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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# THE RELATIONSHIP OF MORPHOLOGY, STRUCTURE AND LITHOLOGY TO THE EMPLACEMENT OF THE HOT CREEK RHYOLITE FLOW, LONG VALLEY, CALIFORNIA

By Thomas J. Holecek

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# The relationship of morphology, structure and lithology to the emplacement of the Hot Creek Rhyolite flow Long Valley, California

By

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(continued)

# INTRODUCTION

The Hot Creek rhyolite flow, located 13 km east of Mammoth Lakes, California, is one of 12 Pleistocene rhyolite flows that erupted in the moat of Long Valley caldera following collapse of the caldera (Bailey and others, 1976.) It erupted 280,000 years ago within Pleistocene Long Valley lake and was in large part sub-lacustrine (Fig.1).

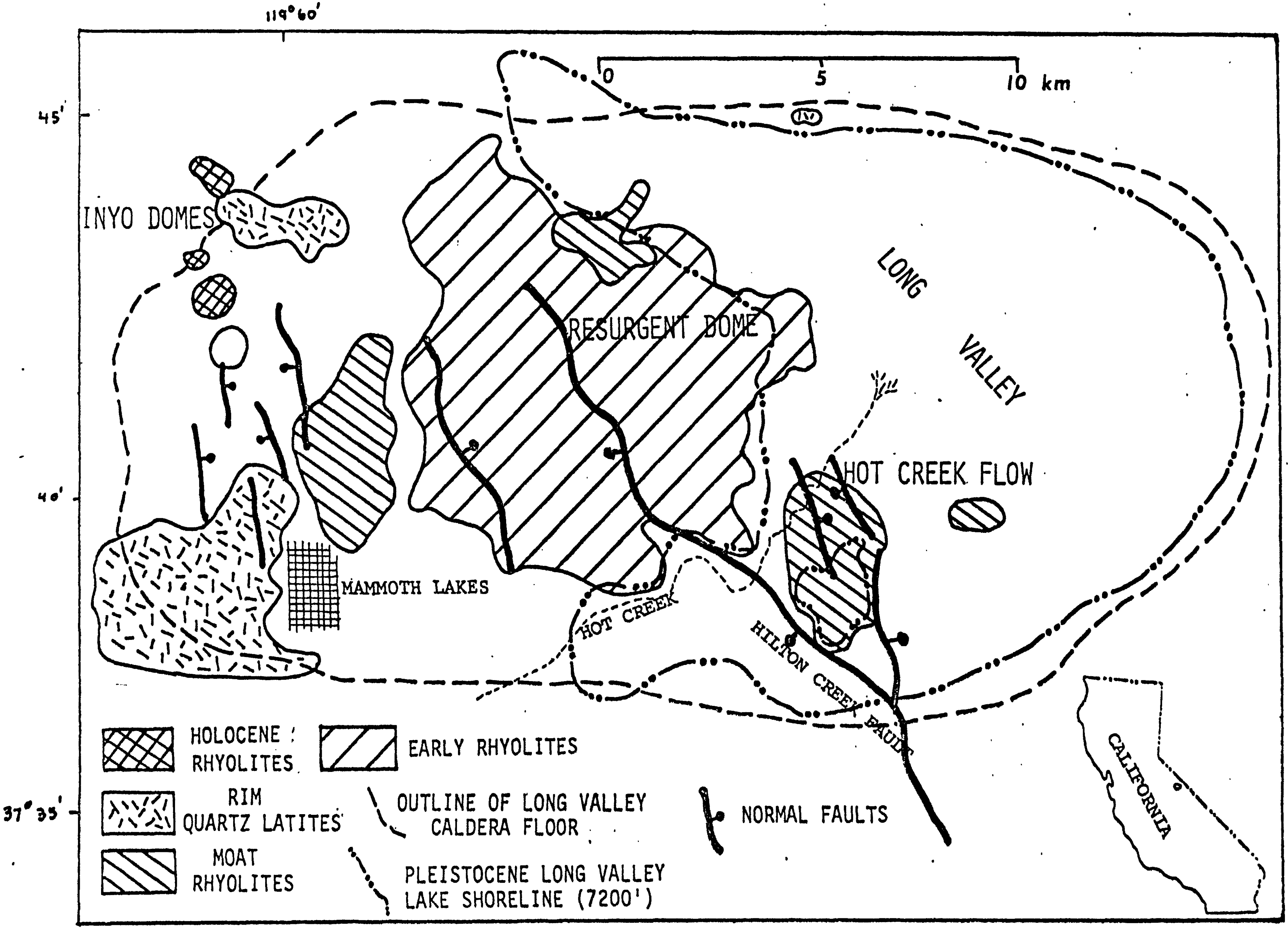
The general purpose of this study is to describe the morphology and internal structure of the flow and to infer from these its emplacement and cooling histories. As about two-thirds of the body was emplaced sub-aqueously, the effect of the lake water on the flow is an important aspect of study.

## PREVIOUS STUDIES

The earliest description of rhyolite flow features, in English, was included in a paper by Iddings (1888). He described and illustrated various textures in the rhyolite of Obsidian Cliff at Yellowstone Park, Wyoming. Iddings also presented an explanation of the process by which foliation developed.

A classic study of domes by Williams (1932) and investigations of the Mono Craters in California by Putnam (1938) and Loney (1968) provided basic information on the structure and lithology of rhyolite extrusions which were useful in the present study. Christiansen and Lipman (1966) described the emplacement and cooling history of Comb Peak Rhyolite flow in Nevada. Fundamental concepts drawn from this paper were used as a basis for study and interpretation of the structure and lithology in Hot Creek flow. A similar study by Haeffner (1975, 1976) of the Shoshone volcanics, Death Valley, California, also provided use-

Figure 1. Generalized geologic map of Long Valley, California (modified from Bailey, 1974) showing relations of Hot Creek flow to other features of Long Valley caldera.


119°60'
45'
40'
37° 35'
0
5
10 km
INYO DOMES
RESURGENT DOME
LONG VALLEY
HOT CREEK FLOW
MAMMOTH LAKES
HOT CREEK
HILTON CREEK FAULT
CALIFORNIA
HOLOCENE RHYOLITES
EARLY RHYOLITES
RIM QUARTZ LATITES
OUTLINE OF LONG VALLEY CALDERA FLOOR
NORMAL FAULTS
MOAT RHYOLITES
PLEISTOCENE LONG VALLEY LAKE SHORELINE (7200')

ful background information.

## FIELD DATA

The field work upon which this study is based was carried out during the summers of 1975 and 1976 and forms part of a broader study of the Long Valley caldera. The topographic map upon which the field data was plotted, was prepared at a scale of 1:7900 from U.S. Forest Service air photos using a Kearn PG-2 plotter. The contours are generally accurate to within ±10 ft. Due to lack of adequate control points, contours at the southern tip of the flow are only accurate to within ± 40 ft.

## ACKNOWLEDGEMENTS

John Lewis and Roy Bailey were co-advisors of this thesis project. I wish to thank John Lewis of the George Washington University for his encouragement during revision of the first and final drafts of the thesis. I also wish to thank Roy Bailey of the U.S. Geological Survey who suggested this study and gave me initial assistance in the field. He contributed many hours of discussion as well as thoughtful guidance and encouragement. He played a major role in the final stages of this project especially as an editor.

Bob Hackman of the U.S. Geological Survey helped prepare the topographic base map. I also wish to thank Joanna Kalber for typing part of the final manuscript and Cynde Sears for helping prepare the lithologic map (Plate I) and proof reading.

## MORPHOLOGY AND GEOLOGY

The Hot Creek flow is roughly elliptical in plan (Fig. 2) and thins from south to north (Fig. 3). Its southern perimeter is bounded by steep slopes and vertical cliffs whereas its northern perimeter is topographically more subdued and partly buried by lake sediments. The presence of the Pleistocene lake is indicated by 1) the surrounding deltaic lake deposits, 2) the gravel-covered lake terraces at various locations around the caldera, and 3) the distribution of ice-rafted granitic and metamorphic float below 7250' on the surface of Hot Creek flow. The lake was fed by a stream flowing in the vicinity of Hot Creek as shown by alluvial gravel deposits south and west of the flow.

The upper surface of the flow exhibits two distinctly different morphologies. (Fig. 2 and Fig. 3a and 3b). The southern third of the flow (Fig. 3c) has greater local topographic relief than the northern two-thirds (Fig. 3d) which has more subdued, rounded topography. The boundary between these two parts of the flow is very irregular and generally coincides with the 7200' to 7250' ft. topographic contours, which in turn coincide with the post-eruptive lake level (see Bailey, 1976). Thus, the boundary is the former lake shoreline. Figures 3a and 3b show in profile, the gradual transition from subaerial to sublacustrine.

The southern, subaerial surface (Fig. 2 and Fig. 6) is composed of nearly equally-spaced, asymmetrical, arcuate ridges as much as 200 m long, that grade into randomly spaced, linear to arcuate ridges of diverse size and shape, separated by narrow swales. The sublacustrine part of the flow surface is characterized by relatively small, linear ridges and rounded knobs which rise above broader, rounded hills and extensive flat areas (for

Figure 2. Stereo-pair of airphotos showing the flow outline, and morphologic differences above and below the paleoshoreline.


PALEOSHORELINE

Figure 3. N-S and E-W profiles of Hot Creek flow showing difference between subaerial and sublacustrine morphology.

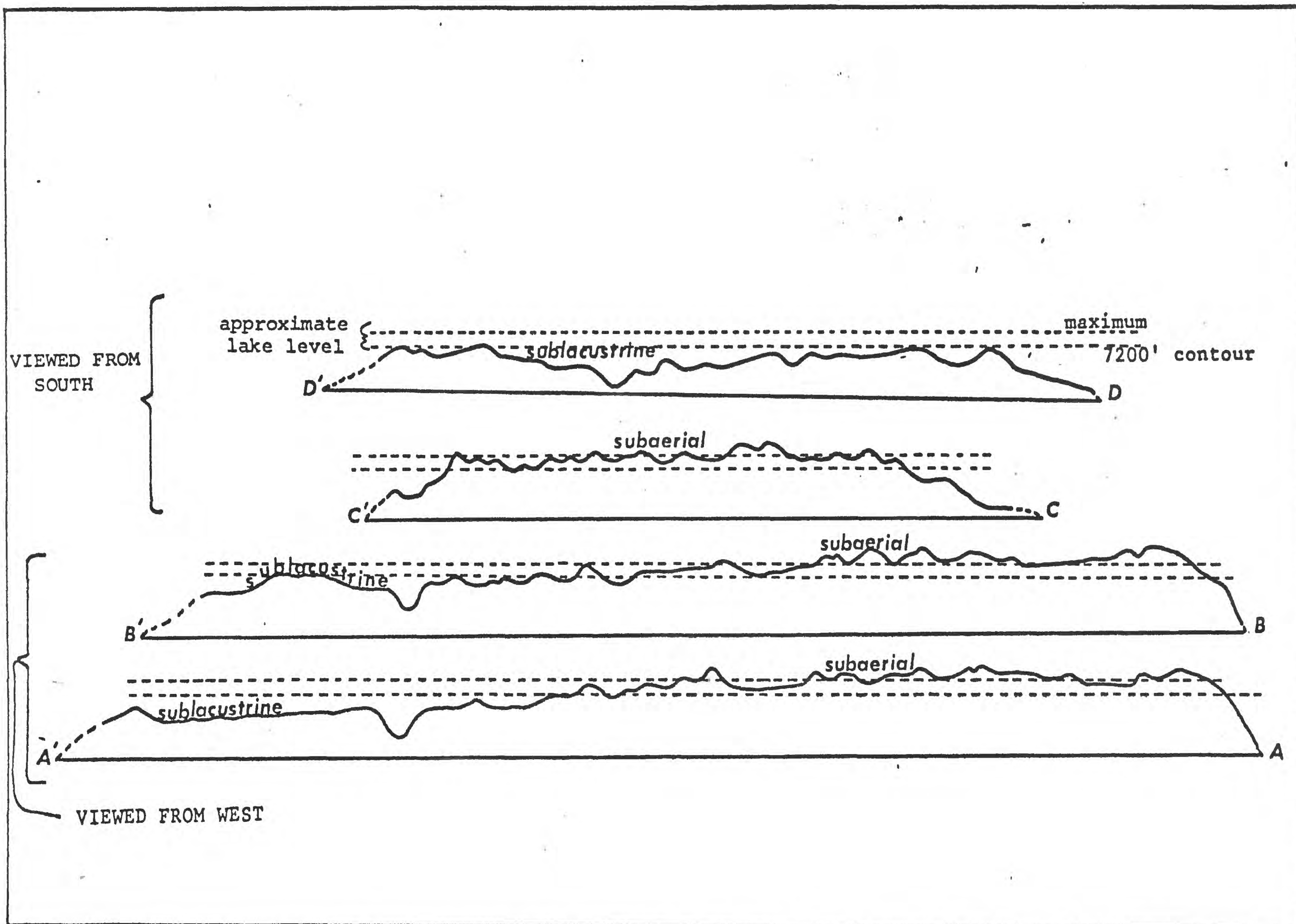
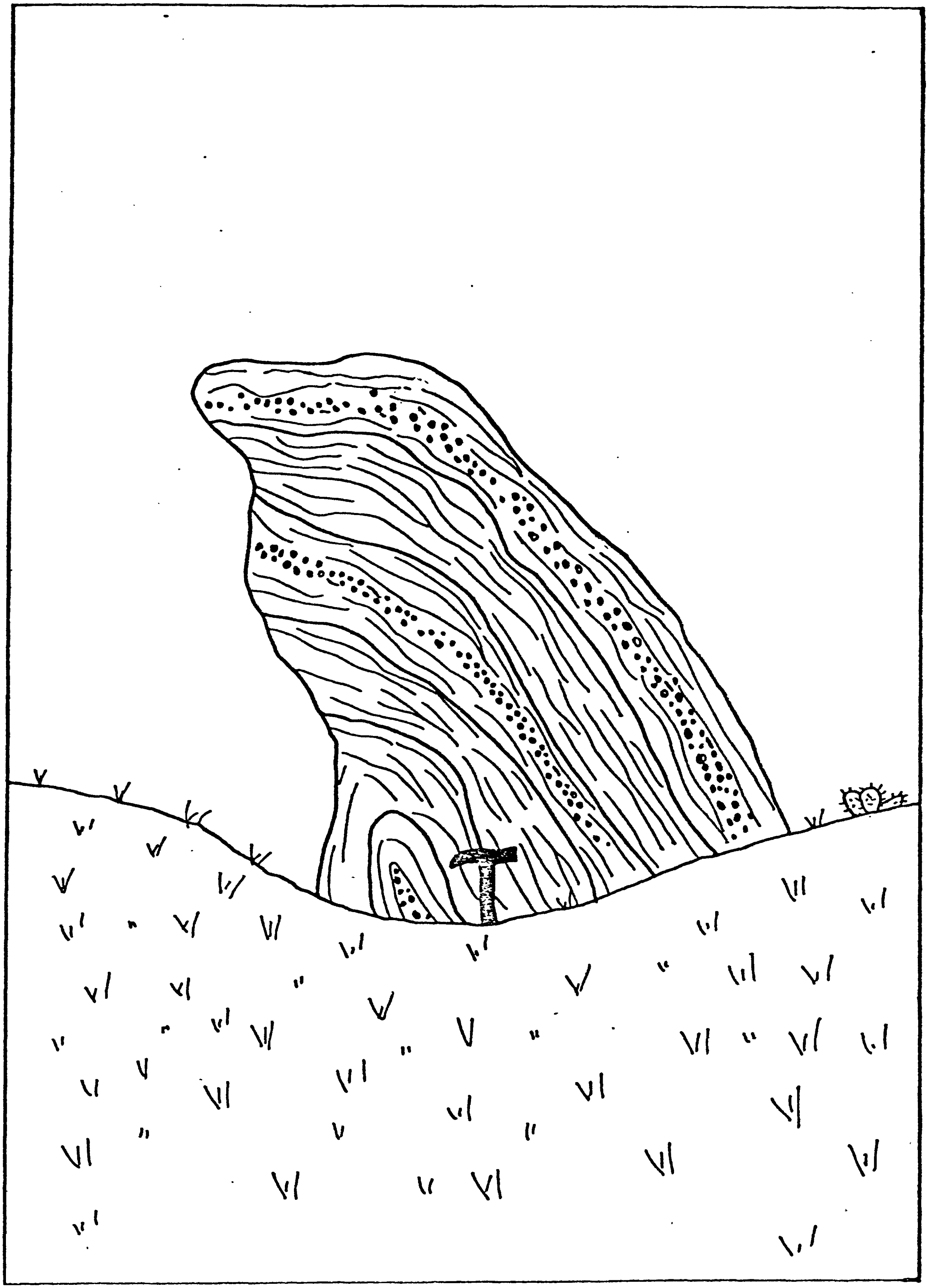

approximate
lake level
maximum
7200' contour
VIEWED FROM
SOUTH
sublacustrine
D'
D
subaerial
C'
C
subaerial
sublacustrine
B'
B
subaerial
sublacustrine
A'
A
VIEWED FROM WEST

Figure 4. Tuffaceous conglomeritic lake sediments deformed by the emplacement of Hot Creek flow. (Photo by R.A. Bailey).

Figure 5. Folded lake sediments consisting of debris from the resurgent dome in contact with post-eruptive, flat-lying topset deltaic sediments. (Photo by R.A. Bailey).

Figure 6. In foreground, typical topography and vegetation of northern, subaerial portion of flow. In the background is the south wall of Long Valley caldera and Mt. Morrison whose summit is 1400 m above Hot Creek flow.

Figure 7. Typical small, knobby outcrop of variably textured rhyolite on sublacustrine portion of flow surface. Black object at center is hammer for scale.



## ERUPTIVE AND POST-ERUPTIVE HISTORY

The flow erupted from a vent on a gently sloping lake bottom at an apparent depth of 60 m. Pre-eruption tuffs, commonly associated with such rhyolite extrusions are not exposed; if present, they are either buried beneath the flow or were carried from the eruption site by sub-lacustrine currents. A pumiceous block and ash deposit north of the flow may be the remnants of an associated hot avalanche deposit.

The flow spread radially from the vent, mostly to the northeast, covering an area of about 10 km (Fig. 2). Over the vent, the flow built upwards a maximum of 30 m above lake level although two-thirds of it remained sub-lacustrine. The flow is between 60 and 90 m thick, thinning to the north and west, and has a volume of approximately .75 km.

As the flow advanced, it deformed the unconsolidated lake deposits into simple folds, a meter or less in amplitude, with steeply dipping limbs (Fig. 4 Photo #21 RAB) and intricate, smaller scale convolutions. Subsequently, as much as 10 m of surface material was eroded from the flow due to lake-induced wave action. This, combined with sediment derived from the nearby resurgent dome, accumulated as flat-lying, tabular, deltaic deposits that cover the northern flow margin (Fig. 5).

Due to tectonic lowering of the south-east rim of the caldera, the lake gradually drained. The south-west arm of the lake was dammed behind Hot Creek flow and eventually became filled with alluvium. Subsequently, Hot Creek flowed across this alluvium and the flow surface as the remaining water in the eastern part of the lake drained, thereby cutting Hot Creek gorge.

example, Fig. 7, also see Fig. 2) Substantially larger, steep-faced knobs, ten or more meters across and ten to twenty meters high typify the flow surface at several localities.

Plate 1 shows the distribution of outcrops as well as the lighology. On the subaerial part of the flow, the outcrops are mostly pumiceous rhyolite, whereas outcrops of obsidian and felsite that were more resistant to lake erosion dominate the sublacustrine part (Plate I). Pumiceous debris stripped from the sublacustrine flow surface now forms the deltaic deposits that are well-exposed around the northern half of the flow (Plate I). The deltaic deposits consist of pumice and obsidian fragments mineralogically identical to the rhyolite of Hot Creek flow as well as abundant detritus from the rhyolite flows of the resurgent dome. Foreset beds dipping to the north indicate that most of the material is from Hot Creek flow.

Some of the outcrops on the more extensive ridges are weathered or fractured into large blocks. The lesser ridges and knobs, particularly in the sublacustrine area often consist of single, continuous outcrops similar in size and shape to those depicted in Figure 5. Both the continuous ridges, and the discontinuous massive outcrops form a broader pattern of ridges which in plane view (Fig. 2) have concentric or lobate form.

During the Pleistocene, Hot Creek was apparently a main channel of drainage for glacial runoff, and as such its eroding powers must have been substantially greater than at present. It is now a 'misfit' as defined by Holmes (1965) since the amplitude of its meanders is less than the width of the valley through which it flows.

Post-eruptive, northwest-southeast and north-south trending faults transect the flow offsetting its surface by as much as 15 meters (Plate I). The irregular and discontinuous faults commonly form narrow graben, consistent with the regional strain pattern. These faults are extensions of the Hilton Creek fault, a major structure along the Sierra front, movement on which was ultimately responsible for draining of Long Valley lake (Bailey, 1976). Active hot springs along the faults, especially in Hot Creek gorge, have altered the rhyolite extensively. Travertine and siliceous sinter are common hydrothermal deposits in the vicinity of the faults.

## MINERALOGY AND CHEMISTRY

The nature of the obsidian indicates that the magma of Hot Creek flow was nearly aphyric at the time of its eruption. The obsidian contains one percent phenocrysts including plagioclase, sanidine, biotite, clinopyroxene, iron-titanium oxides and traces of apatite and zircon. The average size of the phenocrysts is less than one millimeter, although they may be as large as two millimeters. Microphenocrysts, mostly of feldspar and biotite, averaging .1 millimeters in size are also found in the glass matrix. The proportion of microphenocrysts varies considerably among samples. Some samples appear to have no microphenocrysts at all.

Longulites, microlites and trychytes less than .04 millimeters in size, and of felsic composition, are also common in the ground mass; these too vary in size from sample to sample.

Post-eruptive crystallization during cooling of the flow produced a variety of ground mass textures ranging from spherulitic to felsitic. A chemical analysis, CIPW norm, and modal analysis are given in Table 1.

TABLE 1 CHEMICAL ANALYSIS, NORM AND MODAL ANALYSIS OF OBSIDIAN FROM THE SOUTH END OF HOT CREEK RHYOLITE FLOW

Unpublished Data Supplied by R.A. Bailey

| Chemical Analysis | | Norm | | Modal Analysis | |
|---|---|---|---|---|---|
| $SiO_2$ | 75.54 | Q | 31.82 | qtz | 0 |
| $Al_2O_3$ | 13.24 | C | 0.25 | san | .2 |
| $Fe_2O_3$ | 0.38 | Or | 29.18 | plag | .5 |
| FeO | 0.65 | Ab | 33.89 | bio | .1 |
| MgO | 0.10 | An | 2.99 | hbl | 0 |
| CaO | 0.64 | En | 0.25 | cpx | .1 |
| $Na_2O$ | 3.99 | Fs | 0.81 | opx | 0 |
| $K_2O$ | 4.92 | Mt | 0.52 | Fe-Ti ox. | .1 |
| $H_2O$ | 0.26 | Il | 0.21 | | |
| $TiO_2$ | 0.11 | Ap | 0.04 | glass | 99.0 |
| $P_2O_5$ | 0.02 | | | | |
| MnO | 0.04 | Total | 100.00 | Total | |
| $CO_2$ | 0.01 | Salic | 98.15 | phenocrysts | 1.0 |
| | | Femic | 1.84 | | |
| Total | 99.90 | | | | |

## LITHOLOGY AND ZONATION

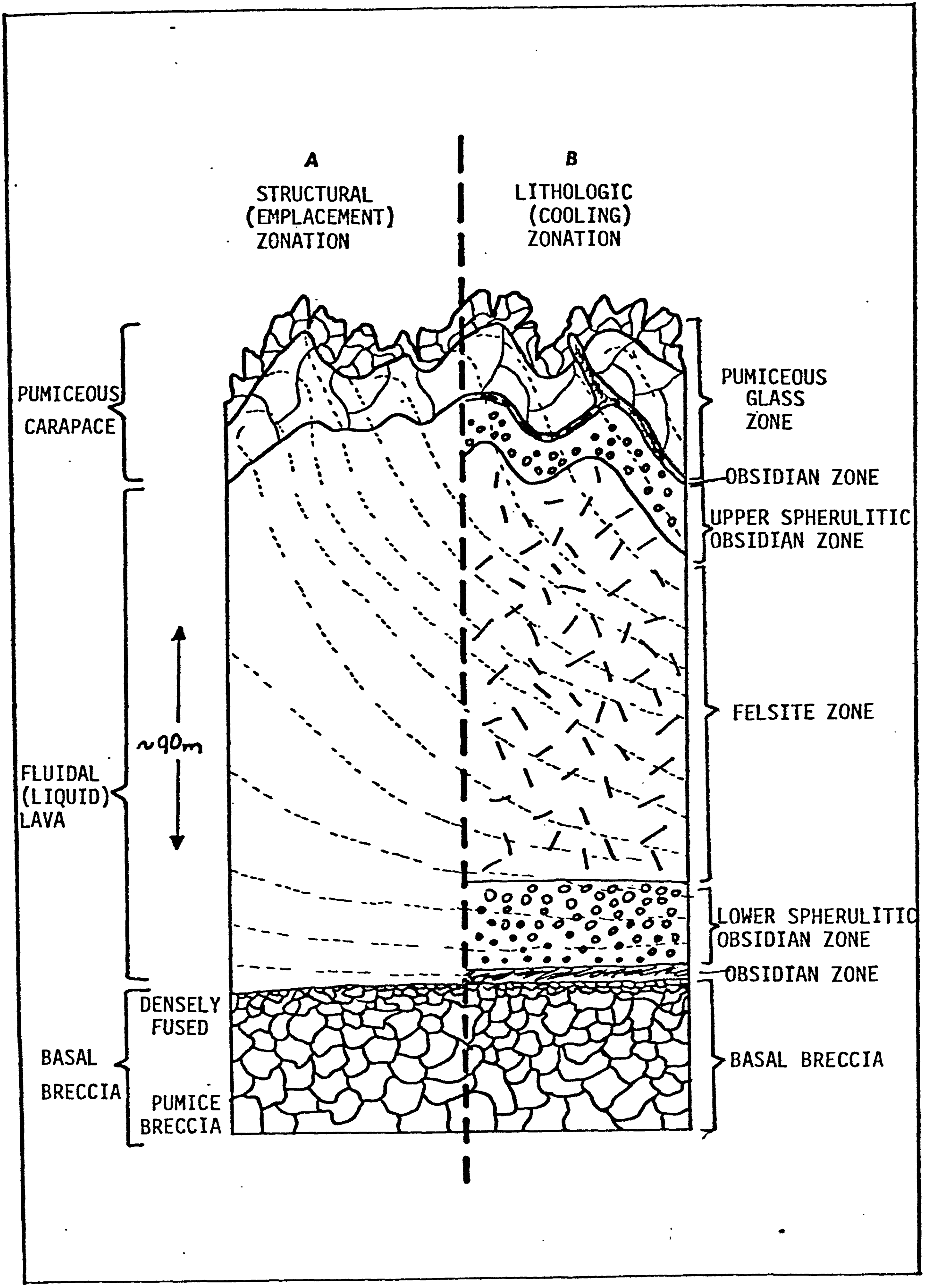
Four distinct lithologies can be distinguished in the lava of Hot Creek flow (Plate I): 1) obsidian, which is commonly altered to perlite by secondary hydration, 2) spherulitic obsidian, 3) felsite and 4) pumiceous glass which may be massive, brecciated or fused. Although on a small scale (less than 1 m) these lithologies may be complexly interlayered, on a broad scale (greater than 1 m) one lithology tends to predominate. On the broader scale, these predominant lithologies are arranged in a zonal pattern that can be related to the top and the bottom of the flow as shown in figure 8.

A structural zonation is defined by the massive flow interior and the brecciated exterior as depicted in figure 8A. Superimposed over this is the lithologic zonation which ideally includes from top to bottom: brecciated pumiceous glass, massive pumiceous glass, obsidian, spherulitic obsidian, felsite, spherulitic obsidian, obsidian, fused pumiceous breccia, and non-fused pumiceous breccia (fig. 8B).

The zonation is a result of two superimposed processes. The structural zonation formed during flow when the spreading lava vesiculated and cooled to form a crust that enveloped the fluidal interior. Once the flow came to rest, slow, progressive cooling and crystallization of the fluidal interior lead to the formation of lithologic zones.

Similar zonation was described by Christiansen and Lipman (1966) for Comb Peak rhyolite flow and by Haeffner (1976) for the rhyolite lavas of the Shoshone volcanic field, Death Valley. Although not as completely exposed as at these localities, the

Figure 8. Idealized cross section showing structural and lithologic zonation.


A
STRUCTURAL
(EMPLACEMENT)
ZONATION
B
LITHOLOGIC
(COOLING)
ZONATION
PUMICEOUS
CARAPACE
FLUIDAL
(LIQUID)
LAVA
~90m
DENSELY
FUSED
BASAL
BRECCIA
PUMICE
BRECCIA
PUMICEOUS
GLASS
ZONE
OBSIDIAN ZONE
UPPER SPHERULITIC
OBSIDIAN ZONE
FELSITE ZONE
LOWER SPHERULITIC
OBSIDIAN ZONE
OBSIDIAN ZONE
BASAL BRECCIA

above zonation is also locally displayed in the Hot Creek flow (fig. 9 A).

The zonation of most rhyolite flows, the Hot Creek flow included, is more complex than that shown in the idealized section of figure 8. The departures from the general zonal pattern of figure 8 shown by the Hot Creek flow are probably the result of local complex flow dynamics and abnormal cooling effects of the lakewaters on the sublacustrine part of the flow.

The partial sections of figure 9 A and the lithologic map of figure 10 show the vertical and horizontal distribution respectively of zones in Hot Creek flow.

SOUTHWESTERN CLIFFS SECTION *a*

A composite vertical section *a*, 75 m high, 15 m above the apparent base of the flow is exposed in and above the marginal southwestern cliffs (fig. 9 and 10). The continuity of the cliffs is locally disrupted by talus-covered benches and slopes. The zones in this section, particularly the spherulitic obsidian zone, are unusually thick owing to abnormal cooling at the flow margin.

The lowest exposure in section *a* is of densely compacted fused basal breccia consisting of flattened obsidian fragments in a gray perlitic, locally oxidized matrix (fig. 11). Only a meter of this fused breccia is exposed, but it probably grades downward into non-fused pumiceous breccia, which is covered.

The basal breccia grades upward into 15 m of massive foliated obsidian. The upper 14 m of this obsidian contain spherulites that increase in size and abundance upward (fig. 12). Lenses and discontinuous layers of small, coalesced spherulites parallel the planar structure [illegible]

Figure 9. A) Three section through the flow showing zones.

B) Synthesized zonation inferred from fig. 18A and Plate I.

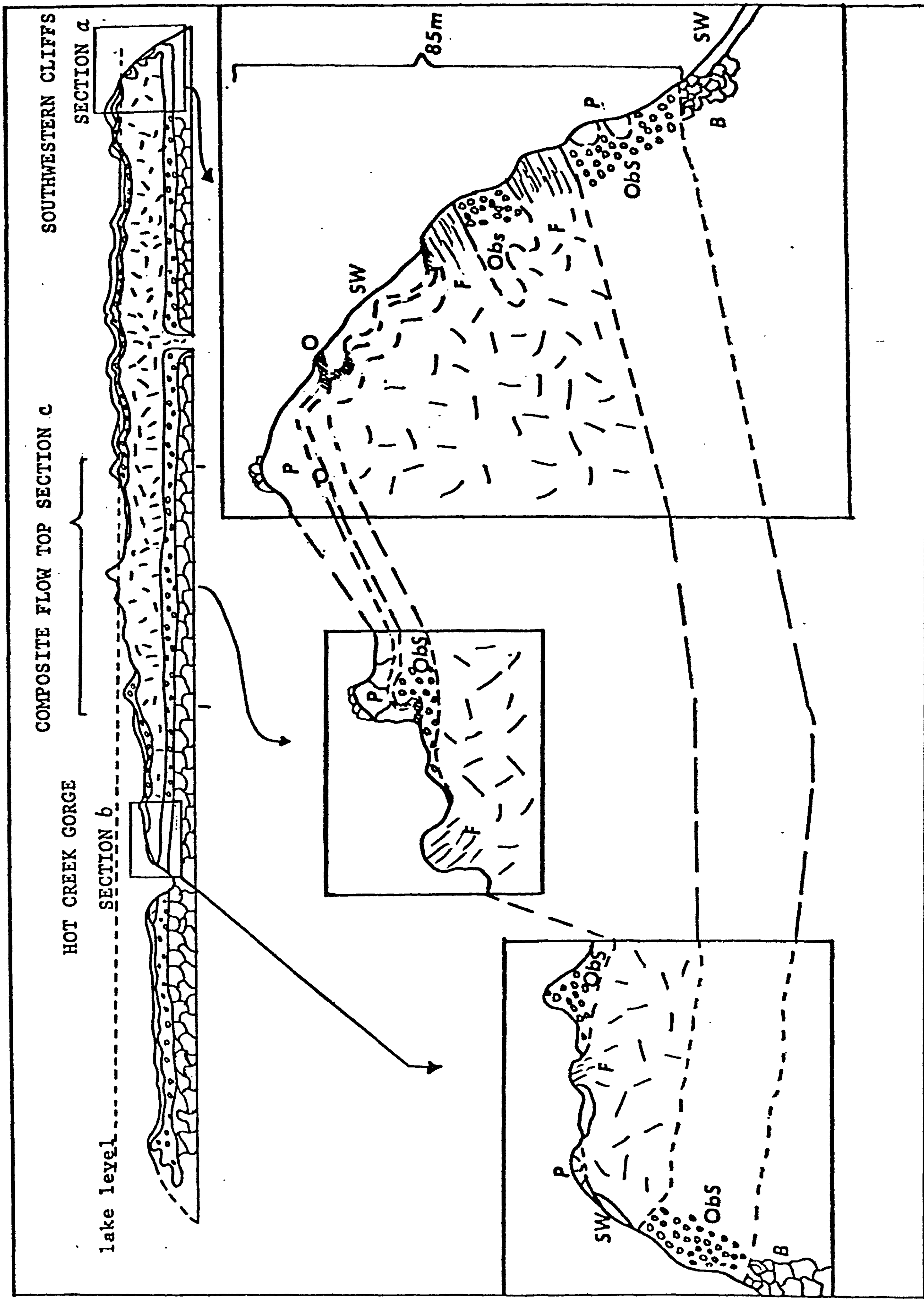

SOUTHWESTERN CLIFFS
SECTION a
COMPOSITE FLOW TOP SECTION c
HOT CREEK GORGE
SECTION b
lake level
85m
SW
P
O
Obs
F
B

Figure 10. Lithologic map showing lateral distribution of zones. (Refer to Plate I for details).

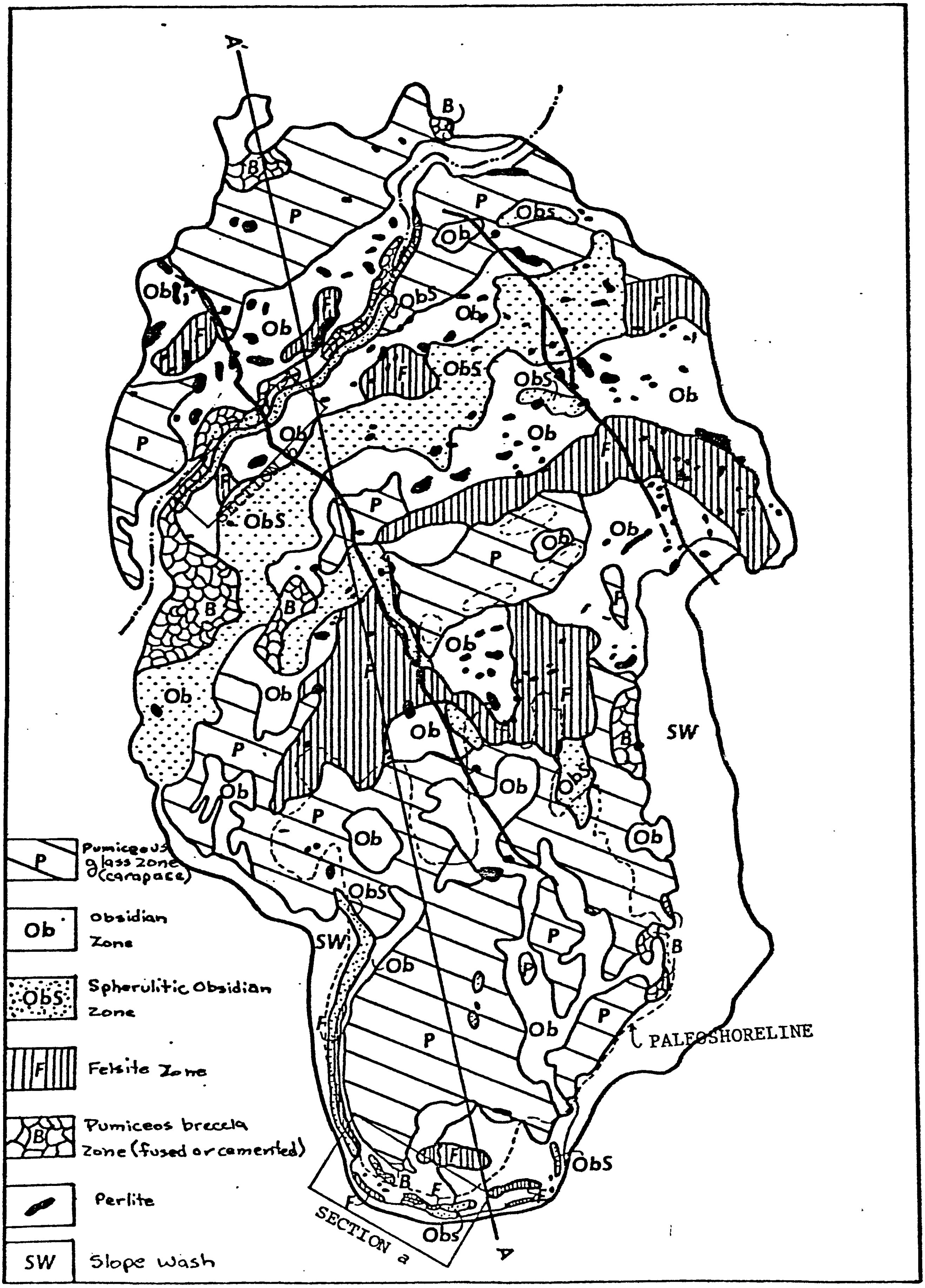
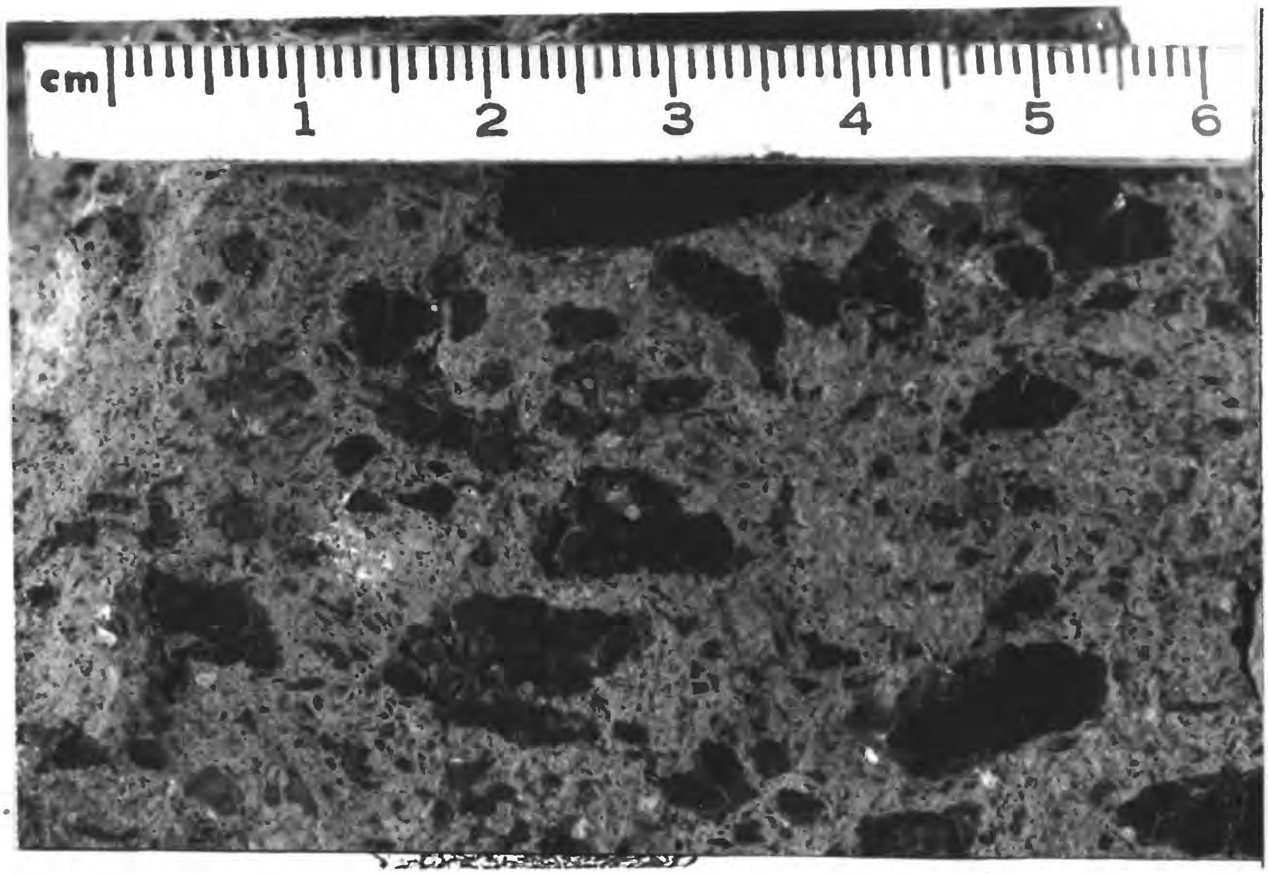
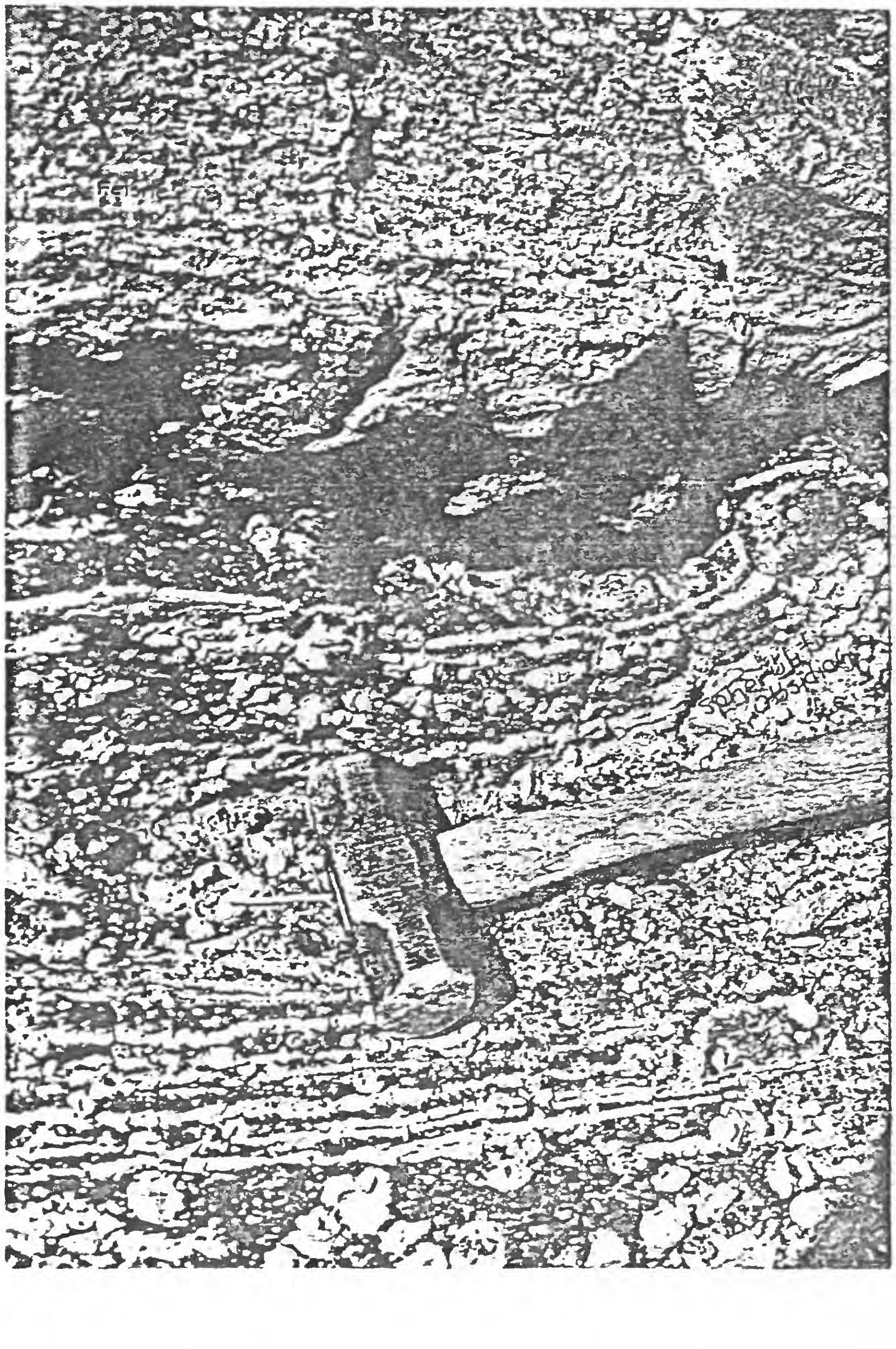

A
A'
P
Ob
ObS
F
B
SW
Obs
SECTION
SECTION a
PALEOSHORELINE
Pumiceous glass zone (carapace)
Obsidian Zone
Spherulitic Obsidian Zone
Felsite Zone
Pumiceos breccia Zone (fused or cemented)
Perlite
Slope wash

Figure 11. Sample of fused basal breccia from base of section a. (See Fig. 9A).


cm
1
2
3
4
5
6



parallel the planar structure of the obsidian. The spherulitic obsidian grades upward into a transitional zone consisting of gray, microcrystalline patches and clusters of spherulites in a matrix of coarsely granular, slightly perlitized obsidian. Layers of felsite are also common in this zone (fig. 12 ).

Upsection, 12 m of pink and gray massive felsite with obscure foliation is poorly exposed. Above the felsite, in the upper 15 m of the cliffs, is exposed a second layer of spherulitic obsidian about 12 m thick which grades upward into 3 m of the felsite.

Above the cliffs, a 1 m thick layer of obsidian, exposed as pebbly float , occurs at the base of a colluvium covered slope that extends upward for 20 m. Very few outcrops are exposed within this 20 m interval, but it is likely that spherulitic obsidian underlies the colluvium (fig. 9A).

At the top of section *a* approximately 10 m of banded pumiceous rhyolite cropout as blocky ridges and knobs. Varying vesicularity between layers accounts for the banded appearance of the pumiceous glass. Bands of sheared obsidian, that are the source of obsidian float over much of the flow, contrast sharply with the more common tan and gray pumiceous layers. Minor knobs of felsite and perlite protrude through the colluvium near the pumiceous outcrops.

HOT CREEK GORGE SECTION *b*

In and adjacent to Hot Creek gorge (fig. 9 and 10) about 50 m of section, including 35 m of cliffs and steep slopes, are exposed. The upper 15 m of section lies just beyond the rim of the gorge. As compared to section *a*, the zonation of section *b* --

is simple. The exposures maintain thickness and character laterally for several hundred meters in certain parts of the gorge.

The lower 20 m of the gorge consists of fused or cemented basal breccia (fig. 13). The largest blocks in the breccia are over 5 m across whereas fused or cemented detritus between the blocks is sand-sized. Most of the blocks are pumiceous although a few are perlitic obsidian.

Above the breccia, a spherulitic perlite outcrops continuously for about 15 m upward. The contact between the two zones is generally gradational, although it is locally sharp.

COMPOSITE FLOW TOP SECTION C

On the upper surface of the flow , adjacent to and beyond the gorge, the section is more complex. Spherulitic obsidian, felsite and pumiceous glass are often interlayered within a relatively small area. The composite flow top section C (fig. 9 A) was derived from the overall lithologic distribution (fig. 10 and Plate I). Exposures on faults were especially useful in constructing this section.

SUMMARY

Figure 9 B shows the inferred distribution of zones within the flow. The internal zonation is contrained by the exposed lithologies (fig. 9 and 10) and is inferred to generally conform with the zonation model (fig. 8 ).

The pumiceous zone generally occurs over the topographically higher, subaerial parts of the flow. It is a chaotic breccia on the upper surface and more massive toward toward its inner boundary with the obsidian zone. Most of the upper breccia has been eroded into low lying swales . Below the paleoshoreline most of

Figure 13. Cemented basal breccia from Hot Creek gorge.

the pumiceous zone is stripped away and deeper zones within the flow are exposed.

The pumiceous zone grades into a transitional banded pumiceous glass-obsidian zone that increases in obsidian content downward, eventually becoming the massive spherulitic obsidian zone. The upper spherulitic obsidian zone is thinner and more variable in thickness than the more continuous lower spherulitic zone exposed in Hot Creek gorge. The underlying felsite zone is exposed at the paleoshoreline apparently where the lake cut deepest into the flow. It is also present around most of the flow margin although it appears to pinch out in the vicinity of Hot Creek gorge, along section A-A' (fig. 9 B). The major exposures of the felsite zone may in part be exposed due to faulting (fig. 10). The lower spherulitic obsidian zone and basal breccia zone are apparently more consistent in thickness than the overlying zones. In general, the zones thin away from the vent, except for basal breccia zone, which thickens. The basal breccia zone is especially well exposed at the flow margins, where it is thickest (fig. 9 and 10).

PERLITIC ALTERATION

As a result of secondary hydration much of the obsidian zone is converted to perlite. Massive outcrops of perlite are exposed, particularly in the sublacustrine part of the flow (fig. 10). Residual obsidian nodules in this area usually have relatively thick hydration rinds.

The perlite may have originated in two ways: 1) at atmospheric temperatures over a relatively long timespan, or 2) at higher temperatures, below 100°C, during cooling of the flow (see Friedman, Smith and Long 1966). The distribution of perlite suggests that the lakewater had some influence over its formation, although outcrops of massive perlite above the shoreline show that it formed in the absence of lakewater as well. As most of the pumiceous carapace is intact in the subaerial part of the flow, a perlitic obsidian zone may exist, but it is not exposed.

# STRUCTURE

Most of the structural data recorded on Plate II and generalized in Fig. 14-17 is limited to exposures within the upper 20 m of the flow, although in Hot Creek gorge, deeper parts of the flow are exposed. The observed structures include flow ridges, foliation, lineation, flow folds, fractures and joints.

## FLOW RIDGES

The flow ridges are described in the section on morphology (page 4). By analogy with younger, less eroded flows, they are formed during emplacement of the lava (see for example Loney, 1968).

## FOLIATION

Flow foliation (Fig. 18) is the most prevalent structure except near the base of the flow, where breccia predominates. Foliation is defined by discontinuous laminae which range from less than one millimeter to several centimeters thick and are enhanced by textural and color variations. The width of laminae and the contrast in texture and color between laminae are relatively constant within individual outcrops but vary widley from one outcrop to another. Individual laminae tend to pinch out within a few meters. (Fig. 18).

## LINEATION

Most foliation planes contain slickenside-like lineations (Fig. 19) which are often faint and can seldom be traced for more than a few meters. Lineations on adjacent foliation planes usually have quite different attitudes.

## FOLDS

Flow laminae are commonly deformed into folds of varying symmetry which range in amplitude from a few millimeters or centimeters (Fig. 20) to several meters (Fig. 7). Bands of folded laminae often alternate with bands of undeformed laminae.

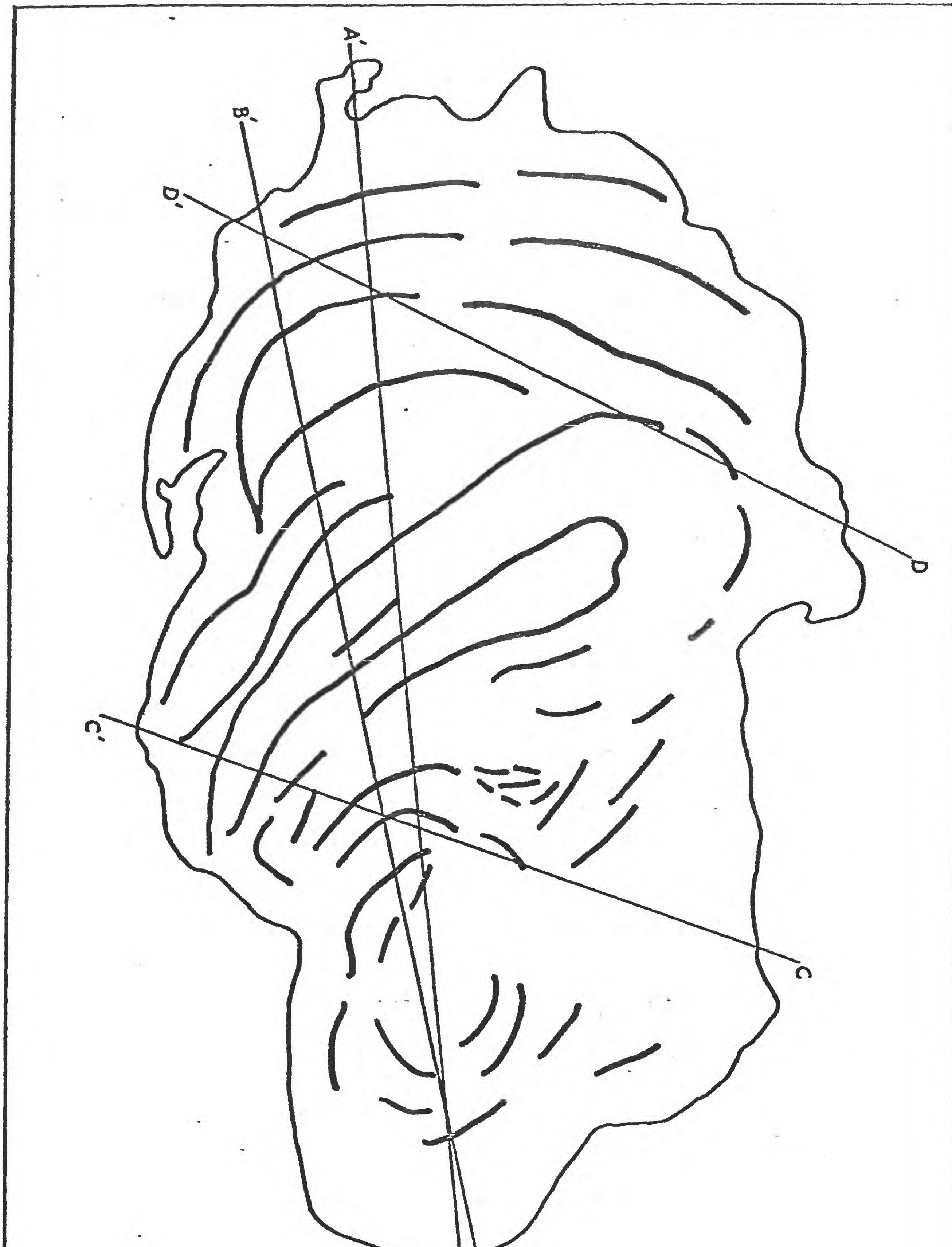

A'
B'
D'
C'
A
B
C
D

Figure 14. Map of flow ridges. (See Fig. 3, pg. 6 for cross sections).

Figure 15. Map of foliation superimposed over map of flow ridges. (See Plate II for angles of dip).

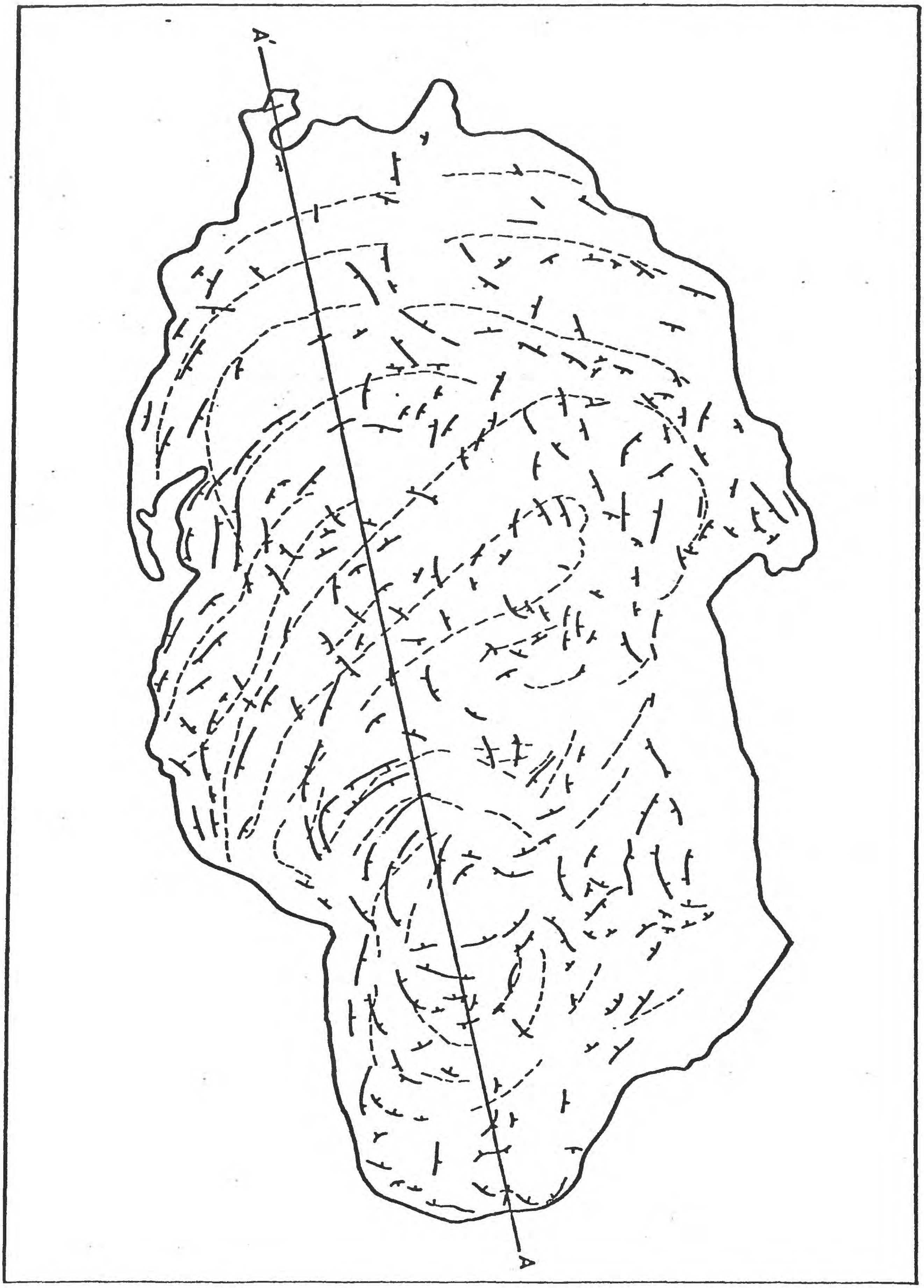

A'
A

Figure 16. Map of lineation superimposed over map of flow ridges. Arrows depict direction of plunge of lineation. (See Plate II for plunge angles).

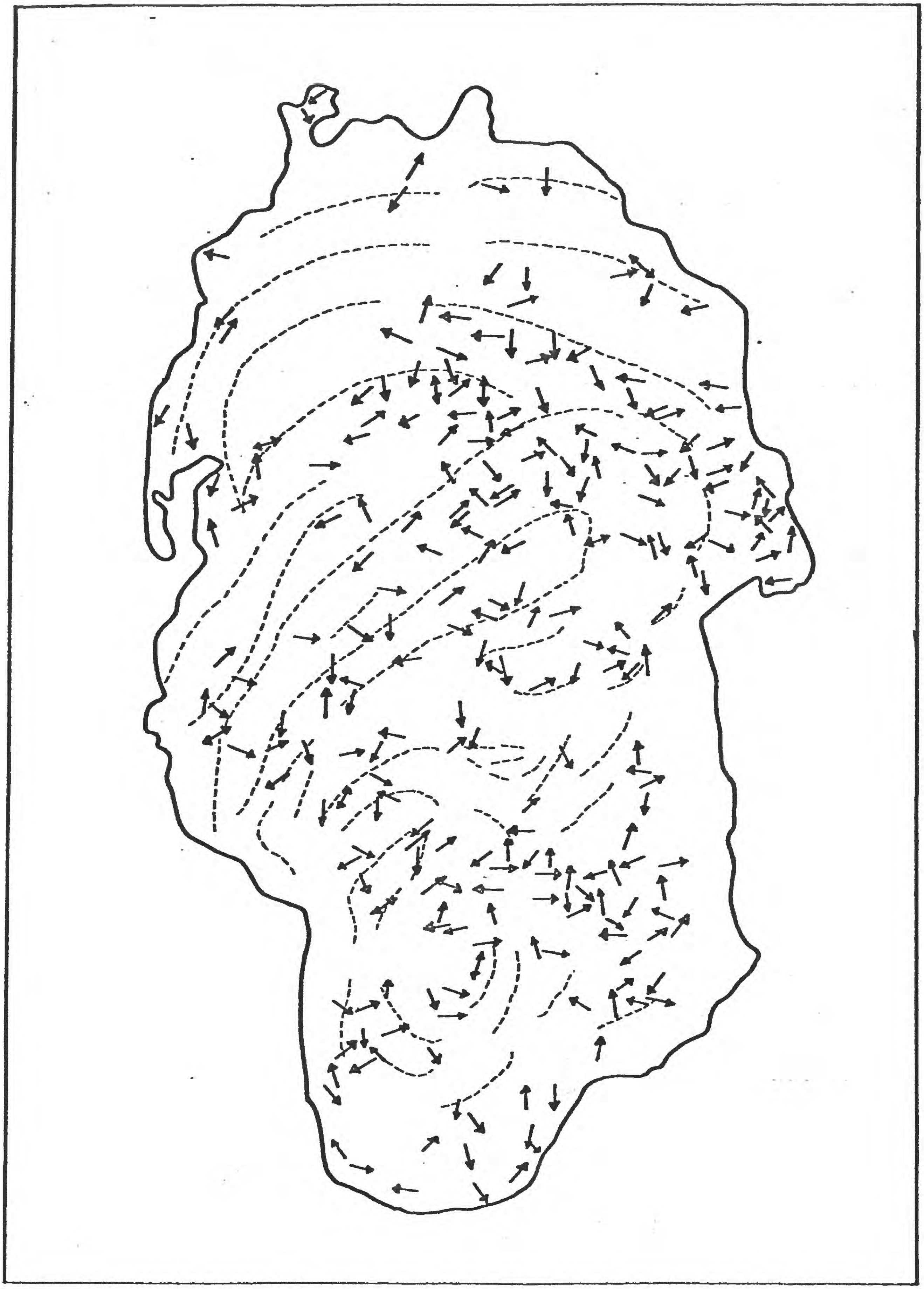


Figure 17. Map of flow folds superimposed over map of flow ridges. Arrows show plunge direction of fold axes. (See Plate II for angle of plunge).

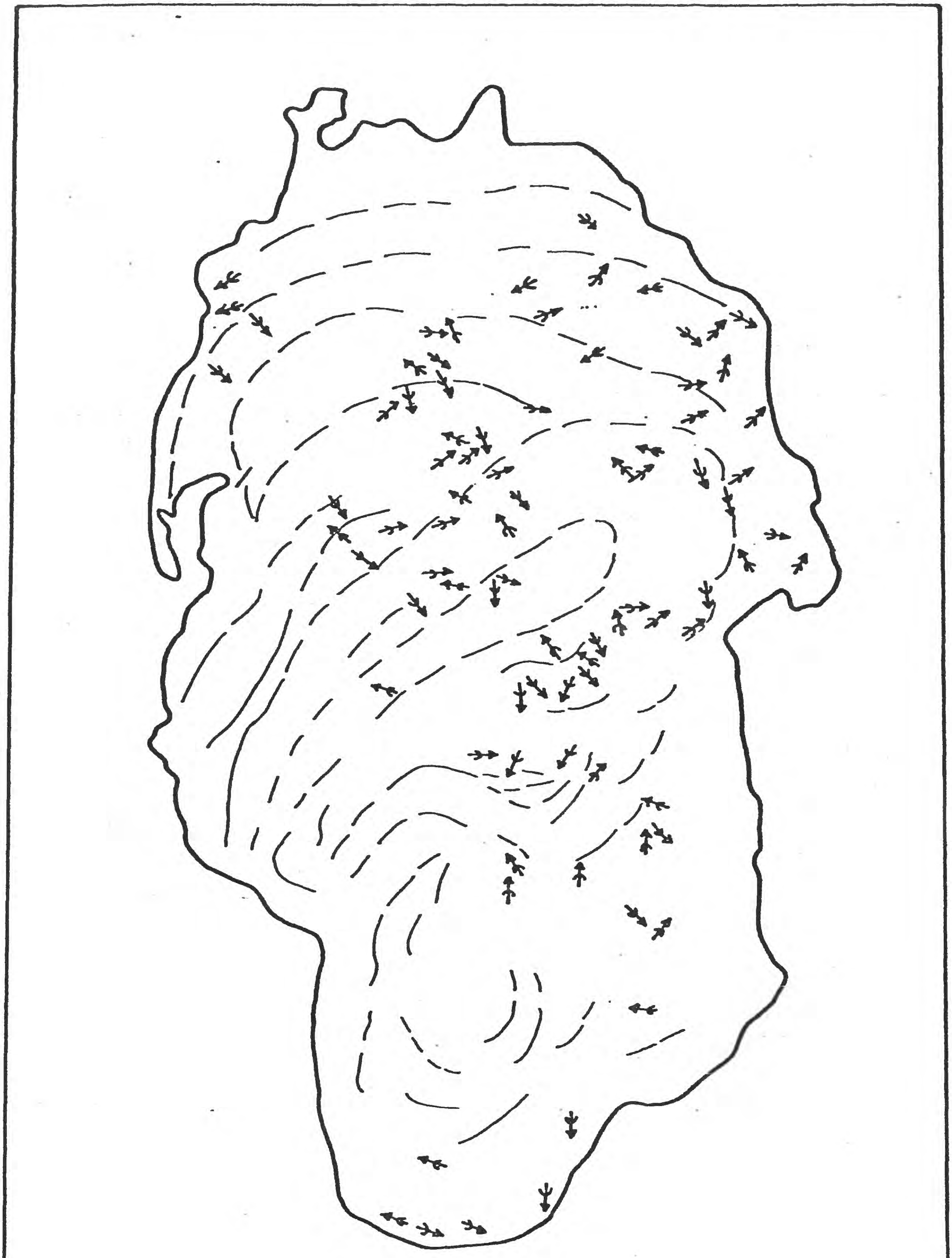


Figure 18. Relatively subtle foliation. Light areas are oxidized rust-brown color and more vesicular than the dark areas which are composed of dark gray, dense perlite (see section on lithology). The tension gashes at the center of the photo are nearly perpendicular to the foliation. The lower one-fourth of the outcrop appears to have been sheared to the left of the photo. Tension cracks transect the laminae at high angles, commonly 90°. The inset shows how the structures are related to the strain; $\lambda_3$ = maximum extension.

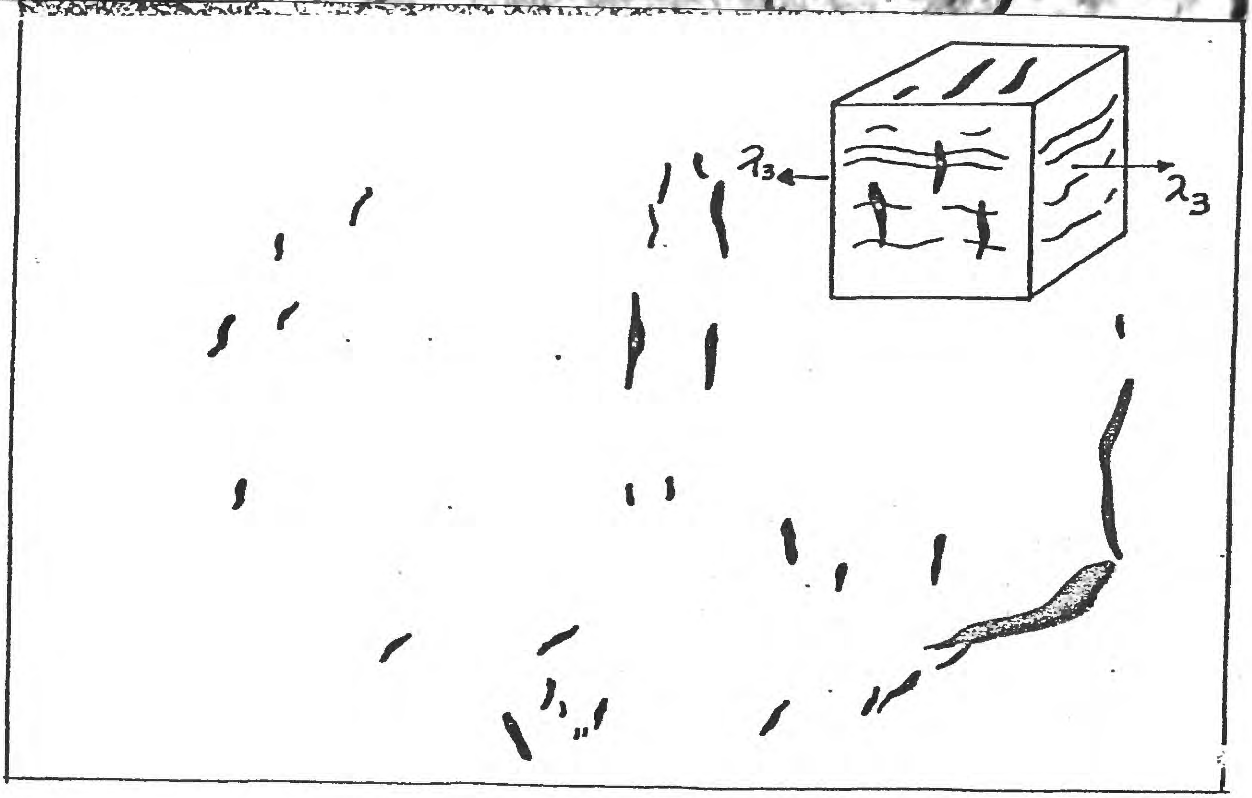
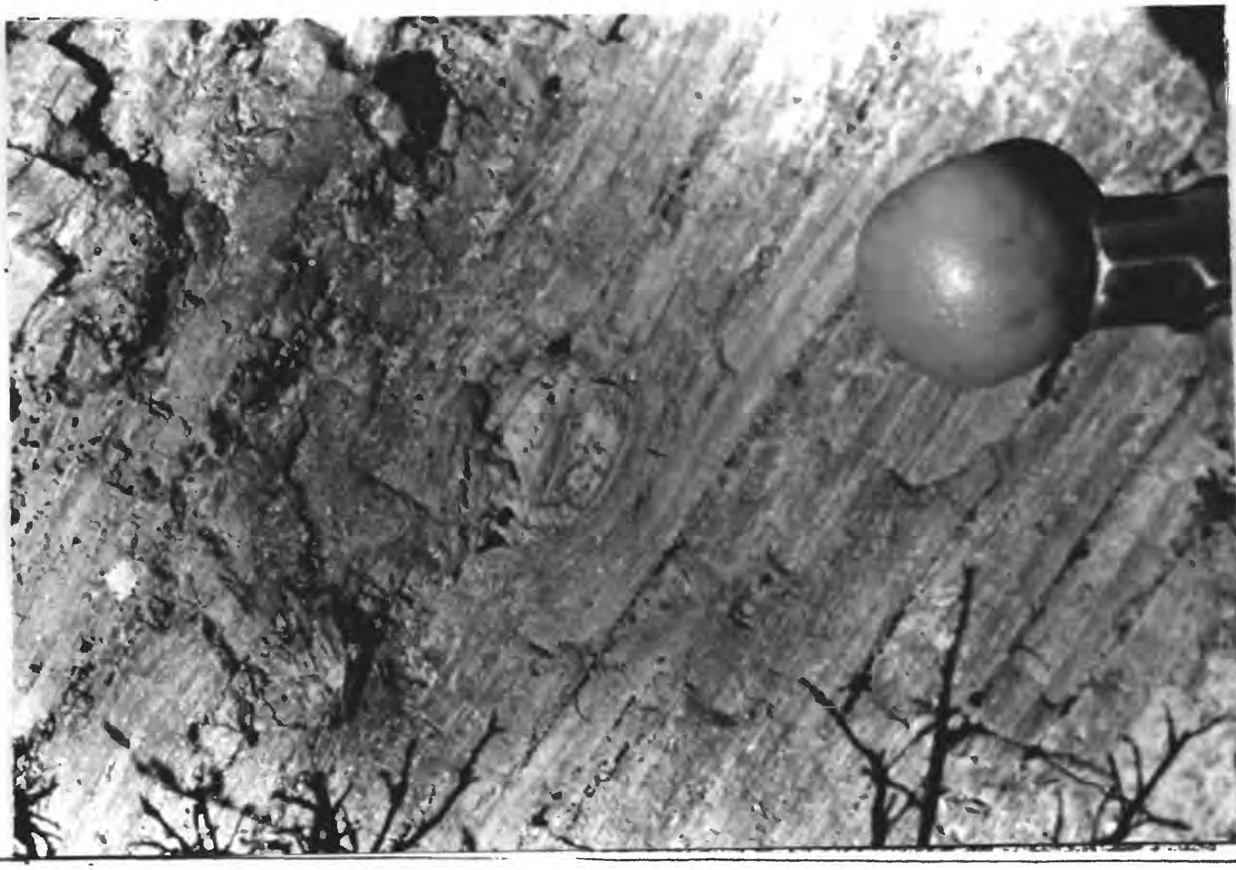

λ3
λ3

Figure 19. Well-developed lineation in foliation plane. The breccia fragment, at center, suggests that relative shear was from lower right to upper left. This sort of criterion for flow direction is uncommon in Hot Creek flow. Note hair-line fractures. Orange and hammer head indicate scale.



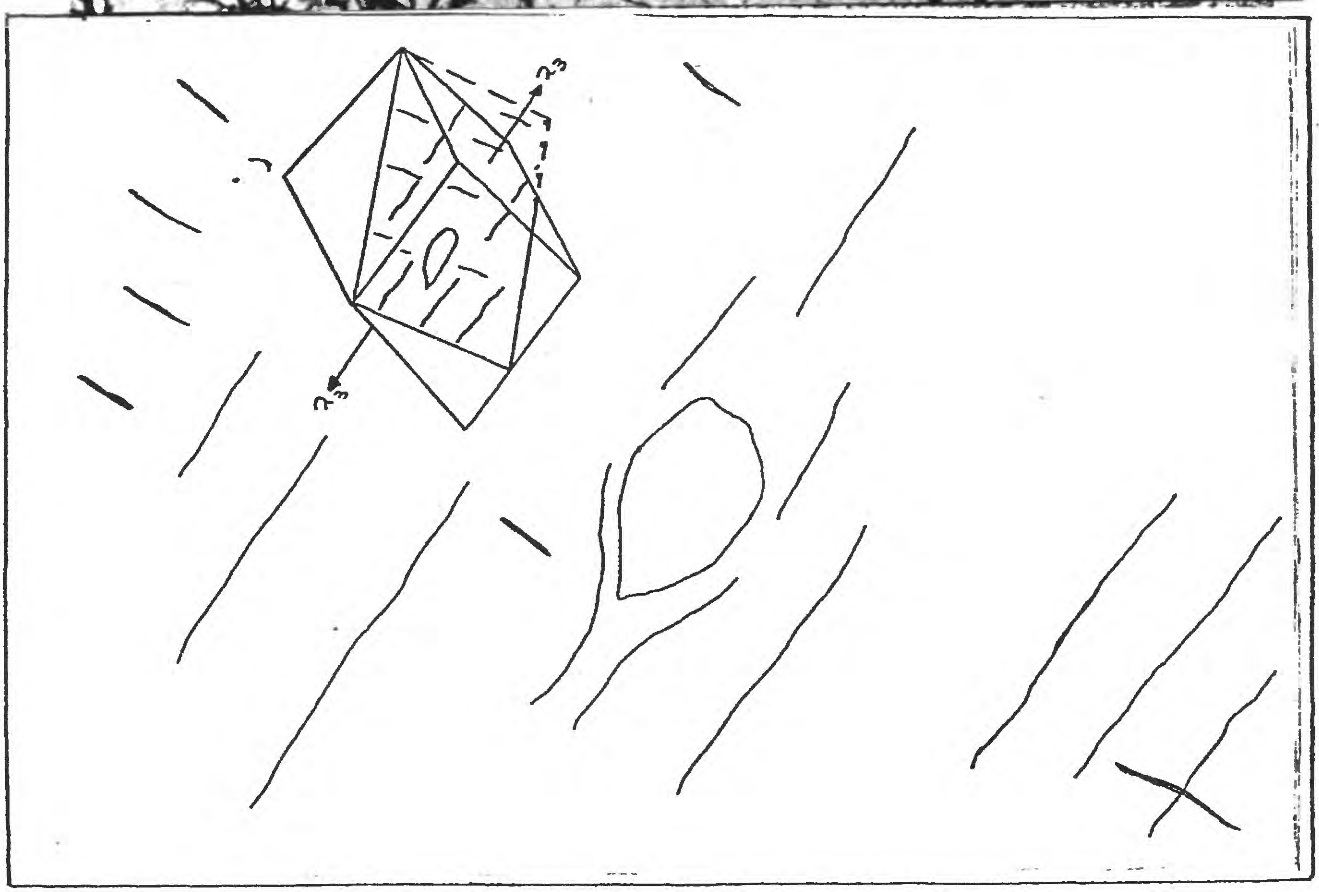
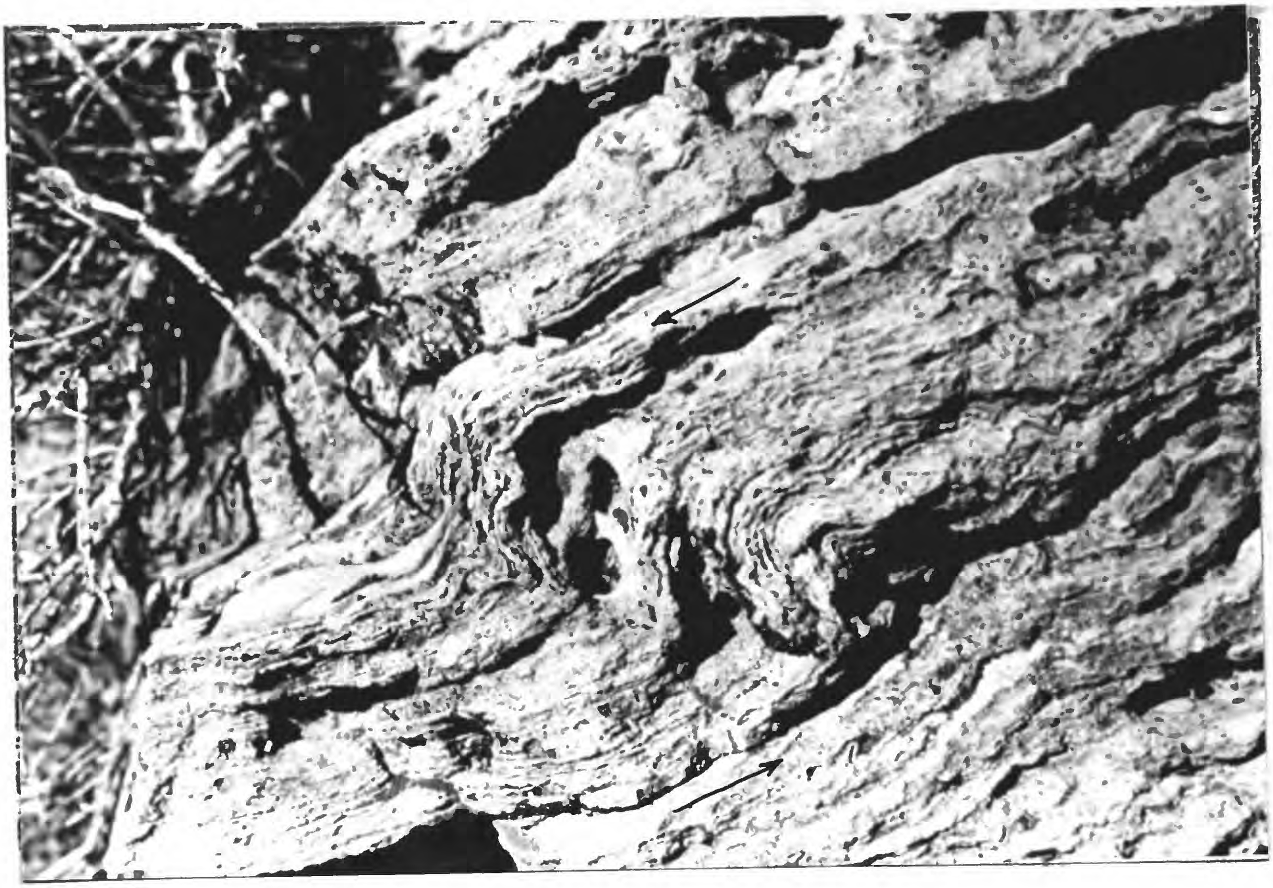


Figure 19a. Hand sample showing well-developed near vertical lineation and hair-line near horizontal fractures.


cm
1
2
3
4
5

Figure 20. Asymmetrical flow folds in dense felsitic rock suggest that local shear sense was from upper right to lower left or vice versa. Such outcrops are uncommon.



JOINTS AND FRACTURES

Joints and fractures of several kinds differing in continuity, surface smoothness and orientation occur within the flow. These include: fractures separating flow laminae, hair-line fractures, tension gashes, inclined conjugate joints and nearly vertical joints.

The physical separations of flow laminae (Fig. 21) vary considerably in extent, surface smoothness and spacing throughout the flow. Perpendicular to the flow laminae and foliation planes are discontinuous open tension gashes (Fig. 18) and smooth and apparently related, closely-spaced, discontinuous hair-line fractures with slightly curved traces (Fig. 19-19a). Less commonly, joints occur in conjugate pairs that transect the foliation obliquely. The most extensive conjugate joints have several centimeters of separation (Fig. 22). Restricted to the flow margins are large, isolated, nearly vertical, open joints with smooth, broadly arched surfaces, showing as much as a meter of separation.

INTERPRETATION OF STRUCTURES

Development of foliation, lineation and flow folds is a function of internal shear caused by fluidal flow. Flow folds reflect either compression, or drag between adjacent layers of lava flowing at different rates.(Bailey, Oral Communication, 1976). The significance of the flow ridges is discussed in the section on emplacement mechanics.

The tension gashes, and related hairline fractures, perpendicular to foliation, indicate that the laminae were subjected to stretching and that the foliation was an actively developing feature realted to shear during flow. Attenuation of laminae is suggested by their progressive thinning and eventual termination within relatively short distances. Stretching of laminae into boudins is quite common. The open vertical fractures and

Figure 21. Well-developed foliation in spherulitic obsidian-felsite. The trend of the foliation in this outcrop is nearly parallel to that of nearby transverse, vertical joints, suggesting that fluidal lava was forced through the fracture into the solidified carapace. South wall of Long Valley caldera in the background.

Figure 22. Conjugate joints in spherulitic obsidian. Arrows show direction of maximum elongation.

and conjugate joints indicate minor extensional solid-state movements (Fig. 22). The fractures between laminae, suggest either solid-state shearing parallel to the foliation, or differential weathering of the shearing surfaces between laminae.

STRUCTURAL PATTERNS

In many studies of lava flows, internal structure has been used to determine the vent of lavas location (for example, Benson and Kittelman, 1968). As the approximate location of the Hot Creek flow vent is known from morphologic criteria such as flow thickness, pre-existing topographic gradient and arrangement of flow ridges, the merits of the various internal structures as indicators of spreading pattern can be evaluated.

Flowage may occur in any direction within a foliation plane. The other structures, by themselves, indicate relative flow direction. (Christiansen and Lipman, 1966). The directions of spreading of the flow as a whole must be inferred from the overall pattern of structures.

Although the relationship of the flow ridges (Fig.14) to the flow margins and the vent suggest that the ridges are gross indicators of flow pattern, the local flow direction may vary considerably within a single section of a flow ridge. The structural and flow ridge patterns are compared in Figures 15-17 in order to determine if there is a relationship between flow-top structure and spreading history.

The trends of flow ridges and strikes of foliation are commonly parallel (Fig. 15)although away from the vent and the flow margins, the foliation pattern is chaotic. Within the structurally chaotic area of the flow surface, foliation forms pronounced local lineaments that appear to cross-cut each other.

The lineation map (Fig. 16) shows the direction of plunge of lineation. Lineation does not form any clear pattern in relation to the flow ridges. But it does suggest that there are two major modes of movement during flow. A lineation perpendicular to the trend of the flow ridges indicates that locally the lava flowed in a direction normal to the ridges. A lineation parallel to the trend of the flow ridges suggests that the flow was stretching laterally with respect to the overall forward movement of the flow. Most of the lineation at the flow margin is parallel to the margin thus suggesting the latter mode of movement.

Flow folds, the least commonly observed structures, appear to be closely related to the flow ridges and foliation (Fig. 17). Many of the fold axes, which generally have gentle plunge, are parallel to the strike of the foliation and to the trend of the flow ridge axes. This suggests that in such cases, the shear or compression which created the folds was perpendicular to the flow ridges. This supports the conclusion that the flow ridges are generally perpendicular to the absolute direction of flow.

## EMPLACEMENT MECHANICS

The relationship of structure and lithology to the emplacement and cooling history of the flow is best explained by referring to figure 23A, a north-south cross-section through the flow, showing the dip of the foliation and the broad structural zonation (see also fig. 8 A).

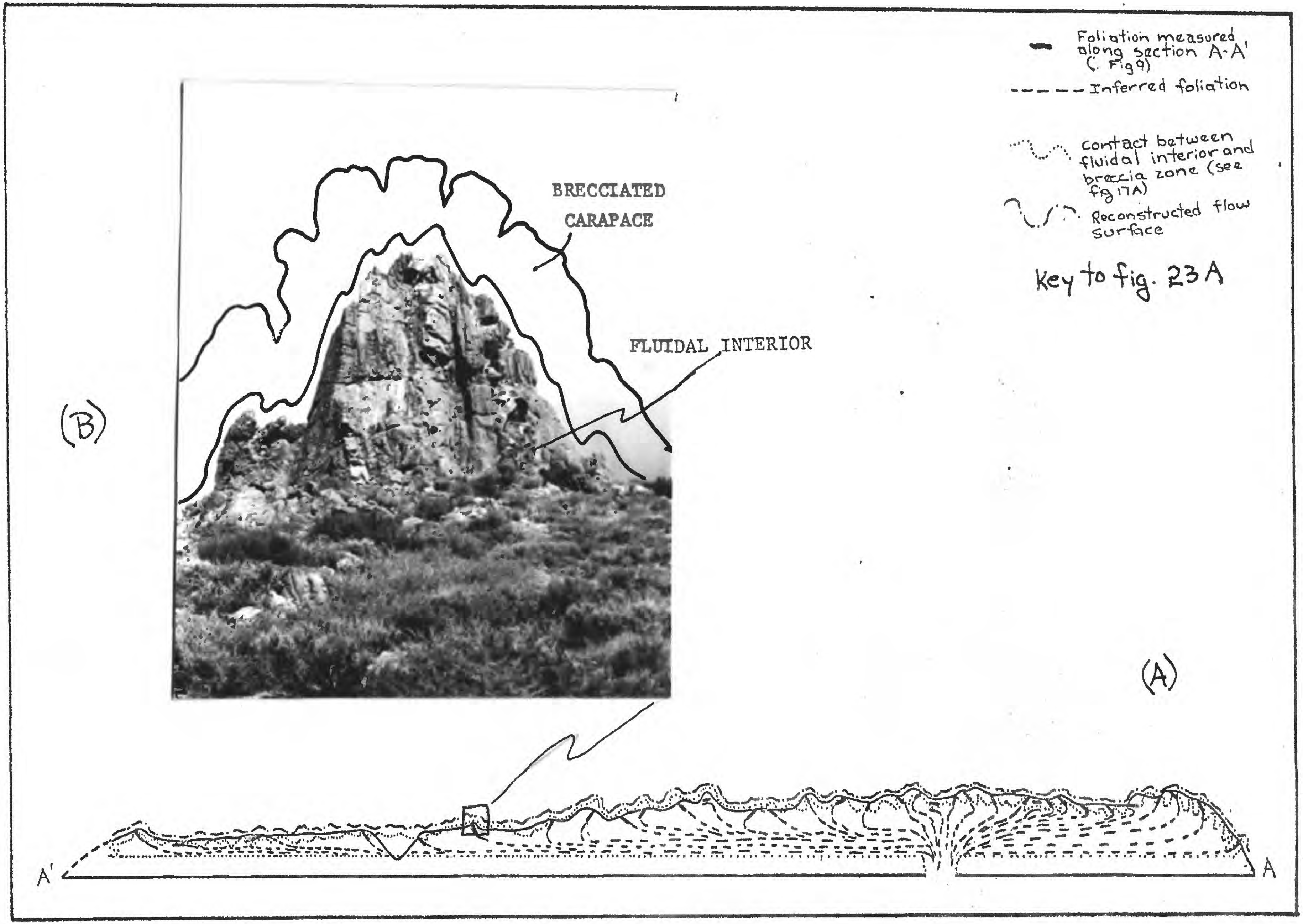
The relationship between foliation and flow ridges is particularly important. Foliation appears to terminate at the top of some of the outcrops which are stripped of pumiceous breccia (fig. 23B). The hypothetical reconstruction of the outcrop in figure 23B assumes that a maximum of 10 m of obsidian and pumiceous glass were eroded, and that the form of the flow before erosion was similar to uneroded surfaces of rhyolite flows, such as the Inyo Domes (see fig. 1 for location).

The foliation and lineation are steeply dipping in the outcrop of figure 23B as well as many massive outcrops on the flow ridges. This suggests that the lava which formed such ridges welled upward into the brecciated carapace as stubby protrusions or ramps. The ramps, once intruded into the carapace, are commonly deformed due to the uneven movement of the flow.

Figure 24a-e is a series of schematic profiles that suggest how the lava moved out of and away from the vent. Although these diagrams are idealized and do not represent actual cross sections through Hot Creek flow, they are based on structures as shown in figure 23. The configuration of time lines and the flow pattern are based on the foliation patterns observed at the surface of the flow (fig. 15).

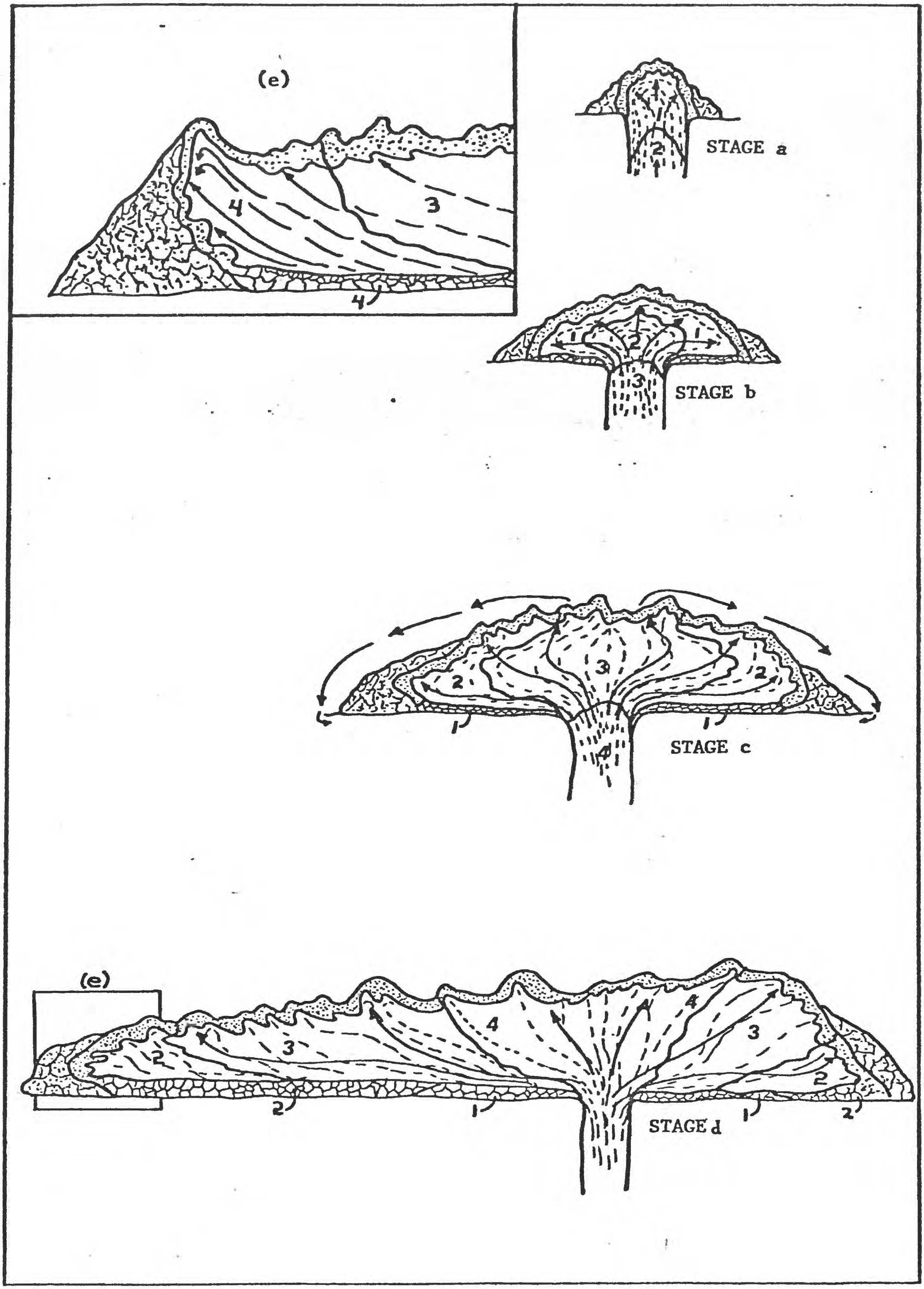
Figure 23. A) Structural section through Hot Creek flow.

B) Ramp structure located on the sublacustrine portion of the flow. Photo also shows typical vegetation over sublacustrine surface.



(B)
BRECCIATED
CARAPACE
FLUIDAL INTERIOR
Foliation measured along section A-A' (. Fig 9)
Inferred foliation
contact between fluidal interior and breccia zone (see fig 17A)
Reconstructed flow surface
Key to fig. 23 A
(A)
A'
A

Figure 24. Schematic cross section showing emplacement history of Hot Creek flow.


(e)
4
3
4
STAGE a
2
STAGE b
2
1
3
STAGE c
2
3
2
1
1
4
(e)
STAGE d
2
3
4
4
3
2
2
1
1
2

Diagrams a-d of figure 24 show progressive stages in the development of the flow. The numbered volumes of lava show the successive movement and positions of those volumes in successive stages. The attitude of foliation is shown by dashed lines, and arrows indicate direction of flow and spreading. The brecciated carapace is shown as stippled. The north and south edges of each diagram show the talus apron.

At stage *a*, lava volume 1 erupts through the vent and has a closed foliation pattern similar to that in the subsurface magma. The lava maintains the shape of the conduit due to its high viscosity. Vesiculation of the lava at the surface leads to the formation of pumiceous carapace which brecciates as it cools and the extrusion expands. At the margins, the loose surface breccia accumulates as a continuous marginal wedge of talus.

During this early stage, the dome grows by expansion from within and is thus endogenous (See Cloos, 1927, and Williams, 1932). The dome builds upwards to some maximum height, limited by the viscosity of the lava, and begins to spread laterally under the influence of gravity and hydrostatic head. The overall movement of the flow is analogous to a tractor tread in motion (Krauskoph, 1948).

With continued extrusion of lava, volume 2 displaces volume 1 and exposes more of 1 to cooling. The carapace at stage *a* and *b* congeals from volume 1 alone. During spreading, the brecciated pumiceous carapace, accumulation as talus at the flow margin, is progressively overrun by the fluidal interior of the flow. Expansion is still from within, and the flow continues to develop endogenously.

accumulated. Lineations in the ramp structures indicate movement occurs not only radially, but more commonly tangentially to the overall flow direction.

Toward the end of eruption, greater proportions of the lava accumulate as a breccia at the flow front and the tendency for ramp structures to form intensifies. Some of the lava may flow upward and out over the flow top, brecciating and fusing the carapace. When flow finally ceases, the signature of movement is imprinted upon the lava as the foliation pattern (fig. 15). Figure 15 shows that the foliation pattern is more complex away from the vent. Near the vent, where the foliation at the surface is concentric, the stresses developed in the vent affect the lava at short distances from the vent. Beyond the area of concentric flow ridge and concentric foliation patterns, the stresses developed in the vent are no longer functional and the stresses related to cooling at the outer flow surface, impedance of the advancing flow by the talus apron, and intrusion of the carapace by ramps become the prime determinants of flow pattern and the orientation of resulting structures.

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