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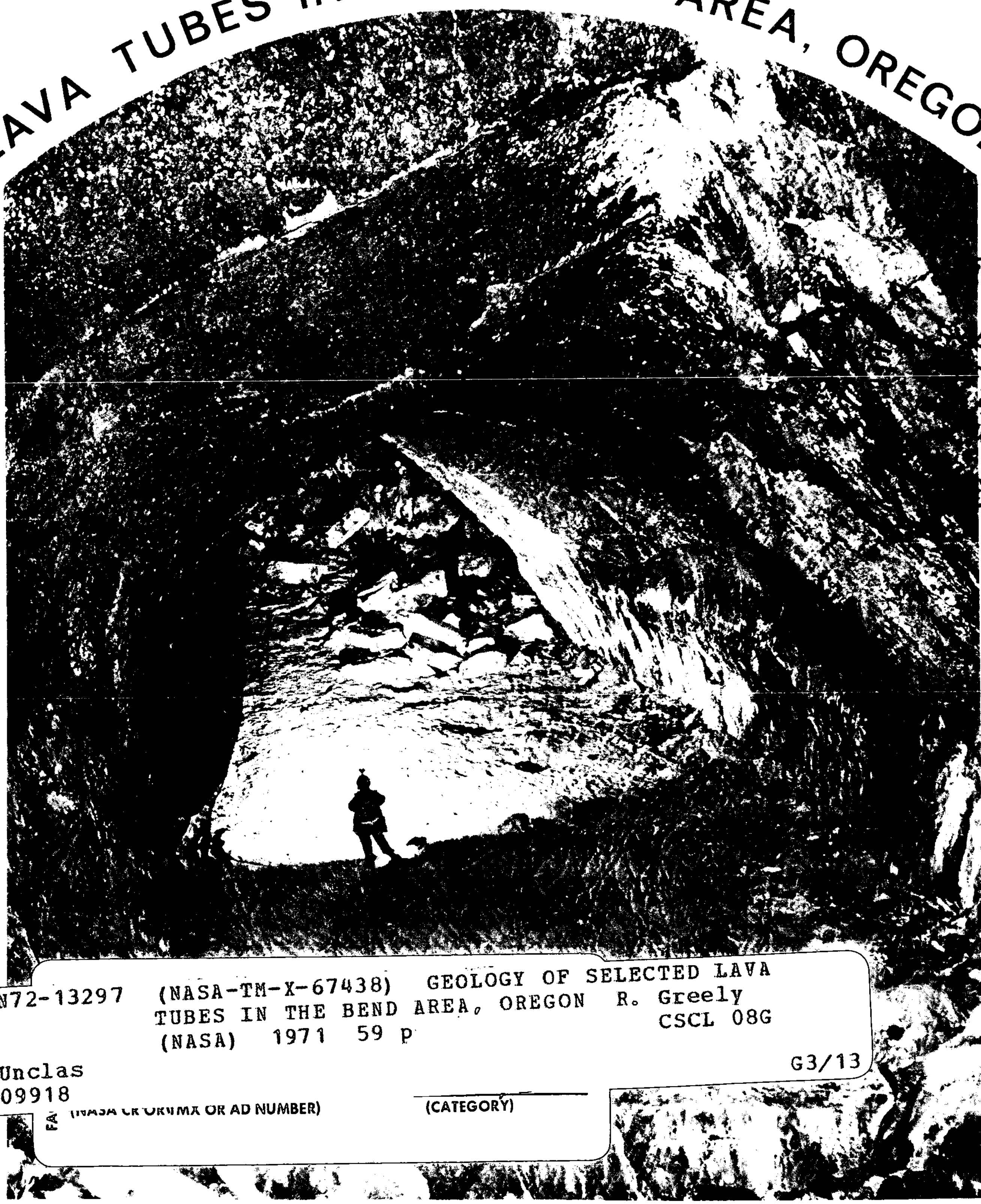
# GEOLOGY OF SELECTED LAVA TUBES IN THE BEND AREA, OREGON





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# GEOLOGY OF SELECTED LAVA TUBES IN THE BEND AREA, OREGON



By
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1971

## FOREWORD

Oregon probably has the greatest diversity of volcanic rock types and landforms of any region in the conterminous United States. The area centering around Bend has come to be known as Oregon's "moon country" because the very young volcanic rocks in this vicinity show features similar to what have been photographed on the lunar surface. The National Aeronautics and Space Administration has, therefore, spent considerable time studying various aspects of the terrain in central Oregon because its scientists have interpreted certain lunar forms, such as the sinuous rilles, as volcanic structures. Mr. Ronald Greeley, the author of this report, believes that some of the smaller lunar rilles probably resulted from lava-tube collapse.

Up to the present time, there has been relatively little study of lava tubes in the western United States to determine their origin, nor have these unusual structures been described in sufficient detail to be classified into different types. Mr. Greeley has selected several lava tubes in the Bend area for such a study because of their excellent development and relative ease of access.

The Department presents this publication with the hope that it will stimulate the interest of others in exploring the many unusual and fascinating geologic features that occur in our "moon country."

R. E. Corcoran
Oregon State Geologist

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# GEOLOGY OF SELECTED LAVA TUBES IN THE BEND AREA, OREGON

by Ronald Greeley


## ABSTRACT

Lava tubes in the vicinity of Bend, Oregon, were mapped and studied in detail to determine their geomorphology and mode of formation. Longitudinal profiles representing 5872.5 m of mapped lava tubes and a photogeologic map relating lava tubes to surface geology, regional structure and topography are presented. Three sets of lava tubes were examined: 1) Arnold Lava Tube System (7km long) composed of collapsed and uncollapsed tube segments and lava ponds, 2) Horse Lava Tube System (11 km long) composed of parallel and anastomosing lava tube segments, and 3) miscellaneous lava tubes. Results of this study tend to confirm the "layered lava" hypothesis of Ollier and Brown (1965) for lava tube formation; however, there are probably several modes of formation for lava tubes in general. Arnold System is a single series of tubes apparently formed in a single basalt flow on a relatively steep gradient. The advancing flow in which the tubes formed was apparently temporarily halted, resulting in the formation of lava ponds which were inflated and later drained by the lava tube system. Horse System probably formed in multiple, interconnected flows. Pre-flow gradient appears to have been less than for Arnold System, and resulted in meandrous, multiple tube networks.


## INTRODUCTION

Interpretation of certain lunar surface features as volcanic structures has resulted in increased interest in the geomorphology of terrestrial volcanic analogs. A recent report (Oberbeck and others, 1969) proposed that some smaller lunar sinuous rilles (generally, those less than about 0.5 km wide) probably resulted from lava tube collapse. Other structures (figure 1) may be partially collapsed lunar lava tubes (Greeley, 1970)

Unfortunately, little is known about the formational mechanisms and geomorphology of lava tubes and it is difficult to establish criteria to distinguish lunar lava tubes, both collapsed and partly collapsed, from other lunar structures without data on terrestrial counterparts. For this reason, some of the major lava tubes in the western United States were examined and surveyed to gain an understanding of the geology of these complex structures. The tubes are of interest to several groups besides geologists, including zoologists interested in cave biota, anthropologists concerned with historic and prehistoric inhabitants, U. S. Forest Service personnel responsible for recreational facilities and safety of National Forest visitors, and the National Speleological Society, an organization of amateur and professional cave explorers.

The Bend, Oregon area is characterized by relatively young, unweathered volcanic features that are well suited for study. In the initial stages of examination of terrestrial analogs to lunar structures, a field conference was held in Bend to study some of the volcanic structures (Peterson and Groh, 1965). Lava tubes, however, were only briefly considered during the conference. This report presents detailed descriptions of selected lava tubes, theory of tube formation, and a sketch of the general geology of the Bend area.

There are many lava tubes in the Bend area. Those that were selected for mapping and study lie mainly east and southeast of Bend. They comprise the Arnold Lava Tube System, the Horse Lava Tube System, and miscellaneous lava tubes such as Skeleton Cave, Boyd Cave, and South Ice Cave. Lava River Cave south of Bend has also been included because of its general interest to the public and its accessibility as a State Park.

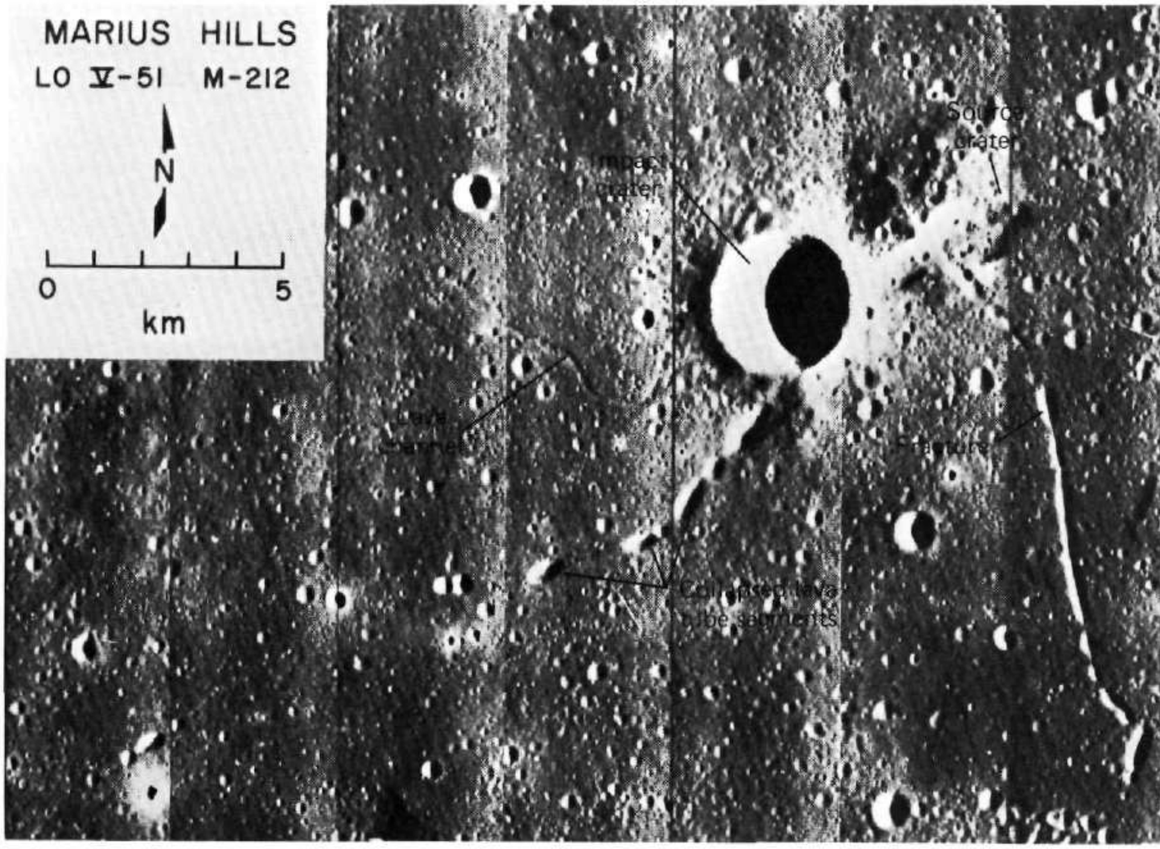


Figure 1. Marius Hills region of the Moon (west-central Oceanus Procellarum). Structure is interpreted to be a partly collapsed lava tube originating from an endogenous crater-vent. From its morphology, the large crater is considered impact generated. Photograph from NASA Lunar Orbiter V, Site 51, Frame M-212.

## FIELD METHODS

The investigation was greatly facilitated by availability of recent, large-scale Forest Service aerial photographs (1967, 1:15,840), topographic maps (U.S.G.S. 7 1/2' quadrangles) and a speleological "caver's" report on lava tubes of the area (Knutson, 1964). Date on aerial photographs and topographic maps covering specific tubes are presented in tabular form in Appendix 1. Prior to field work, a preliminary photogeologic map was prepared and selected tubes identified.

In the field, selected tubes were surveyed by tape measure, Brunton compass, Abney hand level (for surface and subsurface gradients along the lava tube axis) and tied helium-filled balloon for direct ceiling height determinations. Only those tubes in the study area meeting one or more of the following criteria were examined:

1) Lava tubes with interior widths exceeding 50 feet.
2) Tubes that appeared on aerial photographs as part of tube systems longer than 2 km.
3) Tubes that could be related to specific lava flows.
4) Tubes accessible during field work.

After the lava tube interior was traversed, a surface survey was made along the tube axis to obtain topographic slope and to relate surface features to interior tube structures. Roof thicknesses were determined graphically (utilizing longitudinal profiles) from the surface and subsurface gradients and lava tube interior heights. Although local magnetic anomalies probably affected Brunton compass readings, the deviation is apparently about the same for both surface and subsurface azimuths and probably does not affect roof thickness determinations. Accuracy of the method was checked in a tube with two entrances, about half a mile apart; the surface survey ended within 50 feet (planimetrically) of the second entrance. Longitudinal profiles of the lava tubes examined were prepared from the survey and are presented in Plates 1 and 2.

## GEOLOGY AND PHYSIOGRAPHY

Bend, Oregon is in the western fourth of the High Lava Plains physiographic province, an area characterized by relatively undissected Pliocene to Holocene volcanic rocks and mostly interior drainage. Figure 2 shows major structures and the relation of the area to adjacent physiographic divisions. The study area ranges in elevation from 3500 feet near Bend to more than 8000 feet in the Paulina Mountains (remnants of Newberry Caldera rim). Dry lava plains with occasional junipers and sagebrush predominate at the lower elevations; sparse pine forests mark the 4500 to 5200 feet elevations and above 5200 feet vegetation is dense forest, except where devastated by Holocene lava flows. The area is dominated by Newberry Caldera (figure 2), a shield volcano approximately 64 km long by 40 km wide that has been active since the Pleistocene. The center of the area is cut by a series of en echelon faults striking an average of N 30° W. These apparently connect the Brothers Fault Zone on the east (which formed Horse Ridge and Pine Mountain) with the prominent north-south fault zone of the eastern Cascades, north-northwest of Newberry Caldera. The en echelon faults are approximately parallel with the Northwest Rift Zone described by Peterson and Groh (1965, p. 8-9).

Plate 3 is a photogeologic map compiled from Williams (1935, 1957), Peterson and Groh (1965), Walker, Peterson, and Greene (1967), Higgins and Waters (1967), and from laboratory and field analyses of aerial photographs. Basalts exposed in the area erupted during at least three episodes: 1) eruptions from the central caldera during early shield-building phases of Newberry Caldera (Williams 1935, p. 259), 2) fissure eruptions associated with the Brothers Fault Zone, and 3) Holocene eruptions from fissures on the caldera flanks. Flows from the first two (older) sources are contemporaneous and interfinger (Higgins and Waters, 1967, p. 41). The basalt labelled Qb on the map (Plate 3) forms a subtle ridge east and southeast of Bend and may represent a northwest extension of Horse Ridge. Unit Qb may have been a topographic high at the time of Qyb eruptions and possibly channeled Qyb basalt flows (those emanating from the Caldera) to the northwest. Lava Top Butte Flow (Qbf), a caldera flank fissure eruption, apparently was similarly controlled. Its contact with Qb is aligned with the fault zone, Horse Ridge, and the Qb-Qyb contact. Basalt Qyb1 overlaps basalt Qb from the northeast and appears to have originated from an eruptive center a few kilometers north of Horse Ridge.

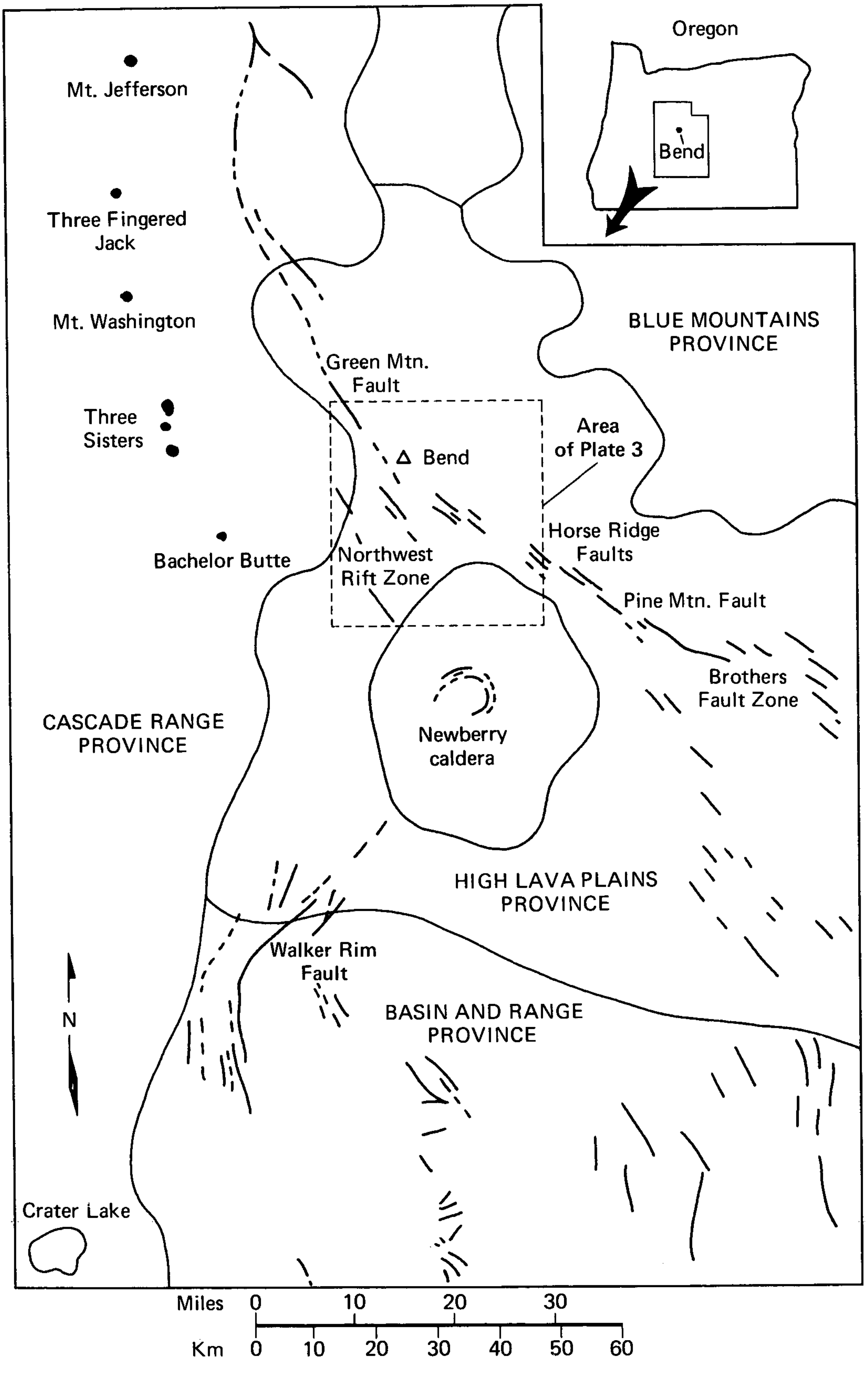


Figure 2. Location map and physiography of central Oregon showing major structural zones and area of investigation near Bend.

Several other fissure eruptions occurred on the caldera flanks. Most notable are those of the Northwest Rift Zone. At least eight basalt flows erupted along the rift zone, one of which (Lava Cast Forest Flow) is dated at 6150 ± 210 years, B. P. (Peterson and Groh 1965). All of these flows are basaltic aa with associated pyroclastic cones and are not known to contain lava tubes. Pyroclastic cinder cones are shown on the map as Qcc. Cinder cones of the Northwest Rift Zone are aligned with the rift; cones in the remainder of the area mapped, however, have no apparent orientation.

Except for the Deschutes River in the northwest corner, there are no major streams in the area. Because the region is geologically young, weathering has produced only a thin veneer of surface debris which, when viewed in conjunction with wind transported silt and sand, is less than 40 cm thick in most places.

## LAVA TUBE FORMATION

Lava Tubes form only in basaltic lava flows and are common in many young basalts of the western United States. A general conception of lava tube formation can be gained from observations of active lava flows (Jaggar, 1947). As molten basalt flows away from its source, the upper surface cools and forms a solid crust while flow of molten lava continues beneath the crust. Eventually, active flow is restricted to a conduit within the basalt flow that feeds the advancing flow front. This conduit is the primitive lava tube. Cessation of the eruption at the source limits the lava supply and fluid material drains from the conduit by gravity, leaving a hollow void, or lava tube.

The single most important factor in tube formation is low viscosity, which is directly related to temperature, chemistry, and the amount of gas dissolved in the lava flow. The lava flow is more fluid and less viscous at higher temperatures and/or with a higher gas content. As the lava cools, loses gases, and crystallizes, it becomes more viscous (Macdonald, 1967, p. 3). Basalt is the only volcanic material fluid enough to permit development of tubes, but even some basalt flows are too viscous for tube formation.

Basalt occurs as block flows, aa flows, or pahoehoe flows, and all are intergradational, depending on viscosity. Block flows are composed of massive basalt blocks resulting from very viscous flows; aa flows are clinkery beds of less viscous basalt; and pahoehoe basalt flows, recognized by smooth ropy surfaces, are the least viscous. A single eruption of basaltic lava may initially be pahoehoe and, as cooling and outgassing progress (increasing the viscosity), change to aa and block basalt. Some pahoehoe flows change directly to blocky lava without passing through the intermediate aa form. Lava tubes, stringently controlled by flow viscosity, form only in pahoehoe basalt.

Tubes are so common in pahoehoe flows that they are evidently the primary means of flow advance. Small distributary tubes branch from the main lava tube to feed the flow front. These feeder tubes usually do not drain and are seldom preserved. If drainage does occur, feeder tubes often fill with lava from later flows. Wide lava flows (several kilometers,or tens of kilometers wide) may have several main lava tubes, some of which interconnect by lateral passages. Lava flows restricted to valleys are narrow and generally have a single main tube, or multiple tubes that are vertically stacked. Each tube level may connect by vertical passages, or levels may combine to form a single, vertically elongate tube (viewed in cross-section, figure 5). These configurations require a complex mode of origin.

Detailed mapping and examination of more than 17,000 m of lava tubes in the western United States permit speculation on the mechanism of lava tube formation.

There appear to be at least two types of tubes (minor lava tubes and major lava tubes) (Hatheway, 1970) and each type requires a somewhat different mode of formation. Minor lava tubes are small, generally less than 10 m wide and a few hundred meters long (Greeley, 1969). These form in small, single-flow units and often occupy nearly the entire flow; the tube roof is markedly arched (figure 3). Minor tubes are often feeder tubes from larger lava tubes. In other cases, they may form in discrete lava flows emanating directly from the vent. Surface tension permits the flow to maintain a high cross section (relative to width), and formation of a crust maintains the integrity of the flow structure; eventually the fluid drains from the system. Occasionally, pahoehoe may flow down an open channel formed in a previous lava flow. The secondary pahoehoe flow can roof over the channel, drain, and form a distinctive lava tube. There are few minor lava tubes in the Bend area.

Major lava tubes of the type described by Ollier and Brown (1965) form in lava flows several kilometers, or more, long. Thick basalt flows are usually subdivided by horizontal discontinuous

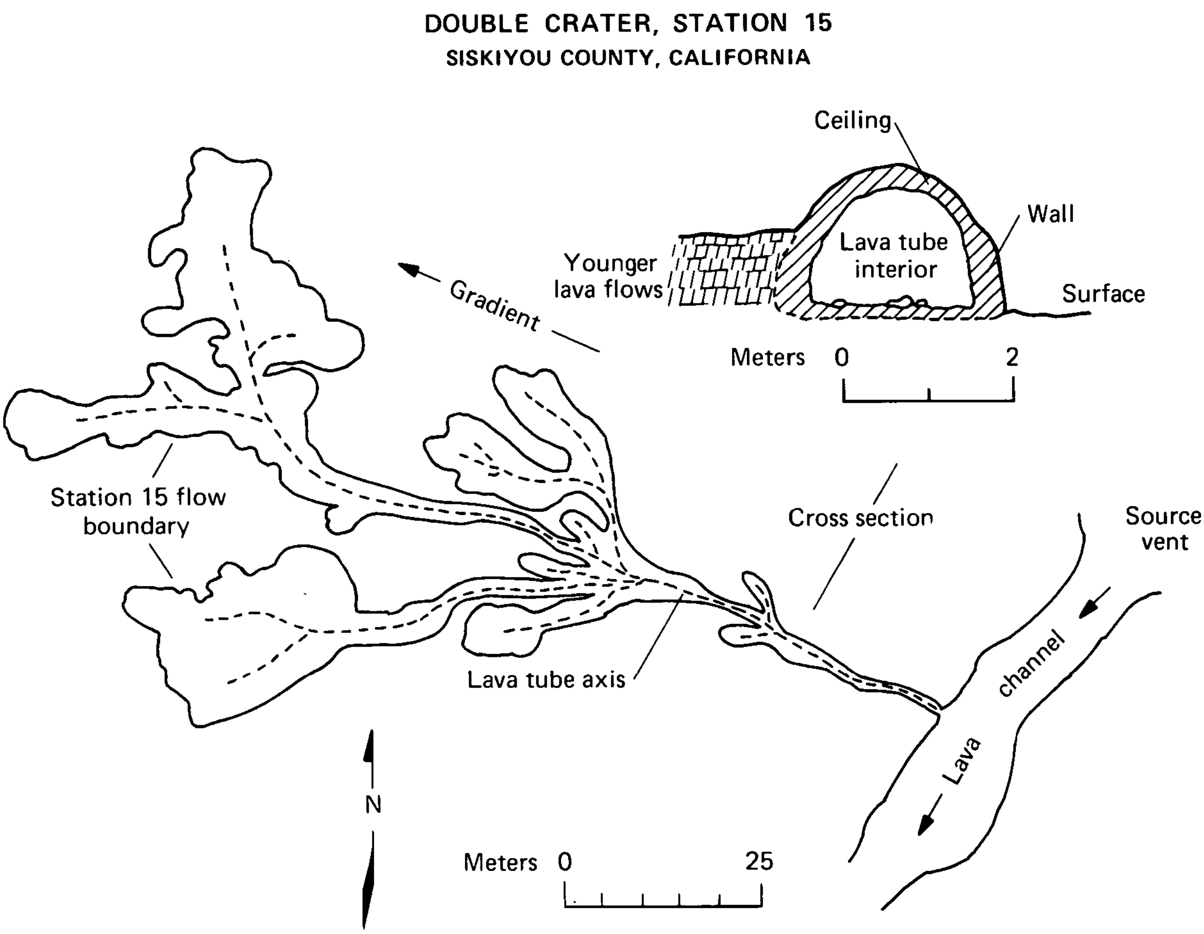


Figure 3. Diagram of a minor lava tube system in northern California (south of Medicine Lake Caldera), showing relationship of lava tube (dashed line) to the lava flow, and one cross section.


Figure 4a. Bear Trap Lava Tube, Blaine and Power Counties, Idaho, showing lava tube lining and layered lava.

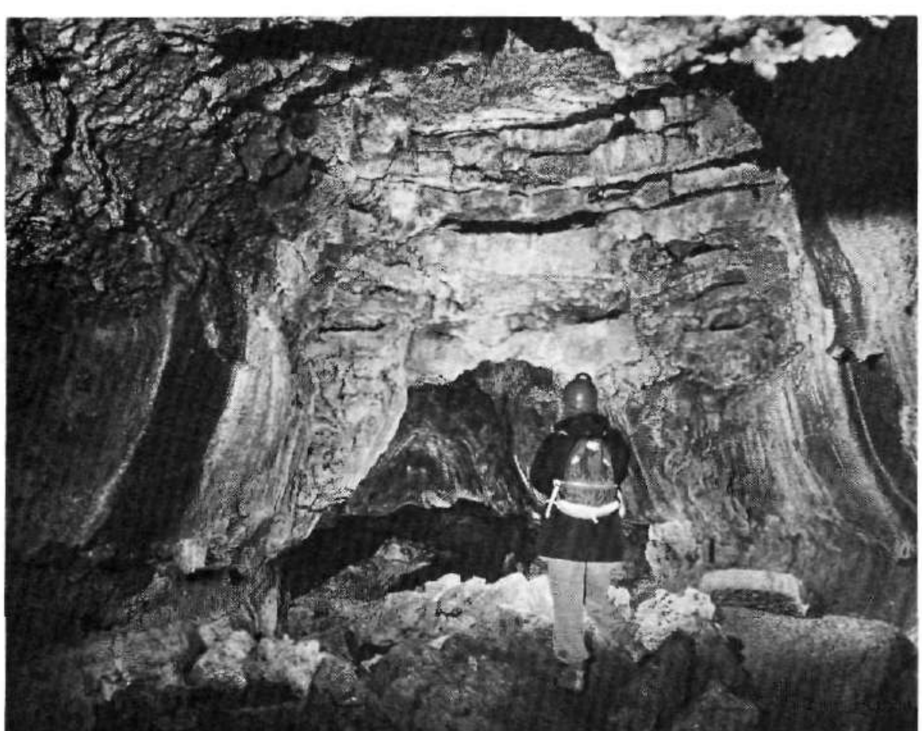

Figure 4b. Jug Cave, Southwest Washington, showing layered lava fused to ceiling. (Photograph by Charlie and Jo Larson, Vancouver, Washington)


Figure 5. Wind Cave (Arnold Lava Tube System), viewed downtube from Station 22. Flow lines are visible on both walls; secondary mineralization has occurred along ceiling fractures; the tube is asymmetric in cross section, forming a cut bank in the meander bend. A large pile of collapse blocks is visible in the background. Maximum height is 15 m. (Photograph by Charlie and Jo Larson, Vancouver, Washington)

partings giving the effect of layered lava (figures 4-a and 4-b), a term applied by Ollier and Brown (1965, p. 221). Many active basaltic lava flows are considered to be laminar. Ollier and Brown believe layered lava results from shear planes (associated with laminar flow) developed within the lava. Layered lava is distinct from multiple lava flow units (individual, superimposed flows), in that it occurs within a single, contemporaneous lava flow. Unfortunately, it is often impossible to distinguish layered lava from multiple flow units. Individual flow units may have formed only a few hours apart and the normal criteria for separating geologic time units (weathered surfaces, etc.) do not apply. Horizontal partings in layered lava are, however, discontinuous, whereas the contacts between flow units are widespread. This difference provides a means of differentiation, although difficulties arise where cross-sections are poorly exposed.

Shear planes and layered lava are essential in the formation of major lava tubes (Ollier and Brown, 1965). Flow apparently is confined to fluid conduits between shear planes. In early stages, molten conduits are mobile and can be repositioned within the flow by reheating cooler parts and by crossing discontinuous shear planes. Repositioning can result from lava surges from the source vent at higher velocities and/or higher temperatures. Mobility of the fluid conduits explains the existence of multiple stacked lava tubes and the ease with which tubes may interconnect horizontally and vertically. Drainage of the fluid conduits results in complex lava tube systems of the type near Bend.

Sinuosity, or degree of meandering, of the tube in planimetric view is attributable to the degree of fluidity of the mobile conduit within the lava flow body. Similar to a meandering flood plain river, the tube may migrate from one side of the flow to the other until it is more firmly positioned by cooling and congealing lava. Thus, the tube may migrate in a three dimensional network, with horizontal and vertical components. Configuration of the tube in transverse cross section (perpendicular to the lava tube axis) can also be compared to a meandering river. The lava tube often has a distinct cut bank and occasionally a slip bank in meander bends (figure 5). These banks probably result from development of a lava "thalweg" (axis of maximum velocity in a stream) in the mobile conduit that erodes by remelting or heating the cooler lava, forming a cut bank, and by accreting cooler lava on the slip bank where the flow velocity is less. Under certain conditions, such as depressions on the pre-flow surface, an advancing lava flow may be ponded temporarily. Lava within tubes continues to flow under hydrostatic pressure and may form inflated blisters or <u>tumuli</u> in the lava pond crust (tumuli commonly form in broad basalt flows, not necessarily in association with lava tubes). Tumuli may collapse or remain as domal structures.

As lava drains from the tube, a lava sheet lines the interior and covers the horizontal layered lava (figure 4) (Ollier and Brown, 1965). The lining is of variable thickness, ranging from a few centimeters to tens of centimeters, depending possibly on the rapidity of drainage. In some cases the lining is glazed with thin glassy lava that may result from very high temperatures associated with out-gassing into the tube. Drainage is not always complete, and tubes may be partly or completely filled with congealed lava (Macdonald, 1967). Drainage may occur before the flow has developed a crust sufficiently thick to support its weight. The crust may fracture and collapse immediately, or it may deform plastically if the roof is semi-molten (Kuiper, <u>et al.</u>, 1966). This type of collapse is evident by inward draping of lava surface sheets toward generally elongate collapse craters (figure 6), or by tensional fractures parallel to the tube axis.

Uncollapsed roofs are attacked by weathering processes leading to eventual collapse. Calculations currently in progress of stresses in lava tube roofs of various dimensions and roof thicknesses give an estimate of areas of likely failure. Failure commonly begins by spallation of the lining, followed by spallation of the layered lava from the center of the ceiling. The result is a jumble of massive basalt blocks covering the floor. Eventually, spallation works through to the surface and forms a collapse depression. Initial breakthrough creates a small, circular hole called a skylight. In vertically stacked tubes, only the upper level may collapse, leaving an intact lava tube beneath the collapsed segment.

Partly or completely cooled lava tubes serve as excellent conduits for younger lava flows erupted from the common source vent. These younger flows are not necessarily pahoehoe and they may partly, or completely, fill the older lava tube. It is difficult to distinguish lava tubes partly filled with subsequent lava flows from tubes partly drained of the original flow. Flow fronts of subsequent flows are, however, occasionally encountered (Greeley and Hyde, 1970). Tubes also fill with exogenous detrital material entering the tube through large collapses, skylights, or roof fractures (figures 7,8).

Figure 6. Rim of collapse pit, Barlow Cave (Horse Lava Tube System), showing plastic deformation of lava crust.

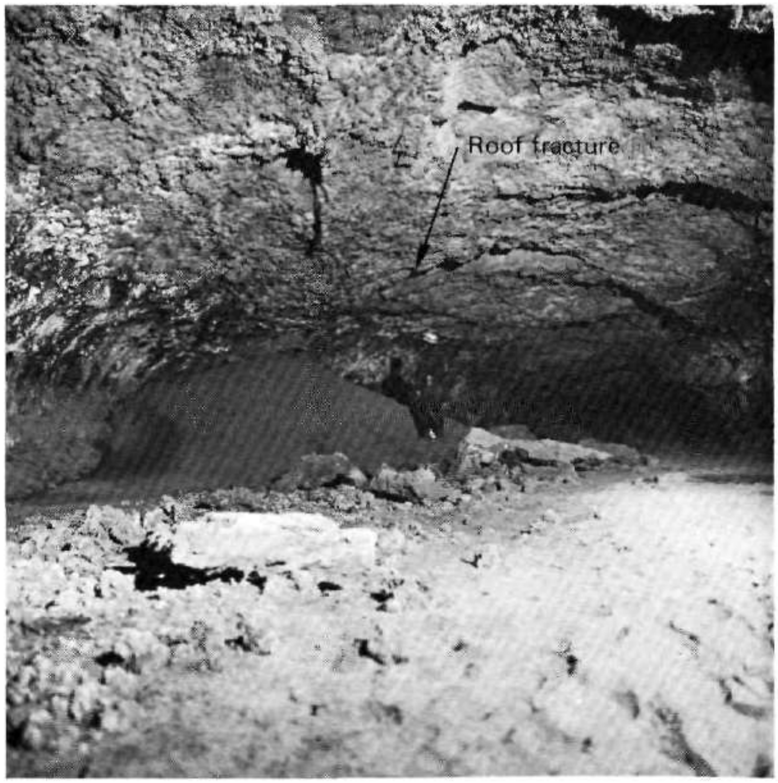


Figure 7. Boyd Cave lava tube, Station 4; surface sand is draining into the lava tube through a roof fracture.

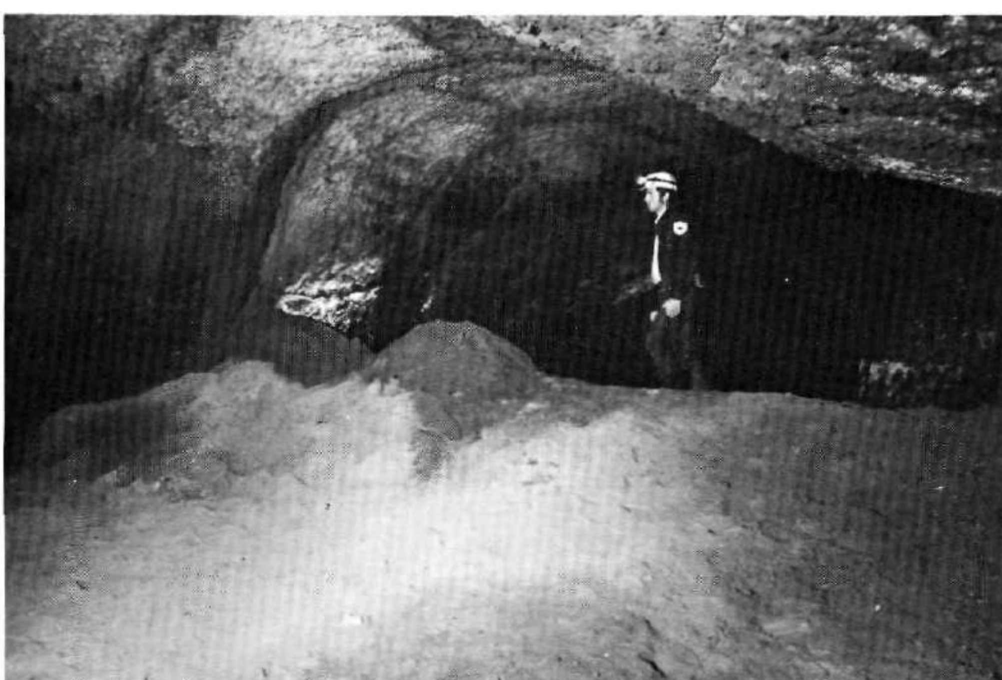

Figure 8. Boyd Cave lava tube, Station 21; drainage of surface sand through a roof fracture, similar to Station 4.

## LAVA TUBE DESCRIPTIONS

Historically, lava tubes have long been of interest to various people. Many lava tube entrances were utilized by Indians as shelters, evidenced by remnants of campfires and pictographs on the walls. Early settlers occasionally used tubes as shelters for themselves or livestock and as a source of ice during the summer (as mentioned below, the insulating quality of basalt preserves through the summer the ice that forms in tubes during the winter). Names applied to caves (uncollapsed lava tube segments) by early discoverers have been retained in papers, on U.S. Geological Survey maps, and in this report.

Lava tubes examined and surveyed are discussed under three categories: Arnold Lava Tube System, Horse Lava Tube System, and miscellaneous. A lava tube system consists of lava tube segments considered to be either (1) part of a single lava tube that has collapsed in several places along its length, resulting in a series of individual lava caves, or (2) a series of anastomising and parallel lava tubes, some partly collapsed, all of which are contained in contemporaneous lava flow units. Most individual caves within a system are named; the system name is taken from the locally best known cave within the system.

### Arnold Lava Tube System

Plate 1 is a longitudinal profile for Arnold Lava Tube System. The system can be traced from a major collapse in E 1/2, NW 1/4, NW 1/4, sec. 27, R. 13 E., T. 19 S. east northeast to its apparent terminus in SE 1/4, NW 1/4 , NW 1/4, sec. 18, R. 14 E., T. 19 S. for a distance of approximately 7 km (figure 9; plate 3). Straight line slope of the system is 0° 45' 30". The Arnold System probably formed during a single eruption and was essentially continuous during active lava flow.

The system is subdivided into three parts, an upper section, middle section, and lower section. The upper section is traced from a large collapse trench, (the first recognizable lava tube element from the source end) through a collapse pit situated over Arnold Ice Cave, and is formed within basalt unit Qb. The middle section consists of a collapsed lava pond, collapsed lava tubes, and uncollapsed lava tube segments, including Bat Cave, a two level lava tube. The section is mapped as Qb, overlain in some areas by younger Lava Top Butte Flow. The lower section is characterized by long uncollapsed lava tubes (Wind Cave, Pictograph Cave), collapsed segments, and large collapsed lava ponds, all formed in basalt Qb.

#### Upper Section

The first discernible segment of Arnold Lava Tube System at the source end is a major collapse trench. This trench (E 1/2, NW 1/4, NW 1/4, sec. 27, R. 13 E., T. 19 S., elevation 4490 ft.) is steepwalled, about 18 m deep, 22 m wide, and 200 m long, and, at the east end has a prominent uncollapsed section 16 m wide with a 4 m thick roof. Topography and geomorphic surface texture indicate a southwest outcrop extension of Qb basalt, not covered by young Qyb units. The reentrant (Plate 3) is a topographic high that may indicate extension of the tube southwest, in the general trend of the Arnold System. A small depression, about 70 m in diameter, is shown on topographic quadrangle Kelsey Butte 7 1/2' (U.S.G.S. advance sheet) in SE 1/4, NE 1/4, SW 1/4, sec. 28, T. 19 S., R. 12 E., elevation 4700 ft., about 1.5 km southwest of the trench, which may represent a collapsed part of the system. On the premise that lava tubes indicate the general direction of lava flow, it appears likely that this part of Qb flow originated from fissures underlying Lava Top Butte, Kelsey Butte, and an unnamed cinder cone about half way between. The flow has been covered by younger basalt apparently obliterating any vestige of older lava tubes.

Immediately north of the large collapse trench and an unimproved dirt road is another collapse depression. Small over-hanging roof sections occur around the depression and there may be connecting passages through the collapse blocks, both south to the trench and north to Charcoal Cave.

Charcoal Cave (NW 1/4, NE 1/4, NW 1/4, sec. 27, R. 13E., T.19S.; elevation 4535 ft.) is about 60 m south of the trench described above. The uncollapsed section is accessible by a steep-walled collapse pit, about 10 m deep. Halliday (1952, p. 48) reported the cave to contain "charred wood, cut with stone axes.....dated to the 13th Century." A full report (historical) on this cave is available in the March 1938 Oregon Historical Society Quarterly.

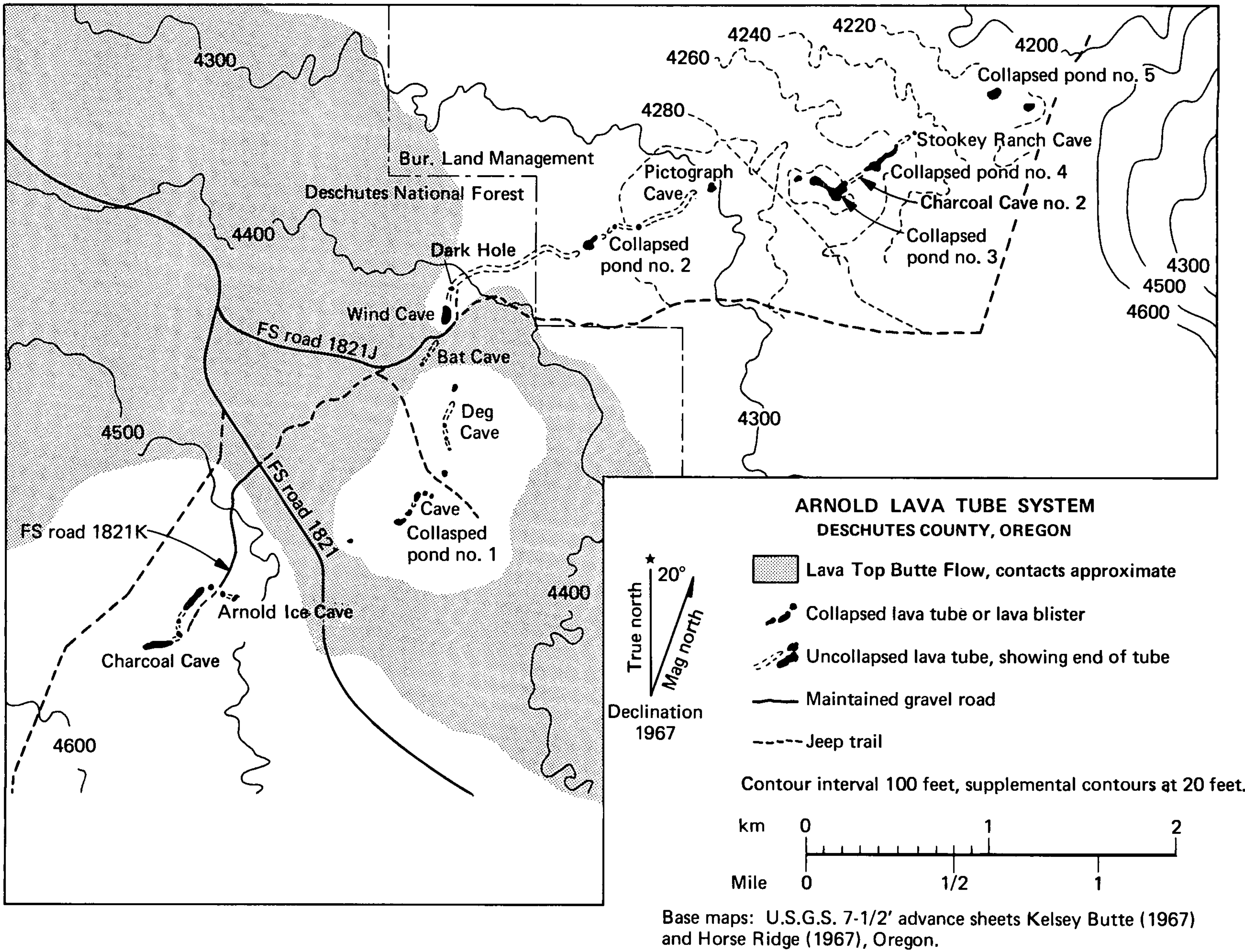


Figure 9. Map of Arnold Lava Tube System.

Figure 10. Oblique aerial view of upper Arnold Lava Tube system viewed uptube. (Photograph provided by Ranger E. Sloniker, Deschutes National Forest)

Charcoal Cave leads toward another very large collapse trench. The trench is approximately 32 m wide x 170 m long x 13 m deep and has a fairly consistent width and depth. The lava tube, before collapsing to form the trench, probably was rather large. The axis of Arnold System along this section forms a pronounced ridge, with the slope away from, and perpendicular to, the axis. This relationship is typical of the Arnold System; figure 12 illustrates three cross-sections across the lower part of the system. A surface ridge, or topographic swell, over the lava tube axis is common in many areas, including northern California (Modoc Lava Tube) and southern Idaho (Bear Trap Lava Tube). Ridges over lava tubes may be buried by subsequent lava flows and no longer be apparent.

At the downslope end of the trench, a small collapse pit has an uncollapsed segment leading a few meters beneath FS Road 1821K, trending toward Arnold Ice Cave (figure 9).

Arnold Ice Cave (SE 1/4, SE 1/4, SW 1/4, sec. 22, R. 13 E., T. 19 S., elevation 4530) is a well-known lava tube segment (from which the system name was derived) entered at the southeast wall of a collapse pit (figure 10). Descent into the tube is quite steep (up to 30°) and much of the passage floor is covered with thick ice sheets (figure 11). Uncollapsed lava tube length is less than 75 meters (slope length); the last 10 meters is somewhat more level, although the ceiling trends downslope 16° to meet the ice-blocked passage. Original lava tube walls and ceiling are preserved only near the end in a small cupola. Three distinct flow lines are visible on the southern wall, the remainder of the tube is marked by wall and ceiling spallation. Although Halliday (1952, p. 47) reported two small rooms leading from the ice-blocked passage, this study was conducted in early spring and ice apparently blocked entrance to these rooms. High porosity and poor conductivity of basalt make it an excellent natural insulating material which, in combination with the roof thickness (about 30 m near the terminus) and orientation of the tube entrance with respect to the sun, results in preservation of ice throughout the year. Early settlers in the Bend area visited Arnold Ice Cave to obtain ice, and at one time the ice was commercially mined. Deschutes National Forest designated the site as the Arnold Geological Area and has constructed a parking facility, pathway, and wooden stairway over the ice slope into the lava tube.

Arnold Ice Cave ends directly under a collapse depression, 30 m in diameter x 10 m deep. The depression is the last element of the upper section of Arnold Lava Tube System. Surface topography steepens downslope over the next 0.5 km to a shallow valley and Forest Service (FS) Road 1821.

## Middle Section

Photogeologic interpretation indicates parts of the middle section have been covered by younger Lava Top Butte Flow (basalt Qbf, Plate 3) originating from an irregularly shaped crater northwest of Lava Top Butte. The exact contact of the flow is difficult to determine. Bat Cave, modified by Lava Top Butte Flow, apparently is directly related to the Arnold System and formed in older basalt Qb. Other lava tubes and collapse elements are generally smaller and closer to the surface in the middle section than in the other two sections.

The middle section begins near FS Road 1821. Topographic slope rises away from the road northeast 180 m (Plate 1) to a collapse depression in SW 1/4, NE 1/4, SE 1/4, sec. 22, R. 13 E., T. 19 S., that is about 35 m in diameter and 8 m deep. A small uncollapsed lava tube segment 10 m long trends toward Arnold Ice Cave. No original tube lining is preserved and the passage ends in collapsed roof blocks. The east side of the pit shows layered basalt dipping toward the pit, indicating plastic roof deformation prior to failure.

Collapsed Lava Pond #1 (SW 1/4, NW 1/4, SW 1/4, sec. 23, R. 13 E., T. 19 S., elevation 4470 ft.). The next element in the middle section is a large irregularly shaped depression interpreted to be a collapsed lava pond. Figure 13 illustrates the pond configuration and its relation to the lava tube. A decrease of the Arnold Lava Tube System gradient (Plate 1) in this area probably reflects a lower flow velocity during lava tube formation. In active flows, reduced velocity often momentarily halts the flow and results in lava ponds. Renewed lava surges from the source vent ruptures the pond walls, and the flow continues its downslope course. During the ponded stage, a crust forms over the flow surface, its thickness dependent on the cooling time. When rupture occurs, liquid lava is drained from beneath the

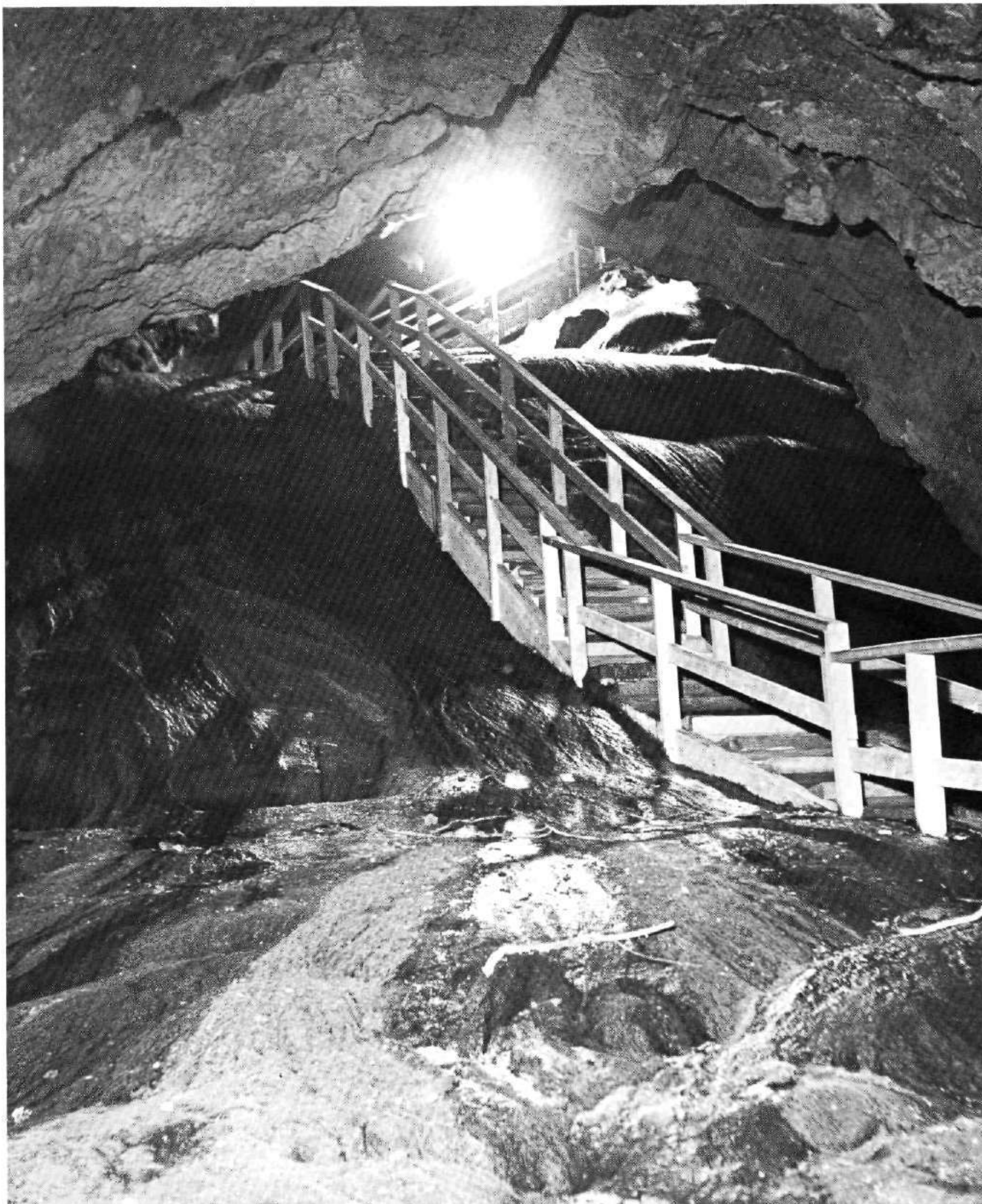

Figure 11. Arnold Ice Cave; view from the bottom of stairway up toward the cave entrance. Massive sheets of ice fill part of tube and cover the lower part of the staircase. (Photograph by Charlie and Jo Larson, Vancouver, Washington)

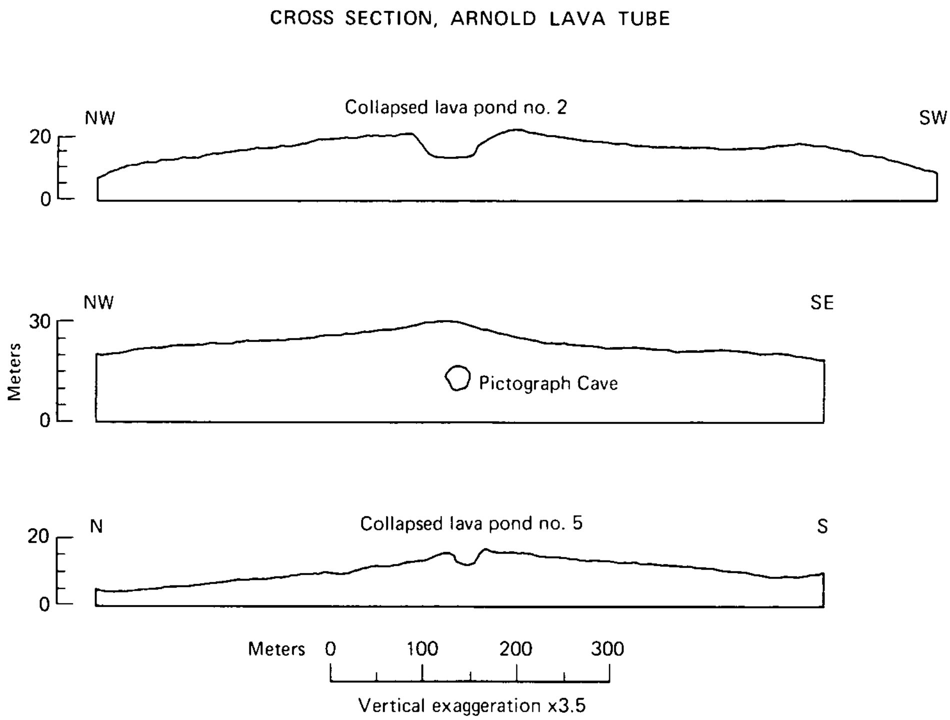


Figure 12. Cross sections, transverse to the lava tube axis, showing the development of a ridge over the axis.

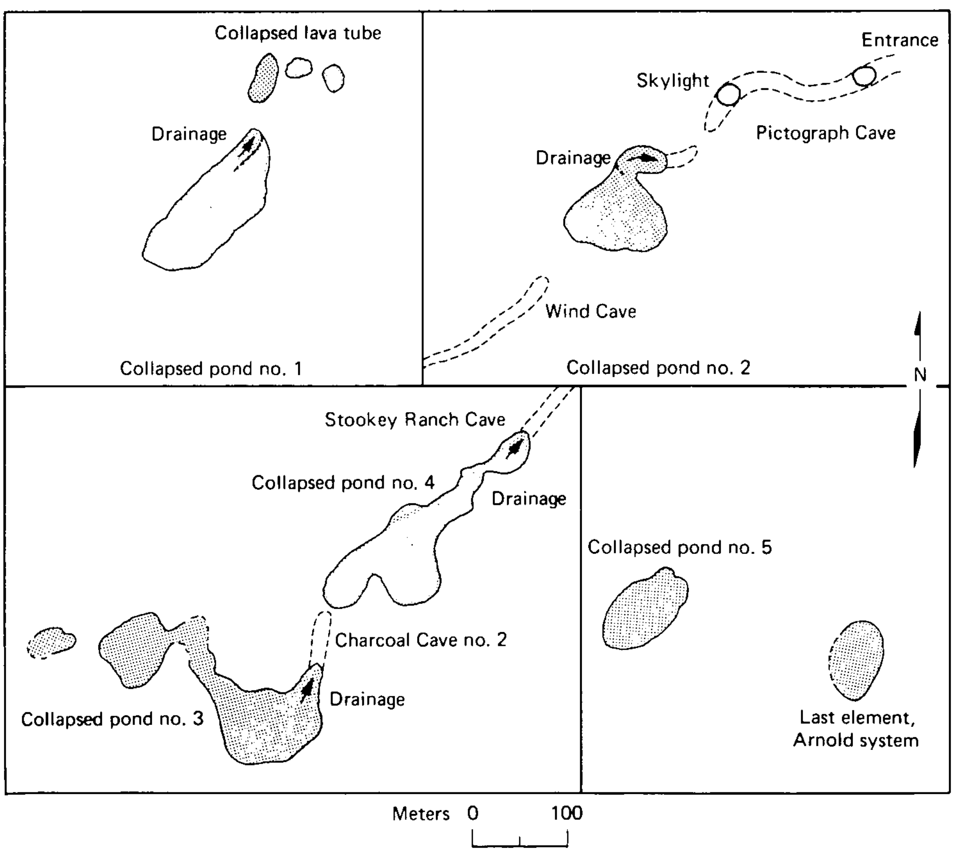


Figure 13. Diagrams of collapse lava ponds of Arnold Lava Tube System. The lowest part of each pond is on the downtube side of the pond.

crust, generally through lava tubes as was the case here, and the crust is lowered to the pond floor. The rim of Collapsed Pond #1 is about 3 m high and has layers of basalt dipping toward the depression, representing parts of the crust deformed during drainage. The deepest part of the structure (figure 13) is near the lower end and represents the tube that drained the structure. The lower end of this residual tube is blocked by collapse.

From the pond, nine depressions trend northward, downslope. Some depressions contain short uncollapsed lava tube segments and nearly all depressions have rims with inward dipping lava layers, an indication that initial collapse occurred while the roof was somewhat plastic. A small cave (inhabited by bats) in NE 1/4, NW 1/4, SW 1/4, sec. 23., R. 13 E., T. 19 S., elevation 4465 ft. (about 90 m southwest of a logging road), extends 40 m north. Most of the cave exhibits interior spallation; however, original walls and ceiling are preserved in the last 11 meters and white secondary mineralization covers much of the tube lining. The cave ends in sand and collapse blocks.

A short uncollapsed tube (40 m long by 23 m wide) connects two depressions in E 1/2, SW 1/4, NW 1/4, sec. 23, R. 13 E., T. 19 S. A small surface bridge (filled with rubble) exhibits plastic deformation on the upper surface and connects with the next downslope depression and the entrance to Deg Cave (NE 1/4, SW 1/4, NW 1/4, sec. 23, R. 13 E., T. 19 S., elevation 4445 ft). The first half of the cave passage is mostly basalt spalled from the ceiling and walls; the last 65 m displays original lava tube lining on the walls and ceiling; the tube ends in a cupola shaped chamber (about 2.5 m high, with the original ceiling intact) blocked by collapsed basalt. A shallow collapse depression, halfway between Deg Cave and Bat Cave, is in an area apparently covered by Lava Top Butte Flow (Qbf).

Bat Cave (NE 1/4, NW 1/4, NW 1/4, sec. 23, R. 13 E., T. 19 S., elevation 4425). This tube is distinguished by having two levels, one above the other. The upper level can be entered through a shallow collapse pit, or through a skylight entrance about 4 m in diameter. The crawlway between the two entrances makes the skylight more desirable for access to the lower level. The upper level trends toward Deg Cave (from the collapse depression) but ends in sand and collapse. From the skylight, the tube trends downslope on a sandy floor to an abrupt drop-off of about 3 m into the lower level. The drop-off can be negotiated (with caution) along a ledge at the far end. This section of the cave is the junction of the upper and lower levels and forms a single lava tube. Flow lines in the pahoehoe floor show that lava drained from the upper level into the lower tube. The lower tube is well preserved, exhibiting original lining material, lava stalactites, and glaze; it extends about 75 m upslope toward Deg Cave. An aa flow covers part of the floor and grades upslope into pahoehoe that has blocked the tube.

Heat, generated by the younger flow, was apparently sufficient to partly remelt the original lava tube lining. Figure 14 illustrates rupture of the lining on one side of the tube and subsequent draping of the lining toward the floor. Secondary mineralization covers much of the lining in the lower level. Bat Cave extends downslope about 40 m from the point of junction of the upper and lower levels. Most of the tube has basalt spalled from the ceiling and walls, and its lower end is blocked by collapse and sand.

Bat Cave is believed to have formed initially in basalt Qb as a part of the lava tube draining from collapsed Pond #1. The downslope portion of the middle section, from about Deg Cave, was covered by younger Lava Top Butte Flow. This flow may have entered the main lava tube through a now buried roof collapse below Deg Cave, flowed downslope, and sealed the upper end of Bat Cave. Younger lava may also have entered the upper level of Bat Cave and, as indicated by lava flow lines, drained into the lower level.

## Lower Section

The lower section originates near the intersection of FS Road 1821 J and the lava tube, in the same area as the contact between Lava Top Butte Flow (Qbf) and basalt Qb (Figure 9 and Plate 3). The lower section, contained entirely within basalt Qb, includes long, uncollapsed lava tube segments and large, irregularly shaped collapsed lava ponds. The first lower section element is a collapsed lava tube segment (on the north side of FS Road #1821 J) that connects through a short lava tube to a large trench. The trench leads north to Wind Cave entrance.

Wind Cave (SE 1/4, SW 1/4, SW 1/4, Sec. 14, R. 13 E., T. 19 S., elevation 4405 ft.). Wind Cave is the longest (1170 m slope length), largest (18 + m, maximum height), and most difficult lava

Figure 14. Bat Cave (Arnold Lava Tube System), lower level. Wall lining deformed plastically and curled away from the wall to the floor. (Photograph provided by Ranger E. Sloniker, Deschutes National Forest)

tube to traverse of the Arnold System. Most of the cave's upper two-thirds has great piles of basalt boulders, some a meter and more in diameter, along the floor. Many rubble piles are higher than 18 m and have angles of repose exceeding 22°. In profile (Plate 1), the series of rubble piles and corresponding ceiling domes, formed by basalt-layer spallation, gives the tube an undulating cross-section. The true lava tube profile, determined along uncollapsed ceiling sections and floor sections not covered by rubble, matches the surface topography fairly well, although some slopes along the floor toward the end of the tube are reverse to the surface topographic slope.

Despite massive spallation, many ceiling and wall sections preserve original lava tube lining and glaze, although in many places the lining is broken by polygonal fractures; minerals produced by weathering are prominent. Multiple flow lines, representing drainage stages of liquid lava, are preserved in some walls and can be traced for tens of meters. Some flow lines developed prominent gutters, or ledges along the walls.

In all but the last few hundred meters, Wind Cave is characteristically skull, or keyhole, shaped in cross section (Plate 2), giving the impression of an upper level and lower level. Considering the probable formational mechanisms for large lava tubes, this configuration is reasonable and is perhaps to be expected. During initial stages of formation, two mobile conduits may be stacked vertically, separated by a shear plane. In the case of Wind Cave, the intervening shear zone may have been so weakly developed that it was removed, or incorporated in the liquid lava, in the final stages of lava tube drainage. Thus, the size and shape of both upper and lower levels would be essentially maintained. Cross sections in straight lengths of the lava tube are symmetrical; in meander bends, cross sections are often asymmetrical, developing cut banks (figure 5) and slip banks.

Geological and structural details of Wind Cave observed during traverse are described by station number (Plate 2), keyed to the longitudinal profile (Plate 1).

Station 7. Darkhole skylight (named on the U.S.G.S. topographic quadrangle), formed by roof collapse, is a 4 m diameter hole about 7 m above the lava tube floor. Weathered basalt, sand, silt, and small basalt blocks drain into the tube through the skylight forming a conical debris pile. On the surface, a shallow, dimple-shaped crater has developed. Some lunar craters with this distinctive morphology may have formed in association with lunar lava tubes (Greeley, 1970). Interior spallation exposes shear plane surfaces and pahoehoe flow structures, visible in the spalled ceiling near Darkhole. On non-spalled wall and ceiling sections, glaze and small lavacicles (term for lava stalactites, Peterson and Groh, 1963) are preserved. In this area, a small feeder tube, about 1 m wide x 30 cm high, trends west into the wall about 2 m.

Station 13. This station marks the beginning of the keyhole shaped cross section, with well-defined upper and lower levels (Plate 2); uptube, the lower level is probably filled with spalled basalt boulders. The lava tube is nearly 13 m high and exhibits original wall and ceiling lining. Near the floor, the west wall lining ruptured and exposed massive basalt.

Station 17. A well-developed lower level cut bank and upper level slip bank formed in the meander bend of the lava tube. This relationship would indicate that the upper and lower levels were connected while the tube was rather fluid. Both levels are about equal in size. The ceiling, more than 18 m high, is one of the highest uncollapsed lava tube sections known.

Station 21. Prominent flow ledges, probably developed during liquid lava drainage of the tube, are visible here and continue downtube.

Station 22. This station is one of the largest cross sections in Wind Cave, about 18 m high x 16m wide, and exhibits seven distinct flow lines on both walls. Downtube (figure 5), flow lines are prominent and the cut bank in Station 23 is visible. A clinkery aa flow covers the tube floor and continues to the lava tube terminus.

Station 30. The lava tube is smaller from here to its terminus and is well preserved with little spallation. Upper and lower levels are nearly symetrical and of equal size. Original tube lining and

Figure 15. Wind Cave, Station 33. Plastic deformation of part of wall lining. Pencil is 13 cm long.

secondary mineralization are prominent. To the next station, the aa flow slope is uphill, reverse to the overall tube slope.

Station 33. Upper level is pinching out, and its loss is reflected by steeper surface slope over the tube (Plate 1). The aa flow shows crude flow lines indicating uptube direction of flow. Part of the wall lining is deformed, possibly from heat generated by subsequent flow exposed on the floor, or by plastic deformation during lava tube drainage, and is peeled away from the wall (figure 15). Lava gutters, 0.5 m wide, are along both walls near the floor and continue nearly to the tube terminus.

Station 38. Wind Cave Terminus. The last 68 m of the lava tube has a gentle upslope gradient (up to 5°), measured along the aa flow and reflected in the ceiling gradient to a lesser degree. The tube terminus is formed by the ceiling abruptly pinching down to the floor. The terminus face has some lining preserved and is slightly clinkery. Slabs spalled from the ceiling and walls are piled at the ceiling-floor juncture and it is difficult to determine the exact nature of the contact. It is probable, however, that aa lava seals the tube.

Collapsed Lava Pond #2 (SW 1/4, NW 1/4, SE 1/4, sec. 14, R. 13 E., T. 19 S., elevation 4360 ft.). Wind Cave terminus is within 6 m of Collapsed Lava Pond #2 rim (Plate 1). The pond, diagramed in figure 13, is 112 m wide, up to 8 m deep, irregular in outline, and has rims raised 2-3 m above ground level. Some basalt layers in the rim dip away from the pond. The pond is situated on a topographic high, with ground slope away from the structure in all directions; however, considering the overall slope of the Arnold System, the pond is in a relatively level section. Average surface slope over Wind Cave is 1° 36'; approximate slope of the pond (measured at the rim) is 0°. The structure is interpreted to be a collapsed lava pond, formed (during active lava flow) by Wind Cave emptying into a temporarily halted part of the flow. The pond apparently was inflated slightly (indicated by the dip of the rim) by hydrostatic pressure of the lava tube. In final stages of drainage and plastic deformation of the system, some liquid lava drained from the pond into Wind Cave, accounting for the slope reversal near the tube's terminus and the aa flow (representing the more viscous, low temperature fluids of the drainage stage). Deflation of the pond may have caused the roof over the tube near its juncture with the pond to deform by gravity, thus sealing the tube.

Fluid lava drained the pond through a downslope lava tube at the north edge of the pond (figure 13). The upper part of the tube collapsed, leaving a trench 32 m wide x 10 m deep. The trench leads to a short uncollapsed tube extending about 40 m north. Tube interior has massive spallation (terminus is blocked by collapsed basalt) and many blocks in the roof appear rather unstable.

Pictograph Cave (SW 1/4, NE 1/4, SE 1/4, sec. 14, R. 13 E., T. 19 S., elevation 4340 ft.) This tube was named from Indian pictographs painted on the cave entrance north wall. From the entrance, the tube extends upslope, passes under a skylight, and continues toward Collapse Lava Pond #2. Most of the tube along this section has massive ceiling collapse and piles of basalt boulders. In size and cross section Pictograph Cave closely resembles Wind Cave. Downslope from the entrance, the first 190 m is marked by massive collapse plus small amounts of sand; the remainder of the tube is well preserved and has a prominent aa flow on the floor. The following station descriptions begin upslope, nearest Collapsed Lava Pond #2.

Station 8-A, upslope end of Pictograph Cave; tube is blocked by ceiling and wall collapse. The surface survey indicates that the tube is separated from Collapse Pond #2 by only a few meters.

Station 6-A, located in the center of a roof break-through (very large skylight) has a maximum width of 30 m measured perpendicularly to the tube axis. Sagebrush and other vegetation grows in the sand and detritus washed into the collapse.

Station 3-A, has a keyhole shaped cross section (Plate 2) very similar to parts of Wind Cave. Although most of walls and ceiling are spalled, some original wall lining is preserved and five distinct flow lines are visible in the lining.

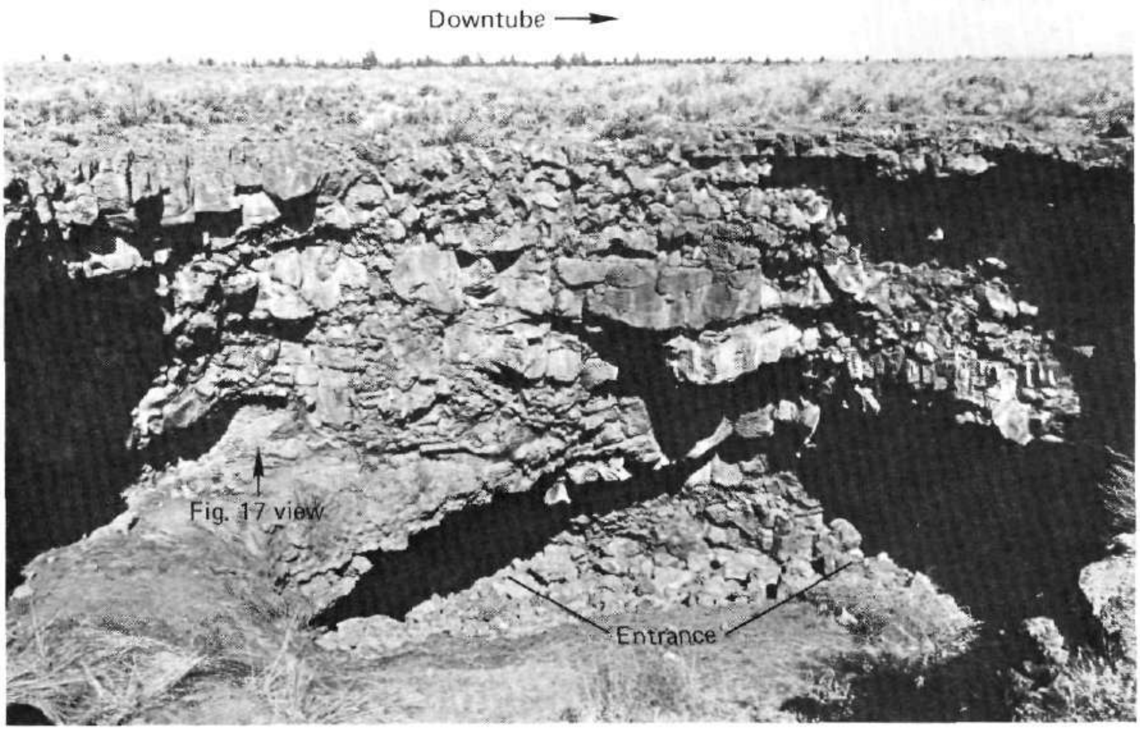


Figure 16. Entrance to Pictograph Cave, vertical distance from surface to the entrance is about 16 m. Lava in the roof is deformed and may represent filled lava tubes and/or channels.

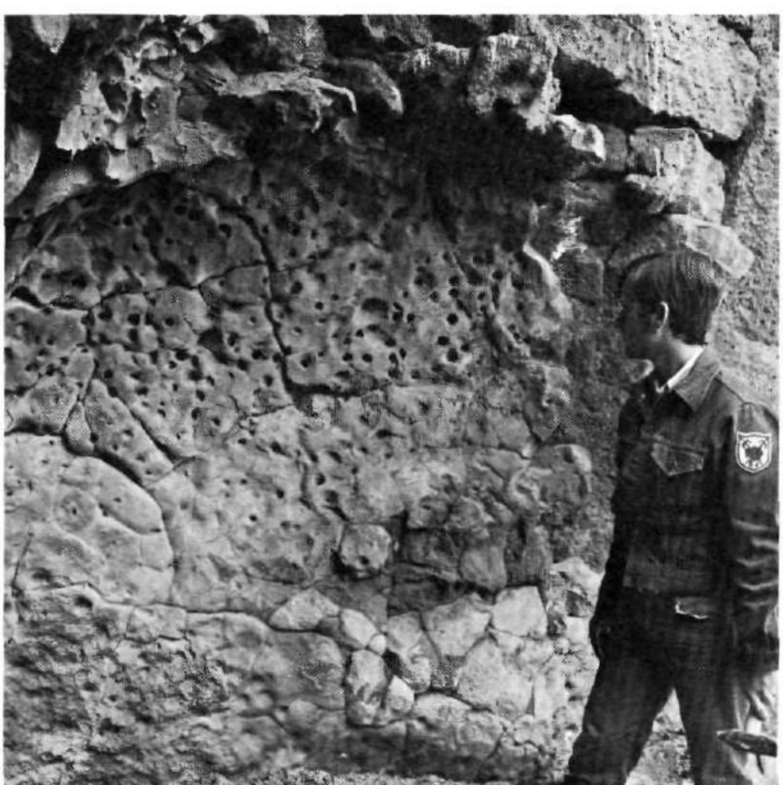

Figure 17. Entrance to Pictograph Cave, small alcove possibly representing a gas pocket. The lining (covering layered lava) is pockmarked with cavities formed contemporaneously with the lining.

Entrance to Pictograph Cave is through a roof collapse and a slumped soil bank. The roof here is very thick, more than 16.5 m, and seems an unlikely place for collapse to occur. The roof (figure 16), however, exhibits disrupted and contorted basalt layers, possible filled lava tubes, and a structure that may represent a gas pocket. These structures apparently weakened the roof leading to eventual collapse. The possible gas pocket (figure 17) is a large alcove (4 to 5 m high) situated on a ledge above the lava tube in the west side of the entrance collapse. It is lined with very dense basalt (specific gravity 2.58) having a prominent pock-marked appearance resulting from smooth holes about 5 cm in diameter x 7 cm deep. The holes appear to be primary structures formed contemporaneously with the lining; the holes have however, been lined with a thin layer of secondary mineralization.

Station 2 shows original lava tube lining and flow lines (figure 18). Some ceiling lining has spalled away to reveal the structure behind the lining. The exposed surface is very smooth with polygonal cracks and secondary mineralization and may represent a second layer of lining. Although not common in the Arnold System, multiple linings are known to occur in lava tubes.

Station 8 to station 9 B has on both walls a well-developed flow line that is undulating in profile; the down-tube side of the flow line dips about 15° and probably represents fairly rapid lava flowage.

Station 12 shows a well-developed cut bank in the tube meander bend and the relationship of the aa floor flow to the tube. On both sides of the floor about 1 meter of pahoehoe laps up on the tube walls. The center of the pahoehoe is covered with the younger aa flow. Aa covers the floor from Station 9B to the end of the tube. The roof remains fairly constant in thickness (profile, Plate 1) and the ceiling is parallel to the surface, with about the same slope. The floor, however, is fairly level initially, then trends upslope the last 30 m to the terminus. Apparently, the aa lava flow was unable to drain and sealed the tube at the terminus.

Pictograph Cave ends at the rim of a shallow surface depression, probably representing a small sag in the tube roof that could have developed during the latter stages of cooling. A similar depression is about 500 m downslope; however, unlike the former depression, it shows definite rims and collapse structures. Basalt layers dip toward the depression, representing possible plastic deformation. The collapse depression leads directly to Collapsed Lava Pond #3.

Collapsed Lava Pond #3 (NE 1/4, NE 1/4, SW 1/4, sec. 13, R. 13 E., T. 19 S., elevation 4285 ft.). This structure is a large, irregularly shaped sinuous depression (figures 13 and 19) interpreted to have formed similarly to Collapse Lava Ponds # 1 and #2. Like these structures, Pond #3 formed in a level area at the base of a steep lava tube section; the surface slope over Pictograph Cave is about 1°2', the slope over the pond is approximately 0°. Many sections of the pond rim dip toward the depression and indicate the pond may not have been inflated, as was Pond #2. Some wall sections have small tubes leading radially from the pond.

The pond trends downslope through a series of depressions that are generally deeper than the floor of the pond. These depressions, some are 7 m deep, may represent individual chambers or cells within the body of the pond. Entrance to Charcoal Cave #2 is at the north end of the pond.

Charcoal Cave #2 (NW 1/4, NW 1/4, SE1/4, sec. 13, R. 13 E., T. 19 S., elevation 4280). The roof over the entrance to this lava tube segment has a small feeder lava tube similar to the tubes found in the pond rim. Most of Charcoal Cave #2 is spalled, although there are small sections of tube lining on the walls and ceiling. Near the end, the tube opens into a cupola about 13 m high × 7 m wide and has slabs of lining spalled from the walls and ceiling.

Collapsed Lava Pond #4 (SE 1/4, SW 1/4, NE 1/4, sec. 13, R. 13 E., T. 19 S., elevation 4270 ft.).

This pond, formed like the others of Arnold System, has rims 3 - 4 m above ground level and deepens downslope, toward Stookey Ranch Cave. Most of the pond is fairly narrow and may have developed a fairly thick crust before crustal failure. Drainage of the pond evidently was slow because much of the crust is intact on the floor, indicating that it was lowered gently by withdrawal of the supporting fluid.

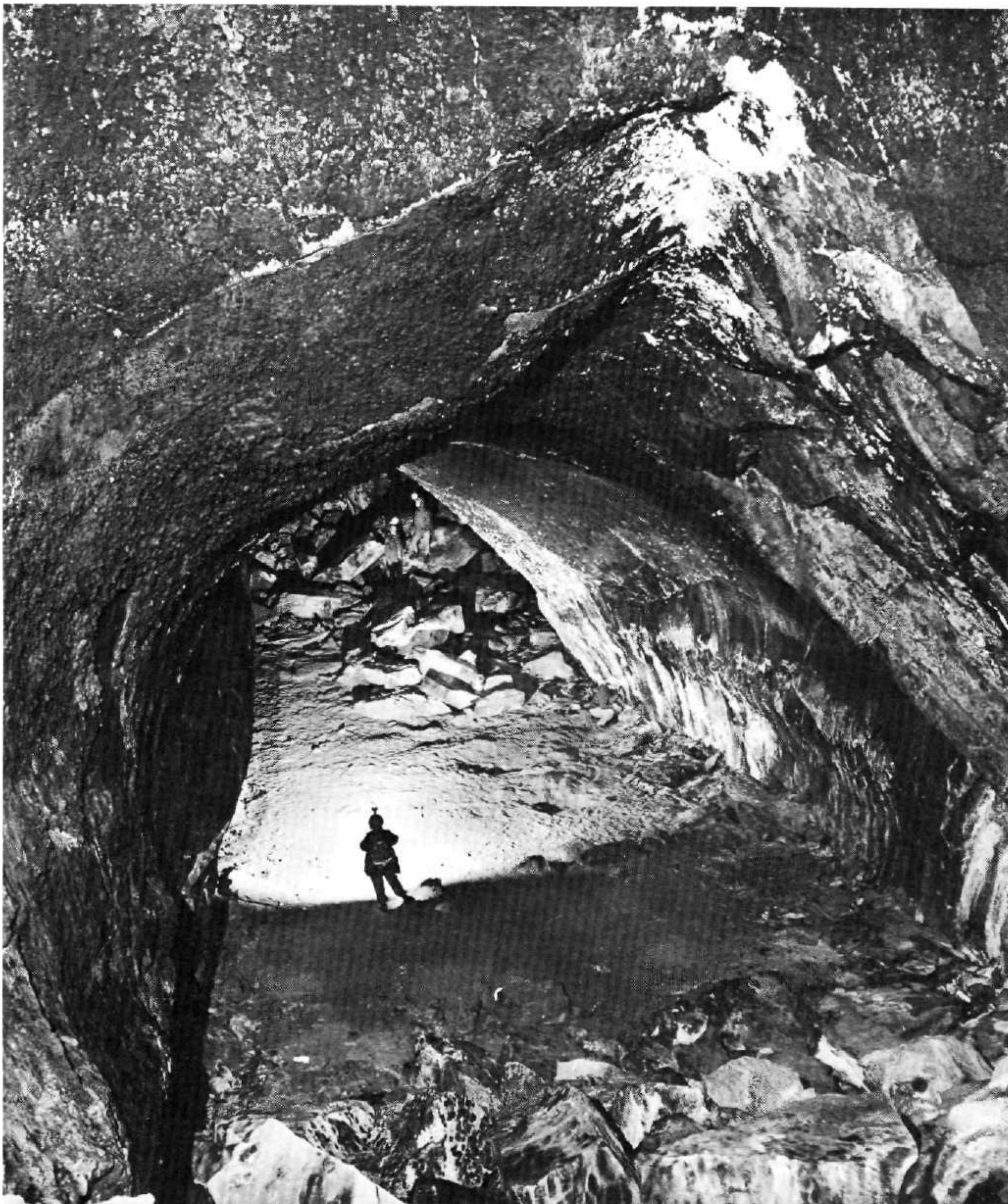

Figure 18. Pictograph Cave, downtube from entrance, showing original tube lining and ceiling unaltered by collapse; about half the tube probably has been filled in by sand and other detritus in this section. (Photograph by Charlie and Jo Larson, Vancouver, Washington)

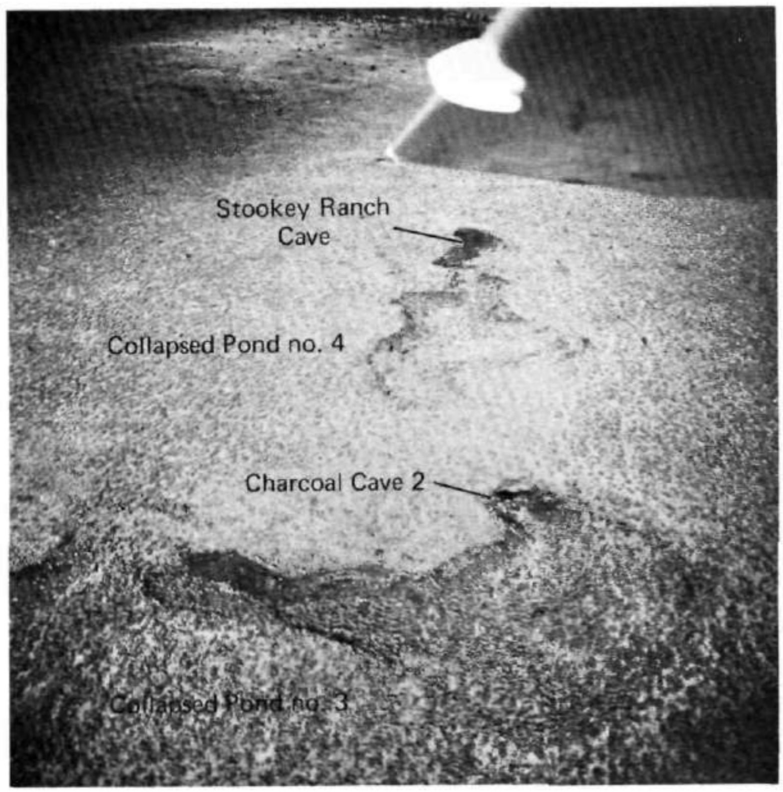


Figure 19. Oblique aerial view of Collapsed Lava Ponds No. 3 and No. 4 and the entrances to Charcoal Cave No. 2 and Stookey Ranch Cave, viewed downslope.

Stookey Ranch Cave (SE 1/4, SW 1/4, NE 1/4, sec. 13, R. 13 E., T. 19 S., elevation 4265 ft.). The roof over the entrance to this cave has a small chamber, possibly a blocked feeder tube, trending parallel to the main tube. About 25 m from the entrance, a small passage leads upward from the tube and connects with a shallow surface collapse depression. Sand and surface debris drains into the lava tube through the passage. The passage trends northeast over piles of collapse basalt blocks and sand to the terminus; many of the basalt blocks in the roof are unstable. The last 60 m of the tube is somewhat more stable and has smooth walls and ceiling. Parts of the wall have broken away, exposing clinkers partly fused by pahoehoe lava. The end of the tube trends upslope over a large sand pile. Sand evidently is draining into the tube from a surface collapse depression. Stookey Ranch Cave is the last known uncollapsed element of the Arnold Lava Tube System.

Collapsed Lava Pond #5 (SW 1/4, NW 1/4, NW 1/4, sec. 18, R. 14 E., T. 19 S., elevation 4240 ft.) is a small collapsed lava blister with rims about 2 m above ground level. Like the other collapse lava ponds described, the deepest part of the depression is at the downslope end, apparently representing the last part of the pond to drain. No uncollapsed tube was found in association with the pond; however, the structure is very shallow and eroded, and the tube may be completely filled with collapse blocks.

A faint depression 80 m east of pond #5 is the last discernable element of the Arnold System. Downslope, the terrain is covered with alluvium and younger basalt flow Qyb. If the system continues, these two units probably filled in, or covered, collapse sections and buried uncollapsed elements. There are, however, small lava caves reported in the basalts 4 km north toward U.S. Highway 20, and beyond. These lava caves could be part of the Arnold System, or could be tubes developed in basalt Qyb; none were examined.

## Horse Lava Tube System

In contrast to Arnold Lava Tube System, Horse Lava Tube System is composed of complex anastomosing, parallel, and often disconnected lava tubes, all formed apparently in a single basalt flow. Many segments probably formed within the flow independently of other segments. Some sections were probably only partly drained of fluid lava, or were plugged by subsequent flow units. The relationship of individual segments to the overall system is apparent in map view (Plate 3). In addition to uncollapsed lava tubes, all depressions found by aerial and ground reconnaissance, indicated on topographic maps, and visible on aerial photographs are shown in figure 20. The depressions are often elongate parallel to the direction of Horse Lava Tube System and from field observations are interpreted as collapsed structures. Some structures are collapsed lava tubes, others probably represent collapsed lava ponds similar to those associated with the Arnold System and ponds not directly associated with tubes, but which resulted from drainage of liquid lava beneath a partly cooled, thin crust.

Individual segments trend nearly parallel to regional topographic slope. The system forms a broad, low ridge approximately two kilometers wide (indicated on topographic maps) similar to the ridge formed by Arnold Lava Tube System, and represents the most mobile part of the lava flow.

Elements of the system are located in basalt Qb, the oldest unit mapped in the area and the same basalt in which the Arnold System formed. Both the source and terminus of Horse Lava Tube System is covered by younger Qyb and Qyb 1 basalts. The system can be traced from Lewis Farm Cave (SE 1/4, NE 1/4, NW 1/4, sec. 15, R. 12 E., T. 18 S.), downslope more than 11 km to Barlow Cave (NE 1/4, NW 1/4, NW 1/4, sec. 19, R. 13 E., T. 17 S.). Straight-line slope of the system is about 0° 28'20", about two-thirds as steep as the Arnold System. Because the source and terminus of the system are concealed by superposed younger basalt, it is not possible to determine the total system length. The tube system probably extends beneath the younger basalt toward the source and northeast toward the flow terminus. Individual tube descriptions begin with Lewis Cave at the source end and progress northeast toward the terminus.

Lewis Farm Caves (location given above, elevation 3745 ft.) consist of two lava tube segments, one of which was examined (figure 21). The tube is entered through a skylight and a vertical drop of

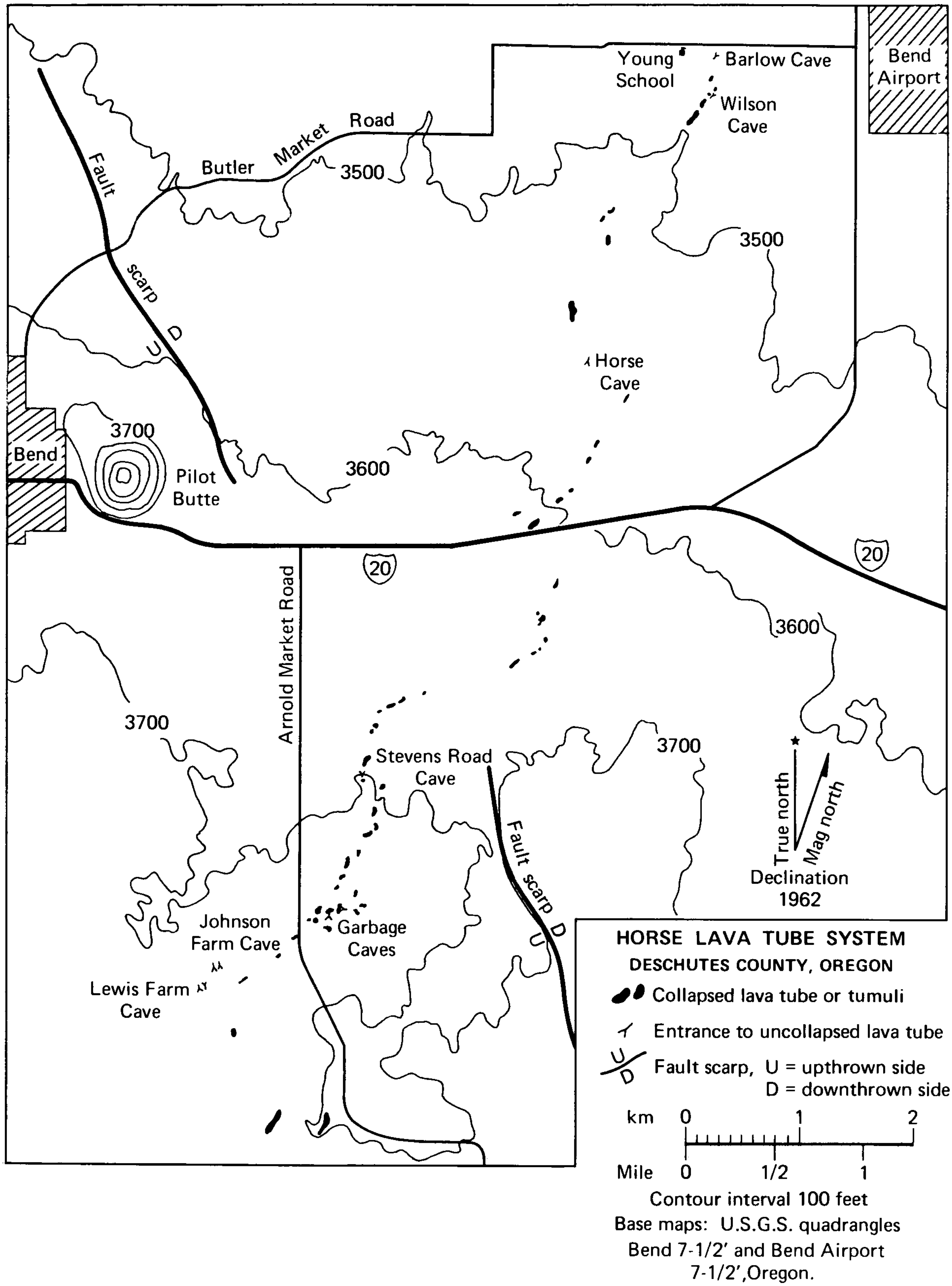


Figure 20. Map of Horse Lava Tube System.

**LEWIS FARM CAVE**
**(HORSE LAVA TUBE SYSTEM)**
**DESCHUTES COUNTY, OREGON**
**Entrance in E 1/2, NE 1/4, NW 1/4, Sec. 15, R 12E, T18S**

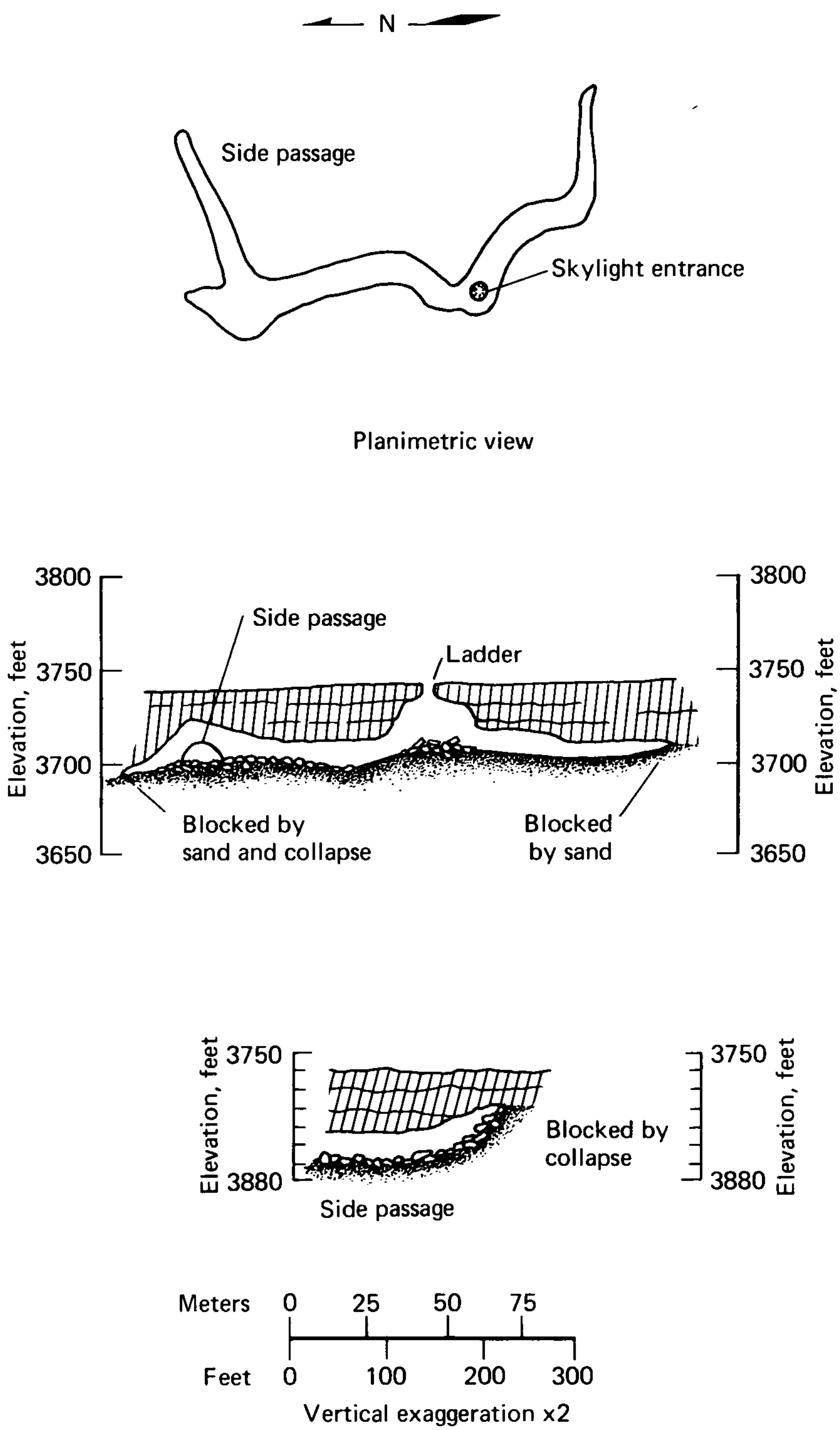


Figure 21. Diagrams of Lewis Farm Cave, Horse Lava Tube System.

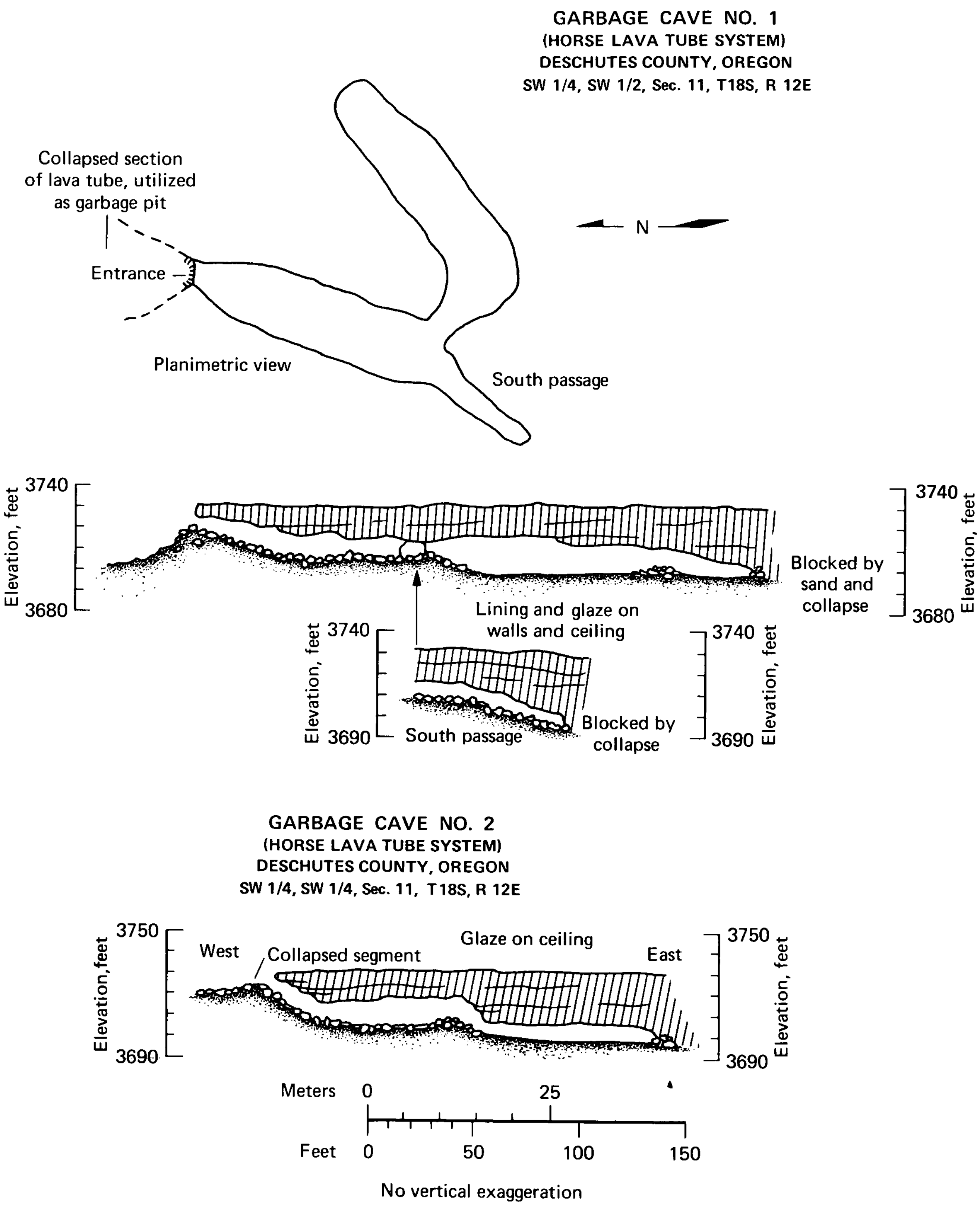


Figure 22. Diagrams of Garbage Caves No. I and No. 2, Horse Lava Tube System.

about 7.5 m. It trends north and southeast from the entrance, with the north passage extending 110 m over sand and basalt blocks before terminating in sand blockage. Parts of the west wall have well-developed pahoehoe flow lines. A side passage, 14 m wide and 55 m long, extends northeast and has pahoehoe flow lines along sections of the southern wall.

The passage southeast from the entrance is about 90 m long, sinuous, and has well-preserved original walls and ceiling with tube lining and glazing present. Although most of the floor is covered with sand, original floor (pahoehoe) is exposed in a short section. The tube pinches out with the ceiling and sand floor converging.

Two caves on the Johnson Farm (NW 1/4, NW 1/4, NE 1/4, sec. 15, R. 12 E., T. 18 S., elevation 3730 ft.), east of Lewis Farm, were not surveyed. Entrances are through crawlways in roof collapse near the farm house and service buildings.

Garbage Caves, east of Arnold Market Road in W 1/2, SW 1/4, sec. 11, R. 12 E., T. 18 S., elevation 3730 ft., are located in Bend City garbage dump. Two individual lava tube sections were examined, although there are reportedly several other large caverns in the area. Garbage Cave #1, (Figure 22) is nearest the present parking area; entrance to the tube is a crawlway leading from a large collapsed lava tube trench currently being filled with refuse. The tube consists of three sections: a west room, 35 m x 10 m, and east room of nearly equal dimensions, and a south passage extending 17 m from the west room. In all sections floors consist of sands and blocks collapsed from the ceiling and passages are terminated by ceiling collapse. Some ceiling and walls in the east room exhibit lava tube lining and glazing. Solid basalt on the south passage floor may represent an in situ part of the original flow.

Garbage Cave #2 (figure 22) is about 150 m northeast of Cave #1 and consists of an uncollapsed lava tube segment about 51 m long. It leads from the end of a large sinuous depression (collapsed lava tube segment) and parallels the general trend of the Horse Lava Tube System. Sand and collapse blocks compose the floor, and the tube is blocked by collapse. Small glaze patches are preserved on parts of the ceiling toward the passage end.

Many collapses in sec. 11, R. 12 E., T. 18 S. (figure 20) have small uncollapsed lava tube segments. Most consist of passages extending a few meters, or tens of meters, and are blocked by collapsed blocks from the walls and ceilings.

Stevens Road Cave (NW 1/4, NE 1/4, NW 1/4, sec. 11, R. 12 E., T. 18 S., elevation 3700 ft.) is a small lava cave entered through a collapse on the south side of Stevens Road. The cave is about 32 m x 27 m and from the shape of the interior apparently is the uncollapsed part of a lava blister. The floor is comprised of sand and basalt blocks; some of the original ceiling is preserved.

Horse Cave (SW 1/4, NW 1/4, SE 1/4, sec. 25, R. 12 E., T. 17 S., elevation 3560 ft.) is a well-known lava tube east of Bend and the lava tube system name was derived from it. Entrance to the tube, through a collapse depression, leads to parallel and interconnecting passages (figure 23) that are typical for Horse Lava Tube System. Except for painted walls and litter left by vandals, the ceilings and walls are well preserved, exhibiting flow lines, lava tube lining, and glaze. The floor is covered by sand and the ends of the passages are blocked by sand. Depth of the sand apparently fluctuates considerably. Some walls display multiple sand and silt varves to a height one meter above the present floor. The roof is fairly thick compared to the diameter of the lava tube and probably explains the lack of abundant collapsed sections. One collapsed section formed a skylight over the eastern passage.

Wilson Cave (NE 1/4, SW 1/4, NW 1/4, sec. 19, R. 13 E., T. 17 S., elevation 3490 ft.) is entered at the south end of a collapse depression and extends 75 m over sand floor before it is blocked by sand and spalled basalt (Plate 2). Two prominent troughs representing collapsed segments of the tube extend southwest from the terminus of Wilson Cave. A small crawlway, trending toward Barlow Cave, at the northern end of Wilson Cave collapse was not examined.

Barlow Cave (NE 1/4, NW 1/4, NW 1/4, sec. 19, R. 13 E., T. 17 S., elevation 3490 ft.) entrance is on a fence line about 90 m south of Butler Market Road. Entrance, through a skylight, leads

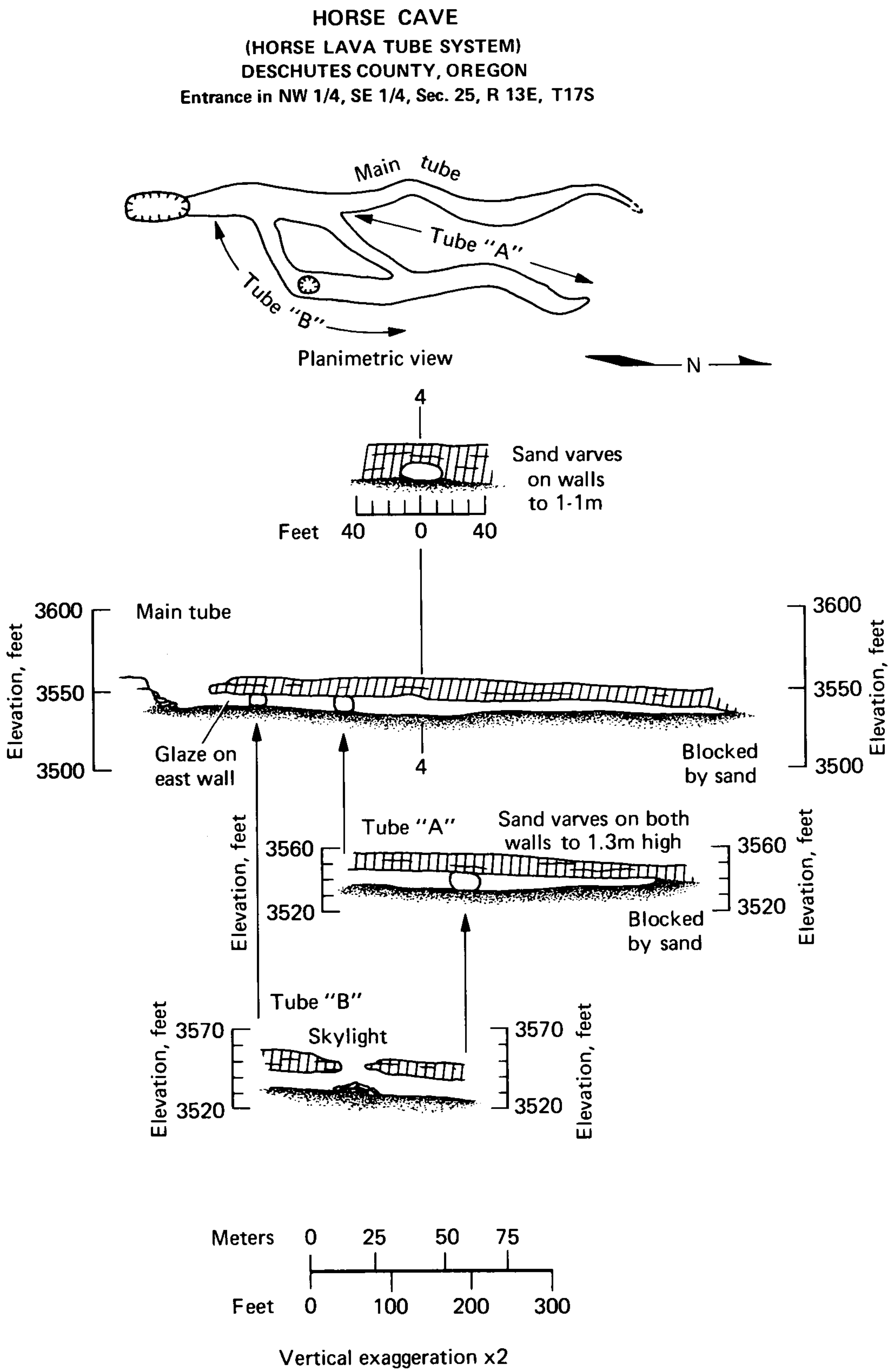


Figure 23. Diagrams of Horse Cave, Horse Lava Tube System.

to a north passage extending about 51 m before blockage by ceiling collapse and sand (Plate 2). At the south end the tube is plugged by wet sand and collapse blocks. An elongate pond about midway between the southern terminus of Barlow Cave and the entrance to Wilson Cave is probably part of the lava tube that collapsed while the roof was semi-molten and plastic. The floor of the depression is relatively impervious and water is retained in the pond throughout much of the year; however, fractures evidently permit some seepage of water into the tube, indicated by wet sand in Barlow Cave.

A prominent pillar and side passage are located about halfway in the southern part of the lava tube. The side passage leads about 15 m from the main tube and terminates in a circular collapse depression with a crawlway leading to the surface. The depression was formed by drainage of molten lava beneath the partly cooled surface crust before the crust was sufficiently thick to support its weight. As a result, the plastic crust sagged under its own weight (figure 6), ruptured, and created the collapse depression. The depression containing the pond, described above, probably formed similarly but the crust did not rupture.

Many caves have been reported in the area east of Bend. Although some are lava tubes, many are small uncollapsed or partly collapsed tumuli. Undoubtedly, there are many undiscovered and poorly known lava tube segments belonging to the Horse Lava Tube System.

## Miscellaneous Lava Tubes

This group includes descriptions for lava tubes in the Bend area not belonging to any apparent system or complex. The tubes were surveyed because they met criteria set forth above and because they provide data on quantitative geomorphology of lava tubes, i.e., roof thicknesses, lava tube diameters, gradient of lava tubes, etc. They include the following: Lava Top Butte Caves, South Ice Cave, Skeleton Cave, Boyd Cave, and Lava River Cave.

### Lava Top Butte Caves (sec. 31, R. 13 E., T. 19 S.)

Five lava caves (caves formed under lava blisters and lava tubes) were examined in the Lava Top Butte Flow. This flow originates from a vent (S 1/2, SE 1/4, sec. 31, R. 13 E., T. 19 S., elevation 5230 ft.) halfway between Lava Top Butte and an unnamed cinder cone (hill 5282) in section 31 (Plate 3). The vent is an irregularly-shaped depression with maximum depth of about 14 m. The flow, north downslope from the vent, consisted of very fluid pahoehoe which formed numerous tumuli pressure ridges and small lava tubes. Cave entrances are on a line extending nearly due north about 1.3 km from the vent.

The first cave is a short tunnel passing through the north rim of the vent crater (NW 1/4, SE 1/4, SE 1/4, sec. 31, R. 13 E., T. 19 S., elevation 5200 ft.). Its passage (13 m long x 2 m high, maximum) contains a few preserved sections of tube lining and small lavacicles. The tube probably formed in one of the last basalt flow units issuing from the vent crater. The second cave is situated to the north, a few hundred meters downslope from the vent crater rim. This cave is in the side of a pressure-ridge and is not considered a lava tube. It is about 10 m long x 1.5 m high x about 2 m wide and is blocked by sand. The third lava cave is in SE 1/4, SE 1/4, NE 1/4, sec. 31, R. 13 E., T. 19 S. (elevation 5160 ft.), on a small ridge. It is about 15 m long x 6 m wide with no original tube lining visible. The fourth lava cave (SE 1/4, NE 1/4, NE 1/4, sec. 31, R. 13 E., T. 19 S., elevation 5090 ft.) is in the side of a small pressure ridge. It has a sand floor and extends less than 10 m under the basalt. The fifth cave is discussed below.

Log Crib Cave (NE 1/4, NE 1/4, NE 1/4, sec. 31. R. 13 E., T. 19 S., elevation 5050ft.) is the best-developed lava tube of those found in the Lava Top Butte Flow. The tube, entered through a roof collapse, is apparently part of a small lava tube complex composed of parallel and branching passages. Log Crib Cave, named for a small log structure in the main chamber, has a north passage about 15 m long and a south passage 14.5 m long. Lava tube lining, glaze, and lavacicles are present throughout the cave. Another short lava tube (about 20 m long) is located near Log Crib Cave and may connect with it through collapsed sections. Both tubes form a small domal structure on the flow surface.

All five lava caves are situated along a broad ridge on the east side of the Lava Top Butte Flow. The caves probably represent the most fluid part of the flow at the time of formation. Undoubtedly, there are many other lava tubes and lava blister caves in the vicinity.

South Ice Cave (SE 1/4, NE 1/4, sec. 18, R. 14 E., T. 23 S., elevation 5020 ft.).

South Ice Cave is a Forest Service recreational facility about 3 miles south of the area shown on Plate 3. It lies about 0.3 km west of the junction of FS Road 2219 and FS Road 2226, southeast of Newberry Caldera, and is the only lava tube examined in this area (figure 24). From the entrance through a large roof collapse the tube trends both north and south (figure 25). The 50-m-long north passage ends in roof and wall collapse. The south passage extends more than 200 m over collapsed basalt blocks and ice to the collapse terminus. Surface water seeps through the roof - the tube is dripping wet - and freezes. Ice glazes most of the passage, and icicles and ice stalagmites are common toward the end of the tube. Near the terminus, part of an aa flow is visible on the floor. South Ice Cave is a fairly large lava tube, and in places is more than 16 m wide and 6 m high. The tube formed in basalt erupted from one of the Newberry Caldera flank flows.

Skeleton Cave (NE 1/4, SE 1/4, SW 1/4, sec. 4, R. 13 E., T. 19 S., elevation 4195 ft.).

Skeleton Cave, a well known lava tube in the Bend area, was named from prehistoric bear and horse fossils discovered by Phil Brogan in the late 1920's (personal communication, Phil Brogan). The Forest Service has designated Skeleton Cave a Geological Area and recreational facility. The tube is well preserved and exhibits many structures typical of lava tubes. In map view (Plate 3), Skeleton Cave trends nearly straight downslope and forms a broad ridge on the surface over the tube. Like Arnold and Horse Lava Tube Systems, Skeleton Cave developed in basalt $\overline{Qb}$. Skeleton Cave has few spalled areas and most of the lining, glaze, and lavacicles are preserved. Because little collapse has occurred (figure 26) and the tube cross sections are unaltered, Skeleton Cave affords the opportunity to relate cross section configuration to planimetric course (Plate 2). In meander bends, cross sections often develop cut banks and slip banks; in straight lava tube sections, the cross section is in general, symmetrical. Some walls have lava benches formed during latter stages of drainage. Structures in pahoehoe floor flows include festoons indicating general flow direction, small ponded areas on the floor, and occasional "back-eddies."

About midway down the lava tube, a tributary lava tube (138 m long) junctures with the main passage from the west (Plate 2). The tributary tube is smaller than the main passage, and clinkery pahoehoe, probably representing cooler lava from the final stages of formation, drained from the tributary into the main passage. A secondary tributary (37 m long) drained into the main tributary tube. Floors of both tributaries are a couple meters higher than the main lava tube floor. The tributary tubes may have originated from more fluid parts of the flow which intersected Skeleton Cave.

Entrance is through a large roof collapse leading to the upper part of the tube. Collapsed basalt blocks the lava tube upslope from the entrance. The roof here is about 2.4 m thick (measured from the true ceiling, evidenced by ceiling lava lining, to the surface), which is relatively thin compared to the roof thickness for the upper half of the tube (4.6 to 8.4 m thick). The relatively thin roof may explain why the tube collapsed only at the entrance.

Sand entering through the collapse and washing downslope through the tube covers the floor from the entrance to the junction with the tributary.

Station 7 is on a meander bend and has a well-developed cut bank. In addition to forming a cut bank, the over all height of the tube increases appreciably from 2.4 m to 5.8 m. Pahoehoe flow patterns are present in the east wall lava bench.

Station 16 is the juncture of the tributary tube from the west and marks the end of the exogenous sand. An aa flow on the floor is present and continues to the end of the tube. Judging from the clinkery character of the lava in the tributary tube, aa in the main lava tube downslope may have originated from the tributary; however, because sand covers the original flow above the juncture, it is difficult to establish the source.

Figure 24. South Ice Cave, viewed toward entrance with collapse blocks in background and layered lava exposed in right wall. Picture taken in late summer when most of the seasonal ice has melted, forming a pool in the foreground. (Photograph by Charlie and Jo Larson, Vancouver, Washington)

Station 19 is in a slight meander bend and the slope steepens from 8° to 32°. The cross section of the tube is nearly circular, possibly in response to the steeper slope, and remains circular until the slope lessens to 8° at about Station 24. The lava tube profile (Plate 2) shows that the surface slope is also steeper, to about Station 22 where it levels off. The tube, however, continues to plunge to Station 23 and as a result, the roof thickens to about 13.5 m, remaining thick to the terminus.

In the last 90 m to the end, the floor is littered with blocks spalled from the ceiling and the passage is blocked by roof collapse. The terminal 30 m of tube is comparatively steeper and is about 18 m below the surface; the surface slope increases upward toward a small pressure ridge beyond the tube terminus.

Boyd Cave (SE 1/4, SE 1/4, NW 1/4, sec. 8, R. 13 E., T. 19 S., elevation 4285 ft.).

Boyd Cave (Plate 3) is in many ways similar to Skeleton Cave. It is a well preserved lava tube, little collapsed, and exhibits flow structures in pahoehoe of the walls, ceiling, and floor. Some of the tube is spalled and sand is draining into the tube through roof fractures. Tube cross sections are typically asymmetrical in meander bends (Plate 2). Unlike Skeleton Cave, Boyd Cave roof is very thin, probably less than 1 m thick in some places. Small feeder tubes are visible at several stations. Most feeders extend from the main passage a few meters, or less, and are plugged.

Entrance to the tube is through a 3 m diameter skylight, via a Forest Service stairway. The tube extends about 25 m upslope and is blocked by sand; however, the tube probably continues upslope beyond the blockage. Sand covers the flow downslope in the tube about 75 m, evidently having washed down from the skylight. A prominent pahoehoe flow line is on the east wall about 1.5 m above the floor. The flow line continues down tube and is usually visible on both walls, although it may be better developed on one wall than the other.

Station 4. A roof fracture, extending to the surface, permits surface sand to drain into the tube, forming a large conical pile of sand in the tube (figure 7).

Station 5. marks the end of sand in the upper part of Boyd Cave. The floor has two flows, a lower pahoehoe flow and a younger aa flow (superimposed on the pahoehoe) that developed lateral levees. These flows continue to the terminus and are probably present uptube beneath the sand.

Station 8. The roof here is extremely thin, possibly less than 1 m where spallation has occurred. There is a prominent pahoehoe bench on the west wall.

Station 16 is in the middle of extensive collapse. The roof here is also quite thin and live roots from surface plants are growing through the ceiling.

Station 18 A small feeder tube leads west. Flow lines on the main tube floor show that lava flowed from the main passage into the feeder tube and plugged it.

Station 21. Another roof fracture, similar to the one described at Station 4, is allowing sand to drain into the tube (figure 8). Sand covers the floor of the tube downslope 200 m and the fracture is apparently the source. There is a crawlway about 40 cm high over sand from this station about 7 m downtube.

Station 33 in cross section is a well-developed cut bank with aa pasted high on the east wall, evidently as a result of centrifugal force as the active aa flow rounded the meander bend. The lava tube continues 10 m beyond this station before the ceiling lowers to form a passage less than 1 m high. A crawlway over aa continues 22 m further, then closes even lower. The tube was not measured to the end. The roof thickens appreciably over the crawlway and the surface slope rises downtube.

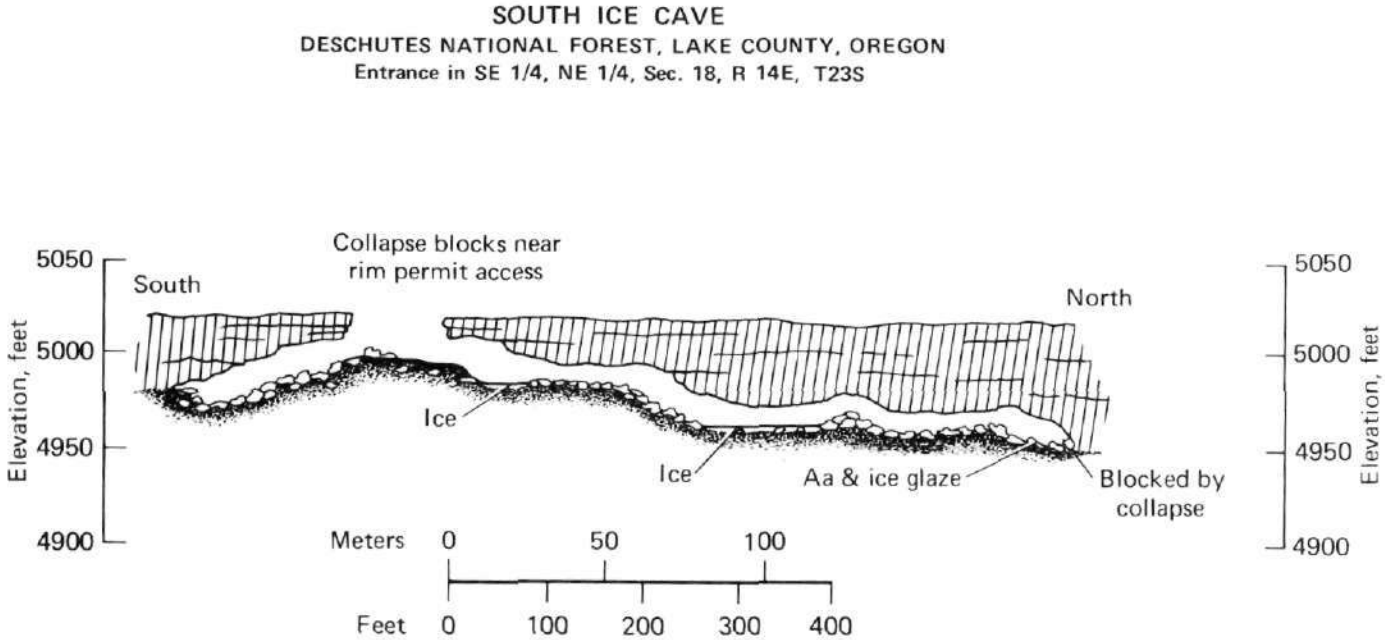


Figure 25. Diagram of South Ice Cave.

Figure 26. Skeleton Cave interior. Lava tube is nearly circular.

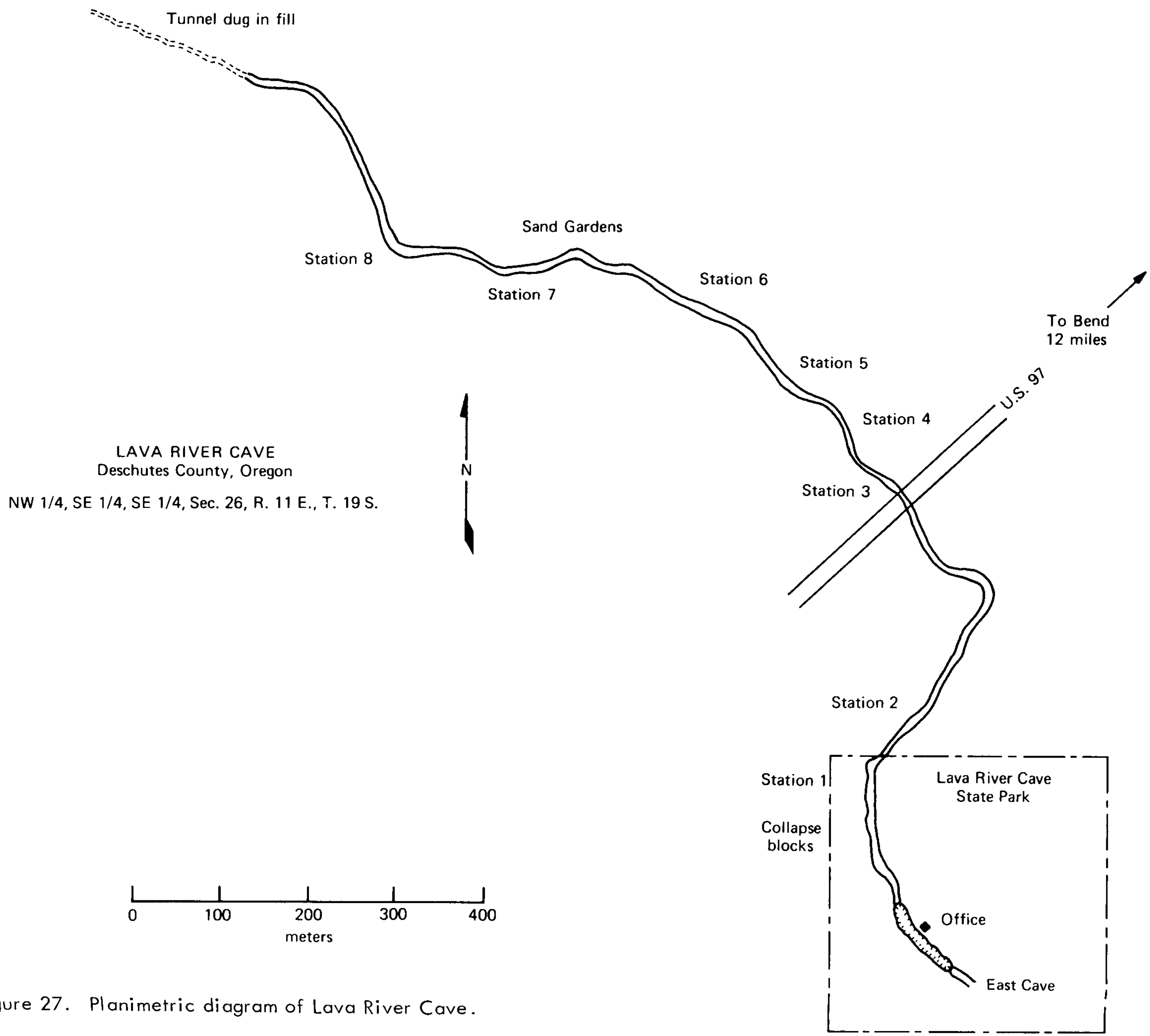


Figure 27. Planimetric diagram of Lava River Cave.

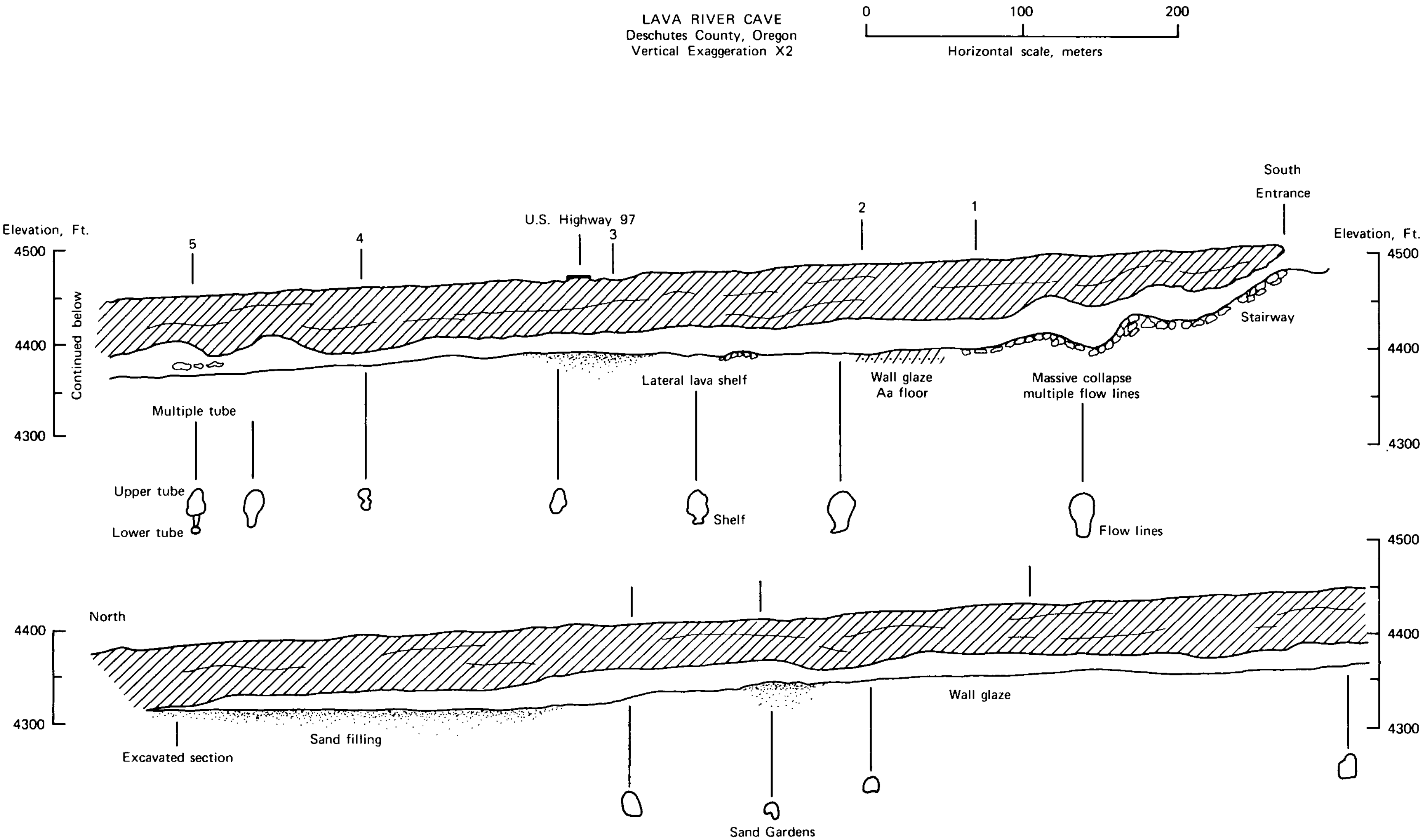


Figure 28. Longitudinal profile of Lava River Cave.

Lava River Cave (NW 1/4, SE 1/4, SE 1/4, sec. 26, R. 11 E., T. 19 S., elevation 4507 ft.).

Lava River Cave (figures 27 and 28), formerly known as Dillman Cave and now preserved as a State Park open to the public, is the longest uncollapsed lava tube examined in the field area. Its location is shown on Plate 3. The tube exhibits many structures characteristic of lava tubes, including well-preserved wall-lining, original floor flows of aa and pahoehoe, lateral flow lines, massive interior spallation and filling of the tube by detritus. The roof, as much as 22 m thick in places is fairly uniform in thickness throughout its length (figure 28; tube survey from Oregon Dept. of Highways and Jim Nieland). From exposures of collapsed parts of the tube near the entrance, there appears to be at least one younger flow, about 3 m thick, that has covered the flow containing the tube. This "burial" of the tube by a subsequent flow appreciably thickened (and strengthened?) the roof and may account for the relatively long uncollapsed lava tube section.

From the collapse trench entrance, the tube extends both north (the main section, open to the public) and southwest. The southwest section was not examined; however, it reportedly (Knutson, 1964) extends more than 300 m over spalled blocks and is eventually closed by collapse.

Entrance to the tube is at the northwest end of a 92-m-long trench, a collapsed part of the tube. The first few hundred meters of the tube are marked by extensive interior spallation and massive piles of collapsed blocks interspersed with short sections of original wall (figure 29). Some wall sections exhibit flow lines and lava tube lining. Beyond the collapsed section, the tube is rather large, about 16 m high by 17 m wide, and it has a skull-shaped cross section similar to Wind Cave. In many sections, the lining appears to have torn free from the wall while partly molten and to have slid part way down the wall. In other areas, the partly cooled lining ruptured and permitted still molten lava to extrude from behind the lining. The east wall at Station 1 displays streamlets of lava as much as 3 cm wide and several meters long that have been extruded from behind the lining in many areas. (Figure 30 illustrates the tube cross section near Station 1.)

At Station 2 the tube lining ranges from 20 to 45 cm thick. Lava clinkers, rather than lava layers, are exposed behind the lining in many areas. The clinkers may have formed as a result of gases trapped between the lining and the main body of the lava flow. In the next 300 meters, much of the tube has prominent lava shelves extending a meter or more into the tube from one or both walls. The shelves may have formed during lava flow of fairly constant level within the tube, allowing the lava to accrete on the walls. The shelves are up to 0.5 m thick and generally have small lavacicles on the underside.

Station 3 marks thick deposits of sand along most of the floor (Figure 31). The sand apparently covers the lower part of the tube, burying the lava shelves (see cross section, figure 28), and reduces the height of the tube to 2.5 m in some places.

At Station 4, the tube is much smaller, about 6 m wide x 2 m high. Two distinct linings can be seen here and the floor displays prominent aa gutters along both walls. Within 30 m the tube enlarges to more than 13 m in height. The walls display delicate lava formations protruding at right angles to the lining. Some of the formations and parts of the wall are covered with secondary minerals and cave slime.

Station 5 locates a section of multiple vertically stacked lava tubes in which an upper tube parallels a lower tube for a distance of about 30 m with intermittent, vertical connecting passages. Lava flow patterns indicate that lava flow was contemporaneous in both levels, with the upper level eventually draining into the lower level. Over the next 300 m the tube gradient flattens somewhat. The floor is composed of aa intermittently covered with sand and the walls often show glaze and lava-cicles.

At Station 6 the State Park has constructed a small wood barrier and designated the area as the "sand garden." Sand covers most of the floor from this point to the tube terminus. The name for the area is derived from the unusual "fairy castle" structures formed in the sand (Figure 32). The structures result from surface water draining into the tube and eroding the sand. It is likely that most of the sand has

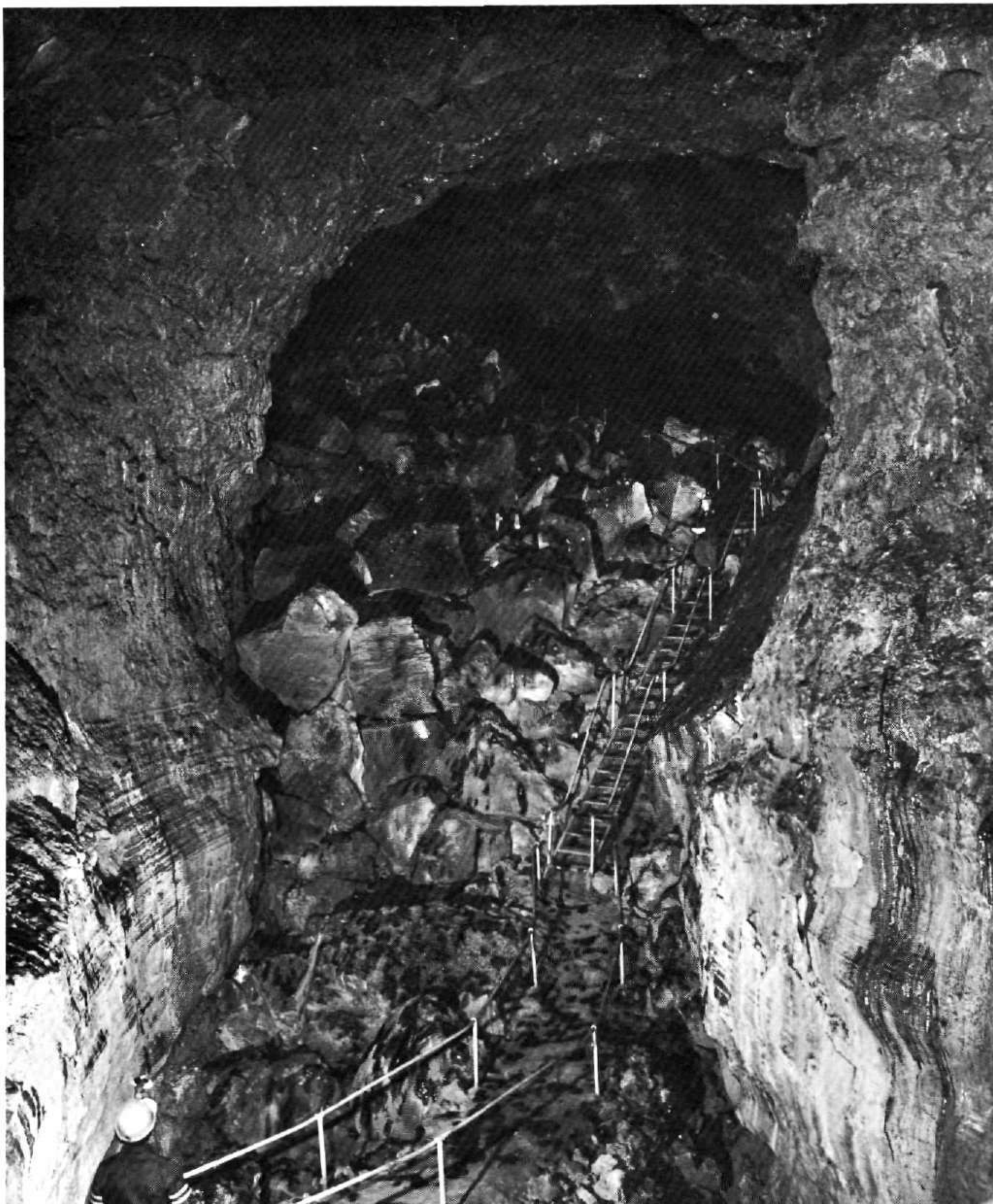

Figure 29. Lava River Cave near entrance showing massive roof collapse in background and multiple flow lines in lava tube lining, left foreground. (Photograph by Charlie and Jo Larson, Vancouver, Washington)

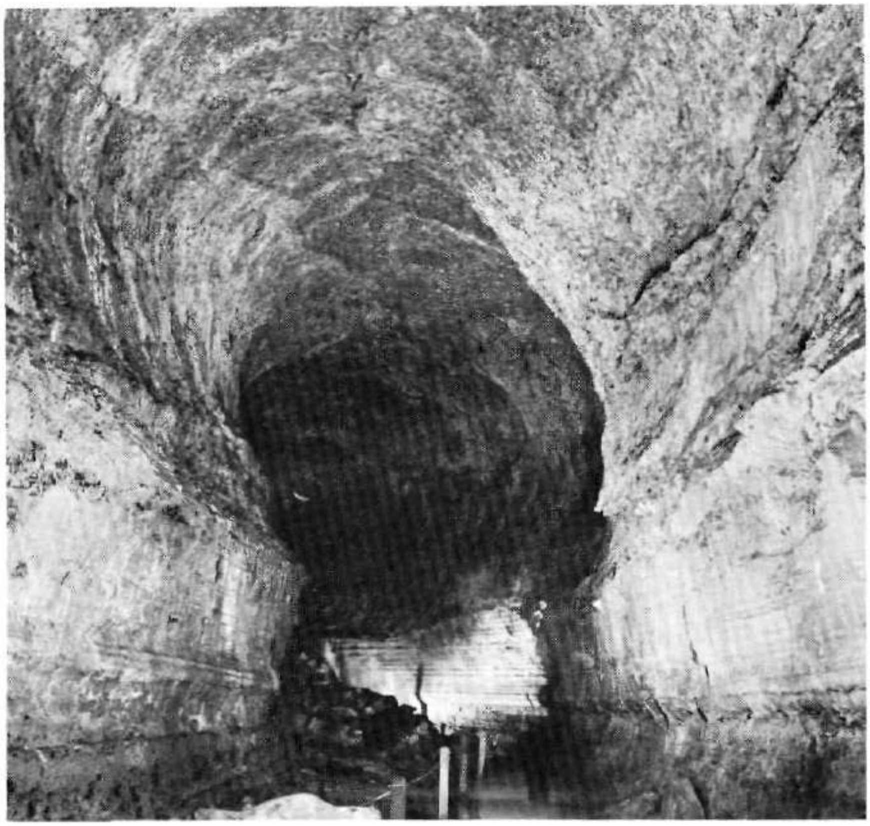

Figure 30. Lava River Cave interior cross section near Station 1.

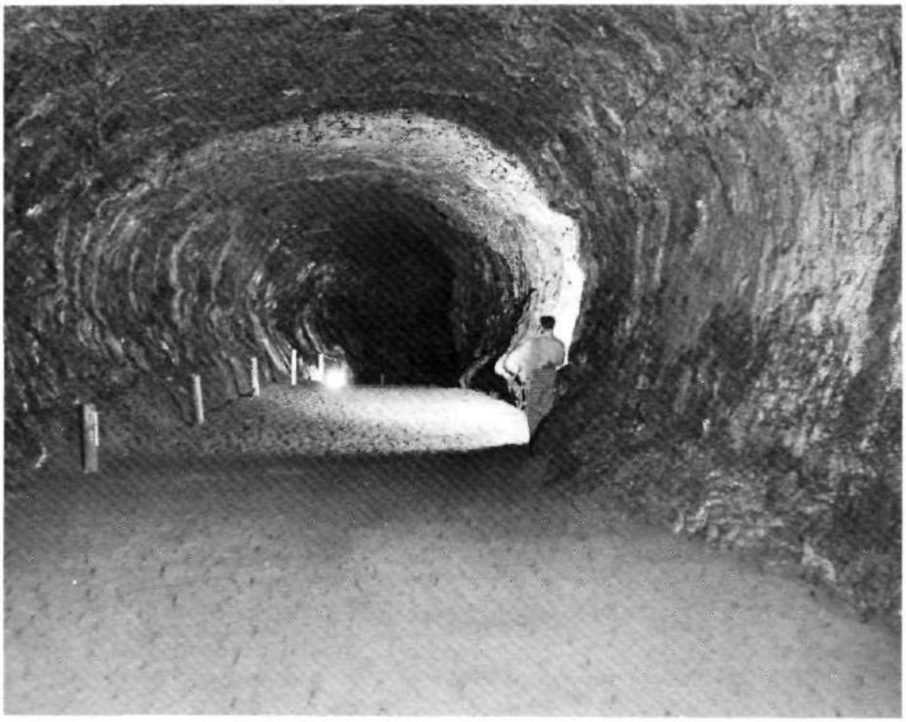

Figure 31. Lava River Cave interior showing oval cross section in foreground, merging into an asymmetric "cutbank" in the background and the tube turns toward the right. Sand along the floor has washed in, partly filling the tube. (Photograph by Oregon State Highway Department)

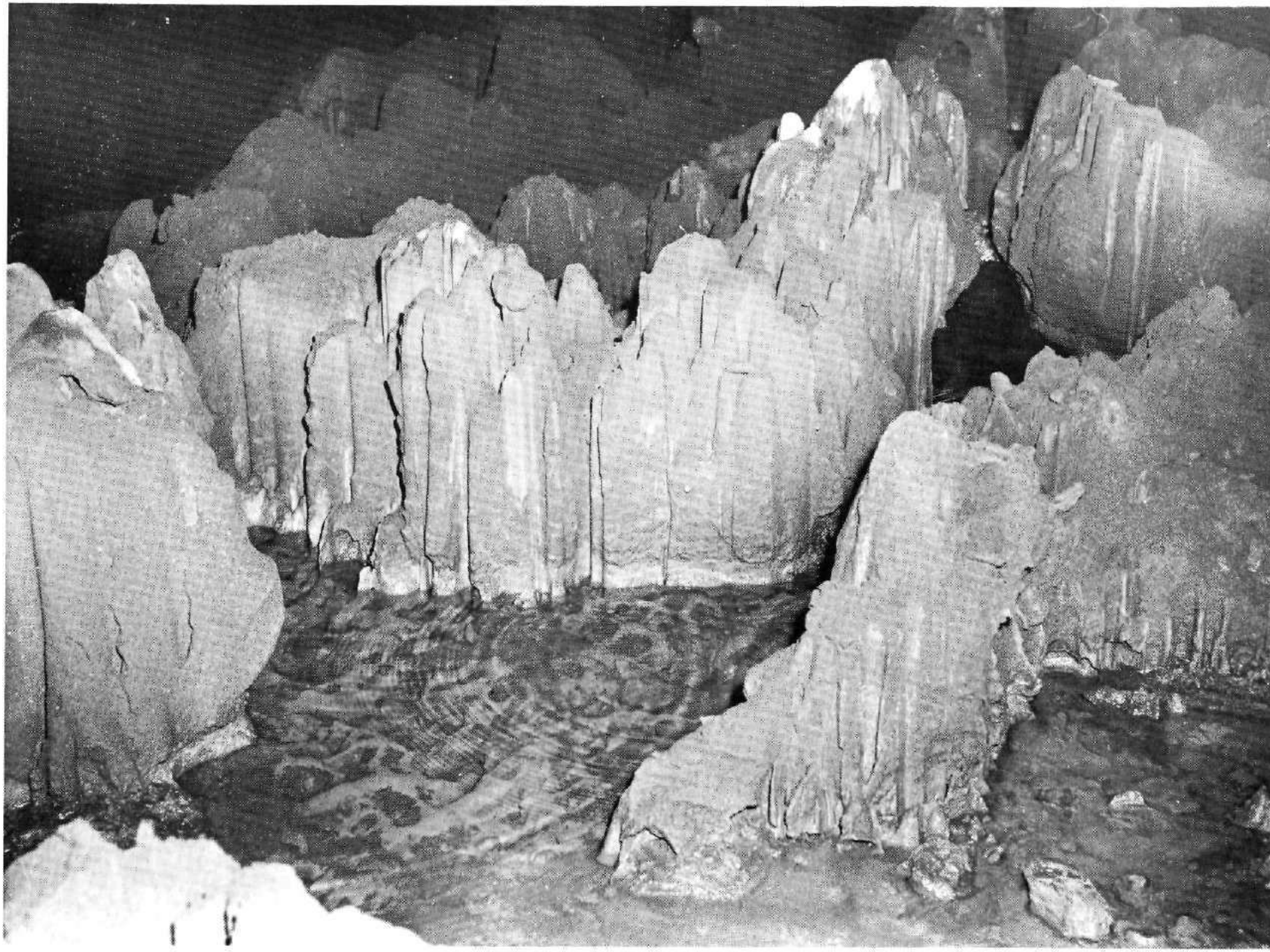

Figure 32. Lava River Cave interior at the Sand Gardens showing the erosive effect of water dripping from the cave roof.
(Photograph by Oregon State Highway Department)

drained into the tube through fractures similar to Boyd Cave. At Station 7, a trench along the east wall exposes 3 m vertical thickness of sand (Figure 33).

Station 8 marks a section of the tube in which the wall lining has collapsed and exposes reddish clinkers. Wall lining ranges from 20 cm to 1 m. The tube cross section is asymmetric, illustrating a typical cutbank along the meander bend in the lava tube. Sand fills more and more of the tube until the tube is completely filled.

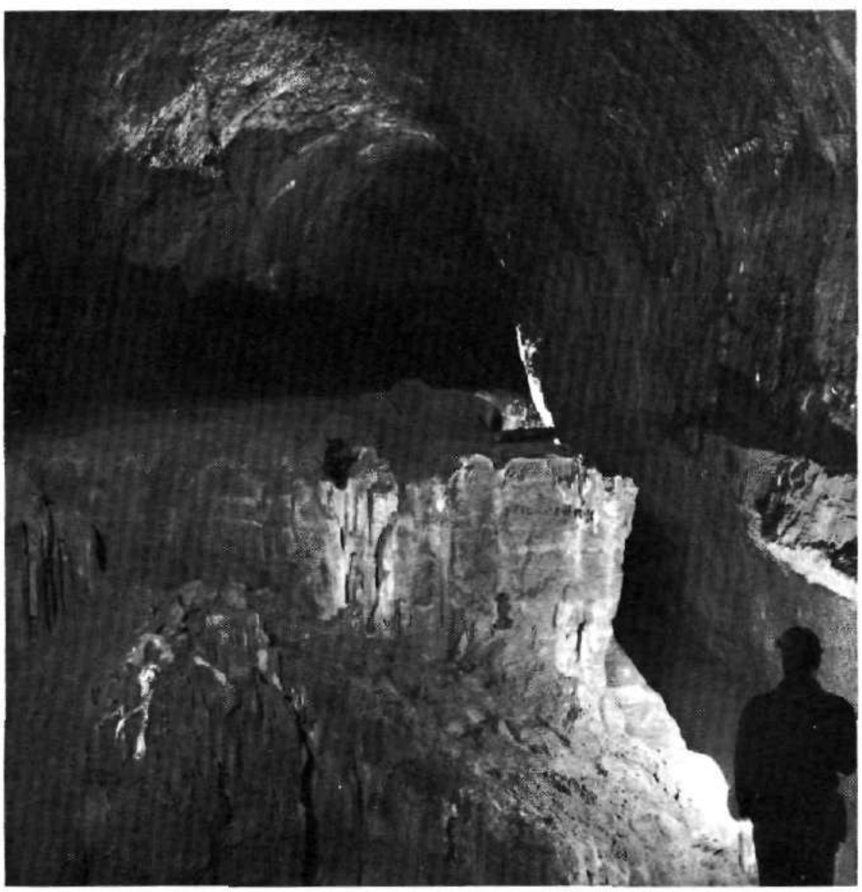

Figure 33. Lava River Cave interior cross section near the Sand Gardens illustrating the large quantity of sand that has entered the lava tube.

## CONCLUSIONS

Lava tubes near Bend, Oregon, provide an opportunity to study long, uncollapsed tube segments, trenches resulting from collapsed lava tubes, surface features related to tubes, and permit speculation on the formation of lava tubes. There appear to be at least two types of lava tubes with each type formed in a distinctive manner. One type, the "major lava tubes," occurs in the Bend area. This report essentially confirms the mode of origin proposed by Ollier and Brown (1965) for the formation of Australian lava tubes. Their theory concerns development of shear planes in active lava flows leading to layered lava. Layered lava and lava-tube linings were found in most lava tubes near Bend.

Some lava ponds, evidently formed in direct association with lava tubes on gentle gradients, appear to result from momentary halts of the advancing lava flow. In some cases, ponds were inflated slightly by hydrostatic pressure of the lava tube feeding the pond. Depending upon the length of time and cooling rate, a crust of variable thickness formed over the pond. Eventually, flow continued downslope movement from beneath the crust and the pond collapsed. Drainage of the pond occurred through lava tubes at the downslope edge of the pond.

With few exceptions, most lava tubes examined east and southeast of Bend belong either to Arnold Lava Tube System or Horse Lava Tube System. Both systems formed in basalt Qb, originating from fissure eruptions from the outer flanks of Newberry Caldera. Even though the source ends are buried by younger basalt flows, the systems are large and can be traced for several kilometers. Arnold System is composed of comparatively large lava tube segments along a single trend, interrupted by large collapsed lava ponds. In contrast, Horse System is composed of generally smaller lava tube segments that are parallel, branching, and often disconnected. Small depressions along the general trend probably represent individual drained pockets of molten lava within the main body of the flow. The difference between the two systems is attributed to the difference in gradient. Arnold System is about 35% steeper than Horse System and the flow may have been deeper and had a higher velocity, permitting large, vertically elongate lava tubes to develop. Horse System, with the more gentle gradient, may have formed in a thinner, more sluggish flow. Branching, meandering, and discontinuous lava tube segments possibly result from low velocity flow conditions.

Several possible lunar analogs are posed by Bend lava tubes. Drainage craters, formed in association with lava tubes typified by Wind and Boyd Caves were discussed in relation to lunar structures previously (Greeley, 1970). Collapsed lava ponds and collapsed lava tubes on the Moon could certainly be large structures. If, through the study of terrestrial counterparts, lava tube diameter and planimetric pattern can be related to lava flow thickness and gradient, it may be possible (through scaling considerations, such as reduced gravity) to apply these same relationships to lunar lava flows.

Although the lava tubes near Bend provided much information, additional data are required for quantitative geomorphic and additional geological relationships. The lateral and horizontal extent of the lava flows containing the tubes cannot be easily determined in the Bend area. Studies are currently in progress of lava tubes in Hawaii and Washington formed in flows of known or estimated volume and areal extent.

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APPENDIX 1. LOCATION OF SURVEYED LAVA TUBES NEAR BEND, OREGON

| Name | System | U. S. G. S. Quadrangle | Location | Elevation in ft. | Aerial Photo No. | | Length | Maximum Height | Maximum Width |
|---|---|---|---|---|---|---|---|---|---|
| Arnold Ice Cave | Arnold | Kelsey Butte 7 1/2'* | SE1/4, SE1/4, SW1/4, Sec. 22, R. 13E., T. 19S. | 4530 | ESF | 29-7 | 41.1m | 5.1m | 11.5m |
| Barlow Cave | Horse | Bend Airport 7 1/2' | NE1/4, NW1/4, NW1/4, Sec. 19, R. 13E., T. 17S. | 3490 | BAY | 7H-147 | 182.2m | 5.1m | 17.3m |
| Bat Cave | Arnold | Kelsey Butte 7 1/2'* | NE1/4, NW1/4, NW1/4, Sec. 23, R. 13E., T. 19S. | 4425 | ESF | 29-7 | 166.0m | 7.3m | 10.6m |
| Boyd Cave | ------ | Kelsey Butte 7 1/2'* | SE1/4, SE1/4, NW1/4, Sec. 8, R. 13E., T. 19S., | 4285 | ESF | 25-156 | 567.8m | 3.9m | 9.7m |
| Charcoal Cave | Arnold | Kelsey Butte 7 1/2'* | NW1/4, NE1/4, NW1/4, Sec. 27, R. 13E, T. 19S. | 4535 | ESF | 29-7 | ------ | ---- | ------ |
| Charcoal Cave #2 | Arnold | Horse Ridge 7 1/2'* | NW1/4, NW1/4, SE1/4, Sec. 13, R. 13E., T. 19S. | 4280 | ESF | 27-245 | 144.1m | 12.1m | 13.4m |
| Deg Cave | Arnold | Kelsey Butte 7 1/2'* | NE1/4, SW1/4, NW1/4, Sec. 23, R. 13E., T. 19S. | 4445 | ESF | 29-7 | 186.9m | 7.6m | 11.8m |
| Garbage Caves | Horse | Bend 7 1/2' | W1/2, SW1/4, Sec. 11, R. 12E., T. 18S. | 3730 | BAY | 7H-94 | 188.3m | 3.6m | 20.7m |
| Horse Cave | Horse | Bend Airport 7 1/2' | SW1/4, NW1/4, SE1/4, Sec. 25, R. 12E., T. 17S. | 3560 | BAY | 7H-148 | 394.7m | 3.9m | 11.5m |
| Lava River Cave | ------ | Lava Butte 7 1/2' | NW1/4, SE1/4, SE1/4, Sec. 26, R-11E., T. 195 | 4507 | ESF | 3-201 | 685.0m | 15.0m | 17.2m |
| Lewis Farm Caves | Horse | Bend 7 1/2' | SE1/4, NE1/4, NW1/4, Sec. 15, R. 12E., T. 18S. | 3745 | BAY | 7H-94 | 235.6m | 7.6m | 16.7m |
| Log Crib Cave | ------ | Kelsey Butte 7 1/2'* | NE1/4, NE1/4, NE1/4, Sec. 31, R. 13E., T. 19S. | 5050 | ESF | 25-153 | 40.2m | 1.9m | 4.5m |
| Pictograph Cave | Arnold | Kelsey Butte 7 1/2'* | SW 1/4, NE 1/4, SE1/4, Sec. 14, R13E., T. 19S | 4340 | ESF | 27-245 | 549.2m | 15.2m | 20.7m |
| Skeleton Cave | ------ | Kelsey Butte 7 1/2'* | NE1/4, SE1/4, SW1/4, Sec. 4, R. 13E., T. 19S., | 4195 | ESF | 25-156 | 1010.0m | 5.7m | 13.1m |
| South Ice Cave | ------ | Newberry 30' | SE1/4, NE1/4, Sec. 18, R. 14E., T. 23S. | 5020 | ESF | 29-173 | 252.6m | 5.4m | 14.6m |
| Stevens Road Cave | Horse | Bend 7 1/2' | NW1/4, NE1/4, NW1/4, Sec. 11, R. 12E., T. 18S. | 3700 | BAY | 7H-94 | 31.3m | 2.2m | 26.2m |
| Stookey Ranch Cave | Arnold | Horse Ridge 7 1/2'* | SE1/4, SW1/4, NE1/4, Sec. 13, R. 13E., T. 19S. | 4265 | ESF | 27-245 | 186.2m | 12.1m | 16.4m |
| Wilson Cave | Horse | Bend Airport 7 1/2' | NE1/4, SW1/4, NW1/4, Sec. 19, R. 13E., T. 17S. | 3490 | BAY | 7H-147 | 70.1m | 3.9m | 15.8m |
| Wind Cave | Arnold | Kelsey Butte 7 1/2'* | SE 1/4, SW1/4, SW1/4, Sec. 14, R. 13E., T. 19S. | 4405 | ESF | 29-6 | 941.2m | 16.7m | 19.2m |

* Unpublished, Advance Manuscript Topographic Maps (U. S. G. S. Topographic Division, Menlo Park, California)

\+ Aerial photographs: ESF = U. S. Forest Service, 1951, Scale 1:15,840,

Bay = U. S. Dept. Agric. Production and Marketing Admin., 1951, scale 1"20,000.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

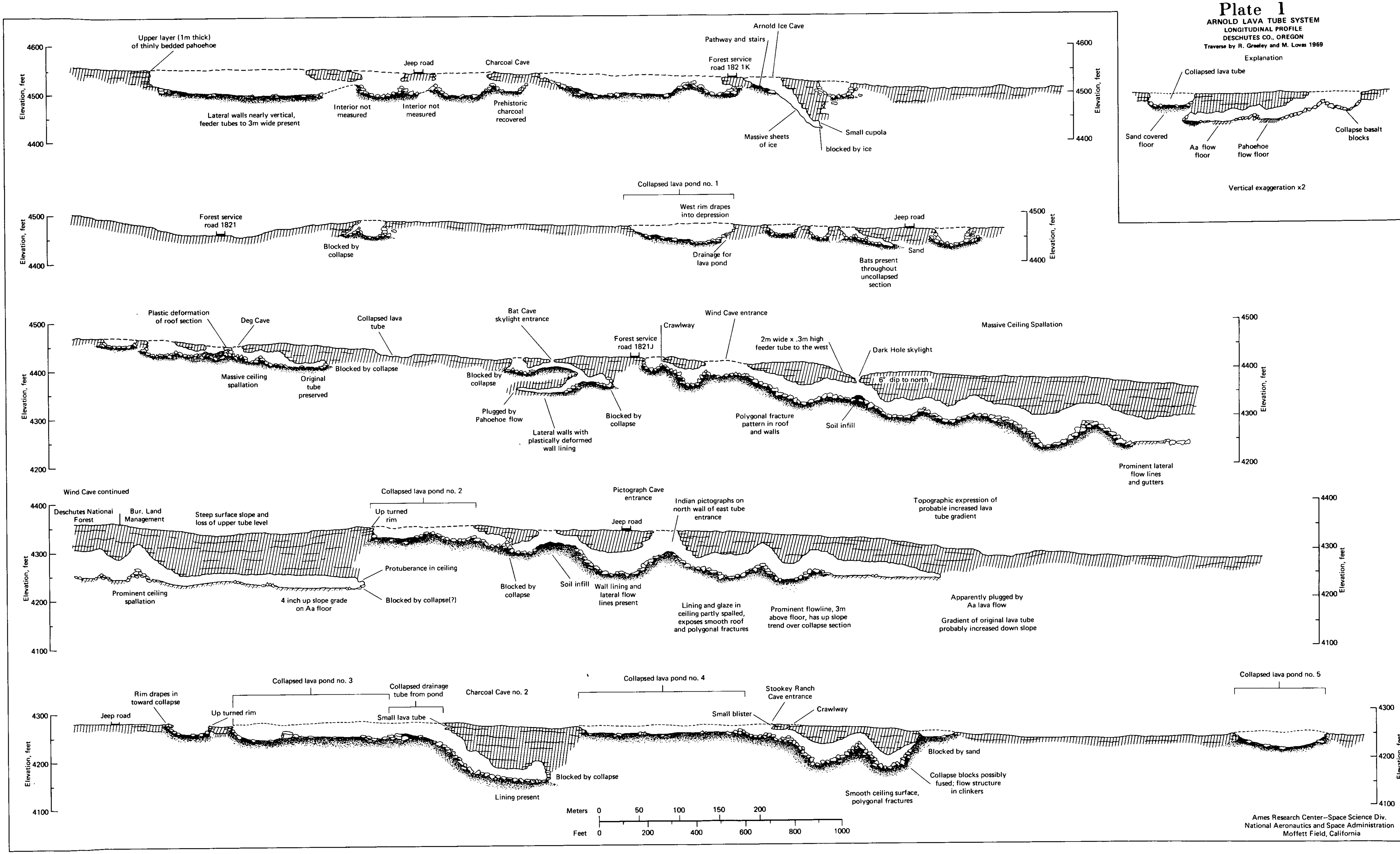



Plate 1
ARNOLD LAVA TUBE SYSTEM
LONGITUDINAL PROFILE
DESCHUTES CO., OREGON
Traverse by R. Greeley and M. Lovas 1969

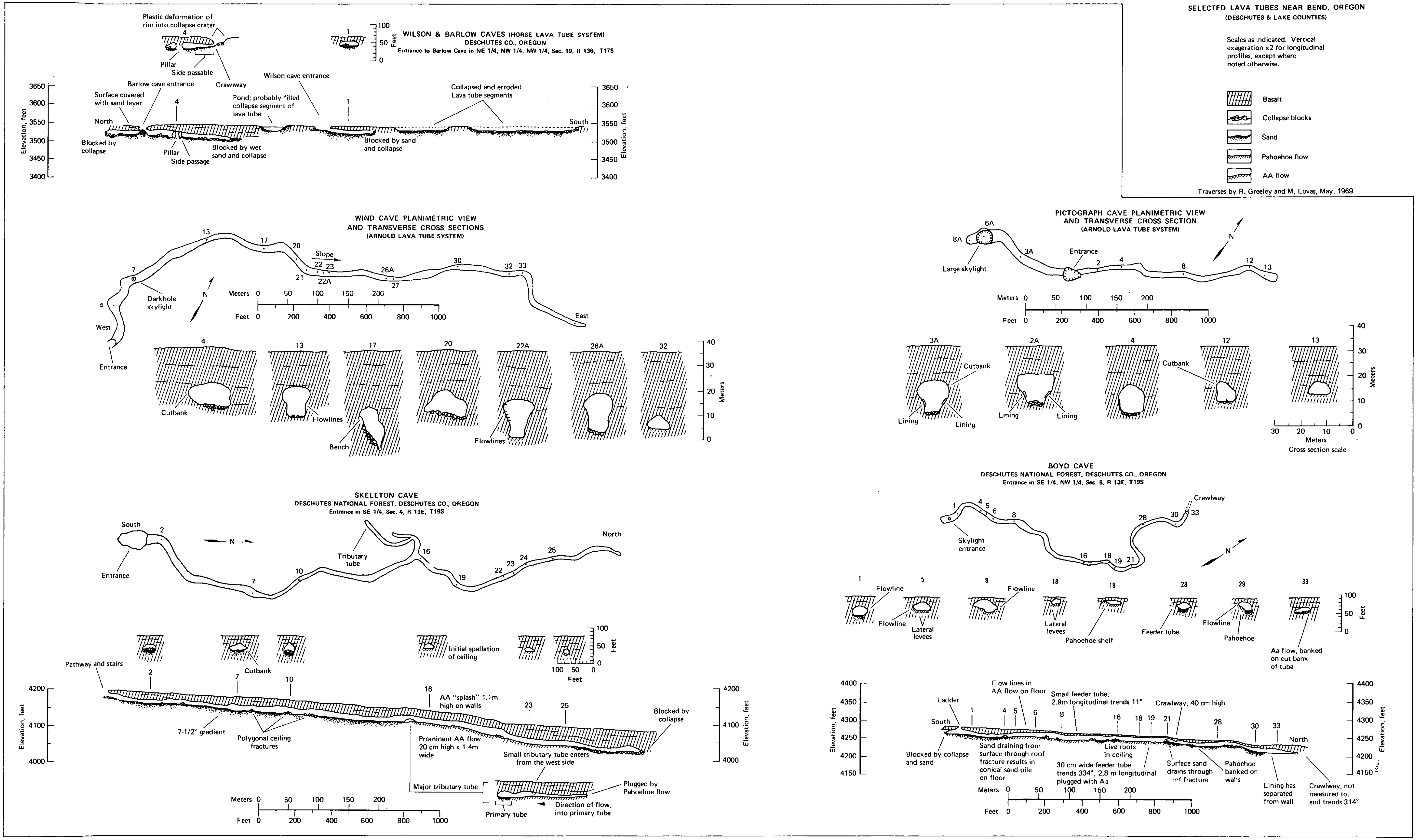
Ames Research Center–Space Science Div.
National Aeronautics and Space Administration
Moffett Field, California

FOLDOUT FRAME 1

FOLDOUT FRAME 2

# Plate 2

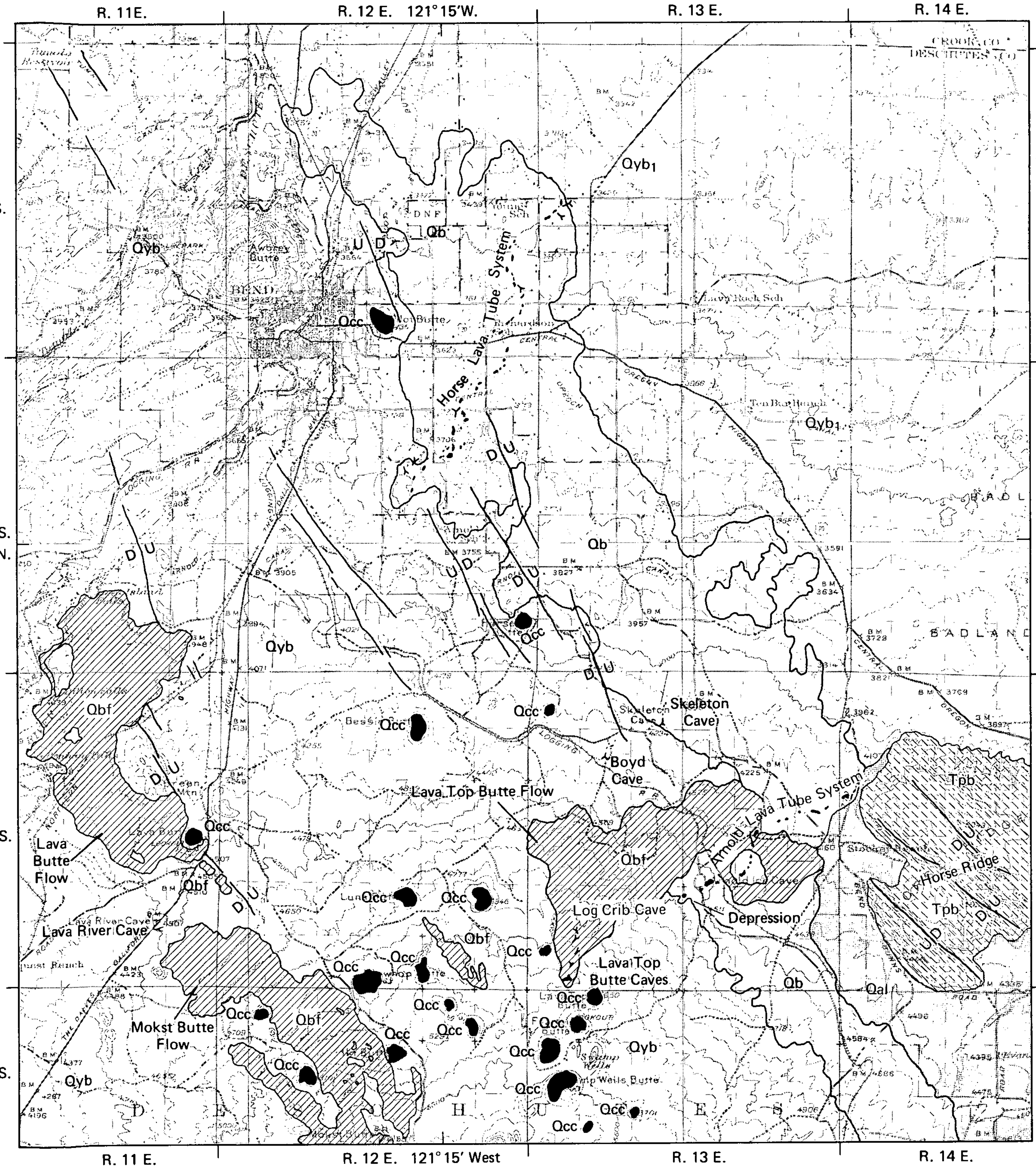
SELECTED LAVA TUBES NEAR BEND, OREGON
(DESCHUTES & LAKE COUNTIES)



FOLDOUT FRAME 1

FOLDOUT FRAME 2

# Plate 3




## PHOTOGEOLOGIC MAP OF THE LAVA TUBES OF PARTS OF BEND AND NEWBERRY 30' QUADRANGLES, OREGON

RONALD GREELEY, 1970

Explanation

Quaternary

- Qal — Alluvium
- Qbf — Basalt, youngest fissure eruptions; individual flows named.
- Qcc — Basaltic cinder cones.
- Qyb — Basalt, youngest, undifferentiated; fissure flows from base of Newberry Caldera and Eastern flank of the Cascades.
- $Qyb_1$ — Basalt east of, and overlapping, Qb; probably erupted from area immediately north of Horse Ridge.
- Qb — Basalt, associated with early caldera building phase; contains prominent lava tubes.

Tertiary

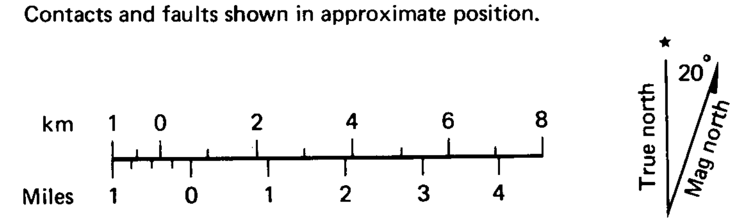
- Tpb — Complex volcanics of Horse Ridge

Fault trace, approximate location (U = upthrown side, D = downthrown side).

Collapsed lava tube segments and blisters

Entrance to uncollapsed lava tube

Contacts and faults shown in approximate position.




Declination 1967

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