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LAVA TUBES OF THE CAVE BASALT, MOUNT ST. HELENS, WASHINGTON

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ABSTRACT

The Cave Basalt, a high-alumina pahoehoe flow containing numerous lava tubes, originated at the southwest flank of Mount St. Helens, southwestern Washington, and flowed down a stream valley incised in older pyroclastic flow deposits. *In situ* charcoal samples from two localities within lava tubes yield C^{14} dates of 1860 ± 250 years B.P. and 1925 ± 95 years B.P. Detailed survey of 9125 m of lava tubes, correlated with surface geologic mapping, yields several geomorphic relationships of basalt flows. Most of the lava tubes apparently formed between shear planes in laminar lava flow, although some tube sections show evidence that the tube roof formed by accretion of spattered lava in turbulent flow. Partial collapse of tube interiors reveals: 1) the wall separating the tube interior from the preflow country rock may be thinner than 25 cm, 2) lava flows can erode the surface over which they flow, 3) collapse of the tube interior can occur immediately after the tube has been drained of molten lava and before the walls cool completely, 4) lava tubes may represent the thickest part of the lava flow, occupying topographic lows (stream channels) and 5) tubes can be modified extensively through accretion and erosion by later lava flows.

Many surface features of basalt flows are directly related to lava tubes. Pressure within the closed lava tube system caused by outgassing and hydrostatic pressure and overflow of lava from ruptured roof sections (or from channel overflow prior to roof formation) result in formation of a topographic high along many sections of the lava tube axis. Unequal pressure and temporary ponding of the lava flow can deform the roof into surface domes 40 to 50 m in diameter. Most of the domes of the Cave

Basalt collapsed, probably as a result of withdrawal of supporting lava during drainage of the lava tubes. Raised-rim craters found in many parts of the flow are associated with lava tubes and were probably formed by collapse of domes.

INTRODUCTION

Results from returned Apollo lunar samples showing basaltic composition for maria surfaces have prompted interest in volcanic landforms as analogs to lunar and planetary surface features. Volcanic geomorphology has been little studied recently, particularly in relation to basalt flow surface features. The existence of lunar lava tubes and channels has previously been proposed (Kuiper *et al.*, 1966; Oberbeck *et al.*, 1969; Greeley, 1970, 1971a). The application of analogs to planetary structures requires a thorough understanding of the terrestrial counterpart. As part of an investigation of terrestrial lava tubes and channels, the tubes of the Cave Basalt (named here) at Mount St. Helens in southwest Washington (Fig. 1) were studied in detail. Their excellent preservation makes these tubes particularly well suited for study because they show features that are less well exposed in lava tubes of other areas. Unlike many basalt flows containing lava tubes, the margins of the Cave Basalt are fairly well defined and certain relationships of the tubes to the configuration of the flow and surface features can be determined.

Eruptive History and Previous Work

Although Mount St. Helens has not erupted during this century, it has been active within historic time (for a review of historic eruptions see Jillson, 1917a; Erdmann and Warren, 1938; Holmes, 1955; and Folsom, 1970). Published eyewitness accounts indicate that the volcano was intermittently active between the mid-1830's and the mid-1850's. Volcanic ash was erupted in November, 1842, and fell at least 105 km to the southeast, and lava may have been erupted on the south side of the volcano in 1844. An eruption of pumice in about 1800 and an eruption of lava on the northwest flank of the volcano sometime between 1800 and the 1830's (Lawrence, 1938, 1939, 1941) evidently were not observed by early explorers or settlers. Recent geologic studies (Mullineaux, 1964; Hyde, 1970; Hopson, 1971) indicate that the present may simply be the most recent quiescent interval between recurring episodes of volcanic activity. The last few hundred years have witnessed frequent violent volcanism accompanied by dome formation, hot pyroclastic flows, lahars, pumice eruptions, and lava flows.

Previous geologic studies of the Cave Basalt have been limited to brief observations made by Verhoogen (1937) and by earlier workers who noted tree wells and lava tubes in the pahoehoe basalt (Gibbs, 1854; Elliott, 1897; Diller, 1899; Jillson, 1917b, 1921; Williams, 1922). Erdmann and Warren (1938) examined several dam sites in the vicinity of the volcano and drew attention to possible volcanic hazards. Lawrence (1938, 1939, 1941, 1954) and Carithers (1946) described recent pyroclastic deposits on the north side of the volcano. Mullineaux and Crandell (1962), Mullineaux (1964), Hyde (1970), and Hopson (1971) have discussed various geologic aspects of the volcanic deposits.

The lava tubes in the Cave Basalt were apparently unrecognized by earlier observers. The first published account of the tubes is an article in *Mazama* (Anon., 1903). Forsyth (1910) described a lava tube (Ole's Cave) and attributed its discovery in 1895 to an early settler, Olie Peterson. However, the other major lava tubes remained undiscovered until the 1950's. Halliday (1963a, 1963b) presented a detailed description of the known tubes and Pryde (1968) discussed the tubes in a popular article. The only geological descriptions of the tubes are by Greeley and Hyde (1970) and Hyde and Greeley (1971).

Method of Study

Prior to field work, photogeologic maps were made of the flow showing the locations of lava tube entrances, surface features, and apparent flow contacts. In the field, contacts were checked and corrected, and additional surface features were noted. Following methods described elsewhere (Greeley, 1971c), the lava tubes were surveyed in detail and, where possible, surface features were related to the tubes. Rock samples for analysis were selected from surface exposures and from within the tube (Fig. 2).

AREAL GEOLOGY

The oldest rocks in the map area (Fig. 2) consist of a series of altered Tertiary volcanic and volcanic-clastic rocks that have been intruded by small bodies of andesite, rhyodacite porphyry, and hypabyssal rocks. These rocks have been studied only in the vicinity of Merrill Lake (Hyde, 1970) where most of the rocks are tuff-breccia, sandstone, and mudstone, each composed predominantly of rocks and minerals of volcanic origin. Tuff-breccia is predominant. Minerals in both matrix and fragments are mostly altered to chlorite, carbonate minerals, and clay. Although the ages of the rocks are unknown, correlation with similar rocks in other parts of the Cascade Range suggests that the rocks studied here are late Oligocene (Hopson, 1971, personal commun.). Marble Mountain, about 10 km southeast of Mount St. Helens, consists mostly of nearly uniform olivine basalt flows. The basalt flows typically are 1 to 3 m thick and consist of layers of clinkery scoria alternating with light-gray to dark-gray basalt. The basalt is massive to platy and dense to phorphyritic with large laths of plagioclase and crystals of olivine. One sample was selected for chemical analysis (sample 6, Table 2); it is easily distinguished from other basalts on a plot of total alkalis and silica (Fig. 3).

The Cave Basalt here named and defined for exposures near Ape Cave is a pahoehoe basalt flow that originated at the southwest flank of Mount St. Helens - its type locality - and flowed south about 11 km down a stream valley cut into pyroclastic flow deposits of late Quaternary age. The upper part of the lava flow (Figs. 2, 4) is covered by younger lava and pyroclastic flows, and is poorly exposed. The Cave Basalt may be present as high as 1465 m elevation on the volcano and can be traced to the Lewis River valley where it terminates on the north bank of the river. The basalt is light gray to dark gray, vesicular to massive, and generally diktytaxitic. It contains phenocrysts of olivine and plagioclase. The vesicles are spherical in contrast to the more irregular shaped vesicles of the aa basalt, range in size from about 0.5 to 8 cm, and make up 1 to 20 percent of the rock. The three chemical analyses (samples 1, 2, 3; Table 2) are remarkably uniform and all fall within the high-alumina basalt field of Kuno (1968). The basalt flow surface is generally hummocky or flat over broad areas and is commonly broken into large tilted slabs. Common surface features include ropy or corded textures, pressure ridges and blisters that are often cracked or collapsed, and large domes and craters. Vertical and horizontal tree molds are common near the margins of the flow and are particularly well displayed near the entrance to Lake Cave.

Excellent exposures on the bluffs overlooking the Lewis River valley and in segments of the lava tubes indicate that the basalt flow filled a stream channel incised in a relatively flat-floored valley. At station 34 (Fig. 5) in Lake Cave, breakdown of the east wall of the lava tube reveals the edge of the stream channel about 3 m above the tube floor. Erosion by running water at the base of the lava flow makes it possible to crawl about 30 m under the relatively flat floor of the lava flow where the *undersides* of tree molds are exposed. The basalt flow was temporarily ponded on the bluffs overlooking Lewis River; apparently a dam was created in the relatively narrow channel incised in the pyroclastic flow deposits. Craters as large as 50 m in diameter in the ponded lava were created by collapse of blisters that apparently were inflated by hydrostatic pressure resulting from lava in the tubes, as discussed below. The age of the basalt flow is probably close to 1900 years B.P. Charcoal from roots at the base of a tree mold exposed in the side passage at station 34 in Lake Cave was dated as 1860 ± 250 years B.P. (W-2270). Charcoal similarly exposed at the base of the lava flow in Ape Cave was dated as 1925 ± 95 years B.P. (GX1673). We found no evidence for intervening periods of surface exposure and weathering; the flow was evidently extruded over a short time interval and may have acted as a single cooling unit.

A basalt flow exposed in the Kalama River valley and in the vicinity of Merrill Lake (Fig. 2) has the same characteristics (Hyde, 1970) as the Cave Basalt and probably was extruded at the same time. The two flows are separated by a covered interval about 5 km wide; however, lava of the Cave Basalt is present at the drainage divide and in the upper part of the Kalama River drainage basin, so the two flows may be connected. One sample of basalt collected from the Kalama valley (sample 3, Table 2) is chemically very similar to samples of Cave Basalt.

Rocks mapped as undivided lava of Mount St. Helens include basalts, andesites, and dacites that crop out in the Swift Creek and Kalama River valleys. A block lava flow at the head of the Kalama River consists at the surface mostly of relatively smooth polyhedral blocks ranging in size from 0.3 m to 2 m on a side. The rocks have a dark glassy luster, often show conchoidal fracture patterns, and are aphanitic. The interior of the flow is well exposed in a roadcut on the south edge of the flow where only brecciated material is visible. The flow has abrupt margins and is about 10 m thick. The block flow has a distinctive chemical composition (sample 4, Table 2; Fig. 3) but its age relation to the Cave Basalt is not clear. Field relations suggest it may be younger.

Aa lava comprises the eastern lobes of the undivided lavas of Mount St. Helens except for andesite belonging to an ancestral St. Helens sequence, just east of Swift Creek (Hopson, 1970; personal commun.). The aa flows are characterized by jagged, clinkery surfaces with individual fragments as large as 1 m. The rocks consist of thin flows of dark-gray basalt alternating with thin layers of scoria. The basalt typically is vesicular and has phenocrysts of plagioclase and olivine. The aa flow clearly overlies the Cave Basalt and at one locality overlies a pyroclastic deposit containing charcoal at its base that has a radiocarbon age of 1740 ± 250 years (W2527). Pyroclastic layer W, erupted from Mount St. Helens about 450 years ago (Crandell, 1969), lies on the surface of the flow.

Extensive deposits of volcanic ash, pyroclastic flows, and lahars (Mullineaux and Crandell, 1962; Hyde, 1970; Hopson, 1971) resulting from explosive eruptions are present in the map area, but discussion of these deposits is beyond the scope of this paper.

LAVA TUBES

Lava Tube Locations

Figures 2 and 6 show the location of the lava tubes within the Cave Basalt; Table 1 lists their geographic coordinates and physical characteristics. The principal lava tube system in the flow is the Mount St. Helens system (Halliday, 1963, p. 97) which exceeds 8333 m in length and is composed of Little Red River Cave, Ape Cave, Lake Cave, and Ole's Cave. Although the system begins in the constricted northern part of the flow, it probably originated upslope, above Little Red River Cave. The system trends southward along the east flow margin and apparently terminates in collapse craters east of Green Mountain kipuka. Ape Cave, with a passage length of 3400 m, is the longest known *continuous* lava tube *segment;* however, longer, discontinuous tubes are known in many areas. Hopeless Cave, several dozen meters north and slightly west of the main entrance to Ape Cave, may have drained into Ape Cave in the late stage (Halliday, personal commun.). A group of small lava tubes in the northern part of the flow (Gremlin Cave, Spider Cave, Flow Cave, and Little People Cave, Figs. 7, 8) may be related to the Mount St. Helens system. Spider Cave and Flow Cave align with the general trend of Little Red River Cave and, as discussed below, may have fed lava to the main system during the final eruptive stages of the Cave Basalt.

Three lava tube segments are west of Green Mountain: Dollar and Dime Cave, Prince Albert Cave, and Bat Cave (Figs. 9, 10). Although these tubes were not examined, discussions with local spelunkers (C. V. Larson, personal commun.) and analyses of diagrams and photographs lead us to believe that these tubes are part of a system extending along the eastern contact of the flow with Green Mountain. These are the only tubes known west of the kipuka.

Power Line Cave, Beaver Cave, and Barney's Cave (Figs. 11, 12) are lava tubes apparently not associated with any particular system. A collapse pit, a short lava tube segment, and several small tubes (Halliday, personal commun.) in the northern part of the flow also seem unrelated to any system.

Formation of Lava Tubes

Lava tube formation is apparently controlled primarily by lava flow viscosity, which in turn is related to the chemistry, dissolved gasses, temperature, and flow velocity of the lava. Lava tubes occur only in pahoehoe, the fluid variety of basalt. At least two modes of tube formation are displayed in the Cave Basalt and both may occur within a single tube in different localities. The first mode of formation is by constructional accretion of the lava tube roof. Observations of active lava tube formation in Hawaii (Greeley, 1971b) show that rapidly flowing lava on steep slopes is turbulent and follows narrow channels. Splashing and spattering lava accretes along the channel edges to form arched levees that eventually merge over the channel, forming an arched roof. The roof may remain after drainage of molten lava at the close of the eruptive stage. Parts of Little Red River Cave probably developed by such accretion. Stations 1 and 4 (Fig. 5) mark very steep lava tube sections in which partial roof collapse reveals agglutinated clots of lava probably formed by accretion. This structure contrasts with the more regular *layered lava* found on less steep tube segments described below.

The second mode of formation occurs in low velocity, laminar lava flows such as those described by Ollier and Brown (1965). Shear planes are believed to form within the flow (Fig. 13) and as the main body of the flow cools, active flow is restricted to the hottest part. At this stage the exact position of the tube is not fixed and the primitive lava tube can shift about (i.e., surges of lava from the vent can cause the tube to migrate from one part of the flow to another). As the lava progressively cools the tube becomes more firmly fixed; eventually the bulk of the flow solidifies, forming layered lava, and the still-molten material drains from the most active part of the flow and leaves a void or lava tube.

Lava tubes seem to develop along the most rapidly flowing part of the active lava flow. Figure 6 shows that tubes are not necessarily in the center of the flow; rather, they are common along the flow margins. Configuration of the preflow surface probably controls the overall trend of lava tubes. The Cave Basalt occupies a former stream valley, as reconstructed in Figure 14. From evidence discussed in the next section, we believe parts of the lava tube are situated in the former stream channel of the valley. As such, the configuration of the channel would (to some degree) determine the shape and ground plan of the lava tube. Interaction of molten lava with stream water, snow, or ground water may lead to phreatic explosions within the lava flow. One area of Ape Cave shows evidence (Hyde and Greeley, 1971) that a phreatic explosion ruptured the wall of the tube and introduced steam charged with particles of country rock (clay), which fused on the tube walls (Fig. 15). Although such events are probably rare, they can significantly deform lava tubes.

As the lava flow advances and spreads laterally, the main lava tube supplies molten lava to the flow front through a series of distributary *feeder tubes*. During drainage of the main tubes, feeder tubes are often plugged or only partly drained. Occasionally, feeder tubes may branch from main tubes. Lava tubes may bifurcate to form two distinct networks, or, as with river channels, may form cutoff branches (Fig. 9).

In the later stages of tube formation, probably during drainage, a layer of lava is accreted along the walls and ceiling to form a *lining* (Fig. 16). Lava tube linings range from less than 1 cm to more than 1 m thick and are generally somewhat more vesicular than the main body of the lava flow. Vesicularity within the lining may increase toward the tube, possibly representing outgassing into the tube.

During or after drainage parts of the lining may develop a glassy surface. Glaze that is deformed (Fig. 17) must have been formed while the lining was still plastic and subject to movement. Formation of glaze is not well understood; however, it appears to develop as a thin coating over the outer vesicular zone of the lining (Greeley, 1969), possibly as a result of rapid cooling by air currents in the lava tube.

As lava drains from the tube, a temporary cessation of drainage can result in horizontal flow lines along both walls. Successive halts produce a series of flow lines (Fig. 18) that can be traced and correlated for hundreds of meters along the tube. Incomplete drainage of low-lying parts of the tube or deformation of the lava tube roof may close tube passages with structures termed *lava seals* by Halliday (1963a, p. 124). The upper ends of Ape Cave and Little Red River Cave are blocked with lava seals (Fig. 5).

Relation of Lava Tubes to Preflow Geology

Many wall sections of the Mount St. Helens lava tube system have collapsed to expose preflow country rock (Figs. 5, 19, 20). In most exposures, country rock deposits (pyroclastic flows) are baked a brilliant red. These exposures (rare in most other areas) provide a unique opportunity to study relationships of lava tubes and flow to preflow topography. For example, station 31 in Lake Cave shows that there may be no more than 2 cm separating the lava tube interior from the outer edge of the flow. Figures 2 and 5 show that many collapses of tube walls occur where the tube is close to the flow edge. Figure 14 shows composite cross sections of parts of the system. From the exposures available, we conclude that parts of the lava tube are situated in a pre-lava flow stream channel. This channel is about as deep and wide as the present stream channel of Panamake Creek, a small stream a few miles west of the Cave Basalt but unaffected by Holocene volcanic eruptions.

Sections of tube along the presumed stream channel assume a skull-shaped cross section; undercutting by the flow may form asymmetric sections. Sections in the middle of the flow on gentle gradients appear to spread laterally to form horizontally oval sections. Tube configurations in meander bends are often asymmetric, forming "cut-banks" similar to stream beds. Further evidence of erosion by lava is found in the form of large inclusions of country rock in the lava flow at station 15, Ape Cave.

Exposures in Little Red River Cave and Ape Cave (Figs. 5, 14B, 19, 20) show country rock overhanging the lava tube. It is unlikely that this was the original configuration of the topography in an area of easily eroded unconsolidated deposits; these overhangs probably represent erosion by the lava flow. Sections of Little Red River Cave, for example, undercut parts of the eastern, preflow hillside (Fig. 14). Thus, to some degree the position of the tube is determined by the erosive capability of the lava flow.

Subsequent Lava Flows

Lava tubes often serve as conduits for later lava flows and subsequently are usually altered. Alteration may be in the form of filling or partial filling the tube (Fig. 21), remelting the lava tube roof to form vertically elongate tubes, reshaping or eroding the tube walls, stacking additional tube levels above the first tube, or any combination of these.

Figure 14 shows several tube sections that appear to have resulted from subsequent flow alteration. In cross section, the tube near the main entrance of Ape Cave (Fig. 18) apparently had two or more lava surges or flows that remelted the existing tube roof (or occupied an open channel) to form a vertically elongate cross section. Many other sections of the Mount St. Helens lava tube system are similarly altered. Unfortunately, correlation of flow units over more than a few hundred meters is impossible because of irregularities in tube shape. In some areas, remelting of the tube roof was incomplete and resulted in distinct upper level lava tubes. Flow patterns in the floors of upper levels indicate that they drained into the lower level (station 10, Ape Cave); in places, the boundary between separate tubes and fused tubes displays unusual lava structures (Fig. 22).

In some instances, subsequent flows intersect and merge with existing lava tubes at some distance from the vent (Greeley, 1971b). For example, the western passage of Lake Cave (Halliday, 1963a, p. 93-96) appears to have been a small surface lava tube that drained into the main tube. A similar formation probably occurred at the upper end of Little Red River Cave. The lava is distinctly red in the upper level, in contrast to the black lava of the lower level, and matches in color and appearance the lava of Flow Cave, a few hundred meters upflow from Little Red River Cave. Flow Cave is a smaller lava tube formed near the surface, similar to the west branch of Lake Cave. We believe Flow Cave drained into and eventually sealed the upper end of Little Red River Cave.

Drainage of subsequent lava flows from an older lava tube may result in the accretion of an additional lining. In theory, it should be possible to determine the number of flows that have occurred by counting the number of linings in a wall section. However, the linings often merge to form one lining, are remelted, or are completely destroyed.

Small subsequent flows are often found along the floors of lava tubes. These flows may be either pahoehoe or aa and may display flow patterns. As with their larger counterparts, small flows may develop channels, levees (Fig. 23), or small lava tubes, resulting in "tube-in-tube" structures (Fig. 24). Interior flows may erode the walls of the larger tube, tearing away parts of the lining and rafting the blocks downtube. Blocks of rafted material are fused to the floor flow in several areas (e.g., near the entrance to Little Red River Cave). In some sections, large clots of lava are fused on the walls (Figs. 25, 26).

Lava Tube Deformation

Plastic collapse of the walls, lining, or roof commonly occurs during and immediately following drainage of lava from a tube. Figure 5 identifies some examples of plastic deformation. In these areas (Figs. 16, 27) the lining tore away from the wall and slid toward the floor. Molten lava behind the lining can flow through the rupture and dribble inside the tube. Station 17 (Ape Cave) marks an exposure of country rock in which the lining and wall collapsed, allowing country rock to slump into the tube. Molten lava then dripped on the country rock and cooled, forming small blobs of glassy basalt. Similar occurrences are found along sections of Lake Cave. Several collapsed sections of the lining of the Mount St. Helens lava tube system expose brick-red lava clinkers (*autobrecciated lava)* between the lining and the massive basalt of the flow. Differential movement of the lining and massive basalt may produce a shear zone along which the autobrecciated lava forms. Brecciation may also have occurred by vesiculation into possible voids and low pressure areas between the lining and the body of the flow, similar to the process described by Parsons (1969) for lava flows in general.

The plastic deformation and inward draping of layered lava toward the entrance to Ape Cave appears to have resulted from roof collapse during or immediately following drainage. Although rare in the lava tubes of the Cave Basalt, this type of roof collapse is fairly common in other areas (Greeley, 1971c). Occasionally the roof may sag slightly and fracture along tens of meters of the tube axis. Although medial fractures usually develop along the axis of the sag they may also form in tubes without roof sag. Other fractures often develop in the lining in addition to the medial fracture to form polygonal fracture patterns.

Some parts of lava tubes seem to have been deformed by pressure on the upper, semiplastic walls and roof. Hydrostatic pressure within the closed tube system and outgassing into the tube interior probably were sufficient to push ceiling sections into bulbous chambers, or *cupolas* (Fig. 5). In some places, pressure was great enough to rupture the roof, as described below.

Lava tube collapse after cooling begins with spalling of the tube lining. This is followed by spalling and collapse of basalt blocks from the roof, eventually forming a small opening (termed a *skylight*) to the surface. Some parts of lava tubes are marked by extensive roof collapse (not necessarily breaking through to the surface, however) which may block the interior passage. Percolation of surface water into tubes and growth of vegetation in the roof contribute to weathering and collapse of lava tubes. Small roots from surface vegetation are visible in Ape Cave. The flow of water through tubes of the Cave Basalt is often voluminous, particularly during the spring runoff. Little Red River Cave was named from a small red stream that runs down the tube for about two-thirds of its length. Water stained with red clay from the baked country rock enters the tube in a series of springs near station 5. The stream flows all year and is apparently fed from surface water and ground water from the Mount St. Helens snow melt.

Seasonal streams flow in most of the other Cave Basalt lava tubes. Sand and other detritus are washed into the tubes or eroded from country rock exposures and transported by the streams. At the tube ends (Little Red River Cave, Lake Cave) and in depressions along tubes, stream water collects in small ponds and deposits sediments. Changes in hydrologic conditions within the tube can result in rejuvenation of the stream, with subsequent down-cutting through the deposits. Sections near station 30 in Ape Cave show eroded terraces with more than a meter of graded silt, sand, and gravel stream deposits.

Continued erosion and weathering leads to complete collapse of the tube roof to form a sinuous trench. Because of their young age and relatively thick roofs, tubes in the Cave Basalt have not yet progressed beyond the skylight stage.

Minor Features

During final drainage of molten lava from the tube several varieties of lava cave formations may develop. Lava dripping from the ceiling can produce lava stalactites and stalagmites; both structures can be tens of centimeters long, although the normal length seldom exceeds 8 or 9 cm. Excellent examples of stalactites and stalagmites are in the Cave Basalt lava tubes (Figs. 28, 29). Figure 30 illustrates incipient lava stalagmites that formed as the floor flow moved downslope, as indicated by the linear array of glassy blobs on the flow surface. Cessation of flow permitted the dripping lava to accrete in one place and to form the stalagmite.

Deformation of plastic semimolten lava tube lining can produce wall drapery along several meters of tube wall. Overhanging sheets of lava (Fig. 31), less than 1 or 2 cm thick, produce *ribbon stalactites* (Halliday, 1963a). Unusual stalactites in Flow Cave are deformed down-tube in a "cross-bedded" pattern, possibly deformed by strong air or gas currents flowing through the tube during the later stages of drainage.

SURFACE FEATURES OF LAVA TUBES

One objective of our study was to determine the relation of lava tubes to the surface topography of the lava flow. Many surface features on the Cave Basalt can be correlated directly with lava tubes. Lava tubes often form subtle ridges along their axes (Greeley, 1971c). Figure 14 illustrates cross sections made transverse to the axes of Lake

Cave and Ape Cave showing their topographic expression. On flows known to contain lava tubes, ridges parallel to the direction of flow may indicate subsurface tubes.

Occasionally, pressure is adequate in an active lava tube to rupture the roof and spill lava on the surface. Sometimes a small hornito may develop over the roof. Entrance 4 to Ole's Cave and the section near station 32 of Lake Cave mark areas where small lava flows erupted from the tube. Many apparently anomalous aa flows found as scattered patches in the middle of pahoehoe probably flowed from lava tubes and represent subsequent lava flows that used the tube as a conduit.

In some instances, pressure within the tube was not sufficient to rupture the roof. Instead, the roof was inflated to form a cupola. The surface expressions of cupolas are often small *domes*. Station 19, Ape Cave, marks a cupola and corresponding surface dome. Most domes apparently collapsed almost immediately following their formation, indicated by plastic deformation of the crust. The resulting structures are craters as large as 50 m in diameter with raised rims. Figure 32 shows the location of craters and domes in relation to part of Lake Cave. Two prominent collapse craters (Fig. 33) mark the end of Ole's Cave. We believe these craters resulted from temporary ponding of the Cave Basalt before the flow spilled into the Lewis River valley. During ponding, lava continued to flow into the pond beneath the crust under hydrostatic pressure from the lava tube (similar to the way in which lava tubes and collapsed lava ponds formed in central Oregon (Greeley, 1971c)). Release of the flow into the valley relieved the pressure; as the lava drained from beneath the dome crust the structure collapsed to form a crater. A large pressure ridge transverse to flow direction is near the south end of the flow (Fig. 6). This structure, about 450 m long, 35 m wide, and as high as 4 m, is believed to have formed as a result of downslope movement and subsequent buckling of the lava pond crust prior to, or during, drainage. Some of the domes (Fig. 34) and collapse craters have small (up to 4 m wide) lava tubes leading downslope away from the rim. These probably developed during collapse when parts of the rim ruptured and molten lava flowed on the surface.

Numerous pressure ridges occur on the Cave Basalt. Although a rigorous analysis of the size, location, and orientation of pressure ridges was not made, there is no apparent relationship of the pressure ridges to the tubes.

SUMMARY AND CONCLUSIONS

The Cave Basalt, a high alumina pahoehoe flow, originated at the southwest flank of Mount St. Helens and flowed south about 11 km in a stream valley incised in pyroclastic flow deposits of late Quaternary age. Two charcoal samples (from different localities within the flow) yield radiocarbon age dates of 1860 ± 250 and 1925 ± 95 years B.P. The flow contains sets of lava tubes extending nearly the entire length of the flow. Most of the tubes apparently formed between shear planes that developed within laminar flow of the molten lava, similar to the mode of formation described by Ollier and Brown (1965). Where the flow gradient increased, however, the active flow probably became turbulent, destroying the laminar flow and shear planes, and forming the tube roof by accretion of spattered lava on lateral levees (e.g., Little Red River Cave, upper section) as observed in active lava flows. Lava tubes and channels of the Cave Basalt have been modified by subsequent surges of lava. Lack of erosional surfaces within the Cave Basalt indicates that the subsequent surges or eruptive phases were all part of the same eruptive event. Tube modifications include partial tube filling (Fig. 21), addition of upper tubes to form multiple levels and vertically elongate cross sections (Fig. 22), and tube enlargement by erosion from subsequent surges of lava.

Lava flows and tubes are controlled to some degree by preflow topography and are usually situated in topographic depressions. Lava tubes represent the zone of highest flow velocity within the overall flow body, analogous to a hydrologic thalweg; as such, the axis of the tube may migrate in a sinuous pattern within active flows. Some sections of the Cave Basalt tubes, however, appear to occupy the bed of a former stream, indicated by exposures of country rock where sides of the tube have collapsed. These exposures also reveal that lava flows are capable of eroding preflow surfaces, shown by undercut sections of country rock (Figs. 19, 20) and country rock inclusions in the basalt.

Several surface features of basalt flows form in association with lava tubes. A topographic ridge often occurs along the lava tube axis, apparently as a result of inflation of the tube and accretion of lava laterally along the tubes. In some places, pressure within the tube was sufficient to deform the ceiling into cupolas, or to deform the roof into small surface domes. Occasionally, the roof ruptured, spilling small lava flows onto the surface. Many domes collapsed to form raised-rim craters. Collapse craters near the terminus of Ole's Cave may have developed by collapse of hydrostatically inflated domes over lava tubes during a temporary damming of the lava flow. Although many pressure ridges occur on the flow surface, there is no apparent relationship to the lava tubes.

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We wish to acknowledge the able field assistance of M. Lovas and K. Oas. We are indebted to the many spelunkers of the Western Speleological Survey and the National Speleological Society who acted as guides and furnished data and photographs; W. R. Halliday, C. Larson, C. Baker, and D. Tubbs were particularly helpful. The manuscript benefited significantly from critical comments by D. R. Cranell, C. A. Hopson, K. G. Snetsinger, S. C. Porter, J. F. Kerridge, and W. R. Halliday. Part of the data was gathered during an U. S. Geological Survey investigation of the potential volcanic hazards of the area by Hyde. Greeley made the study during tenure as a National Academy of Sciences-National Research Council Associate. Radiocarbon age determinations (except for GX1673) were made in the laboratories of the U. S. Geological Survey under supervision of Meyer Rubin.

REFERENCES CITED

Anon.: Mazama, Vol. 2, No. 3, p. 134-135, 1903.

Carithers, W. Pumice and pumicite occurrences of Washington: Wash. Div. Mines and Geology, Rept. Invest. 15, 78 p., 1946.

Crandell, D. R. Surfical geology of Mount Rainier National Park, Washington: U.S. Geol. Survey Bull. 1288, 41 p., 1969.

Diller, J. C. Latest volcanic eruptions of the Pacific coast: Science, N.S., Vol. 9, p. 239-640, 1899.

Elliott, C. P. Mount St. Helens: National Geographic Mag., Vol. 8, p. 226-230, 1897.

Erdmann, C. E.; and Warren, W. Report on the geology of three dam sites on Toutle River, Cowlitz and Skamania Counties, Washington: U.S. Geol. Survey Open-File Rept., 119 p., 1938.

Folsom, M. M. Volcanic eruptions: The pioneers' attitude on the Pacific coast from 1800 to 1875: The Ore Bin, Vol. 32, p. 61-71, 1970.

Forsyth, C. E. Mount St. Helens: The Mountaineer, Vol. 3, p. 56-62, 1910.

Gibbs, G. Report on the geology of the central part of Washington Territory: 33d Cong. 1st Session, House Doc. 129, Vol. 18, Pt. 1, p. 494-512, 1854.

Greeley, R. Geology and morphology of a small lava tube (abstract): Trans. Amer. Geophys. Union, Vol. 50, p. 678, 1969.

Greeley, R. Lava tubes and channels in the lunar Marius Hills: NASA TM X-62,013, 48 p., 1970 (in print, The Moon).

Greeley, R. Lunar Hadley Rille: Considerations of its origin: Science, Vol. 172, p. 722-725, 1971a.

Greeley, R. Observations of actively forming lava tubes and associated structures, Hawaii: Modern Geology, Vol. 2, p. 207-223, 1971b.

Greeley, R. Geology and morphology of selected lava tubes in the vicinity of Bend, Oregon: Bull., Oregon Dept. Geology and Min. Indust., 1971c (in press).

Greeley, R.; and Hyde, J. H. Lava tubes of Mount St. Helens, Washington (abs.): Geol. Soc. Amer. Programs and Abstracts, Vol. 2, No. 2, p. 96, 1970.

Halliday, W. R. Caves of Washington: Wash. Dept. of Conservation, Div. of Mines and Geol., Info. Circ. No. 40, p. 71-104, 1963a.

Halliday, W. R. Features and significance of the Mount St. Helens Cave area: National Parks Mag., Vol. 37, No. 195, p. 11-14, 1963b.

Holmes, K. L. Mount St. Helens' recent eruptions: Oregon Historical Quarterly, Vol. 56, p. 197-210, 1955.

Hopson, C. A. Eruptive sequence at Mount St. Helens, Washington (abs.): Geol. Soc. Amer. Programs and Abstracts, Vol. 3, p. 138, 1971.

Hyde, J. H. Geologic setting of Merrill Lake and evaluation of volcanic hazards in the Kalama River Valley near Mount St. Helens, Washington: U.S. Geol. Survey Open-File Rept., 17 p., 1970.

Hyde, J. H.; and Greeley, R. Phreatic explosion in a lava tube (abs.): Trans. Amer. Geophys. Union, Vol. 52, p. 433, 1971.

Jillson, W. R. The volcanic activity of Mount St. Helens and Mount Hood in historical time: Geographical Review, Vol. 3, p. 481-485, 1917a.

Jillson, W. R. New evidence of a recent volcanic eruption on Mt. St. Helens, Washington: Amer. J. Sci., Vol. 44, No. 259, p. 59-62, 1917b.

Jillson, W. R. Physiographic effects of the volcanism of Mt. St. Helens: Geographical Review, Vol. 11, p. 398-405, 1921.

Kuiper, G. P.; Strom, R. G.; and LePoole, R. S. Interpretation of the Ranger records, *in* Ranger VIII and IX, Pt. 2: Jet Prop. Lab., Calif. Inst. Tech., Tech. Rept. 32-800, p. 35-248, 1966.

Kuno, H. Differentiation of basalt magma, *in* Hess, H. H., and Poldervaart, A., eds., Basalts: The Poldervaart treatise on rocks of basaltic composition: Interscience Publishers, New York, p. 623-688, 1968.

Lawrence, D. B. Trees on the march: Mazama, Vol. 20, No. 12, p. 49-54, 1938.

Lawrence, D. B. Continuing research on the flora of Mt. St. Helen: Mazama, Vol. 21, No. 12, p. 49-59, 1939.

Lawrence, D. B. The "Floating Island" lava flow of Mt. St. Helens: Mazama, Vol. 23, No. 12, p. 56-60, 1941.

Lawrence, D. B. Diagrammatic history of the northeast slope of Mt. St. Helens, Washington: Mazama, Vol. 36, No. 13, p. 41-44, 1954.

Mullineaux, D. R. Extensive recent pumice lapilli and ash layers from Mount St. Helens volcano southern Washington (abs.): Geol. Soc. Amer. Spec. Paper 76, p. 285, 1964.

Mullineaux, D. R.; and Crandell, D. R. Recent lahars from Mount St. Helens, Washington: Geol. Soc. Amer. Bull., Vol. 73, p. 855-870, 1962.

Nockolds, S. R. Average chemical composition of some igneous rocks: Geol. Soc. Amer. Bull., Vol. 65, p. 1007-1052, 1954.

Oberbeck, V. R.; Quaide, W. L.; and Greeley, R. On the origin of lunar sinuous rilles: Modern Geology, Vol. 1, p. 75-80, 1969.

Ollier, C. D.; and Brown, M. C. Lava caves of Victoria: Bull. Volcan., Vol. 28, p. 215-229, 1965.

Parsons, W. H. Criteria for the recognition of volcanic breccias: Review, *in* Larsen, L., Prinz, M., and Manson, V., eds., Igneous and Metamorphic Geology, Geol. Soc. Amer. Mem. 115, p. 270, 1969.

Pryde, P. R. Mount Saint Helens: A possible national monument: National Parks Mag., Vol. 42, No. 248, p. 7-10, 1968.

Verhoogen, J. Mount St. Helens: A recent cascade volcano: California Univ., Dept. Geol. Sci., Bull., Vol. 24, No. 9, p. 263-302, 1937.

Waters, A. C. Stratigraphic and lithologic variations in the Columbia River Basalt: Amer. J. Sci., Vol. 259, p. 583-611, 1961.

Williams, I. A. Tree casts in recent lava: Natural History, Vol. 22, No. 6, p. 543-548, 1922.

TABLE 1. LOCATION AND PHYSICAL CHARACTERISTICS OF LAVA TUBES IN THE CAVE BASALT

Name	Location	Elevation (ft)	Length*	Max. Height	Max. Width	Average Slope
Ape Cave	NE1/4,SW1/4,NE1/4,Sec.8,R.5E,T.8N	2085	3400 m	11.6 m	12.2 m	3.3°,1 m/17.2 m
Barney's Cave	NW1/4,NE1/4,SW1/4,Sec.17,R.5E,T.7N	1670	56 m	2.7 m	3.6 m	2.0°,1 m/27.8 m
Bat Cave**	S1/2,NW1/4,SW1/4,Sec.19,R.5E,T.7N	1160	330 m	3.7 m	16.2 m	-- --
Beaver Cave	SE1/4,SE1/4,Sec.18,R.5E,T.7N	1560	477 m	9.1 m	15.2 m	3.0°,1 m/19.6 m
Dollar-Dime Cave	NW1/4,SE1/4,NW1/4,Sec.19,R.5E,T.7N	1290	--	--	--	-- --
Flow Cave	E1/2,NW1/4,SW1/4,Sec.32,R.5E,T.8N	2835	99 m	2.4 m	4.6 m	3.2°,1 m/17.4 m
Gremlin Cave†	NW1/4,NE1/4,NE1/4,Sec.31,R.5E,T.7N	3000	--	--	--	-- --
Lake Cave	S1/2,SW1/4,SE1/4,Sec.8,R.5E,T.7N	1880	1248 m	15.5 m	9.1 m	2.6°,1 m/22.2 m
Little People Cave	W1/2,NE1/4,SW1/4,Sec.32,R.5E,T.8N	2835	143 m	4.6 m	7.9 m	1.3°,1 m/47.7 m
Little Red River Cave†	W1/2,NE1/4,SW1/4,Sec.32,R.5E,T.8N	2810	1032 m	9.1 m	11.9 m	4.5°,1 m/11.7 m
Ole's Cave†	SW1/4,SW1/4,NW1/4,Sec.20,R.5E,T.7N	1380	1592 m	7.6 m	13.1 m	2.1°,1 m/27.4 m
Powerline Cave	N1/2,Sec.30,R.5E,T.7N	1140	--	--	--	-- --
Prince Albert Cave	N1/2,NW1/4,SW1/4,Sec.19,R.5E,T.7N	1180	480 m	6.1 m	15.0 m	-- --
Spider Cave	W1/2,NW1/4,SW1/4,Sec.32,R.5E,T.8N	2840	271 m	4.6 m	11.4 m	-- --

*For lava tubes with multiple passages, length represents main passage only.

**Dimensions from Halliday (1963a).

†Location given for main entrance.

TABLE 2. CHEMICAL ANALYSES AND MOLECULAR NORMS

Sample	1	2	3	4	5	6	7	8	9	10
Chemical Analyses (Weight Percent)										
SiO_2	50.13	50.28	49.59	62.46	54.09	49.22	50.15	63.16	54.20	49.3
TiO_2	1.65	1.46	1.60	0.92	1.51	1.78	1.02	0.54	1.31	1.6
Al_2O_3	16.73	17.19	17.47	16.82	16.73	17.98	17.81	18.22	17.17	15.6
Fe_2O_3	2.53	1.72	3.32	1.40	2.84	6.16	1.16	1.36	3.48	3.5
FeO	7.94	8.48	7.46	4.28	6.29	3.37	8.82	3.33	5.49	7.8
CaO	9.42	9.72	9.69	5.16	7.76	7.64	10.13	5.24	7.92	10.3
MgO	7.10	6.98	6.62	2.12	5.39	7.18	6.96	2.30	4.36	6.5
MnO	0.15	0.14	0.15	0.08	0.13	0.15	0.18	--	0.15	0.2
Na_2O	3.31	3.38	3.40	4.72	3.92	3.45	3.28	4.06	3.67	2.7
K_2O	0.49	0.50	0.52	1.52	1.06	1.14	0.41	1.16	1.11	0.5
H_2O^+	0.82	0.56	0.27	0.60	0.59	0.67	--	0.40	0.86	1.8
H_2O^-	0.33	0.19	0.13	0.40	0.22	1.00	0.08	0.10	--	
P_2O_5	0.24	0.21	0.16	0.24	0.32	0.38	0.15	0.14	0.28	0.3
Total	100.84	100.81	100.38	100.72	100.85	100.12	100.15	100.01	100.00	99.9
Molecular Norms										
Q	--	--	--	13.05	2.58	--			5.7	
Co	--	--	0.43	--	--	--			--	
Or	2.91	2.95	3.06	9.01	6.26	6.81			6.7	
Ab	29.80	30.25	30.32	42.51	35.19	31.30			30.9	
An	29.43	30.16	29.61	20.28	24.92	30.52			27.2	
Wo	6.35	6.62	--	1.53	4.60	1.19			4.2	
En	13.83	9.98	16.70	5.88	14.88	20.27			10.9	
Fs	5.98	5.24	4.53	4.52	5.87	--			5.3	
Fo	4.38	6.93	7.41	--	--	0.79			--	
Fa	1.89	3.64	2.01	--	--	--			--	
Mt	2.66	1.80	3.45	1.47	2.97	4.51			5.1	
Hm	--	--	--	--	--	1.34			--	
Il	2.31	2.03	2.22	1.29	2.11	2.51			2.4	
Ap	0.51	0.44	0.34	0.51	0.67	0.81			0.7	
Total	100.01	100.01	100.01	100.01	100.01	100.01			99.1	

Sample Description and Location

1 Cave (?) Basalt, Swift Creek, SW1/4,NE1/4, Sec.30, T8N,R5E, this study.
2 Cave Basalt, Lewis River, NW1/4,SW1/4, Sec.25,T7N,R5E, this study.
3 Undivided lava of Mount St. Helens, Kalama River, SW1/4,NW1/4, Sec.33,T8N,R4E, this study.
4 Undivided lava of Mount St. Helens, Swift Creek, NW1/4,SE1/4, Sec.25,T8N,R4E, this study.
5 Undivided lava of Mount St. Helens, Swift Creek, NE1/4,NW1/4, Sec.32,T8N,R5E, this study.
6 Basalt of Marble Mtn., Swift Creek; NE1/4,NE1/4, Sec.16,T7N,R5E, this study.
7 Olivine basalt (Cave Basalt),pahoehoe flow,Lewis River; Verhoogen (1937,p.293).
8 Pyroxene andesite, summit, Mount St. Helens; Verhoogen (1937,p.293).
9 Average andesite, Nockolds (1954, p. 1019).
10 Average Picture Gorge Basalt; Waters (1961, p. 595).

FIGURE LEGENDS

Fig. 1. Location map; "study area" outlines area covered in Figure 2. Straight-line distance from Portland to study area is about 70 km.

Fig. 2. Geological map of the study area.

Fig. 3. Alkali-silica diagram for rocks on the south side of Mount St. Helens, Washington.

Fig. 4. Oblique aerial overview of the Cave Basalt; Mount St. Helens in background; spillway of Swift Reservoir in foreground.

Fig. 5. Longitudinal profile of the Mount St. Helens lava tube system.

Fig. 6. Topographic map of the Cave Basalt.

Fig. 7. Diagram of Spider Cave, plan view.

Fig. 8. Cross section and plan view of Flow Cave.

Fig. 9. Diagram of Prince Albert Cave, plan view.

Fig. 10. Diagram of Bat Cave, plan view (from Halliday, 1963a).

Fig. 11. Cross section and plan view of Beaver Cave.

Fig. 12. Cross section and plan view of Barney's Cave.

Fig. 13. Diagrams illustrating lava tube formation associated with shear planes developed in laminar lava flow. Each stage is shown in longitudinal profile (parallel to flow axis, top diagram) and in transverse cross section (normal to axis, lower diagram).

Fig. 14. Transverse cross sections, Mount St. Helens lava tube system, showing relations of lava tube to lava flow and preflow country rock. In these sections, the lava tube is interpreted to occupy a former stream channel.

Fig. 15. Section in Ape Cave; plan view showing the probable source of fused clay material and site of phreatic explosion.

Fig. 16. Wall section of Lake Cave a few hundred meters from the entrance. Lining (about 20 cm thick) ruptured and slid to the floor; molten lava behind the lining spilled over the lining and into the tube interior.

Fig. 17. Deformed glassy wall glaze on lava tube lining near station 4, Little Red River Cave. Deformation indicates flowage of the lining before it had completely solidified.

Fig. 18. Lava tube interior near main entrance to Ape Cave showing complex cross section, lateral gutters, and multiple flow lines representing successive stages of drainage. Figure on floor indicates scale.

Fig. 19. Near station 11, Ape Cave, illustrating erosion of the unconsolidated pyroclastic flow deposit (country rock) by the lava flow, indicated by the overhang-undercut relation of lava and country rock. Lining here is relatively thin (less than 30 cm separating the tube interior and the country rock).

Fig. 20. Near station 1, Little Red River Cave; contact ("A") of lava on right side and country rock on left side, indicating undercutting and erosion by the lava flow. Dark band along contact is baked zone about 20 cm wide. The "B" marks uncollapsed continuation of the tube; arrow at bottom of picture marks a hardhat for scale.

Fig. 21. Spider Cave in which a subsequent floor flow of aa has partially filled the tube interior. Photograph courtesy of C. Larson.

Fig. 22. Transverse cross sections of lava tubes showing "cutbank" configurations and multiple level development. Stippled area represents lava containing the tube; A, Lake Cave station 15, up-tube view; B, Lake Cave station 24, up-tube view; C, Lake Cave station 39, down-tube view; D, Little Red River Cave station 28, down-tube view; E, Little Red River Cave station 47, down-tube view; F, Ape Cave station 26, up-tube view; G, Ape Cave station 32, up-tube view; H, Ape Cave station 37, up-tube view; I, Ape Cave station 1, down-tube view; J, Ape Cave station 48, up-tube view.

Fig. 23. Floor flow illustrating development of prominent levees along a deep, sinuous channel. Photo by W. Halliday.

Fig. 24. Tube-in-tube structure, south of Entrance 2, Ole's Cave. Formation of small lava tubes and channels in floor flows is relatively common in lava tubes.

Fig. 25. Station 20 in Ape Cave. Unusual lava tube formation in which a ball of lava wedged between and fused to the tube walls during drainage of molten material from the tube.

Fig. 26. "George Washington's Face" (Halliday, 1963a, p. 103) near station 39, Ole's Cave. Structure resulted from accretion of lava on the tube wall.

Fig. 27. Tube wall near station 2, Little Red River Cave, illustrating extremely thin (less than 2 cm) wall separating tube from country rock; tube wall collapsed during the final stages of drainage and exposed country rock. Glove indicates scale.

Fig. 28. Lava stalactite. Photo by W. Halliday.

Fig. 29. Lava stalagmites, some exceeding 40 cm in height, in Bat Cave. Photo courtesy of C. Larson.

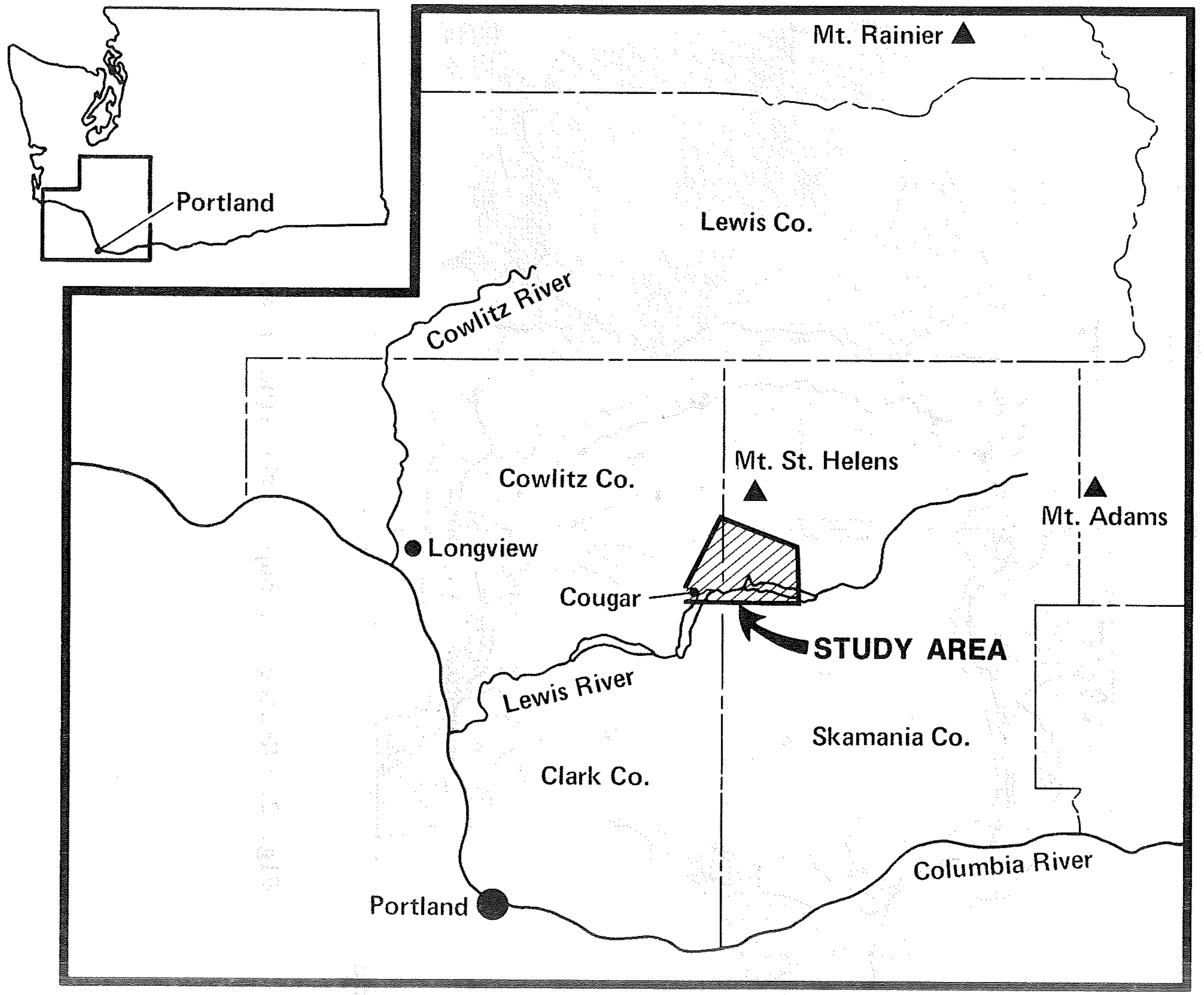
Fig. 30. Section of floor in Spider Cave. A floor flow apparently was moving downtube while molten lava dripped from a single source on the ceiling, forming a chain of glassy blobs (A); cessation of flow permitted a small lava stalagmite to accrete (B). Photo courtesy of C. Larson.

Fig. 31. Ribbon stalactite near station 2, Little Red River Cave; formed by a thin sheet of lava that drained from behind a ruptured part of the tube lining.

Fig. 32. Diagram of part of Lake Cave, showing associated domes, collapsed domes, and collapse craters.

Fig. 33. One of two collapse craters at distal end of Ole's Cave. The crater, about 41 m in diameter, apparently resulted from collapse of a lava dome formed in association with the lava tube.

Fig. 34. Lava dome near the terminus of the Cave Basalt. Several domes similar to this occur on the flow; some appear to be associated with lava tubes, particularly Lake Cave. The dome is about 50 m in diameter (powerline in foreground).



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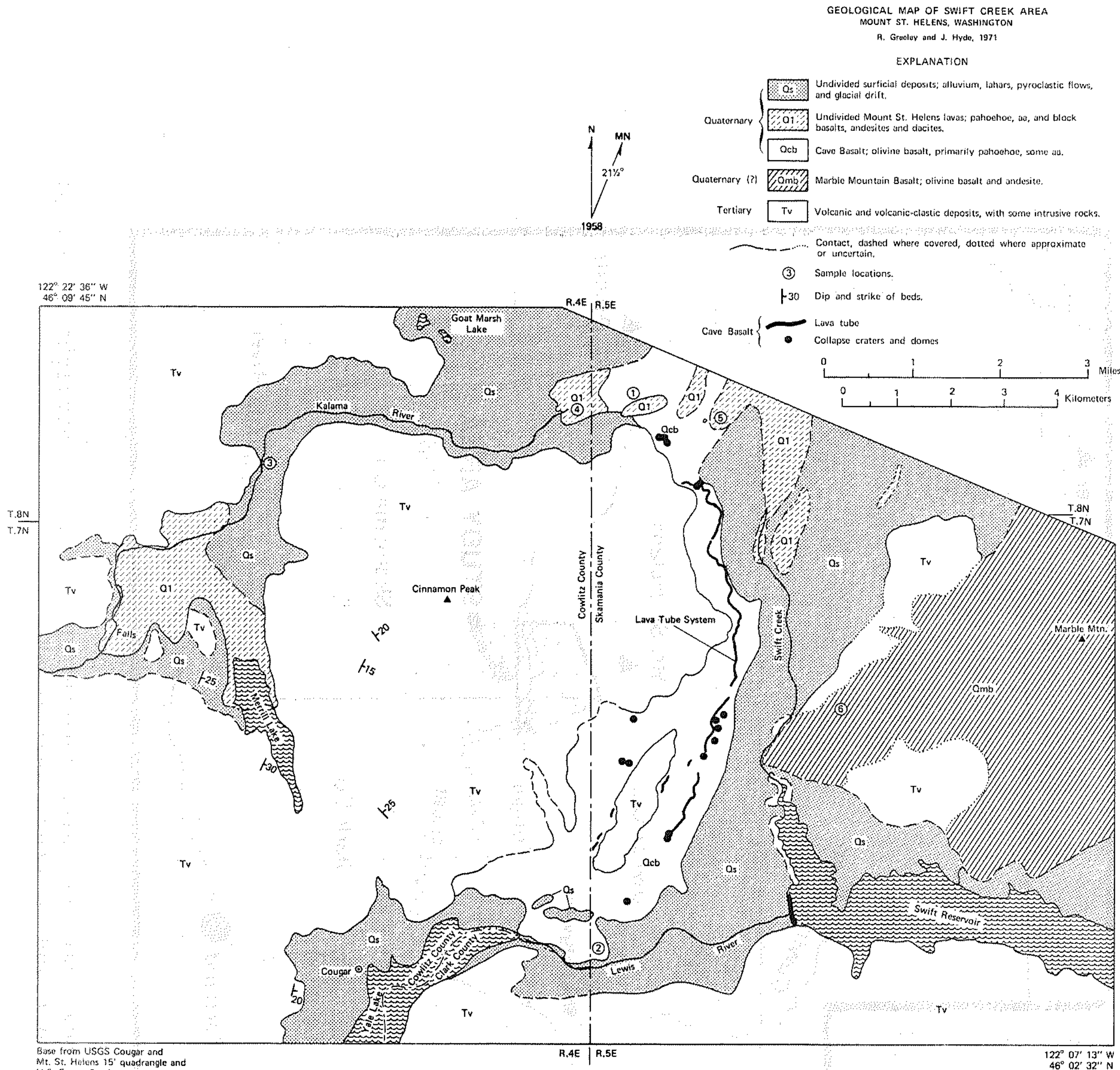


Fig. 2. Geological map of the study area.

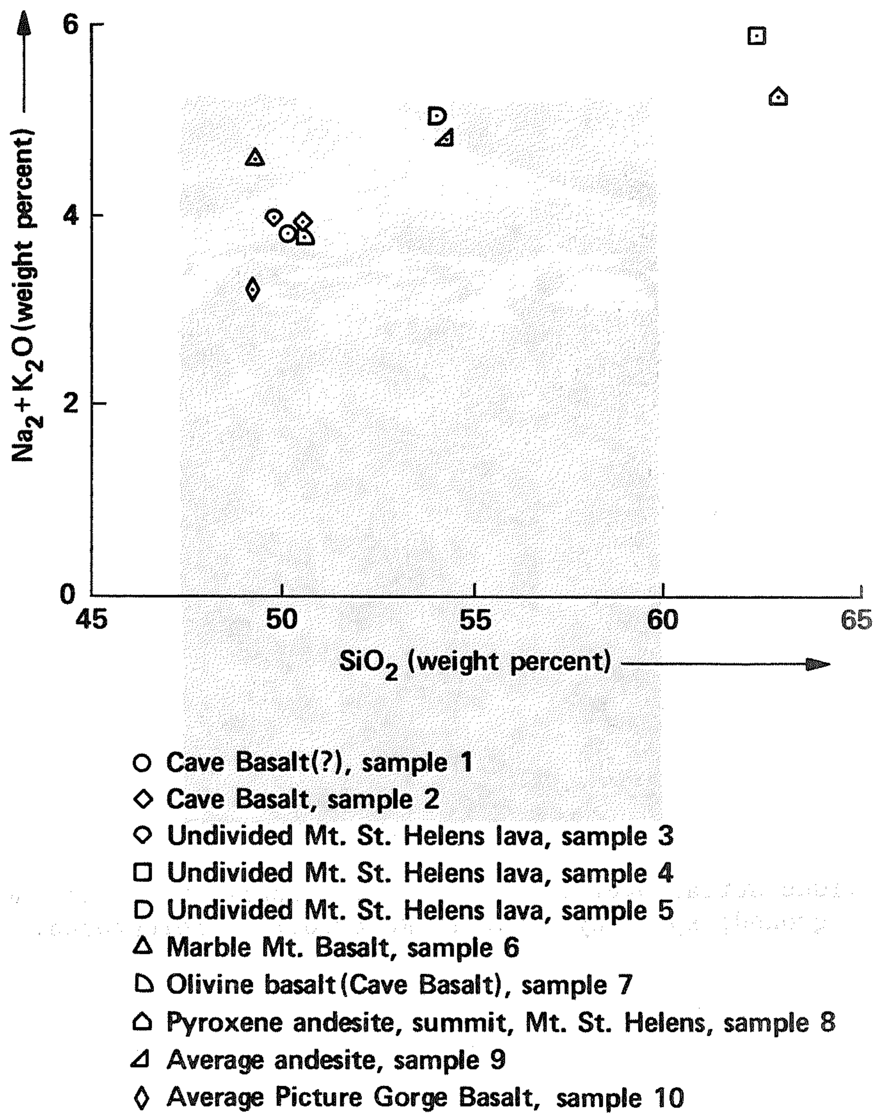
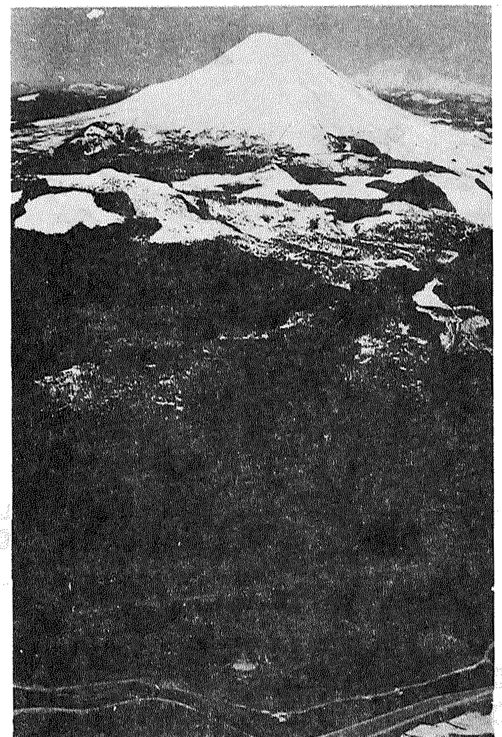


Fig. 3. Alkali-silica diagram for rocks on the south side of Mount St. Helens, Washington.



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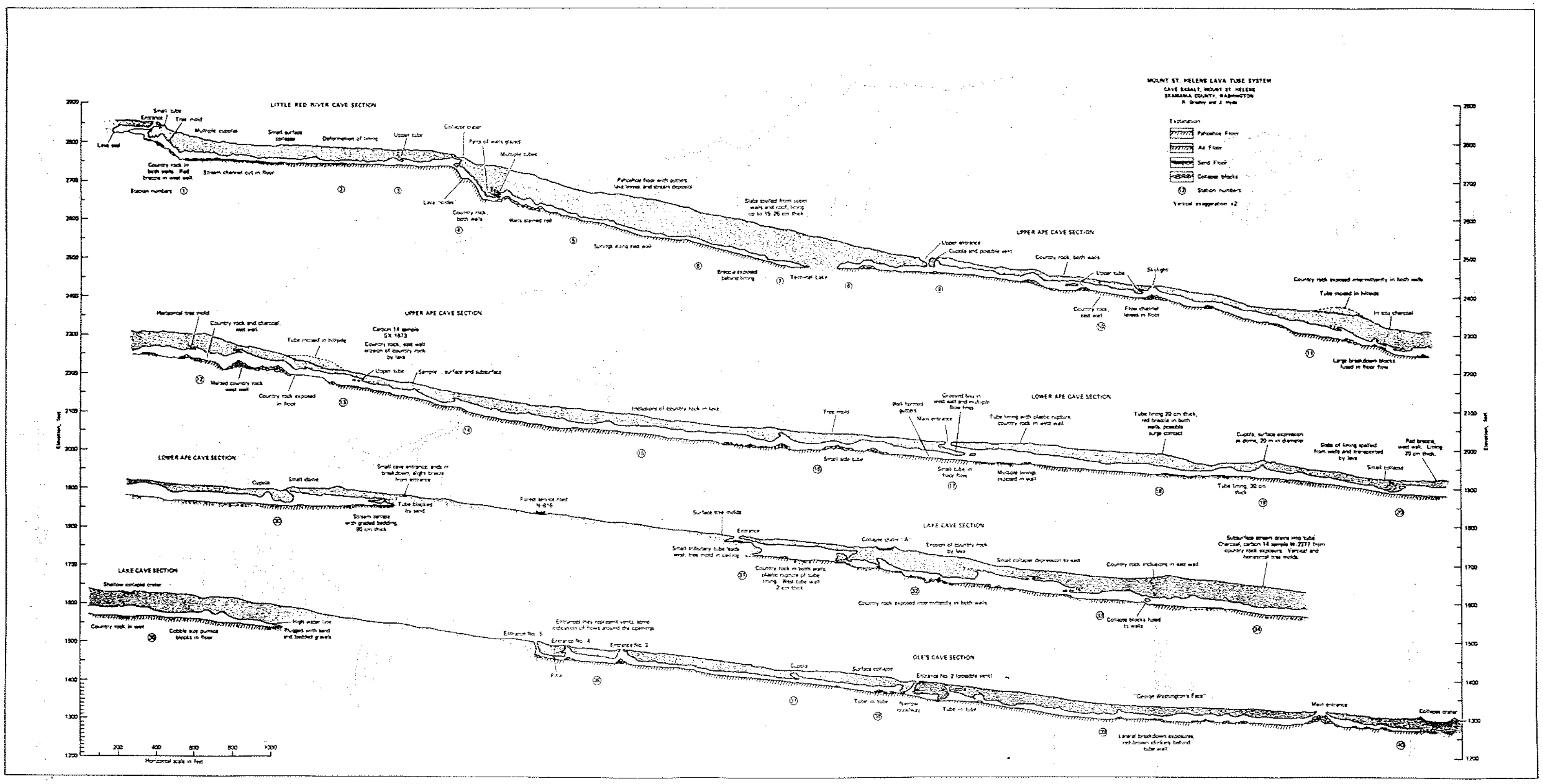


Fig. 5. Longitudinal profile of the Mount St. Helens lava tube system.

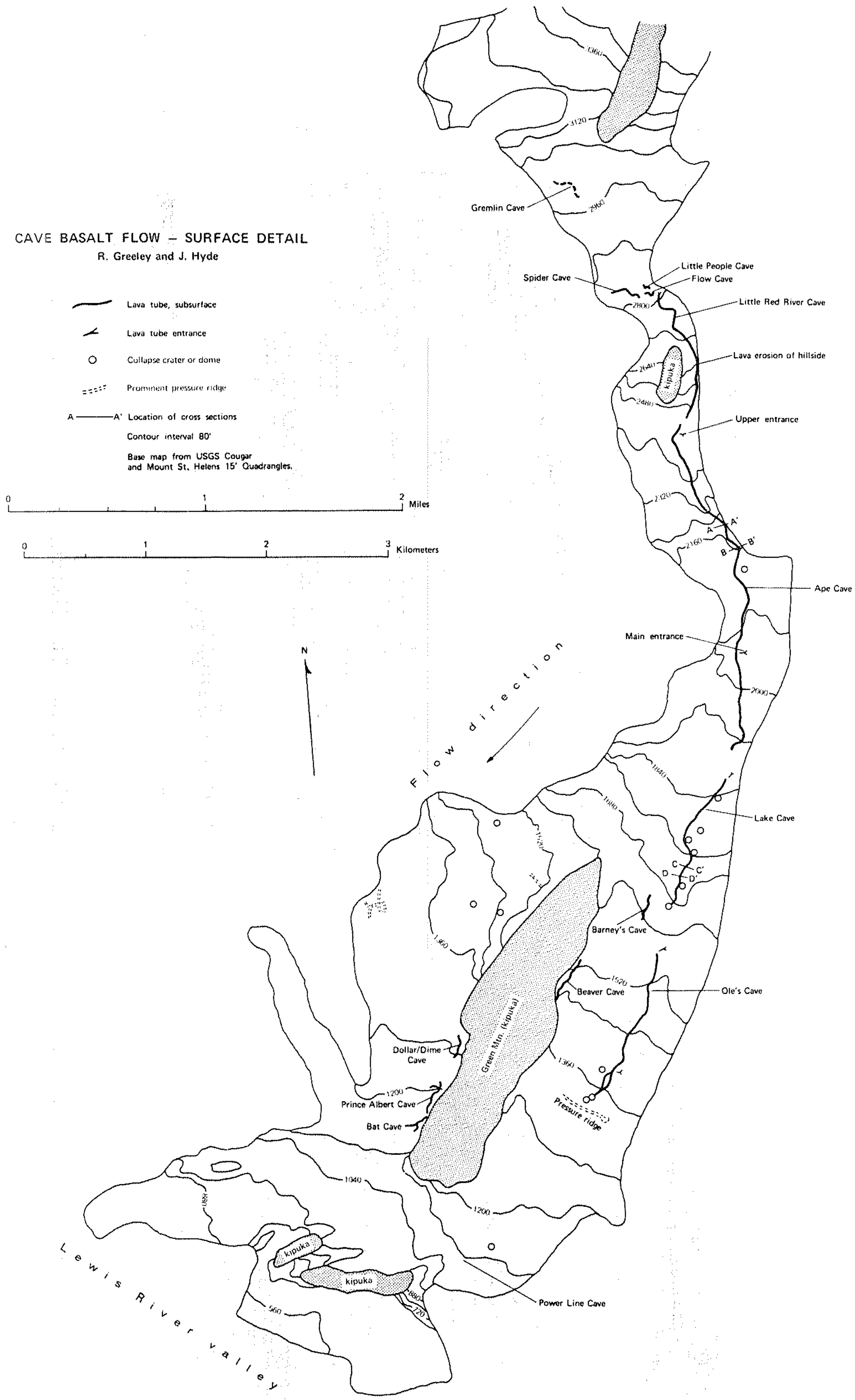


Fig. 6. Topographic map of the Cave Basalt.

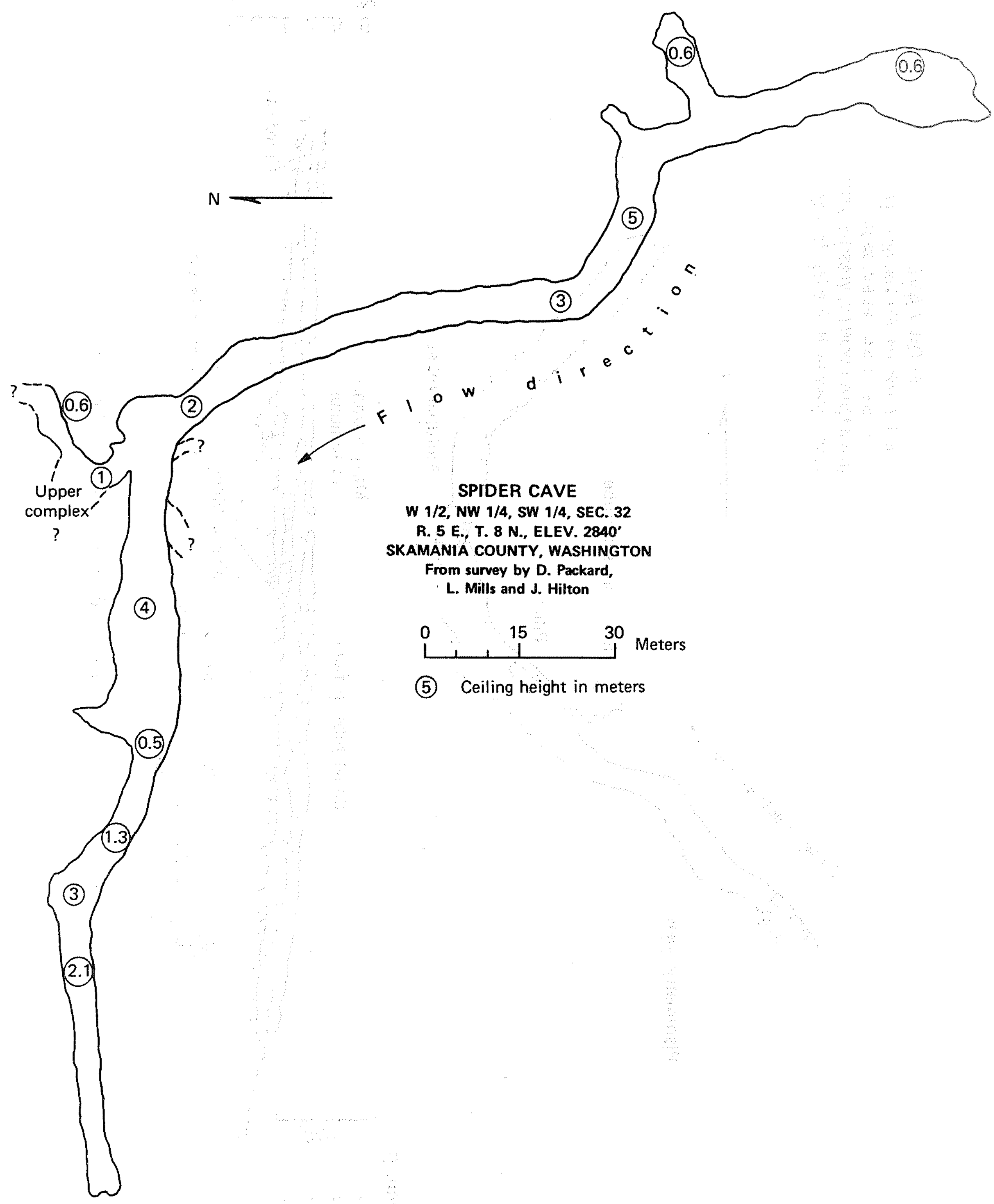


Fig. 7. Diagram of Spider Cave, plan view.

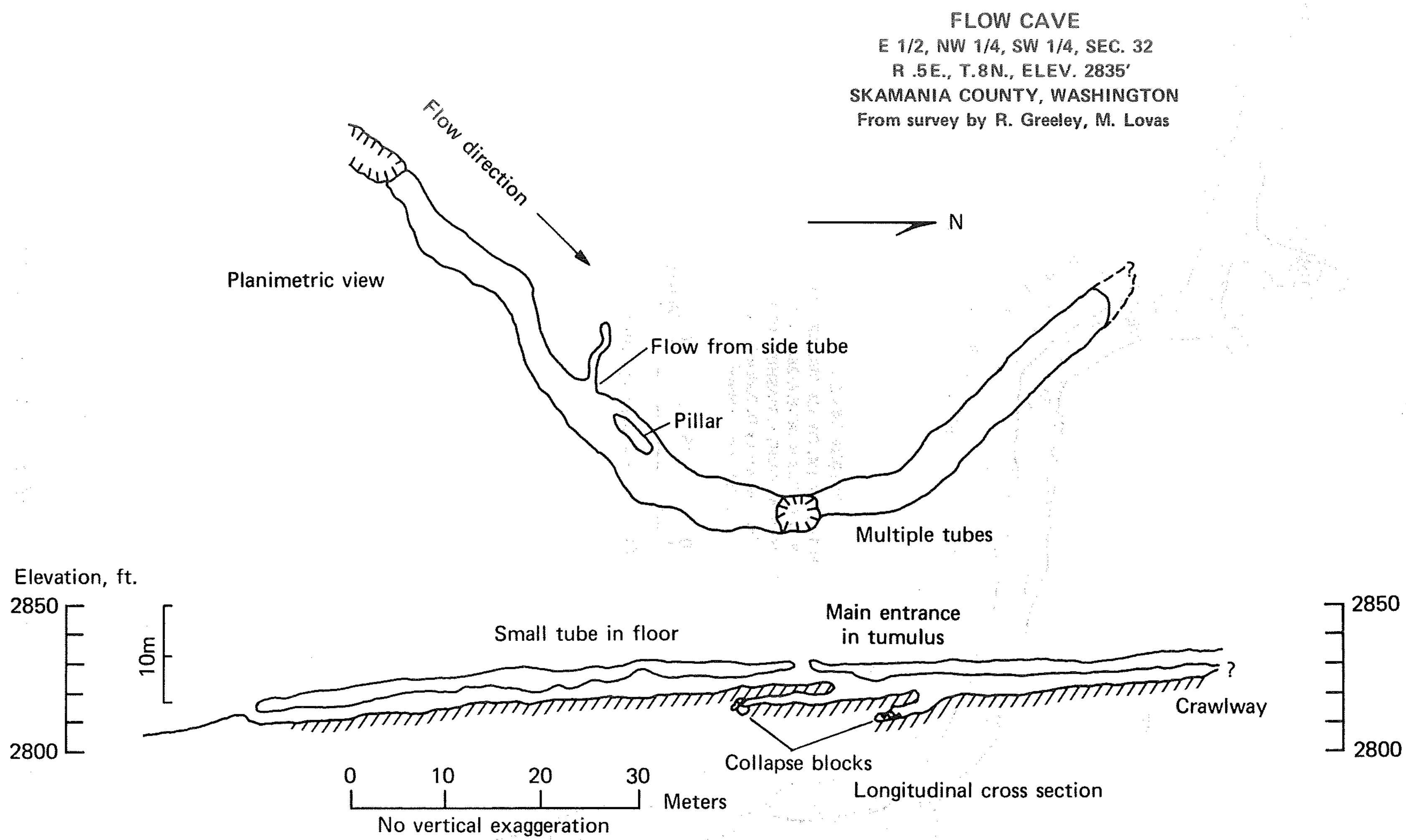


Fig. 8. Cross section and plan vew of Flow Cave.

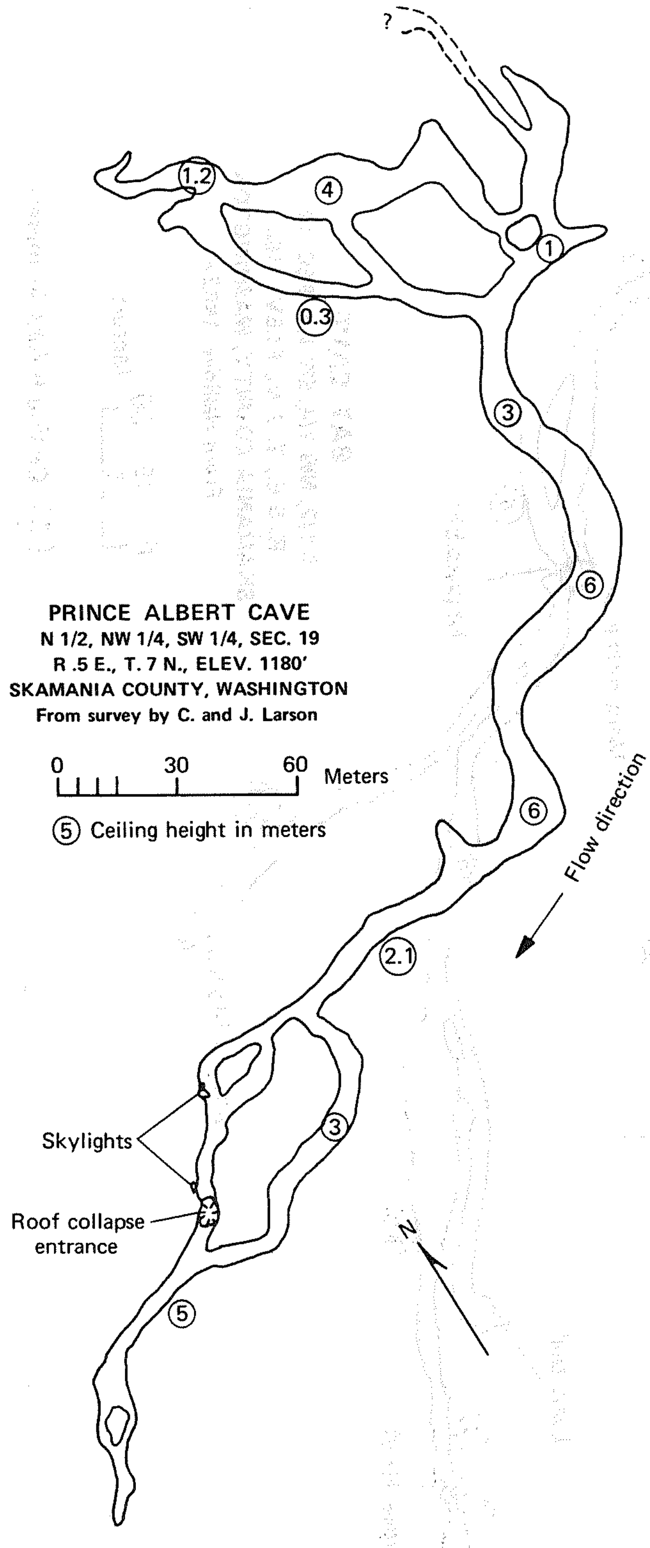


Fig. 9. Diagram of Prince Albert Cave, plan view.

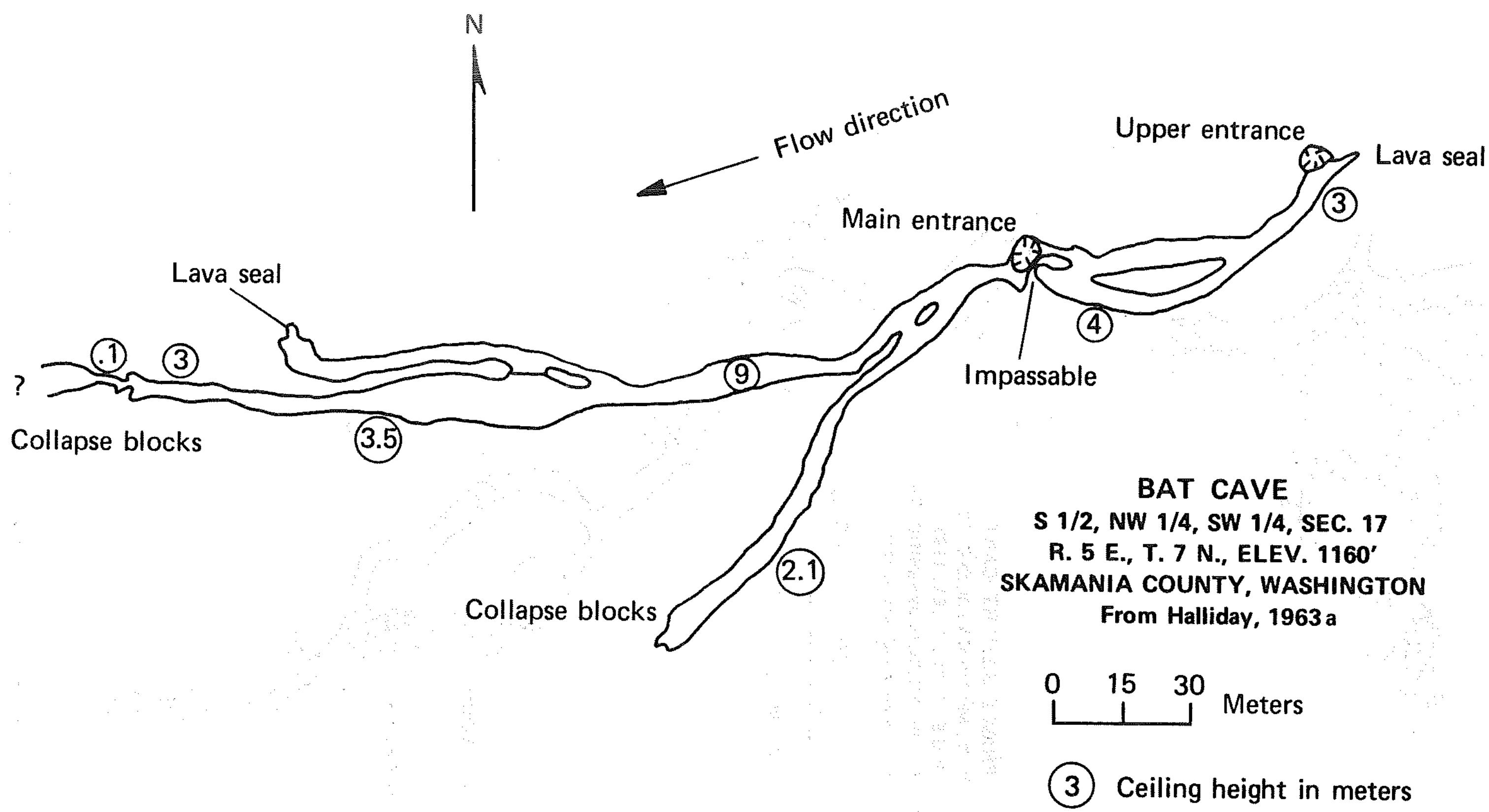


Fig. 10. Diagram of Bat Cave, plan view (from Halliday, 1963a).

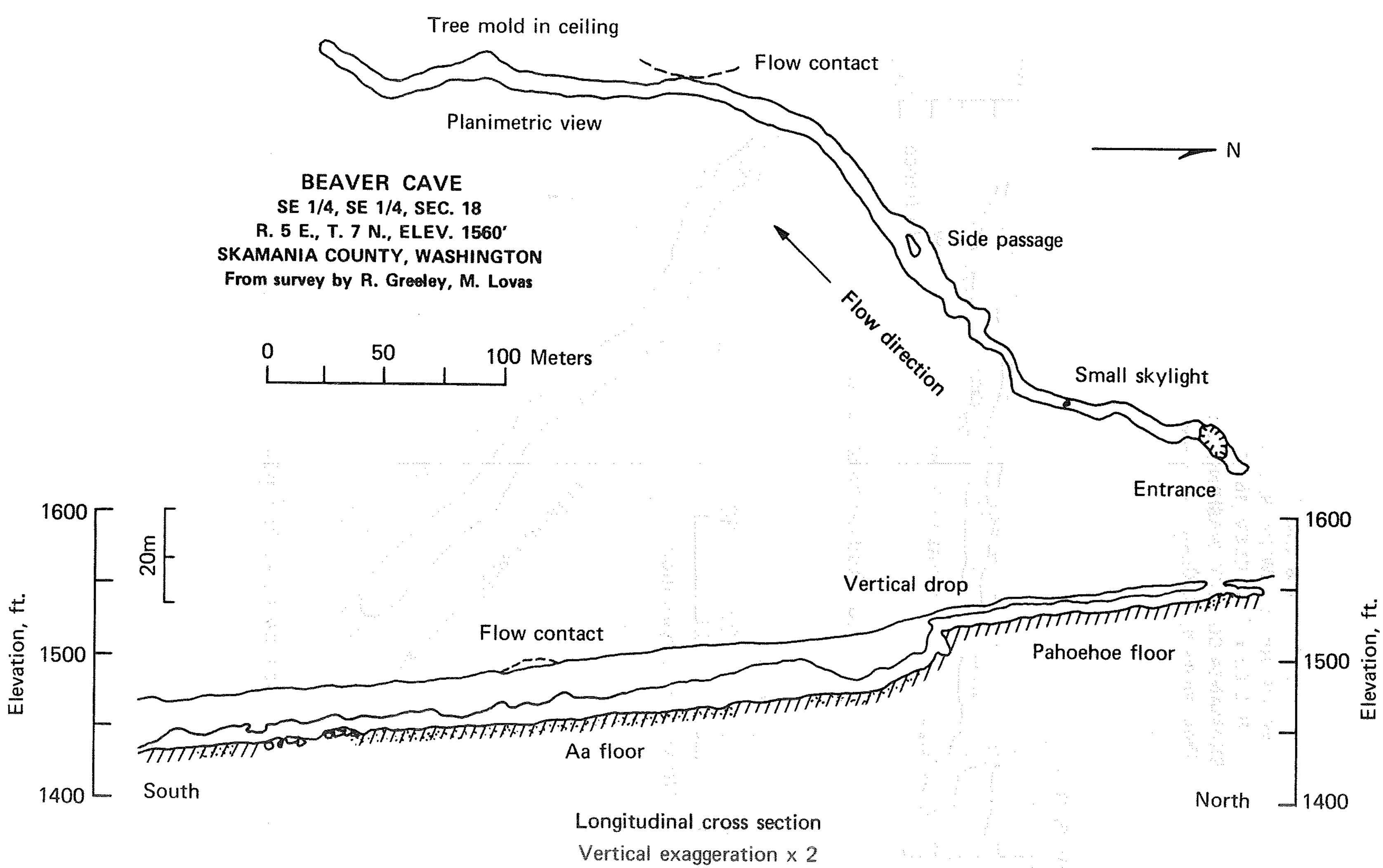


Fig. 11. Cross section and plan view of Beaver Cave.

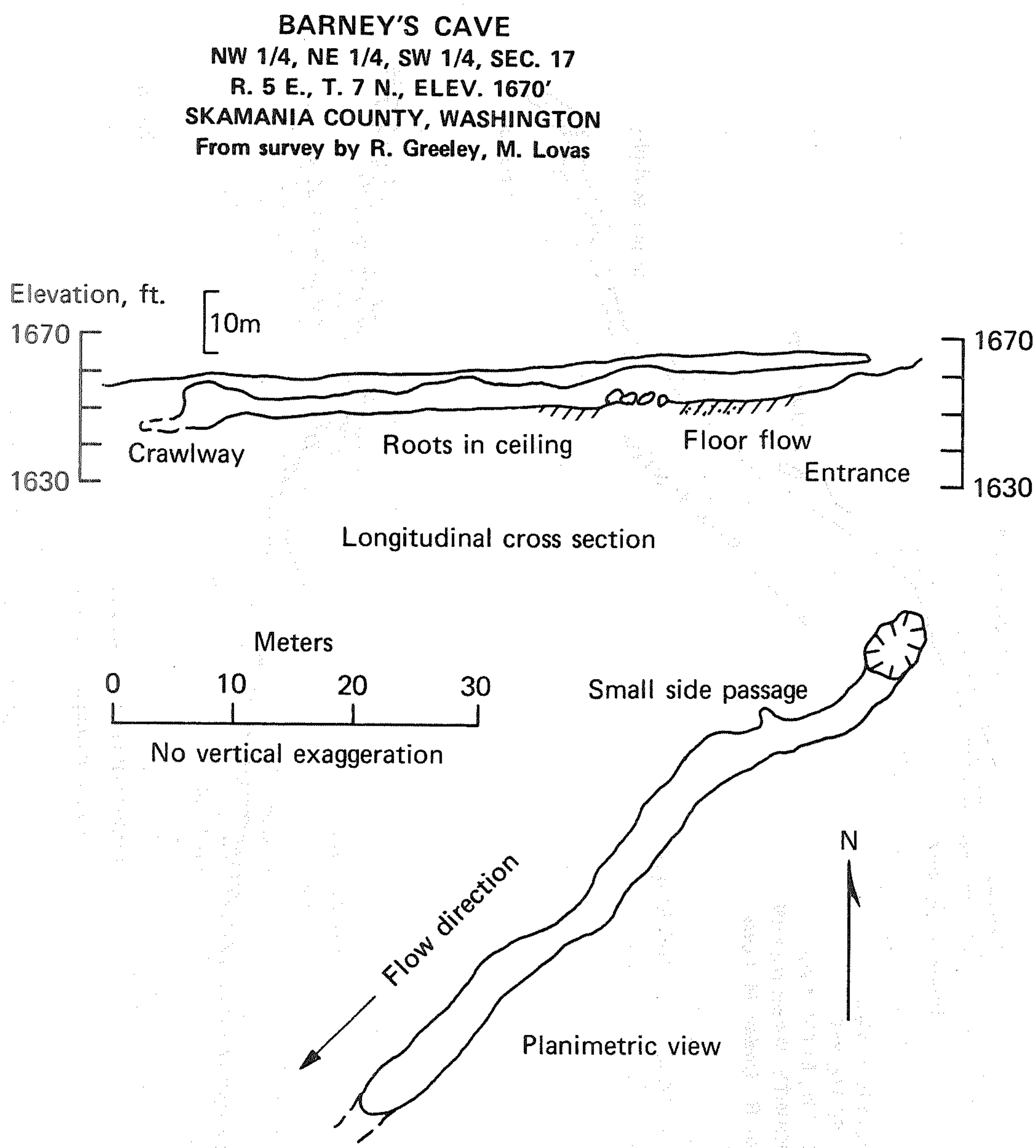
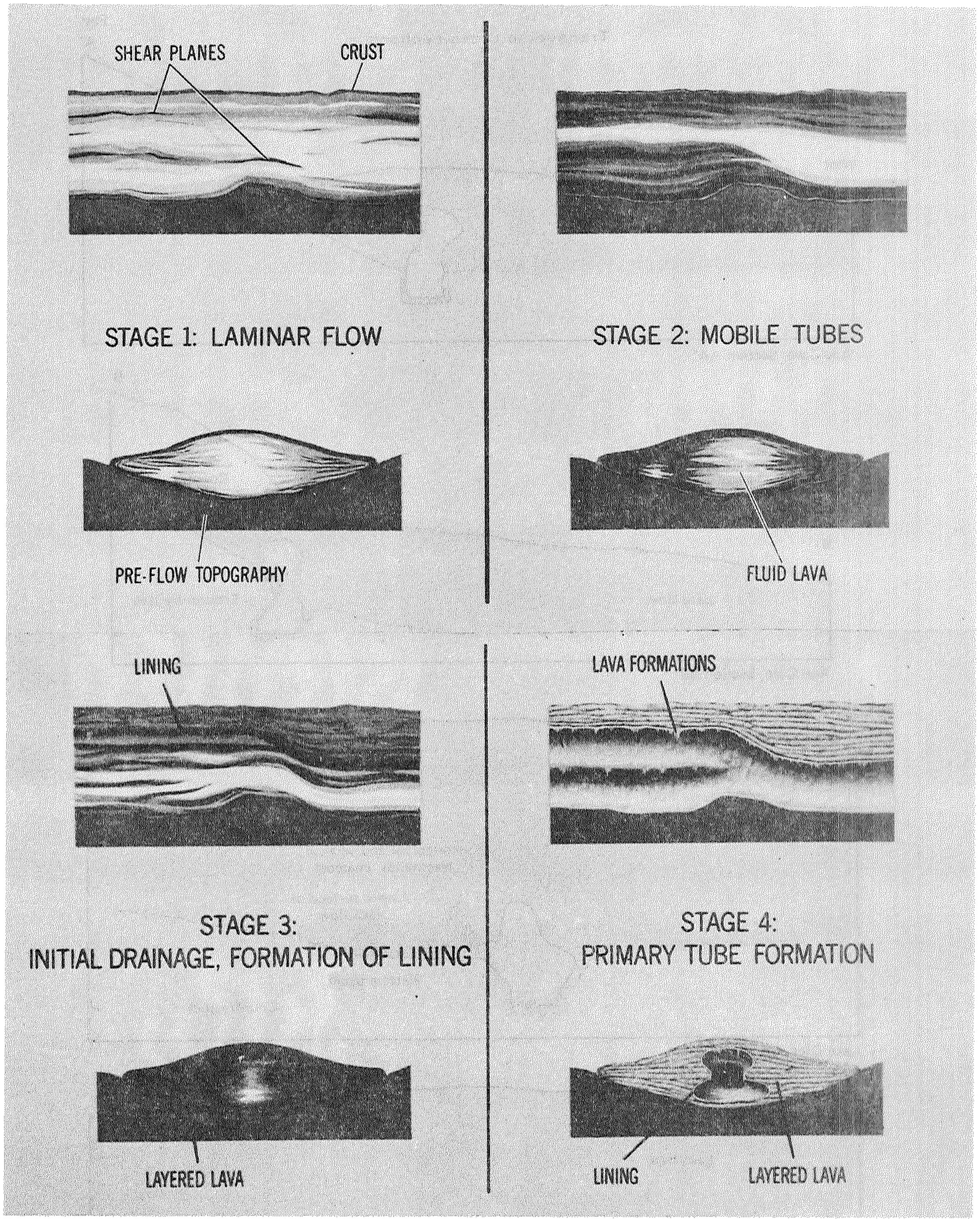


Fig. 12. Cross section and plan view of Barney's Cave.



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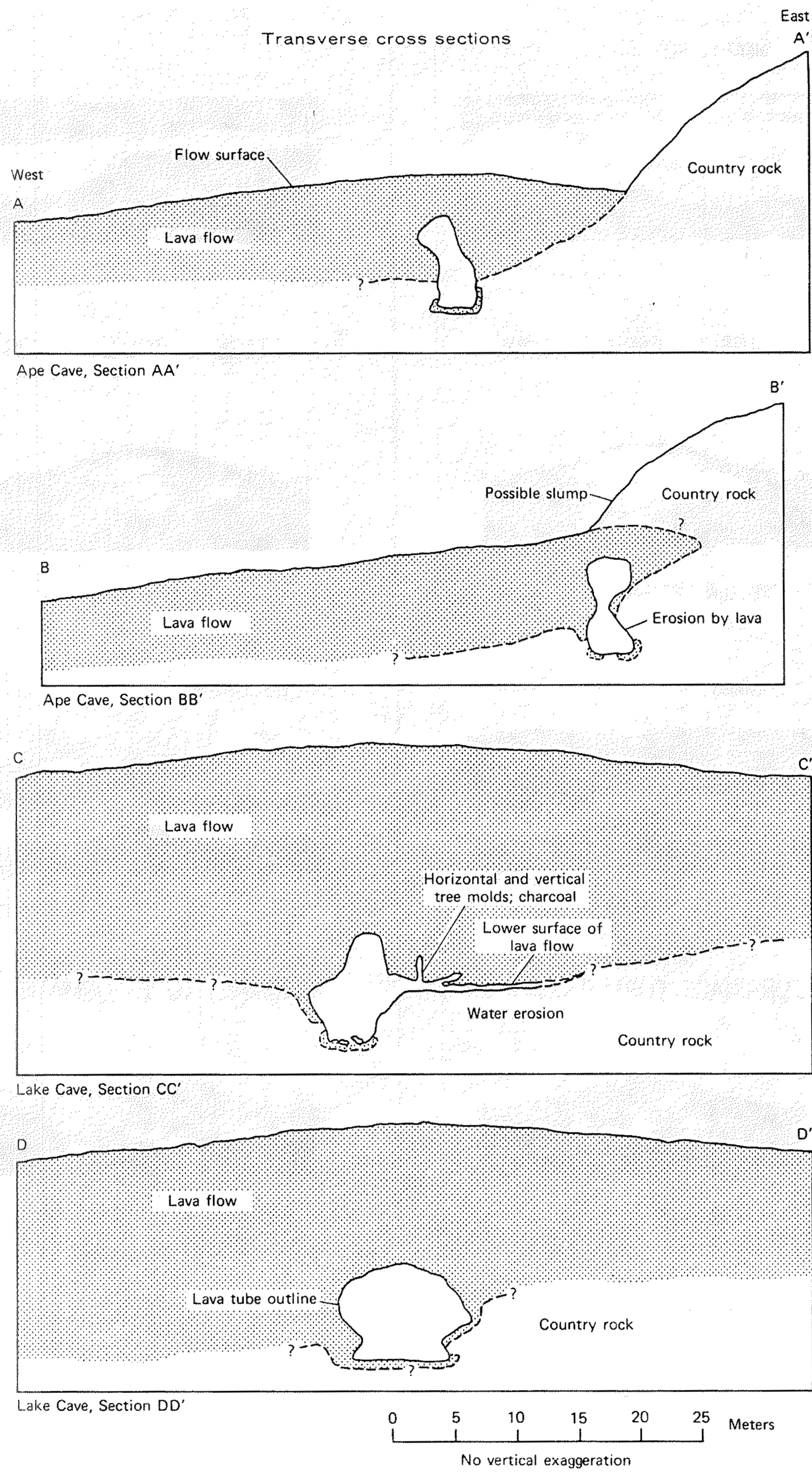

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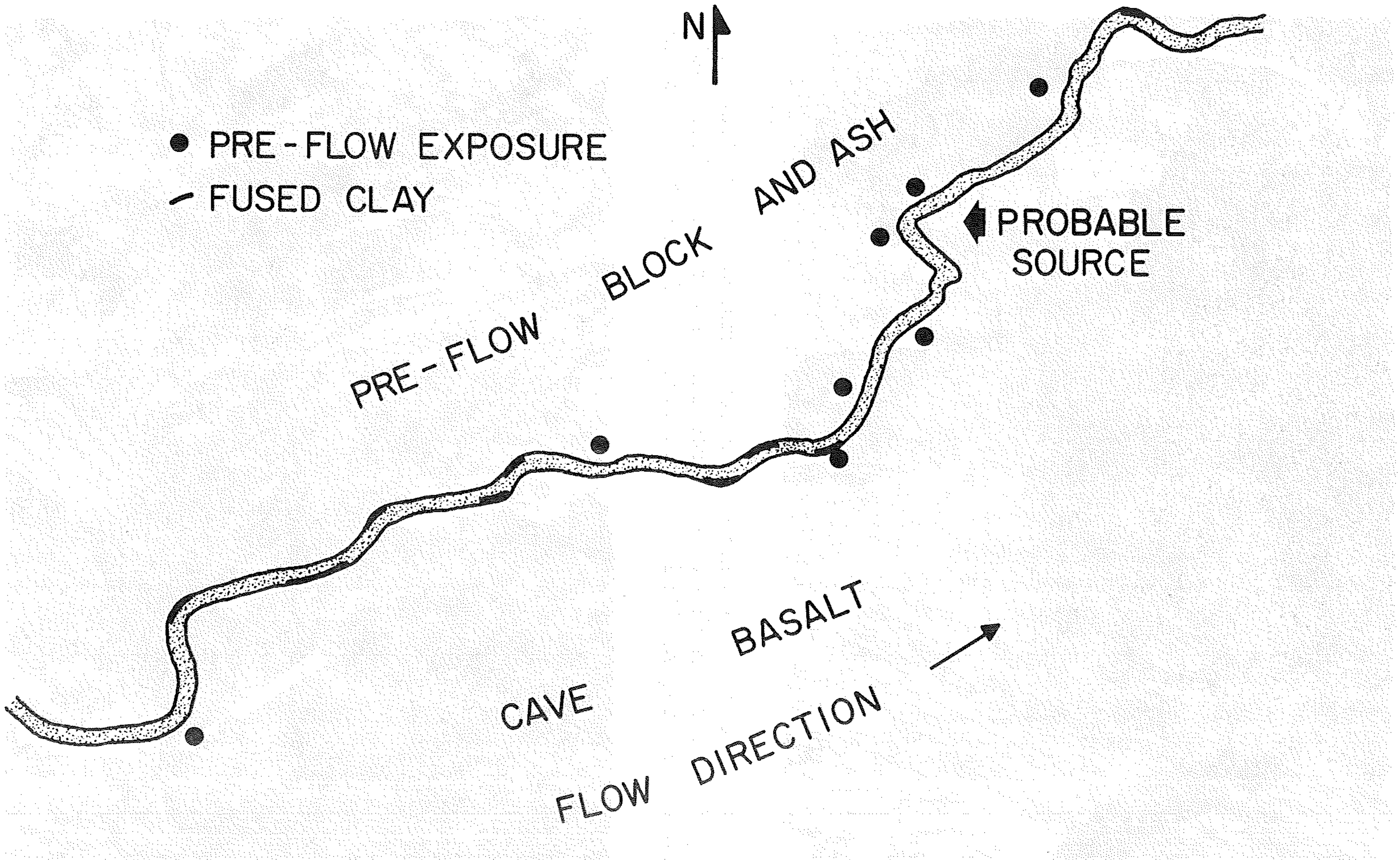

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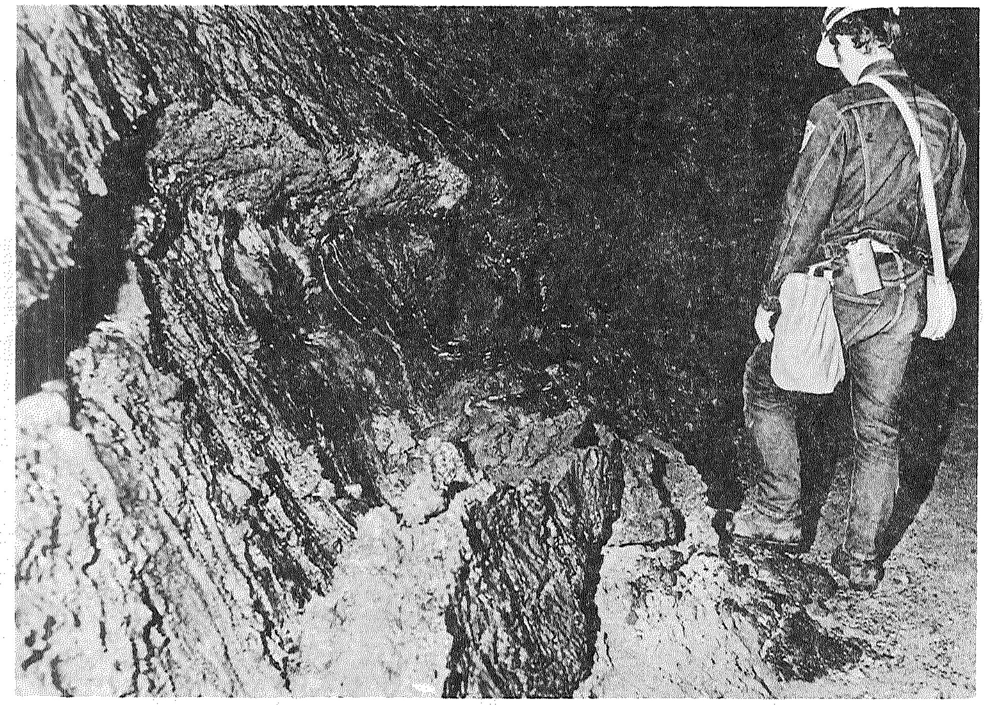

Fig. 16. Wall section of Lake Cave a few hundred meters from the entrance. Lining (about 20 cm thick) ruptured and slid to the floor; molten lava behind the lining spilled over the lining and into the tube interior.

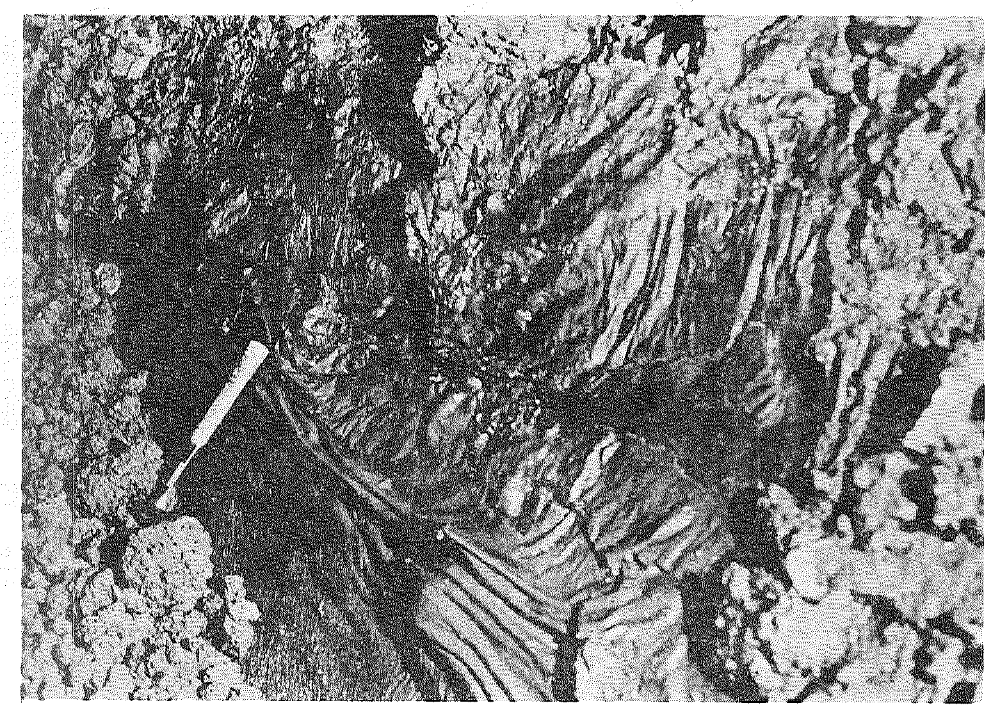

Fig. 17. Deformed glassy wall glaze on lava tube lining near station 4, Little Red River Cave. Deformation indicates flowage of the lining before it had completely solidified.

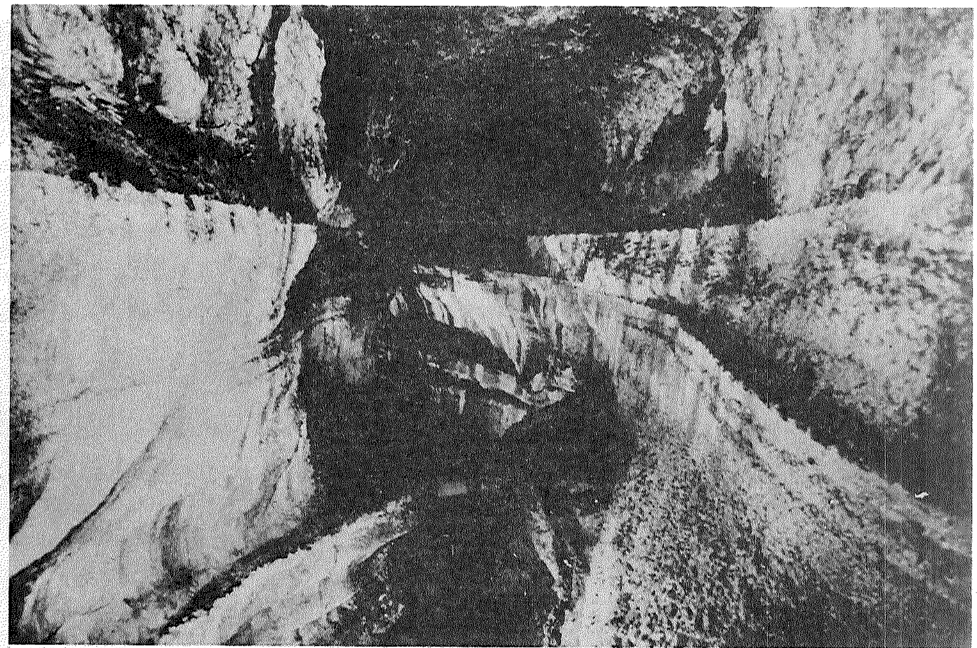

Fig. 18. Lava tube interior near main entrance to Ape Cave showing complex cross section, lateral gutters, and multiple flow lines representing successive stages of drainage. Figure on floor indicates scale.

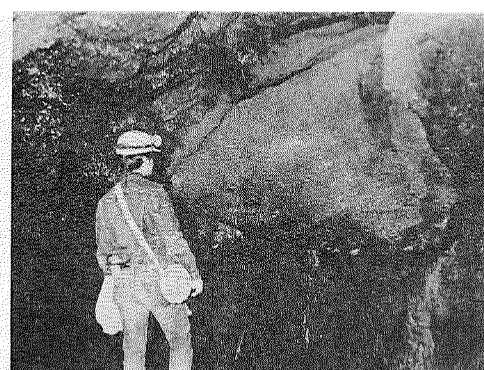

Fig. 19. Near station 11, Ape Cave, illustrating erosion of the unconsolidated pyroclastic flow deposit (country rock) by the lava flow, indicated by the overhang-undercut relation of lava and country rock. Lining here is relatively thin (less than 30 cm separating the tube interior and the country rock).

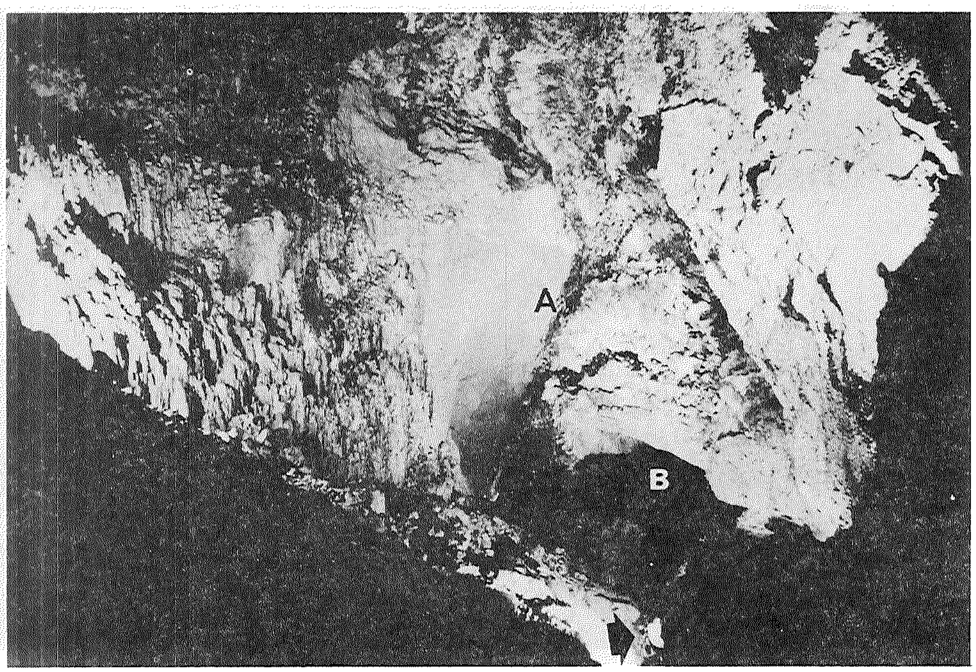

Fig. 20. Near station 1, Little Red River Cave; contact ("A") of lava on right side and country rock on left side, indicating undercutting and erosion by the lava flow. Dark band along contact is baked zone about 20 cm wide. The "B" marks uncollapsed continuation of the tube; arrow at bottom of picture marks a hardhat for scale.

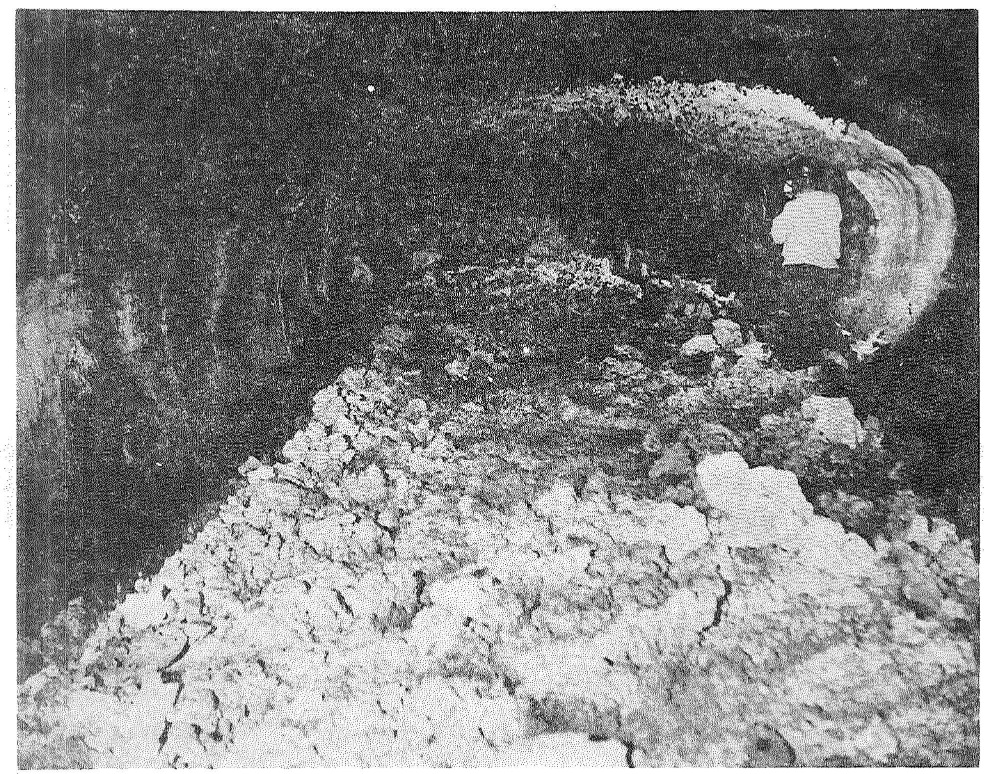

Fig. 21. Spider Cave in which a subsequent floor flow of aa has partially filled the tube interior. Photograph courtesy of C. Larson.

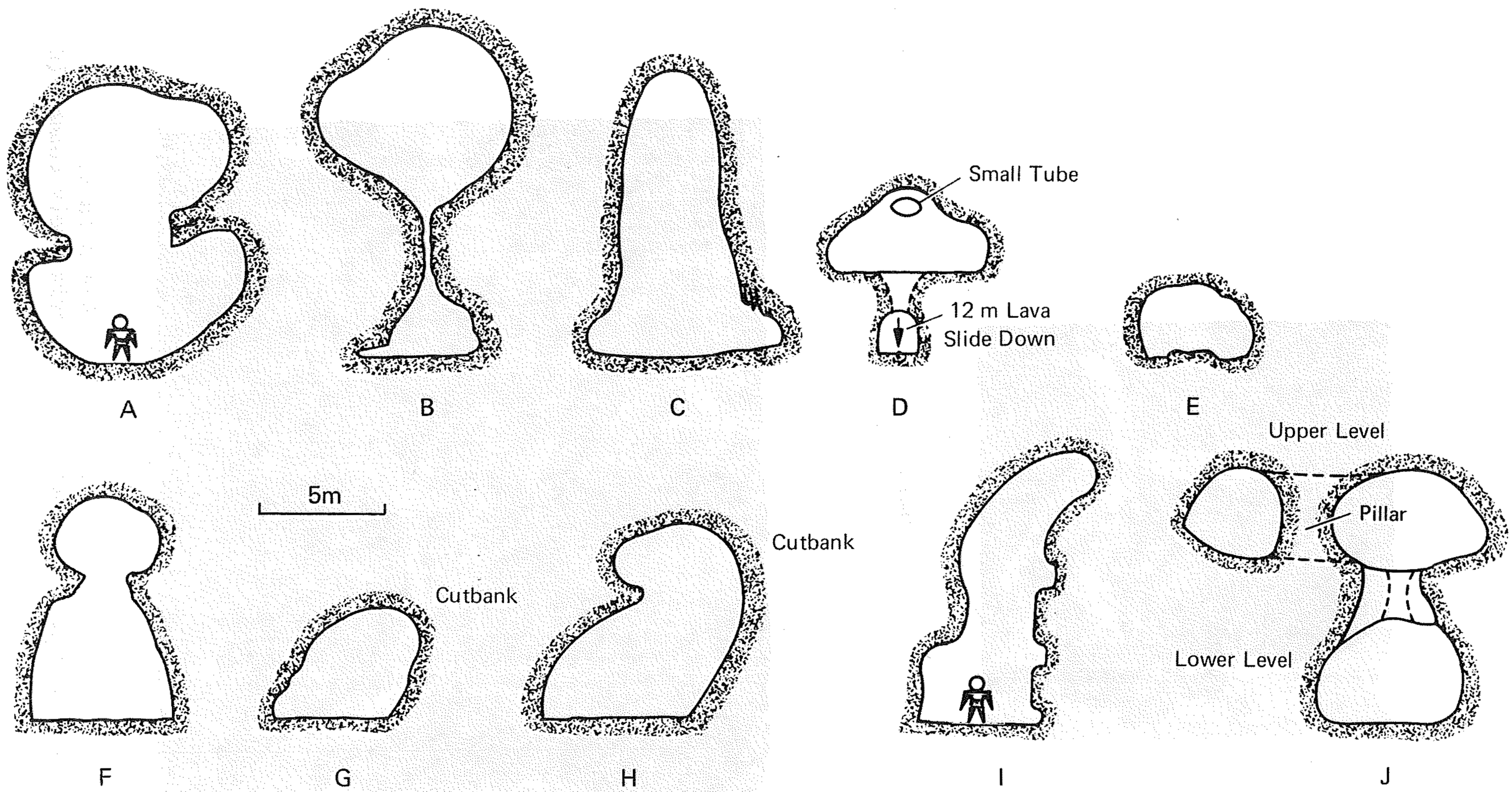

Fig. 22. Transverse cross sections of lava tubes showing "cutbank" configurations and multiple level development. Stippled area represents lava containing the tube; A, Lake Cave station 15, up-tube view; B, Lake Cave station 24, up-tube view; C, Lake Cave station 39, down-tube view; D, Little Red River Cave station 28, down-tube view; E, Little Red River Cave station 47, down-tube view; F, Ape Cave station 26, up-tube view; G, Ape Cave station 32, up-tube view; H, Ape Cave station 37, up-tube view; I, Ape Cave station 1, down-tube view; J, Ape Cave station 48, up-tube view.

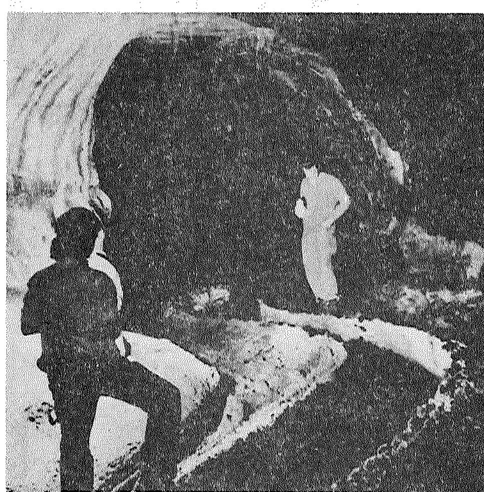

Fig. 23. Floor flow illustrating development of prominent levees along a deep, sinuous channel. Photo by W. Halliday.

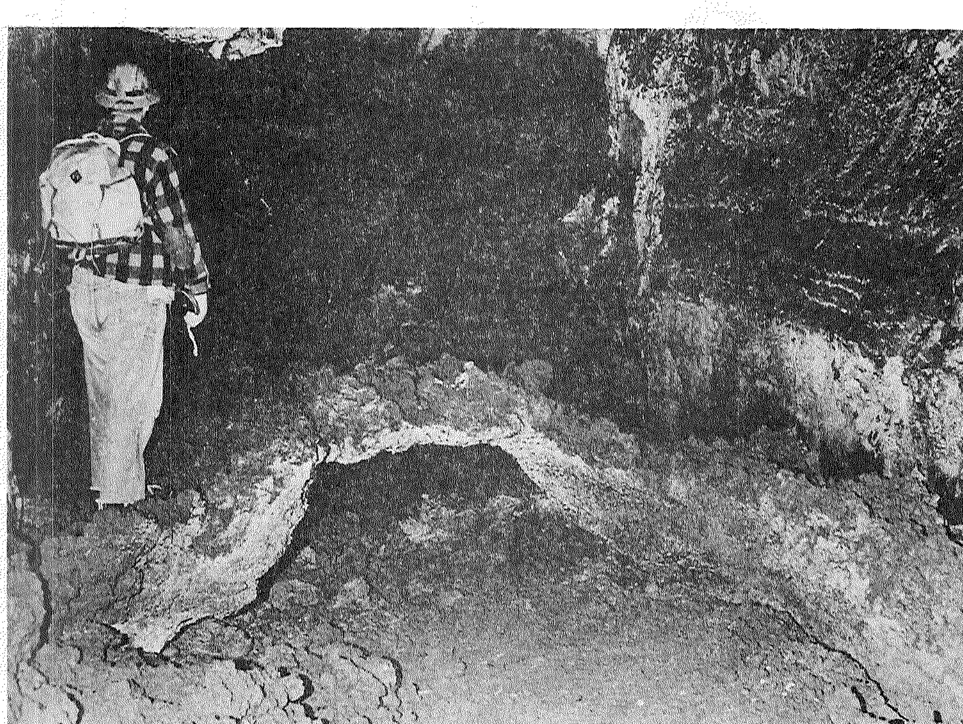

Fig. 24. Tube-in-tube structure, south of Entrance 2, Ole's Cave. Formation of small lava tubes and channels in floor flows is relatively common in lava tubes.

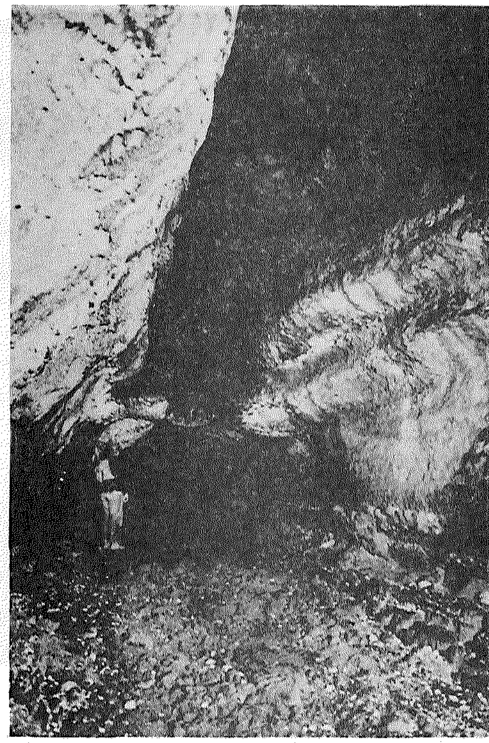

Fig. 25. Station 20 in Ape Cave. Unusual lava tube formation in which a ball of lava wedged between and fused to the tube walls during drainage of molten material from the tube.

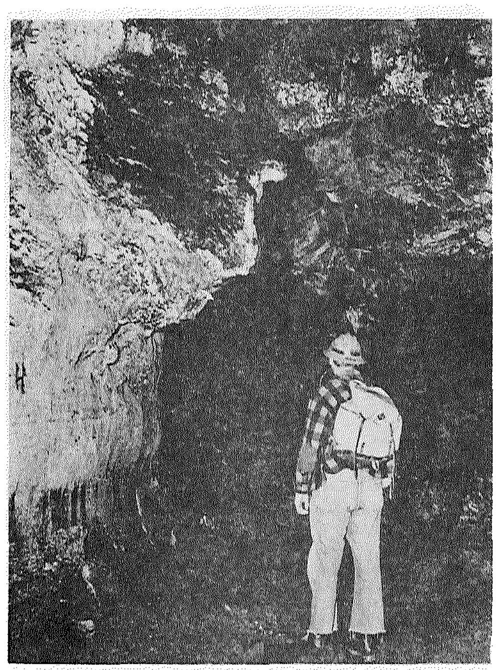

Fig. 26. "George Washington's Face" (Halliday, 1963a, p. 103) near station 39, Ole's Cave. Structure resulted from accretion of lava on the tube wall.

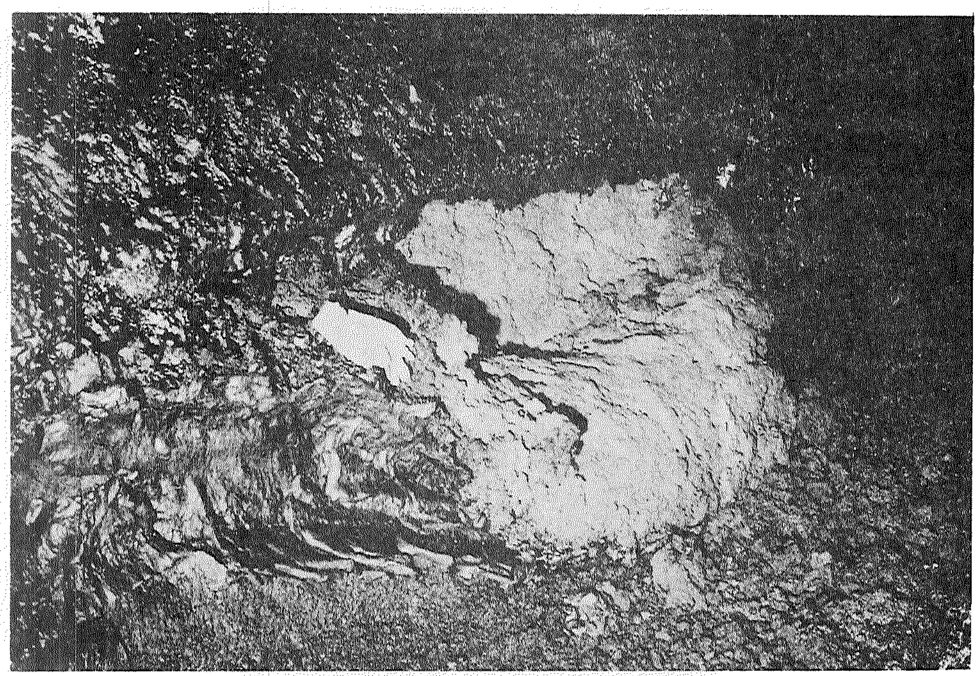

Fig. 27. Tube wall near station 2, Little Red River Cave, illustrating extremely thin (less than 2 cm) wall separating tube from country rock; tube wall collapsed during the final stages of drainage and exposed country rock. Glove indicates scale.

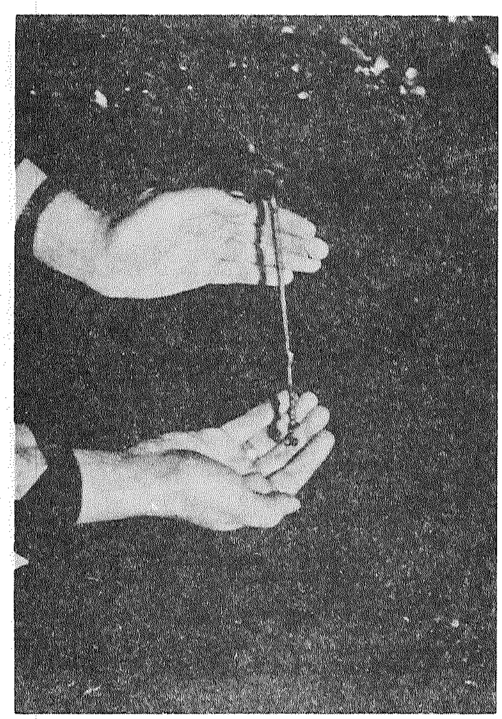

Fig. 28. Lava stalactite. Photo by W. Halliday.

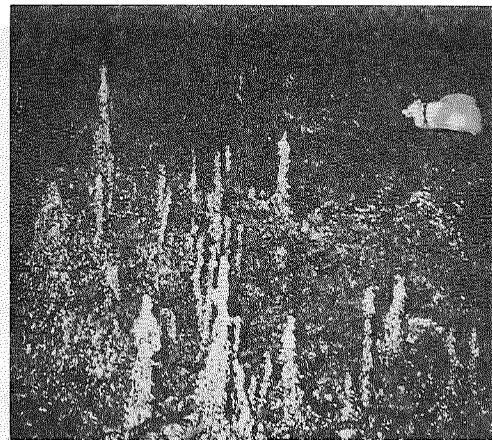

Fig. 29. Lava stalagmites, some exceeding 40 cm in height, in Bat Cave. Photo courtesy of C. Larson.

Fig. 30. Section of floor in Spider Cave. A floor flow apparently was moving downtube while molten lava dripped from a single source on the ceiling, forming a chain of glassy blobs (A); cessation of flow permitted a small lava stalagmite to accrete (B). Photo courtesy of C. Larson.

Fig. 31. Ribbon stalactite near station 2, Little Red River Cave, formed by a thin sheet of lava that drained from behind a ruptured part of the tube lining.

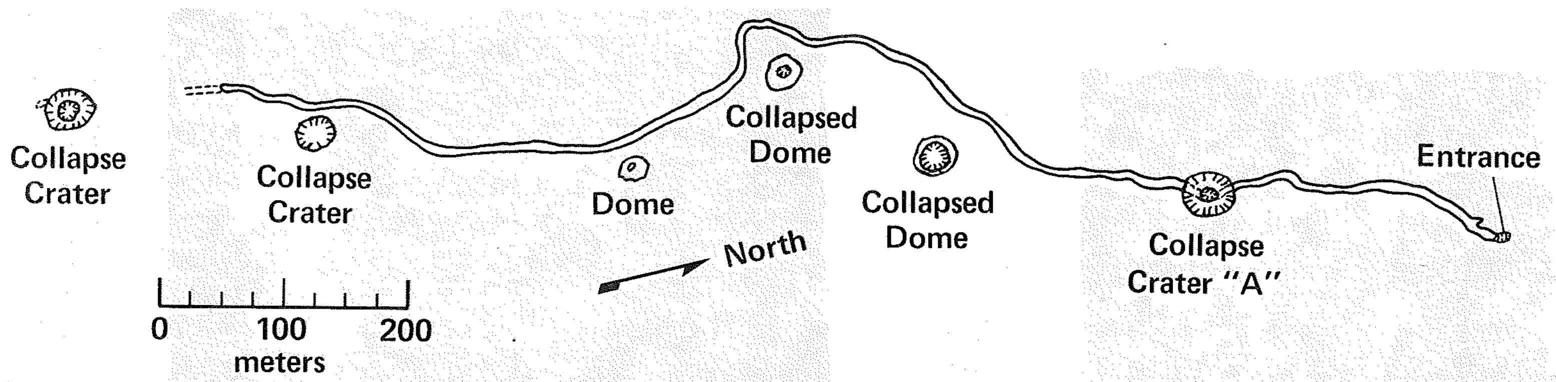

Fig. 32. Diagram of part of Lake Cave, showing associated domes, collapsed domes, and collapse craters.

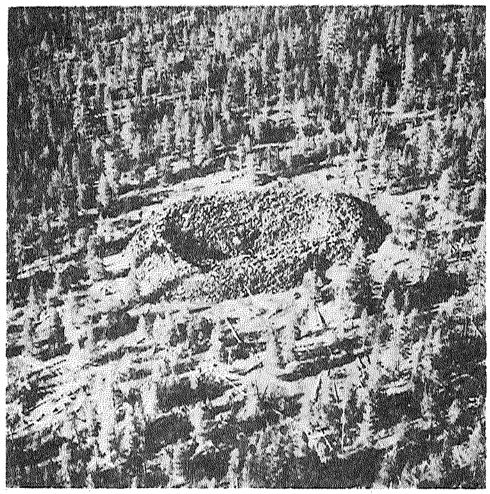

Fig. 33. One of two collapse craters at distal end of Ole's Cave. The crater, about 41 meters in diameter, apparently resulted from collapse of a lava dome formed in association with the lava tube.

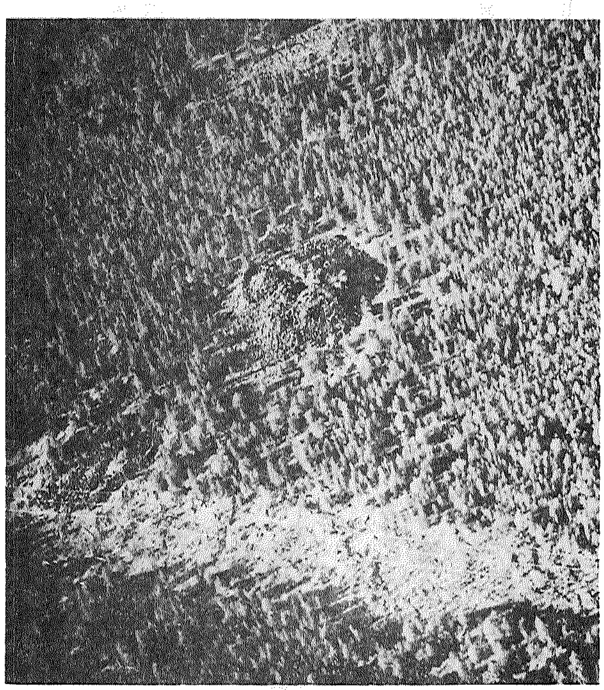

Fig. 34. Lava dome near the terminus of the Cave Basalt. Several domes similar to this occur on the flow; some appear to be associated with lava tubes, particularly Lake Cave. The dome is about 50 meters in diameter (powerline in foreground).