bathtub Drain (see map 3, pl. 1) formed when lava drained into lower level of Catacombs Cave (see fig. 14).

But there are other possibilities. Only 40 ft southwest of the foot of the stair, access is almost blocked by a huge cave-in of the roof (map 3, pl. 1). This particular pile of collapsed blocks is younger than the volcanism; the blocks fell into an already drained tube. Moreover, an earlier collapse at or near the same spot when the lava tubes were active could easily have blocked this tube and raised the level of the lava upstream; thus the direction of flow through the present lava cascades on the northwest wall was reversed, a process which would cause a large flow into The Bathtub. Later the collapse dam might have been breached and removed to leave the features we see today. Nor is this the only place where a collapse would have brought about this sequence of events. A second large area of collapse breccia is in this same tube, 140 ft downstream from the base of the ladder. That earlier collapses may have occurred at these or other nearby sites is clearly indicated by the abundance of rafted blocks downstream. Accumulations of collapse breccia smoothed over by lava occur downstream in both this tube and in the one beneath The Bathtub Drain.

A close study of the many lava falls, ponded lava tubes, and areas of both pre-lava and post-lava collapse breccia within 200 ft of The Bathtub shows that the general sequence of events outlined for The Bathtub was partly duplicated in many of the other nearby tubes. Most show evidence of ponding and of synchronous or later collapse into other tubes that left balconies or other features indicating an earlier ponding. Many abrupt changes in trend or in elevation of lava tubes are difficult to explain, except by the shunting of lava from one tube into another; the details that can be worked out of such changes in the complex area within 250 ft of The Bathtub are a lesson in lava hydraulics, but we can never know the entire story. Much evidence is not available because of ponding in many lava tubes to their roof and by the transport or impounding of collapse breccias by further flow of lava. Such puzzles abound in the Catacombs; downstream, Howards Hole and Cleopatras Grave are outstanding examples.

Northeastern Part of Catacombs Caves

Downstream 250 ft from The Bathtub the complexity of the Catacombs tube system decreases noticeably. Most of the short tubes filled with lava to their roofs. The complex areas of high ceilings, lava falls, and large roof collapses give way to smaller tubes so filled with lava that in many places they can be traversed only by walking in a doubled-up position or by crawling on one's belly.

From The Bathtub 1,100 ft downstream to where the Catacombs tubes become inaccessible, the lava was carried forward through three nearly parallel tubes with small vertical differences. The direction of all three averages N. 55° E., except in the last 200 ft, where each turns sharply to the north. The simplest of the three is the one on the southeast.

The Southeastern Tube

The southeastern passage is the downstream continuation of the tube at the foot of the stair that gives access to The Bathtub. Within the first 200 ft downstream from The Bathtub, it sends two branches north, each of which extends only a few feet before feeding down into the tube that crosses beneath The Bathtub. It also receives one tributary, the Dollar Passage, from the south. The southeastern tube then continues downstream in an overall N. 55° E. direction for 650 ft without receiving a tributary or creating a distributary. Throughout this distance it is a fairly low tube (from 2 to 6 ft in height), well drained of lava fill in most places, but pooled in others to heights requiring a crawl. The roof, walls, and floor of the tube are intact nearly everywhere. Excellent examples of lavacicles and dripstone abound. The floor varies from normal to frothy (or cauliflower) pahoehoe.

At the downstream end of this stretch the tube widens, subdivides around one pillar, and then unites near two other downstream pillars. The area near the pillars underwent a partial roof unraveling over 25 ft long. Its floor contains a narrow trough 2–3 ft wide that begins 50 ft west of the southernmost pillar. It begins as a lava gutter in the smooth pahoehoe floor. It gradually deepens downstream and 25 ft from its origin dives below the surface of the pahoehoe. From here it evidently continues as a small tube-in-tube beneath the floor and surfaces again (with collapsed top) 40 ft farther downstream. Another 20 ft downstream it is again lost beneath the pile of collapse rubble west of the middle pillar. What is probably the same gutter, but with a different trend, emerges from beneath the collapse pile between the two northern pillars and dives steeply beneath the east wall of the main tube before becoming sealed with lava (map 3, pl. 1).

The Elephants Rump, named by J.D. Howard, is a small downstream extension of the northeasternmost pillar at about waist height. It was smoothly plastered over and rounded off by flowing lava but to appreciate its similarity to an elephant's rump does require a bit of imagination.

Other features near these pillars, in addition to the plunging tube, suggest that the main tube feeds into a lower and larger open tube downstream from the pillars. Downstream from the cascade both ceiling and walls of the tube are irregular in height and trend. Heights of 6–10 ft are common, whereas much of the tube upstream can be traversed only by stooping or crawling. A remnant of an adjacent tube, which contains a lava pool, opens in the east wall of the tube near the cascade, and many alcoves are present on the sides of the tube. This remnant tube also changes direction from N. 70° E. to N. 15° E.

Travel within this irregular, high-ceilinged passageway ends abruptly some 400 ft downstream from the pillars due to pooling of lava so close to the roof that further access is nearly impossible.

Two Northeastern Tubes

Running roughly parallel with the passage just described are two lava tubes intertwining horizontally but mostly separated vertically from one another. The southeastern tube is never more than 100 ft southeast from one of these tubes, and in places may approach so closely that the wall between is not more than 10 ft thick. The rough parallelism of these three tubes exists through a length of over 1,000 ft, and then all three bend northerly and become inaccessible due to lava filling. The features of two northeastern tubes are more diverse than the southeastern tube.

Area near Howards Hole

Howards Hole is an oval-shaped vertical collapse pit 8 ft deep, which connects the two northeastern tubes where they cross each other. Unlike at The Bathtub Drain, collapse at Howards Hole was sudden, violent, and delivered much molten lava into the lower tube immediately after collapse. At the time of collapse the tube upstream from the top of Howards Hole was filled to the roof with lava. Downstream and immediately above Howards Hole, the ceiling rises into a cupola with a shelf of ponded lava just below the cupola ceiling. Within the cupola the molten fill had cooled enough to develop a fairly thick crust across its surface. Solidification had also progressed inward from the walls and floor of the tube. A sudden collapse of the tube floor where it crossed over the highest point in the underlying tube produced an opening (Howards Hole), which immediately drained the ponded lava of the upper tube and cupola into the tube below. A large part of the solidified crust of the ponded lava broke into large pasty blocks, many of which lodged in the upper margins of Howards Hole. Many more dropped through the hole and were rafted downstream. Some blocks that stuck on the upstream side of Howards Hole created a low dam, which formed a small puddle of lava in the upper tube just upstream from the hole. For the next 40 ft downstream, however, much of the solidified upper crust survived the collapse and was left hanging as a spearhead-shaped balcony 5–8 ft above the irregular floor. The floor near Howards Hole is irregular due to accumulation of collapse blocks overrun by lava. Most of these blocks are large chunks from fallen parts of the balcony.

Balconies Near Crossover Between Tubes

The collapse at Howards Hole may have triggered further collapses and abrupt changes downstream. Downstream from Howards Hole the upper tube drained out to the northeast and has a normal pahoehoe floor locally embellished with stretched-out pahoehoe lobes. However, evidence that this tube was once filled to the top is seen in numerous small remnants of balconies near the roof.

Downstream 200 ft from Howards Hole a prominent balcony occupies an area extending 45 ft upstream and 25 ft downstream from a tiny crossover connecting this tube with a lower level. The same sequence of events as at Howards Hole seems to have operated here: ponding in the upper tube nearly to its roof, partial solidification, and then sudden draining through the crossover into the lower tube.

Downstream from this crossover both the upper and lower tube show signs of a later ponding. The lava dumped into the lower tube from Howards Hole and the crossover was quickly carried away, and the lower tube was drained beyond the large pillar 20 ft downstream from the crossover. A short distance from here, however, the lava began to pond, and 90 ft downstream from the crossover it ponded to the roof and thus ended further access within this tube.

Relations in the upper tube are superficially similar. Downstream from the crossover, the tube drained and the floor composed of rafted blocks in frothy pahoehoe formed. Downstream 40 ft pooling began where the tube turns abruptly north, and 135 ft beyond the crossover, the tube is filled to its ceiling.

Second Crossover and Area Near Cleopatras Grave

The upper tube system mentioned in the previous section is not accessible. On the right wall of the tube, 85 ft downstream from the crossover and 50 ft upstream from its filled end, is what appears to be a second crossover. It is entered by climbing over a 4-ft-high sill on the east wall of the tube and then traversing down the crossover tube 40 ft to the east to reach a large pool 50 ft across, ponded very close to the roof. Another tube appears to enter this pool very close to the mouth of the crossover. It could well be the continuation of the lower tube, which pooled to the roof only 50 ft upstream (map 3, pl. 1). From this tube a sticky lobe of pahoehoe was exuded onto the surface on the large lava pool. It can be traced 45 ft to where it merges into the larger lava pool. Both masses of lava were molten, or pasty, at the time they came together.

At the tip of a V-shaped irregularity in the wall of this large pool, two tubes take off downstream. One, headed north, with only 1 ft of clearance, is filled to the roof with lava just downstream. The other, headed in the normal downstream direction, has 3–4 ft of clearance allowing entrance to another 400 ft of branching tubes and lava pools.

This final downstream section is complicated. Downstream 80 ft from its exit out of the large lava pool, the tube widens into a small lava pond. This pond is a drainage divide, because one tube actually heads back to the southwest—in exactly the opposite floor direction from the rest of the tubes in this system. After flowing for 45 ft, lava in this tube tumbled over a 4-ft cascade into an oval pool 18 ft long and 11 ft wide. The west wall of this pool is within a few feet of the large pool described previously but is at a lower level (map 3, pl. 1). From this oval pool a small tube, ponded almost to its roof, appears to exit south but instead may be backflow from the oval pool.

The second, longer tube from the drainage divide takes the more consistent northeastern course. Downstream 15 ft from the divide its lava flowed over a cascade and into a wider area where it subdivided and rejoined around three pillars. There is evidence here of two large roof collapses that were smoothed over and partly carried away by the moving lava. Rafted blocks are abundant in the pahoehoe floor; they dot its surface for another 100 ft until a floor jam closes the tube.

One large rafted block, located a few feet south of the middle pillar, is of special interest. Its exposed surface is rounded and smoothed (fig. 13)—it floated with its upper surface rising a few inches above the molten flood. The surrounding lava festooned its edges with two to four discontinuous pahoehoe ropes that seem to set the block in a frame. J.D. Howard found the exposed rafted block surface with its pahoehoe frame strikingly similar to an Egyptian sarcophagus in shape. Therefore, when he explored this part of the tube in 1914, he named the block Cleopatras Grave.

Ovis Cave and Paradise Alleys

Map 4, plate 2, of Ovis Cave and Paradise Alleys, overlaps map 3, plate 1 in the Catacombs Basin area and extends map 3 to the southwest. Paradise Alleys are the upstream continuation of the Catacombs lava-tube system beyond the lava lake that filled the Catacombs Basin. The near-surface Paradise Alleys lava tubes were fed from the large tube of which Ovis Cave and Ovis Bridge are uncollapsed remnants. A large distributary from this feeder once ran northeast just upstream from the head of Ovis Cave but is now represented only by a broad shallow collapse basin that extends N. 65° E. for 125 ft. From the north wall of this collapsed distributary, three near-surface lava tubes extend north. Another eastward-extending lava tube joins them from just under the roof of the south end of Ovis Cave. Beyond Ovis Cave these tubes trend northeastward and form the network of passages that makes up the Paradise Alleys (see maps 4 and 5, pl. 2).

Ovis Cave and Paradise Alleys are difficult to traverse because of partial roof collapse. This collapse has obliterated most of the ceiling features except in some of the smaller tubes of Paradise Alleys. For the student of lava-tube hydraulics, this area furnishes a fascinating look at the anatomy of a major feeder tube and its distributaries.

Ovis Cave

Apparently, E.L. Hopkins was the first white visitor to Ovis Cave (map 4, pl. 2) in the 1890's. He reported finding 36 Bighorn sheep skulls in the cave (fig. 27). J.D. Howard explored this area in 1918 and named the cave Ovis, the Latin word for sheep, although by this time Bighorn (*Ovis canadensis*) had disappeared in this part of the West.

Ovis Cave resembles a huge railroad tunnel 200 ft long, 20–40 ft high, and 30–50 ft wide (fig. 28). When it was formed, its floor was 60 ft or more below the surface. Angular blocks that tumbled from the ceiling buried its floor beneath rubble. Original ceiling features such as lavacicles can be found only on the fallen blocks. Patches of accretionary wall lining, however, have remained intact over half of the original walls. Seven narrow lava balconies indicate that lava flowed at each of these levels long enough to solidify and leave easily traceable ledges. Many of these nearly horizontal ledges resemble continuations of flow layers. This tube developed within a lava pile composed of different flow layers. Contacts between these layers, as seen in the walls of the tube, were plastered over by lava that later drained away.

Figure 27. Skulls of Bighorn sheep were found in Ovis Cave (see fig. 14 and map 4, pl. 2), giving the cave its name.

Figure 28. Entrance of Ovis Cave (see fig. 14 and map 4, pl. 2) as seen from inside this large feeder tube. Person at left for scale.

Deep collapse trenches terminate Ovis Cave at either end. They mark positions along a system of large lava tubes at least 6 mi long, which extends from Mammoth Crater (fig. 4) to beyond Post Office Cave. This system of tubes may extend to Craig Cave and beyond.

Paradise Alleys

The intertwining tubes of the Paradise Alleys can, for convenience, be divided into three levels (map 4, pl. 2), although most of the upper level is only a partially developed drained balcony within the middle level.

Lower Level

High on the east wall of Ovis Cave, just below the roof and near the collapse that terminates the cave's extension to the south, a small lava tube branches off. This small eastern distributary hangs 25 ft above the rubble-covered floor of Ovis Cave and is the head of the lowest and probably oldest level in the Paradise Alleys distributary system. Within 20 ft of its beginning, however, the floor of this tube is left hanging as a balcony on the walls of a second and slightly larger tube. This tube trends northeast from its head on the north wall of an east-trending shallow basin, which branches from the main collapse trench to a point 40 ft east of the head of Ovis Cave (map 4, pl. 2). After they join, both the balcony and the floor of the tube below it turn to the northeast in a series of lava cascades. They pass completely beneath the much wider middle level of Paradise Alleys. The middle level originated and flowed north from the east end of the shallow collapse basin.

Most of the accessible length of the lower-level tube shows lavacicles and dripstone walls whereas its original pahoehoe floor is littered with collapse blocks. Downstream 70 ft below this passage's entrance, a 6-ft-diameter rafted block half-closes the tube. The upper surface of this rafted block is decorated by many broken and distorted lavacicles and by lava, which coated it during its transit along the tube. Downstream 180 ft farther from the entrance is a hole in the left (west) wall of the lower level tube, 10 ft above its floor, which provides ladder access to the middle level of Paradise Alleys. From here visitors can leave via the Paradise Alleys entrance, another 80 ft downstream. Downstream 45 ft from the foot of the ladder, the lower-level tube is blocked to further entry by a roof collapse.

Middle Level

Of these three tubes, the 40-ft-wide middle-level passage is the largest and transmitted the most lava. Only 240 ft of its length is accessible because its continuation downstream below the Paradise Alleys entrance is completely buried by collapse debris. Unquestionably it extended beneath the partly collapsed skylight just to the east, and from there it extended beneath the upper level to a subterranean junction with the lava lake that once filled the Catacombs Basin.

Upper Level

The upper level of the Paradise Alleys tubes begins as a balcony hanging on the east wall of the middle level tube 80 ft upstream from the Paradise Alleys entrance. Here, its rounded upstream end can be entered by climbing a 5-ft ladder. Whereas the middle-level tube bends almost 90° at the entrance to Paradise Alleys, this adjacent upper-level tube continues straight as a smaller tube. From the entrance alcove one can walk downstream for 75 ft to where the tube emerges into a former skylight whose walls have been greatly enlarged by late-stage collapse. As the upper level leaves this skylight downstream, however, the tube changes drastically in character. It becomes larger, 25–40 ft wide, and much of it—especially to the northeast—appears to be filled almost to the roof with lava. Moreover, much of its pooled lava floor has collapsed (fig. 29) into a lower tube. This is best shown by a traverse upstream beginning from its northeast end, where lava fill reaches the roof and blocks access to the northeast; here a jumbled mass of floor blocks lies just below small balcony remnants still attached to the walls. On the left (northwest) wall a huge 30-ft slab of the balcony is detached from the wall and now lies on its side atop fractured blocks of the subsided floor. Another 80 ft upstream where the ceiling is lower, a remnant of balcony crosses the tube and

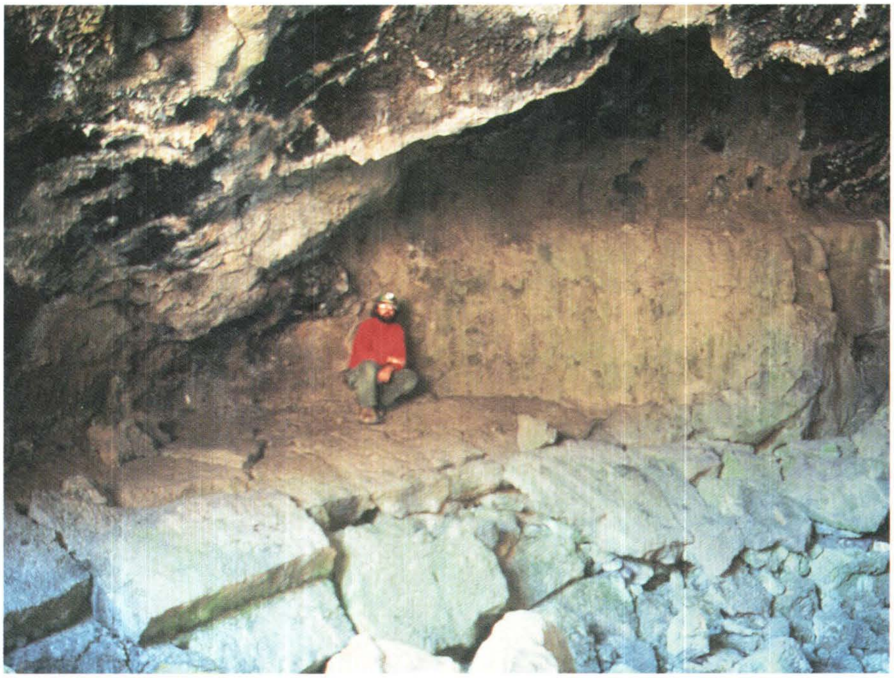


Figure 29. Original pahoehoe floor of upper level Paradise Alleys tube (see fig. 14 and map 4, pl. 2) collapsed when molten lava withdrew underneath chilled surface.

thus forms a bridge over the broken-up floor jam of balcony blocks.

Upstream 95 ft—just southwest of a collapse to the surface—the floor of the upper level has tumbled so completely that its former position is recognized only by a few small balcony remnants 4–6 ft above the jam of collapsed balcony rubble that forms the present floor of the cave. The explanation for these relations is clear. These floor jams and balcony remnants show that the upper level, from the former skylight northeastward, is an unstable fill formed within the middle level. After its 90° bend, the middle level rejoins the small upper tube at the former skylight. What we see from the skylight northeastward is the record of a high-lava fill in the middle level, which persisted at this height long enough for its top to completely solidify from wall to wall. After a solid crust less than a few feet thick had formed, the molten lava beneath continued downstream and ultimately drained to a level 5 ft or more below its former stand. This allowed part of the crusted-over floor to subside and thereby form a jam of balcony blocks in parts of the tube and a bridge in a narrow part close to the roof. The balcony level also survived completely intact in the small upper tube, which continued straight. Remnants of this balcony, changing in places to sloping alcoves, also occur along the middle level all the way to its head in the shallow collapse basin.

In summary, this shallow collapse basin and the middle level of Paradise Alleys constitute the main distributary that supplied lava to the Catacombs system of lava tubes. The lower and upper levels, the balcony, and the floor jams are interesting supplementary records of fluctuation in the height of the lava in both the Paradise Alleys and in the Catacombs Cave.

Former Skylight

The former skylight just east of the entrance to Paradise Alleys provides further evidence of a high-level stand of the molten lava pouring through the Paradise Alleys tubes. The lava overflowed and spilled out to the north and east onto the surface through the skylight. The more prominent spillovers are indicated by dashed lines (enclosing arrows that indicate the direction of flow) on map 4, plate 2. Spillovers from the last highstand of Catacombs Basin lava lake are similarly shown.

Natural Bridge Area

Large, spectacular collapse trenches are present in the area where Cave Loop Road crosses the Mammoth Crater-Post Office Cave line of breakdowns over the feature named the Natural Bridge (map 5, pl. 2). This bridge also marks the point where the feeder tubes from Mammoth Crater began to subdivide into the numerous distributaries that built the sloping plain and the numerous tubes of the Cave Loop Road area (fig. 14). The Paradise Alleys-Catacombs Cave system and the Hercules Leg-Juniper Cave system have their upstream beginnings here. Four short near-surface lava-tube caves—Sunshine, Battered Sherman, Juniper Pole, and Gail—are within this area, as are numerous small spillover lobes of lava, small collapse basins, and miniature breakdowns, and lava trenches.

Because the deep collapse trenches are large features, the scale chosen for the Natural Bridge area map is reduced more than that of the other maps. To clarify the spatial relations between the trenches and nearby cave systems, the area around Ovis Cave, the head of Paradise Alleys, and the part of Hercules Leg Cave upstream from its entrance have been replotted on map 5, plate 2 at a larger scale.

Short remnants of two large feeder tubes have survived nearly intact beneath Natural Bridge. One can walk through two strands of the upper tube (separated by a pillar) and visit a short section of the lower tube through crawlholes. The easiest and most interesting way to visit one of these large tubes, however, is to take the trail through Ovis Cave. Ovis Cave's position and the trails at its downstream end are shown on map 5, plate 2. Ovis Cave, the tube under Ovis Bridge, and the upper tube beneath Natural Bridge are all remnants of the same large lava tube.

Battered Sherman Cave and Sunshine Arch are located along the lava channel leading to Sunshine Cave.

Large Collapse Trenches

The most spectacular features of the Natural Bridge area are the deep collapse trenches. However, the amount of space within the central part of such a trench, as between Natural and Ovis Bridges, presents an interesting puzzle. This trench definitely is too deep and voluminous to be ascribed to a roof fall in the upstream continuation of the lava tube in Ovis Cave. How then is the additional room in this trench to be explained? There are three possibilities. (1) The tube increased in size upstream, due both to a thinning of the roof and to a deepening of the channel, (2) two or three tubes were superposed one above the other, and all of them have collapsed together, or (3) collapse began while lava was actively flowing through the tube, and the fallen blocks were rafted down the tube before volcanism ceased.

From evidence downstream (map 4, pl. 2, map 15, pl. 5, and map 18, pl. 6, and "Ovis," "Post Office," and "Crystal Cave" sections) it is apparent that multiple collapse is the most probable explanation. In fact, by superposing the map of Ovis Cave on that of Crystal Cave one notes that the deepest tube exposed in Crystal Cave lies demolished beneath the deepest section of the trench between Ovis Bridge and Ovis Cave. The second theory sufficiently explains the added space in the deep trench between Natural Bridge and Ovis Bridge. Consistent with this explanation, the profile of the talus on the walls of this trench shows a narrow medial trough with steep cliff sides giving way to gentle talus slopes higher on the walls—the profile to be expected because the lower tube in Crystal Cave is smaller than the one that formed Ovis Cave.

The very large collapse trench that lies upstream from the Natural Bridge, however, contains evidence of a much more complex history that may involve all three processes. This trench shows clear evidence of having developed from an earlier collapse after which molten lava lay ponded in a wide lava lake or sluggish stream open to the sky during at least some major periods of volcanism. Today the rock rim of this trench is a cliff ranging from a few feet to 45 ft in height. From the base of the cliff a talus slope of loose blocks descends to the deep central part of the trench, which is at the projected elevation of the two large superposed lava tubes beneath Natural Bridge.

The deepest hole within this collapse trench is at the trench's extreme northeast corner, directly beneath the upstream entrance to the caves beneath Natural Bridge. Here, a collapse that extends through the upper tube and into the lower tube beneath Natural Bridge has formed a pit over 50 ft deep. This pit is bordered on the southwest by a steep ridge of talus that forms a berm across the head of the trench and divides the main part of the trench from the deep hole just upstream from Natural Bridge. Only near this cave entrance can any clearcut relation be seen between the trench and the passages of the lava tubes. It is clear that both the upper and the lower lava tubes exposed beneath Natural Bridge extended upstream into the northwestern part of the area now occupied by the deep collapse trench. Yet a simple calculation will show that the volume of the collapse trench is at least three times greater than the space required to completely fill lava tubes the size of those beneath Natural Bridge, which are almost certainly the upstream continuations of Ovis Cave and the lower tube in Crystal Cave. No remnants of other tubes that might help with this space problem are known. If they ever did exist, which seems unlikely, they are hidden in the talus of the collapse trench.

Other interpretations of the history of this trench can be inferred from a study of the rock rims along its borders. First we note that the highest elevations around the trench are on these rims; the sagebrush-covered ground on both sides slopes away from the trench, not toward it. As indicated on the map, molten lava spilled over the trench rim as small lobes in many places. Some lobes escaped over the rim through low areas along the northwest side and then coursed northward down the slope. A larger lobe, which contains Sunshine Cave, spread beyond the area of the map. The Sunshine Channel, at the head of this cave, and its connection with the trench, is shown on an inset of the Natural Bridge map (map 5, pl. 2); its passages are described in the section "Battered Sherman Cave and Sunshine Arch." The Sunshine Channel is partly lava gutter and partly small lava tube; farther downstream it is still roofed over to form Battered Sherman Cave; a miniature natural bridge, Sunshine Arch; and the upper part of Sunshine Cave. Note that where the channel leaves the big collapse trench, backflow features developed. Thus it was a lowering of the lava lake within the large collapse trench that stopped the filling of Sunshine tube and allowed it to drain and survive as an open cave.

Lava-Tube Caves in the Natural Bridge Area

Ovis Cave, Paradise Alleys, and Hercules Leg Cave all have their upstream entrances within the Natural Bridge area. Ovis Cave and Paradise Alleys are shown on map 4, plate 2, Hercules Leg and Juniper Caves are shown on map 6, plate 2. Caves shown on map 5 (pl. 2) of the Natural Bridge area include: (1) a complex of two large lava tubes and two small lava tubes beneath Natural Bridge; (2) Gail Cave, a small lava tube with two collapse basins strung along it, which can be traced for 400 ft northeast after branching from the upper tube beneath Natural Bridge; (3) Juniper Pole Cave, south of the embayment at the southeast corner of the large collapse trench upstream from Natural Bridge; (4) Sunshine Cave, Battered Sherman Cave, and Sunshine Arch, northwest of Natural Bridge; and (5) Duffys Old Still Well and Prohibition Cave, upstream from the segment of deep collapse trench.

Caves Beneath Natural Bridge

The caves beneath Natural Bridge are remnants of four different lava tubes, each of a different size and at a different elevation; all these caves can be entered from the large passage beneath Natural Bridge.

At the downstream (northeast) side of Natural Bridge is a large arched cavern 12 ft high and 40 ft wide. It quickly narrows to half this width, because a slide of loose blocks spilled onto the floor from a collapse of part of the southeast roof and wall. Farther upstream 80 ft, however, the tube suddenly widens on both walls, subdivides around a 75-ft-long pillar, and then reunites at the pillar's upper end. In another 20 ft the single tube, now 20 ft high and 45 ft wide, was demolished by the northeast end of the deep collapse trench, which forms the southwest side of Natural Bridge. This tube, labeled "upper tube" on map 5, plate 2, is almost certainly the upstream continuation of the large tube that forms Ovis Cave. Another remnant of it forms the opening beneath Ovis Bridge.

Beneath the upper tube is another large tube—the Hummingbird Flyway. It does not split around the pillar like the upper tube but continues upstream beneath the area adjacent to the pillar (see the cross section of Natural Bridge on map 5, pl. 2). Only about 60 ft of this lower tube is accessible; the rest of it (southeast of the pillar) was demolished by collapse of the upper tube's floor. Along part of this collapse, however, the southeast wall of the lower tube can be traced, curving up in places beneath an overhanging ledge formed by the broken floor of the upper tube. In this stretch the Flyway is more than half filled with collapse debris.

Two crawlways and a pit permit entry into the relatively undamaged part of the lower Hummingbird Flyway tube. One crawlway is located in the upper tube 15 ft southwest from the downstream edge of Natural Bridge, at the northeast margin of the slide that spills out from the southeast wall. The second crawlway is through a maze of huge collapse blocks where the southeast wall of the upper tube swings out around the pillar. It is near the northeast corner of the collapse that dropped part of the floor of the upper tube into the lower tube. The pit is located along the southwest wall of the collapse at its upstream end (see positions of these crawlways and pit on map 5, pl. 2). The remnant of the lower tube that can be traversed between these crawlholes is an oval-shaped tube, 55 ft long, 25 ft wide, and 11 ft high.

An upstream extension of this lower tube might be opened from beneath the upstream side of Natural Bridge. A pile of large collapse blocks lies at the point where the broken ledge of the upper-tube floor intersects and crosses over the southeast wall of the Hummingbird Flyway, roughly 20 ft beneath the upstream side of Natural Bridge. We were able to crawl down among these tumbled blocks to a level equivalent to the floor of the lower tube, but we did not locate an entrance into a cave upstream from them. There is no question, however, that both of these large tubes extended farther upstream before roof collapse demolished the upstream side of Natural Bridge.

Two small tubes can also be explored from the upper tube beneath Natural Bridge: a small tributary, already mentioned, that enters the upper tube from the west by an 18-ft lava cascade and Gail Cave. The tributary tube and cascade is traversable for 90 ft upstream from where it debouches onto the floor of the upper tube. It is blocked by a roof collapse near the point where it was fed from an overspill of the lava lake.

This traverse demonstrates that the lava-tube passages beneath Natural Bridge are much more complicated than the usual simple tunnel beneath most natural bridges of lava-tube origin. These complexities caused J.D. Howard to name it "Compound Bridge," a name that is no longer used.

Gail Cave

Gail Cave, informally named after the wife of one of the assistants on this project, is a shallow and broad lava tube, which can be traced for 400 ft to the northeast. It lies above the upper tube beneath Natural Bridge, and its course is interrupted by two shallow collapse basins (see map 5, pl. 2). The floor of Gail Cave, where it leaves the upper tube, is a lava pond. Apparently lava ponded in both the upper tube and in Gail Cave when collapse occurred. This pond extends into Gail Cave for 20 ft and spreads out around the edges of the first of the two collapse basins. It is advisable not to try to force a passage through the tumbled blocks around the margin of this basin. Instead, return to the surface via the upper tube beneath Natural Bridge and walk southeast along Cave Loop Road to the second collapse basin. In this second small collapse basin is a good entrance into the 200-ft section of the cave that joins the two basins. This part of Gail Cave is very different from the pooled lava floor at the head of the tube. The most interesting feature is the wavy and irregular coarse ropy surface of the lava that fills half the tube and makes it difficult to traverse. This final lobe of lava must have been very viscous and barely able to creep forward as it congealed. A remnant of an earlier stand of lava, perhaps a balcony that was broken up and mostly carried away, is present near the middle of the tube along the southeast wall. A 4-ft-high tongue of lava—evidently a backflow lobe from the northeast basin—is located just inside the entrance to Gail Cave (map 5, pl. 2).

The difference in surface roughness downstream and upstream from the first collapse basin might have been caused by the basin collapse. If a catastrophic collapse of the roof of this basin occurred while lava was flowing within the distributary, it might have pooled the lava upstream but at the same time violently forced half-congealed lava into the downstream part of the tube. This may have been a sufficient disturbance to propel the partly crusted lava downstream into irregular waves and coarse ropy folds that promptly hardened into rock.

Juniper Pole Cave

Juniper Pole Cave is named for a 9-ft-long crude ladder fashioned from a juniper tree, thrust years ago into the small middle entrance to provide access to the cave. Juniper Pole is a relatively simple cave, a small tube split into three distributaries. The enlarged map (on map 5, pl. 2) of this cave tells its own story. The surface flow of lava that contains the cave emerged from the south wall of the shallow basin at the head of the deep collapse trench. It cascaded down a steep slope for 100 ft, turned east following the underlying topography, decreased in gradient, pooled, and split northeastward into distributaries at the point where it lost gradient. Where the subdivision occurred, the floor of this wide area is deeply mantled by collapse blocks from the roof. In many places the piles of loose blocks extend nearly to the ceiling, and, therefore, travel is difficult and hazardous. In the middle of this area there is an 8-ft drop in the collapse rubble. It probably hides a cataract or low lava fall in the floor. The tube, which debouches into this chamber farther upstream, is blocked by peeling linings as well as a 7-ft lava fall at its head.

In contrast with these breakdown areas, the southern distributary of Juniper Pole Cave has a strong roof and an excellent display of pahoehoe, lavacicles, dripstone, and rafted blocks. The ceiling height, however, is so low that one must stoop or crawl to examine these features.

Sunshine Cave

Sunshine Cave is the longest and most interesting of the small tubes in the Natural Bridge area. J.D. Howard explored and named it in January 1921. The entrance to Sunshine Cave is indicated by a sign at a parking lot beside Cave Loop Road just before you reach Natural Bridge.

The topography of the surface shows that the upper part of Sunshine Cave, Battered Sherman Cave, Sunshine Arch, and Sunshine channel upstream from these caves occupy the central axis along a 600-ft-long lobe of lava that spilled over from the former lava lake in the large breakdown just upstream from Natural Bridge (map 5, pl. 2). The part of Sunshine tube that is contained in this lobe could not have extended more than 250 ft. This figure, however, is no criterion of the true length of the Sunshine tube, nor of the total volume of lava that passed through it. The reason becomes clear only after we examine that part of the tube 220 ft downstream from the entrance, where it makes an abrupt turn to the northeast. At this locality the weight of the lava in the Sunshine lava lobe forced a breakdown (or else the lava discovered a roof collapse) into an older open tube formed in a deeper flow. A large but unknown volume of lava tumbled into this lower distributary and continued to flow until ultimately all but 200 ft of the upstream part of this lower tube was filled to its roof, and thus access was terminated to the northeast.

Collapse blocks from the surface clutter the Sunshine entrance, but otherwise the first 200 ft of the cave shows typical lava-tube features. The roof is decorated with lavacicles that bend and flow into dripstone as the roof rounds onto the walls. Near the entrance a prominent narrow bench is present on both walls 12 ft above the floor. A less conspicuous high-lava mark is 7 ft above the floor. A 5-ft cascade is located 50 ft from the entrance, and a second 3-ft cascade is another 120 ft farther downstream. Between these two cascades is a 55-ft stretch of floor where the partly solidified pahoehoe broke up into a block jam. Final draining below the cascades left a cave floor of frothy pahoehoe.

At 210 ft downstream from the entrance, the Sunshine tube turns abruptly to the right (northeast) and just beyond the turn many of its physical features change in appearance (map 5, pl. 2). In this area is where flowing lava discovered or else forced a breakthrough into an underlying open lava tube. The exact place where the breakthrough occurred is difficult to pinpoint, because once a spill into a lower tube is effected, further collapse enlarges and spreads the area of breakdown. Such spreading of the collapse clearly did occur in the Sunshine Cave, but it is likely that the first collapse may still be preserved in the round pit crossed by the catwalk 20 ft beyond the abrupt bend to the right, 230 ft from the entrance. Inspect the edge of this pit and note that lava poured into it from all sides. Unfortunately, collapse filling obscures the junction of the lower part of the pit with the underlying tube. Clearly this hole served to transmit lava to the lower level, but it may not have been the site of the first collapse.

Additional collapses in the Sunshine tube occurred where the floor of the upper tube disappears piecemeal into the lower tube 90 ft farther downstream, at the point where the trail descends into the lower level via a short stairway. Most of the collapse debris was carried away by the flowing lava, but some may remain buried beneath the lava on the floor. Indeed, the stairway does not reach the original floor of the lower level, which lies beneath ponded lava. Such ponding may have been caused by a small dam of collapse debris.

Another 15 ft downstream the congealed Sunshine lava flood subdivided around a pillar and cascaded for a vertical distance of nearly 8 ft before reuniting on the downstream side of the pillar. Was there a jam of collapsed blocks against the upstream end of this pillar that created the 15-ft-long pond? It seems likely, for several rafted blocks are frozen into the lava surface just upstream from the pillar, and downstream from the cascades many rafted blocks were being carried away when the lava solidified. One large block is shown on the map and is found on the eastern margin of the lava stream where it rounds the next bend. A post-lava collapse that broke through above ground nearly closes the tube in an area 50 ft downstream from the catwalk. At the Mouse Hole, 50 ft farther and a total of 465 ft downstream from the entrance, the lava pooled until its floor was only 6 in. from the roof of the tube.

Battered Sherman Cave and Sunshine Arch

As lava drained out of the channel, the roof of the short upstream extension of Sunshine Cave partially collapsed, a process that formed Battered Sherman Cave and Sunshine Arch. The entrance to Battered Sherman Cave is between collapsed blocks at the downstream end of the cave. Post-lava-flow breakdown has obliterated virtually all of the original linings of the cave; indeed nowhere does the ceiling height exceed 4 ft. A chaos of blocks has to be traversed along its 38-ft length to reach the collapse area at its upstream end. A battered Sherman live animal trap was found in the cave when it was explored in 1988, hence its name.

Sunshine Arch is located between Battered Sherman Cave and the entrance collapse of Sunshine Cave proper. It is a very small remnant of the roofed tube upstream from Sunshine Cave. The 7-ft diameter and 5-ft long arch has undergone extensive unraveling and nothing remains of its original interior surfaces. A similar arch is shown in figure 30.

Another spillover lobe immediately east of the Sunshine Channel also formed a lava gutter, became roofed over, and, after a few right-angle turns, tumbled into the upper tube beneath Natural Bridge in an 18-ft cascade. One cannot walk through this connection today because access is denied by a roof collapse at the point where the gutter went underground.

Evidently at the time when lava was feeding into these overspills and small distributary tubes the site of most of the present deep collapse trench must have been occupied by a large lava lake, perhaps mostly crusted over but including parts where molten lava was open to the sky. Evidence of the lava lake can be seen near the head of the trench. Two spillover lobes are shown on the map just to the east of the shallow basin that forms a "bay" at the southern end of the collapse trench. Before the formation of these small lobes, a much larger flow of lava evidently escaped from this bay in the side of the trench. This flow contained lava tubes within its core. Most of these tubes filled with lava, but the upper parts of some still remain open as in the case of Juniper Pole Cave, a network of subdividing near-surface distributary tubes. Downstream, all tubes are filled with congealed lava.

One of the more interesting features formed by overspills from the large lava lake is a small flat-topped ridge known as The Wall. It borders the south side of the wide bulge in the middle of the trench. Two small collapse basins on the south side of The Wall indicate that another flow of lava, comparable to the one that contained the Juniper Pole Cave, spilled over the rim of the trench at this point. This lava flow must have also developed lava tubes, and the upper parts of these tubes collapsed to form the two small basins. The Wall itself developed from inch-thick sheets of lava continually deposited and cooled from slight spillovers of the oscillating lava lake level. This thick and sturdy rock wall, 4–15 ft thick and 5–8 ft high along its south side, consists of dozens of thin lava sheets stacked on top of one another. Some layers are only small rod-like trickles instead of sheets, as seen on the outside of The Wall. The interior side of The Wall is a caved surface formed when the lava lake dropped to a lower level and drained out. It shows broken edges of sheets, smoothed over in places by a coating of lava plaster stuck against them as the molten lava lowered.

What caused the lava lake in the first place? And how did it disappear and its site become covered with talus? Judging by what we can see of the continuation of the major lava tubes downstream in such places as Ovis, Crystal, Sentinel, and Post Office Caves, it seems many fillings and drainings of the lava lake occurred as different eruptions rose to a climax and then waned. Lava also backed up into the tubes when roof collapse partly or completely blocked its flow (see the maps of Crystal (map 18, pl. 6), Skull (map 12, pl. 4), and Post Office (map 15, pl. 5) Caves). The lava tubes that formed within the site of this particular stretch of trench undoubtedly have repeatedly lost parts of their walls and roofs as molten lava coursed through them, for in no other way can we account for the size of the present trench except by the rafting of both old tumbled and newly congealed thin roof blocks and wall linings down the tube. After collapse and rafting of this rock, intermittent blockage of the tubes downstream created the rise of a lava lake until it overflowed. Such a sequence of events was probably repeated many times during the buildup of the lava plain that slopes away on both sides of this major trench. This plain also includes the northeast slope honeycombed with the near-surface lava tubes upon which Cave Loop Road is built.

Within the area shown on the Natural Bridge map (map 5, pl. 2), two more breakdowns upstream from the deep collapse trench give additional clues to the position of the line of major lava tubes underground. One is a deep trench, 80 ft long and about 50 ft wide. The upstream side is breached by a shallow draw 50 ft long. From the south edge of this draw a broad spillover lobe of lava escaped to the south but narrowed to a point and congealed within 100 ft.

Another 125 ft upstream is a deep pit called Duffys Old Still Well that is 85 ft long and 25 ft wide at the surface but with vertical to overhanging walls in its deeper parts. The collapse debris on its floor is only a few feet thick, and an open lava tube extends both upstream and down-

Figure 30. Arch-shaped natural bridge of lava is similar to that at Sunshine Arch. This arch was formed by collapse of lava tube carrying basalt of Giant Crater on south flank of Medicine Lake volcano (see fig. 1).

stream from the bottom of the pit. The small pile of collapse debris on the floor of this pit accounts for less than 3 percent of the missing parts removed from the basalt units seen on the pit's walls. Evidently, the missing materials were rafted down the tube. This deep vertical pit is very similar to one located east of Post Office Cave along the same line of collapse trenches. We named this pit Duffys Old Still Well because in prohibition days a still was concealed beneath the overhang produced by the egress tube at the north corner of the well. This pit has been shown as "Duffys Well" on old maps of the area.

Prohibition Cave

Southwest 100 ft from Duffys Old Still Well is the upstream continuation of the collapse trench. At the trench's downstream end is a small preserved segment of lava tube. Two small entrances lead down into Prohibition Cave through collapse rubble. Virtually no interior surfaces remain in the cave's single chamber because the walls and ceiling have unraveled extensively and covered the floor with collapse rubble. Collapse blocks prevent any travel beyond the first 35 ft down the tube toward the small cave at Duffys Old Still Well. Prohibition Cave is a continuation of the main tube that extends both upstream and downstream from Duffys Old Still Well, and its name is derived from the dashed hopes of explorers to find an easier way into Duffys Old Still Well.

Hercules Leg and Juniper Caves

The Hercules Leg and Juniper Caves (map 6, pl. 2) constitute an interconnected system of near-surface lava tubes and irregular short passages. Altogether they contain 4,810 ft of passage if one counts the deviations around the many pillars, short blind tubes, and alcoves. The two major entrances to this cave system were discovered and named by J.D. Howard in 1918.

The entrance to Hercules Leg Cave is adjacent to Cave Loop Road. It is marked by a sign and parking area. The entrance to Juniper Cave, the downstream continuation of Hercules Leg Cave, is reached by a trail leading east from the Juniper parking area.

The near-surface nature of the Hercules Leg-Juniper Cave system can be seen in the shallow surface breakdowns in the caves. At most breakdowns the roof of the cave is less than 10 ft thick. Collapse blocks clutter the floors of many underground passages, and approximately a quarter of the floor of the caves is completely covered with fallen blocks. Because this slow unraveling of the roof is still in process, parts of these passages must be considered dangerous.

The Hercules Leg Cave is undoubtedly a distributary from the large feeder tubes that once conveyed molten lava from Mammoth Crater to Natural Bridge and then on through Ovis and Sentinel Caves to Indian Well and beyond. The collapse trench closest to the upstream end of Hercules Leg Cave is the one between Ovis Bridge and Ovis Cave (see map 5, pl. 2, Natural Bridge area). No direct connection between this talus-walled trench and the head of Hercules Leg Cave is visible in the field; however, an underground connection seems likely because the head of this tube is less than 100 ft from the wall of the trench, and the upper part of the Hercules Leg tube lies beneath a surface lobe of lava that spreads eastward from this area.

The actual visible underground source of the lava that once poured through Hercules Leg Cave can be reached by a traverse of 235 ft upstream (west) from the entrance. Here, at the head of this low tube, upwelling lava formed a mound as it rose from below. This mound is the top of a connector to a lower lava-filled tube, which must have split off from the feeder tubes to the west.

An unusual feature of Hercules Leg and Juniper Caves is four abrupt right-angle turns of the main lava tube (map 6, pl. 2). The lava flowed first to the east for 500–700 ft, then turned north for about the same distance then repeated this pattern. A complicated melange of pillars, short dead-end passages, and alcoves generally formed at the abrupt bends.

Features Near Entrance

The entrance to Hercules Leg Cave is a halfdome-like opening, which appears to have been a large gas blister developed under a thin-roofed part of the lava-filled tube. The north wall of this blister, plus a part of the tube roof upstream from it, has fallen in and left a pile of rubble in the opening. The main trail leads underground (left) into the downstream part of the tube.

A second and little-used trail takes off over the pile of collapse rubble and heads upstream (right). At the farthest upstream point along this part of the Hercules Leg tube, the source of the upwelling lava can be seen. Also, numerous pillars, lava cascades, and rafted blocks are present on the pahoehoe floor of this segment. There is much evidence that molten lava once filled this section to the roof. High-lava marks are common on the tube walls and on the plastered sides of the pillars. Lava cascades accentuated the flow around pillars, especially near the downstream ends.

By following the main trail downstream from the entrance, one can observe many interesting features on the way to the Barrel Skylight collapse nearly 550 ft downstream. For the first 150 ft the lava was confined to one relatively straight and high tube, but over the next 350 ft the tube splits up into an intricate network consisting of an intact west branch and segmented east branch with crossovers and numerous irregular connections. This part of the Hercules Leg Cave displays the pattern of parallel tubes with crossovers as seen in the Catacombs system, but here it is not as well developed. The similarity is closer if we restore the connection that evidently formerly existed between the collapse area at the Birdshead Lava Pool (map 6, pl. 2) and the two lava tubes 50 ft farther east. If this restoration is made, we can visualize three parallel tubes dumping lava over small cascades into one medium-sized tube draining the collected lava of all three to the north past Barrel Skylight. Downstream 160 ft from Barrel Skylight the tube makes its first right-angle bend. A floor jam of stretched and tilted pahoehoe blocks occupies the lava pool just upstream from the Unga Dunga entrance where the channel starts its northward trend. In the area just downstream from the junction of Hercules Leg Cave with Upper Juniper Cave (nearly 350 ft southwest of the Juniper Cave entrance), the similar rapid congealing of molten lava within a lava flow thinner than at Catacombs preserved an early stage in the development of the anastomosing tube pattern so typical of the upper part of Catacombs and some parts of the Labyrinth Cave system.

Features of Hercules Leg Cave between the entrance and the right-angle bends are much like the pillared area west of the entrance. High-lava marks and narrow perched lava benches indicate former highstands of the lava. Sloping floors covered with frothy pahoehoe alternate with gently sloping pools of smoother pahoehoe, much like the alternating rapids and slack areas in a mountain brook. Some roof failure occurred when lava was flowing in the tube, as indicated by the small piles of collapse breccia that were overridden with lava and by blocks rafted in frothy pahoehoe.

Middle and Lower Parts of Hercules Leg Cave

From the area at the Unga Dunga entrance, Hercules Leg Cave runs in gently sweeping curves northward for 750 ft and then makes a right-angle turn to the east for 320 ft. It then angles northeast 90 ft to its junction with Upper Juniper Cave, a tributary tube (map 6, pl. 2). In this part of its course the cave is mostly a single large tube with few complications. The right turn to the east is a rounded curve complicated only by a split of the tube around a large (80 by 45 ft) pillar.

The middle and lower sections of Hercules Leg have the most intact roof; only minor amounts of collapse breccia litter its floor except at the two ends where large collapses occurred. The central parts of this area, including the two tubes which detour around the big pillar, are excellent examples of unscarred lavacicle ceilings, dripstone walls (fig. 31), and frothy pahoehoe floor adorned with rafted blocks.

Near the large pillar where the tube bends east is a former skylight roofed over with lava. A roof collapse has shattered and blocked the upper end of the tube that went around the east side of this large pillar. Three additional pillars are present downstream, including one 260 ft farther with a hanging tube that widens into a balcony 7–10 ft above the floor of the main passage. Many alcoves in this part of Hercules Leg show evidence of slow withdrawal of lava as the tube drained.

There are more rafted blocks in the pahoehoe floor of Hercules Leg Cave than in other tubes of the Cave Loop Road area. This probably reflects its closeness to the surface; many blocks fell into the lava stream from its thin roof during volcanism. Collapse to the surface may also have occurred at this time but was later roofed over, as at the skylight. Remnants of collapse breccia penetrated and smoothed over by lava are not abundant, however. A large floor jam of blocks occurs at the junction of Hercules Leg tube with Upper Juniper Tube.

Juniper Cave

Relation to Hercules Leg Cave

Juniper Cave is the downstream continuation of Hercules Leg Cave. After it picks up a short tributary from the south (Upper Juniper Cave), the combined system makes a sharp bend to the north, continues for 200 ft, and then makes a 90° turn east past the Juniper entrance collapse. The area where two right-angle bends closely follow one another is a jumble of large pillars between which the main tube subdivides and reunites in a network of separate strands. Large areas of roof collapse (fig. 32), including an extensive one at the Petroglyph entrance, add to the confusion. In this maze of tubes and pillars, lava cascades, pools, floor jams, irregularly shaped alcoves, and piles of collapse rubble are jumbled together. Another tributary enters Juniper Cave from the southwest, 200 ft downstream from where the main tube turns sharply east.

The tributary from the south (Upper Juniper Cave) joins Hercules Leg tube at its junction with Juniper Cave 300 ft downstream from its source and was fed from a surface lava flow. At the Swallet entrance located at the head of this tributary, a short lava gutter leads from a wide basin on the surface directly into the tube. This basin was once filled by a lava flow. After the flow had drained through this tributary tube for some time, the pooled basin lava fill at the surface broke through an obstruction on its northeast rim and continued downslope as a surface flow. This partial draining of the lava basin fed the upper Juniper tube. The final trickle of lava down the Juniper tributary tube made a low central ridge of frothy pahoehoe, which stands 1–2 ft above the older lava floor; shallow gutter-like areas formed on both sides of the ridge against each wall (see cross section on map 6, pl. 2 near upper end of tube).

The question of whether the lava flow that fed Upper Juniper Cave penetrated a breakdown in an older empty tube or was simply part of the outpouring of lava associated with the Hercules Leg tube has not been resolved. An outpouring seems more likely because the draining of both tubes appears to have occurred at the same time, as shown by evidence at the floor jam at their junction.

Floor Jam at the Junction of Hercules Leg Tube and Upper Juniper Tube

The largest floor jam of lava blocks in the Cave Loop Road area is in the Bat Whistle Room at the junction of Hercules Leg tube and Upper Juniper Tube. The jam's top in each of these two tubes is elevated a few feet above the confluence of the tube floors, but the floor jam is largest and best developed in the lower part of Hercules Leg. All of the Hercules Leg passage is not occupied, however. A 40-ft ledge of collapse breccia seals off an alcove on the north side of the mouth of Hercules Leg; this ledge formed a wall that funneled the floor jam blocks into a constriction between a large pillar and the north wall of the tube. Above this constriction the floor jam consists of smooth, integrated blocks of pahoehoe broken by deep crevasses. A few blocks of varying size from the roof were also incorporated in the jam; three of the largest rafted blocks are shown on the map (map 6, pl. 2). The floor jam is not present in the alcove behind the 40-ft ridge of collapse breccia, where pull marks reveal only slow drainage from a higher level. The collapse breccia on this floor proves that drainage of the alcove was complete before the collapse. As noted earlier, however, the collapse breccia is older than the pahoehoe of the floor jam, which was funneled south by this collapse ridge.

Below this constriction the nature of the lava floor jam changes. The blocks are much smaller and have jostled together into a lobe of loose rubble. Many are frothy, spiny, highly inflated pahoehoe. Where this lobe advanced against the pillar on the south and the tube wall to the north, floor blocks near the walls are definitely overridden and shoved aside. This constricted part of the lobe has a high gradient; it is essentially a cascade of jumbled blocks, which may have moved catastrophically like a rockfall or rock avalanche. At the foot of this cascade the lobe rolled out over the flat surface of a pahoehoe pool and then collided with a wall of collapsed blocks at the narrow upper entrance of a branch from the tube around another pillar (map 6, pl. 2). These collapsed blocks may have fallen from the roof and walls between the two adjacent pillars at the same time the floor avalanche advanced.

The avalanche caused unusual changes when it crossed the pahoehoe. Evidently the lava pool had a solid crust above a molten interior because its surface bowed beneath the weight of the avalanche debris and collapsed roof blocks. The displaced lava was squeezed farther downstream, where its crust lifted into a pressure ridge. Part of this uplift also swelled into a rounded blister with radiating cracks in its top.

Whether the rock avalanche and the roof collapse at its toe were triggered by an earthquake, which struck the area after most, but not all, the lava in the tube had drained, is a theory that might explain the time relations within this small area. However, no concrete evidence substantiates this theory. The quake theory does support the observation that although the lava throughout the Hercules Leg-Juniper Cave system contains a large number of rafted roof blocks, almost no large areas exist where collapse breccia was overridden by lava.

Sentinel Cave

Sentinel Cave consists of the ruins of four large lava tubes superposed, with the fourth and lowest level slightly offset from the upper three. They have tumbled into a chaos of large angular blocks by partial collapse of their roof and floors after volcanism ceased. In places segments of a tube's floor and walls survive as benches or balconies perched above piles of rubble. In other places tube floors have survived the general collapse, but are seldom seen because they are deeply covered by rubble from above. Many floor segments gradually gave way under this load and broke through into the underlying tube. Roof areas covered by lavacicles or other primary features are uncommon; indeed, a light played over the ceiling in many places reveals only spaces where roof blocks have tumbled out. Many loosened blocks remain precariously perched, indicating that collapse of the roof is still

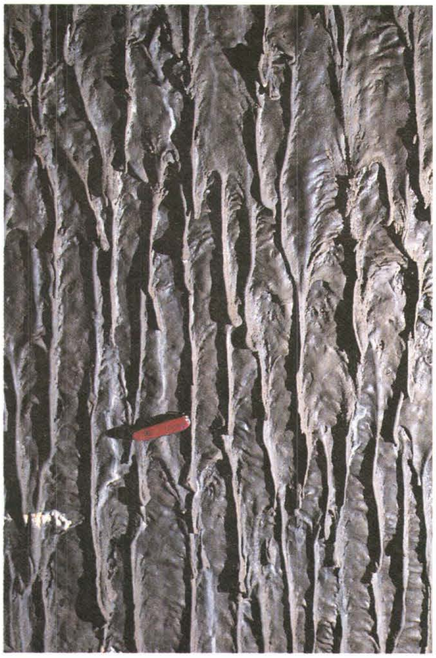


Figure 31. Dripstone wall in Hercules Leg Cave (see fig. 14 and map 6, pl. 2). Pocket knife for scale.

Figure 32. Collapse blocks from tube's roof litter floor of Juniper Cave (see fig. 14 and map 6, pl. 2). National Park Service photograph.

underway. Collapse to the surface has occurred at all four entrances. In fact, the near-total collapse of the uppermost tube to the surface, a process which left a train of breakdown depressions, reveals the course of this main lava feeder channel connecting Natural Bridge to Ovis, Indian Well, and Sentinel Caves. This is the tube system that also spawned the Labyrinth, Catacombs, and Hercules Leg-Juniper Cave systems. Sentinel Cave's roof is the largest remnant to survive along the course of this highest feeder tube of the Cave Loop Road area.

Features Near Upper Entrance

At the upper entrance to Sentinel Cave are two large collapse pits with a natural bridge between them (map 7, pl. 2). The ceiling of the upper tube has been thinned almost to the surface by roof collapse, and collapse breccia covers the floor.

Located 50 ft from the entrance and 10 ft above the present floor is a fragment of the tube wall and a lava bench. They were protected from collapse because they were in a 20-ft-diameter alcove on the southeast wall of the tube. As the floor of the alcove cooled and solidified, the underlying lava began to drain back into the main tube, a process which formed a 2-in.-wide tension crack in the upper crust. Another 50 ft downstream the collapse blocks on the cave floor end abruptly, and a remnant of each wall of the tube is perched on either side. One remnant runs beneath the stairs on the west side; the other is separated from the present east wall of the cave by collapse blocks that represent an 8-ft retreat of the original southeast wall.

Both remnants have a lava bench, or balcony, 3 ft above the pahoehoe, which probably marks the former floor of the tube. Evidently, throughout most of this area the floor of the upper tube collapsed into the middle tube below. A little farther downstream, at the abrupt bend of the tube to the north, is an almost impassable chaos of deep pits partly filled with huge blocks. High ceilings, caused by unraveling of the roof almost to the surface, characterize this area. These features indicate collapse of all three upper-tube levels, an event confirmed by the lowest tube being closed by debris in this area.

The trail avoids this chaotic section of the cave by following a small branch of the upper level that swings around a pillar to the west and reenters the main tube 90 ft downstream. Here a natural catwalk crosses the deep collapse pits in the main cave. This catwalk is anchored at either end to remnants of the pahoehoe bench that formed the floor of the upper tube. An upper balcony, 3 ft higher than the catwalk, still adjoins the lower-floor bench at either end of the catwalk. Pahoehoe lava in a tributary to this upper balcony is exposed at intervals within the small tube forming the trail bypass. This balcony continues on the north wall of the bypass tube for 20 ft west of the catwalk. A remnant of the floor of the upper tube extends as a narrow natural bridge about halfway across part of the deep chasm 15 ft south of the catwalk. Together with fallen roof blocks at the west side, the remnant forms a second precarious crossing over the collapsed tube. The numerous benches, partial bridges, and balconies where these two passages join indicate a complex series of events.

North of the catwalk the chasm of collapsed blocks ends abruptly. The trail from the east end of the catwalk continues along the narrow bench, 3 ft below the balcony bench, and over a lava fall until it reaches the intact floor of the upper tube. Downstream this tube floor, littered with fallen roof blocks, can be traced for 95 ft to where it is buried under collapse rubble.

Two interesting features appear along this stretch of intact floor. One is a collapse pit resembling a well only a few feet in diameter, which gives access to the middle level below. The other is a small tube-in-tube less than 2 ft deep and 3 ft wide; its cross section is best seen on the north wall of the collapse pit, just beneath the surface. South of the pit most of the tube-in-tube has collapsed, either from its own weight or by bombardment of falling roof blocks (map 7, pl. 2). In this section of the cave, the main passage measures 10 ft wide and as much as 25 ft high.

Nearly 25 ft north of the collapse pit the trail begins to rise steeply on a huge mound of collapse rubble. No primary features of the lava tube are seen in this section except on the surfaces of fallen blocks. From the top of this collapse mound the trail rounds a sharp corner, passes a tiny branching tube from the north, and descends a stairway into a deep collapse. Here the entire floor of the upper level has fallen into the lower tubes. This collapsed area extends northeast for 210 ft, where the trail again ascends to a partially rubble filled upper tube.

At the east end of the collapsed area where the stairs descend from the upper level, the middle level extends south beneath an overhang. Through the floor of the middle level, beneath this overhang, a narrow vertical chimney-like pit opens below steep slopes of rubble. The pit gives access to the lowest levels of Sentinel Cave and is covered by a gate.

Middle Level of Sentinel Cave

The entire length of the middle level of Sentinel Cave is covered by rubble from the collapse of the upper level. Small remnants of lava benches and balconies provide glimpses of tube walls in and above the middle level (map 7, pl. 2). These remnants have not been correlated with one another, nor with the two benches described in the upper level. Halfway along this east-trending, 20-ft-wide passage is a double skylight, the Tube and Pillar entrance, named for the small natural bridge and pillar within a near-surface tube. The ceiling height of the main passage gradually decreases from 12 ft to 9 ft at the lower entrance.

Tubes Intersecting Sentinel Cave

A side tube that crosses the collapsed middle level of Sentinel Cave approximately 400 ft upstream from the lower entrance is the continuation of the tiny branching tube just upstream from the stairway. At its upstream entrance, this small tube is a 3-ft-diameter crawlway with a smooth pahoehoe floor. The tube enlarges slightly before swinging east and rejoining the main tube 16 ft above the floor of collapse rubble. The eastern continuation of this side tube hangs 5 ft lower on the east wall of the main passage because of a lip formed by draining of the lava back into Sentinel Cave immediately after collapse joined the tubes. From the sill above this lip the empty tube can be followed downstream 115 ft, where it again intersects the main Sentinel tube by means of a 7-ft lava fall. Midway along its course this side tube is partly choked by a mass of collapse breccia that was overrun and smoothed out by the withdrawing lava. From this point, the tube cannot be followed downstream into the west wall of Sentinel Cave.

Another tube (which may be an earlier westward continuation of the upper level) enters Sentinel Cave from the west 6 ft above the main passage floor at the corner where the trail along the middle tube rises over a rubble scarp 8 ft high and then turns east along upper Sentinel Cave's collapsed continuation. This 20-ft-wide upper-level tube quickly disintegrates into a maze of collapse rubble and irregular low rooms. The tube continues back to the south with most of its pahoehoe floor buried. This tube can also be reached by the Wabbit entrance (map 7, pl. 2).

Lower Entrance and Downstream Extension

Exit from Sentinel Cave is through the lower entrance, a large collapse pit 66 ft vertically below the upper entrance. To the east, an entrance hole, the Annex entrance, leads down into a 15-ft-diameter tube with a relatively clean pahoehoe floor. The character of this northern part of Sentinel Cave is very different from the main part previously described. Here the walls and floor are largely intact; the walls are moist and nearly black, and the temperature of the cave is much colder. Multiple benches, partially peeled wall linings, and a ropy pahoehoe floor are present along this section of the tube. Some collapse rubble and a long peeled lining along the north wall are found just upstream from a low tube-in-tube that meanders down the center of the cave for over 100 ft. The main tube then turns to the north and becomes triangular in cross section (fig. 33) for several tens of feet. Along this segment, the elevation of the floor is 85 ft below the upper entrance. Farther along the passage, the ceiling drops to 5 ft near a large pile of collapse rubble; just beyond this pile is the start of another collapsed tube-in-tube, which can be followed for 50 ft. This main passage contains two sets of benches,

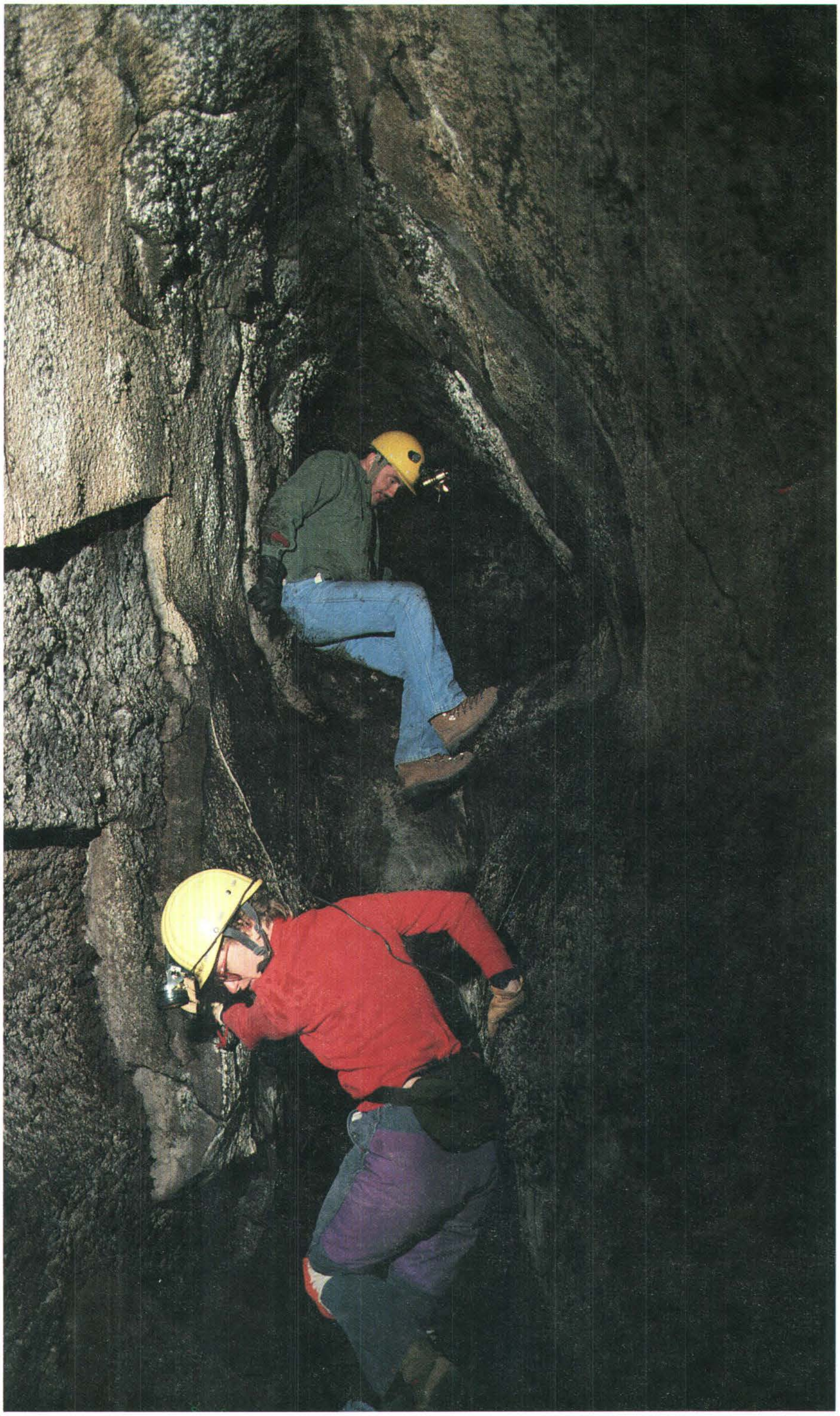


Figure 33. Two explorers negotiate a narrow passage of Sentinel Cave (see fig. 14 and map 7, pl. 2). Portions of left wall linings have sloughed off.

one located just below ceiling height and the other directly above the collapsed tube. The remaining several hundred feet of cave consists of a 10-ft-wide passage whose ceiling gradually lowers. The tube is sealed by pahoehoe lava at a point some 106 ft vertically below the upper entrance. Spalled wall linings cover the floor of the last section of the cave and make it difficult to traverse. The downstream continuation of this tube contains Indian Well Cave.

OTHER CAVES IN OR NEAR THE MONUMENT

In addition to the caves, shown on maps 1–7 of plates 1 and 2, that are easily accessible from Cave Loop Road, a number of interesting caves are easily reached by roads in other parts of the monument; these caves are shown on maps 8–14 of plates 3–5. Four additional caves that are among the most interesting in the monument are shown on maps 15–18 of plates 5 and 6; access to two of these caves, Crystal and Fern Caves, is restricted because of the fragility of their contents.

Two maps on plate 6 show surface features; map 19 shows Mammoth Crater and adjoining areas, and map 20 shows the short caves and interesting features associated with collapse trenches along a major lava-tube system within a little-visited part of the monument area.

Valentine Cave

Records at Lava Beds National Monument report that Valentine Cave (map 8, pl. 3) was "discovered and named by Ross R. Musselman on Valentine's Day, 1933." This cave can be reached from monument headquarters by driving southeast for 2 mi on the paved road connecting the monument to California Highway 139. As this road rounds the north end of Caldwell Butte, a paved road to the left (north) marked with a sign for Valentine Cave turns off and ends within 0.25 mi of the parking lot adjacent to the cave entrance (fig. 34).

Valentine is a deservedly popular cave among visitors—it is interesting, clean, and varied. Here one can see a lava-tube system that is only slightly damaged by collapse (see frontispiece). The cave shows most of the features to be found in lava tubes: pahoehoe floors, lava pools, lava cascades (fig. 35), and well-developed lavacicle ceilings and dripstone walls. Two kinds of lava benches are present: one marks a high-level stand of an extremely viscous lava flow, which attempted to crust outward from the walls as the lava was flowing;

Figure 34. Stairway leading to entrance of Valentine Cave (see fig. 4 and map 8, pl. 3).

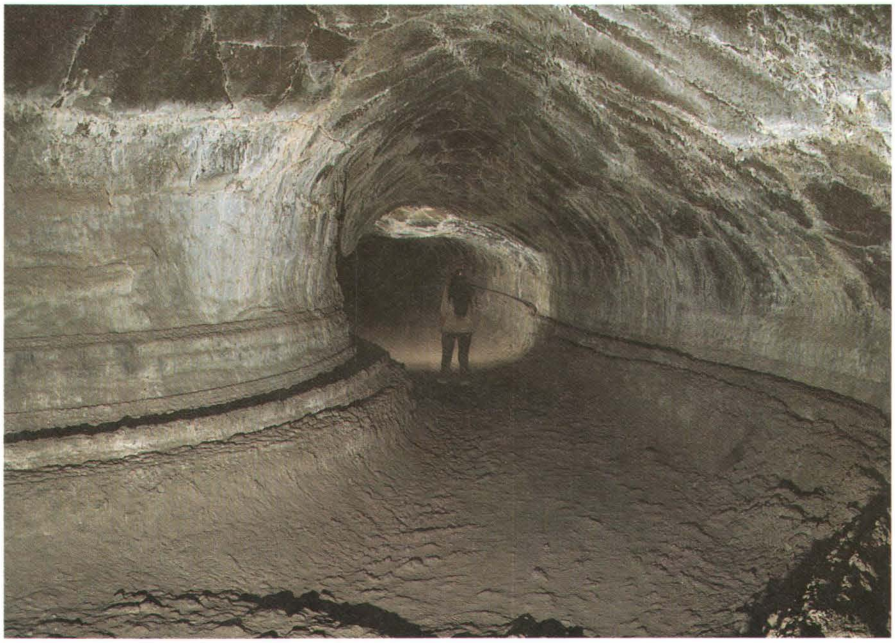


Figure 35. Lava benches on walls of Valentine Cave (see fig. 4 and map 8, pl. 3) indicate high-lava mark from higher stands of lava that occupied the tube.

the second kind was made by the penetration and bulldozing of collapse blocks, due to hydraulic pressure from lava forcing its way through the tube. Large pillars around which the lava stream divided and reunited are present in the upper part of the cave. The central part of the cave contains lava falls and cascades through which the lava stream transferred from a higher lava tube to an open tube at a lower level. Downstream from this area of subsurface breakdowns Valentine Cave divides into distributaries, which are filled with lava downstream.

The accessible passages within the cave total 1,635 ft. Most of the accessible area is in one main tube, blocked 950 ft downstream from the entrance by lava. The Valentine Cave entrance is a shallow collapse pit with an overhang upstream as well as downstream, but upstream access is blocked within 20 ft by roof collapse.

Surface Features Near Entrance

The size of the tube and its relation to surface features indicate that Valentine Cave continued much farther upstream and downstream. It can be traced upstream on the surface from a chain of collapse trenches, natural bridges, and short cave segments, which wind around the northwest side of Caldwell Butte. The basalt of Valentine Cave (Donnelly-Nolan and Champion, 1987) erupted from a set of spatter vents outside the monument, 1 mi southeast of Mammoth Crater, known as the Tickner Chimneys (map 9, pl. 3) and from additional spatter vents farther south. Tickner and Berthas Cupboard Caves (map 9, pl. 3) are in this same basalt flow just downstream from the vents and about 3 mi upstream from Valentine Cave. The basalt flowed north against the earlier basalt of Mammoth Crater, and then it flowed east and surrounded Caldwell Butte, and then it spread out north and east. Valentine Cave is within the north-trending lobe. There is surface evidence that a tube collapse 150 ft south of the entrance to Valentine Cave may have diverted the lava entering Valentine Cave at that time to the east; this diversion would have cut off the lava supply and allowed the now accessible portions of Valentine Cave to drain almost completely. The surface breakdown on the site of this collapse is rimmed by a rampart 10–20 ft high on its north side. This rampart was formed by lava forcing its way northward within a blocked tube. The ponded lava escaped through a tube that drained southeast from this point. The collapse rubble that blocks the head of Valentine Cave, only 100 ft north from this rampart, shows no sign of having been overrun by lava, although small slopover spills escaped northward between the upraised blocks of the rampart at a level 15 ft higher than the floor of Valentine Cave.

Schollendomes

The shallow collapse pit that gives access to Valentine tube is in a surface flow containing scattered schollendomes. Schollendomes are oval-shaped hills of lava, with a deep cleft running along the length of the hilltop. They form on some flows whose molten interior is still creeping forward after the flow surface has solidified. See Waters (1981) and figure 36 for descriptions of schollendomes in Captain Jacks Stronghold (fig. 4) at the north edge of the monument. Nichols (1946) shows photographs of similar features on the McCartys basalt flow in New Mexico, which he describes as pressure ridges. Wentworth and MacDonald (1953, p. 45) call similar Hawaiian features tumuli, which they state are "also known as pressure domes or schollendomes." They consider tumuli to be gradational into the more elongate forms known as pressure ridges. A detailed discussion of terminology and mode of origin is available in Champion and Greeley (1977).

Upper Part of Valentine Cave

The first 350 ft of Valentine Cave downstream from the entrance contains many interesting features. At the entrance the tube is 25 ft wide and 8–10 ft

Figure 36. Pathway through Captain Jacks Stronghold (see fig. 4) follows axial trace of schollendome, which formed by cracking of chilled lava surface over molten interior. These natural trenches were utilized as defensive positions by the Modoc Indians during the Modoc War of 1872–73.

high, but it immediately widens to 40 ft as it divides around a pillar 60 ft long and 20 ft wide. A second pillar of about the same dimensions is present 120 ft farther downstream.

The final surge of lava to pass through the tube was only 2–4 ft deep, and it left many records of its passage. Its surface began to crust over and solidify along the sluggish parts of the lava stream, such as the upstream and downstream ends of the pillars and in the alcoves along the outside walls. On the sides of the pillars and in other restricted areas of the tube, however, the sticky lava was pulled and sheared into ribbonlike masses, which piled up against one another in vertical sheets. In some places these accreted layers were later sheared off while other layers were added; thus, complex benches were completely torn off and carried away by the flood, and only a high-lava mark was left on the wall of the tube. In these highly sheared areas the wall below the high-lava mark is not covered with normal dripstone; instead it is smooth and shows only horizontal striations and grooves, where the viscous and partly solid lava was sheared and dragged along the wall.

In alcoves of the wall and on the upstream and downstream ends of the pillars these benches were able to grow out into the moving lava flood. Such areas are particularly significant because they record the fluctuations of the lava surface as well as indicating the velocity of the surges. No two areas are exactly alike. Moreover, between each accretionary layer, the dynamics of viscous flow are revealed not only by sheared surfaces but also by smeared-out bubbles, tensional cracks, and extended drag folds. A particularly good place to see some of these features is near the alcove on the east wall of the tube downstream from the second pillar (280 ft downstream from the entrance). Other excellent places are on the east wall between the pillars and on their upstream and downstream ends. These benches are labeled on map 8, plate 3.

The first 350 ft of Valentine Cave is a good example of a lava tube that has almost completely drained. The lava remaining on the floor is mostly pahoehoe; in places it is glassy and lustrous whereas at the cascades it is frothy. Only a small amount of soil and a few scattered collapse blocks litter the tube floor. Rodent pellets are present at several places and, where rainwater seeping through the roof has moistened them, their phosphatic composition causes a green fluorescent glow when a flashlight is played on them.

The ceiling of this part of the cave contains excellent lavacicles, and the walls above the benches display fine examples of lava dripstone. Many lavacicles are short thick blades resembling shark teeth. The roof of the cave is also riven with innumerable tight cracks, mostly tensional, formed as the lava cooled and solidified. They meet in triple junctions (three cracks radiating from a point). In addition there are a few long, straight cracks parallel to the course of the tube. Striking examples are present near the entrance west of the first pillar extending from it for over 100 ft. Percolating rainwater seeping through the roof along the cracks has loosened the lavacicle plaster from the wall rock above. A few large blocks of the roof have tumbled to the floor, and many others appear ready to fall.

Percolating water also produced another interesting effect on the roof. Water wets the surface along both large and small cracks and drips to the floor from their edges. Most of the water evaporates and forms a thin precipitate of white caliche (calcium carbonate). Because of the strong color contrast between the white caliche and the shiny black lavacicles, the roof of many parts of Valentine Cave appears to be a mosaic of irregularly shaped black tiles held together by a white cement.

Two Central Breakdowns

An abrupt change in the Valentine Cave occurs 370 ft downstream from its entrance. The width of the tube, 30–50 ft in the upper part, closes to 12 ft, and the floor drops over two long cascades and three small lava falls into a broad compound lava pool at the bottom of the slope. The tube is over 75 ft wide in this pooled area.

Just above the head of the cascades three small tubes split off from the main tube. One enters the west wall a few feet upstream from the head of the cascades and is filled with frothy pahoehoe. The other two tubes, 4–7 ft wide and 3–5 ft high, take off from the east wall on a northeast course but then turn back to the north. Nearly 90 ft downstream they merge together around a kidney-shaped pillar 85 ft long and 20 ft thick. In the lower 25 ft of their course the lava in these high-gradient tubes cascaded down a steep slope, which drained their combined flow into the southeastern part of a large compound lava pool. This pool also received the flow from the main tube's cascades 40 ft farther west.

The upstream parts of these two tubes are good examples of lava tubes that have been completely drained. They have typically flattened oval cross sections with a broadly rounded roof and floor that curves sharply upward at their walls. These tubes also contain excellent examples of dripstone walls and lavacicles. At their lower end, where the steep cascades begin, their floors drop abruptly 8 ft to a lava pool. The final trickle of lava into this pool arrived in a narrow channel cut a foot deep into the floor of the lava cascades. The roof of the tubes, however, does not drop with these cascades but instead arches northward over them to extend high over the eastern part of the wide pool area.

On the east side directly downstream from the easternmost of the two small tubes is a sloping lava bench located 3–8 ft above pool level. Its upper surface is covered with pahoehoe whose ropes clearly show that lava from the eastern small tube once flowed over this bench. The latest channel of the eastern tube turned sharply to the left and cut through this bench. Its truncated edges are evidence that the bench originally was a large pile of tumbled roof blocks, which were later completely immersed in molten lava. This lava carried away parts of the collapse and the bench was left as a remnant. The channel forms a steep cascade that joins the cascade from the other small tube. A similar bench, in which fallen collapse blocks coated with lava are clearly visible, is present in the alcove on the same wall 20 ft farther downstream.

The compound pooled area, which was fed by the main tube and these two small tubes, is in a room roughly divided into northwestern and southeastern parts by two small pillars. Both pools have floors at approximately the same level, and the lava from both flowed downstream through a tube only 18 ft across—a width contrasting strikingly with the 75-ft width of the pooled area.

The roofs of the two parts of the pooled area, however, are very different. The roof of the lava pool northwest of the two pillars is a broad expanse of lavacicles, which lie only 2–4 ft above the pool's floor. In contrast, the roof on the southeast side of the pillars is 10–20 ft above the pooled surface and is dominated by a variety of collapse features. The former course of two small lava tubes, whose floors collapsed into this huge room, can be followed for tens of feet by their outlines indented in the roof of the large room. It is evident that several tubes on different levels merged to form this room and that the collapses which joined them together occurred prior or even during the last time that Valentine Cave was filled with molten lava. Much of the collapse debris was carried away in the molten floods, but some was left as benches and as alcove fillings of collapsed blocks penetrated and smoothed over by the flowing lava. More debris probably lies completely buried by congealed lava at the bottom of the two lava pools.

The last lava to course through Valentine Cave flowed out of this pooled area in a broad pahoehoe stream, which pooled again after flowing only another 40 ft. This pool is the floor of another complicated area of tube junctions and roof collapses forming an irregular Y-shaped room 600 ft downstream from the cave entrance. At this point Valentine Cave divides into two major distributaries—one continuing to the north and the other (and larger) tube trending N. 70° E.

The most striking feature in this second large room is the pile of roof collapse debris that partially blocks the north-trending tributary and spilled collapse blocks halfway across the Y-shaped lava pool. The collapse pile, although it rises high into the roof, does not provide access to the surface. The distributary tube to the north can be easily entered by skirting the collapse pile along the west wall of the tube.

Downstream Distributaries

The Millipede Distributary extends north 180 ft then turns 45° to the west (map 8, pl. 3). It narrows abruptly to a short crawlspace, then expands into a pahoehoe pool roughly 25 ft in diameter, but the roof is less than 3 ft above the pool's surface. This pool ends the accessible part of the north branch of Valentine Cave. The tube contains excellent lavacicles, dripstone walls, and pahoehoe floor. There are two small areas of roof collapse 60 and 80 ft from its downstream end and a huge roof collapse at its junction with the main tube.

The northeast-trending Bubble Distributary is more diversified. Within the second area of breakdown about 180 ft downstream from where this tube begins are benches on either side; both benches consist of collapse breccia partly eroded by flowing lava. Evidently the collapse that partly blocks the tube junction was preceded by one or more collapses, which spilled blocks into the molten lava. One large pile of collapse blocks that was cemented by lava fills a large alcove on the north wall of the distributary at its source. As the lava level lowered within the tube, this collapse pile first appeared as an island above the flood. With further drainage, a trough appeared between this "island" and the wall of the tube. High-lava marks indicate backflow in the upstream direction within this trough (see map 8, pl. 3). Several alcoves farther downstream contain piles of collapse breccia that were bulldozed into these sheltered spots by the moving lava. During the last stages of drainage many of these piles were connected by a discontinuous lava bench, which bordered both sides of the tube and widened across the alcoves. Between the benches is an open channel, which is 2–3 ft deep. The final surge of lava down this part of the tube built a lobe of spiny pahoehoe, a little thicker in its center than the channel is deep. In most places, however, it did not completely fill the channel but left a small gutter between the wall of the channel and the rounded surface of the frothy pahoehoe lobe. In a few places this last lobe of lava developed a spiny surface and began to break up into separate blocks, and so the lobe is transitional toward aa. Many peeled linings are present along this section of the passage.

Parts of this tube have low ceilings, and it is evident that the tube is filled with congealed lava downstream. Finally the tube again splits into north and east distributaries. At this split the benches disappear and smooth pahoehoe that formed pools as it rose left only a crawlspace between the ceiling and floor. This north distributary is filled and becomes inaccessible only 15 ft from the junction. One can crawl down the east branch for 75 ft to a lava boil on the floor. This lava boil may represent an overflow from a lower tube possibly fed from the twin lava pools several hundred feet upstream. Just past this boil the passage is sealed by a lava pool.

Tickner and Berthas Cupboard Caves and Tickner Chimneys

Unlike most large lava-tube cave systems in Lava Beds National Monument, Tickner and Berthas Cupboard Caves (map 9, pl. 3), along with Valentine Cave (map 8, pl. 3), did not originate from molten lava erupted from Mammoth Crater. Instead the Tickner Cave lava reached the surface through vents associated with a northwest-trending fissure system on the north slope of the Medicine Lake volcano 1 mi southeast of Mammoth Crater (fig. 4). This lava flowed north then east to Valentine Cave and beyond. It overlies the basalt of Mammoth Crater and is known as the basalt of Valentine Cave (Donnelly-Nolan and Champion, 1987). Small agglutinate cones known locally as the Tickner Chimneys are the most conspicuous features of the vent area, but an interesting network of small lava tubes is present both on the surface and stacked at shallow depths along fissures. Many small spillover lobes of lava were formed during the final stages of eruptive activity.

The material that built this lava field was transported almost entirely through lava tubes; the main tubes preserved are Tickner and Berthas Cupboard Caves. J.D. Howard explored these features in the 1920's (his notes are on file at the Visitor Center). He named Tickner Cave and the Tickner Chimneys after H.C. Tickner, an early freighter who lived in Yreka and pioneered the Tickner Road (map 9, pl. 3), an important wagon route in the late 1800's.

Howard also found a cave at a lower level, which extends the cave system to the northeast, and named this deeper level Berthas Cupboard Cave in honor of Bertha Heppe, the wife of an early homesteader in the area. The word "cupboard" refers to the shelf-like openings and irregular small grottos that lie between flow units of lava in the southeast corner of the well-like breakdown forming the main entrance. They are shown in a schematic cross section on map 9, plate 3 and also in figure 37.

Tickner Road, a little-traveled dirt road through the logged-over forest just south of the monument boundary, is the only access road to this area. Tickner Road crosses a collapsed and filled part of Tickner Cave (map 9, pl. 3) at a point about 1 mi (by road) east of the junction of Tickner Road with the Medicine Lake-Lava Beds Road. The caves are unmarked; the land survey location of this crossing is in the NE 1/4 sec. 5, T. 44 N., R. 4 E. An abandoned logging road joins Tickner Road 200 ft west of the Tickner Cave crossing and provides access to the Tickner Chimneys farther upstream to the south.

The position of Tickner and Berthas Cupboard Caves is easily located because of the line of collapse pits and trenches formed along roof cave-ins (fig. 38). This line is at the center of the lava flow, which trends north and then northeast. The surface of the ground slopes away on either side. Near the downstream end of the lava field, Berthas Cupboard Cave is so filled with ponded lava and collapse debris that it can no longer be traversed. The underground tube, however, must have continued northeast because small patches of aa broke through and welled out of cave roofs at points along the eastern continuation of this line.

Farther upstream, during early and late stages of volcanism, lobes of pahoehoe flowed from skylights and fissures in the roofs of the Tickner and Berthas Cupboard tubes. These spillover lobes were important components in building the apical ridge along the sloping surface of the lava flow.

Tickner Cave

The upper entrance to Tickner Cave is at the northeast end of a lava chute 10 ft wide that increases from 2 to 10 ft in depth downstream. This chute marks the site of a 150-ft-long former cascade in a surface stream of molten lava that flowed downhill on a 10° slope. Horizontal striations preserved on the walls of the chute indicate places where viscous lava was dragged against the walls. The gradient became shallower at the northeast end of the chute where the lava plunged underground into what is now Tickner Cave. Spatter on the rims of the chute and over the roof of the cave entrance testifies that limited fountaining of the molten lava took place at the point where it surged underground.

From this point Tickner Cave can be traversed for 1,450 ft downstream. At several places along its course molten lava broke out onto the surface through skylights and medial cracks along the

Figure 37. Entrance area shows stacked holes that lent name to Berthas Cupboard Cave (see fig. 4 and map 9, pl. 3).

axis of the roof. Along the lowest 500 ft of its course, lava in the tube leaked down through at least three holes in its floor into the upstream part of underlying Berthas Cupboard Cave.

Throughout its extent Tickner Cave lies very close to the surface. Many collapse holes (fig. 39) reveal a roof thickness of only 1–4 ft. In places along the axis of the cave slabs of roof rock were raised and tilted. In some of these arched areas evidence indicates that parts of the broken roof collapsed during volcanism. The lava flowed in up to 100-ft-long gutter-like open streams along the axis of the tube. Contact with the air caused solidification on the sides and surface of the molten stream. Thus most of these gaps were soon bridged over with a solid lava cap that was gradually thickened from below and welded onto broken edges of the former roof. As a result, the ceiling height of Tickner Cave varies considerably. The ceiling today contains many cupolas and domes, which were either former skylights or collapsed parts of the former roof now joined to the collapsed walls by coatings of several layers of lavacicles and dripstone. Only where parts of the roof have subsequently collapsed can one see the separate coatings of lava plaster and the successive linings of lavacicles and dripstone. These layers reveal that Tickner tube was repeatedly filled and drained of molten lava and that much lava spilled onto the surface.

The floor of Tickner Cave is also complicated by many interesting features caused during the partial draining of the last lava to occupy the tube. Because remnants of this final flow form numerous balconies clinging to the walls of the cave, we named it the "Balcony flow."

During the downstream flow of the molten lava, a roof collapse occurred 200 ft upstream from the lower end of Tickner Cave at the broad part of the paddle-shaped collapse trench. The lava backed up behind this barricade and filled half the tube as far as the upstream entrance of the cave. The lava lifted the cave's roof on the west side of the collapse and poured out on the surface, tilting part of the roof to a right-angle position as it opened an exit (map 9, pl. 3). Another part of the lava, however, flowed around the sides of the collapse pile forming the two small tubes on either side of this paddle-shaped feature. Also, an irregular plexus of tiny lava lobes burrowed beneath the collapse debris; some drained out and left open lava tubes large enough to crawl into. Furthermore, at least three main areas of leakage occurred through the floor of Tickner Cave; lava dumped into the upstream part of Berthas Cupboard Cave below. One of these leaks is 100 ft upstream from the paddle-shaped

Figure 38. Surface collapse of upper tube allows entrance to Tickner Cave (see fig. 4 and map 9, pl. 3). Gentle arch shape over tube is a common feature of tube-bearing basalt flows.

collapse (map 9, pl. 3). Two others are still farther upstream at the head of two branches in Berthas Cupboard Cave; the branch on the east forms the now rubble-filled upper Crawl entrance to Berthas Cupboard, the one on the west is completely blocked with collapse debris.

During the waning stages of volcanism, a surface of lava developed within Tickner Cave that fluctuated only a foot or two in height because incoming lava was essentially in equilibrium with the amount of lava both detouring around the paddle-shaped barricade and leaking into Berthas Cupboard Cave. This equilibrium allowed a crust of solidified lava to form on top of the flow, and so a "false floor" was built completely across the tube upstream from the area of collapse. This crust, however, was unstable; slight fluctuations in the amount of lava heaved it up or let it sag from lack of support. Moreover, the crust was thin over the wider and deeper parts of the lava tube, where large pools of molten lava retained elevated temperatures for a longer time. The crust was stronger and thicker in the narrow, quicker cooling parts of the tube. Finally, with cessation of volcanism, much of the molten lava beneath the crust drained into Berthas Cupboard Cave. This drainage resulted in large sections of the thin crust in the wider parts of the cave collapsing and being carried away. However, along the walls, where the crust was thicker and more rigid, extensive remnants were left clinging to the walls as benches (fig. 40). In narrower parts of the tube the crust remained essentially intact as an underground natural bridge, with a tube-in-tube forming a culvert beneath it.

The difference in shape of Tickner Cave compared to most other lava tubes is immediately apparent upon entering this cave. The floor, instead of rising gradually into the dripstone walls, intersects the walls at an acute angle. At the junction is a bench with an irregular top 1–3 ft high and seldom more than 3 ft wide. It is made up of thin slabs of congealed lava, some of which tilt up steeply from the junction of floor and wall and have irregular broken edges. Other slabs extend out nearly flat and then sag down from the walls, whereas still others turn down and curl in toward the wall. These thin slabs of broken or curled lava record minor fluctuations in the height of the molten lava surface within the tube. Such fluctuations allowed thin, fragile crusts of rock called peeled linings to congeal and extend outward from the walls for a foot or more before they were either broken and heaved up by a slight rise in the level, or were let down and curled under as the height of the lava flood subsided a few inches. Low benches of these broken and

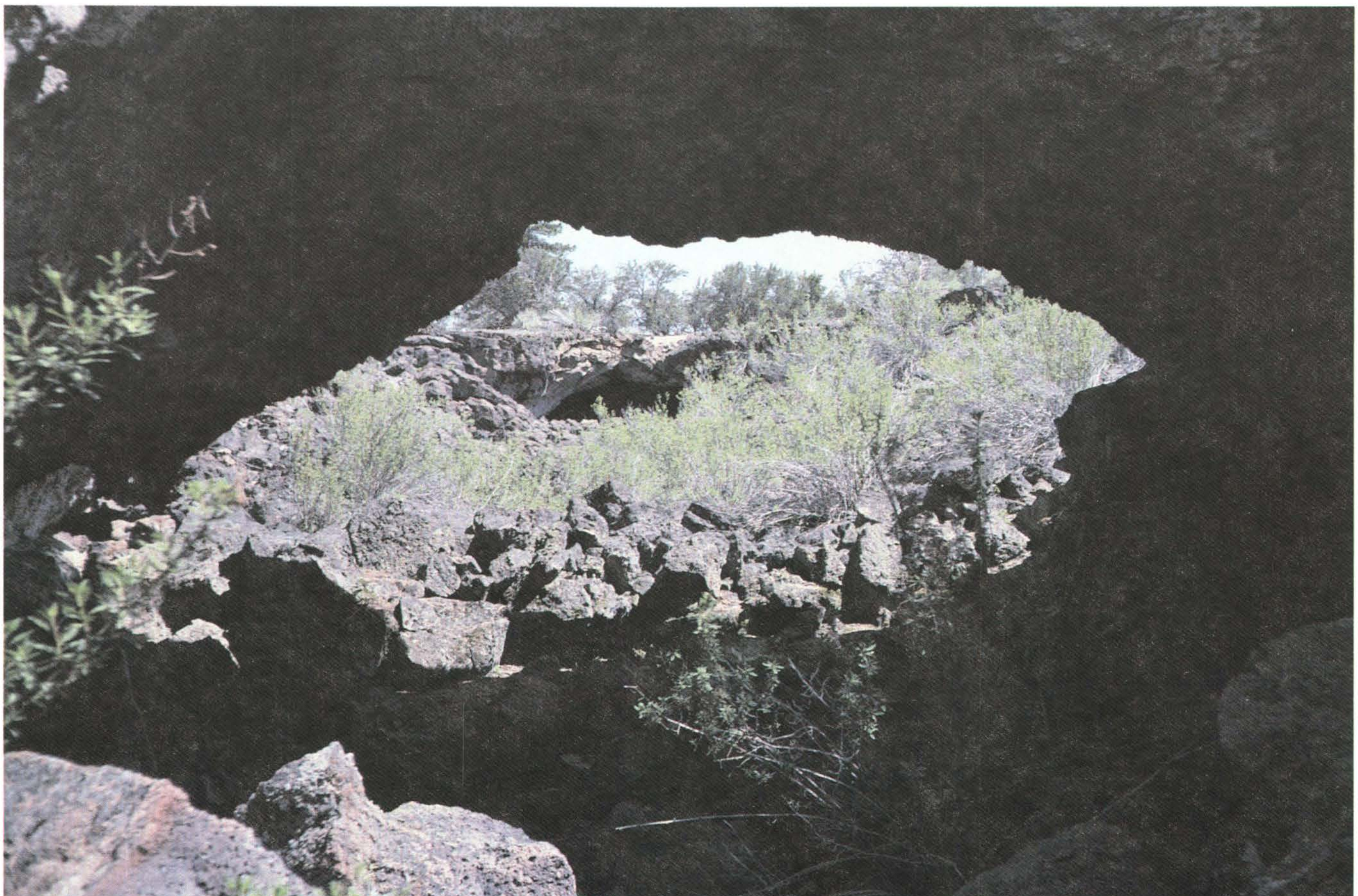


Figure 39. Pair of collapse holes along Tickner tube forms this natural bridge near entrance to Tickner Cave (see fig. 4 and map 9, pl. 3).

curled lava crusts are nearly continuous on both walls in this part of the cave.

Notice, also, that the cave does not have the typical oval cross section of a completely drained lava tube; instead it appears to be the upper part of a much larger lava tube that is now half- to three-fourths filled with congealed lava. We will find this inference of a partly filled larger tube to be true as we traverse downstream. This upper part of the Tickner tube is illustrated and explained in the cross section near the upper end of map 9, plate 3.

Downstream 180 ft from the upper entrance, and just beyond a low area in the roof, the floor of Tickner Cave changes markedly. The well-developed pahoehoe ropes are less prominent in some areas and completely absent over large areas. The surface is smooth, similar to that developed where lava has ponded, but this floor is not like the smooth level surface of the lava ponds in Valentine Cave. Instead the floor sagged irregularly into small basins separated by hummocks. Many hummocks with short cracks on their crest are shaped like miniature schollendomes. Moreover, the broken and curled slabs that formed benches along the walls are either lower or absent in this area, but in places the smooth pahoehoe shows evidence of having been stretched and dragged downstream against the walls. Finally, at a point 300 ft downstream from the entrance, or 100 ft upstream from where Tickner Road crosses Tickner Cave, the smooth floor breaks up into slabs 2–10 ft across (fig. 41). These slabs were rafted forward and jostled together, a process that produced a floor jam as much as 6 ft high and 25 ft long, which extends across the cave. The downstream edge of this floor jam is an amphitheater-like scarp. Below it a frozen lava cascade, containing rafted blocks from the floor jam, descends to the true floor of the lava tube 12 ft below the level of the balcony floor at the top of the floor jam. Evidently this frozen cascade marks the place where the final part of the Balcony flow kept moving below its solidified crust during the waning stages of volcanism. The moving lava carried away large parts of its former crusts, below the lip of the amphitheater, and the remaining crust sagged into a hummocky and partly floor jammed surface for another 150 ft downstream.

Figure 40. Pronounced benches form lower walls of Tickner Cave (see fig. 4 and map 9, pl. 3) near entrance. Benches formed when molten interior of lava flow half-filling the tube flowed away and left chilled rind against walls.

For a short distance below the collapse amphitheater, passage is blocked by the fill for Tickner Road and by collapse breccia. Access to the surface is provided by a crawlhole that emerges on the south edge of the road (South Road entrance) and reentry to the cave by both a small crawlhole (North Road entrance) and a large oval roof collapse 250 ft north. There are also three holes through the roof of the tube between Tickner Road and this large oval collapse (see map 9, pl. 3).

The most striking features in Tickner Cave between the road and the oval collapse are large remnants of the Balcony flow, which hang as true balconies above the present floor of the cave. These balconies have turned-down edges and curl back into an overhang in places. Of particular interest are remnants of the flow (one oval, the other pear-shaped), which are not attached to the cave walls, standing isolated within the drained area (map 9, pl. 3). The oval remnant has a top that is tilted up on its edges like a saucer; the pear-shaped one is tilted downstream, but the direction and amount of tilt are not the same as that of the nearby wall-attached balconies. The most logical explanation is that these two remnants broke loose from the east wall, as the lava flood withdrew from beneath them, and then slid toward the central part of the cave. The surface of these isolated remnants is lower than that of adjacent wall-clinging balconies, a fact which supports the inference that they slid downhill from their former positions. The floor of the cave in this area is a jumble of slabs of collapsed balcony (map 9, pl. 3).

One of the most instructive areas of balcony collapse is a 100-ft stretch of Tickner Cave between the northeast edge of a large oval roof collapse and the point downstream where it narrows abruptly near the north side of a pillar in its west wall. In the wide cavern upstream from this narrow spot a remnant of the Balcony flow 80 ft long and 5 ft wide hangs from the east wall 8–12 ft above the floor of the cave. On the opposite (west) wall of the tube the remnant counterpart is only 1–2 ft wide and is missing from the southern part of the cave wall. On the floor of the cave, however, rests a huge block from this balcony. It is 45 ft long and tapers in width from 14 ft at its south end to 2 ft at its north end. This balcony remnant toppled out from the west wall and now lies on its side, with its pooled pahoehoe surface vertical and facing east. Molten lava was evidently flowing through the tube when the block broke away from the west wall and toppled eastward, because the upturned face of the block shows spatters of lava and pieces of fallen lavacicles upon it. The relatively smooth broken-off wall of the cave west of this block contains small ridges and troughs running horizontally that can be matched exactly with corresponding features on the upward-facing surface on the fallen block.

Figure 41. Buckled floor plates of Tickner Cave (see fig. 4 and map 9, pl. 3) formed when interior of lava flow drained away, and chilled pahoehoe surface lost support.

The broken-off west wall contrasts noticeably with the east wall—the east wall is embellished by one of the most spectacular and photogenic displays of dripstone in any cave described herein. The last thin coating of brown dripstone that ran down this wall probably came from the liquid lava splashed against it when the block from the west balcony toppled.

The pillar at the downstream end of this room has a small tube routed through its west side. The floor of this small tube hangs a few feet above the surface of the balcony. Downstream 50 ft farther, the intact balcony becomes the actual floor of the cave and forms a wide natural bridge within the cave. Beneath this bridge, molten lava was conveyed downstream through a tube-in-tube. This culvert-like drain is now only 2–5 ft in diameter because successive linings of lava plaster almost closed off the space between its walls, roof, and floor. Only the downstream one-fourth of this tube-in-tube is large enough to crawl into. The broken-off upper end of the tube reveals the linings that successively diminished the size of the tube-in-tube. The thin edge of the large toppled block of balcony described previously is jammed against the east wall, alongside the upstream end of this culvert.

At its downstream end the tube-in-tube emerges onto a lava floor at the west edge of another amphitheater-like lava cascade, similar to but not as high as the one above Tickner Road. This new floor, 4–7 ft lower than the balcony level, disappears another 40 ft downstream beneath the rubble of a 200-ft-long roof collapse. Apparently, the lava in equilibrium with this lower-floor level was draining into Berthas Cupboard Cave through the two cataracts exposed at the head of that cave. A low crawlway (the Crawl entrance) through the collapse rubble is formed by the southeastern cataract; the northwestern crawl is completely blocked by massive collapse debris.

Downstream from the next 200-ft-long roof collapse, the floor of the cave is also a part of the Balcony flow. Here, however, it formed a smooth pool of lava ponded against the barricade formed by the floor jam at the head of the paddle-shaped collapse farther downstream in the Club Room. As noted previously, molten lava escaped from beneath this pooled surface via the two small tubes on either side of the barricade. At the downstream end of the 200-ft-long collapse, the lava also escaped by a tube plunging through the east wall that fed into Berthas Cupboard Cave 200 ft farther downstream from the cascades at the head of Berthas Cupboard Cave.

Tickner Cave loses its identity as a large lava tube at the head of the paddle-shaped collapse (map 9, pl. 3). Here, as noted earlier, part of the molten lava rose and spilled out at the surface, in separate lobes, while more flowed underground around and below the collapse debris. Much of the molten lava, however, had already exited the tube through the two cataracts, which enter Berthas Cupboard Cave 300 ft upstream from the Club Room at the head of the paddle. By the time the Balcony flow had crusted over, perhaps all of the lava flowing through Tickner Cave was draining into Berthas Cupboard through these cataracts.

Small tubes and other fascinating features are present in and around the paddle-shaped collapse at the Club Room. The collapse debris at the broad head of the paddle has been smoothed and rounded, like a ship's prow, by the lava that advanced around its sides. Blocks in this area were cemented into a tight mass by lava that flowed along the former cave floor. Part of the collapse debris was overrun by tongues of molten lava that broke through to the surface and, in the process, turned parts of the cave roof on end, and then they spilled northwest as a surface lobe. Details of the edges of this surface lobe, however, are obscured by later accumulations of pumice and windblown sand. Downstream from the paddle a small underground tube continues to the northeast; part of it has collapsed to form the handle of the paddle, but a section of a tube-in-tube within it remains intact. The remaining roofed-over section of the tube continues northeast for 25 ft beyond the end of the paddle's handle. Beyond the handle it is filled to the roof with a spiny pahoehoe formed by lava so viscous that it congealed into large ropes transitional to aa lava. This tube is barely beneath the surface of the ground. Its 3-ft-thick roof arches above the ground surface, and a medial crack runs through the roof along the entire course of the tube.

Berthas Cupboard Cave

Because the upstream part of Berthas Cupboard Cave (map 9, pl. 3) is at a deeper level than Tickner Cave, and also received leaking lava from Tickner, Berthas Cupboard must have formed independently from a flow of lava underlying the Tickner flow. At its downstream end, however, Berthas Cupboard Cave filled with lava transmitted to it through the Tickner lava tube. Still farther downstream this lava burst through to the surface and formed small aa flows. Therefore the lava tubes are all parts of one large system having its origin in the fissures beneath the Tickner chimneys and vents farther south. The tubes were the principal conduits through which this molten lava was transmitted north and northeast to build the basalt of Valentine Cave.

The upper part of Berthas Cupboard Cave is divided into two parallel tubes that are interconnected with one another around the ends of one small and three large pillars. Both tubes are floored by gently sloping lava flows, which rise southwest along the sides of the pillar farthest upstream; both are demolished upstream at the head of this pillar by a roof collapse.

The tube on the southeast side of the pillar contains rough balconies that rise above the central cascade on both wall and pillar sides. These balconies are remnants from the collapse of a tube-in-tube. Upstream the roof collapse hides both cascade and balconies, but a crawlhole through the collapse blocks provides the small upstream entrance to Berthas Cupboard Cave from Tickner Cave, as indicated on map 9, plate 3.

The parallel tube on the northwest side of the pillar is similar but even more complex. It contains remnants of more than one tube-in-tube. Some remnants form balconies along the sides of the tube, and other partly collapsed segments of tube-in-tubes clutter areas along the center of the larger tube. Upstream this complex tube subdivides into two tubes, one of which is at a higher level and slightly offset from the lower one. Farther upstream the whole network of tubes is buried beneath the collapse rubble at the head of the pillar. Some complications among the tube-in-tubes in both branches around this pillar surely were caused by recurrent violent cascades of lava, which leaked from overlying Tickner tube into both branches of Berthas Cupboard Cave.

At the downstream side of this pillar the two branches of Berthas Cupboard Cave unite in the Mush Room, a room 50 ft wide and 60 ft long, floored by pahoehoe, which spread out and pooled at the foot of the cascades that debouched from both branches. From the center of this pahoehoe pool rises another pillar—the Mushroom—only 6 ft in diameter at floor level, which widens into a 27-ft oval-shaped slab where it joins the roof (fig. 42). Evidently the lower parts of the pillar were spalled and rafted away by the lava flowing around it. The remnant at the roofline continues the trend and medial position of the group of three long pillars shown on the map.

From the Mush Room, the lava tube subdivides around the next long pillar downstream. The main flow was along the northwest side of the pillar. A roof collapse chokes much of the smaller southeast tube and leaves only a crawlway at its upper end. Evidence of tube-in-tubes such as those upstream is not present here, but almost continuous small benches, 1–3 ft high, and seldom wider, project from both walls and encircle the two large downstream pillars. These benches are made of many sheets only 1–3 in. thick that solidified as crusts from the walls of the molten lava and curled down (fig. 43) or broke off as the lava changed in level. They have the same origin but even better form than the benches at the upper end of Tickner Cave.

The last of the large pillars downstream is canted at a slight angle to the west wall. The tube on the northwest side of it therefore narrows downstream where a large floor jam piled up. It consists not only of slabs from the floor, but also of rafted blocks from the collapsed tube-in-tubes upstream and some debris from roof collapses. Downstream from this last pillar the combined flow narrows into one tube, which narrows abruptly to 15–20 ft another 75 ft farther, only one-third of its upstream width. In this narrow section the benches of curled-lava plates change to higher and broader balconies, with turned down edges covered with dripstone. This tube decreases to a width of only 12 ft with a height of less than 5 ft. A very low tube-in-tube occupies the center of the passage for nearly 70 ft; on either side the floor consists of plates buckled by the last lava flow into waves 1 ft high and 6 ft crest to crest. A lava boil 1 ft high and 12 ft wide nearly closes off this passage at the Gates of Dis. Beyond the Gates of Dis, the tube suddenly broadens downstream into a high-domed chamber 75 ft long, 40 ft wide, and originally 27 ft high at the apex of the dome. This room has shelf-like openings in its walls and at several levels of the arched sides of the dome. These are separations between flow units that have been pulled apart. Grotto-like clefts also break across flow units and extend outward into the walls. Two collapses to the surface are closely associated with this dome: one is a small cupola (11 ft in diameter) that demolished part of the sloping roof of the northwest part of the dome and left a shelf of debris against the northwest wall, and the other is a large irregular collapse pit roughly 40 by 30 ft at the surface with a floor that is at the same level as the floor of the dome. This larger collapse, which provides the main entrance to Berthas Cupboard Cave, lies only a few feet downstream from the edge of the dome, but the connection between them has such a low ceiling that one must stoop to enter the dome. Also like the dome, this collapse pit contains several open separations between the flow units exposed on its walls. It is these shelf-like openings on the walls of this pit, and the irregular grottos between them, that prompted Howard to name the cave Berthas Cupboard (see fig. 37 and the sketch of this breakdown on map 9, pl. 3.)

Within the dome, collapse fragments dropping from these shelf-like separations have built a ring of debris on the floor of the cave near its walls. An arcuate ring of tumbled debris, 5–15 ft high, borders the west rim of the dome. Many pieces dropped from the sloping roof of the dome and from edges of flow units in the dome's walls when the rock was hot and plastic. They welded together on impact. This arcuate ridge of collapse debris is also responsible for the low ceilings that must be negotiated when leaving the dome in either direction. A short natural bridge is present at the southwest corner of this debris ring.

Downstream from the dome, Berthas Cupboard Cave can be traversed for 650 ft before access is denied by partial lava filling and roof collapse. This part of the cave has a thick covering of collapse debris compared with the upstream part of Tickner Cave. It is a typical near-

Figure 42. Large pillar in Berthas Cupboard Cave (see fig. 4) is known as the Mushroom (see map 9, pl. 3).

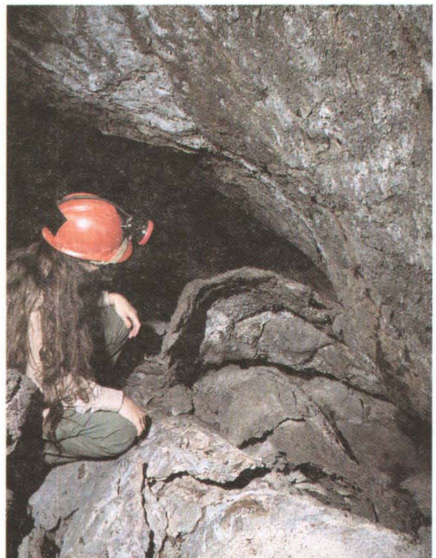


Figure 43. Curled lining of Berthas Cupboard Cave (see fig. 4 and map 9, pl. 3) peeled away while still hot.

surface lava tube ranging from 20 to 30 ft wide. It is also wetter than the upper parts of the cave. The latest lava flow formed a gently sloping floor of pahoehoe with the lava fill gradually increasing downstream. Pahoehoe ropes also tend to be more spiny and broken farther down the tube. Approximately 160 ft downstream from the entrance pit a section of jammed floor blocks marks the start of a section of intact roof called The Silver Lining after the reflections from water droplets on its surface. Debris from roof falls is scattered along the floor and rises in several large collapse mounds. A particularly large pile of roof-collapse debris almost closes the tube in the area where the tube changes direction from northeast to east. Entrance to the final 250 ft of the cave requires negotiating a very tight, wet crawlway. In this final segment a tube-in-tube exposed in the cave roof above another floor jam of blocks can be explored for 35 ft. Farther downstream a small side tube surrounds a pillar on the north wall of the cave; a few feet beyond this pillar access is denied by a roof collapse. Although the collapse prevents a crawl to the surface, it is apparent that the surface is not far above because warm air can be felt descending into the cave and small animals make their homes here.

Tickner Chimneys

The Tickner Chimneys (map 9 inset, pl. 3) were not studied in detail. Most of them surmount the fissures through which the basalt of Valentine Cave was erupted. Additional spatter vents lie farther south along the same trend and are not shown on the map. The chimneys are small agglutinate cones, most of which are less than 5 ft high. They formed where clots of molten lava fountained and accumulated along the fissure. A few chimneys rise from smaller fissures parallel to the main one. Some chimneys are connected underground by short lava tubes, which trend along the course of the fissure. Surface features in the vent area also include many lava gutters and spillover lava lobes. Many of the small agglutinate cones have miniature spill-out lava lobes and tiny surface lava tubes radiating from them. Unfortunately a thick coating of pumice and an almost impenetrable thicket of mountain mahogany prevents close inspection of many of these small-scale features. Therefore we prepared only a reconnaissance map of the vent area, at a different scale from the map of the caves. The visitor interested in acquiring a knowledge of this kind of vent area is better advised to visit the excellently exposed Ross Chimneys (fig. 44) in the monument.

Merrill Ice Cave, Bearpaw Cave, and Nearby Collapse Trenches

A line of large collapse trenches begins along the east base of the large cinder and agglutinate cone named Bearpaw Butte, 2 mi north of Mammoth Crater. From there, this line of collapse trenches can be traced east and north around the Schonchin Butte flow for about 10 mi. The collapse trenches were formed by the collapse of roofs in a system of two to three or more lava tubes stacked above one another. These tubes served as feeder conduits through which molten lava escaped from a former lava lake fed by Mammoth Crater (map 19, pl. 6). This lava built a plain downstream covering approximately 50 square miles to the north and northeast of Bearpaw Butte. The lava dispersed through the Bearpaw tubes, surrounded Schonchin Butte, and spread northward to the shores of Tule Lake. The lava lake that spawned the Bearpaw tubes eventually drained to a lower level through a lava tube that burrowed through loose cinders around the base of Red Butte and then contributed to the lava-tube system of the Cave Loop Road area.

Most of the surface collapse trenches that currently mark the position of feeder tubes in the Bearpaw-Skull system range from 50 to 1,500 ft long. Partly destroyed relics of lava tubes survive between the collapse trenches as caves, natural bridges, and tubes blocked with congealed lava. Two of these caves, a natural bridge, and three large collapse trenches are shown on map 10, plate 4.

Merrill Ice Cave is accessible by a paved road leading to a parking lot, and then by trails and stairs to the cave's two levels. Bearpaw Cave is also easily accessible, although not by developed trails. Its entrance is the mouth of a huge domed cavern at the upstream (south) end of the large collapse trench over which the paved road crosses via a natural bridge.

According to National Park Service records, the names "Bearpaw Cave" and "Bearpaw Butte" are derived from the activities of pioneer trapper Tom Durham, who killed a bear and nailed its severed paws to a juniper tree above the entrance of the cave. Merrill Ice Cave whose deeper, ice-bearing level was discovered later was named "Bearpaw Cave" at first, but in 1938 the Park Service changed the name to "Merrill Ice Cave" in honor of Charles Henry Merrill whose land was donated to the monument (National Park Service, unpub. data, 1965).

Merrill Ice Cave consists of two superposed lava tubes. The entrance level is accessible for a distance of 290 ft. The lower ice level is 360 ft long; about one-third of its floor area is occupied by pools of ice or by collapse rubble cemented with ice. The only entrance to the ice level is by a steel ladder placed through a hole a few feet in diameter in the floor of the entrance level. On the map the ice level is offset from its true position to avoid confusion with the lines and lettering of the entrance level.

Bearpaw Cave is accessible for 300 ft upstream from its high-domed entrance. The cavern at its mouth is 60 ft high and 35–50 ft wide. The upper section of the cave is much smaller and is nearly closed at its south end by large blocks of collapse rubble.

Merrill Ice Cave, Entrance Level

From the north side of the parking lot a trail leads northeast 250 ft to a stairway (fig. 45) placed against the west wall of a 20-ft-diameter hole in the roof of a lava tube, which constitutes the entrance level of Merrill Ice Cave. From the foot of the stair the tube extends upstream 85 ft to where it opens into the north end of the collapse trench that lies just northeast of the parking lot. At the opposite upstream (southwest) end of the collapse trench is the natural bridge that supports the road to Merrill Ice Cave.

Downstream from the base of the stairway, a trail and in some places a boardwalk provide easy access over the hummocky piles of collapse rubble littering the cave floor. A narrow bench on the southwest wall of the tube records shallow ponding of lava during a late episode of withdrawal. Some collapse blocks appear to have been derived from tube-in-tubes, which may have only partly filled the main tube before their drainage and eventual collapse.

At a point 160 ft downstream from the stairway, a 16-ft ladder extends down through a small hole in the floor of the entrance level to the edge of an ice pond on the lower level. The entrance level extends downstream only another 40 ft beyond the top of the ladder, and it is this short section that reveals much information about the origin of the entrance level. In this downstream section, the level is blocked by successive shells of lava accreted to the walls. Each shell is a record of one episode of filling and partial draining. Each molten flood deposited a layer of lava plaster upon the tube's walls, roof, and floor as its edges chilled against the colder rock encasing it; then, the still-molten lava beneath the thin coating drained away before completely solidifying.

At this downstream end the tube plunges and is constricted to a fraction of its upstream size. A smaller opening once drained lava from the entrance level to an underlying tube. Nevertheless, during each episode of maximum volcanic activity the tube would fill completely with lava, and as the eruption waned, the molten interior drained slowly through the opening and left a layer of lava plaster behind. Successive layers thus accreted until, as seen today, the opening is too small to crawl into. Since cessation of volcanism many of the accreted layers have loosened and partially peeled away from the roof and walls. Peeling layers are also well exposed at the upstream end of this level where the wall of the collapse trench slices across the lava tube to reveal telescoped shells of dripstone and lavacicles.

Figure 44. Ross Chimneys in north-central Lava Beds National Monument are similar to poorly exposed Tickner Chimneys, outside monument. Spatter vents formed by accumulation of hot lava spatter blown into air from an erupting fissure. Hammer on middle chimney for scale.

Merrill Ice Cave, Ice Level

The ice level of Merrill Ice Cave is a 360-ft-long remnant of a medium-sized lava tube that is 15–20 ft wide and originally was 12 ft high. It is closed by roof collapse at both ends and its floor is completely obscured by collapse rubble and ice ponds. The roof and walls have been so greatly enlarged by slow unraveling of collapse blocks that few original features remain. Low benches are partially visible from beneath the collapse debris in the downstream part.

The most striking geologic feature in this level is a steep-walled depression in the floor 40 ft upstream from the foot of the ladder. An ice pond 25 ft in diameter occupies the central part of this depression. Steep slopes of ice-encased collapse rubble rise on both ends of the ice pond, and the upstream slope actually forms a frozen cascade. It seems that the pond marks the site where the floor of the ice level collapsed into a third, and probably larger, lava tube below. Moreover, it seems probable that this lower tube is currently filled with ice.

An account of how ice develops within caves and descriptions of more impressive ice deposits are given in the "Crystal Cave" and "Ice Deposits" sections. Merrill Ice Cave, however, is a much safer cave than either Crystal Cave or Skull Cave's ice level. Moreover, the well-planned trail makes the extensive ice accumulations in Merrill Ice Cave easy to visit.

Three ice pools (map 10, pl. 4) occupy one-fourth of the floor space. One at the foot of the ladder and another near the upstream end of the ice level tube that extends 70 ft and includes many "islands" are situated in low spots on the floor of the lava tube. The third pool is at a lower elevation and, as mentioned, fills a round hole that apparently connects the ice level with a lower ice-filled tube.

Most ice in the shallow upstream pool is fairly transparent, and shadowy outlines of the blocks that project above the pool's surface can be traced to depths of a few feet below the surface. Much of the cave's ice, however, is murky with dust, small bubbles, cracks, and organic growth.

The beautiful draperies of transparent icicles and expanses of permanent hoarfrost in Crystal Cave are totally absent in Merrill Ice Cave. Thin rimes of hoarfrost form in parts of Merrill Ice Cave during the winter months, and short, thin icicles develop for a brief period during the spring thaw; but these features come and go with the changing seasons. The formation of a water puddle in the late summer and autumn over the top of all three ice ponds is evidence of a greater seasonal exchange of warm air for cold air in the two levels of the cave. Why the difference between the two caves? Two explanations seem probable. (1) Crystal Cave is much larger and deeper than the ice level in Merrill Ice Cave. A far greater volume of air must be exchanged before there is a marked temperature change in Crystal Cave. (2) Although both caves have only one obvious entrance, one must consider air flow from a second area into Merrill Ice Cave through the ice level. Note on the map that the south end of the ice level is closed by the steep slope of collapse rubble from the northernmost collapse trench. Openings between these large blocks are surely big enough to allow considerable interchange of the cave air with the outside air. The sun shines strongly upon this part of the collapse trench at midday, affording an ideal case where cold air of the cave flows out into the collapse depression, is warmed, and rises—a continual mechanism pumping cold air from the cave between day and night during the summer months.

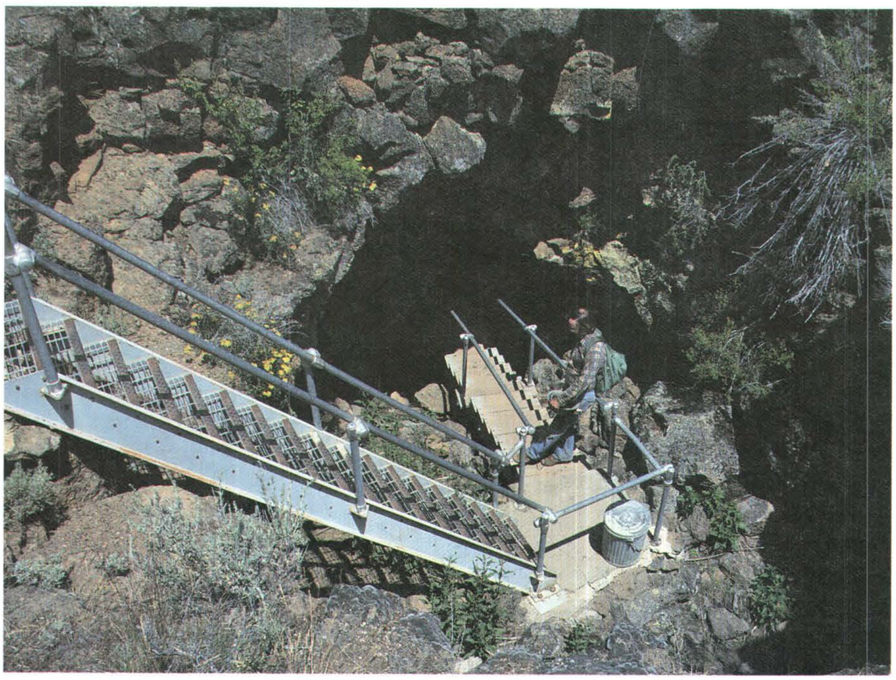


Figure 45. Stairway leading down to entrance of Merrill Ice Cave (see fig. 4 and map 10, pl. 4).

Bearpaw Cave

Bearpaw Cave is a large lava tube that has lost nearly all of its primary features by slow unraveling of its roof and walls (map 10, pl. 4). The entire cave floor is mantled with collapse rubble. A long-abandoned well, dug into this rubble at a point 55 ft upstream from the entrance contains water; thus the pahoehoe floor of the cave was probably reached by the well. In the same area, remnants of a lava bench, almost obliterated by the cover of rubble, are present in places along each wall. On the west wall, above the bench, is a large curving alcove on which dripstone still remains. The alcove slopes out at its base and merges with the bench below.

Upstream beyond the large cavern that contains the alcove, bench, and water well, the cave changes markedly. The ceiling height drops as the amount of rubble on the cave floor increases. The walls narrow until the passage is only 18–20 ft wide, but the west wall swings out another 10 ft into a rounded alcove near the top of the incline. This upward-funneling tube extends upstream for 170 ft almost to the end of the accessible part of the cave. Nowhere on this moderately steep slope is there an exposure of the original floor of the cave; it appears to be everywhere buried under collapse rubble. The length and uniform gradient of the slope, however, are a strong indication that this part of the tube was a lava cascade.

The southernmost end of the accessible part of Bearpaw Cave is a small passageway that opens amid the collapse blocks beneath the northwest corner of a big collapse trench to the south. This passageway is only a random hole in the collapse rubble; it does not indicate the course of the former upstream continuation of the original lava tube.

Collapse Trenches

To many monument visitors the deep collapse trenches, the varied topography to the south and west of the Merrill Ice Cave parking lot, and the sharp changes in biologic life zones may be more interesting than the caves. This parking lot is a junction between three zones of vegetation. To the south the deep collapse trenches are obscured upstream beneath dense thickets of mountain mahogany, which occupy the rough schollendomed surface between Bearpaw Butte and Hippo Butte (fig. 4). Immediately to the west Bearpaw Butte rises high enough to support an evergreen forest. North and east of the parking lot are rough plains cloaked with bitter cherry, rabbit brush, sagebrush, and small annuals. Additionally, various plant communities thrive in the microclimates of the caves and collapse trenches, including lichens and mosses that grow on the shady side of the vertical-walled collapse trenches and in the moist, cool air of the cave entrances.

A limited supply of water remains throughout part of the summer in small shaded rock niches—similar to the "tanks" in the Southwest, as they are called by naturalists. A poorly accessible but permanent supply of water is found in the abandoned well of Bearpaw Cave, and water also comes from partial melting of ice pools in Merrill Ice Cave. Availability of water is a critical factor in supporting a larger than average population of animals, especially rodents. Birds are more abundant here than in most parts of the monument.

The two northern collapse trenches (map 10, pl. 4) are geologically quite ordinary. Note their vertical scarps, which expose flow units of lava (for a description of flow units and their relation to lava tubes, see the "Post Office Cave" section). Below these scarps the floors are elongate saucers of collapse rubble. A simple calculation of the volume of the trenches below ground level shows that roof collapse of both levels of Merrill Ice Cave is inadequate to provide the space occupied by the trenches. Either or both of two explanations could account for this discrepancy. (1) Beneath the ice level of Merrill Ice Cave there is one or more lava tubes whose collapse provided the extra space to hold the rubble. (2) Molten lava flowing through the collapsing tube or tubes was of sufficient volume to remove most of the blocks that fell into it. Very likely, both processes contributed. Good examples of collapse blocks smoothed over or rafted away by lava are present in Valentine (map 8, pl. 3), Catacombs (map 3, pl. 1), and Tickner and Berthas Cupboard Caves (both on map 9, pl. 3). Examples of collapse trenches whose volume conforms with the size of the tube, and some that do not, are found along the course of the same lava-tube system downstream from Merrill Ice Cave—especially in the 5-mi stretch downstream from Skull Cave (see map 20, pl. 6, and the "Skull Cave" section).

Hydraulic Rampart

At the northeast end of the collapse trench at the head of Bearpaw Cave is evidence of uplift and subsidence of the roof of Bearpaw Cave at a time when it was filled with molten lava. The evidence here also sheds some light on the probable origin of the inferred lava cascade in the upper part of Bearpaw Cave.

The downstream end of this southern collapse trench is bordered by two unusual deposits not found around the edges of the other two downstream collapses. One is a partial girdle of loose lava blocks derived from the flow that formed the vertical cliffs along the edge of the collapse. These blocks, however, are piled up in a ridge on the top of the flow, like a ring of dirt thrown out from an excavation. The other feature, at the northwest corner of the trench, is a short lobe of pahoehoe lava that spilled over the wall of the trench and extended 50 ft on the surface before its source of lava subsided into the trench (see map 10, pl. 4).

Ridges of loose blocks that rise above the rim of certain breakdowns are interesting structures, which we have named "hydraulic ramparts" (fig. 46). Hydraulic ramparts may form when an obstruction backs up lava within a tube. The ponded lava rises upstream inside the tube until its hydraulic pressure becomes great enough to either break through the obstruction or else force a hole through a weak spot in the roof of the tube, allowing the lava to spill out onto the surface as a lava flow.

We infer that hydraulic pressure above a blockage in Bearpaw tube lifted the roof of the tube over the downstream part of the present collapse trench by breaking the roof along two lines, one across the course of the tube and the other parallel to its west wall. This pie-shaped slab was tilted up, similar to lifting a trap door, as molten lava rose beneath it. As this occurred, its north edge collapsed and formed the hydraulic rampart shown on the map. Simultaneously, molten lava squeezed up the break along the west side and spilled onto the surface as a pahoehoe lobe (see map 10, pl. 4). Prior to this, however, the impeded lava enlarged the outlet underground by prying up the roof north of the intersection of the two breakage lines and created a new passage along the route of the inferred lava cascade in the upper part of Bearpaw Cave; this process caused the lava level to fall in the upstream part of the tube.

The trap door began to close, and the lava feeding the pahoehoe surface lobe was diverted back down to the underground lava cascade. With cessation of volcanic activity the tube drained, and this draining allowed the trap door to tumble into the collapse trench as a pile of loose blocks.

This scenario is somewhat hypothetical because the only evidence is part of a hydraulic rampart, a small overspill of pahoehoe on the surface, and an inferred lava cascade obscured by collapse debris. If the scenario is correct, the obstruction probably occurred in a former extension of Bearpaw tube just northeast of the hydraulic rampart. This part of the inferred tube may have extended much farther northeast and followed the projected course of the collapse trench in the area upstream from the hydraulic rampart. After taking this inferred course for at least 100 ft, the tube turned abruptly west and joined the Bearpaw tube at the curving alcove in the large entrance cavern. Obstructions in lava tubes are frequently caused by roof collapse at sharp bends and are augmented by lava jams behind the collapsed blocks. The obstruction backed up the lava sufficiently to raise the trap door, and so a little lava spilled onto the surface. Then, a ridge of talus (hydraulic rampart) collapsed across the downstream break before the lava took an underground shortcut across the former bend by means of a lava cascade around the west side of the blocked area.

Kirk Whites and Beaconlight Caves

Downstream from Merrill Ice Cave along the same tube system are Kirk Whites and Beaconlight Caves, two short but large caverns. They are remnants of a lava-tube system, which heads in the steep schollendome front of a lava field, which erupted from Mammoth Crater. The tube system begins where the lava flowed northward through the gap between Hippo and Bearpaw Buttes (fig. 4). The tube's former position can be traced by a line of collapse trenches, which starts at a horizontal hole in the schollendome front north-northeast of Modoc Crater and crosses the east side of Bearpaw Butte to Bearpaw Cave. Donnelly-Nolan and Champion (1987) believe instead that Modoc Crater was the point of origin of this major tube. Whether the lava came from Modoc or Mammoth Crater, it was all part of the same eruptive event. From Merrill Ice Cave the line of collapse trenches zigzags to the base of Schonchin Butte, where it skirts around the south and east sides of

Figure 46. Collapse trench near Merrill Ice Cave (see fig. 4 and map 10, pl. 4). Collapse of tube roof occurred before final flow of lava through tube. Lava backed up in tube and pushed blocks out, forming an encircling rim of loose blocks, called a "hydraulic rampart," best seen in left foreground. In distance to north is Tule Lake, bounded on west by fault scarp known as Gillem Bluff.

the older Schonchin Butte lava flow. Kirk Whites, Beaconlight, Skull, and Frozen River Caves are located along this tube system. The line of trenches (map 20, pl. 6) extends north for another 6 mi and then turns east. Many distributaries fan out toward former Tule Lake (fig. 1), although one major tube may continue east and then north to Fern Cave.

The large lava field built by flows from this major lava tube is older than the one built from the feeder tubes in the Cave Loop Road area. Roof collapse ruined far more of the underground passages along this lava tube than along the Cave Loop Road lava tubes. The large collapse trenches and pits that resulted are spectacular features of the landscape when viewed from an airplane, but on the ground most are invisible until you approach their rims.

Between the collapse trenches are natural bridges and short caves that reveal parts of the underground lava-tube system. Most such caves, however, are disappointing to the student of underground "lava plumbing" because they have been greatly defaced by the unraveling of rock from their walls and roof, a process that continues today. Overhead are many loosened blocks held precariously against the side of a neighboring loose block. Along the walls are slides of loose talus. The floors of such caves are difficult to traverse because blocks of all sizes clutter their floors and may shift under your weight when you step on them.

Kirk Whites and Beaconlight Caves are typical of the many short caves that lie along this line of collapse trenches. We chose to study them because they are near the paved road through the monument. Caves along this line between Merrill Ice Cave and Skull Cave include Castle, Kirk Whites, The Igloo, Beaconlight, Symbol Bridge, and Irish Bridge. Caves downstream from Skull are Ship Cavern, White Lace, Big Painted, Peninsula Bridge, Frozen River, and Captain Jacks Ice Cave. Most of these are shown on map 20, plate 6—a reconnaissance map of the collapse trenches from Skull Cave to the Three Bridges area.

Kirk Whites Cave

Kirk Whites Cave (map 11, pl. 4), named by J.D. Howard, has a large entrance room 185 ft long, 60–70 ft wide, and 20 ft high. Enter the cavern on the trail built in the 1930's by the Civilian Conservation Corps and note that the original roof and walls have been obliterated throughout the cave by slow unraveling from rockfalls. The floor, except for a small space at its upper end, is completely covered with thick piles of collapse debris including many very large blocks. Details of the massive lava flow in which the cave developed can be seen in places along the wall of the cavern, but they are better displayed on the northwest wall of the collapse trench.

Near its upstream end the cavern tapers to a width of 35 ft, and then nearly the full width of its floor falls away into a lower tube, the Mouseoleum. Remnants of the pahoehoe lava that formed the true floor of the original lava tube are left as overhanging ledges around parts of the rim of this collapse pit. Two small holes through the pahoehoe floor at the northwest corner of the entrance cavern provide a relatively easy entry into the lower tube; however, there is little to see. Upstream and downstream it is completely closed by collapse blocks that have fallen from the walls or been dumped through its roof, and only a small room 45 ft in diameter, which is one-half to two-thirds filled with collapse blocks, remains. In the few places where a true wall of the lower tube is exposed, dripstone forms a thin coating over red volcanic breccia instead of the basalt flow that enclosed the upper cavern. Underneath the overhanging ledges that partly ring the top of this room, the nearly horizontal contact between this red breccia and the overlying flow is visible in places. It was the collapse of this unstable red breccia inward through the walls of the lower tube that destroyed the tube's continuity upstream.

The Igloo

Of greater geologic interest, although smaller than Kirk Whites Cave, is The Igloo, which lies at the opposite (southeast) end of the collapse trench that also provides the entrance to Kirk Whites Cave (map 11, pl. 4). This 40-ft-long cave is shaped like an elongate dome. The highest point on the ceiling (11 ft) is at the cave's center; from here, the roof rounds down rapidly in all directions. Well-preserved lavacicles and dripstone line the surface of this dome. You enter the cave through a small opening where collapse debris spilled onto the floor of the cave. Downstream from the toe of this slide the floor is a jam of jostled pahoehoe blocks produced by the lava's attempt to drag its already solidified crust beneath the sloping roof of the cave at the downstream end. Undoubtedly, the domal shape and its walls of congealed dripstone suggested the name "The Igloo."

The Igloo may have formed as a short distributary tube from the upper part of the main lava tube, or it may be a cupola in the main tube with its floor having formed by the crusting-over of a balcony fill of lava in the main tube. It is impossible to decide between these alternatives because there is no access to the continuation of the tube either upstream or downstream.

Beaconlight Cave

Beaconlight Cave (map 11, pl. 3) is large in girth but only 340 ft long. It consists of two chambers: an entrance cavern 150 ft long, 50 ft wide, and as much as 35 ft high; and a larger chamber downstream, the Silver Clouds Cavern, which is 190 ft long and in places more than 50 ft high. Silver Clouds Cavern appears offset about 55 ft to the right (southeast) from the entrance cavern. A short arch 30 ft across connects the present roof of the two caverns above a high talus pile.

From the large alcove in the south corner of the Silver Clouds Cavern, a 10-ft-wide break in the floor spills a steep slide of collapse rubble into a lower tube 12 ft below. This deeper tube is 20 ft wide and 8 ft high; it trends almost due east for about 30 ft, and it has retained outstanding examples of pahoehoe floor, dripstone walls, and lavacicle roof. Only 50 ft downstream from the base of the slide, this tube is demolished by a slide of massive amounts of red breccia through its roof. At its northeast end the Silver Clouds Cavern terminates downstream where it plunges east into a lower level, but this lower tube is inaccessible because of lava accreted to its walls.

The name "Beaconlight" was given to this cave by J.D. Howard, after the Modoc Indian practice of illuminating the interior of caves in the search for water by building a row of bonfires of sagebrush inward from the entrance. Water does stand for a part of the year in the deepest part of the Silver Clouds Cavern, and also in a low spot in the lower tube. The name "Silver Cloud" derives from irregular patches of off-white caliche covering part of the roof of this room—when wet after seepage from rain, the caliche reflects light with a silvery glow.

Beaconlight Cave is the partly collapsed remnant of a large lava tube. Little of the original walls and virtually none of its ceiling have survived the slow unraveling of blocks loosened by frost action. Thick collapse rubble covers almost the entire floor of the cave except for a short stretch in the lower and smaller tube. Retreat of the walls by collapse provides good exposures of thin flow units in the thick lava flow in which the upper large tube developed. In the lowest parts of the two upper rooms this thick flow of lava rests in a few places upon a red breccia, which appears to completely encompass the lower small tube. The red breccia may be the underground extension of the tuffs and breccias, which make up the Schonchin Butte cinder and agglutinate cone (see map 12, pl. 4 and the "Skull Cave" section).

The most interesting geological area in Beaconlight Cave is the northeastern end of the Silver Clouds Cavern. The chamber narrows, turns abruptly almost due east, and plunges steeply into a lower level through an inclined tube 20 ft in diameter. This tube cannot be entered because it is blocked by many accretionary linings (each the remnant of a tube-in-tube) along the east wall, and because it is filled with collapse rubble on the west side. This downslope termination of a lava tube by accretionary linings is very similar to that of Arch Cave, Silver Cave, and to parts of Tickner Cave, except that it is larger and not as well exposed. Not all of the collapse rubble in Beaconlight Cave is of post-lava origin. At two places along the northwest and northeast walls of Silver Clouds Cavern, older collapse breccia was partly covered with dripstone of congealed lava.

Skull Cave

Skull Cave (map 12, pl. 4) was first visited by modern explorers in 1898 following E.L. Hopkins' sighting of the long collapse trench at the head of the cave from the top of Crescent Butte. On investigation he found on the lower level, partly embedded in ice, two human skeletons and abundant bones of antelope, bighorn sheep, and mountain goats. A broken log also lay on the ice. Apparently two Indians had attempted to lower the log to serve as a ladder but let it slip, and they were swept off the balcony to their deaths.

Skull Cave is located at the end of a well-marked paved road. It is a remnant of two large lava tubes superposed upon one another. Like Kirk Whites and Beaconlight it is on the line of collapse trenches and caves, which skirt the south side of Schonchin Butte. The upper tube has suffered so much collapse of its roof, floor, and walls that most details of its original form are lost. The lower tube, however, retains many of its primary features despite large collapses through its roof and extensive slides through its walls.

Two balconies can be seen from the stairs built to access the downstream part of the lower tube. These might be considered two additional separate levels; however, because the upper balcony ends downstream in a blunt semicircular wall, and the lower balcony ends 60 ft upstream by filling to its roof, they are more appropriately considered local balconies marking periods during which draining of the eastern part of the lower tube halted. This downstream part of the lower level is nearly cut off from a large upstream chamber by a huge pile of collapse blocks (see longitudinal section on map 12, pl. 4). Passage between the two chambers of the lower level is through a narrow crawlspace up and around the northeast side of this roof-collapse pile. The upstream chamber has been nicknamed "Boneless Cavern" by disappointed spelunkers who had hoped to find another rich store of animal bones after they negotiated the narrow crawl. Neither of the two balconies that are so conspicuous in the lower level are present in the Boneless Cavern.

The complexities of Skull Cave make it a prime example for studying a large feeder-tube system. If we consider the two levels and balconies and count the overlaps where they are superposed, over 1,000 ft of linear passage is available for study and exploration. These passages record some information, but they also provide some unsolved puzzles concerning the origin and hydraulics of the large feeder tubes that transmitted vast quantities of lava from vents for the basalt of Mammoth Crater to the lowlands bordering Tule Lake (a distance of approximately 15 mi).

Upper Level

The entrance into Skull Cave (fig. 47) is at the east end of an impressive collapse trench, 460 ft long and 100 ft wide. The upper level resembles a huge tunnel, 60–80 ft wide and 30–65 ft high. At a point 480 ft east of the entrance the upper tube ends abruptly at a semicircular wall. Here, lava in the upper tube found an opening into a lower level. A small remnant of the lava that poured into this connector survives as a frozen lava fall. The lava cascade marking the top of this fall can be seen from the base of the first (upper) stairs on the trail to the south wall of the tunnel, and then it curves east against the south wall of the tube for 25 ft. The north half of the lava fall remnant is completely buried beneath the debris of a later roof collapse.

The only locality where the original floor of the upper level can be seen is at the top of the lava fall, in the southwest corner of the upper level. Upstream from here to the entrance, the tube is floored by huge fallen blocks caved from its roof. Eventually, the entire roof of Skull Cave will collapse and extend the large collapse trench.

After the lava drained from the cave, many additional collapses occurred in both roof and floor of the upper level. Some parts of the present floor—an irregular jumble of fallen blocks—are lower than the floor at the top of the aforementioned lava fall. This can only mean that large sections of the floor upstream from the lava fall tumbled into the tube below. Indeed, the lower tube is blocked at the west, upstream end and is almost blocked in the middle (see longitudinal section on map 12, pl. 4) by huge piles of talus, which accumulated in the lower tube at the appropriate places to account for the sags in the debris forming the floor of the upper level.

No trace of lavacicles and only one small patch of dripstone are present on the ceiling or walls of the upper level. Collapse has apparently increased ceiling height, widened the walls, and either buried the floor deeply under fallen blocks or dropped it piecemeal into the tube below.

The wall rocks, from which the upper tube was developed, are well displayed in natural cross sections created by wall collapse. They consist of thick (8–35 ft) flow units of olivine basalt, some with pahoehoe tops containing only a bubbly zone of vesicles. Thin (1–5 ft) beds of flow-top breccia separate some flow units. Individual flow units cannot be traced far along the walls because they thicken, thin, pinch out, or are replaced by others. Three to five flow units can be seen on a vertical wall at any one place.

Lower Level

Much of the lower level is so filled or modified by post-volcanic roof collapse, and by bursts of red cinders and scoria fragments through its walls, that original dimensions are difficult to determine. Some cross sections are preserved, complete with lavacicle roofs, dripstone walls, and pooled pahoehoe floors; they indicate that the lower tube is presently

Figure 47. Collapse trench and entrance to Skull Cave (see fig. 4 and map 12, pl. 4), one of the largest caves in Lava Beds National Monument.

less than half the size of the one that originally occupied the upper level. It ranges from 20 to 35 ft wide where its thickness can be seen in the broken sections and from 10 to 45 ft high in the lower (downstream) part, not counting the areas where balconies create overhangs. Despite its smaller size, this tube was large enough to transport the vast amounts of lava needed for the downstream continuation of the Mammoth-Bearpaw lava-tube drainage system.

The lower tube is accessible for only 400 ft along its length. Of this, the 100-ft section upstream from the ice floor at the foot of the stairs, known as Boneless Cavern, is almost blocked off by a 50-ft-long collapse through the roof. To reach the Boneless Cavern section beyond this roof collapse requires a crawl through a narrow passage that begins at the northeast corner of the ice floor and rounds the north side of the roof collapse. One enters through a small hole between and beneath large collapse blocks on the south, and alongside a lava wall lined with dripstone on the north. After crawling 15 ft one emerges in a narrow dripstone-lined slot nearly 3 ft wide. The crawlspace continues upward and westward as a wider and higher opening, which skirts a slide of red breccia. The western extension of the narrow lava tubelet was broken into and pushed southward by this slide, as deduced from small broken remnants of its walls and one large remnant of its roof exposed just south of the highest point on the crawl across the red slide. Upon descending into the Boneless Cavern one reaches still another intact fragment of the narrow tube, which arches over the trail as an unbroken roof segment 15 ft above the floor of the cavern. Its eastward continuation was demolished by the red slide. The south wall of the eastern continuation of the Boneless Cavern is buried beneath collapse blocks. No lava occupied either the Boneless Cavern, or the small tube adjacent to its north wall, after these collapses occurred.

Where the west foot of the crawlway emerges in Boneless Cavern, it is immediately apparent that this cavern is the upstream continuation of the lower tube. It is more than 100 ft long, blocked by roof collapses at either end, and broken into slides of red scoria. The scoria is composed of loose bombs, blocks, abundant lapilli, and cinders. These red slides burst through the tube walls and roof at many points. One large slide demolished over half of the south wall, carrying huge fragments of the dripstone wall and fragments of one-third of the south lavacicle-lined roof northward past the middle of the tube. A similar but smaller slide occurred on the north wall, at the upstream end of the cavern. At numerous other points the relatively intact parts of the walls are cracked and broken; these openings allow the red pyroclastics, which encircle both walls and roof, to dribble into the cave. It appears that the thin dripstone walls are barely preventing the collapse of the entire cavern.

The intact upstream sections of this room reveal a history of lava occupation surprisingly different from the downstream eastern part of the lower level. No balconies are present, and there are no indications of higher lava stands on the walls except for a narrow (1–3 ft) bench 2–3 ft above a lava pool floor, which is partly covered with ice. At the time the bench was formed it must have been just a plastic scum less than 2 in. thick on the margin of the lava pool, because as the lava lowered, the thin plastic layer drooped down from the walls and in places broke and curled up like a jelly roll. Above this bench the walls of the cavern are plastered with well-formed dripstone, which rounds upward into a typical lavacicle roof. This evidence implies that the cavern was brimful of lava just before it drained.

One small feature in the southwest corner of this cavern is worth observing. Set back into the wall at a height of 8 ft above the floor is a box-like cupola 18 ft long, 7 ft wide, and 10 ft high. The top of the alcove is a few feet above the top of the tube at this point. The ceiling of the cupola tapers upward into two pipe-like extensions, each 2 ft long and 1 ft in diameter. They project upward less than a foot and end in the loose red tuff and scoria breccia, which form the wall rock outside the tube. The entire interior of this cupola and its two pipes are lined with dripstone, which deviates radially downward from the pipes. The pipes appear to be gas vents, which released steam and other gases, as well as some spatter, from the top of the lava-filled tube into the porous breccia above.

In contrast to Boneless Cavern, the part of the lower level reached by the stairs (map 12, pl. 4) records two periods of highstands of the lava surface, during which solidification set in from the walls and top of the lava long enough to produce extensive balconies when the lava lowered. A high-lava mark 4–6 ft higher than the upper balcony records a brief but higher stand.

The lower balcony lies 5–12 ft above the mixed ice and rubble floor of the eastern cavern. It forms extensive overhanging flanges along the south wall and is also developed across the west end of the cavern and along its north side. On the south wall it is a sloping shelf 6–25 ft wide, with an overhang of 2–12 ft beyond the wall beneath it. Just upstream from the foot of the stairs this shelf swings across the tube in a wide arc. Here, it resembles the downstream entrance to a natural bridge, but the "other side" of the natural bridge is not present. Instead, that part of the tube beneath the overhang extends upstream with a smooth ice floor and gradually lowering roof to the point where the trail across the ice ends at a point 90 ft upstream from the base of the stairs. It is at the north side of this collapse that the crawlspace into Boneless Cavern is found.

The upper surface of this balcony also extends upstream from the stairs, where it becomes the floor of a separate small lava tube—a middle level 10 ft above the ice level of Skull Cave. This low, flat tube becomes inaccessible farther upstream; its roof slopes down to the point where it meets the floor 60 ft upstream from the stairs. Parts of this small tube, especially its north wall and roof, appear to be in collapse breccia, which was penetrated and smoothed over by lava.

On the north wall of the lower level, this lower balcony is represented by a narrow ledge or bench; in the eastern part of the cave, opposite the big red slide through the south wall, the lower balcony is a shelf 2–12 ft wide and 40 ft long.

One cannot walk beneath it, as under the overhanging parts to the south and west, because an overhang has fallen into a steep talus of rubble beneath the balcony edge.

The higher balcony, 32 ft above the ice floor at the foot of the stairs, records events shortly after the collapse of the upper tube into the lower tube. It is developed only in the immediate area where the collapse occurred; its remnants consist of a fragile natural bridge that spreads into a balcony remnant forming the bridge's abutment for 60 ft along the south wall. The balcony is missing, except as a thin bench covered over with dripstone, in the middle of the semicircular wall at the east end of the upper tube. Two alcoves, 8–12 ft long, penetrate the east end of this semicircular wall at the level of the high-lava mark crossing the lava falls that terminated the flow of lava in the upper level. This high-lava mark becomes a thin bench as it crosses the south abutment of the upper balcony. It gradually widens eastward and is 8 ft wide where it merges with the floor of the southeastern alcove. On the opposite (north) wall the same relations are found. Another remnant of the balcony forms a shorter abutment, 30 ft long, which anchors the natural bridge to the north wall. This abutment is 4–10 ft lower than the balcony against the south wall because the balcony is tilted downstream in the direction of lava flow. By contrast, the high-lava mark maintains approximately the same elevation that it had on the south wall of the tube. As on the south wall, it widens into a bench downstream and merges into the second alcove. These relations on the north wall, however, are less conspicuous because of collapse.

The flow, which left the high-lava mark across the face of the frozen lava fall, produced dripstone during its withdrawal that flowed onto the surface of the upper balcony. Thus lava ponded at this level is closely related in time to the formation of the upper balcony. Draining of the lava to the level of the lower balcony left the natural bridge and its abutments, the benches formed at the high-lava mark, and the two alcoves at the east end of the upper level—all hanging far above the chasm below. It was from the natural bridge on this balcony that the two humans met disaster in attempting to lower their log to the ice pool beneath.

Red Tuff and Volcanic Breccia

An unusual feature of the lower level of Skull Cave is that the wall rocks which enclose the lava tube are of pyroclastic (fragmental) origin—they are volcanic cinders and breccia, not the massive basalt present in the interior of lava flows. This red tuff and breccia is seen through numerous cracks in the dripstone plaster on the walls of the lower tube and also bursts through the walls in huge steep slides on the south sides of both the upstream and downstream caverns. Their red color easily distinguishes the slides from the surface and underground roof collapses, as does the small size of the fragments of lapilli and frothy scoria, which contrast strikingly with the huge blocks of massive basalt characteristic of the collapse breccia.

Lava tubes typically form in the interior of thick lava flows. How, then, did the lava tube of Boneless Cavern form within loose pyroclastic cinders and ash beneath the lava flow that contained the upper-level tube? Surely the lava of the tube did not melt its way down into the red scoria, for many contacts between the lava tube lining and red scoria can be seen on the edges of cracks in the walls and at the margins of the red slides that burst through the walls of both caverns on the lower level. These contacts show that the basalt lava plastered onto the fragments of scoria, penetrating and molding itself upon this rough surface, yet heating it only enough to make a firm bond at the points of contact. Instead of melting the scoria the invading lava apparently was chilled against it, as shown by its finer grain and much higher content of basaltic glass.

If the lava did not melt its way down into the ash and cinders, then did it penetrate and form tubes of sufficient size to transport large amounts of lava to lower levels? The answer cannot be found by examining the passages in Skull Cave alone, but a plausible explanation may be constructed by combining observations in Skull with those from other nearby caves, and from examining the surface breakdowns along the paths of the main feeder tubes as they round the southeast half of Schonchin Butte. A look at aerial photographs of these collapse trenches shows that the lava-tube system did not curve around Schonchin Butte, but instead made its way downstream in a series of jagged offsets of short tube segments separated by lava cascades or breakdowns. At each offset the downstream end of a tube (or breakdown) drops vertically and is offset to the right. Or, stated another way, at each break in direction the tube drops to a lower level and steps abruptly away from Schonchin Butte. Moreover, in all of the tube remnants that can be examined along this part of the line of collapse trenches, a tube occupying the interior of a basalt flow, when followed downstream, ends abruptly by dropping to a lower level. In every one of the accessible two-level caves examined (Castle, Kirk Whites, Beaconlight, Skull, White Lace, Frozen River—named in downstream order), the lava entering the lower level penetrated pyroclastics.

What is the source of these pyroclastics? They may have been deposited during eruptions that built the Schonchin Butte cinder cone. Basaltic lava is capable of mechanically displacing lightweight loose cinders and scoria, as exemplified by the large number of cinder cones that are breached and partly carried away by lava. As the flows of Mammoth Crater lava piled up higher and higher over the flanks of Schonchin Butte, they encroached farther to the north, and if each major flow formed tubes, successive tubes rounding the butte at higher levels would be offset closer to the cinder cone. Lava in an upper tube might break through its floor and work its way through the underlying cinders into an open tube farther downstream and at the same time be offset to the right (away from Schonchin Butte).

Certain additional factors suggest that a tube-fed tongue of lava might have little difficulty in penetrating the Schonchin Butte cinders. Skull, White Lace, and Frozen River are caves with ice;

Castle Cave was also reported by J.D. Howard to contain ice. Cave ice freezes in winter from water that percolates downward through the porous cinders, and summer air does not penetrate deeply enough to melt all the accumulated ice. Furthermore, the cinders adjacent to these lava tubes are red, whereas the normal cinders and bombs of Schonchin Butte away from close contact with lava tubes (except inside the crater area) are black or gray. Both field observations and laboratory experiments demonstrate that water vapor and air at high temperature oxidizes the iron in volcanic glass to hydrous red iron oxides. Thus, oxidation by steam and volcanic heat accounts for the red staining seen in many craters; Fleener and Ross Chimneys (fig. 4) are good examples within the monument. Lava within a tube would supply the heat necessary to flash water or ice within the cinders into steam upon contact. The steam-impregnated cinders, pressurized by the lava in the adjacent tube, would have exploded into any available opening that permitted a relief of pressure, and the lava would then press in and follow the steam-cinder blast. After the eruption had ceased and lava had drained from the cinder-encased tube, the fragile walls collapsed because the thin lining of dripstone would not have been strong enough to hold back the essentially unconsolidated Schonchin pyroclastics. As the tube walls collapsed, access by humans would be denied, and evidence to trace the exact sequence of events would be lost. Such collapses could form either temporary or permanent blockage if volcanism were renewed.

This hypothesis explains the constant changes in course of the collapse trenches near Schonchin Butte and the abandonment of the upper levels after the lava made its way downward and southward through the red tuff. It also explains why the two caverns along the lower level of Skull Cave appear to have different histories of lava occupancy. Boneless Cavern probably formed later, instead of being an integral part of the lower level at the time when lava in the upper tube was flowing into the eastern cavern at the upper balcony and its natural bridge.

Ice in Skull Cave

The ice deposits in Skull Cave are not nearly as large nor as interesting as those of Crystal Cave. In addition, the ice floors are particularly dirty because of the red dust and silt washed in from the slides during the spring rains and snowmelt. These slides are the principal source of water that seeps into the caves and freezes in winter. Sheets of ice that cover parts of the slides mark places where springs emerge. Such ice-encased areas are conspicuous on each of the big slides in the south wall of the lower level. Each cavern has a floor of solid ice, although in the downstream cavern large areas of the ice floor are concealed by collapse debris. The collapse that closes the lower tube at its downstream end consists of cinders and large lava blocks encased in a sheath of ice.

Boulevard, Balcony, and Sharks Mouth Caves

Several near-surface caves just off the main monument road offer a variety of features. Boulevard, Balcony, and Sharks Mouth Caves (map 13, pl. 4) are interesting for general exploration. The part of Balcony Cave called Balcony Extension is of interest to those who wish to examine the different stages of a collapsing tube-in-tube.

This group of small caves spreads out just beneath the ground surface 0.5 mi northwest of Schonchin Butte in an area 1,500 ft long and 300 ft wide. They are visited by leaving your car at the parking area marked both "Earth Movement" and "Schonchin Butte." It is beside the main road 3 mi northwest of the Visitor Center. These caves are parts of a near-surface distributary tube system of the basalt of Mammoth Crater. The main distributary, represented in this area by the Upper Cavern, branched to the northeast from a major feeder tube about 0.25 mi south of Bat Butte (fig. 4). This tube system lies north of the Bearpaw-Skull tube system. A discontinuous line of collapse trenches marks the course of this distributary from near Bat Butte to the Upper Cavern, whose entrance lies west of the main road. Below the Upper Cavern the distributary subdivides into numerous smaller lava tubes, some of which reunite downstream, leaving large pillars between them. In many places the roofs of these tubes are only a few feet thick, and large parts of the shallow tube system have collapsed, leaving the tubes segmented into many small caves separated by short collapse trenches. All of the distributary branches are blocked by lava filling downstream, but in the upstream direction cave access is generally terminated by roof collapse.

Nearly all of these caves show evidence of a period of major lava ponding. Some were filled to their roofs with molten lava; others were only partly filled and developed a crust of solidified lava at the new, higher level. Before solidification of the ponded lava was complete, however, most of the larger caves record that the obstruction which dammed the lava downstream was broken or circumvented by the lava. Partial draining of still-molten lava began from beneath the solidified crust and left balconies, benches, or high-lava marks on the walls of some tubes as well as additional floors, natural bridges, and other features. Deep drainage gutters formed beneath balconies, and in places peeling walls of lava plaster and rough wavy folds from partly collapsed tube-in-tubes developed during the draining episode. Tube-in-tubes that partly collapsed during solidification into rough ridges or broken and bent blocks greatly hinder access along the floor of two of these caves.

Boulevard Cave is farthest downstream, and the caves along this lava-tube system end upstream with the Upper Cavern of Balcony Cave.

Boulevard Cave

Boulevard Cave and Balcony Cave (map 13, pl. 4) were named by J.D. Howard, who explored them on January 4, 1918. He chose the name "Boulevard" for the cave farthest downstream because of its remarkably smooth floor. This floor is the solidified surface of a former lava pool that filled half the lava tube.

The large entrance chamber of Boulevard Cave—The Flushing Bird

Room—is actually a natural bridge, which has been left as a remnant between two surface collapses along a 20- to 30-ft-wide underground tube. Only 30 ft after going underground the trail turns a half circle to the right and climbs a short incline into a distributary tube that branches from beneath the natural bridge. At the top of this incline, 7 ft higher than the tube junction and 20 ft to the north, the trail emerges onto the smooth-surfaced lava pool that gave the cave its name—Boulevard (fig. 48). Farther northeast within the cave, the roof lowers until it is only a 3-ft-high crawlway. Here the floor of the Boulevard drops off in a 2-ft-high lava cascade. The tube continues with a normal downstream gradient for another 250 ft with two tight crawls. This part of the tube was partially drained soon after solidification of the top of the Boulevard pool, but the lava level did not drop enough to reveal the former floor of the tube. Nearly 150 ft beyond the cascade marking the north edge of the Boulevard, the tube divides into two distributaries. The one on the left (west) is filled nearly to the roof, but the distributary on the right makes a shallow S-curve and continues northeast for another 75 ft. Near its end the tube enters a cupola-like dome with a ceiling 9 ft above the floor. However, the tiny outlet of this room is impossible to traverse because there is less than a foot of clearance between the ceiling and floor.

Throughout its length Boulevard Cave displays well-formed lavacicles and dripstone walls, but its main attraction is its short stretch of smooth floor (the Boulevard). In the cave's entrance chamber is evidence of how the lava pond that produced the Boulevard was partly drained after solidification of its upper surface, and of the relation of Boulevard Cave to the other caves of this group.

Boulevard Entrance Chamber and East Branch of Balcony Cave

As previously noted, the upstream end of Boulevard Cave is in a broad chamber—The Flushing Bird Room—formed at the junction of two distributary tubes (map 13, pl. 4). The floors of the two tubes are at different levels, and the smooth floor of the Boulevard is 7 ft higher than that of the eastern tube. Yet, at one time molten lava must have been at the same level in both tubes. A high-lava mark present in both tubes shows that the same level as the Boulevard is preserved in several places within the eastern tube's entrance chamber. Some obstruction downstream that had ponded the lava evidently gave way and the lava surface within the entrance chamber was quickly lowered. The Boulevard floor had already congealed, but material just beneath this floor must have been so hot and plastic that it oozed upstream as a backflow that formed a sloping apron 7 ft high and 20 ft long, which now connects the Boulevard with the floor of the East Branch. Stretched bubbles and open tensional cracks remain frozen into this apron surface. Still later, a final surge of hot molten lava entered the entrance chamber from upstream and left a second high-lava mark in the form of a thin yellow lava scum plastered across this sloping apron 2 ft above the present floor. A curious feature of the entrance chamber, rarely seen in lava tubes of this area, is a small patch of waterworn pebbles and sand deposited in the lowest part of the chamber. Evidently, flash floods or rapid snowmelt cascaded into the entrance chamber from the shallow drainage just to the west and deposited loads of sandy gravel in this tiny basin beneath the natural bridge, then filtered out through a maze of coarse collapse blocks. The loose blocks that provided this filter mark the upper end of a collapse trench 80 ft long, which lies on the site of the downstream continuation of the East Branch.

The East Branch tube can be entered through a stoopway at the north end of this collapse trench. Despite the difficulty of low ceilings and a remarkably rough and wavy floor, one can traverse the tube for another 140 ft underground. Evidence indicates that this part of the East Branch tube was completely filled with molten lava at the time of the Boulevard ponding except for one high-ceilinged area 30 ft downstream from the low entrance. Here, a fallen block left a hole in the roof large enough to stand in and peer around a flat-bottomed chamber above the roof of the present cave. Although this chamber is only 1–3 ft high, its dimensions and roof features clearly indicate that it was a high place in

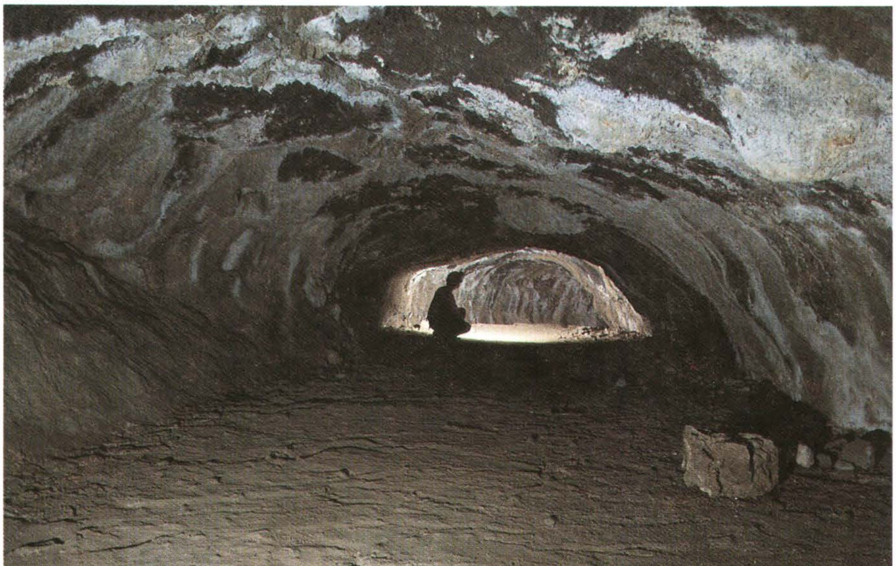


Figure 48. The smooth floor of this tube provided inspiration for J.D. Howard to name it Boulevard Cave (see fig. 4 and map 13, pl. 4).

the roof of the East Branch tube prior to the Boulevard's ponding. During ponding, molten lava rose to the level of this chamber's present floor, solidification formed a crust 1–2 ft thick, and then the molten lava below drained out, a process which left this balcony remnant 4–5 ft above the tube's present floor.

The East Branch tube can be traversed beyond the balcony in its roof for only another 100 ft downstream. At this point, the cave ends in a floor jam of broken and tilted blocks that prevent further access down the tube. A small well-like hole in the floor may connect to a lower tube, but it is too small to enter. Why is the floor of the East Branch so extremely rough and wavy—a striking contrast to that of Boulevard Cave? One must see and study it throughout its entire length for a valid answer. This surface formed from the last surge of lava that entered the cave after the ponded lava of the Boulevard stage drained out. It left the 2-ft-high lava mark in the entrance chamber. In this part of the East Branch the lava flowed as a narrow lobe containing a tube-in-tube only about 3 ft thick, with an arched roof and steep sides. Narrow troughs between the lobe and the former walls of the cave reveal a pahoehoe floor beneath it. The source that supplied new lava into this thin lobe slowed and eventually stopped, but in the final stages of flow the hot interior of this small arched-roof tube continued to drain, possibly through the well-like feature at the end of the tube. This drainage left a putty-like skin of half-congealed lava on the roof and sides of the lobe that sagged toward the tube's interior and was dragged downstream. The dragging of this lava formed the wave-like folds, basins, and irregularly tilted blocks that make the cave so difficult to traverse. Some of the ridges rose almost to the ceiling and then broke open; the opening reveals the hollow tube-in-tube of the flow lobe. Other ridge parts were pushed down and blocked parts of the outflowing lava. In short, this buckled and twisted final lobe is another form of tube-in-tube. Had it acquired a thicker skin before draining began it would have remained as a typical small tube-in-tube, but the skin was so soft and thin that it collapsed irregularly to form the wavy and broken surface found throughout the 140-ft length of the East Branch.

Balcony Cave

Upstream from the entrance chamber of Boulevard Cave is a collapse trench, followed by a second natural bridge, and then another collapse trench (map 13, pl. 4) containing the entrance to Balcony Cave. The reason Howard gave it this name is immediately apparent after walking a few feet into it. As in Boulevard Cave, lava ponded in this much larger lava tube almost to the roof. Enough time elapsed after the lava pool was emplaced so that solidification from the walls formed a crust 2 to 5 ft thick throughout the entire cave. Later the molten lava beneath this crust resumed motion. Because the crust over the deeper central part of the tube was not strong enough to bridge the entire 25- to 40-ft width of this larger tube, its axial section caved into the molten flood to form a channel 4–9 ft wide while parts of the cave system here and upstream drained. This channel is preserved as a narrow trough with nearly vertical walls that rise above the spiny pahoehoe floor at the bottom of the trench. The trail leads up the bottom of this narrow trench, passing under a natural bridge 80 ft upstream from the entrance. Here, for a distance of 10 ft, the balcony remained intact and did not collapse into the narrow channel. Upstream from the natural bridge the central channel continues for another 100 ft to where the channel and balcony above are both buried beneath a large collapse that nearly prevents further access upstream.

The balcony (fig. 49), 11–20 ft above the trail, is fascinating, but many parts are difficult to reach without a ladder or innovative climbing maneuvers. Once on the balcony, travel is slow because the balcony floor is so close to the cave ceiling that one must crawl or walk in a stooped position. At the upstream end of the trail, there is an easy ascent to the balcony where fallen roof blocks form a natural stairway from which one can crawl out upon the balcony west of the central channel. The balcony can also be reached at a place 60 ft downstream, where a small roof collapse has made a hole 5 ft in diameter that is open to the sky. Fallen blocks have been piled high enough in a mound beneath this hole to stand on and reach the west wall of the trench and pull oneself up onto the surface of the balcony. This part of the balcony is particularly interesting because on the west sides of two pillars connecting the balcony with the roof are remnants of a former distributary, which apparently branched from the main tube in the large area upstream now covered by collapse debris. Only a small part of this distributary tube is visible. On the west side of the larger (northern) pillar the balcony surface tilts west into this small tube. Traced to the north, this tube diverges from the balcony at its northwest corner and is almost completely filled with lava to its roof. Upstream the continuation of this small tube follows the west edge of the tilted balcony block, then dives into the walls of a scarp, and continues beneath the untilted balcony floor upstream. The course of this tube upstream beneath the balcony can be followed (crawlspace only) to the place where it is demolished by the surface collapse.

The balcony on the east side of the collapse trench is a narrow shelf 3–15 ft wide, hanging 12–20 ft above the trench. Access without a ladder is difficult. It can be reached from the balcony on the west side via the natural bridge across the trench, but this approach requires crawling for 25 ft along a narrow ledge formed by the west balcony around a constriction in its west wall. An easier approach is to climb onto the east balcony from the pile of collapse blocks at the entrance to Balcony Cave. Here, the ceiling is sufficiently high for walking upstream on the balcony for a short distance, but it lowers to a level where stooping or crawling is necessary a short distance upstream.

The most interesting feature along this east balcony is the mouth of a tributary tube, which enters the main tube exactly at the balcony level. Only the top of the tributary tube is visible, a fact indicating that lava in the main tube pooled in the mouth of the tributary at the time of ponding. One can enter the tributary from the balcony and traverse it for 450 ft upstream, but this route requires a tight and unpleasant crawl. A much easier access is found farther upstream, through the South Branch of Balcony Cave, as we refer to this tributary tube.

South Branch of Balcony Cave

The South Branch is a very ordinary segment of a small near-surface lava tube. Downstream from the entrance one walks on a normal pahoehoe floor for 60 ft to where the floor is covered with debris from another collapse hole that has opened to the surface. The pahoehoe floor is uncluttered farther downstream, and evidence of a higher stand of lava is recorded as a lava bench 2 ft high clinging to the east wall near this second opening. An alcove on the east wall has a sloping apron that formed when lava standing 2–4 ft higher than the present floor slowly withdrew to the present level. Another 40 ft downstream the roof of the cave lowers, and the floor is increasingly littered with collapse blocks. Nearly 220 ft downstream from where we entered the cave, the pooled lava lies only 1–3 ft below the roof. This lava marks the upstream end of the 35-ft crawlway that leads to the east balcony in Balcony Cave.

If we traverse upstream from the entrance, we find that the tube has a high ceiling, widens abruptly upstream, and divides around a large (120 by 30 ft) pillar. The wider branch is on the west side of this big pillar, and a small pillar also lies in the middle of this wide channel. The ceiling lowers, until at the south end of the large pillar the roof over much of the area is only 2–4 ft above the channel. Here the channel appears to split into three channels upstream—or there may be just two roof dividers within a wide channel filled almost to its roof with lava (see map 13, pl. 4). Whatever the geometry, access ends because each of the three strands is blocked upstream by the large collapse area that surrounds the entrance to Balcony Extension. From the southeast corner of the large pillar a wider and better exposed tube starts upstream, but becomes inaccessible in 60 ft because it,

Figure 49. Balcony Cave (see fig. 4 and map 13, pl. 4) derived its name from this balcony, formed when a late flow of lava drained away, leaving its chilled upper surface attached to the walls.

too, is filled with lava and fallen blocks from roof collapse.

Balcony Extension

The more interesting parts of Balcony Extension are accessible near the main road. A large collapse pit lies 20 ft northeast of the road. At the bottom of the north side is an arched entrance through which you can walk into Balcony Extension.

The last flow to enter the cave emerges 15 ft inside this entrance from beneath the pile of collapse rubble that covers the floor on the north and west sides of the entrance. This basalt flow advanced downstream along the floor of the cave as a sticky lobe of spiny pahoehoe only 3–6 ft thick. Its surface was pushed in the direction of flow into complicated arcuate ridges. The surface crust of this lobe is also riven by large longitudinal fissures along its crest and by curving cross fractures. Some of these breaks opened far enough so that you can see the hollow interior of the flow. This flow lobe, in other words, was a collapsing tube-in-tube, similar to the one in the East Branch of Boulevard Cave. The main difference is that the crust of this lobe was thicker; therefore, brittle cracking accompanied the bending as support of the semiplastic crust was withdrawn by draining of the tube-in-tube.

As in the East Branch, this sticky lobe did not spread to the walls throughout the cave. The old smooth pahoehoe floor that it covered is generally visible as a narrow strip between the lobe and the cave's walls. Sixty feet downstream from the entrance two branches of the main tube reunite after having flowed around a large pillar just west of the entrance. The floor of the tube in this area is a pool. The lobe of spiny pahoehoe evidently spread across this pool when it had a congealed crust but a still plastic interior. The crust on the pool bowed down toward the edge of the new lobe and cracked in places or heaved up to accommodate the weight of encroaching spiny pahoehoe.

This partly deflated tube-in-tube of spiny pahoehoe can be followed downstream 180 ft toward Balcony Cave from the entrance. It is lost under extensive collapse debris 80 ft upstream from the crawlway exit that leads to the surface collapse basin. Parts of this large pile of debris consist of broken sheets of lava plastered onto the roof of the cave during early ponding. One such sheet 20 ft long, 8 ft wide, and 2 ft thick still hangs attached to the roof but is pulled away from it as much as 3 ft at one end. Along the east wall a small tributary tube floored with pahoehoe enters the main tube but is filled with lava 25 ft upstream. Access through the collapse block to the exit hole at its end is found adjacent to either wall of the tube.

It would be interesting to know whether the collapsing tube in Balcony Extension is the same flow as the spiny pahoehoe lobe that occupies the bottom of the trench in Balcony Cave, but the evidence is hidden beneath collapse breccia that denies access for 160 ft between the two caves.

Another distributary branch leaves the Balcony Extension tube to the left (west) 130 ft downstream from the entrance. It flows northwest for 45 ft and turns in a broad arc to the north and northeast for another 100 ft, where it expands into a large room over 50 ft across. This room is shaped like an inverted saucer because it is filled nearly to its roof with collapse debris. Anyone wishing to traverse it will find that the easiest course is along the wall on its west and northwest side. The north end of this tube has been demolished by a roof collapse. Two crawlholes through blocks at the north end of this room serve as alternative exits into a surface collapse pit, as noted earlier. The route along the west wall leads directly to one of them. Except for the large debris-choked room, this distributary is a normal small lava tube, which drained and left a floor of ropy pahoehoe. However, this distributary affords the only entrance into Sharks Mouth Cave—one of the most fascinating caves of this group.

Sharks Mouth Cave

In the big room partly filled with collapse debris described previously, a small tube extends from the floor into the east wall. Although 8 ft wide, this tube is scarcely noticeable because its roof is so low that one must lie on the floor to peer into it (map 13, pl. 4). Shine a light down it and note that as the tube drops lower its floor appears from the rubble as a gently sloping lava cascade, and that roof and floor are close together until only 2 ft or less of space separates them. Focus light to illuminate the area beyond this tight opening and see that within 10–15 ft the floor ends against a vertical wall. The logical conclusion is that this is a short dead-end cave filled to the roof with congealed lava. However, if you crawl down into the tight section, you find the tube makes an abrupt right-angle turn to the north. Beyond the area where it turns right, the tube is wider, its gradient steeper, and the ceiling height doubles to 4 ft. Follow the tube downstream for 70 ft, past a pile of collapse rubble on the left, and it widens out into a room over 80 ft wide but only 5 ft high. Evidently this room is the upper part of a large tube, supported in its middle by two pillars, which extends downstream (to the north) for another 275 ft to where access is blocked completely by lava filling. The cave is 50–80 ft wide where it divides and reunites at the ends of the two pillars. Downstream it narrows to 30 ft and then 20 ft, yet the ceiling heights are only 3–4 ft throughout nearly all of the cave.

How was a cave of such great width and low ceiling height formed? It seems that the original lava tube was large, with ceiling heights of at least 6 to 10 ft. It occupied a deeper level than the Balcony Extension distributary upstream. There was probably another connection between these two lava tubes, perhaps a lava fall now buried under the surface collapse that demolished parts of both caves. In the last stages of lava occupancy this lower tube filled almost to its roof, and then the lava congealed completely without further draining of the molten interior. A tight seal of lavacicles on the cave's roof has slowed or prevented ingress of pumice, clay, and caliche from the surface.

Although this cave is difficult and even painful to traverse, the lava-cave enthusiast will be delighted with the perfection and cleanliness of its lavacicle-encrusted roof and with the untarnished quality of the intricate patterns of pahoehoe ropes on its floor. Very likely the last stream of molten lava filled the cave to its roof, then slowly lowered 2–4 ft. Lava may have continued to splash the roof with molten material as long as flow continued because in places the roof is a forest of spiny, black lavacicles, some of which are several inches long. Evidently some of them continued to elongate as successive splashes hit the ceiling. The floor, too, is composed of similarly clean jet-black glassy lava twisted into pahoehoe ropes dotted with short lavacicles that fell from the roof while still plastic. Scarcely any sediment or dust litters the floor except near the collapse breccia at the upper end of the cave.

While crawling and shining a light ahead to gauge the distance between lavacicle-studded roof and rough pahoehoe floor, notice the resemblance of the cave's cross section to the slightly opened mouth of a shark. We have therefore given it the name "Sharks Mouth Cave."

Other Caves

A maze of dead-end crawlways surround the deep collapse pit that serves as the entrance to Balcony Extension, and some are shown on map 13, plate 4. A continuous traverse can be made around the large pillar just west of the entrance via a group of crawls. There are many more tight crawls on the south and southeast side of the breakdown, one leading to a very small skylight opening just southwest from the main road. Undoubtedly the tube from the Balcony Extension entrance once extended upstream to the Upper Cavern and it was connected downstream with Balcony's South Branch upstream end, but a wide and extensive area of collapse rubble now obscures the exact relations.

The numerous passages southward from Balcony Extension are in an area where many blocks in the ceiling remain loosely suspended, and some loose blocks on the floor shift under one's weight.

Southwest of the main road, along what is the upstream continuation of the Balcony-Boulevard distributary, is the large Upper Cavern, 90 ft long and as much as 40 ft wide. It, too, has undergone extensive collapse, and most of the original features of its roof and walls have fallen to the cave's floor. At its south (upstream) end there is a natural bridge and a long collapse trench.

Silver Cave

Silver Cave is a near-surface lava tube, which is relatively undamaged by collapse. It contains excellently preserved examples of features common to lava tubes, such as lavacicles, dripstone walls, and pahoehoe floors. More complicated features include several kinds of tube-in-tubes; levee-like lobes of lava spilled from cracks in tube-in-tubes; peeled accretionary walls of lava plaster; lava cascades, benches, and gutters; and pillars, alcoves, and skylights.

The area near the head of Silver Cave (see lower right corner of map 14, pl. 5) is unusual. It originates in a lava cascade that blocks further access upstream but geometrically lies within the Post Office system of superposed lava tubes. Downstream 100 ft from this cascade, Silver Cave divides. The north-trending fork leads to Post Office Cave and furnishes the only route by which three short levels within Post Office Cave can be reached. This overlap between the two cave systems is shown on both maps 14 and 15, plate 5.

The core of Silver Cave is 1,400 ft long. More than 850 ft are added if we include the overlap with Post Office, the division around one pillar, and the length of those tube-in-tubes that can be traversed by crawling. Thus the total accessible passage is 2,250 ft.

Silver Cave was named by J.D. Howard, who explored it in January 1918. Near the entrance, percolating water has deposited white caliche on the walls and ceiling of the cave. On a winter day the caliche is frequently covered with droplets of water, which give off a brilliant silvery reflection when a light is played upon it; Howard named the cave for this effect.

Features at Entrance

The collapse at the entrance formerly was a skylight in the roof when lava flowed in the tube. As the tube filled with lava, the lava must have repeatedly surged upward through the skylight during eruptive peaks because the lip surrounding the skylight is covered with driblets of lava that were flowing back into the tube as they solidified. The shell of lava that partially overhangs the entrance was caused by gas pressure that inflated a lava blister of thin semiplastic crust over the skylight. Subsequent partial collapse of more than half of this blister, plus collapse of many similar blisters and of other debris surging within the skylight, built a mound on the floor of the tube beneath the skylight.

Features Downstream from Entrance

Downstream from the entrance the floor of the tube is hidden by lava driblets and collapse debris for 30 ft, at which point a bench along each wall appears from beneath the rubble. The projection of these benches 2–5 ft from each wall left a narrow central channel between the benches. The floor of this channel is masked with loose rubble for another 25 ft downstream, where a lava lobe with a spiny pahoehoe surface is visible beneath the collapse rubble. The edges of its rounded upper surface are lower than the benches on either wall, and so the lobe is contained in the channel between them.

The gradient of the tube begins to steepen downstream where the spiny pahoehoe in the channel cascaded and broke into an aa surface. In places the aa in the channel overflowed and covered the smooth benches. The gradient is still steeper 150 ft downstream from the entrance; then the gradient decreases, and the northwest wall of the tube is indented by a gently sloping alcove. At the center of the inner edge of this alcove, a large block that fell from the roof stands out conspicuously. Subsequent to its fall this block was completely immersed in lava, which then drained away and left a blanket of lava plaster and dripstone over the surface of the collapse block and the adjoining alcove (see map 14, pl. 5).

Downstream 60 ft from the alcove the benches on both sides of the tube are completely inundated by spiny pahoehoe that welled up and issued from a break in the surface of the aa lobe of lava between the benches. Lava beneath the aa surface apparently ponded and swelled up when it reached the gentle slope downstream from the area of steep gradient. The hydraulic pressure on the molten material beneath the aa crust became great enough to rupture the aa surface; this rupture allowed the molten lava to spill out and continue downstream as a new flow unit of spiny pahoehoe that spread over both the benches and the downstream surface of the aa. Downstream another 40 ft, this lobe of spiny pahoehoe in turn changes into a collapsed tube-in-tube, and several short sections of crude benches built by its collapse are preserved along the walls.

Collapse blocks litter the floor of the cave near its downstream end whereas the walls and ceiling are lined with thin accretionary layers of lava. The inside of each successive tube lining has lavacicles and dripstone on its surface. Some lavacicles were sheared off and embedded in the outer surface of the next successive tube lining that rose and crowded against them. Forty feet from the end of the tube, one of these linings peeled back from the walls while still in a semiplastic state, but 20 ft from the end this lining is not peeled off; it still sticks tightly against the walls and ceiling of the tube. The downstream end of Silver Cave is closed by lava fill and by many thin accretionary linings peeled from the roof and walls.

Features Upstream from Entrance

The floor of Silver Cave is concealed by collapse debris for 75 ft upstream from the entrance skylight (map 14, pl. 5). Within this area of collapse blocks, the tube widens abruptly from 25 to 50 ft. On the east wall, 80 ft upstream from the entrance, a lava cascade joins the tube. This cascade apparently was fed into the main tube from a surface flow that found access through a breakdown.

A smooth pahoehoe floor emerges from the collapse rubble just upstream from this lava cascade. This is the same pahoehoe floor that forms the smooth benches downstream from the entrance to the cave, but here it has no channel. Two shallow breakdowns (collapse trenches) in this floor, however—one 120 ft and the other 160 ft upstream from the entrance—reveal a shallow tube-in-tube that underlies this floor and extends far upstream. The channel between the benches downstream from the entrance is probably the downstream continuation of this episode of draining.

At the upstream end of the shallow breakdowns, a narrow medial crack developed along the middle of the pahoehoe floor and continues upstream for at least another 80 ft. During volcanism the underlying shallow tube-in-tube overfilled, heaved up, split open the pahoehoe floor above it, and spilled lava out through the medial crack. The overflows formed thin lobes of spiny pahoehoe, which flowed down the shallow gutters along the walls of the tube.

Upstream from these overspill lobes the tube makes a sharp 40° bend to the southwest. The ceiling and floor almost close together in the section where the tube changes direction. This results in a very tight 12- to 18-in.-high crawlspace for 15 ft along the tube. This difficult crawl is enough to discourage all but the most enthusiastic spelunkers, but it is the only way to visit the upstream part of Silver Cave and three short levels of Post Office Cave.

At the upstream end of this route the tube widens to 30 ft, and ceiling heights gradually increase to 3 ft. Lava pooled here and formed a wide smooth pahoehoe floor. Upstream 30 ft from the crawlspace, a breakdown in the smooth pahoehoe floor opened a 2- to 3-ft-high tube-in-tube in which one can crawl back downstream for 125 ft, directly beneath the upper tube. This tube-in-tube lies exactly beneath the medial part of the upper main tube; it is the upstream part of the tube-in-tube that overflowed through the medial crack and formed the spiny pahoehoe lobes that spread into the gutters along the walls.

Farther upstream from the breakdown that gave access to this tube-in-tube, a larger shallow breakdown extends upstream along the middle of the tube for 80 ft, paralleled by flat benches that project from the walls on either side. The breakdown floor defines a channel between the benches generally 3–4 ft deep. A small natural bridge (fig. 50) unites the benches between the two breakdowns (see map 14, pl. 5). Large collapse blocks on the pooled surface in the area around this natural bridge were later plastered over with lava. Collapse blocks such as these could easily have broken through the thin crust in the middle part of the pooled surface and probably contributed to the 80-ft-long breakdown in this area.

The floor of the channel between the smooth benches on either side of the 80-ft-long breakdown contains a 1- to 2-ft-high tube-in-tube, which extends upstream far beyond the breakdown. This small tube-in-tube records a series of instructive transformations as it is followed upstream from the natural bridge for the next 410 ft (see cross sections on map 14, pl. 5). Its top is missing 45 ft upstream from the natural bridge, and the remaining sides of the tube form narrow levee-like ridges that contain a shallow channel between them partly filled with spiny pahoehoe. Whether the roof of this small tube collapsed and was carried away by molten lava, or whether it was never roofed over by the buildup of the steep levees on either side is a moot question because each process probably occurred along different parts of this 410-ft stretch. Where steep levees are present, they are bordered by gutters between them and the wall of the adjoining lava bench. In these places the flat-topped benches projecting from the walls overlook gutters, levees, and a partly filled central channel in the breakdown between them.

Upstream from the natural bridges the pahoehoe benches decrease in width until they are completely absent 90 ft above the natural bridge. They are present 40 ft farther upstream where the tube turns 40° toward the south. Farther upstream the top of the small tube between the benches is open, and the gutters, steep compound levees, and a narrow channel half-filled with a small flow of spiny pahoehoe are all contained between the benches. The levees are well developed here, arching up over the channel in places and forming at one point a complete tube-in-tube that persists for 100 ft. Where a medial crack is present, the tube-in-tube changes in form and opens into a channel that is confined by 6- to 12-in.-high near-vertical levees. Because the confining levees were weak in places, the spiny pahoehoe broke through in several spots and filled sections of the bordering gutter.

The height of the pahoehoe benches decreases from 4 ft beneath the natural bridge to 1 ft above the floor 400 ft upstream from the natural bridge. The benches are continuous, very flat on top, and at the same level on both sides of the tube.

The course of the main large tube along this 400-ft section is reminiscent of river meanders. The tube swings smoothly through several gentle curves and is preserved without collapse. High-lava marks are continuous on the walls of the tube 1 ft above the top of the benches. Well-developed dripstone and lavacicles cover the walls and ceiling above these high-lava marks.

Silver Cave subdivides around a large pillar 320 ft upstream from the natural bridge. On the upstream side of the pillar, a tube at a slightly higher level than the main tube departs to the north, turns east, and reunites with the main tube 80 ft downstream. Because the floor of this side tube is 3–4 ft higher than the floor of the main tube, the lava drained back into the main tube from both ends of the side tube as the final lava flow lowered and left small frozen lava cascades at each junction.

The front of a later lava lobe came to rest on the floor of the main tube just 20 ft upstream from the pillar. This new flow covered the benches, gutters, levees, and channel and prevents further study of them upstream. The flow front is a tongue of lava 3 ft high; from it, a pahoehoe toe protrudes into one of the gutters. The viscous character of this flow is shown by its slab-pahoehoe surface upstream, which consists of a 30-ft-long crust of broken, twisted, and imbricated slabs of pahoehoe. This flow continues to form the floor of the main tube upstream to Silver Cave's connection with Post Office Cave. From this junction the flow can be traced upstream another 60 ft until one crawls into a small chamber 20 ft across blocked upstream by a lava cascade. A lower lava cascade just downstream from the chamber shows steeply plunging ridges of a smooth yellowish-brown lava. These parallel ridges evidently resulted when a smooth-surfaced pool of unusually colored lava cascaded from the lip of the upstream chamber. Colorful splashes of yellow dripstone line the roof on the tube in the same area.

The branch to the north is a small part of Post Office Cave. It contains parts of three levels, each of which is terminated by lava fill upstream. Successive downstream breakdown lips drop the two upper short levels in steps to the lowest level of the three. The floor of this lowest level falls away into the Silver Connector. This connector is the product of a complicated series of breakdowns between at least five superposed tubes, accompanied and interrupted by recurrent refilling and draining of lava. Its development evidently spanned several periods of eruptive activity followed by enlargement during post-lava collapse. Vertical layers of lava plaster adhere to the broken separations between levels in some parts of the connector. (See "Silver Connector Level " section and map 15, pl. 5).

Figure 50. Balcony forms natural bridge in Silver Cave (see fig. 4 and map 14, pl. 5). Lower tube was created when interior of late lava flow drained away.

Post Office Cave

Post Office Cave (map 15, pl. 5) is geologically the most complex lava-cave system in Lava Beds National Monument and is one of the most difficult to explore. The entrance and exit to Post Office Cave used when the cave was mapped in 1975 were closed by a slide and a rockfall in 1977–78, but by 1988 they had been reopened. The cave is entered at the downstream end. The cave system extends upstream for a linear distance of 2,080 ft, but many different levels of the cave system are superimposed one above another. Counting the footage of each accessible level, the Post Office Cave has more than 5,170 ft of passageway (see longitudinal section the map). It is much easier to find one's way from the upstream end of the Cocoa Pipeline (the deepest lava tube of Post Office Cave) to the surface via the exit than it is to climb down into the deep parts of the cave using the upstream opening as an entrance.

General Pattern of Post Office Cave

The Post Office Cave system consists of the collapse remnants of from four to seven lava tubes superposed almost directly above one another (fig. 51). Collapse through their floors and ceilings now connect and provide access to these vertically stacked tubes. Most breakdowns between levels occurred after volcanism ceased, but fine examples of collapses that occurred while molten lava still occupied one or more of the tubes are also present. In places spectacular lava falls and lava cascades, frozen upon the edges of the breakdowns, are preserved undamaged. Post-lava collapses, however, allow examination of the rocks that enclose a lava tube. The last lava to fill a tube seals its walls and ceiling with dripstone and lavacicles and its floor with pahoehoe; thus, the record of earlier events is hidden beneath a coating of lava plaster. The broken walls, floors, and ceilings of the Post Office Cave conduits reveal extremely complex stages of recurrent filling, collapse, and draining of lava tubes.

The superposition of the Post Office lava tubes in a nearly vertical stack appears to have been controlled by preexisting topography. The flow that contains the deepest tube evidently followed a valley or canyon. Flow-unit contacts and platy jointing in these lower lavas dip toward the axis of the system. As later flows were added to the pile, the lava tubes—which formed in the thickest and most rapidly flowing part of a lava flow—were superposed by confinement of the flows between the valley walls. Eventually, however, some new surface flows spilled over the valley walls and sent distributary lobes away from the axis of the former valley. One of the more complex examples is Silver Cave (map 14, pl. 5), which splits off as a distributary from one of the highest lava tubes of the Post Office axis. The Silver Cave lava tube, however, diverged from the Post Office axis for only a short distance before flowing roughly parallel with the axis again.

Before entering Post Office Cave it is worthwhile to make a brief study of the profile and map to acquire a general impression of the cave's complicated overlapping passageways. A glance at the profile shows that the central part of the cave consists of two lava tubes. An upper larger one called the Silver Connector level is superposed above a smaller tube called the Cocoa Pipeline. Closer examination of the map and the cross section (map 15, pl. 5), and especially a visit to the two cave levels, shows at once that the Cocoa Pipeline is no smaller in width than the upper level, however, its ceiling is lower. The Cocoa Pipeline is a large, fairly intact lava tube—15–30 ft wide and 8–12 ft high—with a uniform oval cross section like that of a subway tunnel. It displays the typical features that characterize intact lava tubes. On the other hand, the Silver Connector level is more varied in width, although on average it is no wider than the Cocoa Pipeline. In striking contrast to the Cocoa Pipeline its cross section is vertically elongated instead of horizontally oval. Its ceiling height varies between 30 and 45 ft, and in parts of its course that height would be doubled if we could remove the piles of collapse debris which litter its floor. The Silver Connector level is the hole left after piecemeal collapse of at least five lava tubes originally stacked one above another. This wholesale collapse of the separations between the

Figure 51. Multiple stacked tubes characterize Post Office Cave (see fig. 4). The Silver Connector (see map 15, pl. 5) internal breakdown exposes at least seven superposed levels. The deepest known point in Post Office Cave is 136 ft below surface. Person in lower tube for scale.

tubes created a cave floor that is hummocky and difficult to traverse. Many blocks are exceptionally large—a few are as long as 40 ft. Very few "in-place" remnants of the walls of the original lava tubes have survived. The remarkable feature about this level is that it did not completely collapse to the surface and form an open collapse trench like the one at the downstream entrance. One possible explanation of the strength of this part of the roof is that the highest accessible lava tube at both the upstream and downstream ends of the Post Office Cave is filled with congealed lava. This filling may have formed a strong massive strut that has prevented interior collapse from working upward to the surface.

Remnants of certain passageways that collapsed together to form the high central part of the Silver Connector level have been given names to facilitate description (see map 15, pl. 5). Where a passageway consists of an opening formed by the integration of two or more tubes by collapse, we call it a "level." If only one main lava tube is dominant, we call that one a "tube." Only the larger tubes and levels have been named. Small vertical breakdowns between tubes or levels are unnamed, but we use "connector" for the larger semicylindrical breakdowns that cross vertically through the position of two or more tubes and yet do not reach the surface.

Two connectors described herein at some length are the Silver Connector (fig. 51 and map 15, pl. 5) and the Cataract Connector. The Cataract Connector, near the east end of Post Office Cave, is an excellent example of a connector that formed by collapse between the lava tubes while one or more were occupied by molten lava. One of its walls has an 18-ft-high lava cataract that was frozen in place while molten lava was cascading into the hole. Other parts of this connector's walls are plastered with lava dripstone that leaked through holes in the fragile floor of a level above them.

The Silver Connector gives its name to the Silver Connector level. The Cataract Connector gives its name to two lava tubes, the Upper Cataract Tube and the Lower Cataract Tube. Each tube is compound and in places splits into two or more parts, but this splitting is due to the building of internal balconies and not to breakdown between separate tubes.

The Upper Cataract Tube lies just beneath the eastern part of the Silver Connector level and at its west end merges with that level through a roof collapse. In the much deeper parts of the Silver Connector level farther west, the Upper Cataract Tube is undoubtedly one of the components of the enlarged Silver Connector level (see longitudinal section on map 15, pl. 5).

At the upstream end of the Post Office Cave the relations of passageways are similar. Above the Cocoa Pipeline the four largest tubes or levels have been given names. Above the Cocoa Pipeline tube is the Cocoa entrance level, which involved two tubes, one above the other. Still higher is the upper entrance level; it subdivides eastward into upper and lower tubes. And still higher are the Silver Cave levels (maps 14 and 15, pl. 5).

The Silver Connector extends vertically through at least four and perhaps seven of these levels; it stops below them but above the Cocoa Pipeline. Within 200 ft downstream from the Silver Connector, most of these levels have merged through collapse to form the high-ceilinged part of the Silver Connector level. The Cocoa Connector, and the Central Connector downstream, are breakdown holes that reach the Cocoa Pipeline.

Because of the difficulty of showing superposed levels on a map, some levels are offset for the sake of clarity and line variations are used to help distinguish certain levels. Collapse rubble completely covers the floors of the Silver Connector level and Cocoa entrance levels but is almost absent in the roofed-over parts of the Cocoa Pipeline and a few of the other tubes.

With this preliminary explanation of the features, an upstream traverse through Post Office Cave is described. It starts at the collapse trench that gives access to the main entrance and ends at the upstream end of the Cocoa Pipeline with a climb through overlying tubes and levels to the upstream exit.

Collapse Trench at Downstream Entrance

The collapse trench that leads to the downstream entrance of Post Office Cave (map 15, pl. 5) is 220 ft long, 80 ft across at its widest point, and 50 ft deep. Its walls in most places are nearly vertical, and large underground caverns open at either end of the trench. The downstream cavern leads beneath Post Office Natural Bridge to a downstream breakdown trench; the upstream cavern contains the entrance to Post Office Cave.

In January of 1918, J.D. Howard clambered down the upstream wall of the trench, explored the cavern at its head, and from the side of this cavern crawled upstream along the downstream entrance tube (see map 15, pl. 5) to the point where his way was blocked by lava that filled the tube to its roof. Evidently he did not find the small and inconspicuous crawlway through collapse debris in the middle of the entrance cavern floor that gives access to the main parts of Post Office Cave, for he disappointedly wrote, "it isn't much of a cave, as it is only an opening with a crawler at the back end." Howard called the cave Post Office because of the many "pigeon holes" in the cliff above the entrance cavern. These reminded him of post office boxes. This clutter of small openings is one of the particularly interesting features of the collapse trench. They apparently formed in either a skylight on the top of a large tube or in a surface channel through which molten lava was actively moving downstream. In either case the surface of the molten flood (as observed in Hawaii and at other active volcanoes by Peterson and Swanson, 1974) congeals from the walls of the opening, but before it can crust over completely, minor fluctuations in the height of the lava river cause recurrent partial crusts to form and attach to the walls of the opening at slightly different heights. Withdrawal may occur when a crust is so thin, hot, and pliable that it cannot support itself; it breaks and may curve downward into a roll. A rise in lava level may break it and curl it upward. In other places the broken-off edges of such crusts are plastered over by lava splashing upon them, or by rise of the lava surface. The holes are by no means as geometric and regular as post office boxes. Some are rectangular, most are irregular, and a few are almost cylindrical. Some also contain curls of lava crust, like rolled magazines thrust into a small post office box. The wall above the Post Office entrance cavern is an excellent example of the filling to be expected on the edges of a crusted-over skylight.

The collapse trench continues downstream after interruption by the Post Office Natural Bridge and another natural bridge. Similar skylight-type features show in places on the roof and in parts of the ends of these natural bridges as well, but these features do not extend through the entire length of the bridges.

Flow Units

Another feature of interest in the collapse trench is the division of the lava in the sides of this trench into many flow units (Nichols, 1936). Flow units are created when a surface lobe of erupting lava advances fast enough to continuously override the lava surges that recurrently burst out from its front and sides as the lava advances. Flow units are easy to recognize when pahoehoe rubble has been formed and welded together at the top and bottom of each successive surge. Often, however, the contact between many flow units consists only of lava froth with bubbles of steam and air that was smeared into patches and partings by either an overriding or underriding flow unit (Waters, 1960). The order in which flow units congeal is not necessarily from the bottom of the flow upward. Basalt flows may produce a thick crust on their top while the interior of the flow is still molten and moving forward. It is in this kind of layered lava that many large lava tubes develop (Ollier and Brown, 1965; Hatheway and Herring, 1970; Greeley and Hyde, 1972; Wood, 1976). Most flow units in the walls of the Post Office collapse trench are 2–12 ft thick, but some appear to be thicker. On closer inspection one finds that most thicker units are compound and subdivided by platy partings that show evidence of shearing and recongealing along surfaces of flow. The north wall of the collapse trench shows a continuous 75-ft-thick section of flow units; the thickest unit is as much as 20 ft thick, but it is a compound unit divided into several subunits along discontinuous zones of flattened vesicles or along platy joints that were formed by the collapsing and shearing of vesicles.

Lava tubes, according to one prevailing theory, are supposed to form within the thickest and most rapidly moving parts of lava flows. Such flows generally subdivide into flow units of the various kinds well displayed on the walls of this trench. Halfway up the south wall, the flow units dip gently inward as they approach the axis of the Post Office tube system—a relation commonly seen adjacent to the walls of most large lava tubes. By contrast, high on the north wall of this trench the flow units dip outward, roughly parallel to the ground surface. These upper flow units may indicate that the valley which contained the vertical stack of Post Office tubes had filled and that younger flows subsequently overtopped the valley walls to the north; then levees of flow units and thin flows spread outward from the channel. When this levee-building situation is reached, the topmost feeder tube within a pile generally begins to subdivide into numerous small distributaries. A characteristic example, previously described, is the complicated distributary pattern of Catacombs Cave.

Entrance Cavern and Downstream Entrance Level

Howard's statement, "an opening with a crawler at the back end" is an appropriate summary. The big cavern at the entrance has ceiling heights of as much as 40 ft. Its southeast wall has collapsed extensively and forms a slope of loose blocks that extends to the middle of the cavern floor. The northwest wall is more intact with patches of dripstone and small rubble piles. Upstream the cavern walls narrow markedly, and at a point 160 ft upstream the ceiling lowers to 10–12 ft. Still farther upstream the downstream entrance level is free from collapse but is filled nearly to its roof with lava. Continuous lavacicles and dripstone cover its walls and ceiling. The last 30 ft is a "crawler" only 1–2 ft high, which is impassable farther upstream. Mapping of the remainder of Post Office Cave showed, however, that this tube is a continuation of the final tapering downstream end of the upper part of the Silver Connector level. The inaccessible part between them is only 10 ft long, but it prevented Howard from discovering the main parts of Post Office Cave.

A breakdown in the ceiling of the cavern 200 ft from the cavern entrance opens a hole that leads to a small upper tube. A ladder 20 ft or longer is needed to reach the hole. Complete collapse of its floor contributed to the 40-ft ceiling height of the entrance cavern.

Upper Cataract Tube

At a point 180 ft upstream from the mouth of the entrance cavern, a crooked 2- to 3-ft crawlway leads 20 ft downward through collapse blocks. The passageway drops through the ceiling into a 7-ft-high lava tube called the Upper Cataract Tube (see longitudinal section on map 15, pl. 5). This tube continues upstream 375 ft to a point where its roof opens into the overlying, extensive Silver Connector level.

The walls of the downstream part of the Upper Cataract Tube arch upward steeply for 50 ft and meet overhead at an acute angle. The remainder of the tube upstream has a normal, smoothly rounded ceiling. Many features indicate that the Upper Cataract Tube has had a long, complex history of repeated draining of and refilling by molten lava. Both angled and rounded ceilings show several successive accretionary linings of lava plaster. In places these have peeled from the roof and walls in such quantity that the floor is covered with rubble.

Much additional evidence of repeated draining and refilling of this compound tube can be gained from the study of four breakdowns in the floor of the tube and from investigation of the interesting passages, rooms, and subbalcony passages into which these breakdowns lead. These breakdowns are described in order as one proceeds upstream through the Upper Cataract Tube.

Red Plaster Room

Upstream 45 ft from the crawlway entrance, the floor of the Upper Cataract Tube drops away in a semicircular hole onto a rubble-covered slope 8 ft below. This slope tilts downstream (northeast), and one can follow it by squeezing under a low-ceilinged arch beneath the lip of the breakdown scarp. Beyond the arch is an irregularly shaped room 40 ft long, as much as 18 ft wide, and 6–10 ft high. We named it the Red Plaster Room for a thin coating of reddish lava plaster—one of many lava coatings—that was deposited upon the walls and roof of this room.

This extremely complicated room is evidently a short remnant of a lava tube that once extended much farther downstream. Direct evidence of its former extension as a tube is present in the high shelf just under the roof at the downstream end of the room. One can extend a stadia rod more than 20 ft beyond the thin crawlspace on the top of this shelf.

On the east wall of the Red Plaster Room, 4 ft above the floor, are the remains of a lava bench marking the highstand of a pool of lava that occupied this room long enough for a thick lava crust to form inward from the wall. This bench juts out from the wall as a shelf 2–4 ft wide. Several blocks as much as 2 ft long have tumbled from the roof and walls and landed on this shelf. Some of these blocks evidently dropped while the crust of the pool was hot and plastic, for parts of the bench sag beneath them. The continuation of the congealing crust toward the center of the room was broken off and carried downstream by a resurgence of new lava in addition to lava still draining beneath the crust. Soon after this episode, molten lava again filled the Red Plaster Room to well above the level of the bench. This lava completely plastered over and welded together the remains of the bench and the fallen blocks resting upon it (fig. 52). The molten lava again withdrew and left a 2- to 6-in.-thick coating of lava plaster. The outline of the fallen blocks, the broken-off bench, and many other features on the walls of the room can be identified despite this coating.

On the west wall in irregular alcoves, projections, and reentrants (made where fallen blocks were carried away by the flowing lava), layer upon layer of lava plaster was accreted at irregular openings in the walls and roof. Evidently the Red Plaster Room was repeatedly filled by surges of lava that drained out of the chamber almost as soon as it was filled.

Some clues to the possible cause of these repeated fillings and drainings can be gained from the geometry of the Red Plaster Room in relation to the nearby passages and openings. As noted, a uniform slope connects the upstream floor of the Red Plaster Room with the floor of the Upper Cataract Tube above. The incline drops 20 ft over a horizontal distance of 30–35 ft. The slope is so thoroughly masked under collapse rubble that the exact nature of its surface cannot be determined definitely, but it seems reasonable to assume that this slope marks a lava cascade, which dropped molten lava 20 ft into an underlying tube. The Red Plaster Room, at the base of this cascade, is a remnant of this tube. Irregular surges and changes in level would be expected at the base of a cascade as lava forced its way downstream through a tube cluttered and constricted with roof collapses.

Second Breakdown

Leave the Red Plaster Room, proceed 90 ft up the Upper Cataract Tube, and note a small oval hole in the floor of the tube. One can squeeze through this hole and into a well-preserved broad (8 ft) but flat-topped and 3-ft-high tube that extends back downstream for 95 ft to where it is terminated by collapse rubble. Mapping shows that this shallow tube lies directly beneath the flat floor of the Upper Cataract Tube and that the walls of

Figure 52. Lava entirely filled this part (Red Plaster Room) of Post Office Cave (see fig. 4 and map 15, pl. 5) and then drained away leaving a thin coating of lava. Lumpy shapes in lower right are fallen blocks coated with a late plaster of lava. Scale bar is 1 ft long.

the two tubes are almost coincident. This relation strongly suggests that the floor of the Upper Cataract Tube is a balcony. The tube was one-third filled with lava that had crusted over when the material beneath this crust drained and left the small open tube beneath the balcony floor (reexamine the profile and map of this tube on map 15, pl. 5).

Cataract Connector

Upstream 85 ft beyond the small breakdown and 225 ft upstream from the Red Plaster Room is a large collapse trench 45 ft long and 8–12 ft wide in the floor of the Upper Cataract Tube. This trench is the top of the Cataract Connector, which joins this tube with the Lower Cataract Tube. This compound tube extends downstream from the bottom of the connector for 380 ft to where it is closed by collapse rubble at a point directly below the entrance cavern.

Upstream from the Cataract Connector the Upper Cataract Tube is again divided by a balcony floor, very much like that upstream from the Red Plaster Room. From the lower tube in this pair, an 18-ft-high cataract of lava (fig. 53) tumbled to the base of the Cataract Connector. This cataract forms the west wall of the Cataract Connector and inspired its name.

One can easily reach the bottom of the Cataract Connector from the upper-balcony level of the Upper Cataract Tube by skirting the north edge of the connector breakdown and working down over a rubble slope into the tube beneath the balcony at the head of the lava cataract. What now remains to indicate the position of the cataract is a steep chute, partly covered with rubble, which must have contained a river of lava at least 3–4 ft deep where it plunged into the connector. The chute slopes at an angle of 50°, but its floor is obscured by loose rubble and a few rafted lava blocks welded into the floor of the chute. Bench-like curbs of frothy lava accreted to the walls of the chute as lava splashed down the cataract. These curbs permit the steep chute to be traversed with ease. Their rough surfaces, a few feet above the floor of the chute, make a natural railing that affords firm handholds when descending the cataract.

The east wall of the Cataract Connector is unlike the cataract on its west wall, because where the Lower Cataract Tube (match line on map 15, pl. 5) drains the bottom of the connector to the east, the Cataract Connector is much wider than it is at the top. This widening is due to the presence of "extra walls" on the sides of the connector, which lie outside of the internal walls (see the small cross section near the end of the Lower Cataract Tube on map 15, pl. 5). The origin of these extra walls is not fully understood. Apparently when the connector first formed as a breakdown between two levels, one or more of the levels overlying the connector was filled with molten lava, and dripstone coatings developed on the walls as lava leaked through from the overlying tubes. Conditions were not uniform; however, different parts of the wall of the connector record different histories. For example, the downstream side of the connector does not show a continuation of the segment of the Upper Cataract Tube from which the lava cascade poured that mantles the upstream wall of the connector. Yet high on the wall of the downstream side, and in the appropriate position of the balcony that divides the Upper Cataract Tube into two parts, is the outline of what appears to have been a former opening. This opening, however, is now closed by at least 15 roughly horizontal layers of lava plaster 3–12 in. thick. This plaster must have accreted from beneath because lavacicles on the undersides of many layers confirm building of the layers from the top downward. Both sides of these horizontal layers are buttressed against vertical walls of dripstone. This vertical lining could only have occurred when the

Figure 53. Cataract Connector of Post Office Cave (see fig. 4 and map 15, pl. 5) contains late frozen lava fall that took advantage of collapse of Upper Cataract Tube into Lower Cataract Tube. Connectors allow access between tube levels within a cave.

two levels were joined by a breakdown. At some time lava pooled within the opening and formed a horizontal crust. Repeated fluctuations of lava height within the lower tube accreted a series of these crusts until the opening was filled.

In its early stage the upper part of the Cataract Connector probably started as a breakdown between two tubes, and it later enlarged by further leakage and collapse. That the Cataract Connector had a leaky roof from even higher levels than that of the Upper Cataract Tube is shown by separate small cascades of dripstone spilling onto its walls in numerous places. At least some of these leaky spots probably formed the puzzling high cupolas with near-vertical walls that lie outside of the inner wall of the Cataract Connector and that rise in places to elevations even higher than the top of the Upper Cataract Tube. A cross section through two of these cupolas, showing their relations to different levels, is shown on map 15 (pl. 5) just right of the match line to Lower Cataract Tube. The dripstone that lines some of these cupolas must have come from lava that was active in the overlying Silver Connector level because the cupolas are higher than the roof of the Upper Cataract Tube.

The growth of dripstone-lined cupolas and alcoves, and the collapse of the deeper parts of the Cataract Connector itself, may have been triggered and extended by the presence of a lightweight cindery red breccia, which is the wall rock in this part of the cave. Similar red breccias are associated with connectors and with unusual wall collapses in other caves at Lava Beds National Monument—among them are Skull, Crystal, Kirk Whites, and White Lace Caves. This loose breccia apparently is easily penetrated and carried away by molten lava. If the breccia contains water, steam explosions occurring when molten lava invades the water-soaked breccia aid in the process (see "Skull Cave" section and map 12, pl. 4).

Lower Cataract Tube

The tube that drains the Cataract Connector narrows abruptly as it leaves the area of vertical-walled cupolas in red breccia. It runs east with a moderately steep gradient and its floor is mostly obscured by collapse rubble. Downstream 90 ft from the base of the Cataract Connector, narrow curbs of lava accreted to the walls of the tube as the lava plunged down a 3-ft cascade into a pool below. Horizontal striations occur on the walls and along smooth benches and curbs upstream from this cascade. The striations are narrow, continuous, very pronounced, and undoubtedly were caused by viscous flow and shearing against the margins of the tube as lava was forced through this constriction.

The Lower Cataract Tube is divided by a balcony into a double tube 120 ft downstream from the connector. The upper tube is smaller and can be followed for 50 ft. Its smooth pahoehoe floor ends abruptly against a dripstone wall. The lower tube beneath the balcony contains a collapsed tube-in-tube 50 ft long with a red spiny pahoehoe surface. This tube-in-tube inflated, drained, and then collapsed while its thin walls were still hot and plastic.

A ceiling collapse opens another segment of what is probably a continuation of the upper part of the tube 250 ft downstream from the Cataract Connector. Both the upper and lower passageways can be traversed downstream until they are cut off by roof collapse. The walls of the tube above the balcony contain excellent examples of dripstone. The collapse that closed both parts of the tube at this downstream end opened a high chamber in cindery red breccia 18 ft above the upper passageway.

Tubes Upstream from Cataract Connector

Two tubes, separated by a balcony, continue the Upper Cataract Tube to the west (map 15, pl. 5). The lower tube, which fed the cataract for which the Cataract Connector is named, is 3–4 ft high. Its roof is flat, and its walls lie precisely below those of the upper half of the Upper Cataract Tube. This double tube can be explained in the same way as the subfloor tube between the Red Plaster Room and the small breakdown hole 95 ft upstream: a large tube was divided into two tubes by the formation of a solid crust over a lava pond, followed by drainage of molten lava after the crust hardened.

It is tempting to assume that these two very similar double tubes were once connected as a single long tube separated because of the Cataract Connector breakdown. However, a difficulty arises with this explanation. That is, the two balcony divisions occur at slightly different elevations and therefore could not have been the crust over a single lava pool. A more likely explanation is that ponding to produce the two separate pools occurred at different times, but in similar settings. Note that at each locality the tube below the septum was drained by a cataract; the eastern cataract drained into the Red Plaster Room, and the western, or upstream, cataract drained through the Cataract Connector into the Lower Cataract Tube. A collapse in the roof of the Upper Cataract Tube, in or near the Red Plaster Room, ponded lava in the Upper Cataract Tube to a depth a little less than half of its height. Soon after a crust had formed on the surface of the lava pool, the floor of the Upper Cataract Tube gave way, cascading lava into the Red Plaster Room. Exactly the same sequence of events probably took place farther upstream during formation of the Cataract Connector.

Silver Connector Level

The Silver Connector level, which extends for most of the length of Post Office Cave, is not to be confused with the Silver Connector breakdown that connects vertically between tubes near the upstream end of the cave. This level is the highest and most extensive passageway in Post Office Cave and is over 1,700 ft long. Throughout most of their course the superposed lava tubes coalesced to form a narrow passage 30–60 ft high. Throughout most of the level the height-width ratio is greater than 3 to 1. In these high-ceilinged areas the entire floor of the Silver Connector level is deeply buried beneath collapse blocks.

The upstream and downstream ends of the Silver Connector level are indefinite because the completely collapsed central section spreads into still-uncollapsed tubes. The upper part of the Silver Connector level decreases in height and continues eastward, where it is nearly filled with lava. It eventually becomes a crawlway that continues for 30 ft to where it is plugged with congealed lava. It is open another 10 ft farther downstream as the western end of the downstream entrance level.

Part of the middle section of the Silver Connector level is equivalent to the Upper Cataract Tube, but collapse of both floor and roof prevents tracing this connection.

The upstream (western) end of the Silver Connector level is even more complex: west of the Silver Connector breakdown this level extends into parts of at least five tubes. The highest three levels are reached from Silver Cave (map 14, pl. 5), whose roof lies only 10–12 ft below the ground surface. The lowest passage extending north from the base of the Silver Connector is 85 ft below the surface but still 25 ft above the underlying Cocoa Pipeline.

Two breakdowns in the floor of the Silver Connector level give access to the Cocoa Pipeline: the eastern (downstream), Central Connector is an easy and safe passage into the pipeline; the other, 540 ft upstream, is the deep, steep-sided, and very unstable Cocoa Connector.

The Silver Connector level seems geologically uninteresting at first; its floor is nothing but a hummocky jumble of large fallen blocks that are difficult to walk over. The walls are more instructive, for patches of dripstone show the perched remains of a collapsed tube here and there, and irregular shelf-like extensions from the walls can be identified as edges of the floor of a broken-off tube. Only rarely can one see any primary features in the high and inaccessible roof. In fact, playing a strong light over this roof, 15–60 ft overhead, is a disconcerting experience when one notices the many precariously perched blocks that appear ready to fall. However, no other cave in Lava Beds National Monument provides such insights into the structure and mechanics of operation of lava tubes as does Post Office. Just as the shambles after an earthquake reveal the structural details of broken buildings, an inspection of the collapsed walls of the Silver Connector level provides details of tube construction and of the mechanics of plastic flow in lava tubes that could never be inferred from well-preserved lava tubes coated with lava plaster. A few select features of this remarkable lava-tube ruin that contribute to the understanding of lava tubes are described herein. Areas of special interest or beauty are also described. Not all features shown on the map are described herein.

The floor of the Silver Connector level, 200 ft upstream from the breakdown that connects it with the Upper Cataract Tube, is surmounted by an unusually high and steep conical pile of collapse debris. The pile rises 45 ft above the thick blanket of tumbled blocks that forms the floor of the cave. Nearby are irregular benches jutting from the wall at various points, remnants of at least three tubes that coalesced to create a cave 30–45 ft high. Farther upstream (northwest) 65 ft from the base of this huge collapse pile, the floor of the Silver Connector level drops away into the Central Connector, a breakdown 60 ft long and 6–15 ft wide. This connector gives easy access to the eastern part of the Cocoa Pipeline lava tube, 25 ft below. Before visiting this very different level, however, continue upstream in the Silver Connector level by carefully skirting the Central Connector along the top of its southeast wall. For some distance upstream from the Central Connector, the ceiling of the Silver Connector level is nearly 35 ft high and coated with off-white caliche (calcium carbonate crusts). If illuminated while wet, caliche has a highly reflective, silvery glow. Water dripping from this roof has deposited upon collapse blocks on the floor fine examples of the fragile arborescent growths of caliche popularly called "cave coral." Most growths are white, but where stained by hydrous iron and manganese oxides, organic soil compounds, or fungi, they can be deep red, lustrous black, yellow, pink, silky gray, and light blue.

The next major interruption, 540 ft farther upstream from the Central Connector, is the Cocoa Connector, a deep, unstable 22- by 15-ft hole. The descent through the Cocoa Connector to the floor of the Cocoa Pipeline, 40 ft below, is over loose and easily rolled debris. A descent here is neither recommended nor necessary because there are two safer entrances into the Cocoa Pipeline. Upstream toward the Cocoa Connector, the blanket of collapse blocks on the floor thickens, and many huge blocks as much as 40 ft long are embedded in the debris. Some of these large blocks show surface features, which testify that they are large pieces of the separations between two superposed levels. Collapse over considerable areas must have occurred in places, as such large blocks surely are not due to the slow unraveling upward of roof slabs loosened along minor joints and cracks. The truncated edges of some floor benches still hanging from the walls also imply large-scale rockfalls. The piles of collapse blocks are a jigsaw puzzle of surface features and the broken walls of lava tubes. It is common to find large fallen blocks with several coatings of lava plaster sliced in cross-section on one or more broken edges.

Downstream 65 ft from the Cocoa Connector, the Silver Connector level makes a 45° turn to the left (as viewed looking upstream) and heads almost due south. The Cocoa Pipeline below turns the same corner with an even sharper bend. The effect of a sharp bend in the original, pre-lava topographic valley in controlling the superposition of the two lava tubes seems clear, because the curve became gentler as the pre-flow depression was filled in.

The dangerous Cocoa Connector can be skirted safely on its northwest side. Once around it one climbs a steep 15- to 20-ft pile of collapse rubble. In another 190 ft is the large vertical hole through several levels called the Silver Connector.

Silver Connector

The breakdown 190 ft upstream from the Cocoa Connector (map 15, pl. 5) has for several years been called the Silver Connector (fig. 51) because its top is in Silver Cave. It extends vertically for 60 ft and passes through several levels. Its base is in a short tube that slopes north for an additional 25 ft and ends in a rounded pocket 85 ft below ground, but above the floor of the Cocoa Pipeline. Details of some lava tubes that intersect the Silver Connector have not been worked out because they are inaccessible, and the edges of all levels that intersect the connector are very loose. Moreover, the top three lava tubes can only be approached by a difficult crawl through a constriction in Silver Cave.

The Silver Connector level changes markedly near the Silver Connector and upstream from it. It spreads out into at least seven superposed lava tubes, all of which were truncated by the collapses that formed the Silver Connector. The tube that we call Lower Entrance Tube is readily accessible from the base of the Silver Connector.

Lower Entrance Tube

To enter the Lower Entrance Tube from the base of the Silver Connector, you must pick your way upstream beneath a natural bridge and then up a steep rubble slope into the tube. Farther upstream 50 ft another breakdown, only 8 ft deep, interrupts the floor of the tube for another 45 ft. From the upstream end of this breakdown it is possible to descend through an opening and work down into still lower tubes; we continue, however, in the main part of the Lower Entrance Tube.

This tube has ceiling heights of 10–12 ft and is characterized by thin layers of accretionary lining that are partly peeled away from its walls and ceiling. Upstream 240 ft from the Silver Connector, these accretionary linings arch steeply from the tube's walls and in places are vertical along the axis of the roof. The roof has a steep gable instead of a rounded top. The tube continues to narrow upstream to the Veritable Venturi and acquires an A-frame shape (fig. 54) where it makes a smooth 70° turn to the right (west). Just beyond this turn, 290 ft upstream from the Silver Connector, a breakdown closes the continuation of the tube to the west but permits one to climb into the upper entrance level and continue to the cave exit, a tight crawlhole leading to the surface.

Cocoa Pipeline

The 1,040-ft-long Cocoa Pipeline, approximately 110 ft below the surface, is the deepest well-preserved lava tube in the upstream half of Post Office Cave. This tube is oval in cross section and, except at one small cascade near its downstream end, measures 12–14 ft high and 18–20 ft wide. The pahoehoe floor has an overall gradient of less than one degree. The oval cross-section is close to the ideal hydraulic form to be expected of a heavy liquid flowing through a viscous medium. The thick roof that separates the tube from the overlying Silver Connector level also indicates that the Cocoa Pipeline developed in an unusually thick lava flow, perhaps near the bottom of the first major flow to occupy the inferred canyon or valley that determined the site of the superposed lava tubes comprising Post Office Cave.

The Cocoa Pipeline is nearly intact, with very little collapse except at the two connectors that join it with the overlying level. There are four possible entrances through the roof of the Cocoa Pipeline: the Central and Cocoa Connectors and two upstream-end crawlways leading through collapse blocks within an overlying maze of partly collapsed small tubes. The evolution of the collapse-free Cocoa Pipeline contrasts strikingly with that of the Silver Connector level. The Pipeline seems to have been little affected by the complex series of breakdowns, drainings, and recurrent lava fillings that characterize the overlying levels. Its basal position and its thicker roof may have allowed it to remain insulated and full of molten lava during fluctuation of lava in the shallower levels. Some of the draining and refilling in upper tubes may have been caused by surging of lava upward through connectors as hydraulic pressure changed within the completely filled Cocoa Pipeline.

The accessible part of the Cocoa Pipeline lacks tributaries or distributaries and is so uniform in shape that routine description of its upstream course is unnecessary. Only a few of the more interesting localities are described.

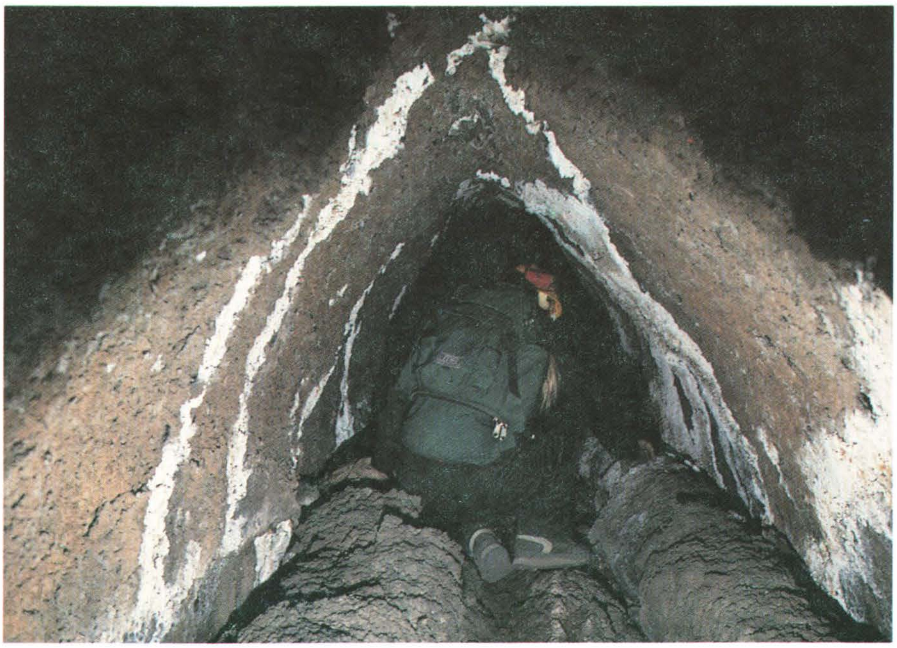


Figure 54. Small triangular-shaped passage was left in Post Office Cave (see fig. 4 and map 15, pl. 5) when late, stiff lava flow failed to fill tube and formed pronounced lava curbs. Triangular shape may have been caused by inward slumping of tube walls.

The Central Connector, along the eastern (downstream) collapse from the Silver Connector level, provides an easy entry into the Cocoa Pipeline. Downstream 100 ft from the Central Connector, the Cocoa Pipeline is blocked by a roof collapse. This blockage is directly beneath the upstream edge of the huge collapse pile, which rises 45 ft above the floor of the overlying Silver Connector level. Perhaps a hidden connector filled with lava and collapse debris is buried within this huge collapse pile. Such a connector might extend all the way from 15 ft below the surface to the Cocoa Pipeline. The Cocoa Pipeline's downstream continuation beyond this blockage appears to be the Lower Cataract Tube. The elevations are compatible because the lowest accessible point in the Lower Cataract Tube is 139 ft below the surface (map 15, pl. 5). Yet the upper part of the Cocoa Pipeline is much simpler in form than the irregular-walled structure of the Lower Cataract Tube. This difference in form, however, may only be the result of the Lower Cataract Tube having to make its way, at least in part, through the red pyroclastic tuff and breccia.

The Cocoa Pipeline can be followed upstream for 1,040 ft to where it is blocked by a collapse. Only 25 ft upstream from the downstream end, a small 10-ft mound of breakdown on the floor and corresponding dome in the roof record the beginning of a new collapse. Next we come to the Central Connector; this collapse from the Silver Connector level has built a mound 10 to 20 ft high and 70 ft long on the floor of the Cocoa Pipeline.

Another 100 ft farther upstream from the Central Connector, the floor rises 3 ft in a short lava cascade. Here the pipeline constricts to only half its downstream width. Above the cascade the tube widens, and narrow floor-level benches 2 ft high are present on both sides for 200 ft upstream. Below the cascade, in the constricted part of the tube, the equivalent of the 2-ft bench is a collapsed tube-in-tube, which litters the floor of the pipeline.

The next point of interest upstream is the Cocoa Connector, an opening that left a steep-sided conical pile of debris 18 ft high on the floor of the pipeline. The roof of the overlying level, visible through this connector, is 78 ft above the floor of the Cocoa Pipeline.

Nearly 200 ft upstream from the Cocoa Connector, lava stalagmites (fig. 10) are found on the floor of the Cocoa Pipeline and extend in a line for 40–50 ft. A few are quite large—as much as 2 ft in diameter and 3 ft high. It is puzzling that none of these stalagmites appear to have an obvious source of lava drippage on the ceiling directly above them. One might assume they were rafted on a partly solidified lava crust to their present position from a source farther upstream. A possible source might be a small cataract, which delivered lava through the roof of the Cocoa Pipeline from the overlying Cocoa entrance level, near the point where the Cocoa Pipeline is blocked by a collapse at its upper end. It is also possible that a series of localized ceiling hot spots may have caused the ceiling lining to melt and thus form the stalagmites.

The upstream blockage of the Cocoa Pipeline is a slope of fallen blocks, which rises steeply and joins the funnel of coarse blocks that collapsed from the level above (see longitudinal section on map 15, pl. 5). From the roof of the Cocoa Pipeline near its right (north) wall, a small but conspicuous vertical crawlhole rises between fallen blocks into the tip of this steep funnel of loose and precariously balanced blocks. This is not the preferred exit to the higher level because it is extremely unstable. Directly across the Cocoa Pipeline from this hole in its roof, but down at the level of the sloping debris on the floor, is another inconspicuous crawlway. It pierces the left (south) wall of the pipeline and except for the first 3 ft is a roomy crawl, which can be easily negotiated by a large man. After 16 ft one reaches a wider incline that is the surface of a lava cascade. There is little difficulty in scrambling up this lower angle cascade, even though much of it is mantled by collapse blocks. Within 40 ft one emerges in a small collapse that opens into the upstream portion of the Cocoa entrance level.

Cocoa Entrance Level

The Cocoa entrance level on map 15, plate 5 is offset from its actual position for clarity. The various parts of the Cocoa entrance level are badly ruined by collapse so that they are of perhaps lesser interest to either the lay visitor or geologist, but this level does furnish a shortcut exit from Post Office Cave.

The geometry of the Cocoa entrance level is irregular horizontally and vertically. The main elements are a passageway 200 ft long and a sublevel of half this length beneath its downstream part. In addition, the large cascade is an inclined distributary extending from the Cocoa entrance level's floor into the Cocoa Pipeline. The lava that formed the stalagmites downstream in the Cocoa Pipeline may have dripped from this cascade onto the sluggishly moving lava in the Cocoa Pipeline.

The surface can be reached from this complex collapse ruin by following the steps described. First crawl up the cascade into a large room 50 ft wide. Turn and cross over to the opposite (east) wall of this room, edging south around the top of the steep funnel of collapse debris. Follow the east wall of the room uphill (north) into a small branch tube for 40 ft. Here a hole between collapse blocks leads upward into the lower entrance level, which is an upstream extension of a part of the Silver Connector level. Just after climbing out of the lower Cocoa entrance level, reverse direction and walk upstream (south) around a broad curve to the upstream end of the lower entrance level and then through a shallow connector into the upper entrance level. Continue upstream for 220 ft, where the upper entrance level ends in a dirt-covered slope that rises higher into a snug vertical chimney that opens to the surface.

Upper Entrance Level

The upper entrance level can be examined both upstream and downstream from where it intersects the Veritable Venturi. The exit is upstream (southwest). Downstream it extends 120 ft to where it is filled with lava. Downstream, the ceiling heights drop, the walls narrow, the tube takes on an A-frame cross section (fig. 54) like that in the Veritable Venturi beneath, and the walls have spiny pahoehoe benches 1 ft high that curb a shallow central channel.

Upstream from its intersection with the Lower Entrance Tube, the tube is larger and farther upstream the floor is entirely covered with collapse debris. Ceiling heights increase markedly 50 ft upstream from the breakdown, where the remains of a filled lava tube can be seen in the roof. A steep-sided collapse pile covers the floor a little farther upstream, and the tube widens to 50 ft in the area of this collapse. The floor of the tube then descends to a low spot on the upstream side of this collapse pile, and from there a soil-covered slope leads upstream to the vertical chimney, which is the upstream exit from Post Office Cave (fig. 55).

Lava Transport

Using average underground flow rates of 0.6–3.6 mi per hour, as determined by Peterson and Swanson (1974) from observations through skylights on active lava tubes in Hawaii, the volume of lava transported in a full tube of known cross-sectional area can be calculated. Assuming these Hawaiian flow rates and the same gradient, a tube the size of the Cocoa Pipeline could transport 14–86 million cubic feet of lava per day, the lower number being comparable to typical Hawaiian eruption rates (Peterson and Swanson, 1974). At least five large lava-tube systems operated during emplacement of the basalt of Mammoth Crater, although they were probably not all active at the same time. The five are, from west to east, (1) Upper Ice Cave, (2) north of Bearpaw Butte, (3) Bearpaw-Skull, (4) Heppe-Cave Loop Road-Post Office-Craig, and (5) Hidden Valley. Volume is estimated to be nearly 1.2 cubic miles covering approximately 100 square miles and spreading west and east beyond the boundaries of the monument (fig. 1). The basalt of Mammoth Crater also possesses a single remanent paleomagnetic direction, and this data suggests a very short duration, perhaps as little as a decade, for emplacement of the entire unit (Donnelly-Nolan and Champion, 1987). If 1.2 cubic miles of basalt were emplaced in 10 years, the calculated flow rate would be 48 million cubic feet per day; this figure is slightly more than three times higher than the typical Hawaiian flow rates cited by Peterson and Swanson (1974) but within the range of Hawaiian eruption rates. If the basalt of Mammoth Crater erupted at approximately the same rate as in a typical Hawaiian eruption, 30 years may have been required for the eruption. Note that Post Office tubes transported a large volume of lava (at least some of which probably traveled through Craig Cave tube) 5 to 10 mi to the east and northeast from the east monument boundary nearly to California Highway 139. However, some of this large expanse of basalt of Mammoth Crater may have been transported by the inferred Hidden Valley tube system, which is buried by the basalt of Valentine Cave.

Intermittent changes of hydraulic pressure and flow rate occur within such a tube system. Also, roof collapses that partially or completely plug flowing tubes affect the hydraulic pressure within tube systems. Pooling of lava behind an annealed flow front or a lava collapse, along with short-term fluctuations in eruptive rates, probably represented the only conditions under which any of the Post Office tubes were completely filled with lava for an extended period of time, with the possible exception of the Cocoa Pipeline. Tube-in-tubes, smooth pahoehoe benches, and the many thin accretionary linings in the tubes of Post Office Cave support this reasoning, for they record repeated periods of pooling, withdrawal, and refilling with lava.

Craig Cave and Craig Temple

An oval collapse trench 125 ft long and 60 ft wide provides entrances for both Craig Temple and Craig Cave. Downstream from this breakdown most of Craig Cave is nearly drained of lava; the last trickle of pahoehoe lava to occupy the tube filled only the rounded central part of the tube's floor and seldom reached the steep walls except on the outside of bends. At its downstream end the lava tube is plugged by a roof collapse. In contrast, Craig Temple, the part of the tube upstream from the breakdown, is two-thirds filled by two tongues

Figure 55. Explorer emerges from narrow exit of Post Office Cave (see fig. 4 and map 15, pl. 5). Information about cave access, along with safety and exploration guidelines are obtained at Visitor Center in Lava Beds National Monument.

of lava. A late tongue of the basalt of Mammoth Crater that formed the tube advanced downstream. A tongue of the much younger basalt of Valentine Cave entered from the surface and flowed into the upstream end of the collapse trench (fig. 56); it then cascaded over the upstream slope of the collapse pile that lies at the entrance to Craig Temple.

Craig Cave was named by J.D. Howard in honor of the Craig brothers, who first guided him to the cave. Some confusion exists in records at Lava Beds National Monument regarding use of the name "Craig Temple." It is reasonably certain that Howard applied this name only to the upstream continuation of the cave above the collapse trench, which he explored during a second visit. One can imagine a resemblance to a temple in the upper extension of the cave where two steeply sloping and rough-surfaced flow fronts produced a room 40 ft wide and 100 ft long, with an impressive domed roof rising above it. The extremely rough surface of huge tilted and upturned pahoehoe slabs on the flow that advanced upstream from the breakdown may be likened to pews in a cathedral. The downstream flow advanced in flow units and produced a series of altar-like steps. On map 16 (pl. 5), the name "Craig Temple" is used only for this room in upstream Craig Cave tube. However, at some time in the past, the words "Craig Temple" were painted on the rock above the entrance to Craig Cave. To add to the confusion, the pamphlet "Origin of Geographical, Geological, and Historical Features in Lava Beds National Monument and Adjacent Lands" (available at the Visitor Center) states that Craig Cave "was originally called Craig Temple."

Craig Cave

An impressive cavern more than 50 ft wide yawns beneath a broad arch in the cave roof (fig. 57) at the downstream end of the collapse trench, which provides access to the Craig lava tube (map 16, pl. 5). In the roof of the cave, and in the north wall of the trench, are several well-defined flow units of basalt lava. Most are less than 4 ft thick and are similar to the flow units from the collapse trench at the downstream entrance to Post Office Cave. The Craig tube is probably a downstream continuation of the tube system that forms Post Office

Figure 56. Frozen tongue of much later basalt of Valentine Cave (see fig. 4 and map 8, pl. 3) flowed over edge of collapse trench that allows access to Craig Cave (left edge of photograph). Continued flow of this younger basalt would have filled Craig Cave (see fig. 4 and map 16, pl. 5) and buried trench. Craig Temple, upstream, was partly filled by the younger flow.

Cave. Collapse rubble half fills Craig Cave directly beneath the entrance overhang and slopes steeply downstream to the cave floor. At the base of this pile the ceiling height is 20–25 ft. From this entrance the lava tube extends southeast on a gentle gradient for 156 ft and then rounds a broad curve until, 145 ft farther, the tube turns due south. A blanket of collapse blocks from the ceiling masks most of the floor, but three large patches of pahoehoe are free of rubble. They are in the central part of the tube, and the floor rounds upward into the walls on either side of them.

The left (northeast) wall over this 240-ft stretch of tube has lost most of its dripstone due to collapse, but on the opposite (southwest) wall several layers of dripstone plaster are peeling off near the base. Some large areas of dripstone remain attached to the higher parts of the wall. Very few areas of lavacicles remain on the high ceiling (from 20 to 25 ft) because most have peeled loose and fallen to the floor.

For the next 450 ft downstream, the tube's course is a large smoothly rounded curve open to the northeast; then it changes direction to almost due east and maintains this easterly course for the remaining 580 ft of the cave.

In the area of the broad curve the patches of pahoehoe that appear from beneath the rubble are concentrated along the south (outside) wall of the bend, and the tube is deeper here than on the north wall, as in the deepest part of a channel (thalweg) of a meandering river. Moreover, the south wall is relatively free of collapse rubble, except for thick slabs of dripstone plaster that have peeled away from the walls; the ragged upturned edges of these slabs form thin, irregular bench-like projections along the base of the south wall. Patches of excellent clean pahoehoe in the floor exhibit ropes that reveal the curving direction of the last lava flow that swept around this large meander-like bend.

A similar but relatively straight stretch continues downstream on an easterly course. The tube widens to an average of 60 ft over much of this stretch. Patches of dripstone plaster are peeling from the base of the walls on either side. At approximately the middle of this stretch very large collapse blocks—as much as 20 ft long—are scattered over a large collapse pile. These must have come down in a massive rockfall instead of by the slow upward unraveling of the roof when vertical cracks and columnar joints gradually spread open and divide the flow units of the roof into small blocks. Lava stalagmites (small piles of lava accumulated by drippage from the ceiling) embellish the pahoehoe floor of the cave at several places.

At the downstream end of the accessible part of the tube a huge collapse pile rises in a steep talus slope 50 ft above the floor. The broad top of this collapse pile lies beneath a collapse cupola about 20 ft above the original roof of the lava tube. The top of this cupola intersects an interbed between two lava flows that consists of red tuffaceous material, chiefly silt and sand, which is 3–4 ft thick. That abundant tree rootlets extend downward through cracks into this interbed shows the surface is not far above.

The broad top of the collapse pile beneath this cupola reverses slope and descends to the east on a gentle incline. Within 20–30 ft, however, the collapse blocks crowd against the steeper slope of the roof of the cupola above and seal off further access. Near the center of the slope one can work down another 20–30 ft along a small crawlway between fallen blocks just under the roof of the cupola. As J.D. Howard wrote after his examination of the cave 50 years earlier, "the passageway is caved in at the east, but it possibly could be opened up."

Figure 57. Entrance to large tube containing Craig Cave (see fig. 4 and map 16, pl. 5) is roofed by numerous thin layers of lava.

Entrance Collapse Trench

In contrast to the huge arched cavern, which opens Craig Cave to the east, the entrance into Craig Temple (map 16, pl. 5) at the upstream end of the breakdown is nearly hidden.

The most interesting features of the collapse trench between the two entrances are three small lobes of younger lava of the basalt of Valentine Cave that spilled into the trench over its south wall. Each lobe must have been moving slowly, almost devoid of energy. A lava cataract that formed where the eastern lobe spilled over the near-vertical wall of the trench is perfectly preserved, still adhering to the breakdown wall (fig. 56). Only a small amount of lava made it to the floor of the trench, where it spread in a tiny delta over nearby collapse blocks. The second lobe, which rounded the west side of the obstruction on the rim, was even more sluggish. It congealed in place as it began the drop over the rim.

A third lobe of molten lava spilled into the northwest end of the entrance trench. This lobe had more energy and supplied a larger volume of lava. The lava eventually congealed after half filling the large Craig tube 80 ft upstream. The lava stream forms half of the floor of the large room called Craig Temple. If the eruption feeding the basalt of Valentine Cave had continued slightly longer, both Craig Cave and Craig Temple would have been filled and completely buried.

Craig Temple

The part of the Craig tube that lies upstream from the entrance collapse is 240 ft long, but only 125 ft of its downstream segment forms the high-ceilinged room that Howard called "Craig Temple" (map 16, pl. 5). The remaining 115 ft is a broad low-ceilinged area, parts of which can be reached only by crawling.

Craig Temple was formed by the underground merger of two flows of lava. The younger one, the basalt of Valentine Cave, advanced upstream in the Craig tube over the apron of collapse rubble. Its surface is very rough and uneven and reveals how the flow subdivided into trickles and tongues among the collapsed blocks as it cascaded down the steep apron of rubble onto the floor of the Craig tube. The other flow was a late tongue of basalt of Mammoth Crater, the same basalt that built the Craig tube. It spread downstream from within upper Craig tube. This compound flow is the lava fill that blocks the tube 240 ft upstream from the entrance and ends downstream with a sharp junction against the younger upstream-flowing lobe of basalt of Valentine Cave. This junction is 160 ft downstream from where the tube is blocked by lava rising to its roof and is 80 ft upstream from the west edge of the entrance. This junction is the lowest area in Craig Temple; the arched roof above is more than 50 ft wide and 10 to 18 ft high.

The late Mammoth Crater flow within Craig Temple is not a single flow that filled the 25-ft-high Craig tube at one time. Instead it is composed of dozens of small flow units, most only 1–5 ft thick. They moved slowly and piled on top of one another as the flow advanced. The congealed flow fronts of some of the thicker flow units form a series of lobe-like steps, 3–5 ft high, that form the dais-like structure of the temple. Each successive bench near the upstream end of the cave becomes thinner and more discontinuous, and the stack of benches finally reaches the roof, blocking further upstream access. The lava seems to have been fed very slowly into the tube and to have lost its energy by the time it arrived at this section.

Fern Cave

The entrance to Fern Cave (map 17, pl. 5) is 1.5 mi southeast of Hospital Rock near the northeast corner of the monument. Ferns flourish within the circle of light from a small (8 by 10 ft) entrance hole in the cave's roof. J.D. Howard named the cave and mentioned the abundance of toads as well as ferns beneath the entrance in his notes. The hole in the roof provides the only access for humans; however, a locked grate has been installed across the entrance hole to protect the ferns and some well-preserved Indian pictographs from vandalism. Visits to the cave can be arranged at the Visitor Center. Below the grate, a steel staircase in the entrance hole leads to the top of a fern-covered mound of loose blocks and soil (fig. 58). The top of this mound is flat and only about 9–10 ft in diameter, but it spreads outward to both walls of the cave. Other than this mound of rubble, and another large pile from a roof collapse upstream, most of Fern Cave is relatively free of collapse blocks or other debris.

The cave can be traversed for 1,300 ft. At each end, further access is completely blocked by lava. At the downstream end the roof lowers until along the last 30–50 ft there is only a crawlspace between ceiling and floor. The upstream end, by contrast, is a near vertical semicircular wall about 12 ft high. Into this underground amphitheater, lava that now forms the cave floor boiled upward from some deeper source. This molten lava almost certainly rose through a connector from an overfilled lava tube below.

Fern lava tube is large; in places the passage is more than 60 ft wide, and most of the tube is 30–40 ft wide. Ceiling

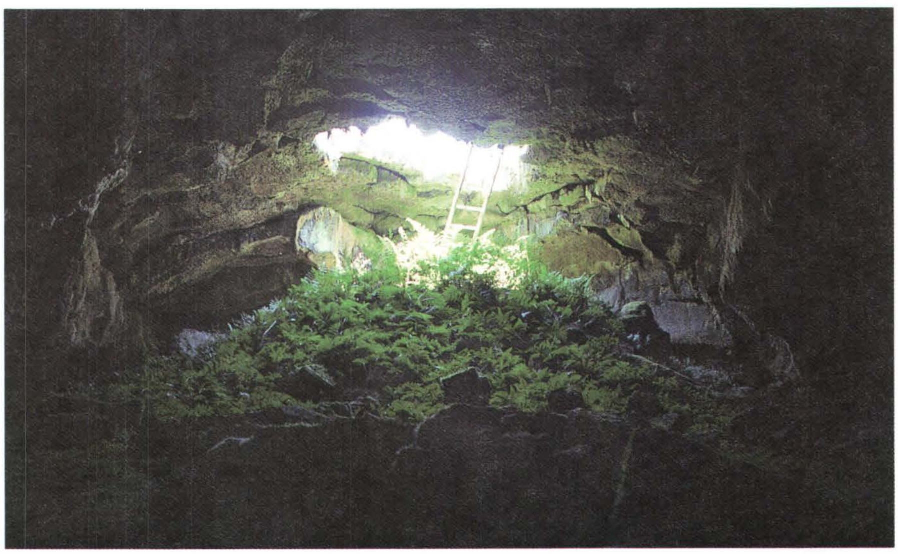


Figure 58. Fern-covered mound at entrance gives Fern Cave (see fig. 4 and map 17, pl. 5) its name. Entry is through 12-ft-diameter roof collapse.

heights are between 12 and 20 ft in the upstream part of the cave. Downstream from the entrance, the distance between floor and roof gradually decreases, but in most places one can stand upright until about 150 ft from the downstream end.

Fern Cave is large enough to be a downstream continuation of the Bear-paw-Skull lava tube system (fig. 4). It is likely that this major artery for the dispersal of molten lava turned east near the north end of the Schonchin Butte flow, then north near Juniper Butte, and connected with Fern Cave. However, we were unable to trace such a direct connection through the field of lava that lies south of Fern Cave.

The events of the last volcanism are recorded on the floor of Fern Cave as two recent lava flows; each can be traced the full length of the cave. The older flow is of smooth pahoehoe, which originally stood at a higher level long enough to start solidifying along its walls, but then drained down and pooled at a level 3–5 ft lower than its former stand. This process left benches 2–4 ft high with sagging edges in the downstream part of the tube where a firm crust had formed. The benches narrow and grade into a sloping apron, which connects a high-lava mark on the wall with the pahoehoe floor in the upstream third of the cave. A final flow of spiny pahoehoe occupies the central part of the cave's floor throughout its length, but it failed to overrun the aprons and downstream benches of the older flow along the walls. Thus, almost continuous gutters border the edges of this lobe in the upstream two-thirds of the cave. In most places the gutter is 2–3 ft deep; its inner wall is formed by the steep edge of the spiny pahoehoe lobe (fig. 59), and its outer wall is formed by the sloping apron or bench of the smoother older flow. The gutter is narrow in most of the upper tube but widens, and so large patches of the surface of the older flow can be seen in the downstream part of the tube. The spiny last lobe had lost most of its energy by the time it reached this downstream area; it was too viscous to spread clear to the benches, let alone cover and overwhelm them, except at the downstream end where it blocks the tube.

Downstream Through Fern Cave

In the amphitheater at the upstream end of Fern Cave is a low mound of lava that rose into the cave from an unknown source below (map 17, pl. 5). During the final stages of this upwelling, a few blocks fell from the roof and stuck in the pasty half-molten lava on the surface of this mound. Other, mostly larger collapse blocks within the same area tumbled onto the surface after the lava had congealed.

The relatively smooth mound of upwelled lava becomes spiny pahoehoe downstream. As previously mentioned, the final lava lobe does not cover the entire floor of the cave: its edges form the inside walls of the lava gutters that developed along each wall of the cave.

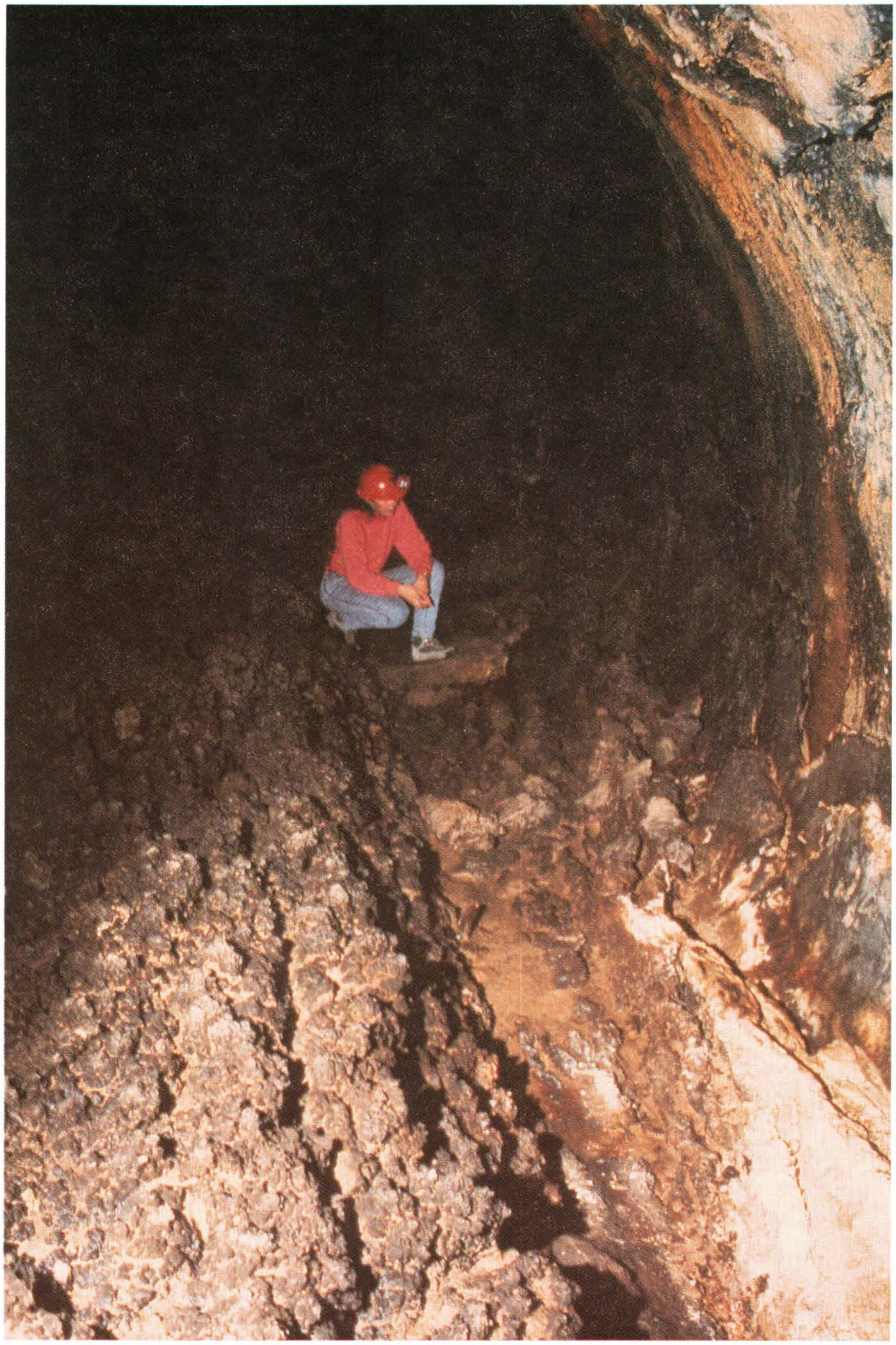


Figure 59. Lava gutter formed at edge of slow-moving lava flow that last occupied Fern Cave (see fig. 4 and map 17, pl. 5).

The edge of the older flow is seen as a sloping apron that forms the outer wall of the lava gutters. Patches of this apron also can be seen on the walls of the amphitheater at a level slightly higher than the top of the upwelled mound.

The tube makes a sharp right-angle bend to the left (northwest) 125 ft downstream. The gutters continue on, but the one on the northeast side is partly overridden by young spiny pahoehoe where this flow rounded the outside of the bend. At small alcoves along the wall, the more recent spiny pahoehoe cuts across the alcove to reveal wide areas of the older pahoehoe beneath.

Throughout this upstream several hundred feet of passage are patches of tan silt. The silt has slowly filtered down cracks in the cave's roof and formed four irregular layered deposits. Amorphous silica has cemented the upper surfaces of the silt as well as lining the small drip pits—called conulites—in these silt patches.

Lavacicles occur on the roof of Fern Cave except where roof collapse has removed them. A few faint high-lava marks are present on the walls; however, peeling edges of lava plaster are much more common than high-lava marks as records of recurrent fluctuation of lava level within the tube prior to development of the two final flows. The walls have a flowing drapery of generally unbroken dripstone plastered over most areas. Nearly 175 ft farther down the tube is an area of small lava stalagmites built up of lava droplets from the ceiling. Downstream 140 ft farther is a lone rafted block nearly buried at the edge of the down-peeled east balcony.

Approximately 525 ft downstream from the right-angle bend, a huge pile of large collapse blocks fell from the roof, and for 150 ft they restrict access through the tube. The easiest and safest bypass is along the east wall.

The upstream edge of the collapse breccia is a reference point for finding two interesting minor features. On the west wall, 20–30 ft upstream from the edge of the collapse pile, and just where the wall turns right (north) downstream, a patch of hollow dripstone tubelets emerges from a crack in the wall 5 ft above the floor. Near a point 100 ft upstream from the big collapse pile in the middle and eastern section of the tube are lava stalagmites built up 4–8 in. above the spiny pahoehoe floor. They are few in number but increase upstream over a distance of 100 ft.

Downstream from the big collapse pile the next feature to note is the mound of blocks, pumice, and soil beneath the hole in the roof. The abundant ferns, lichens, mosses, and other plants release water vapor and oxygen to the air. The feel and smell is somewhat like that in a greenhouse. Within the area where a circle of light from the entrance illuminates the cave are the most abundant records of early human habitation. The finest display of pictographs within the monument is on the walls of the cave (fig. 60) upstream from the entrance. Some are faint and possibly quite old; others appear very clear and fresh. Archaeologists have enhanced large areas with a white overlay. Grinding holes for preparing food pit the surface of several roof blocks strewn around the edge of the fern-covered mound.

Downstream, the most notable geologic feature is the absence of the sloping apron on the outside wall of the gutters and its replacement by a lava bench. Some wider parts of this lava bench record an earlier history. Here peelings of thin lava plaster contributed more to the volume of the bench than solidification at the high-lava line of the next-to-last flow that occupied the cave. Some areas of the early lava floor as much as 110 ft long and 20 ft wide were not covered by the late lobe of spiny pahoehoe.

The ceiling height lowers to 6 ft or less in the area within 250 ft from the downstream end of the tube, and it is much easier to examine the distribution of lavacicles in detail on this lowered ceiling. Near the west wall of the tube, 120–200 ft upstream from the tube's end (where the tube makes a slight bend to the left—northwest—as you look downstream), the lavacicles are oriented along parallel ribs in the ceiling. The lavacicles on these ribs are wide triangular blades resembling large shark teeth more than icicles. Near the center of the tube are thin, spindly lavacicles; some are curved at their tips as if buffeted by gusts of hot gases while they were forming.

The downstream end of the tube shows very clearly how the last two lava flows gradually filled in this large tube until the spiny lobe met the ceiling. Two small extensions remained open with a 6-in. clearance on either side of the central area where the lava first touched the roof, but each of these is closed tight in another 5–10 ft. It is unusual that lava did not pile up in a block jam behind this constriction. The lava did swell up, raising its central part, but we observed no marked fracturing of a congealed surface as would be created by lava pushing up from beneath.

Crystal Cave

Crystal Cave consists of collapse remnants of three major levels and of a few smaller lava tubes superposed upon one another (map 18, pl. 6). The cave extends beneath the floor of the large collapse trench that marks the course along which molten lava was delivered from Mammoth Crater through lava tubes that extend far beyond the Cave Loop Road area. The upstream termination of the mapped part of Crystal Cave is below a point 50 ft upstream from the lower end of the deep collapse trench that lies between Natural Bridge and Ovis Bridge. Ovis Bridge and Ovis Cave are uncollapsed sections of a large lava tube whose course lies almost directly above the lava tubes that compose Crystal Cave. To prevent a clutter of heavy lines on the map of Crystal Cave, only a small part of the overlying collapse trench near the cave entrance is shown, but details of the geometry of Crystal Cave in relation to the collapse trench, Ovis Cave, and Ovis Bridge can be seen by visually superimposing the Crystal Cave map (map 18, pl. 6) upon the Ovis Cave and Paradise Alleys map (map 4, pl. 2).

The only entrance to Crystal Cave is covered by a locked grating. Once across the ice slope at the foot of the entrance ladder, it is fairly easy to visit three levels, which have a combined length of 2,890 ft (see map 18, pl. 6). From the

Blue Glacier Room, where continuation of the lower level is closed upstream by ice and a roof collapse, one can traverse an ascending ledge to a higher passageway (the Overpass level), which gives access to 200 ft of a lava tube directly above the upstream continuation of the lower level. From the Overpass two additional parts of the cave can be reached. One is Fantasy Passage, a segment of a lava tube lying 35 ft above the Overpass level; the other is Crystal Grotto, a segment of the lower level that extends upstream from the foot of a steep ice cascade descending from the upstream end of the Overpass.

Crystal Cave surpasses all other caves in the monument in the beauty and variety of its ice deposits. J.D. Howard named the cave from large (as much as 2 in. in diameter) ice crystals that occur in the hoarfrost, which forms a rime over parts of the cave's walls and roof. Beautiful draperies of large clear icicles hang where springs enter the levels from high ledges and water drips from cracks in the roof. Pools of clear ice accumulate in hollows on the floor. Some sections of cave floor are carpeted with a litter of tumbled frost crystals and broken icicles. Such litter is also welded onto rock blocks and crystal-clear ice stalagmites.

Upper Level

A combination of ice and collapse debris blocks the upper level downstream from the foot of the entrance ladder; but upstream the cave opens into a large chamber called Entry Hall, which is 18–25 ft high, 25–35 ft wide, and 100 ft long. In the southwest part of this chamber the ice floor gives way to a hummocky deposit of thick collapse rubble. Upstream 80 ft from the ladder the left (southeast) wall of the cavern contains a semicircular alcove 30 ft across. Here the rubble on the floor of the cavern slopes steeply into a small breakdown beneath the south wall of the alcove. This opening provides the only entrance into the middle and lower levels of Crystal Cave.

Beyond this alcove the upper level narrows abruptly to 8 ft, but it maintains ceiling heights of 18–25 ft that characterize the entrance cavern downstream. Shelf-like projections a little more than halfway up the walls are the broken edges of parts of the floor, clear evidence that this narrow but high level once consisted of two superposed tubes that have merged into a single passageway by

Figure 60. Indian pictographs on wall of Fern Cave (see fig. 4) near entrance are among the best-preserved in Lava Beds National Monument.

collapse of the upper tube. Molten lava must have filled the tube after collapse because in places vertical lava plaster coats the surface of the broken shelves and remnants of the floor of these upper tubes. Above a few such floors are openings 2–3 ft high, sufficiently large to enter and explore, but because of their low ceilings and inaccessibility, these small flat openings were not mapped.

This composite tube extends upstream for 110 ft and then abruptly doubles in width. Remnants of the upper tube are still present in this section but are less abundant than in the narrow part of the upper level. The wider section is blocked 90 ft farther upstream by collapse rubble encased in ice. A fine display of icicles 5–15 ft long forms a drapery along the south wall adjacent to the collapse. A narrow ice cascade decorated with ice columns occupies a bottomless roof tube down the center of the ceiling at a point 80 ft downstream.

Middle and Lower Levels

The middle and lower levels are described as a composite unit because one is superposed exactly above the other and the two have merged completely, due to collapse, for over 250 ft downstream from the Red Ice Room. Moreover, the two levels are connected by five additional collapse openings farther downstream. On the composite map view (map 18, pl. 6), the lower level is offset to avoid the lines of the other levels. The middle level is shown with a dashed line on this composite view. Match lines (see map views of each level on map 18, pl. 6) denote the five breakdowns connecting the two levels. One of these match lines marks the connection and provides the only easily traversable route between the middle and lower levels. The other four openings can be negotiated only with ladders or ropes.

It might appear that the middle and lower levels were originally one lava tube, which later became segmented into two tubes by balcony building. This hypothesis would imply half-filling of the original tube with molten lava, which ponded long enough at the height of the middle level's present floor to allow solidification of a thick crust over the top of the lava pool. Then, perhaps by collapse of an obstruction downstream, the still molten lava beneath the crust would have drained away and left the crust as a septum dividing a former large tube into upper and lower parts. Where the crust was thin, parts of it might have tumbled into and been carried away by the lava as it withdrew. Only the margins were left hanging as balconies along the wall.

This hypothesis does not stand up, however, even though there is much evidence of local balcony building at various times during the formation of the middle and lower levels. The detailed history of lava occupancy and other events, which shaped these two levels, is far too complex to unravel completely from the limited exposures provided by Crystal Cave—only a small sample of a lava-tube system many miles long. The collapse trench and other associated features show that the tube system extended far upstream and downstream from the places where its continuations are blocked by collapse debris or by ice in Crystal Cave. Nevertheless, even a leisurely 2-hour traverse through the middle and upper levels of Crystal Cave discloses a long and complicated history of recurrent filling and draining of molten lava, not a single episode of lava ponding, balcony building, and drainage. Significant parts of this record are summarized below.

1. If we could remove the septum between the middle and lower levels—which is exactly what happened in the upstream 250 ft of the lower level—we would see that the cave's cross section does not have the oval shape indicative of hydraulic equilibrium from a single lava tube encased in a basalt flow. Instead, this cave is elongated vertically; ceiling heights are 35–45 ft and widths are less than 20 ft except where enlarged by collapse of the walls. This shape implies the merging by collapse of at least two superposed tubes.
2. In the upstream 250 ft of the lower level, more than one basalt flow can be seen in collapsed parts of the walls. The downstream half of the lower and middle levels cuts into red tuffs and breccias, which underlie the basalt flows constituting the wall rock of the upstream part of the cave. Good contact relations between a basalt flow and the red breccia immediately beneath it can be seen in the middle level just below the wall of the access breakdown between the upper and middle levels, and on the north wall of the middle level 120 ft farther upstream. In the downstream part of the lower level, red breccia and tuff is present nearly everywhere slides or cracks in the wall lining of the tube expose the wall rock. Continuation of the lower level downstream is blocked at the Red Ice Room by red breccia rock slides cemented with ice. Other cracks and slides in the coatings of lava plaster and dripstone that line the lower level show that this part of the lava tube is completely surrounded by red breccia. For 120 ft upstream, most slides and cracks in the walls also reveal red pyroclastic material as the dominant type of wall rock. (For hypothesis on the origin of the red color in these breccias and the probable mechanics of emplacement of lava tubes within red pyroclastics, see "Red Tuff and Volcanic Breccia" section and map 12, pl. 4.)
3. The septum between the middle and the lower levels is more variable in thickness than would be expected from simple balcony building. This is best seen by comparing the thickness in the walls of the six breakdown holes through this septum. Also, note the measured thicknesses shown in the longitudinal section and compare with ceiling heights shown on map 18 (pl. 6); as shown on the longitudinal section, remnants of a shallow-ceilinged tube are exposed within those breakdowns where the septum is thickest.
4. The walls of the breakdowns also record episodes of lava refilling after the collapse occurred. In several places remnants of lava plaster or dripstone coat the walls of a breakdown. The first three breakdowns

upstream from the one noted by the match line (map 18, pl. 6) show large patches of such plaster within their openings, and through them lava overflowed from the lower level and spread as lobes over the Middle Earth Passage floor (position and direction of flow shown on map). Many more lobes undoubtedly spread from several breakdowns on this level but are buried beneath the thick mantle of collapse rubble covering the floor of the middle level.

5. Many streams of lava that coursed through the lower level during late stages of volcanism were not voluminous enough to inundate the middle level. Numerous narrow benches and stretched or sheared curbs of formerly hot and sticky lava indicate the position of high-lava marks. A particularly informative place to examine how these congealing features were sheared by the moving lava is a 200-ft stretch of the southwest wall in the middle of the lower level (fig. 25 and map 18, pl. 6).
6. One of the final streams of lava, only about 6 ft deep, built a balcony completely across the floor of the lower level for a distance of 100 ft. When the thin crust forming this balcony was less than 2 ft thick, the still-molten lava below it drained and left a shallow flat-topped tube-in-tube only 2–5 ft high. Collapsed areas in its roof give access to this tube-in-tube (see longitudinal section on map 18, pl. 6). Downstream from the lowest breakdown this crust was too thin to survive collapse, and farther downstream continuations of this crust are preserved only in discontinuous remnants of a 3-ft bench along the walls.

Overpass Level

At a point 40 ft downstream from the Blue Glacier, a narrow ramp-like ledge starts at the floor on the west wall of the lower level and climbs at an angle of 20°–30° up the wall until it enters a hole in the roof. Here the ledge widens and is obviously the congealed surface of a lava cataract, which continues upstream another 35 ft, where it opens into a high-ceilinged room in an overlying level. The ramp along the wall is the collapsed lower end of this cataract. The level at the head of the cataract can be traversed for another 200 ft upstream before it is blocked. Near its upstream end, a hole 10 ft long and 2–3 ft wide extends across part of the floor of the level. This hole drops onto a very steep ice cascade, which descends precipitously into a room called "Crystal Grotto" that is evidently an upstream segment of the lower level. Because this level lies above a collapsed part of the lower level, to which it is connected by a lava-cataract ramp on one end and an ice cascade on the other, we named it the "Overpass."

A large roof collapse near the downstream end of the Overpass reveals segments of still another lava tube, the Fantasy Passage, 35 ft above the floor of the Overpass (see longitudinal section on map 18, pl. 6).

Original details of the walls, floor, and roof of the Overpass have been largely obliterated by collapse or obscured by rimes of hoarfrost. The floor of the middle section of this level is considerably lower than either end because it tumbled into and filled the lower level below. An ice pool formed in this low spot, and undoubtedly the ice here is interconnected with the ice that fills the spaces of the collapse breccia in Crystal Grotto upstream from the Blue Glacier Room. Upstream from the ice pool, much of the Overpass level's collapse debris is also cemented by ice. Drip water collected and flowed along the floor adjacent to the east wall, producing an "ice brook" that steepens into an ice cascade as it approaches the pool.

Ice Deposits

There are two basic requirements for permanent ice to develop in caves within a temperate climatic zone: (1) Rainwater or snowmelt must penetrate down to the cave through cracks or other openings, and (2) the air in the cave must remain relatively stagnant throughout the year. Strong underground circulation of air through caves—particularly those that have a surface opening in the low area of a basin or valley and a second on a high ridgecrest—prevents the ice that may form in winter from surviving the following summer.

Crystal Cave is not only an excellent example of conditions that are almost ideal for the growth and stabilization of ice in caves, but it also demonstrates the use of the convection principle in discovering previously unknown caves. Aside from small pores and cracks through its roof rock, Crystal Cave has only one surface opening: the entrance collapse, located at the highest point of this cave's underground passageways. In the winter months the cold dense air above ground descends through this hole and displaces the lighter and warmer air within the cave up to the surface. On a cold, sunny, and windless day in winter, especially when the temperature has dropped substantially overnight to below freezing, the cave passages appear to be "breathing." As the cold surface air descends into the cave, the lighter, warmer, and more moist air is pushed upward onto the surface. Chilled in the freezing temperature above ground, the small amount of water vapor dissolved in the cave air immediately condenses into tiny water droplets, just as your breath does in cold air each time you exhale. Thus a persistent plume of fog rising from a patch of loose boulders indicates that a minor excavation of the boulder pile might reveal an opening into a cave.

In caves like Crystal the cold air that seeps down to fill all the passageways in winter does not warm in summer. Because the summer air outside the cave is less dense than the heavy cold air inside, it cannot descend to displace the cold air. By late summer, however, the temperature of the air in such a cave may rise as high as the average annual temperature of the region. As soon as it warms above 32 °F, melting of the ice begins. However, because it requires 80 calories to melt one gram of ice and a further 539 calories to convert a gram of ice water to water vapor, the temperature of the almost stagnant air immediately adjacent to the ice mass soon stabilizes at or near the freezing point of water (32 °F). Ice will either melt or build up by filling the openings until a fairly stable equilibrium is reached in which the amount of ice melted and vaporized in summer fluctuates little from the amount of ice accumulated during the winter months. It is a sensitive equilibrium: the heat supplied and the agitation of the air caused by a large number of visitors passing through a cave in summer increase melting; visitors in winter add to the ice by precipitation of moisture from their breath. This is the reason that access to Crystal Cave is restricted to small groups of visitors on a limited schedule.

Ice in Crystal Cave occurs in four main forms:

(1) *Icicles and Ice Stalagmites.* Crystal-clear icicles form where water drips from cracks in the roof or dribbles over ledges, and ice stalagmites grow up from the floor where falling water droplets freeze on impact.

A spectacular drapery of coalesced icicles festoons the southeast wall of the lower level from 145 ft to 200 ft downstream from the Blue Glacier Room near the Dolphin, a 4-ft-high ice stalagmite (see map 18, pl. 6). Individual icicles in this drapery are up to 20 ft long (fig. 61) whereas others are coalescing and overlapping shafts 3–15 ft long. All are so transparent that details of the wall rock behind them are clearly visible through the 0.5- to 3-ft-thick covering. Ice stalagmites have grown up from the floor to meet the icicles in parts of this drapery but are not conspicuous. On the other hand, large stalagmites as much as 4 ft high and several feet in diameter are scattered along the floor of the cave in front of the icicle drapery and for another 50 ft downstream. No correlation appears to exist between the size of a stalagmite on the floor and the size of an icicle directly above it; some large icicles have grown completely from roof to floor without a companion stalagmite rising to meet them (fig. 62). Variations in the ratio of water supply to rate of freezing appear to cause these differences in size of icicles versus ice stalagmites. A similar, smaller drapery of icicles occurs at the upstream end of the upper level and throughout Fantasy Passage.

One of the most beautiful displays of icicles and other ice forms is found in the

Figure 61. Ice drapery on wall of Crystal Cave (see fig. 14 and map 18, pl. 6).

Figure 62. Ice stalactites from roof joined floor to form this ice fall in Crystal Cave (see fig. 14 and map 18, pl. 6).

Red Ice Room (fig. 63), which lies at the extreme downstream end of the accessible part of the lower level. The 35 ft long and 20 ft wide Red Ice Room is seldom visited because it requires a crawl in ice water beneath a 1-ft-high roof. This crawlway is at the downstream base of the large collapse pile, which descends to the lower level. As previously noted, red tuffs and breccias line the tube in this passage. It is these walls of red pyroclastics enhanced by draperies of icicles and a varnish of clear ice that give color to this room—not red ice, but clear icicles and ice dripstone covering a pink to red background. In addition to "pink" icicles, this room contains a floor of "pink" ice. Slides of coarse red rubble that block the tube downstream are cemented by and coated with transparent ice as well.

(2) *Ice Pools and Ice Mounds*. Meltwater pools that have frozen into ice are rare in Crystal Cave, but large parts of the cave floor are covered by ice mounds and hummocky ice slopes. These are built by drops of water and melted bits of icicles and frost that fall from the roof and walls. The ice slope below the entrance of Crystal Cave is a large mound that accumulated from rain and snow blown in through the entrance. The semicircular ice mound along the west wall another 20 ft downstream is an overgrown stalagmite formed by drip from the roof. At the south end of the lower level is the Blue Glacier Room, so named because the large ice mound on its floor is a murky powder blue. It is not known whether admixed dust, algal growth, or a finely cracked texture of the ice is responsible for the scattering of light that causes this color—it may be a combination of all three.

(3) *Ice-cemented Breccia*. Collapse breccia at the upstream and downstream ends of the upper level are encased in ice, but because of the rock color here, the results are less spectacular than the ice-encased breccias in the Red Ice Room. As noted before, almost the entire floor of the Overpass is a hummocky pile of collapse blocks encased in ice, as are the breccias adjacent to the Blue Glacier, which block upstream continuation of the lower level.

(4) *Frost*. Rivaling the draperies of icicles in beauty are the rimes of pure white hoarfrost that cover large parts of Crystal Cave's walls and roof (fig. 64). Hoarfrost is extensive near the larger masses of permanent ice, especially in Fantasy Passage, and can also be found spreading outward from the large drapery of icicles on the lower level. It grows most abundantly on the one lava flow in the wall that is more porous than the others. Unlike the transparency of an icicle display, hoarfrost forms pure white rimes that appear to be opaque when viewed at a distance. Closer inspection shows that they are composed of intricately interlocking frost crystals, some in well-developed hexagonal plates or in cleavage rhombs two inches or more across. Others are lacy and interlocking crystals of varying sizes. In fact, each crystal is transparent or translucent, but the lacy intertwining forms and abundant cleavage cracks give frost rimes a whitish luster (fig. 65) quite different from the limpid transparency of ice stalagmites and icicles.

Some of the frost crystals show evidence of repeated, probably seasonal, growth. Zonally arranged inclusions of fine dust were deposited upon an irregularly etched crystal, then covered by an overgrowth of clear ice, which is in optical continuity with the core crystal. Several such zonal bands can be counted within some of the larger hoarfrost crystals. Very likely they record seasonal

Figure 63. Icicles, ice glaze, and ice crystals decorate wall of Red Ice Room in Crystal Cave (see fig. 14 and map 18, pl. 6).

Figure 64. Hexagonal ice crystals as much as 1 in. across present in winter on walls of Fantasy Passage, Crystal Cave (see fig. 14 and map 18, pl. 6).

changes: etching and pitting of the crystals during the late spring and summer thaw; dust and some organic debris deposited in the late summer and autumn; and another clear ice rim added during the late winter and early spring.

Hoarfrost in the Red Ice Room varies in appearance from pale pink to white, depending on the thickness of the rime. In places, however, so much red dust has been entrained within the crystals that they retain their pink color even if removed from the wall.

Heppe Caves and the Mammoth Crater-Hidden Valley Area

A semipermanent supply of ice-cold water forms a pool, 40 ft wide and (depending on the season) as much as 12 ft deep, on the floor of a cave 0.5 mi north of Mammoth Crater (map 19, pl. 6). Attracted by this supply of good water, Bertha and Earnest Heppe filed a homestead claim on the land containing the cave, despite the inhospitable nature of the surrounding area for agriculture. This cave and a second cave a short distance from it became known as the Heppe Caves. Also, a small agglutinate cone west of the upper cave was named "Heppe Chimney." Several years later, J.D. Howard named a lava-tube cave lying about 1.5 mi east-southeast of the Heppe homestead Berthas Cupboard Cave in honor of Bertha Heppe.

The Heppe homestead was abandoned long ago, but the old wagon road that led to the site of their house is still visible and is used as a trail. It merges into the main Medicine Lake-Lava Beds road at a sharp bend 0.3 mi from the Heppe Caves. At the west end of the wagon road a trail descends the south rim of a steep-sided collapse. From the bottom of this collapse pit a rock-walled trail constructed by the Heppes leads deeper underground by zigzagging down a talus slope to the surface of the water pool. Access to Lower Heppe Cave is easily gained by walking north out of Upper Heppe Cave into a second very deep collapse pit (labeled "Central Collapse" on map 19, pl. 6) surrounded by spectacular cliffed walls. From Upper Heppe Cave, cross over the bottom of this deep pit past Heppe Grotto, and proceed into the cavernous opening of Lower Heppe Cave (fig. 66).

At the request of Paul Haertel, former superintendent of Lava Beds National Monument, we mapped the Heppe Caves at a scale of 40 ft to the inch. A reduced-scale version of this plan is used an inset on map 19 (pl. 6), but the main purpose of the map is to depict the source areas of four major lava dispersal systems whose lava came from Mammoth Crater or from the dike-filled fissures that intersected Mammoth Crater during the periods of volcanism. The Bearpaw-Skull lava-tube system also had its source in a lava lake fed from Mammoth Crater and its dikes. Donnelly-Nolan and Champion (1987) preferred the interpre-

Figure 65. Ice stalactites in the Red Ice Room in Crystal Cave (see fig. 14 and map 18, pl. 6) composed of 1-in.-diameter hexagonal ice crystals stacked one atop another.

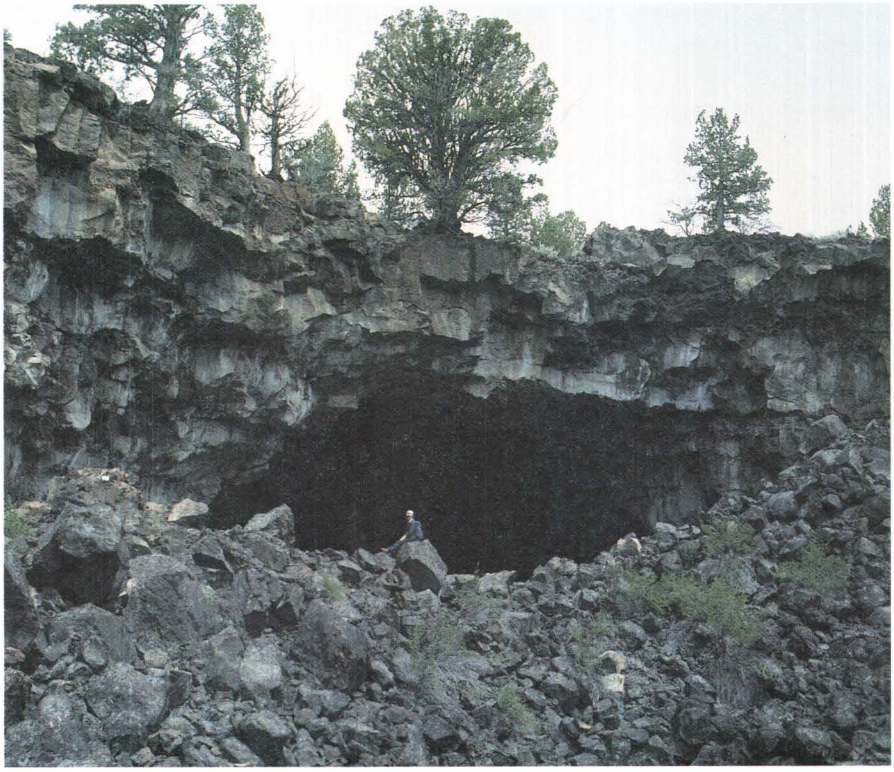


Figure 66. Entrance to Lower Heppe Cave (see map 19, pl. 6).

tation that this tube system was fed from Modoc Crater, another vent for the basalt of Mammoth Crater.

Some other features shown on map 19, plate 6, are Eagle Nest Butte, which is a deeply eroded cinder cone older than the Mammoth Crater lava, and a small part of the Callahan flow of blocky lava. This young flow is almost free of vegetation and it was erupted from the base of Cinder Butte, a cinder cone in an isolated area near the southwest corner of the monument (see fig. 4).

Geology of the Heppe Caves

The Heppe Caves are remnants of a large lava tube, originally 25–30 ft wide and 15–25 ft high. Nearly all primary features have been lost by slow collapse of the roof and walls. Behind the places where blocks of dripstone lining have fallen, one can see edges of the flow units. These units are separated by sporadic accumulations of bombs and ash; most units are less than 3 ft thick, and many have ropy pahoehoe tops. These flow units dip to the north, away from Mammoth Crater. Less well defined flow units with only sparse accumulation of pyroclastic material between them are present higher on the walls, especially in the scenic cliffs that ring the top of the collapse pit separating the two Heppe Caves.

In the Upper Heppe Cave floor, a permanent mass of ice probably fills the interstices between the collapse blocks. When we mapped the cave in late May of 1976, the topmost edges of this ice mass could be seen in spaces between the fallen blocks around the edges of the water pool and also all along the floor of the alcove that extends into the east side of the cave (map 19, pl. 6). The lobes of ice between the blocks had sharp crests, similar to seracs on the surface of a glacier. In September 1977, no ice was visible and the pool was dry, whereas during 1985 to 1988 the ice block and pool were present.

Lower Heppe Cave is so defaced by collapse blocks that no original features remain in place. Nevertheless, it is evident that a collapse of an upper tube into a lower tube dropped both ceiling and floor 20 ft. Thus, the upper tube did not continue downstream but must have ended in a semicircular wall, as did the upper tube in Skull Cave (map 12, pl. 4). An oval collapse pit (labeled "East Collapse" on map 19, pl. 6), with a hydraulic rampart of loose blocks piled on its northern lip, ends Lower Heppe Cave. On the east side of this collapse pit, a remnant of the lava tube plunges beneath a narrow natural bridge, Heppe Bridge. Beyond this bridge the line of collapsed trenches continues around the south and east sides of Red Butte, but they are small with only a few caves open to the surface until the Natural Bridge area at the southwest end of Cave Loop Road (map 5, pl. 2). It is apparent, however, that large tubes were required to transmit the lava to the caves along Cave Loop Road and then eastward through Post Office Cave (map 15, pl. 5). Sections of these large tubes are filled with lava or ice where they have not been destroyed by collapse.

Heppe Chimney

Heppe Chimney is an agglutinate or spatter cone. Such cones are built of pasty bombs that spattered out of a vent and welded into a coherent conical mass enclosing the orifice. In addition a sticky spillover of lava emerged at the northeast base of this cone and spread to the northeast for 20 ft before it solidified.

The connection (if any) of the Heppe Chimney with the adjacent Heppe tube is obscured by talus. It seems likely, however, that the Heppe Chimney is a rootless volcano—that is, it was built through a skylight on the roof of an active lava tube, not as part of a dike arising from a deep magmatic source. However, dikes trending north-south appear in both the north and the south walls of Mammoth Crater, and it is possible that the Heppe Chimney may lie above a northern extension of one of these dikes.

Mammoth Crater

Mammoth Crater (fig. 4 and map 19, pl. 6) is a funnel-shaped pit slightly more than 0.25 mi in diameter and 340 ft deep. Eighty percent of its steeply sloping walls are mantled with talus. A cliff of thin flow units forms the southwest wall just below the crest, and these flows also continue eastward to form a broad sloping shelf, which lies well beneath the crest along the southeast wall of the crater. In a notch on the south wall several small vertical basalt dikes cut through the cliff of lava flows. On the south slope of the Mammoth shield is a large spatter rampart 660 ft long and 50–100 ft high, which obviously marks the southward continuation of the dikes. The rampart contains two elongate spatter cones with deep clefts on their ends, above the position of the underlying dikes.

On the opposite (north) slope of the Mammoth shield are two large, shallow talus-covered depressions that resemble the pit craters of Hawaii. Such craters are generally attributed to subsidence of crater walls into underlying dikes of molten magma. These depressions, however, may be only wide collapse trenches over shallow lava tubes that surmount the line of dikes. In any case it is apparent that large lava tubes transmitted great quantities of lava northward beneath the two craters, and then into three systems of lava tubes. As they leave Mammoth Crater the feeder tubes surmount, or possibly lie partly within, the northward extension of the plexus of dikes on the north wall of Mammoth Crater.

Two examples of filled lava tubes surmounting basalt dikes can actually be seen, despite partial masking by loose talus blocks, on the north wall of Mammoth Crater (map 19, pl. 6). That the higher and westernmost tube of this overlapping pair shows many thick concentric shells of lava indicates it was filled and drained numerous times. The massive, coarser grained texture of lower and older tube filling indicates that lava ponded within it for a long time prior to solidification. Both are oriented north-south and extended beneath the nearby pit craters on the north slope of the Mammoth shield. Note on the map that a lava gutter nicks the margin of Mammoth Crater above the deeper and older lava tube. A later blanket of tuff and lava prevents tracing the gutter beyond the crater rim.

Another filled lava tube is poorly exposed in the talus slope that forms the east wall of Mammoth Crater just north of the bench of basalt lava flows. This filled tube plunges east and transmitted lava eastward from Mammoth Crater into the Hidden Valley area.

Hidden Valley

The head of Hidden Valley (map 19, pl. 6) is a cliffed amphitheater with walls 60–100 ft high that lies "hidden" by a forest of conifers on the southwest and a dense thicket of mountain mahogany on the north and northeast. It is always a surprise to emerge suddenly at the top of a high cliff after beating your way through the dense vegetation that borders this amphitheater on the north side. A short trail, however, leads to the top of the westernmost cliff and a longer unpaved trail skirts the south edge and descends to the floor of the valley.

The origin of Hidden Valley is enigmatic; it may have been a lava channel that enlarged laterally and headward as the eruption proceeded. Downstream from Hidden Valley, the basalt that must have flowed through this channel was buried by the younger basalt of Valentine Cave. The size of Hidden Valley suggests that a major tube system from Mammoth Crater once occupied or emerged from this valley and fed lava flows that extend east of the monument nearly to California Highway 139.

Former Lava Lake North of Mammoth Crater

When volcanism began at Mammoth Crater, the topography was probably more diverse than it is today. Clusters of steep-sided conical buttes, northward-sloping lava flows, and north-trending fault blocks dominated the landscape. Mammoth Crater is located 8 mi northeast of Medicine Lake, which lies in the caldera of the Medicine Lake shield volcano (Anderson, 1941). The flanks of this huge shield are embellished by more than 200 satellite volcanoes, including many steep-sided cinder and agglutinate cones such as Schonchin Butte (fig. 67), rounded lava domes, and stubby flows of obsidian. Some andesitic volcanoes were built over the fault zones that define the caldera rim. Numerous studies of various aspects of Medicine Lake volcano include Mertzman (1977), Grove and others (1982), and Donnelly-Nolan (1988). A geologic field trip guide to Medicine Lake volcano and Lava Beds National Monument is also available (Donnelly-Nolan, 1987).

The Mammoth basaltic shield differs greatly in form from the many nearby steep-sided cinder and spatter cones because its lava flowed downslope in smooth lava flows and in tubes. Only rarely did the Mammoth vent expel large quantities of ash and bombs. Had the Mammoth shield been built on flat ground, its flows would slope away on all sides from the central crater. Because Mammoth Crater formed on the already sloping flank of a much larger shield, however, most of its lava traveled downslope to the north and east. The lava was diverted at many points by older cinder and spatter cones and lava flows such as Schonchin Butte and the Schonchin Butte flow. Locally the lava ponded in swales between obstructions such as the cones and north-trending fault blocks.

Downslope from Mammoth Crater a cluster of six cinder and spatter cones in various stages of erosional truncation combined to dam a large lava lake (fig. 68). The lake, fed from Mammoth Crater, lay ponded during the active stages of volcanism but evidently fluctuated erratically in level as different surface outlets along its periphery formed and closed as the lava congealed. Short-lived overspills occurred along the periphery of the lake while occasionally a more permanent outlet would open underground as the increasing hydraulic pressure of the ponded lava overcame a blockage in a lava tube. In the last stages of this lake's existence, and after a crust at least 5 to 10 ft thick had congealed over its surface, the molten interior of the lake drained toward an opening approximately 50 ft below the lake's former level. This opening occurred at a point 0.3 mi downstream (east) of the Heppe Caves, where the feature labeled "backflow outlet" joins the line of breakdowns (fig. 68). As the level of the lake dropped, its solid surface crust broke into blocks, which moved toward the newly opened drain and produced a tangle of fissures and schollendomes. Heavily fis

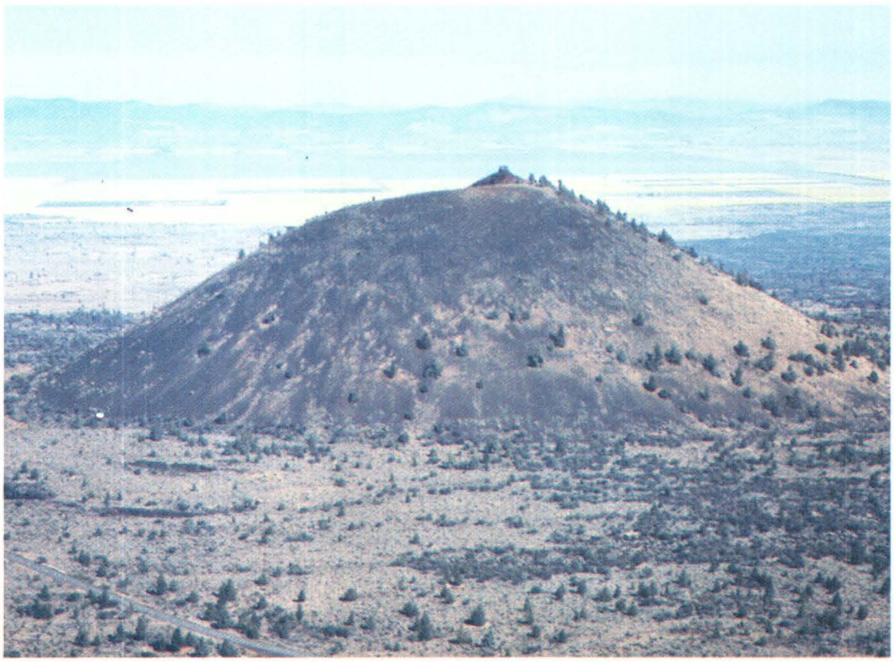


Figure 67. View of Schonchin Butte from top of Hippo Butte. Schonchin Butte is the principal landmark within the Lava Beds National Monument. A trail to a fire lookout at the top provides excellent views.

sured ground now occupies nearly two-thirds of the former lake's surface. It is very difficult to traverse this ground because of its uneven surface and the thicket of mountain mahogany, which grows in profusion wherever deep fissures provide opportunity for roots to reach water. The strong limbs of this vigorous tree-like shrub make an almost impenetrable tangle.

Prior to the opening of the drain around Red Butte, another larger drain at a higher elevation may have stabilized the molten lake level for a long period of time. This outlet was connected to the now-collapsed upstream continuation of Bearpaw Cave (see map 10, pl. 4), and may even have changed its position and depth within the tangled expanse of north-sloping lava lobes between Hippo and Bearpaw Buttes before the outlet became entrenched in the loose ash and cinders along the east side of Bearpaw Butte (fig. 4).

Before the lava lake filled to its highest level, much lava from Mammoth Crater had escaped to the northwest through the gap between Bearpaw and Eagle Nest Buttes. These flows rounded the west base of Bearpaw Butte and followed the swale east of Gillem fault (fig. 4) to the shoreline of former Tule Lake. A major lava-tube system developed within these flows, most of it older than the Bearpaw-Skull system whose flows overlap it. As shown on map 19, plate 6, the shallow basins with slumped edges and the surface gutters labeled "Heppe-Modoc system" lie on the top of a ridge that topped the near-source part of this major lava-tube system late in its development. Direct connection downstream, however, is lost in a steeply sloping field of schollendomes and tangled lava lobes and gutters, which lies west of Modoc Crater and northwest of Bearpaw Butte. That the west shoreline of the lava lake once abutted Heppe-Modoc ridge indicates that the ridge predated the highest level of the lava lake.

The Bearpaw-Skull line of breakdowns is in vertically stacked tubes that began in a lava lake fed by eruptions rising in or near Mammoth Crater. The lava that flowed into Tule Lake at Canby Bay was also delivered via lava tubes originating in Mammoth Crater. Earlier observers (and more recently, Donnelly-Nolan and Champion, 1987) thought the Bearpaw-Skull line of lava tubes was fed from Modoc Crater. However, Modoc Crater is apparently surrounded by a sea

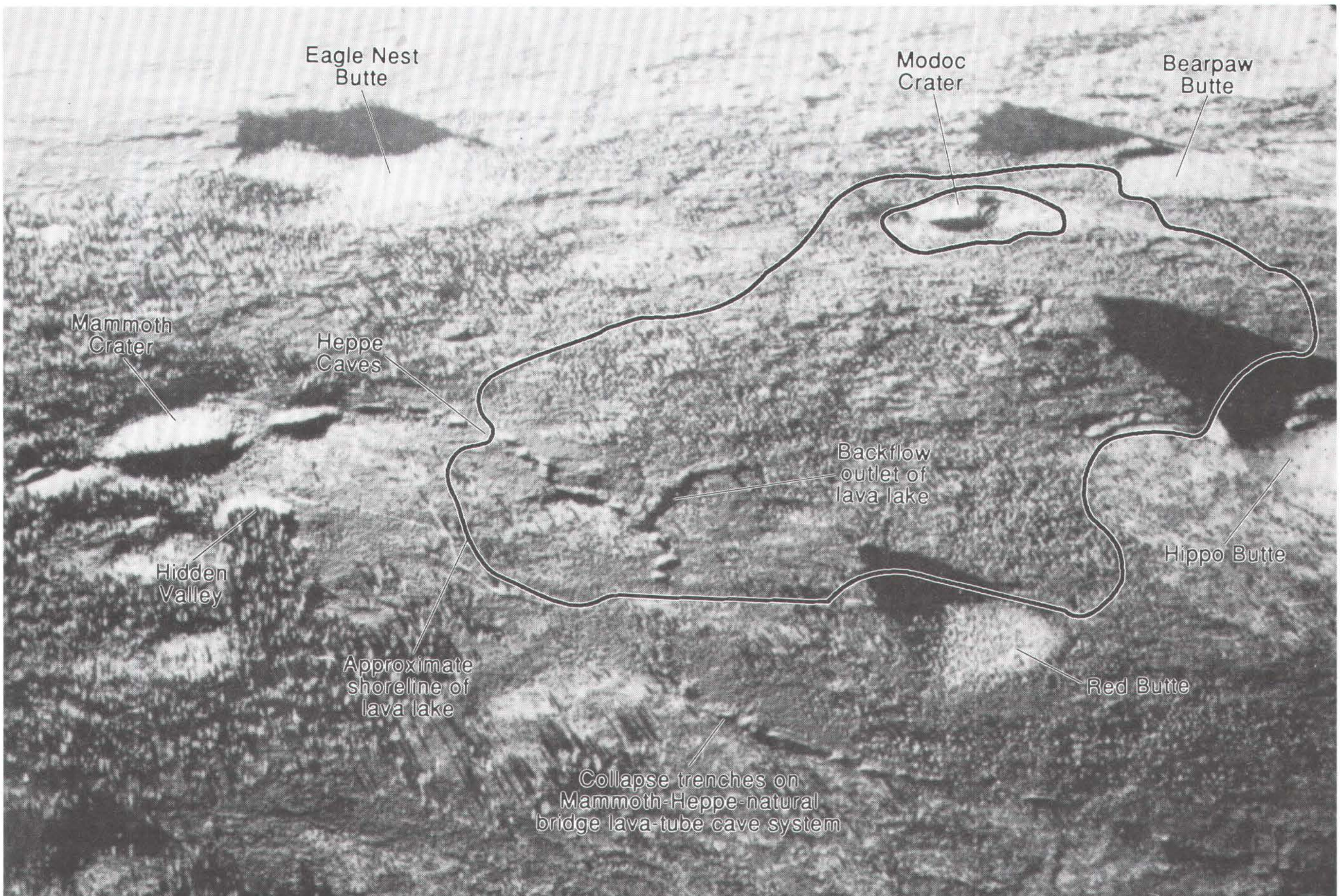


Figure 68. Oblique aerial view (westward) of former lava lake (outlined), now a maze of rugged collapsed lava. Distance from Bearpaw Butte to Red Butte is about 2 mi. Drain for lake is at Y-shaped intersection of breakdowns west of Red Butte. See fig. 4 for location of these features in Lava Beds National Monument.

of Mammoth lava that flowed around it, united on its north side, and impinged against the southeast part of Bearpaw Butte. The collapse trench upstream from Bearpaw Cave began within this Mammoth lava. No feeder tube from Bearpaw Butte intersects this tube or its breakdowns; instead, the tube cut into and displaced the loose ash forming the east slope of Bearpaw Butte.

A small cone on the north flank of Bearpaw Butte did erupt after Bearpaw and Merrill Ice Caves were formed. From this vent a small lava tube, built entirely upon the surface, coursed down the north slope of the satellite cone and stopped at the edge of a large collapse pit in Mammoth lava that flowed around the base of Bearpaw Butte.

Shoreline of the Lava Lake

To support the interpretation that both the Bearpaw-Skull and Cave Loop Road lava-tube systems originated from a former lava lake fed from Mammoth Crater additional details are needed to document the position of the shoreline of this lake during its most recent stand. Evidence of the shoreline can be observed on the sides of all of the buttes that helped to contain the lake on its north and east sides (fig. 68). Red Butte is closest to the outlet that drained the lake. Remnants of the black Mammoth lava, joined to the reddish pyroclastics of Red Butte, are well exposed where the paved road rounds the northwest side of the butte. Here the elevation of the lava shoreline is 5,160±10 ft.

The next butte to the north is Hippo. On its southwest flank, parts of a bench of basalt marking the highest shoreline adhere to the side of the butte at 5,180 ft elevation.

Sighting with a hand level from this point to Modoc Crater and to Bearpaw Butte, roughly a mile to the west, one can pick out reference points at the same elevation. These points, and others identified on the ground as the highstand of Mammoth lava against both Modoc Crater and the southeast side of Bearpaw Butte, all fall between the 5,160 and 5,200 ft contours on the U.S. Geological Survey Medicine Lake 15-minute quadrangle map. Considering the rough margins typical of lava lakes, this is good agreement.

On the southwest side of the lava lake, no older buttes display a definite shoreline. However, the fissured and schollendomed area thins and eventually disappears against the higher topography of the preexisting Heppe-Modoc ridge formed by the Heppe-Modoc lava tube (fig. 68) below the 5,200-ft contour (see U.S. Geological Survey Medicine Lake 15-minute quadrangle topographic map).

A lava lake should not be thought of as similar to a lake of water in a temperate climate. An arctic lake (or sea) with its crust of ice is comparable, but notable differences remain. Even during the course of a major eruption, a lava lake would be partly covered with congealed blocks as seen during the slow transit of an almost complete cover of floating blocks across the Mauna Ulu lava lake in Hawaii during major eruptive activity. Such blocks of congealed crust will tend to jam together and block any surface outlet, a process which causes constant shift in the position of the outlets and corresponding fluctuations in the elevation of the lake level. Evidence that tangled surface lobes of block-rich lava escaped from many points on the perimeter of the lava lake north of Mammoth Crater can be seen where irregular skeins and lobes of lava poured out and solidified with steep slopes facing to the east between Red Butte and Hippo Butte, to the north between Hippo Butte and Bearpaw Butte, and to the northwest in the area west of Modoc Crater and southwest of Bearpaw Butte. Underground outlets (lava tubes) have a better chance of being preserved when they tap the molten lake beneath its solidified crust. With waning volcanism, however, they become blocked with lava jams and drain out as the lake level drops and its crust collapses into an expanse of schollendomes.

Upper Ice Cave

Upper Ice Cave is a small lava tube filled with ice that extends beneath the edge of the younger Callahan lava flow just south of Eagle Nest Butte (see map 19, pl. 6). Upstream from the cave, a mile-long chain of shallow breakdowns, small lava gutters, and short lava tubes can be traced toward the two pit craters north of Mammoth Crater. The place where they join the lava tubes from Mammoth Crater is lost beneath a blanket of younger pyroclastic debris and lava lobes from the crater. It seems likely that the Upper Ice Cave line of gutters and shallow breakdowns is a minor distributary developed in the last stages of building the Heppe-Modoc lava-tube system, which extended from Mammoth Crater through the gap between Eagle Nest and Bearpaw Buttes and then on to Canby Bay (fig. 4). Two similar but smaller lava gutter systems drained off this ridge to the west, and each of them originated in small sag basins that cap this ridge north of the Upper Ice Cave lava gutters.

Callahan Flow

The Callahan flow composed mostly of aa and block lava (fig. 69) is the youngest geologic feature in this area. Donnelly-Nolan and Champion (1987) report a radiocarbon age of 1110±60 yr B.P. Much of this large lava flow poured from a boca (the Spanish word for mouth) on the side of Cinder Butte, a steep-sided cinder cone with a small undissected crater at its top. Cinder Butte is located 0.5 mi south of the southwest corner of Lava Beds National Monument (fig. 4).

Collapse Trenches Between Skull Cave and Three Bridges Area

More than 40 small caves, and a few that can be traversed for more than 300 ft, lie downstream along the same lava-tube system that contains Skull Cave (map 20, pl. 6). Collapse has obliterated most of the primary features of many of these caves, as well as segmenting the tubes into short sections with floors so cluttered with rubble that they are difficult to traverse.

The larger and more interesting caves along this tube system are shown on maps 10, 11, and 12 of plate 4 and described in previous sections on Bearpaw, Merrill Ice, Kirk Whites, Beaconlight, and particularly Skull Caves. Therefore, associated surface features—the breakdowns, sag basins, skylights, surface spillovers, and various kinds of hydraulic ramparts that surround or partly border some of the collapse trenches—are shown on map 20, plate 6. It shows the surface features along a 5-mi stretch extending downstream from the collapse trench at the head of Skull Cave. This part of the lava-tube system zigzags along in a broad curve around the older Schonchin Butte flow (fig. 70). Near the north end of the Schonchin Butte flow, many distributaries branch off to the north and are lost in a field of schollendomes that occupy a broad band within the monument between Captain Jacks Stronghold and Fern Cave.

Skull Breakdown to Captain Jacks Bridge

A large collapse trench gives entrance to Skull Cave. Vehicles can be left at the Skull Cave parking lot. From this point the unpaved part of Lyons Road (now abandoned and closed to all vehicular traffic because it is within a wilderness area) furnishes a good access trail, which lies close to the lava-tube system for the first 2.5 mi.

Skull Cave breakdown is one of the largest and deepest collapse trenches in the monument. Cliffed walls around its edge provide excellent exposures of flow units within a thick lava flow. From the base of these cliffs long talus piles of very coarse blocks merge into an irregular and hummocky sea of tumbled blocks of all sizes. Looking downstream into the entrance of Skull Cave (fig. 47), one is startled by its thin roof and the realization that it is only a matter of time until the collapse trench will extend throughout the entire length of Skull Cave.

The next collapse feature downstream is offset 600 ft southeast from a point on the surface that lies above the downstream end of Skull Cave. It is a roughly circular shallow depression about 300 ft in diameter, located on the south side of Lyons Road. Parts of it are so overgrown with brush that it is difficult to tell whether this feature is merely a sag basin with gently tilted edges or whether its margins were let down by small displacements along numerous arcuate faults. Near its center is a small pit that is surely the surface expression of collapse into an underlying lava tube. Just east of the rim of this basin lies a deep collapse hole that reveals a tiny remnant of the lava tube at its base. Another deep collapse, 350 ft to the east, opens up another two short sections of lava tube that J.D. Howard named Robin

Figure 69. Edge of Callahan flow near Whitney Butte, west side of Lava Beds National Monument. Flow front of block lava is about 30 ft high. Callahan flow is about 1,100 years old, youngest in the monument.

Cave and Ship Cavern. Farther northeast is a somewhat larger elongate collapse that is the entrance to White Lace Cave, named by Howard from the open filigree of white caliche decorating nearly all of this cave's roof and walls. Within this cave, a steep connector slants down to the north into a lower tube.

Southwest of White Lace Cave the line of collapse features turns to the northeast. Downstream another 600 ft is an oval sag basin with walls that slope gently toward its center. In places, cracks and small faults rift the basin's margins. Occupying the central part of this shallow basin is a "cork" bounded by a ring fracture. It appears to be part of the roof of a lava tube, which was uplifted slightly when molten lava was present and then stuck in its present position when the lava in the tube lowered and the sag basin formed.

Just beyond the northeast edge of this sag basin is a deep collapse trench—the trace of a large lava tube whose roof has collapsed. At the northeast end of the trench one can enter a cave, which continues the tube to the northeast. Thin flow units are well exposed on the upper walls of the collapse trench. A spillover surface flow escaped from the northeast end of this collapse and flowed east in a channel 8 ft deep at the point where it joins the northeast end of the breakdown. This lava spillover is the first evidence that an obstruction, probably a roof collapse, occurred somewhere downstream while molten lava was flowing through the tube. The obstruction forced lava to back up behind it, as recorded by several features. Downstream 440 ft and across Lyons Road is a tiny skylight out of which three small overspills of lava emerged, flowed several tens of feet, and then solidified. Farther downstream 200 ft is another shallow depression with overspills of lava on its east side. Nearly 50 ft farther is the upstream end of an unusual-shaped large collapse trench with hydraulic block ramparts (fig. 46) rising to heights of 10–15 ft along its southeast margin. This large roughly "C" shaped breakdown probably marks a site where a major lava tube was temporarily blocked by roof collapse and then reopened by magma forcing a detour around one side of the collapse. As the molten lava backed up behind the collapse, it raised and tilted a segment of the tube's roof high enough to shed a wall of talus blocks, which form the hydraulic rampart (map 20, pl. 6) along its southeast margin. The backed-up lava also produced the spillover tubes and lobes from the skylight and trenches upstream. When flow of lava in the tube was resumed, either by forming a bypass around the obstruction or by entraining and bulldozing the collapsed blocks, the raised parts of the tube's roof lowered; thus, the direction of tilt of the roof blocks that previously had shed the ram-

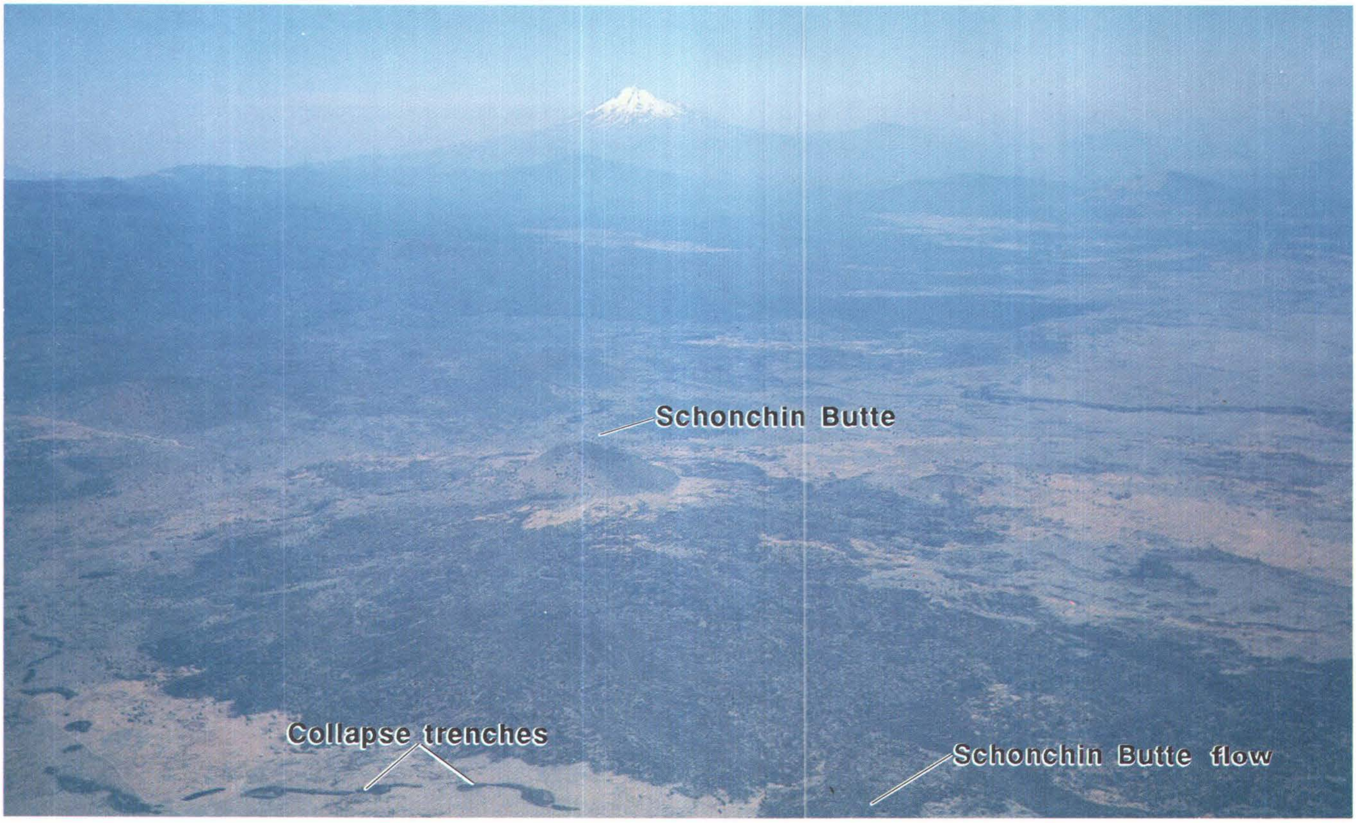


Figure 70. Aerial view southwest showing snowcapped Mount Shasta in hazy distance. Schonchin Butte and its block lava flow showing in foreground as dark area near center of Lava Beds National Monument. Elongate dark patches south and east of Schonchin Butte flow are collapse trenches formed along Merrill Ice-Skull Cave lava tube, which formed in basalt of Mammoth Crater that flowed around the preexisting Schonchin Butte flow.

part talus was reversed. Moreover, after volcanism had ended, further collapse toppled the roofs of both the original tube and its bypass. This produced the odd shape of the breakdown and also closed entry to this part of the lava tube. A downstream section of the tube, however, can be visited beneath Peninsula Bridge, which lies at the northeast end of this oddly shaped breakdown.

Northeast from Peninsula Bridge are three short collapse trenches separated by two natural bridges. At the north edge of the third trench a filled skylight is present on the surface. Out of this skylight narrow spillover lobes of lava emerged and built miniature lava tubes above ground. These surface tubes spread to the north and east, and they cross over an uncollapsed part of the main lava tube. One of these surface tubes then splits into four smaller distributary tubes (map 20, pl. 6).

The next feature downstream is a collapse trench 400 ft long. The ground adjacent to this trench is riven by a few curved fissures labeled "cracks" on map 20, plate 6. Access to a section of the lava tube can be made from the northwest edge of the breakdown. The tube continues beneath a natural bridge for 300 ft to a point where it is demolished within a collapse trench that trends northwest—almost at a right angle to the upstream trend. At its downstream end, however, this collapse trench curves right (north) and this curved trench gradually resumes the former northeast trend of the lava-tube system. Along the northeast side of this curving collapse trench, many short spillover lobes of molten lava emerged, solidified, and then were decapitated by collapse into the trench. On the opposite (southwest) side of this curving collapse trench, a group of shallow sag basins lowered the ground surface irregularly and a short lava spillover emerged from one of the sag basins. The lava tube continues northeastward beneath another lava bridge at the northeast end of this curving breakdown and is closed by a small collapse pit 350 ft farther downstream.

The next breakdown to the north is one of the most interesting collapse features along this part of the lava-tube system. It is shaped like half a coke bottle lengthwise and laid on its side with the sawed surface upward. It is located just southwest of Frozen River Cave and of the point where the tube system passes beneath Lyons Road (map 20, pl. 6). The neck of the bottle is a normal-width small collapse trench. The body of the bottle, however, is a large, shallow collapse area more than twice as wide as nearby accessible parts of the lava tube. The collapse's central part is strewn with blocks from the former tube's roof, some of which are as much as 20 ft in length. Similar large roof blocks, partly included within a talus pile of smaller roof blocks, are tilted outward away from the breakdown and form a continuous hydraulic rampart perched on the rim of the breakdown. This encircling rampart rises 3–35 ft above the surface of the surrounding plain. The tilted blocks and accompanying talus forming the rampart must have been shed outward upon the rim when molten lava, under hydraulic pressure within the underlying partially blocked lava tube, pried loose and heaved upward a large area of the tube's roof, a process which caused it to shed collapse material on all sides. Evidently the pressure was relieved downstream before molten lava could surface through this heaved-up roof. As the lava drained from the tube, the shattered roof blocks were lowered and jostled together to form the floor of the present depression whose surface now lies well below the rampart on its rims. Originally the rampart was continuous across the neck of the bottle, but this part of the rampart has tumbled into the short collapse trench forming the neck of the bottle.

The entrance into Frozen River Cave is at the mouth of the bottle. One hundred feet inside the cave a steep loose connector can be negotiated to a lower level that contains ice during most of the year. J.D. Howard named Frozen River Cave from the ice floor in this lower tube and in an alcove on its east side.

From Frozen River Cave the lava-tube system can be traced downstream on the east side of Lyons Road on a northeasterly course for 1,300 ft before it turns north. Two small collapse trenches reveal the position of the lava-tube system along this northeast trend, but entry into the tube is impossible from these breakdowns.

The northerly trend continues without entrances to caves for 1,700 ft to Captain Jacks Bridge. The approximate position of the lava-tube system, however, is apparent from two large breakdown complexes, which resemble—but are more complicated than—the coke bottle-shaped breakdown upstream. Both lie a short distance east of Lyons Road. The southernmost is a teardrop-shaped area 760 ft long and 240 ft wide across its blunt northern part, but it tapers to only 40 ft wide at its south end. On its east side this area is bordered by a 5- to 25-ft-high block rampart containing some short tilted-block sections. This rampart curls around the north end for a short distance, but the west margin of the teardrop is a jagged low cliff with little or no rampart material on its top.

The interior of this area is a maze of broken roof blocks. Five large pieces can be recognized (shown on map 20, pl. 6). Each consists of a fairly intact, although somewhat broken, part of the roof. Each piece appears to have been rafted toward and slightly raised against its neighbor to the north. Minor block ramparts tend to form on the north and northeast edges of the interior blocks, but in other places a carpet of loose blocks separates the different pieces. One large fissure, with blocks piled above its east edge, mirrors parts of the eastern wall of the breakdown. Out of this fissure, and much more copiously out of the break that forms the east edge of this complicated area, small spillovers of molten lava emerged and flowed to the north and east beneath or through gaps in the rampart. Three of these spillovers are large enough to be shown on the map, whereas other miniature spillovers barely reached the surface between the interior rafted blocks. That two tiny holes on the floor of the western part of the broad area of the teardrop were probed with a 13-ft-long stadia rod without touching bottom indicates the presence of a drained lava tube beneath.

At the north end of this complex, a 40-ft-wide strip of ground with low indefinite sags extends along the northerly trend for another 210 ft. The hummocky surface suggests the presence of a large tube, but we could find no entrance into it. To the north this strip of uneven ground is demolished by a large oval breakdown 440 ft long and 215 ft wide. This breakdown is rimmed by block ramparts (and by a short stretch of tilted rampart) 5 to 20 ft high, except across its north end. Here the oval breakdown is nicked by a smaller younger oval collapse oriented at a 45° angle to its larger companion. This smaller collapse feature is also surrounded by a tilted rampart that rises 6–10 ft above the plain. Where the two oval breakdowns join, a sharp-topped ridge of talus forms a sill that separates the two basins.

Approximately 30 ft northwest of the smaller oval is the small and deep collapse pit, which lies at the east end of Captain Jacks Bridge. On the floor of this pit is the entrance into Captain Jacks Ice Cave.

Captain Jacks Bridge to Three Bridges Area

On the floor of the deep collapse pit at the east end of Captain Jacks Bridge, a dark hole leads down into the collapsed remains of a lower lava tube named Captain Jacks Ice Cave. The cave provided water, and Captain Jacks Bridge and a nearby smaller cave provided shelter, for the Modoc Chief and his retreating band after they stole away from their stronghold on the shore of Tule Lake (fig. 71) during the Modoc War of 1872–73 (Thompson 1971; Waters 1981). We did not explore or map this deeper lava tube that contains the ice except for a short distance beyond its entrance. A shallower collapse pit lies 100 ft northeast of the ice cave, and from it a small near-surface lava tube curves off to the west. This tube is large enough to have provided a warmer and more easily reached shelter but contains no water.

At the downstream end of the deep collapse trench that extends west from Captain Jacks Bridge, a remnant of the large lava tube takes off on a northwest course. This cave is accessible for only 150 ft before it is blocked by collapse. The downstream continuation of the lava-tube system along this course, however, can be followed on the surface by seven breakdowns and attached short cave segments of the lava tube for a total distance of 3,160 ft before it curves into a N. 10° E. course.

The first of the seven breakdowns along the northwest stretch is a complex, crudely heart shaped depression 400 ft

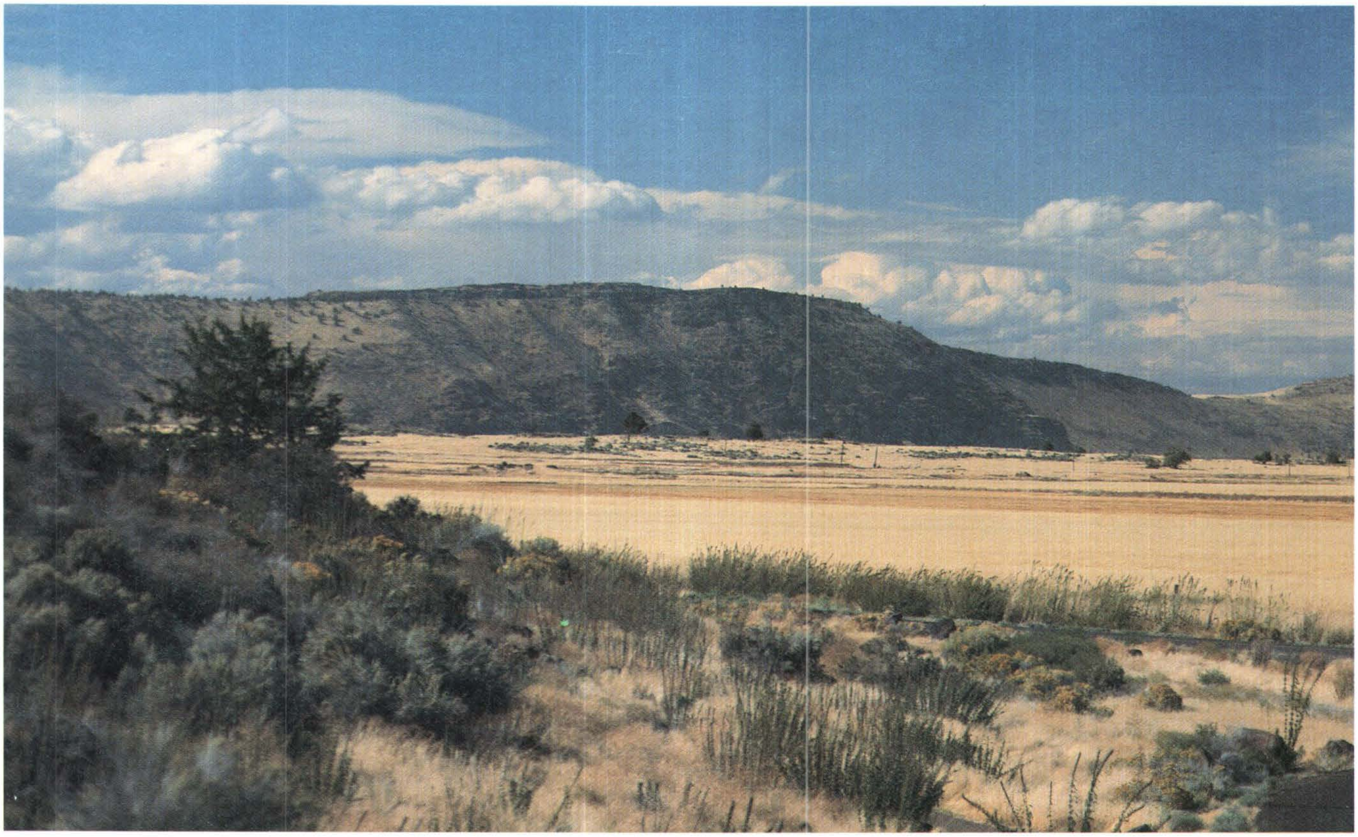


Figure 71. View west to Gillem Bluff across southern end of Tule Lake, now reclaimed as farmland. Lake provided water to Indians hiding in Captain Jacks Stronghold during the Modoc War of 1872–73. Photograph taken from northern edge of Lava Beds National Monument near Stronghold.

long and 300 ft in maximum width. The rim of the breakdown is continuously surrounded by a rampart of talus and tilted roof blocks ranging in height from 8 to 20 ft. However, before the rampart was formed, the heart-shaped area had sagged in toward the center of the depression, and so the rampart itself is surrounded by a "moat" up to 8 ft deep. Most interior breakdown now consists of a "cork" of somewhat broken and variously tilted, but still relatively intact, roof rock. The inner edge of the breakdown is separated from this central cork by talus and broken rock, which spread from the low cliff of the breakdown and from the shattered edges of the cork (map 20, pl. 6).

The position of the large lava tube apparently was beneath the west side of the heart-shaped depression. The blocked cave upstream projects into the west side of the depression, whereas at the widest part of the depression a skylight drops into another segment of tube. Also near this part of the depression a shallow collapse trench of the normal width for the tube leaves the breakdown and continues to the east side of the next large breakdown to the north. This collapse trench extends north-northwest for 440 ft, changes into a 250-ft-long shallow linear sag with narrow turndown sides, and disappears 70 ft short of the southeast corner of the next breakdown

The next breakdown is shaped like a rectangle with rounded-off corners. It is similar in size but a little smaller than its heart-shaped companion. A mixed block-and-tilted rampart 8–35 ft high surrounds the collapse with part of this rampart standing in a moat 2–8 ft deep. The interior of this breakdown, however, does not contain any intact cork. Instead a hummocky carpet of loose blocks spreads from all sides.

The four breakdowns that complete the N. 40° W. trend are fairly shallow collapse trenches of a size and depth consistent with the collapse of a tube averaging 30–50 ft wide. They are distributed in two pairs of small breakdowns with 345 ft of relatively uncollapsed lava tube between. A skylight 45 ft deep punctures the west edge of a lava-tube cave at a point 50 ft north of the southern pair. A small fissure that deviates to the northeast from the south side of the northern pair has a small block rampart rising above it.

At the downstream end of the northern pair the lava-tube system turns on a N. 10° E. course and maintains this trend for a distance of a little more than 1 mi. It then fades out into a widespread area of low sag basins north of the Three Bridges area. The actual walking distance is more than a mile because this part of the lava-tube system meanders in a series of broad open curves.

Many interesting features occur along this stretch of trench, and most are variations of features previously described. The first breakdown is rimmed by a block rampart 8–20 ft high, parts of which are bordered by a moat as much as 5 ft deep. A skylight is present at the northwest corner of the collapse, whereas on the opposite (east) side a schollendome with almost vertical sides may indicate a second lava tube that contributed to the collapse. Both of these inferred lava-tube caves appear to converge farther north into a curving (concave to the west) small breakdown. At the north end of this breakdown a cave can be entered that swings to the east, almost at a right angle to the former trench. At the northeast end of this cave, a very large oval breakdown 980 ft long and 350 ft wide trends N. 10° E. Block ramparts 15–20 ft high are perched above its north periphery, but they lower to 10–12 ft around its south end. The interior of this large collapse consists mostly of hummocky piles of loose blocks, but a dozen large fragments of the roof can be shown on the map. The largest is a thin flat-topped table 430 ft long (labeled on map 20, pl. 6 as "table") that occupies the north-central part of the breakdown.

A smaller oval breakdown overlaps the northwest corner of the large collapse. It has no ramparts, and its central part is a cork of intact roof rock, warped into a spoon shape at its northwest end.

A cave curves sharply right from the north end of this breakdown and then 200 ft farther downstream turns sharply left and connects with a collapse pit about 50 ft in diameter. This lava tube is the first of the three caves separated by breakdowns that inspired the name "Three Bridges."

The smaller breakdown between the first and second caves is separated by a sill from a larger 320-ft-long and 75-ft-wide larger neighbor. A spillover channel lies over the sill. This breakdown is rimmed on all sides by a hydraulic rampart ranging from 5 to 15 ft high and sits in a narrow moat as much as 5 ft deep. At the downstream end of this breakdown a small collapse pit provides entrance into the second section of lava tube—a cave 260 ft long—which, in turn, is interrupted at its north end by a section of collapse trench 330 ft long. At the downstream end of this trench the third cave extends 220 ft to where it is interrupted by a collapse pit. Another cave entrance is present on the north side of the collapse pit, but we did not explore this cave beyond its entrance.

North of the Three Bridges is a broad area of indefinite shallow sag basins and a few linear streaks that may be surface lava channels. The course of the lava-tube system across this area is indefinite, probably because the main tube split into a cluster of anastomosing smaller tubes. If so, some of these reunite downstream and continue the overall N. 10° E. trend beyond the north edge of the map area.

The offset in the lava-tube system just north of the Three Bridges area (map 20, pl. 6) was inferred primarily from anastomosing tube channels associated with the shallow sag basins. Two additional tiny breakdowns lie directly on this line within the belt of indefinite sag basins. Other, larger breakdowns are enclosed within still larger sag basins to the west. Farther northeast four other large collapses are clustered within one large sag basin with indefinite boundaries. Another large collapse lies still farther north inside a much larger shallow sag basin.

As mentioned previously, the lava-tube system continues northward beyond the map area, then it swings eastward toward Juniper Butte (fig. 4), and then it probably continues northward to Fern Cave. Along its easterly course it spawns many distributaries to the northwest and north.

Schonchin Butte Flow

As can be seen from map 20, plate 6, the east edge of the Schonchin Butte flow and this lava-tube system are roughly parallel. Although the margin of the Schonchin Butte flow (fig. 70) is deeply indented on a small scale, its east edge is seldom more than 0.25 mi west of the trace of the lava-tube system from White Lace Cave to beyond the north edge of the map area. The Schonchin Butte flow is older than the basalt of Mammoth Crater whose mostly pahoehoe flows lap against the blocky east edge of the andesite of Schonchin Butte.

Schonchin Butte (fig. 67) and its neighbors Hippo Butte, Crescent Butte, and Bearpaw Butte had been built to their present dimensions (and Crescent Butte had been deeply eroded) before the basalt flows from Mammoth Crater were erupted (figs. 1 and 4). These basalt flows, transmitted mainly through lava tubes, impinged against and ultimately surrounded the basal parts of the older buttes. The chains of breakdowns that now mark the lava-tube systems are situated at the crest of low ridges on this northward-sloping lava plain because levees, overspills, and distributaries constantly built the ground surface higher adjacent to the major lava-tube systems.

The Schonchin Butte flow is a large multiple flow consisting of countless overlapping narrow and wide lobes of aa and block lava. The flow erupted out of a boca on the east side of Schonchin Butte (fig. 67), a conspicuous landmark in Lava Beds National Monument.

The lava that formed the Schonchin Butte flow is of different composition and was considerably more viscous than the Mammoth Crater lava. Its surface features are almost entirely of aa and of block lava. Such lava is crowded with tiny bubbles and was already partly crystallized when extruded, so its partly congealed surfaces broke up into blocks as it slowly moved forward. These physical features explain why it piled up in steep overlapping lobes, each with a steep front and sides of talus. The fronts and sides of major lobes may be bordered by steep loose talus slopes or by treacherous cliffs of slightly agglutinated blocks. Such flow fronts may be from a few feet to more than 100 ft in height.

From this brief description it is apparent that the Schonchin Butte flow, 4 mi long and 1.5 mi wide, is an obstacle to all traffic. Only the major flow lobes along this part of its periphery (map 20, pl. 6) are shown. An experienced outdoor person, equipped with excellent boots and heavy gloves, may require 2 or more hours to get across the flow.

A FINAL NOTE

A great deal can be learned about lava flows by studying lava-tube cave systems because they preserve the fascinating and precise records that reveal the mechanics of volcanic flow, which operated in former infernos. Moreover, you can examine these records and ponder them at your leisure in the cool, quiet environment of a cave without the apprehension involved in personally witnessing an active eruption during the creation of a lava tube. While watching actively flowing lava, you can only guess at what goes on beneath the flow surface while your mind is intermittently occupied by the overriding question, "Am I at a safe distance?"

You do not need to be a scientist to enjoy the caves or even to write articles about them. If you are interested in some special feature, such as lavacicles or tube-in-tubes, safe and enjoyable cave trips can be planned using the text and maps of this report. Then study the appropriate maps and descriptions, and always take the map with you when entering the cave. Remember that multiple lights are necessary for all caves except Mushpot, and that access to some caves may be restricted. Information about access is available at the Visitor Center, where important exploration and safety guidelines are also distributed.

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