

HAT CREEK LAVA FLOW.

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ABSTRACT. The Hat Creek basalt flow, north of Lassen Peak, California, was erupted along a line of north-south fissures probably within the past 2,000 years. In spite of the holocrystalline texture of the bulk of the lava, it possesses many characters indicating marked fluidity at the time of eruption (numerous lava tubes, ropy pahoehoe surfaces, pressure ridges, and slump scarps). The history of crystallization was simultaneous separation of olivine and plagioclase followed by pigeonitic pyroxene, plagioclase, and iron ores forming a subophitic (diabasic) texture. The Hat Creek basalt is of the same composition and texture as the Pliocene Warner basalt, also of fissure origin.

INTRODUCTION.

RECENT lava flows of fissure origin, other than flank eruptions from volcanic cones, are not numerous and any example is worth noting. While studying the volcanic rocks on the Burney and Halls Flat quadrangles north of Lassen Volcanic National Park in California, the writer mapped a recent fissure flow in Hat Creek Valley. The lava is largely holocrystalline with an ophitic to subophitic texture, and a petrographic study has given information concerning the sequence of crystallization.

Hat Creek Valley begins about ten miles north-northeast of Lassen Peak, and extends in a north-northwest direction for a distance of 25 miles, merging into the plateau through which the Pit River has cut a canyon. The width of Hat Creek Valley varies from one to four miles. To the west are three prominent cones: Magee Mountain, Stoney Peak, and Burney Mountain, rising above a complex of smaller andesitic cones. These are a part of the Cascade Range (Text Fig. 1), the chain of volcanic cones terminating in Lassen Peak to the south. East of the valley, horizontal basalt flows form a part of the Modoc Lava Plateau, and perched on this surface are a number of cinder cones and small shield volcanoes.

The eastern margin of Hat Creek Valley is a beautiful example of a slightly eroded fault scarp (Text Fig. 2). In part the displacement was along a series of parallel and converging faults bordering step-like blocks, each with an easterly tilt.

At the south end of the valley, the scarp has a height of 700 feet, while nine miles north there is a drop of 1,500 feet from the level of the plateau to Hat Creek Valley, but this displacement is distributed along three fault blocks. In contrast there is no evidence indicating that the western margin of Hat Creek Valley was formed by faulting. The two western faults shown

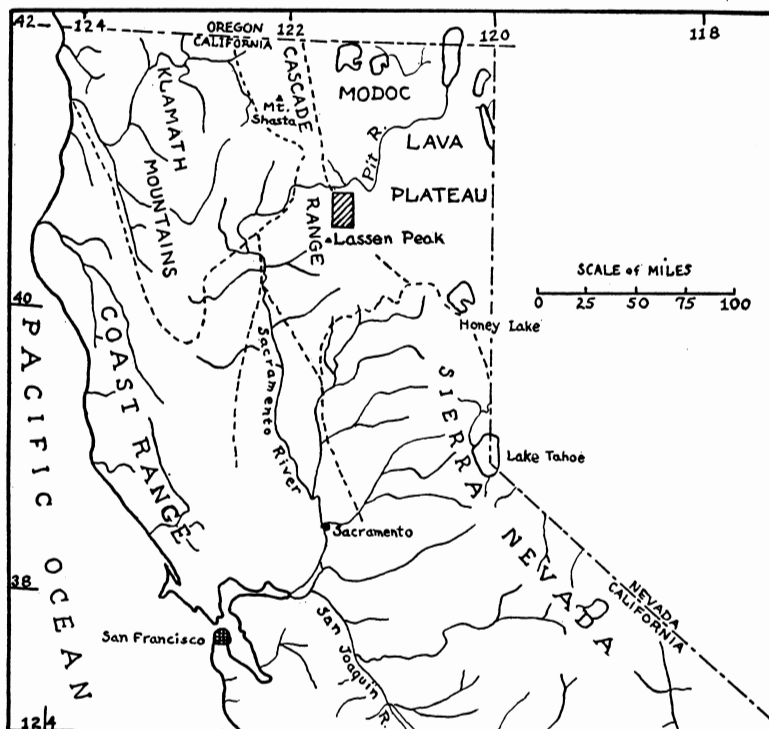


Fig. 1. Index map of northern California outlining the various geologic provinces and locating Fig. 2 (shaded area).

in Text Fig. 2, although of small displacement, have the down-throw side on the west, exactly as the eastern faults. A discussion of the origin of Hat Creek Valley is not pertinent to the main subject of this paper, but the available evidence indicates that all of the fault blocks have an easterly tilt, suggesting that Hat Creek Valley is either a large block with an easterly tilt or several smaller fault blocks with the same tilt, covered by later lava.

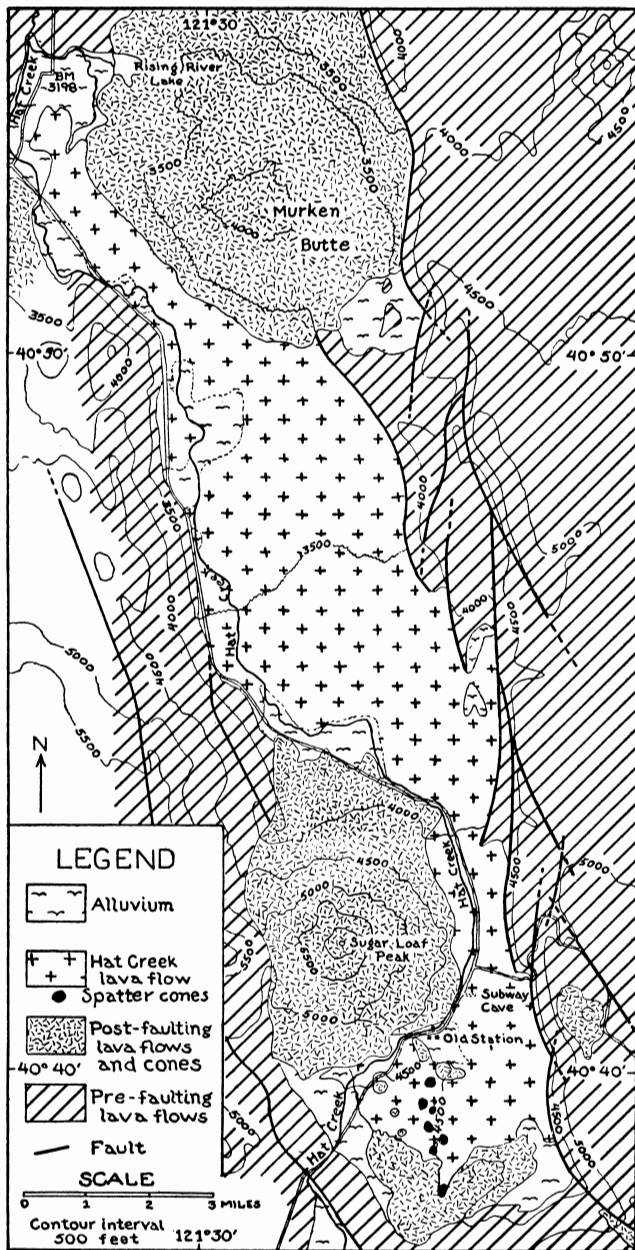


Fig. 2. Geologic map of Hat Creek Valley. Topography from Burney and Halls Flat quadrangles.

After faulting, new volcanoes of the central type were built, their vents spaced along faults or in alignment parallel to known faults. Sugar Loaf Peak is an andesitic cone, largely composed of lava flows capped by a cinder cone. The remaining post-faulting cones and flows are basaltic but differ in texture and appearance from the latest flow that poured down Hat Creek Valley.

HAT CREEK FLOW.

The lava of the Hat Creek flow was discharged from north-south fissures located south of Old Station (Text Fig. 2). That this area was the source is clearly shown by the rise of the lava surface to a broad ridge ranging in elevation from 4,600 to 4,700 feet and trending north-south. Scattered over this ridge in a belt one-quarter of a mile wide are a series of spatter or driblet cones, very roughly aligned. Their location is somewhat generalized on Text Fig. 2. The spatter cones range from three to 30 feet in height, the diameter of each spatter cone increasing with the height. In most of these there is a shallow central depression, but in a few there are cylindrical depressions as much as 40 feet deep. The spatter cones are composed of clots of highly vesicular hypocrySTALLINE lava weakly adhering to each other (agglutinate). Most of the clots were plastic enough to flatten out and become parallel to the slope of the cone (Plate 1, Fig. 1). Evidently these cones represent the accumulation of jets of lava hurled from a series of lava fountains spaced along the feeding fissures, comparable to those developed from Mauna Loa flank eruptions¹.

Some secondary fusion of the holocrystalline basalt is indicated adjacent to some of the spatter cones. At the surface the lava is locally separated into layers two to eight inches thick, parallel to the surface of the flow. Along these "horizontal joints," a thin, glassy coating is present, and in places vertical joints connecting the horizontal fractures are also lined with glass, these vertical cracks doubtless serving as channels for upward escaping gases at temperatures high enough to fuse the basalt. Microscopic studies reveal that the glass coating is thin and sharply set off from the holocrystalline lava; if the glass was formed by original quick cooling, the lava should

¹ Stearns, H. T., and Clark, W. O.: *Geology and water resources of the Kau District, Hawaii*, U. S. Geol. Surv. Water Supply Paper 616, p. 122, 1930.

have a hypocrySTALLINE texture as in the spatter cakes. Secondary reheating by oxidation of escaping gases has been suggested for other examples² of fusion of previously consolidated lava and is undoubtedly the explanation for the glass selvages noted in the Hat Creek flow.

Tongues of vesicular basalt lead from the spatter cones and merge into the main lava field, clearly demonstrating that the source of the lava was from fissures underlying the spatter cones. These tongues have a corrugated surface, the small ridges covering lava tubes one to two feet high and three to four feet wide. The faults in the immediate region trend either north-south or northnorthwest-southsoutheast, and the alignment of the spatter cones indicates that the underlying fissures parallel the north-south tectonic lines. Spatter cones over feeding fissures have been described by Reck³ as characteristic features of fissure eruptions. If explosive eruptions preceded the outpouring of the Hat Creek lava, as in the case of the famous Laki eruption of 1783, the pyroclastic products have either been buried or swept away by the succeeding floods of lava.

Some of the lava moved westward, surrounding several older basaltic cinder cones, but much of it poured downstream to the north, joining the main lava flow near Old Station. The main stream poured eastward from the source vents, then north down Hat Creek Valley. East of Sugar Loaf, Hat Creek Valley is only about a mile wide owing to the upbuilding of the Sugar Loaf andesitic cone, post-faulting in age. To the north, the Hat Creek flow widens until it is restricted by the post-faulting basaltic shield volcano of Murken Butte. The distal end of the flow is about 16 miles north of the feeding fissures.

Lava tubes are rather common throughout the flow, but most of them are small, not more than one to four feet in height. The best known tube, Subway Cave (Plate 2, Fig. 1), is located a mile northeast of Old Station; it has a height of 12 to 15 feet and can be followed for a distance of one-half

² Nichols, R. L.: Surficial banding and shark's tooth projection in the cracks of basaltic lava, *This Journal*, Vol. 237, p. 190, 1939; Stearns, H. T., and Clark, W. O.: *op. cit.* pp. 113-114; Diller, J. S.: Surface fusion of lava, *Bull. Geol. Soc. Amer.*, Vol. 33, 142-144, 1922.

³ Reck, Hans: Islandische Masseneruptionen, *Geol. Palaeo. Abhand.*, N. F., Band 9, p. 42, 1910.

mile. In detail, ropy surfaces (pahoehoe) are present, but these are fairly rough to the touch and lack the satiny lustre as seen on many pahoehoe surfaces. The absence of glass in the lava probably accounts for the roughened surface. There are many elongate ridges five to ten feet high and one hundred to several hundred feet long (Plate 1, Fig. 2). Casually the smaller ones resemble "schollendome" or "tumuli" but where examined in detail are seen to lack the oval form. When viewed from the eastern scarp or studied on aerial photographs, these ridges can be resolved into a pattern convex downstream, indicating that they were formed by the deformation of a highly viscous crust because of the downstream movement of the underlying liquid lava, and Russell's⁴ term "pressure ridge" seems appropriate for them.

Finch⁵ has previously called attention to the slump scarps along the eastern margin of the flow, but they are important enough that their description be repeated. Where the flow impinged against the eastern fault scarp, the lava froze immediately while the main portion of the flow contained a liquid interior, which in time was drained northward, causing the original solidified crust to collapse. At some places, the lava was viscous enough to bend downward from the frozen margin, but usually the collapse was along vertical joints forming a cliff, locally as high as 30 feet (Plate 2, Fig. 2). These slump scarps are found along most of the eastern margin of the flow and a preliminary examination might indicate that the scarp was formed by renewed faulting. However, when the slump scarps are traced in detail, they are found to coincide with the irregularities of the eroded fault scarp, and where spurs projected into Hat Creek Valley allowing a large lava pool to form, which later drained to the north, large slump scarps were formed. A profile section drawn by Finch and reproduced here (Text Fig. 3) illustrates how the center of the flow may have the same elevation as the selvage of frozen lava, while lowering of the lava surface is local, near the margin of the flow, eliminating faulting as a cause.

In contrast, there is a complete absence of slump scarps along the western margin and along the borders of the Murken Butte shield volcano. The character of the pre-Hat Creek lava

⁴ Russell, I. C.: Geology and water resources of the Snake River plains of Idaho, U. S. Geol. Surv. Bull. 199, p. 94, 1902.

⁵ Finch, R. H.: Slump scarps, Jour. Geol., Vol. 41, pp. 647-649, 1933.

surface apparently determines their absence, for along the western margin "kipukas" or islands of older lava jut through the Hat Creek flow, indicating that here the lava is comparatively thin. This suggests further that the original surface was tilted to the east, so that lava filling Hat Creek Valley would be rather thick at the eastern margin but thin along the west. It would be in the deep portion of the lava flow that conditions would be most favorable for subsurface drainage of liquid lava and subsequent lowering of the lava surface.

Because of the highly jointed character of the lava and presence of numerous tubes, the Hat Creek flow is pervious to water. Hat Creek is the only stream that flows continually over the lava flow. On the east side of the valley, a stream

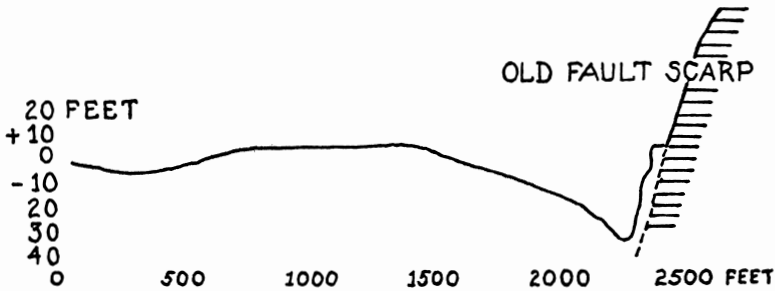


Fig. 3. Profile across Hat Creek lava flow. Vertical scale exaggerated ten times. After Finch.

coming down from the plateau flows northward for a distance of five miles before disappearing into the pervious lava. At the distal end of the Hat Creek flow the water table is close to the surface of the lava, so that pools of water fill depressions on the lava surface, these gradually merging into a stream, Rising River.

In the absence of historical data, the precise age of the Hat Creek flow is difficult to determine. Clearly it is the youngest lava flow in the immediate region of Hat Creek. Murken Butte is almost devoid of vegetation, yet the Hat Creek flow is younger. Preservation of the original flow surface in most places and absence of products of chemical decomposition are the chief criteria for assigning a very recent age to the flow. Bordering Hat Creek, the flow is frequently veneered with flood plain and mud flow deposits. In the southern end of Hat Creek Valley these deposits are forested, whereas to the north

meadows are common. The remainder of the flow is covered with chaparral and scattered trees, many of these growing in the lava joints. However, there is an appreciable accumulation of volcanic ash in depressions on the lava surface (Plate 1, Fig. 2) and these are favorable for plant growth. Presumably these ash accumulations came from Lassen Peak and vicinity, for pumice lapilli and ash from the 1915 eruptions⁶ are easily found. Not over 300 to 400 years ago, ash and lapilli were erupted in considerable volume from the Chaos Crags⁷, north of Lassen Peak, and some of the ejecta probably covered the Hat Creek flow, as the prevailing winds are from the southwest. Some "soil" has been added by the washing down of rock debris from the eastern fault scarp. As the vegetation is largely growing on deposited material, it has no significance as to the amount of weathering since the outpouring of the lava.

Throughout much of the course of Hat Creek, the channel in the Hat Creek flow is very shallow, not more than three feet deep from the top of the flow. The channel itself is usually deeper because of the superposed cover of gravel and sand. Presumably some time was required to establish the stream course, as the pervious openings in the lava would have to be filled before stream flow was established. The deepest channel observed in the lava is eight feet deep, but here the gradient of the stream is locally steepened. Considering the gradient (average gradient of the stream is 100 feet per mile), volume of water (average flow is 98.7 second feet⁸), and available rock load, the stream might have deepened the eight-foot channel at a rate of 0.05 to 0.1 inch per year. At the former rate it would take less than 2,000 years and at the latter less than 1,000 years to cut the eight-foot gorge. This would be in agreement with the unweathered nature of the flow surface, although it must be admitted that no adequate data are available to estimate the rate of chemical weathering of lava flows in this region. There is no question that the flow is fairly recent, judged from its appearance, and the statement that it

⁶ Williams, Howel: Geology of the Lassen Volcanic National Park, California, Univ. Calif. Publ. Bull., Dept. Geol. Sci., Vol. 21, pp. 321-330, 1932.

⁷ *Ibid.* pp. 346-350.

⁸ Groves, N. D.: Surface water supply of United States 1937, part 2, Pacific Slope Basins in California, U. S. Geol. Surv. Water Supply Paper 831, p. 251, 1938.



FIG. 1



FIG. 2

FIG. 1. Spatter cone built up of flattened clots of lava plastic at time of eruption and weakly adhering to each other.

FIG. 2. Pressure ridge produced by deformation of plastic crust of lava flow. In the foreground, accumulation of volcanic ash derived from Lassen Peak and vicinity.

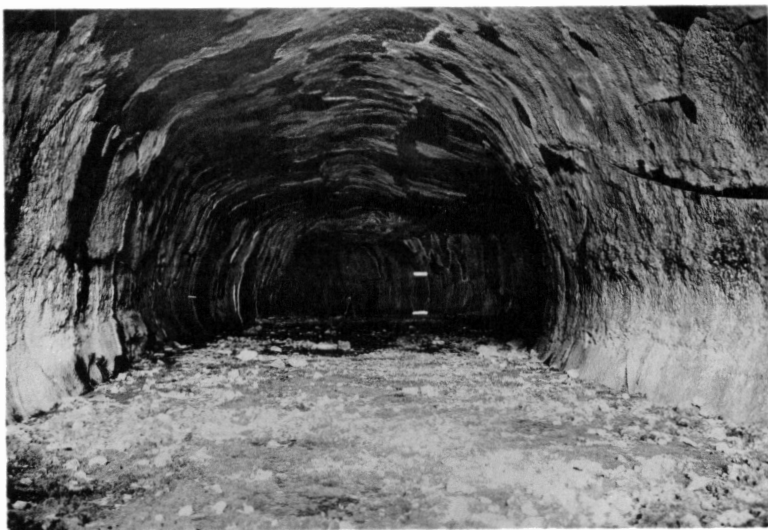


FIG. 1.

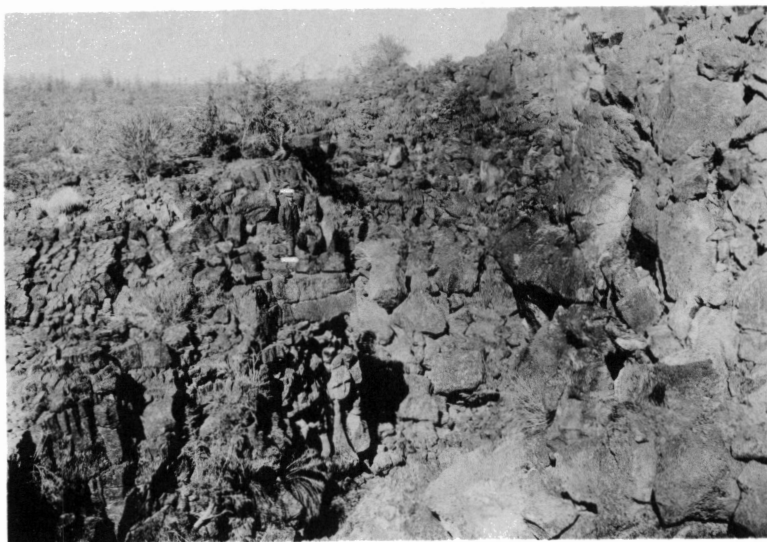


FIG. 2

FIG. 1. Subway Cave, a lava tube in the Hat Creek flow. White lines indicate height of man to give scale. Photo by H. C. Lind.

FIG. 2. Slump scarp at eastern margin of Hat Creek flow (looking north). White lines indicate height of man to give scale. In the background chaparral cover on surface of flow. Photo by R. H. Finch.

is probably not more than two thousand years old is conservative in the light of the available evidence.

PETROGRAPHY.

Typical specimens of the Hat Creek lava are essentially holocrystalline, containing plagioclase, olivine, pigeonitic pyroxene, and iron ores. The plagioclase is usually euhedral and in excess of the pyroxene, which may be in anhedral grains interstitial to the plagioclase, or more rarely in large crystals enveloping the feldspar. The texture may be described as ophitic or diabasic, depending on the definition given to these terms, a subject admirably discussed by Johannsen.⁹ The writer is reluctant to use "diabasic" for the texture of an extrusive rock, since this is the term commonly used in the United States for intrusive rocks (diabases). On the other hand, ophitic is usually limited to a variety of poikilitic texture, where the pyroxene is the host mineral enclosing euhedral plagioclase crystals. In this paper, this limited definition is followed (Text Fig. 5b), and for the rocks with interstitial pyroxene molded in part about the feldspars the term subophitic is used (Text Fig. 4b).

There has been some discussion as to the order of separation of the minerals in rocks having the subophitic (ophitic, diabasic) texture, but part of the difficulty is owing to the various uses of the terms. So far as the writer is aware, there is no argument concerning the ophitic texture in its limited meaning, that is, the pyroxene followed the crystallization of the feldspar. The same explanation has been advanced for the sequence of crystallization in rocks with subophitic or diabasic texture (ophitic in a broad sense). On the other hand, Fenner¹⁰ presented very definite evidence in support of the simultaneous crystallization of plagioclase and pyroxene in rocks with this texture and Bowen¹¹ as a result of his laboratory studies has reached the same conclusion. More recently, Krokstrom¹² advocated the late crystallization of pyroxene in rocks with subophitic texture and presented evidence in support of this conclusion.

⁹ Johannsen, A.: A descriptive petrography of the igneous rocks, Vol. 1, pp. 43-47, 1931.

¹⁰ Fenner, C. N.: The crystallization of a basaltic magma from the standpoint of physical chemistry, *This Journal*, Vol. 29, pp. 217-234, 1910.

¹¹ Bowen, N. L.: The evolution of the igneous rocks, pp. 67-69, 1928.

¹² Krokstrom, Torsten: On the ophitic texture and the order of crystallization of basaltic magmas, *Bull. Geol. Inst. Upsala*, Vol. 24, pp. 197-216, 1932.

TABLE I.

	1	2	3	4	5	6	7
SiO ₂	46.84	47.98	48.50	48.20	50.61	50.66	51.9
Al ₂ O ₃	17.98	18.66	18.22	18.07	13.58	14.28	14.3
TiO ₂	1.05	1.18	.81	1.54	1.91	1.30	
Fe ₂ O ₃	7.82	.94	.26	1.76	3.19	3.41	14.3
FeO	2.18	8.66	8.69	9.16	9.92	8.58	
MnO .....	.18	.15	.15	.15	.16	.12	
MgO	8.66	9.48	8.97	5.94	5.46	6.92	4.0
CaO	10.34	9.92	11.58	9.93	9.45	8.60	8.4
Na ₂ O	1.96	2.48	2.24	2.25	2.60	2.92	2.9
K ₂ O .....	.88	.27	.09	1.46	.72	.72	1.6
H ₂ O+	2.02	.04	.12	.94	2.13	2.28	
H ₂ O- .....	.15	.05	.18	.28			
P ₂ O ₅ .....	.06	.07	tr	.38	.39	.17	
	100.12	99.88	99.81	99.78	100.12	99.96	
qu					4.14		
or	5.56	1.67	.56	8.90	4.45		
ab	16.77	20.96	18.34	19.39	22.01		
an	37.25	38.92	39.48	34.47	23.07		
di	10.80	8.34	14.74	9.87	17.41		
hy	15.30	8.53	9.63	9.88	17.78		
ol .....	.98	17.51	14.66	10.72			
mt	4.64	1.39	.46	2.55	4.64		
il	2.13	2.28	1.52	2.89	3.65		
ap				1.01	1.01		
hm	4.64						

1. Vesicular hyalopilitic basalt from spatter cone, Hat Creek flow. Herdsman, analyst.
2. Subophitic basalt, Hat Creek flow. Herdsman, analyst.
3. Warner basalt (Pliocene) subophitic, Modoc lava plateau. Herdsman, analyst.
4. Olivine-bearing marginal facies of central dolerite, Breven dolerite dike. T. Krokstrom: The Breven dolerite dike, Upsala Univ. Geol. Inst. Bull., Vol. 23, p. 303, 1932.
5. Average Deccan basalt; H. S. Washington, Deccan traps and other plateau basalts, Bull. Geol. Soc. Amer., Vol. 33, p. 797, 1922.
6. Average New Jersey basalt; *ibid.*
7. Average Miocene Columbia plateau basalt; computed by A. C. Waters from selected analyses.

Fortunately the method used so effectively by Fenner can be used on the Hat Creek flow, for the lava composing the spatter cones contains a large amount of glass, representing quenched liquid. The phenocrysts are the crystals that had separated from the melt. In order to be certain that the spatter material is essentially of the same composition as the holocrystalline, a chemical analysis was made of each (Table I, Nos. 1 and 2), and with the exception of the high ferric iron

oxide in the spatter material, the result of oxidation at the time of eruption, the two analyses are essentially the same. So it can be concluded with some assurance that the subophitic lava crystallized from a melt of the same composition as that which formed the hyalopilitic spatter.

The hyalopilitic lava is vesicular and contains plagioclase crystals averaging about 0.1 mm. in length, a few having a length of 0.6 mm. The refractive indices indicate that the

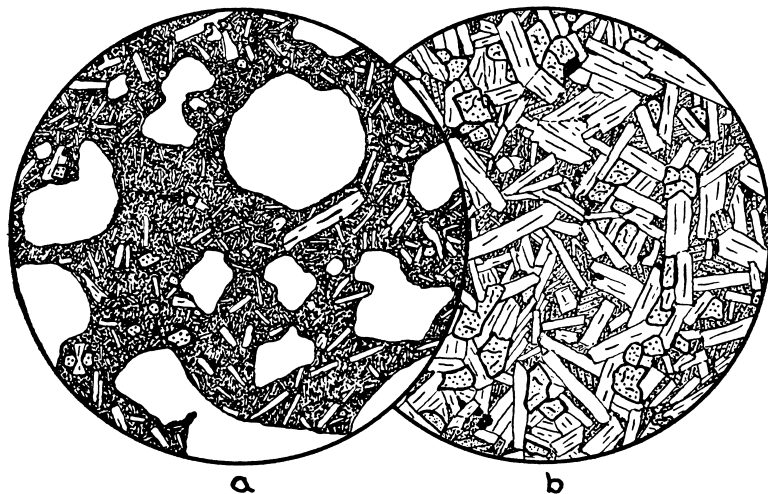


Fig. 4. (a) Vesicular hyalopilitic basalt from spatter cone. Microphenocrysts of plagioclase and olivine imbedded in brownish black glass containing minute granules of pyroxene, iron ores, feldspar microlites. X37. Analysis, Table I, No. 1.

(b) Typical subophitic Hat Creek basalt. Plagioclase and olivine crystals separated by interstitial pyroxene and scattered iron ores. X37. Analysis, Table I, No. 2.

plagioclase is bytownite (An_{85}). Associated with the feldspar are round crystals of olivine, averaging only 0.04 mm., the largest diameter observed reaching 0.06 mm. These two minerals are imbedded in a brownish black mesostasis composed largely of glass in which minute granules of pyroxene and iron ore are associated with a few microlites of feldspar (Text Fig. 4a). The index of refraction of the glass is $1.625 \pm .005$, indicating about 47 per cent of SiO_2 , according to the curves by George,¹³

¹³ George, W. O.: The relationship of the physical properties of natural glasses to their chemical composition, Jour. Geol., Vol. 32, p. 366, 1924.

a value in keeping with the chemical analysis. There appears to be no question but that there was early simultaneous crystallization of plagioclase and olivine followed by late crystallization of pyroxene, iron ore, and a little feldspar.

In the holocrystalline lava, the plagioclase crystals are of larger size, having crystallized in tablets averaging 0.3 by 0.06 mm. in dimension, and they are richer in albite (An_{70}) than the plagioclase in the hyalopilitic lava. The olivine crystals

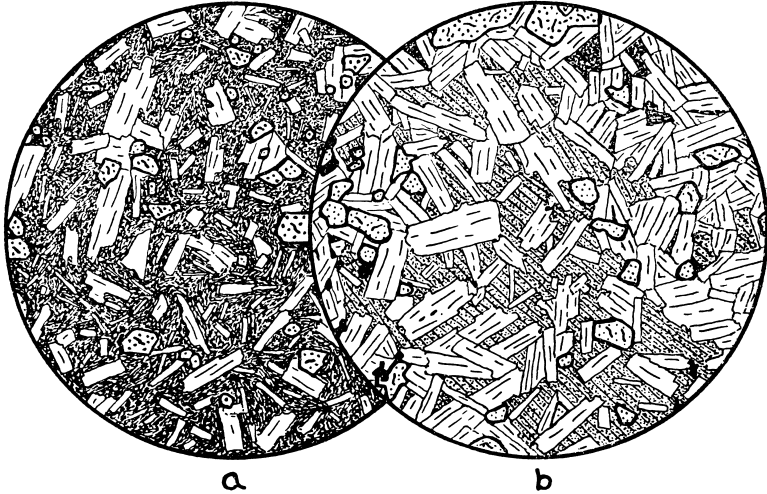


Fig. 5. (a) Intersertal to intergranular Hat Creek basalt from surface of flow. Scattered plagioclase and olivine crystals separated by pyroxene and iron-ore granules, plagioclase microlites, and glass. X37. (b) Ophitic variation in Hat Creek basalt 12 feet below 5a. Large pyroxene crystals enclosing plagioclase, olivine, and iron ores. In upper part of drawing, dark-colored glass interstitial to feldspar (intersertal). X37.

average 0.1 mm., with a few reaching a diameter of 0.75 mm.; these larger crystals may have picotite inclusions. The refractive indices and very large optic angle indicate that the olivine is rich in magnesia (Fa_{18-20}). Plagioclase crystals molded about olivine have been noted as well as the reverse, indicating more or less simultaneous crystallization. The pyroxene is usually interstitial to the plagioclase and olivine (Text Fig. 4b), but a few examples of slightly prismatic crystals were noted. There are a few small plagioclase crystals associated with the interstitial pyroxene, indicating some simultaneous

crystallization of these minerals. Occasionally the pyroxene is in large crystals 1 mm. across enclosing euhedral plagioclase (Text Fig. 5b). The pyroxene is usually slightly purplish but non-pleochroic; in a few examples it is greenish gray. It is largely clinopyroxene, Z to c averaging 45° . The optic angle is 48° (measured with a universal stage). The indices of refraction and extinction angle measured on cleavage fragments indicate a pyroxene of the composition $Wo_{25}En_{45}Fs_{30}$,¹⁴ which might be described as pigeonitic in character.

In one sample of the surface vesicular phase, plagioclase and olivine crystals are separated by an intersertal to intergranular aggregate (Text Fig. 5a) consisting of tiny iron ore granules, prisms of pyroxene, microlites of feldspar, and glass. Under high magnifications, some of the pyroxene prisms extinguish parallel, suggesting hypersthene, but other prisms show inclined extinction and larger granules of unquestioned clinopyroxene were recognized. This section is of importance in that it also indicates early simultaneous crystallization of plagioclase and olivine with late crystallization of pyroxene, iron ores, and some feldspar.

Barth¹⁵ has recently discussed the crystallization history of basalt and has suggested that the initial composition of the basaltic magma determines whether pyroxene or feldspar will be the first to crystallize, thereby changing the composition to a point where simultaneous crystallization will take place. Using the normative minerals, ab , an , di , and hy for the corners of a tetrahedron, he deduced from the evidence of crystallization a boundary surface separating the plagioclase from the pyroxene fields. An equation $ab' + 2di' + 2.3hy' = 123$ ¹⁶ represents the position of the boundary surface in the tetrahedron. The sum $ab' + 2di' + 2.3hy'$ is called the $f(\text{norm})$; and if it approximates 123, it indicates that the basalt falls on or near the boundary surface and simultaneous crystallization of pyroxene and plagioclase is to be expected. This is suggested by the plateau basalts, for which simultaneous crystallization is

¹⁴ Tomita, Toru: Variations in optical properties, according to chemical composition, in the pyroxenes of the clinoenstatite-clinohypersthene-diopside-hedenbergite system, Jour. Shanghai Sci. Inst. Section II, Vol. 1, pp. 41-58, 1934.

¹⁵ Barth, Tom. F. W.: The crystallization process of basalt, This Journal, Vol. 31, pp. 321-351, 1936.

¹⁶ Ab' , di' , hy' , and an' are the normative constituents recalculated to 100 per cent. Barth, *op. cit.* p. 334.

indicated by textural studies and the $f(\text{norm})$ approximates 123. If the $f(\text{norm})$ is less, it indicates that the basalt was in the plagioclase field, necessarily providing early precipitation of plagioclase until the liquid approached the composition that allows simultaneous crystallization of pyroxene and plagioclase. In this regard, the $f(\text{norm})$ of the hyalopilitic Hat Creek basalt is 92, and 75 for the subophitic. The high Fe_2O_3 content of the former influences the amount of normative pyroxene, but both values are substantially below 123. According to Barth's tetrahedron, in which only pyroxene and feldspar are considered, this indicates an initial position in the feldspar field. The evidence of the diagram is verified by the fact that much plagioclase did crystallize before pyroxene. Barth does not discuss the crystallization of olivine except to mention that in some rocks the olivine may represent pyroxene in the early stages of crystallization and if equilibrium were reached, the olivine would be converted to pyroxene.

The Hat Creek basalt is undersaturated as shown by the high content of normative olivine, and comparison between the modal and normative composition is interesting.

	Mode	Norm
Plagioclase	56 per cent	61.5 per cent
Olivine	16 " "	17.5 " "
Pyroxene	24 " "	17 " "
Iron ores	4 " "	4 " "

The modal pyroxene undoubtedly contains some alumina and lime, which would subtract from the normative feldspar and add to the normative pyroxene. The correspondence between the modal and normative olivine is of interest because it indicates that the olivine is in equilibrium with the pyroxene, so that none of the olivine represents pyroxene in the early stages of crystallization. The pyroxene, in keeping with Barth's suggestion, is definitely later than a large portion of the plagioclase.

The Breven dolerite dike is similar to the Hat Creek basalt in chemical composition except for lower magnesia content (Table I, No. 4), and the mineral composition and texture are the same. Krokstrom¹⁷ has stated that wedges of augitic material penetrating plagioclase laths and small, broken fragments of feldspar within pyroxene clearly indicate the earlier formation of the greater part of the feldspar. Olivine is of early

¹⁷ *Op. cit.* p. 200.

crystallization. The $f(\text{norm})$ of the Breven dolerite is 84, also similar to the Hat Creek basalt. Both rocks are high in alumina as compared to the plateau basalts (Table I) and this would result in excess feldspar, which would cause precipitation to start in the feldspar field rather than near the boundary of the feldspar and pyroxene fields. On the other hand, the plateau basalts are usually saturated with respect to silica and contain normative quartz.¹⁸ Olivine is frequently absent or present only in small quantities that represent pyroxene in the early stages of crystallization. Also the lower amount of alumina (Table I, Nos. 5 and 6) results in less feldspar, so that the magma would begin to crystallize near the boundary surface of the pyroxene and plagioclase fields and simultaneous crystallization of these minerals soon follows after the initiation of crystallization.

It seems clear therefore that the composition of the initial magma, as suggested by Barth, determines the course of crystallization in basalts, and the evidence in the Hat Creek basalt and Breven dolerite indicates that for undersaturated basaltic magmas high in alumina, plagioclase and olivine will crystallize early and more or less simultaneously, and late in the crystallization sequence pyroxene will separate accompanied by some feldspar and the iron ores. If the chilling is rapid, hyalopilitic, intersertal, or intergranular textures will result, but with slower cooling, subophitic textures will develop with local areas of ophitic (poikilitic) texture.

COMPARISON WITH THE PLIOCENE WARNER BASALT.

It should be emphasized that the recent Hat Creek basalt is essentially of the same chemical composition (Table I, Nos. 1, 2, 3) and texture as the widespread Pliocene Warner basalt which covers a large portion of northeastern California, forming the major part of the Modoc lava plateau (Text Fig. 1). Also it was discharged in the same manner, the Warner basalt representing fissure eruptions on a moderate scale. There may be some genetic connection in this region between this manner of eruption and composition of the lava. Elsewhere the writer¹⁹ has discussed the chemical composition of the War-

¹⁸ Washington, H. S.: Deccan traps and other plateau basalts, *Bull. Geol. Soc. Amer.*, Vol. 33, pp. 765-804, 1922.

¹⁹ Anderson, C. A.: Volcanoes of the Medicine Lake Highland, California, *Univ. Calif. Publ. Bull.*, Dept. Geol. Sci. In press.

ner and related basalts; the essential point to note here is that it departs considerably from that of the widespread Miocene plateau lavas of eastern Oregon and Washington (Table I, No. 7) and more closely approaches in composition the Porphyritic Central Magma type of Mull, although lacking the porphyritic texture.

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