THE GEOLOGY OF THE MONO CRATERS, CALIFORNIA

Minor Thesis by

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ABSTRACT

The Mono Craters are a chain of extinct obsidian domes, coulees, and lapilli cones lying south of Mono Lake in eastern California. They are slightly more than ten miles long, are ranged along a curving fracture roughly parallel to the Sierra Nevada, and are divided into three nearly equal parts by two large obsidian flows, or coulees. In general, there has been a shift of activity from the center of the range to the two extremities.

The volcanic vents in the Mono Craters, in the typical case, pass through a sequence in which activity commences with a series of explosions. Ash and lapilli are hurled out, and a funnel shaped explosion pit is formed. The explosions are succeeded by the rise of an obsidian dome near the center of the lapilli ring. The dome expands beyond the confines of the lapilli collar and produces a coulee if a sufficient volume of obsidian reaches the surface. Explosions of decreasing intensity may occur during any of the later stages in the sequence.

The structure of the average obsidian dome is determined by the viscous nature of the semi-solid obsidian, and the narrow conduit through which it rises. The lava expands in a sheaf-like form upon reaching the surface. The obsidian is traversed by a multitude of joints on cooling, and rapidly disintegrates into angular blocks. The force responsible for the elevation of the obsidian is not known, but may well be exerted by the gas contained in the magma.

The principal rock types in the Mono Craters are the frothy lapilli of the explosion vents; gray or purple, sanidine-bearing, pumiceous obsidian; black, vitreous obsidian; and the near-rhyolitic variety of "intrusive obsidian" found in the deeper parts of the volcanic conduits. Associated with the obsidian of the Mono Craters are two older rocks, the West Portal Rhyolite and the Black Butte Basalt. The nature of the West Portal Rhyolite, and its relation to the older glacial deposits, is clearly shown by the cross-section exposed in the water tunnel driven under the southern end of the craters by the Los Angeles Bureau of Water Works and Supply.

The Mono Craters were active in the late Pleistocene. Although some ash is interstratified with deposits of Mono Lake, no shorelines cut the more recent craters. The Southern Coulee buries one of the earlier lateral moraines of one of the principal Sierra glaciers. Explosion pits at the southeastern end of the craters erupted through the floor of a late Pleistocene lake, part of a chain lying to the east of the main group of craters.

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INTRODUCTION

The Mono Craters are one of the most distinctive landmarks on the southern side of Lake Mono. They stand some distance from the eastern boundary of the Sierra Nevada, which, in this area, is a bold escarpment overlooking the desert of western Nevada. The craters rise nearly 3000 feet above a broadly undulating, pumice covered lowland between the Sierra and Lake Mono. In the words of I. C. Russell (1), "could this range of craters

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(1) I. C. Russell, "Quaternary History of Mono Valley, California," U. S. Geol. Survey, 8th Annual Report, Part 1, p. 378, June 30, 1887.

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and lava flows be transported to a region of low relief, as the valley of the Mississippi for instance, it would be far-famed for its magnificent scenery as well as for its geological interest. In its present location it is rendered of secondary importance by the vastly greater range whose crest is barely ten miles distant."

The craters, mirrored in the dark waters of Lake Mono, are a striking sight in their isolation. A forest of Jeffery Pines encircles their southern and eastern base, but only a few relatively hardy individuals grow on their rocky or pumice-covered slopes. Beyond and behind the craters to the south and west rise the castellated summits of the higher Sierra. To the east are the lower, more barren hills of the desert.

In addition to their unique appearance and the beauty of their surroundings, the craters have an inherently great interest in their own right. This interest centers about the magnificent scale on which the type of eruption represented here has occurred and also its recency.

The late position in the geologic record is indicated by the blanket of pumice which covers the moraines of even the late recessional stages of the last glaciations; by the burial of terminal moraines under one of the obsidian coulees, and by the absence of any of the high-level shorelines of Lake Mono on any of the last-formed volcanic slopes.

The Mono Craters are particularly noteworthy for:

1.) Their association with the lacustrine and glacial record of Lake Mono and the eastern Sierra Nevada.

2.) Their extreme recency, shown by the fact that this lake and glacial record in large measure precedes the time of maximum volcanic activity.

3.) The impressive size of the obsidian domes and coulees, and the clarity with which the succession of events in the history of the range is revealed.

4.) The light that this history casts upon the problem of the origin and character of volcanic domes.

5.) The occurrence of obsidian in a quantity in both domes and coulees which is without parallel elsewhere in the United States.

6.) The construction of a water tunnel through the southern end of the chain by the City of Los Angeles which has revealed something of the nature of the foundation, as well as the internal structure of the volcanoes.

ACKNOWLEDGMENTS

It is a pleasure to recall the great interest and kindly criticism of Dr. Ian Campbell of the California Institute of Technology, Pasadena, California, both in the field and during the various stages in the completion of this study. The numerous suggestions of Dr. J. P. Buwalda of the same institution proved of great help, and are gratefully acknowledged.

The author is indebted to the Bureau of Water Works and Supply of the Department of Water and Power, City of Los Angeles, for many courtesies. More particularly, credit may be given to Mr. H. A. Van Norman, Chief Engineer and General Manager, and Hugh Mulholland, General Foreman in Charge, for permission to enter the tunnels and shafts, as well as to board at the various camps on the Mono Craters Tunnel Project. The innumerable courtesies extended by Mr. M. D. Burris, petrographer, made the author's stay more profitable and pleasant than it might otherwise have been.

He is also in the debt of Mr. E. S. Bayley, Chief Surveyor, for much information, and for the recollection of a number of memorable conversations. Mr. R. R. Proctor and Mr. S. S. Nelson of the Field Engineering Division and Mr. B. S. Grant, Executive Assistant, proved particularly helpful in arranging for the author's stay at the project.

PREVIOUS WORK

Surprisingly little geologic work has been done in this area in spite of its interest and accessibilty. In fact, most of the little that has been accomplished was achieved in the pioneer period when problems of transportation and subsistence were more difficult than at present.

Probably the first white man to visit the region, and to leave an account of his venture was Captain Elisha Walker who passed this way in 1833. The geologists of the Wheeler Survey carried on a reconnaissance of the country to the South, and were not so vitally concerned with the problems of the Mono Basin. The members of the Whitney Survey visited the area, and made a number of observations on the lake as well as the volcanoes.(2)

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(2) J. D. Whitney, "Geology, Vol. I," Geological Survey of California, pp. 451-455, 1860-1864.

Among these early accounts one of the most concise, and at the same time expressive, is the one contained in the journal of William H. Brewer(3)

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(3) Francis P. Farquhar, "Up and Down Californis in 1860-1864, the journal of William H. Brewer, Professor of Agriculture in the Sheffield Scientific School from 1864 to 1903, "Yale University Press, New Haven, p. 416, 1930.

July 8, 1863. "Hoffman and I visited a chain of extinct volcanoes which stretches south of Lake Mono. They are remarkable hills, a series of truncated cones, which rise about 9,700 feet above the sea. Rock peeps out in places, but most of the surface is of dry, loose, volcanic ashes lying as steep as the material will allow. The rocks of these volcanoes are a gray lava, pumice stone so light that it will float on water, obsidian, or volcanic glass, and similar volcanic products. It was a laborious climb to get to the summit. We sank to the ankles or deeper at every step, and slid back most of each step. But it was easy enough getting down- one slope that took three hours to ascend we came down leisurely in forty-five minutes. The scene from the top is desolate enough- barren volcanic mountains standing in a desert cannot form a cheering picture. Lake Mono, that American "Dead Sea," lies at the foot. Between these hills and our camp lie about six miles of desert, which is very tedious to ride over- dry sand, with pebbles of pumice, supporting a growth of crabbed, dry sagebrushes, whose yellow-gray foliage does not enliven the scene."

Joseph le Conte[4] visited Mono Lake and was

(4) Joseph le Conte, "On the extinct volcanoes about Mono Lake and their relation to the glacial drift," Amer. Jour. of Science, 3rd series, Vol. 18, pp. 35-42, 1879.

impressed by the recency of the craters. He was probably the first observer to note that the volcanic ejecta, as well as the obsidian, rest upon glacial debris.

The work of I. C. Russell[5] sets a standard

(5) I. C. Russell, "Quaternary History of Mono Valley, California," U. S. Geol. Survey, 8th Annual Report, Part 1, pp. 259-394, June 30, 1887.

which none of the earlier investigators excelled, and even today with all the advance in knowledge since his time, and even the improvements in transportation, it would be difficult to measure up to his accomplishment.

It stands as a remarkable intellectual achievement, particularly when the area covered and the diversity of subjects investigated are considered. No errors of observations of any importance were noted, and the majority of interpretations are as valid today as at the time they were made over 50 years ago. In addition, Russell's literary style and quality of expression set a goal which few modern writers succeed in attaining.

The topographic maps and diagrams drawn by W. D. Johnson are models of accuracy and clarity, and in his map few serious errors were uncovered by the far more elaborate survey of the same ground made by the Bureau of Water Works and Supply.

After the monographic work by Russell was finished, interest in the area lagged, and until the second and third decades of the Twentieth Century few important investigations were carried on. In fact, outside the brief, but excellent, reconnaisance of Panum and Wilson Domes by Howel Williams (6) no paper dealing with the Mono Craters

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(6) Howel Williams, "The History and Character of Volcanic Domes," Univ. of Calif. Publ., Bull. Dept. of Geol. Sci., Vol. 21, no. 5, pp. 51-146, Feb. 13, 1932.

as a separate study has appeared. Their relation to the glacial deposits of the eastern Sierra is discussed by Eliot Blackwelder (7).

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(7) Eliot Blackwelder, " Pleistocene glaciation in the Sierra Nevada and Basin Ranges," Bull. Geol. Soc. of America Vol. 42, pp. 865-922, 1932.

________________, "Eastern Slope of the Sierra Nevada," XVI International Geological Congress, Guidebook 16, pp. 81-95, 1933.

Some of the aspects of the geology of the volcanoes that bear on the engineering problems connected with the construction of the Mono Craters Tunnel are briefly treated in an umpublished report by C. P. Berkey for the Los Angeles Bureau of Water Works and Supply.

In conclusion it may be said that, with the exception of the report by Russell, the literature dealing with the volcanoes is surprisingly meager. So far as the author is aware no investigation of the craters as a problem by themselves has been undertaken.

GEOGRAPHY

Location and transportation

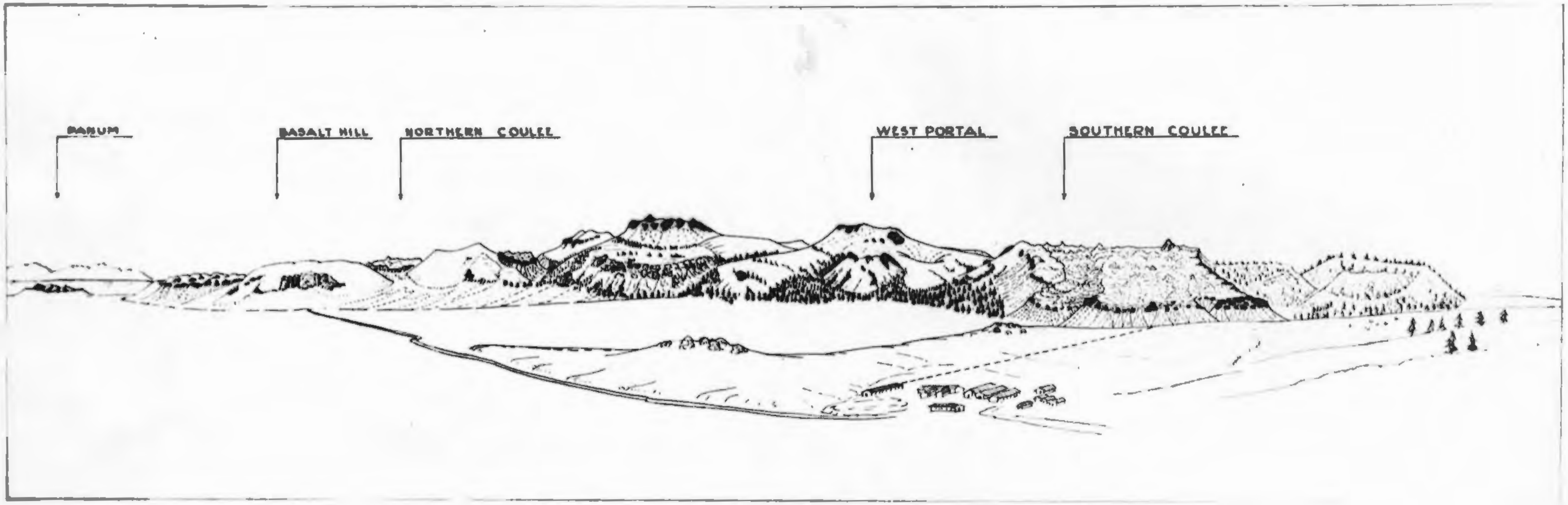
The Mono Craters stand in the center of a low and gently rolling plain nearly ten miles to the east of the main divide of the Sierra Nevada. They approach to within three fourths of a mile of the southern shore of Lake Mono, and follow a line almost due south from it. Were a line to be drawn along the axis of the range, passing through most of the principal vents, instead of being straight it would more nearly approximate a segment of a circle, with the convex side of the curve facing east.

The Mount Diablo Base Line crosses the northern end of the craters, which indicates that they are in a latitude very nearly equal to that of San Francisco. In fact, their actual position is Lat. 37°52' N. and Long. 119° W. They are easily reached by a paved road (U. S. 395) from Lake Tahoe (115 miles) and Los Angeles (325 miles), and are 60 miles north from Bishop, California.

Unsurfaced and pumice-covered roads make all sides of the craters accessible. Most of these roads are

PLATE I

Panorama of the Mono Craters from the Eolian Buttes



BASALT HILL
NORTHERN COULEE
WEST PORTAL
SOUTHERN COULEE

in fair condition, but all are rather treacherous in wet weather. No roads, or even trails, are to be found on the craters, except for the driveway built by the Water Bureau to West Control. Elsewhere the way is over angular obsidian blocks or yielding slopes of pumice.

Physical features:

Mono Craters:

As mentioned before, the range shows a curvilinear pattern on the map with a well defined central axis. The slopes to the summit are abrupt, and are determined either by the angle of repose for pumice and lapilli, or by the blocky, talus-mantled fronts of the obsidian coulees. For loose pumice this slope may be as great as 38°, and for solid obsidian either vertical or overhanging.

The crest of the range is dominated by the circular, truncated cones of three central domes, and by the broad and craggy surfaces of two great coulees. These flows serve to divide the chain into three separate areas. The northern includes the isolated dome and lapilli collar of Panum, two small coulees, four obsidian domes, and extensive lapilli area, and a basaltic eruptive center much older than the true Mono Craters.

The central area is occupied by three great domes with a number of lesser plugs and coulees on their flanks, in addition to several large explosion pits. The whole area is rather completely masked by a blanket of silvery-gray pumice.

The southern area is divided into two parts by the tunnel road built by the Water Bureau. To the north of this road are tow comparatively old, lapilli covered obsidian plugs, one of which grades into a blunt coulee. To the south are two obsidian domes, two cones, and a rather remarkable double caldera. Farther south, at the base of Deer Mountain, are two unique explosion pits without obsidian plugs.

Beyond the main highway to the west of the Mono Craters are two extraordinary obsidian domes. These will be briefly discussed, although they are both more properly grouped with the Inyo Craters. No tuff cone is visible at the base of either of them, and both show more perfectly than any other dome save Panum, the mechanism of emplacement of an obsidian dome.

Adjoining territory

The country surrounding the Mono Craters, when contrasted with their abrupt elevation, seems almost flat. The variety it does possess is the result of, (1) glacial deposition, (2) the irregular surface formed by early Pleistocene lava flows, and (3) the presence of granitic outliers of the main Sierra Nevada. The east and west sides of the craters are somewhat unlike, and may be considered as separate areas in spite of the fact that they are connected at the north and south ends of the chain.

Western Side of Mono Craters

The area from the southern shore of Mono Lake to the Southern Coulee is known as Pumice Valley, and is crossed by two streams on its northern margin that unite to form Rush Creek. For the most part the valley is the abandoned floor of Lake Mono, occupied by water during the high-stand of the lake, and now incised by the rejuvenated drainage of the current cycle.

The western side of Pumice Valley is fringed by the terminal and lateral moraines of the Sierra glaciers. On the southern side the valley is bounded by the Eolian

Buttes, and other smaller hills nearer the craters. These low hills are underlain by pink rhyolite which outcrops in places above the olive-green sagebrush in fantastic, wind-sculptured turrets and pinnacles.

From the Eolian Buttes southward the topography becomes increasingly rugged. Two morainal ridges of the Rush Creek glacier reach as far as the Mono Craters, and are actually overlapped by the Southern Coulee. A large number of basaltic crags occupy the depression abandoned by the glacier and rise above the till covered floor.

Eastern Side

For the most part the eastern side of the Mono Craters is a broadly arched, pumice-buried plain that slopes away to north and south from a medial ridge approximately two miles south of Mono Mills. The surface of this low plain south of a line drawn from the Northern Coulee, through Mono Mills, and extending to the northeast supports a forest of red-trunked Jeffery Pines.

Paralleling the western margin, near the base of the craters, are a number of curious barren meadows.

The dark wall of the forest surrounds them. They stand in sterile contrast to this forest with their desolate, pumice-strewn floors covered with only the scantiest growth of short grass and scattered flowers in the belated spring of high altitudes. These "meadows" are in reality dry-lake beds, and survive from the time of heavier precipitation during the last part of the Ice Age. The pumice which floors their basins is of special interest, for it indicates that the explosive activity of the Mono Craters extended into late-Pleistocene times.

Figure 1

Pumice Lake east of Punchbowl Craters

Place Names

One of the greatest difficulties encountered in an attempt to describe the various features of the Mono Craters is the almost complete lack of any place names within the limits of the chain. None of the higher peaks is named, and as there are no streams, this usually fertile source of local nomenclature is lacking.

For the purposes of this paper a number of new ones have had to be coined. Three sources have been utilized, (1) the names applied in 1881-83 by I. C. Russell, as Panum and the Northern and Southern Coulees, (2) the names given rather prominent landmarks by the surveyors for the Water Bureau in their triangulation net, and (3) either locally recognized ones or names which are the author's own inventions. Among the latter the most important are Russell and Johnson Domes, names which were given to two of the three higher central domes. It seemed particularly appropriate to have the highest summits of the range commemorate the signal pioneering achievements of I. C. Russell and W. D. Johnson, the first to explore, map and describe this wilderness.

Climate and Vegetation

The climate of the Mono Craters is ideal for field work during the summer. The air at their altitude is cool and ivigorating, and although the temperature may be high during the middle of the day, there is almost always a fresh breeze off the Sierra to alleviate it. The nights are invariably cool, and the humidity is low at all times. The often heavy snowfall of the winter is the most important form of precipitation. A little rain falls during the summer in short-lived, but often spectacular, thunder showers which may occasionally develop into cloudbursts.

At no time is the precipitation great, as the entire region lies in the rain shadow of the Sierra. No lakes, streams, or surface water are to be found on the Mono Craters. One reason for this lack of water is the extreme permeability of the pumice blanket.

Rainfall records have been kept only since 1932 by the Water Bureau at Cain Ranch Camp, situated on the dry west side of Pumice Valley. It may be that the total is somewhat higher on the summit of the craters.

Year	Total Inches
1932	10.23
1933	10.08
1934	6.76
1935	14.94

The temperature showed a good deal of variation during this period, from a summer maximum 98° to a winter minimum of -14°.

The important thing about the climate is its aridity. The region should be thought of as a high-altitude semi-desert. Not enough water is present for freezing and thawing to be particularly effective, and of course the lack of water, coupled with the low winter temperatures, inhibits any chemical decay. As a result, the strongly jointed obsidian of the coulees and domes shows few signs of atmospheric attack. In fact, the rock is almost as fresh looking as the day it solidified.

The vegetation is sparse, as is to be expected from the combination of scanty precipitation, altitude, and permeability of the pumice. The southern half of the craters is flanked by an open forest of Jeffery Pines (*Pinus jefferyi*), a high-altitude, symmetrical-coned, sub-species of Yellow Pine. There is little undergrowth, and the forest cover is no hindrance to field work.

The trees easily succumb to the strong southwest winds of winter, and over wide areas scores of them blow down each year. Almost all are oriented in the same direction. Instead of breaking off above the ground level, their roots are turned out, and may be seen as bowl-shaped affairs without a central tap root. They are loosely anchored in the unconsolidated pumice, and leave shallow craters when uprooted. Large blocks of accidental ejecta are brought up frequently where interlacing roots have been entwined about them. The trees must be almost entirely dependent upon the winter snowfall for moisture.

Many of the Jeffery Pines seem to be weakened by the practice of the Piutes of encircling the trunk with a shallow ditch, filling it with brushwood, and firing the lower part of the tree in order to catch the caterpillars clinging to the bole. Throughout the forest a significant number of these fire-scarred, ringed trees are encountered.

The forest encircling the southern end of the craters ends abruptly along the line drawn a short distance south of the Eolian Buttes, extending across the craters,

Figure 2

Indian Tree Ring

and projecting northeast through Mono Mills. Only a few widely scattered trees survive on the summits of the craters, which extend into the Alpine Zone.

The reason for the disappearance of the trees north of the line is the lower altitude and greater aridity of the area that forms the southern shore of Lake Mono. The lower limit for the Jeffery Pine in this station is marked approximately by the 7250 foot contour, and the upper by the

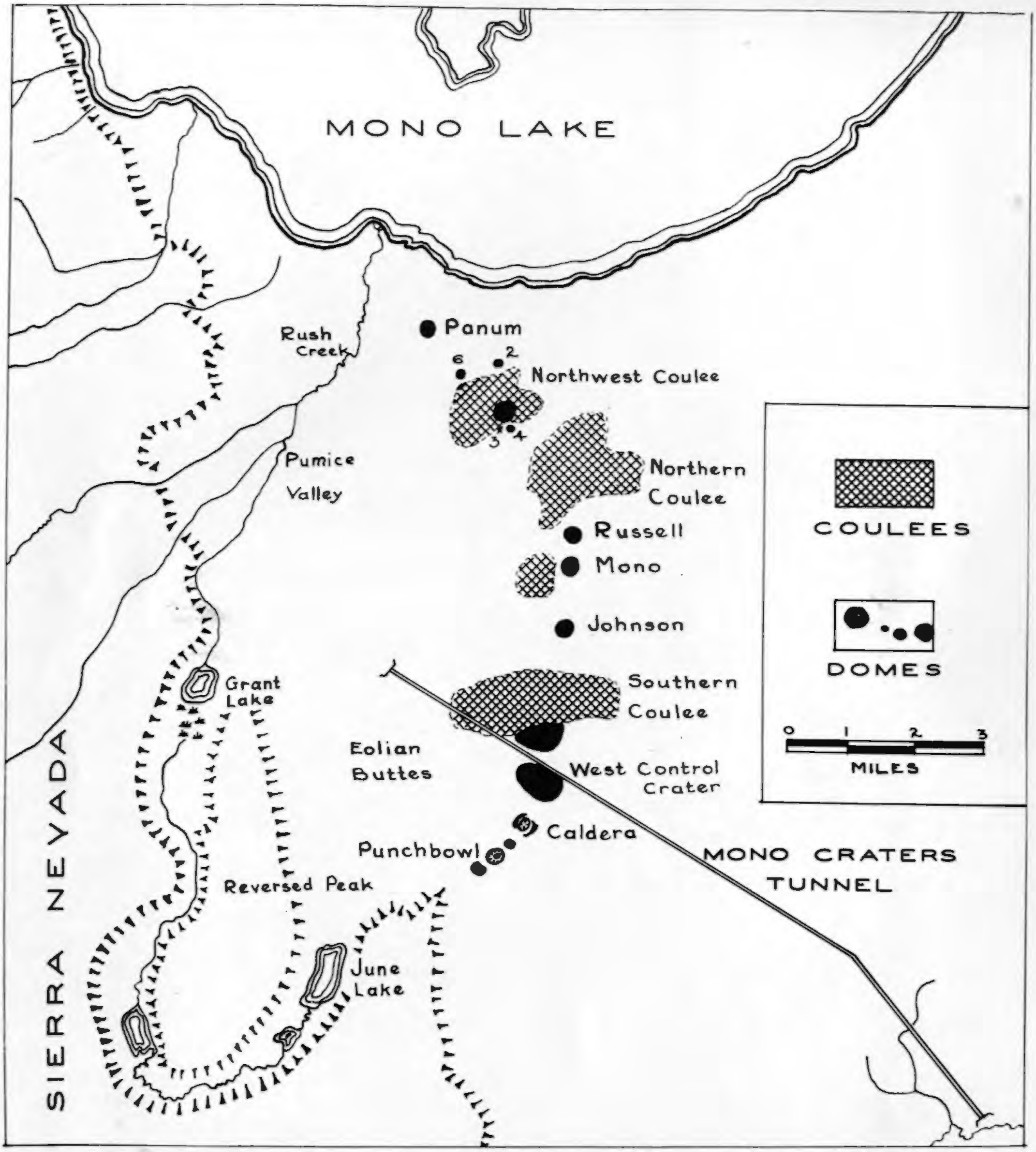
8500 foot level.

Almost the entire floor of Pumice Valley is a dusty green plain, covered with xerophytes, among which the sagebrush (Artemsia) dominates, and becomes the sole survivor on the lower slopes of the craters. It proves particularly successful on the outer slopes of lapilli cones, but meets with only indifferent fortune on the bare obsidian of central domes and coulees.

Plate II

Index map of the Mono Craters

California



MONO CRATERS, CALIFORNIA

REGIONAL GEOLOGY

In the sections to follow the geology of the principal centers of volcanic activity will be described in detail. The tripartite division of the range by the two coulees will be used as a natural basis of separation, and the various features will be treated in succession from the northern to the southern end of the Mono Craters. Any local names which do not appear on the Mount Morrison or Mount Lyell Quadrangles are shown on the geologic map (Plate II).

The Northern Area

The northern area includes the section from Panum Crater through the Northern Coulee. One of the most recent parts of the chain to achieve its present appearance, it includes some of the oldest vents. The volcanic centers which will be discussed in this section are; Panum Crater, the cluster of domes and coulees including Craters 2, 6, 4, 3, and 5, the Northern Lapilli Area, Basalt Hill, the Toboggan Slide, and the Northern Coulee.

Panum Crater

This isolated dome and its encircling lapilli collar is the northernmost of the series. It stands by itself nearly one mile north of the main group of craters, and about one mile south of Lake Mono. According to Russell (8) the name is taken from the Pa-vi-o-osi (Piute) language

(8) op. cit., (8th Annual Rept.) p. 382.

and means "lake".

Figure 3

Panum Crater

No other crater is more accessible or complete. It is only a few hundred yards from the branch road leading to Rush Creek delta, and about one half mile from the Leevining-Benton road. It is noteworthy, not only for the ease of approach, but also for the unusual degree of its perfection.

Panum Crater consists of three rather distinctive parts; a central steep-walled obsidian dome, a deep moat encircling it, and an outer lapilli ring heaped up during an early explosive phase. On the southeastern rim, and nearer the main group of craters, is the breached and eroded remnant of an older lapilli cone with a small weathered remnant of an obsidian plug near its core.

Russell believed that the obsidian plug had been formed by two protrusions, but Williams[9] failed to

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(9) op. cit., (Univ. of Calif. Bull., Vol 21) p. 78

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observe any evidence to support this belief, and cites Cloos and Balk[10] to bear him out.

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(10) Cloos, H. and E., "Das Strömungsbild der Wolkenburg im Siebengebirge," Zeitschrift für Vulkanologie, Vol. 11, p. 95, 1927.

It is difficult to tell from Russell's account how much importance he attached to the supposed double eruption. The lapilli cone clearly indicates a double explosion, but the evidence in the case of the dome is less decisive. There was a small extrusion of lava of no great importance in the central fissure after the main dome had solidified.

Before considering in detail the various parts of Panum Crater it may be of value to record some of the more important dimensions to give a quantitative picture of one of the most perfect of the obsidian domes. These measurements are based on the large scale survey made by the Water Bureau.

Total outside dimensions from rim to rim of tuff cone	3000' x 4000'
Height of tuff cone above surrounding country	240'
Maximum depth of moat	210'
Maximum height of dome above moat	230'
Width of dome	1200' x 1500'

The Lapilli Cone:

The lapilli cone, a deep elliptical bowl, completely surrounds the central dome. No solid rock appears, either in the walls, or in the floor of the moat; and it is composed entirely of fragmental material hurled out of a central vent by the explosions that heralded the approach of the obsidian.

The lapilli rim has not a uniform height throughout its circumference. There are two distinct maxima, the greatest on the northeast side, and the least on the west. This greatest height on the northeast is an expectable consequence from the direction of the prevailing wind which blows most frequently from the southwest. Not only is the northeast section of the rim the highest, but also it is the only one to have a well-developed "tail".

The double nature of the lapilli cone is best shown in the floor of the moat. This depression has a step in it along an east-west line drawn through the center of the dome and projected across the lapilli ring. The deeper part of the moat is the northern half. It would appear that there had been either a double, and almost simultaneous explosion; or that explosive activity had endured for a slightly longer time in the northern half of the crater.

For the most part the walls of the cone consist of loose fragments of finely-spun, silvery gray, frothy pumice which ranges in size from sand to lapilli 2 or 3 inches in diameter. Interspersed throughout the dominant gray pumice are small (1 inch or less) pellets of black obsidian. At times these obsidian fragments may be fairly large (1 foot or more) and appear to have been hurled out as bombs. Upon landing they were shattered, but have fallen apart along well-defined conchoidal fracture planes.

Included with these products, clearly derived from a volcanic source, are others which are exotic. These are either water-rounded or angular pieces of granodiorite and various metamorphic rocks. They are clearly out of place resting on the surface of a lapilli cone, and more properly belong in the Sierran complex some 10 miles away. Many are of fair size, a foot or more in diameter, but the majority of the ones found on Panum are somewhat less. None of those inspected shows any trace of glacial striae. The greater number are well-rounded, and would probably be classed as cobbles.

There is little doubt that these fragments are accidental ejecta, and have a similar origin to the limestone fragments hurled out on the slopes of Vesuvius. They represent the type of material that the explosive blast, responsible for the lapilli cone, passed through on its way to the surface. For the most part this type of ejecta seems

Figure 4

Talus slope of Panum Dome and crater wall of pumiceous lapilli

to have come from lacustrine and delta deposits laid down in Pleistocene Lake Mono.

The Obsidian Dome:

The central obsidian dome, with its pinnacled summit, vertical parapet, and steep talus embankment, is the most distinctive part of Panum Crater. With its deep purplish-brown color, and battlemented crest it resembes a feudal castle and is an arresting sight, even when viewed from a distance.

The top of the dome is a chaos of narrow spires. They lean precariously over a jumbled array of crags, pinnacles, and loosely piled angular blocks of brown, pumiceous obsidian. Few patterns are repeated, but it may be noted that most of the spires are concentrated about the periphery of the dome, that many of the accumulations of blocks show a tendency towards a crescentic arrangement, and that the dome is crossed by a deep fracture from north to south near its eastern margin.

In the spires the flow banding is nearly vertical, with a tendency to fan outwards in the larger pinnacles. This radial effect is best developed in those spires nearest the edge of the dome, and in a number of these the flow planes approach the horizontal, and may even be inclined outwards. For the most part the spines have nearly perpendicular sides, are penetrated by numerous joints, and have a tendency to break down into loose piles of sharp-edged blocks.

Figure 5

Obsidian Spines on summit of Panum Dome

The spires are made of gray to brown, pumiceous obsidian. Along the walls of the numerous joints the surface is usually glazed, and sometimes has a breadcrust texture with a brilliant grayish, glassy skin. This glassy skin is formed by the remelting of the obsidian by gases streaming through the fractures opened in the newly solidified rock.

Figure 6

Obsidian Spine on summit of Panum Dome

Some of the outer surfaces of the best preserved spines have vertical slickenslides caused by the rise of the semi-solid spine through a narrow orifice. Crossing these vertical striae at right angles are less well developed ridges which may be growth lines formed during pauses in the upward rise of the spine.

Figure 7

"Breadcrust" texture and glazed surface of obsidian block

A great variety of fractures penetrate the solid part of the dome. This highly shattered nature of the obsidian is responsible for the formation of the great quantity of angular blocks which cover the surface of the dome, and mask its flanks as talus. As soon as the obsidian spires rise to any height above the dome, they shatter and collapse into heaps of razor-edged, pumiceous blocks.

Figure 8

Fractured obsidian spires, Panum Dome, north side of Northwest Coulee and summit of Basalt Hill in background

The talus is formed in a similar fashion. The obsidian tends to push out towards the periphery of the dome, fractures, and when unsupported, slides down to form heaps of debris (Breches d' ecroulement). Thus, according to Williams, the talus embankment is to be considered as much a primary feature as the spines on the summit of the dome. The accumulation of most of the debris takes place at the same time that the obsidian rises, and tends to mask the true shape of the dome. As pointed out by Russell, and restated by Williams, the obsidian dome of Panum, were its cover of talus to be stripped away, would probably be a cylinder with nearly vertical walls.

The dominant rock type on the dome of Panum is the purplish-brown, pumiceous obsidian that occurs in sharp-edged blocks, so characteristic of the last-formed coulees and domes. On a freshly broken surface it is a light silvery gray, and the laminated appearance due to the alternation of vitreous obsidian and more frothy pumice is often pronounced. Every gradation may be found from jet black obsidian with a conchoidal fracture, to the most vesicular pumice.

The familar black variety of obsidian is comparatively rare, although more abundant on Panum than any other dome, except the North Inyo Crater. It seems to have been intruded into the fractures of the already solidified pumiceous form, and reaches the surface only in narrow, tongue-like extrusions which appeared at a comparatively late stage. This black variety shows the best fluidal banding, as may be seen in the accompanying illustration (Fig. 9).

Williams[11] sums up the mode of origin of the

(11) <u>op. cit.</u>, (Univ. of Calif. Bull., Vol. 21) p. 78

Panum Dome in the following concise statement.

Figure 9

Fluidal banded obsidian, Panum Dome

"The writer supposes the obsidian to have issued through a narrow conduit, many times smaller in diameter than the dome itself, and to have spilled sluggishly from it, immediately building a levee that prevented further expansion. As fresh magma welled up it was increasingly confined by the steepening of the levee, until it was finally constrained to rise vertically. Throughout this process, the chilling of the obsidian must have been rapid and the crust of the mass virtually solid. Any attempt to flow laterally was therefore checked; before the vertically moving lava commenced to bend over, it was sufficiently solid to fracture into blocks. Locally, perhaps, where the lava was richer in volatiles, or for other reasons cooled more slowly, flow was prolonged, so that pinnacles and spines developed on the summit."

Crater 2

This small dome is immediately south of the Leevining-Benton road, and stands at the extreme northern end of the Mono Craters proper. It rests on the flank of the Northwest Coulee, and is manifestly younger than the coulee as it is superimposed upon it.

The crater is particularly noteworthy as a small, but nearly perfect, example of an obsidian dome without an accompanying lapilli cone. The lapilli cone may be lacking, or it may have been buried by obsidian built out over its slopes. There is good reason to believe that the

the first supposition is the valid one, and that a lapilli rim was never formed. There is a strong resemblance between this obsidian dome and Wilson Dome at the opposite end of the craters.

Figure 10

Crater 2

Some little interest is attached to Crater 2 from the fact that Russell[12] singled it out as a type ex-

(12) op. cit., (8th Annual Rept.) p. 382

ample for a particular sort of eruption.

"The small cup on the northern edge of a coulee, at the extreme northern end of the main range, is an exception to the others in the series, as it is largely composed of scoriaceous rhyolite, instead of fragmental material. * * * * * * * The sides of the depression are extremely steep and rugged and form a funnel-shaped crater about seventy-five feet deep."

The dome repeats on a small scale the conditions described for Panum, with the exception of the preliminary explosive phase. The dome is almost circular and rises 240 feet above the surrounding country. It has a breadth of 1100 feet, and at the summit is a distinct funnel-shaped depression, 90 feet deep.

Little may be observed of the appearance of the walls of the dome, hidden beneath long streams of angular blocks in the talus. It probably is a cylinder with nearly vertical sides; the same shape that was inferred for Panum. The dome is not covered with ash, and was formed after the time of most intensive explosive activity in the Mono Craters. It also clearly precedes the extravasation of the Northwest Coulee, but its time relation to such Craters as 3 and 4 on the opposite side of the coulee is hard to determine. The evidence would indicate that it is quite late in the succession, and probably is about equivalent to Panum Dome. Both are essentially contemporaneous with Dome and Coulee 3.

Panum and Crater 2 are late Pleistocene or early Recent. At least both are later than the high-level stage of Lake Mono, as no shore lines are cut in their flanks. Shorelines, if they were to be present, would be will developed on both these craters that stood farthest out in the area once occupied by the lake.

Crater 6

This lapilli crater and its central dome are a consqicuous part of the northern end of the Mono Craters. The relation of Crater 6 to the Northwest Coulee is most apparent from the west side of the craters. Its southern flank is buried by the more recent Northwest Coulee, which has overwhelmed the lapilli cone, and covered the southern half of the dome.

Figure 11

Crater 6, partially buried by the Northwest Coulee

As most of the spines which formerly covered the dome have crumbled, it is covered with loose rubble, blanketed to a moderate degree by pumice. No large open fractures remain, as in Panum Dome, and most of the obsidian blocks project above a rounded, ash-covered surface. The most prominent feature on the top of the dome is the two large obsidian ridges crossing its summit, and showing a parallel orientation with the main axis of the range. These ridges have vertical sides, and arched, comb-like crests. Some trace of slicken-sides is preserved on their margins. They may represent masses of solidified obsidian elevated along fractures crossing the summit of the dome.

The obsidian in this dome shows a marked difference in appearance from the variety cropping out in Panum or Crater 2. Petrographically the two are quite similar, but as seen in the field they appear somewhat unlike. The obsidian in Crater 6, particularly where it appears to be intrusive into the lapilli cone, is a darker gray color than at Panum. It is distinctly more pumiceous, for the black vitreous stages are lacking, and the presence of large, glassy phenocrysts of sanidine is particularly characteristic.

The lapilli cone is well preserved on the north and west sides of the central dome. It has been obliterated to the south by the Northwest Coulee, and is lacking to the east where it has apparently been buried by obsidian from the central dome. The greatest height of the lapilli rim is on the north and northeastern sides, as is to be expected from the direction of the prevailing winds. The lowest side is the western, and here the cross-cutting relationship of the Northwest Coulee is best shown.

There can be little doubt that Crater 6 is older than the Northwest Coulee, which in turn is older than Craters 2, 3, and 4. This place in the succession makes Crater 6 the oldest in the series of vents located north of the Northern Lapilli Area. In spite of its relatively greater age, it still is young in terms of the geologic time scale. No lake shorelines are cut in the unconsolidated slopes of the tuff cone, which would have shown little resistance to wave-attack had it been in existence at the time Lake Mono covered this area.

Northwest Coulee (5)

The oldest coulee in the chain also forms the best defined northern limit for the main group of craters. The two previously described, Craters 2 and 6, are small salients beyond the main rampart of the coulee, one resting upon it, and the other overwhelmed by it.

Figure 12

The irregular surface and western end of the Northwest Coulee

The coulee extends from the eastern to the western side of the range, and reaches the valley floor on both sides. Its length, measured at right angles to the main trend of the range, is 1.2 miles, and its breadth, 0.8 miles. The front of the coulee is typically abrupt, for this sort of flow, but is less precipitous than either the Northern or Southern Coulees. Instead of appearing to override the present land surface, the foot of the talus merges with the valley floor.

The western end of the coulee appears to be slightly more recent than the eastern; however, this seeming difference in age may be due simply to the thicker ash blanket on the eastern side. Most of the hollows on the surface of the coulee are filled with ash; consequently, it makes a less desolate appearance than the barren top of the Southern Coulee.

A number of pinnacles and spines still surrive and rise above the pumice, but the majority have disintegrated to form beehive-shaped accumulations of angular blocks. Many of these former spines still show traces of fumarolic activity, and the surface of the obsidian blocks is stained red with hematite or yellow with sulphur. As a rule these fumaroles are concentrated near the central part of the coulee.

No trace remains of a central vent, or a pronouncedly larger group of spines built up along a medial fracture. If there were a localized center for the outpouring of the obsidian, it may well be buried under the slopes of Crater 3, which has been built upon the surface of the Northwest Coulee.

Aside from the slightly greater age, this coulee resembles its southern neighbors in every important particular:

1.) It crosses the chain of craters at right angles to their trend.
2.) It extends away in both directions from a central fissure.
3.) The flow has maintained an almost vertical front and now appears as a parapet overlooking a steep talus.
4.) Block lava which stands in pinnacles and spines is the dominant type.
5.) There seem to have been secondary centers of local activity on the surface of the coulee.
6.) In places black, vitreous obsidian showing well-developed fluidal banding was extruded through fractures in the block lava.
7.) The black obsidian shows every gradation into the pumiceous variety.
8.) Most of the obsidian on the surface of the coulee is the purplish-brown, pumiceous variety with comparatively small sanidine phenocrysts.

9.) The period of coulee formation was closed by an episode of mild explosive activity.

10.) The pumice blown out during these explosions is a dark gray glassy variety composed of small fragments of obsidian.

<u>Dome and Coulee 3</u>

This interesting dome and coulee would be overlooked by an observer who saw only the western side of the craters. Its characteristics are best observed from the summit of the range, even though it does stand out prominently on the eastern side. The particular significance of this crater is the clear-cut example it provides of the derivation of a coulee from a central dome.

A further unique feature is the fact that it has been built upon the surface of an older obsidian flow, the Northwest Coulee. It also overshadows the smaller, but otherwise identical, cup-like Crater 4 on its southern flank.

There is little to distinguish between Crater 3 and Crater 2 or Panum Dome except size. In each of these examples, a plug of essentially solid, blocky pumiceous obsidian has risen as a dome above a constricted passage through which the lava reached the surface. Save for the presence of a stubby coulee in the case of Crater 3 the appearance of all is much the same--a battlemented parapet overlooking a steep talus slope, and surmounted by a central depression on the summit of the dome.

Figure 13

The steep sided coulee and dome of Crater 3

The resemblance of this crater to a medieval walled town is very striking, especially in the early morning when the spires of the upper rim stand out like a multitude of towers. The illusion is further strengthened by a deep moat at the foot of the talus on the southwest side.

Figure 14

The obsidian dome of Crater 3 built upon the surface of the Northwest Coulee

The dome rises 250 feet above the surface of the Northwest Coulee, which, in itself, is a not inconsiderable accumulation of obsidian. The central part of the dome is a deep, funnel-shaped depression, filled in by talus sloping down from all sides to the apex of the cone. The "crater" is encircled by a distinct wall which was breached on the east side to form a short coulee. The central pit may have been formed through the undermining of the solidified crust of the dome by the removal of the magma supplied to the coulee.

The Coulee is especially interesting for the clear fashion in which it may be seen cutting across the former lapilli cone, (Figs. 15 and 16) as well as for the excellent example it provides of a coulee derived from a central dome.

As in the case of both Panum and Crater 2, no ash covers the surface of this dome, which is also composed of the purplish-brown obsidian characteristic of the later eruptions. There is no doubt that this crater is

Figure 15

Figure 16

Dome and coulee of Crater 3 cutting across tuff rim.

older than the Northwest Coulee, as it is built almost entirely upon its surface. Although it was formed in the same volcanic episode as Crater 4, it is slightly younger, since it overlaps the north edge of Crater 4.

Probably Crater 3 and its coulee are contemporaneous with Panum and Crater 2. They are so widely separated that little more than a guess can be made of their relative ages. Certainly all of them are pre-Northwest Coulee, and all seem to show an identical freshness of appearance. The building of these domes was one of the last events in the volcanic history of the northern one-third of the range.

Crater 4

Crater 4 is a small obsidian dome on the southern side of the main dome of Crater 3. It is almost hidden from sight on the floor of the large moat that is the north boundary of the Northern Lapilli Area.

The dome has no visible tuff cone, and in appearance and size is almost a duplicate of Crater 2. It has a nearly circular outline, and is perhaps 100 yards across, and is only 50 feet high on its lowest and southern side.

At the center of the dome is an unusually deep-throated vent into which a chaotic array of knife-edged obsidian blocks have tumbled. The walls of the vent intersect at the bottom to form a steeply flaring, inverted cone whose apex is at a lower elevation than the talus foot on the outside. A profile drawn across the dome would more nearly fit the figure in Russell's Report than the diagram supposedly representing Crater 2. Crater 4 is an almost ideal illustration of the type which he describes as consisting of "scoriaceous rhyolite".

The walls of the vent are colored a brilliant yellow by sulphur, and occasionally red with hematite. Most of the colors are concentrated near the bottom and up the slope of the western and northern walls. They are caused by fumarolic activity which reached its maximum after the dome had acquired its present form.

It is doubtful that the central vent was caused by an explosion. A more logical assumption for the origin would be that the depression was caused by a collapse of the solid surface of the dome through the drawing away of magma from beneath to form Crater 3.

Both craters were formed almost simultaneously.

Figure 17

Crater 4, in the lower foreground, partially buried by Crater 3

Neither one is covered with ash, and both give every indication of extreme recency. That Crater 4 is slightly older than Crater 3 is shown by the fact that it is overlapped by the talus from Crater 3, and is nearly buried on its north side. Both vents may have been in eruption at the same time during the early stage of their history, but some advantage operated in favor of Crater 3 and it eventually outstripped Crater 4.

The Northern Lapilli Area

The Northern Lapilli Area, between the cluster of craters described above and the Northern Coulee, is a difficult part of the range to decipher. No obsidian crops out, and the entire area is hidden beneath a cover of pumice. This unevenly distributed coat consists of ash, of silvery-gray, frothy pumice, and lapilli, and blocky fragments, either of black obsidian or accidental ejecta.

Most of this material is less than an inch in diameter, and would be described as ash. Pumice fragments up to 6 inches are not uncommon, and would be classed as lapilli. There is a slight tendency for many of the larger blocks to be concentrated towards the southern margin, in the direction of the Southern Coulee.

It is quite difficult to determine what the underlying structure of the Northern Lapilli Area may be, but it seems to consist essentially of a group of explosion vents. Their original outline has been modified by the work of the wind, and by additions of ash from later eruptions to north and south.

The slope is steepest on the eastern side of the area, and here a uniformly inclined wall of pumice, with an inclination averaging 35 degrees, serves to separate the Northern Coulee from the short one issuing from Crater 3. The lapilli ring crossed by the coulee of Crater 3 merges with the surface of this ash covered area, but seems to be slightly later.

The Northern Coulee rests on the surface of the lapilli area, and the same relation holds for Crater 3 and 4, as well as the Northwest Coulee. There is little doubt that the Northern Lapilli Area was formed during an episode of explosive activity early in the history of the northern part of the range.

The unusual features of the area are:

1.) The great volume of pyroclastic material.

2.) The absence of solid obsidian on the surface.

3.) The presence of an unrelated rock type in Basalt Hill in the western part of the area.

Basalt Hill

Probably the most anomalous feature of the Northern Lapilli Area is the maturely rounded hill which projects beyond the western boundary of the range into the Pumice Valley. It forms the southern side of the moat south of the Northwest Coulee. The top of the hill is covered with lapilli, and ash has accumulated along the northern slope in a large wind drift.

The shape of the hill is quite different from its neighbors. It has a rounded, whale-back summit, and lacks the pinnacles and steep talus associated with the obsidian domes. Instead, the dark rocks cropping out on its sides are arranged in concentric layers, one superimposed on the other, and all conforming to the arched profile of the hill. They look very much as though they were successive layers of a viscous tar-like fluid which has been poured out on a rounded surface, and had there solidified.

Normal to these concentric surfaces the rock shows a rude columnar structure. Numerous joints penetrate it, and near many of these fractures the rock has most of its cavities filled with white, glazzy zeolites. The ground mass is aphanitic and black, although plagioclase phenocrysts are visible in it. Under the microscope the rock shows a diabasic texture formed by lath-like crystals of labradorite intergrown with augite, surrounded by a glassy mesostasis. The other important minerals present are olivine and magnetite.

The rock is basalt, although it was identified by Russell (13) as a hornblende andesite.

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(13) <u>op. cit</u>., '(8th Annual Rept.) p. 379

The major problem to be solved is the relation the basalt bears to the Mono Craters; composed as they are of such dominantly persilicic rocks as obsidian and rhyolite. Both the location and appearance of the hill are germane to this problem.

In the first place, the hill stands about one mile from the main axis of the craters along which practically all the vents are aligned. Secondly, it has a more mature profile and appears to have been eroded for a longer time than its neighbors. The slope is interrupted on the western side by a fairly well-defined bench whose surface is covered with wave-rounded pumice.

The bench stands at the same height as similar ones on the opposite side of Pumice Valley. These were cut by waves during the high-level stand of Lake Mono. In short, Basalt Hill is the only one of the crater series which has a shoreline on it.

The Basalt Hill, in all probability, is not a true part of the Mono Craters. As pointed out above, it stands to the west of the main axis, it is composed of an unrelated rock type, and probably was in existence as a low, rounded hill at the time of the earliest explosive activity in the Mono Craters.

Although the basalt is not in direct contact with any of the other igneous rocks of the region, it closely resembles the basalt exposed in scattered outcrops on the floor of Pumice Valley, as well as in the trough once occupied by the eastern tongue of Rush Creek glacier. The basalt is younger than the West Portal Rhyolite, which is exposed in the water tunnel, and also at "Pink" triangulation point. The relationship of the two rocks are described in the section dealing with the surface geology of the tunnel route.

The Northern Coulee

The Northern Coulee, named by Russell, is a steep-walled obsidian flow originating near the axis of the craters, and extending as a broad promontory beyond the normal eastern limit of the range. With its southern counterpart, these two coulees are among the largest recent obsidian flows in the United States. The Northern Coulee contains nearly 0.13 cubic mile of rock.

Figure 18

The Northern Coulee with Lake Mono in background. The white area is pumice over which the obsidian flow has advanced.

The Northern Coulee, while not so large as the southern, is fully as impressive, and because of the less rainfall, and consequently sparser cover of vegetation about its base presents an even more recent appearance. The area covered by the flow is nearly square, and is about 2 miles on a side. The coulee is not a single flow, but branches near the center to form two very distinct tongues, with a small cove between them extending back into the flow three-fourths of a mile.

Figure 19

Branching obsidian flows of Northern Coulee.

The Northern Coulee differs from the southern in that it is almost entirely restricted to the eastern side of the range. The only parts of the flow which reach the western side are two short lobes on either side of the ash cone in the central part of the western edge of the coulee.

The surface of most of the coulee is incredibly rugged. It is covered with heaped up blocks of obsidian which show little if any regularity of pattern in their distribution. These blocky accumulations presumably represent localized areas along fissures where the still fluid obsidian beneath was able to elevate the solidified surface. They are analogous in their origin to the spines about the margin of an obsidian dome.

Figure 20

Short flow of black obsidian on surface of Northern Coulee.

Where the surface was strongly fractured, black, fluidal-banded obsidian broke through, and either heaped up in short spines, or formed minute lava flows on the surface of the larger coulee. This banded obsidian on cooling acquires a rather distinctive platy form, especially if it is slightly pumiceous. In fact, this characteristic may be so well developed that the rock has a distinct parting, and may approximate a schist or roofing slate in appearance. With a further increase in the pumice content, the same laminated appearance results, but the rock exhibits a peculiar fluted appearance, resembling the ridges and depressions on the surface of a wind-eroded sandstone.

Figure 21

Fluted, pumiceous obsidian on surface of Northern Coulee.

A minor amount of obsidian appears on the summit of the coulee, compared to the quantity exposed on the parapet, or cliff edge of the coulee. The usually persistent cliff above the talus slope is diversified by minaret-like pinnacles of vitreous to pumiceous obsidian. In the spines the dip of the flow planes is surprisingly gentle, usually horizontal or inclined slightly inwards, although on occasion it may even show an outward dip.

The obsidian exposed above the talus, and underlying the blocky coulee surface seems to have been part of the once fluid interior of the coulee. As the flow moved forward and solidified rapidly, fragments were detached along the numerous fracture planes, and tumbled down to form the steep talus. This process is described by Russell[(14)] as follows:

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(14) op. cit., (8th Annual Rept.) p. 385

"The extreme ruggedness of the coulees is due to the fact that they hardened at the surface during the time they were still moving. The crust thus formed became broken and involved in the pasty material beneath in a most complicated manner. The steepness of the scarps formed at the ends and sides of the coulees was also due to the viscid condition of the glass composing them. In flowind down the sides of the craters the lava descended slopes that had an inclination of fifteen or twenty degrees, but only in the case of the great eruptions did the viscid streams reach the foot of the cones. In no instance did they continue their course for a considerable distance after leaving the abrupt slopes. * * * * * * * * * * * * * * *

Figure 22

The southern obsidian flow of the Northern Coulee.

"Had the lava been more liquid, the ends of the coulees would have been low and would have terminated in an indefinite way without forming scarps; but being viscid and flowing slowly they advanced with a precipitous front, but having a height of from two to three hundred feet. Before the edges of the coulees were broken and defaced by weathering they must have been perpendicular or perhaps overhanging. Even at the present day, after many blocks have fallen and the formation of a talus slope has commenced, the climber finds it extremely difficult to scale these rugged and broken escarpments of glassy fragments."

Figure 23

The north wall of the Southern Coulee. The obsidian has buried the pumice of the Northern Lapilli Area.

Many of the numerous spines are made of "obsidian breccia", composed of obsidian blocks cemented by a matrix of obsidian intruded between them. The wall of these spines are generally slickensided, and their surfaces have occasionally been glazed to a silvery, glassy skin. As in the similar examples described for Panum, this glazing is probably due to remelting by gases streaming through the numerous cracks between the blocks.

Figure 24

The precipitous front of the Northern Coulee

A great number of the obsidian blocks have been stained red by hematite or yellow by sulphur, and in some instances opalized. These secondary changes are the result of fumarolic activity, which seems to have reached its maximum along the western side of the coulee. The western part is the highest section of the flow, and overlies the source.

The central part of the western margin of the Northern Coulee is hidden by an impressive slope of volcanic ejecta which stands at the steep inclination of 35 to 39 degrees. This single slope is more than 900 feet high, and has a length slightly in excess of one half mile. Its remarkably uniform surface, both in color and declivity, is especially noteworthy. From a moderate distance it resembles a gray veil draped over an unusually smooth surface. Aside from a few scattered trees, and a number of isolated rock outcrops near the eastern edge, there are no interruptions to the monotone bluish-gray of its surface.

If this surface is viewed from the summit, the entire ash slope becomes a single line, with no part of it projecting above the general dead-level. Instead of being composed of uniformly graded flour-like ash, as one would imagine, the slope is made up of material including not only lapilli and ash, but also a sizeable fraction of rock fragments up to 8 - 9 inches in diameter.

Figure 25

Pumice slope covering the west side of the Northern Coulee.

Another extremely interesting ash deposit is on the opposite, or eastern, side of the coulee, and is especially well developed in the area where the virgation of the flow occurs. The surface of the ash is devoid of vegetation, and stretches away from the craters in a train of white desolation toward Lake Mono. It is a broad expanse of snow-white pumice, as a rule less than one inch in diameter, loosely spread over the surface.

Figure 26

Pumice blanket over western surface of Northern Coulee.

Figure 27

Pumice area partially covered by obsidian of Northern Coulee

The close connection between the distribution of this pumice and the position of the Northern Coulee appears to be more than coincidence. In appearance it is suggestive of the wasteland produced by the horizontal blast of 1915 at Mount Lassen, or photographs of the country devastated by the Nuee ardentes of Mount Pelee.

It may well be that this ash was blown out in advance of the coulee by a similar horizontal blast, or Glutwolken, immediately before the Northern Coulee was extruded. That the explosion preceded the outpouring of obsidian is indicated by the fact that the ash is buried by the lava.

The Central Area

The Central Area includes the craters between the Northern and Southern Coulees. In addition to being the center of the range, it is also the highest and oldest part of the true Mono Craters. The most distinctive features are the three prominent truncated cones in the middle of the area, and the explosion vents at the crest of the range, that occupy the saddles between the obsidian domes. There are no large coulees in the Central Area. The only one of any importance is about one quarter mile long, and is a minor feature on the flank of the central dome.

One difficulty in describing the features in this area is the complete lack of any local names. Although this same situation is true for the rest of the craters it is especially acute for the Central Area. The curious thing is that the highest peaks in the range are found here. They are quite distinctive, stand apart from one another, are visible from a great distance, and possess a rather unique appearance; yet so far as the author is aware they have never been named.

The one exception is the central peak. It is occupied by the triangulation station of "Mono", and will be called the Mono Dome in this paper. For the purposes of this report, the northernmost of the three central domes will be termed the Russell Dome, and the southernmost, ash-blanketed one, the Johnson Dome.

Figure 28

Mono and Johnson Domes in the Central Area of the Mono Craters.

Russell Dome

The northern peak in the triumvirate of blunt obsidian domes which crown the central part of the range is also the oldest. Its summit stands at a lower elevation than the other two, and is almost hidden beneath a thick covering of ash. The southern slope passes beneath the northern side of Mono Dome. On the other hand the northern flank of Russell is buried by the lava of the Northern Coulee.

Figure 29

Russell Dome from the surface of the Northern Coulee.

The summit of the dome is more completely blanketed by ash than the other two in the series. In fact, it is buried to such a degree that virtually no obsidian crops out on top, and little trace survives of a central depression. The ash is uniformly distributed over the southern slope, the side nearest the later explosion vents.

On top of the dome the ash is heaped in long windrows. Although much of it has been derived from the southern vents, a considerable quantity must be indigenous. Traces of what appear to be three explosion vents may be seen on the summit. Their age relationships are uncertain as they interfere with one another, and have been effaced by the wind to about the same degree as those in the Northern Lapilli Area.

For the most part the pumice covering the dome consists of silvery gray lapilli and ash with small pellets of obsidian interspersed throughout. The largest ejecta are found on the north and northeast rim, where occurs a distinct blanket, 10 to 20 feet thick, of sharp-edged, jet black obsidian fragments ranging up to six inches diameter.

with the obsidian is a fairly high concentration of accidental ejecta, in which angular fragments of granodiorite are dominant.

An insignificant amount of obsidian is exposed on the summit of the dome. The principal outcrop is on the eastern edge where a low rampart rises above the pumice. No prominent spines, similar to its southern neighbors, occur. The variety of obsidian exposed here is almost a counterpart of the characteristic type of Mono and Johnson Domes. It usually is a faint purplish gray or brown on the outside, light grayish-blue on a freshly fractured surface. The interior is distinctly pumiceous, with definite flow banding, best indicated by the parallel orientation of glassy sanidine phenocrysts.

From a distance, this same obsidian may be seen exposed around all margins of the dome, except the southern one. It is especially well developed on the north and west sides where it forms a well-nigh unscalable wall. As mentioned above, this obsidian fails to appear on the summit as it has been almost completely buried by the ash strewn across the crest of the dome.

It may safely be inferred that the Russell Dome is the oldest of the three in the Central Area. The evidence is 1.) the mature appearance, 2) the depth of burial beneath the pumice, 3.) and most significantly the lower elevation and inferior position with respect to Mono Dome.

Mono Dome

This peak is the highest, and at the same time most impressive dome in the Mono Craters. Its castellated circular summit, and smoothly sweeping lower slopes are strongly suggestive of a turret, or a fortification of the type of Hadrian's Tomb.

The mountain is a nearly cylindrical plug, with a depressed, pumice-filled crater, ringed by obsidian spines. The obsidian pinnacles at the summit of the dome give way at a lower elevation to long concave slopes that hide the foundation on which the dome rests.

Figure 30

Summit of Mono Dome

Part of this foundation may be revealed in the short coulee on the western side of the dome. It is difficult to tell whether or not this is an outbreak from the flanks of Mono Dome, or whether Mono Dome has been superimposed on it. The evidence would seem to favor the last hypothesis. At least it is clear that the outpouring of lava in the coulee preceded the activity of the explosion vents south of Johnson Dome. Another part of the foundation of Mono Dome is the nearly obliterated remnant of a former obsidian dome, whose eastern wall still crops out above the pumice in the lapilli area between Johnson and Mono Domes.

The actual Mono Summit is dish-shaped, and is encircled by spires and pinnacles of gray to light purplish-brown, blocky obsidian. This rock has a pumiceous texture and includes numerous sanidine phenocrysts. No trace of obsidian, in the ordinary sense of the word, is found in place, but fragments of it are scattered through the lapilli.

The spines ranged about the central depression are made of loosely piled, angular blocks, and resemble cairns more than they do any natural structure. They are produced by the collapse of spines similar to those still preserved intact on the summit of Panum Dome. The highest one is in the central part of the east rim, and rises distinctly above its neighbors to 9169 feet, the greatest altitude in the range.

Figure 31

Obsidian spines on summit of Mono Dome

The central depression is so deeply buried under an accumulation of lapilli and ash that little may be told of its original appearance. The presumption is strong that it was comparatively shallow, and was lined in much the same fashion as Crater 3.

That the intrusion of the obsidian plug in the Mono Dome was preceded by episode of explosive activity is indicated by the partially buried lapilli cone on the south flank. The lapilli rim is covered by the central dome on the north and east sides, but the south and west margins survive as a crescent-shaped ring.

The explosion pit, occupied by Mono Dome, is about equivalent in time, but possibly slightly later than an even larger pit midway between Johnson and Mono Domes. Although there is some reason to believe that the larger vent may have been active during the emplacement of the Mono Dome, the balance of evidence indicates a slightly earlier age. The larger vent is cut by the tuff cone at the base of Mono, which itself is older than the obsidian dome occupying its center.

The relation Johnson and Mono Dome bear to one another is difficult to determine as the two areas are not in contact. Both may be regarded as approximately coequal. There is no question that Mono is more recent than Russell Dome, and following the same line of reasoning, Johnson also is probably younger than Russell.

Johnson Dome

Johnson Dome rises to an almost equal height with Mono, and with the exception of a somewhat greater covering of ash makes an almost identical appearance. The two domes stand in rather pleasing symmetry at the very apex of the range, and are placed quite near its center. Aside from the greater covering of ash, there is little to distinguish between the two. The mode of origin is the same, the rocks in each dome are similar, and both were formed nearly simultaneously.

The top of Johnson Dome is surmounted by the same type of castellated rim as that of Mono, although in this case it is somewhat less obvious because of the deeper blanket of ash. As a consequence, the cairn-like accumulations of obsidian blocks do not rise so high.

Figure 32

The pumice blanketed slopes of Johnson Dome seen from Mono Dome.

The obsidian cropping out about the margin is the same pumiceous, flow-banded, porphyritic variety. It often has a well developed platy habit, somewhat similar to the examples for the Northern Coulee. For the most part the flow planes have a very gentle dip, usually directed radially towards the center of the dome.

The ash blanket on top of the dome is especially interesting. The coarse, sandy ash and lapilli are arranged in parallel waves, with the steep side to the east. These waves seem to advance in serried ranks across the crater floor. The wind has shown a certain selective effect in their formation. The front slopes are usually silver-gray with pumice fragments dominant. The back slope, where the force of the wind is most effective, has a greater concentration of heavier obsidian fragments. These are left as a residue in much the same fashion as the "desert pavement". The variegated color pattern produced by this wind action gives a singularly pleasing effect.

These waves advance up the western slope of Johnson Dome, cross the crater, and disappear over the eastern and northern rim. The pumice derived from the explosion vent at the southwest base of Johnson, was hurled completely over the summit of the crater. Since the time of the explosion it has been aided in its migration by the prevailing southwest wind. Some of the waves have a height of 2 to 3 feet, and a length of 5 to 8 feet.

Figure 33

Wind formed waves in pumice on summit of Johnson Dome.

Mono Dome in background

The beautifully involved patterns formed by the differential stripping away of the ash blanket by the wind are a pleasure to see. The alternating bands of light and dark colored ash swing in broadly flowing curves, closed figures, eye-like shapes, etc. very similar to those seen on water-marked silk.

Figure 34

Pumice covered western slope of Johnson Dome and explosion pit at base.

Explosion Pits

Two large and recent explosion pits occur in the summit area between Johnson Dome and the Southern Coulee. The more impressive of the two lies to the west of the main divide, and is at the southwest base of Johnson Dome. The second, almost midway between the dome and the coulee, stands practically on the center line of the range, and several hundred feet above and to the south of the first pit. Of the two vents, the lower at the base of Johnson Dome seems slightly younger, although there is little reason not to believe that the two may have been in simultaneous eruption.

No solid obsidian is visible in either of these pits. They are deep, conical depressions, lined on both the walls and bottom with unconsolidated ash and lapilli. The two pits are probably the finest examples in the range of the first, or explosive, stage in the formation of an obsidian dome. The next event, had the sequence been completed, would have been the appearance of a small obsidian dome on the floor of the lapilli cone.

The ejecta in these cones is comparatively small, and mostly pearly-gray pumice, jet black obsidian, and small (2 to 3 inch) angular, but unstriated, granodiorite fragments. The lapilli and ash have been cemented along bands, where a flour-like, dusty powder appears on the surface. The powder is gritty, and gives off a faint sulphurous odor. The direction of the prevailing wind has exercised a marked control over the distribution of this pyroclastic material. The upper explosion pit has a long windrow tailing out behind it for over a half mile. This dune-like accumulation of ash extends as far as the base of Johnson Dome, and even reaches part way around the eastern side of the dome. As mentioned before, the two pits may be considered as contemporaries of one another. That they postdate the rise of Johnson Dome is shown by the fact that the ash from the two pits blankets its surface.

Figure 35

Upper Explosion Pit with Southern Coulee in background.

Figure 36

Lower Explosion Pit at the base of Johnson Dome.

The remaining problem bearing on the time of their origin is whether they are earlier or later than the obsidian outpouring of the Southern Coulee. That the period of explosive activity responsible for these pits preceded the appearance of the Southern Coulee is shown by the following:

1.) A view from the east, looking towards the chain of craters, shows that the obsidian of the Southern Coulee rests upon the ash blown out of the explosion pits.

2.) Fragments of black, flow-banded obsidian from the last flows on top of the coulee have been hurled out on the surface of the ash.

3.) None of the ash rests on the obsidian.

4.) The characteristic black obsidian ash of the last explosive phase of the Southern Coulee covers the white pumiceous ash from the explosion vents.

The Southern Coulee

The Southern Coulee is the greatest single outpouring of obsidian in the range. In actual area the Northern Coulee is nearly equal, but does not extend down both sides of the range like the southern one. The Southern Coulee has an approximate volume of 0.16 cubic mile of rock.

The obsidian in the Southern Coulee has not issued from a single vent, but has reached the surface along a fissure. This fissure is near the axis of the range, has a north-south trend, and is in line with all the other important volcanic centers, both domes and explosion pits. The fissure is slightly more than three fourths of a mile long and is surmounted by spires and pinnacles.

The largest spine is at the extreme southern end of the center line of the coulee, and dominates the southern rampart. This spine rises little more than 100 feet above the surface of the coulee, and is composed of blocky, brownish obsidian, often brecciated. The walls are slickensided and the whole structure closely resembles the classic spine of Pelee.

Figure 37

South rampart and central spire of Southern Coulee.

There is a strong family resemblance between the two coulees. In both instances the surface is covered with a bewildering array of angular, sharp-edged blocks. There have been occasional outbreaks of black obsidian through the block lava, notably on the surface of the eastern half. Fumarolic activity has been of some importance near the central fissure, and large areas are frequently stained red (hematite), yellow (sulphur), and pale yellow-green (opalized).

One of the later events in the history of the Southern Coulee was a short-lived paroxysm of explosive activity during which black to dark gray obsidian ash was blown out from a number of small vents. Most of these are near the center of the flow on its north side. The steel gray ash has built up a long slope which is draped over the northern rampart on its west side. The dark ash resulting from the series of short-lived explosions on the coulee covers the lighter colored pumice from the two explosion vents between Johnson Dome and the Southern Coulee.

Figure 38

Craggy surface of Southern Coulee, central spire in distance.

That this explosive interlude was not the last event in the history of the Southern Coulee is shown by a rather distinctive obsidian flow near its southern side. This flow starts near the crest of the coulee and extends across the coulee surface down to and beyond the western scarp. The significant thing is that no ash covers the surface of the recent obsidian flow, although it occurs on both sides of the remainder of the coulee surface. Other similar recent flows have occurred, especially on the eastern side, where a layer of black, flow-banded obsidian rests upon the blocky obsidian underneath.

One of the interesting features of the Southern Coulee is the fact that it provides a means of correlating the volcanic and glacial records of the Mono Basin. The scarp at the end of the western part of the coulee rests upon the lateral moraine of the Rush Creek Glacier.

The superposition of the obsidian on the morainal material indicates that the Southern Coulee is post-middle Pleistocene. Since no shorelines of Lake Mono cut the escarpment of the Southern Coulee, there is every reason to believe that it is later and is late Pleistocene or early Recent.

Figure 40

Figure 41

Spines on parapet of Southern Coulee

The Southern Area

The Southern Area is more accessible than the northern. In spite of the lower altitude and less rugged nature the succession of events in this district is difficult to work out. This area includes the section of the Mono Craters between their end and the south wall of the Southern Coulee. The area is rather conveniently divided into two sections by the road constructed along the route of the aqueduct by the Bureau of Water Works and Supply. To the north of the road are tow rather distinctive, blunt-topped, pumice-covered domes which will be termed the Southern Craters. On the summit of the southernmost of the two is located the West Control point for the tunnel line. South of the road is a group of craters, domes, and explosion pits, closely related to one another. These will be named the Punchbowl Group, after one of the better known members, the Devil's Punchbowl.

The Southern Craters

The two craters south of the Southern Coulee are about the same age, and are obviously older than the Coulee which buries nearly half of the northern one of the two. The barrier imposed by the Coulee makes it impossible to work out their relationship to the Northern or Central Areas.

Figure 42

Northernmost of Southern Craters partially buried by Southern Coulee.

Presumably the Southern Craters are in much the same age group as Crater 6 at the northern end. There are no coulees connected with them, and the dominant type of obsidian is the grayish-brown, sanidine bearing variety rather than the blocky, pumiceous sort found in Panum or the two main coulees.

The northernmost dome is buried on its north side by the Southern Coulee. On the eastern margin it is flanked by a prominent tuff embankment, which reaches a maximum height of 500 feet on its eastern side. The tuff ring and the moat separating it from the central dome are cross-cut by the Southern Coulee.

Figure 43

Summit of Northernmost of Southern Craters, Southern Coulee in background.

The tuff ring is lacking on the west side of the central dome which has cut across it. This cross-cutting relationship, in addition to nearly unifrom western tilt of the surface of the obsidian dome, suggests that it is a combination dome and coulee, and is an older example of the type represented by Crater 3.

Figure 44

Shattered obsidian spines on northernmost of Southern Craters.

The structure of these southern craters is made difficult to determine by the extensive cover of pumice. In the case of the northern one, the only indication of the central dome is the scattered cairns of obsidian blocks on its surface. Little trace survives of a central depression, and the presence of a stubby coulee is deduced largely from the external form.

The more southerly is the larger, and at the same time the younger of the two craters. It is quite an impressive sight when viewed broadside from wither west or east. Its bulk is hard to appreciate on account of the denser stand of trees on its slopes than on the side of its barren northern neighbors.

The tuff cone is best developed on the eastern side, due to the direction of the prevailing wind. It is on the summit of this high lapilli cone that the "West Control" station for the tunnel line is located. This outer lapilli rim, like those developed about the older craters, as Crater 3 includes many outcrops of gray, pumiceous obsidian with numerous sanidine phenocrysts. On the inner wall of this particular tuff cone, especially beneath the West Control station, the obsidian appears as ribs supporting the tuff ring.

Figure 45

The West Control Crater

The large tuff cone which makes a practically complete circuit of the Central Dome is nearly breached on its northwest side. The central depression inside the tuff ring is filled by a comparatively large obsidian dome. Superficially it resembles the northern one, with its scattered, blocky crags, the extensive blanket of ash, and rather flourishing stand of pines. The essential difference is the absence of a coulee. The dome is confined by its moat, and in this respect is a subdued replica of Panum. It maintains a conical shape to its crest, rather than a uniformly sloping summit. Its crest is surmounted by a small depression which in turn holds inside it a still smaller obsidian cone.

The relationship between the southernmost of the two southern craters and the one at a lower elevation on the opposite side of the tunnel road is surprisingly difficult to determine. This crater is occupied by a large caldera. At first glance it would seem a s simple matter to determine which cone overlaps the other, but on closer inspection it proves to be nearly an impossible task. After the evidence is considered it seems likely that the two cones were formed at essentially the same time and during a relatively short period. The balance of the evidence is inclined in favor of a slighly more recent age for the West Control Crater.

Figure 46

The Southern Craters and the domical profile of the Southern Coulee.

The Punchbowl Craters

This compact group of four distinct volcanic centers and two related explosion pits is the most accessible; and at the same time among the more interesting of the Mono Craters. They stand somewhat apart from the main group and have a more nearly east-west trend. Instead of paralleling the Sierra, their strike intersects the range, and they appear as a prolongation of the ridge forming the southern side of June Lake.

No coulees have formed in this group and only a comparatively small amount of obsidian has appeared in the two central domes. Most of the activity has been explosive and in these craters has reached its maximum effect. Evidence is available to show that these explosions continued into the late recessional stage of the last glaciation.

The craters in this group include the large pit crater south of the tunnel road, which will be named the Caldera, and obsidian dome west of it, the deep lapilli cone and obsidian dome known as the Devil's Punchbowl, and at the western terminus the End Crater. Associated with this group are two explosion pits, which lie south of the main group and are at the base of Deer Mountain.

The Caldera

This deep-throated crater is in many ways the most significant one in the Punchbowl Group; if not in the entire chain of Mono Craters. The reason for this importance is in the fact that the unusual depth of the floor of the central pit records a remarkably complete cross section of the crater. More may be learned of the internal structure of an obsidian dome from this crater than from any other.

From a distance the crater does not have a very imposing appearance. It looks much like a low tuff cone, somewhat higher on its northern than its southern rim. No solid rock appears on the outer slopes, which are composed entirely of loose lapilli and ash covered with a comparatively dense growth of sage brush.

Figure 47

Floor of main caldera. Rim of Secondary Crater on right side. Central Dome of Punchbowl shows in background.

The only departure from the profile of a normal tuff cone is the greater degree of truncation. The outer slopes leave a distinct impression on an observer that the upper part has been destroyed. This suspicion is confirmed when the rim of the crater is reached. From the edge of the apparent tuff cone is presented an altogether different view from that seen in any other crater. The summit is occupied by an exceptionally deep, flat-floored and vertical walled caldera. This deep depression is divided into two sections. The first and main pit is several times larger than the other and is the central part of the crater. It is flanked on its northern wall by the second depression which is a comparatively small, steep-sided explosion vent with obsidian walls.

Obsidian is exposed in vertical cliffs on the north and south sides of the main crater, but is lacking on the eastern and western ends. These slopes are blanketed with pumice. The eastern end rises as high as the rock-defended walls to north and south, but the western end is much lower and merges with the floor of the tuff cone to the south.

The total length of the caldera is 2000 feet, the breadth is 1700 feet, and it is 360 feet deep. The smaller satellite crater has a length of 800 feet, a width of 700 feet, and is 320 feet deep on the steeper northern side and 50 feet deep on the more shallow southern one.

Figure 48

Secondary Crater on west wall of main Caldera.

The greatest significance of this crater is the virtually complete picture given of the internal structure of a typical obsidian dome. The most favorable cross-section illustrating the structural pattern is to be seen on the nearly vertical north wall of the smaller crater.

Pale gray to pink rhyolite obsidian occurs near the bottome of the vent, and is exposed for more than half the distance up the walls. This rock shows well-developed flow banding a pinkish aphanitic to glassy ground mass with small phenocrysts of sanidine and quartz. The flow banding is especially well developed and in an outcrop gives the rock a laminated appearance. Although the rock is obsidian it very nearly approaches a rhyolitic texture, and may be spoken of as "intrusive obsidian", because of the fact that it solidified in the volcanic neck and not on the surface. At the base of the vent the flow banding of this so-called "intrusive obsidian" is vertical, and appears to have issued from a narrow orifice. At a middle point in the crater wall, the flow banding spreads outwards like the top of a sheaf of grain. It remains vertical in the center, but dips away from it in all directions near the margin of the column. At first this dip is fairly high with the inclination towards the center; then it becomes horizontal and finally near the edge of the dome the flow banding dips away from the center.

Another point of special significance is the relationship of this "intrusive obsidian" to the blocky, pumiceous form which crops out on the surface. The contact between the tow is sharp, and appears as a dark line around the rim of the crater. This line separates the pink or pale gray "intrusive obsidian" from the brown, pumiceous block form which stands in cairn-like conical heaps on the surface of all the other domes. The line of demarcation seems to consist of a band of the common black variety of obsidian. Frequently it is the cementing medium in breccia composed of angular fragments of the "intrusive" form. At other times a type with large spherulites up to one inch in diameter is common.

Figure 49

Dark line across center of picture marks contact between block and "intrusive" varieties of obsidian.

The black obsidian band may be thought of as a cooling surface, somewhat akin to the under side of the slag layer in a reverberatory furnace; or to use a more homely example, the area underlying the crust on a loaf of bread. Above this band the obsidian solidified rapidly and in the presence of an abundant supply of gas developed a pumiceous texture. Below the line the lava cooled slowly in a more confined space and acquired a more vitreous texture with well developed flow banding. Where cooling occurred at a slow enough pace, incipient crystallization started and went to near completion.

Figure 50

Vertical flow-banded "intrusive obsidian". Black spot is fumarolic area. Fissure leading to it may be traced down crater wall to isolated pine tree.

Over the center of the vent where the stream of lava moved vertically, the black obsidian band almost intersects the surface. It presumably is in such an environment that the black vitreous form of obsidian is most readily forced to the surface through the fractures in the block lava. Also at the same point, where the "intrusive obsidian" most nearly approaches the surface, the pumiceous, block obsidian is stained red and yellow by fumarolic deposits. In fact, these colors may be traced down the sides of a fissure wall into the vertically banded "intrusive obsidian".

In summary: where the fluid obsidian beneath the solidified crust moves with a maximum upward velocity it is able to penetrate the greatest distance towards the surface. With it is carried the greatest volume of gas, which on escaping through the fractured zone overlying the ascending obsidian gives rise to fumarolic activity.

The problem of determining the manner in which the caldera was formed is a rather difficult one. This crater differs from any other in the Mono Craters in the size and nature of the central depression. Instead of a conical pit lined with unconsolidated ash and lapilli, its walls are nearly vertical and are composed of solid rock. Obviously, a large quantity of material has been removed to form this crater. The problem is to determine whether this material has been removed by subsidence, or whether it has been blown out by explosions.

Russell[15] apparently favored the idea of subsidence, as indicated in the following passage.

"Another crater of scoriaceous rock, * * * * * * * occurs near the southern end of the range. The peculiar form of this circular depression is perhaps to be accounted for on the assumption that molten rock rose in a bowl of lapilli and then subsided, leaving the level floored basin now to be observed."

The evidence for the subsidence of a dome in the area now occupied by the caldera is not clear cut. There are no step faults about the periphery and little to indicate that the central area has been down-dropped. Unfortunately most of the proof that subsidence has not occurred is negative, and a conclusion could not be reached. It may well be that a combination of both explosion and engulfment has occurred.

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(15) op. cit., (8th Annual Report) p. 382.

The reasons which may be advanced in opposition to the subsidence hypothesis are listed below:

1.) The top of the obsidian exposed in the north and south cliffs is buried beneath 30 to 50 feet of volcanic ash. This same ash also covers the entire outer slope, and gives the original obsidian dome, the appearance of a lapilli cone. The ash was produced by a series of explosions which are post-intrusion of the obsidian.

2.) The secondary crater on the rim of the larger is clearly explosive. The only difference between the two is in size. In appearance they are nearly identical.

3.) The lack of any of the features commonly associated with subsidence is of some signifance. There are no circular peripheral faults, partially collapsed segments etc.

4.) The collapse of large areas of volcanic ground seems to be best developed in basaltic shield volcanoes. The disturbance of equilibrium is not so great here, as in the case under broad piles of nearly horizontal layers of basalt.

5.) The mushroom shape of the intrusive makes subsidence rather difficult mechanically. The obsidian is keyed into place in much the same fashion as a dam of the type of Boulder Dam.

6.) Explosions have been a common event in the history of these craters, both before and after the obsidian is emplace. No other clear example of large-scale subsidence was found.

Before deciding whether explosion or subsidence has been dominant it should be remembered that volcanic eruptions are complex affairs, and it may well be that both were operating concomittantly. If the dome which formerly stood over the space now occupied by the caldera is older than the two domes to north and south, it may be that part of its lava reservoir was drained away at the time the other two were formed. As a consequence of this removal of support from beneath a certain amount of collapse may have occurred. More important, perhaps, was the opportunity provided by the opening of additional space beneath the dome for gas pressure to build up until it exceeded the confining pressure of the comparatively unsupported cover. According to this compromise hypothesis, the caldera was produced by a combination of subsidence and explosion with the last process the ruling one.

The Central Dome

The obsidian dome, which stands in the space between the arms of the crescent formed by the breached western wall of the Caldera, may be termed the Central Dome of the Punchbowl series. It is almost as fine an example as Panum of a lapilli encircled obsidian dome. The principal difference from Panum is the less complete lapilli ring, and the older appearance of this tree-covered dome.

Figure 51

Spines on summit of Central Dome.

The reddish obsidian dome is a nearly perfect circle with a diameter of 1500 feet and rises 220 feet above its base. There is a well defined depression at the summit surrounded by obsidian spines. Crossing the summit depression are three distinct obsidian ridges which are aligned with the principal axis of the range. The depression is filled in to some extent with pumice, which also mantles the talus slope around the base of the dome.

The lapilli rim is of great interest as a connecting link between this crater and the Punchbowl and Caldera. On the east side the lapilli ring crosses the breached wall of the Caldera, and thus is younger than the Caldera. The relation on the western side between the lapilli cones of the Central Dome and the Punchbowl is more complex. The two lapilli rims intersect opposite the western edge of the Central Dome, and both appear to have formed simultaneously. It cannot be demonstrated conclusively that one cuts the other and from a study of the tuff cones no decision except that they are contemporaneous can be made.

In determining the relative age of the craters, the relation of the two obsidian domes may be of more significance than were the tuff cones. The obsidian dome on the floor of the Punchbowl is smaller than the Central Dome, which has buried both the north rim of the Punchbowl and the north side of smaller dome. There is little question that of the two obsidian domes the Central Dome is the younger. On the basis of the greater recency of the Central Dome, it might be argued that its lapilli cone is more youthful than the Punchbowl Crater.

The Devil's Punchbowl

The Devil's Punchbowl, true to its name, is a bowl shaped lapilli cone. It is a small, but almost perfect, example of an explosion pit with a nearly circular rim and steeply sloping walls. The pit has a diameter of 1200 feet and depth of 140 feet. The walls slope at an angle of 36 degrees towards the center, and produce an almost symmetrical funnel.

At the bottom of the crater is a very small obsidian plug. Its base is about 250 feet long and it rises 40 feet above the floor. The dome is composed entirely of reddish angular blocks, heaped up in a double-humped cairn nearest the eastern end of the crater. It is this small dome in the Punchbowl which is partially buried by talus of the much larger Central Dome.

Figure 52

Obsidian Dome on the floor of Devil's Punchbowl

The crater gives every appearance of comparative recency. The outlines of the lapilli cone are distinct and have undergone scarcely any modification by erosion. The lapilli cone is clearly older than the late Pleistocene, pumice-floored lake whose shoreline cuts the eastern slope. It is younger than the lateral and terminal moraines of the Rush Creek glacier immediately west of it.

The End Crater

The last dome of the true Mono Craters series is only one half mile from the base of the Sierra, and also forms the west side of the Punchbowl. A pumice-buried obsidian dome, it resembles the Central Dome, except for the lack of a lapilli ring and a smaller amount of obsidian exposed on the surface. It is a truncated, steep-sided cone which rises 180 to 200 feet above a base 2000 feet in diameter.

No obsidian crops out on the surface, with the exception of the one small ridge on the northern side of the summit on which the triangulation station of "Punchbowl" is located. The obsidian exposed here is the gray pumiceous variety with sanidine phenocrysts and forms a blocky ridge oriented in the same direction as the craters trend.

The center of the cone is slightly depressed, but the summit is so blanketed with pumice that it appears more like a tableland. This pumice has probably been derived from the explosion of the Punchbowl Crater. This explosive eruption was clearly a later event that the building of the End Crater Dome, which is deeply indented on the side next to the Punchbowl.

Age Succession of the Punchbowl Craters

From the discussion of the individual craters in the preceding sections it may be seen that the age succession of the Punchbowl Craters is far from being an orderly progression along a definite fissure. Rather the focus of volcanic activity has shifted rapidly from one vent to another, and in at least one case was operating from at least two simultaneously.

In the subjoined table the succession of eruptions are listed in as nearly their proper order as may be inferred from the evidence, with the oldest event placed at the head of the list.

1.) (Building up of Caldera Dome
(
(Building up of End Crater Dome.

2.) Explosion to form the Caldera.

3.) Explosion of Punchbowl and intrusion of obsidian dome.

4.) Explosion of Central Dome Crater at about the same time as (3) and formation of Central Dome.

5.) Weak explosions in the Caldera Crater.

Deer Mountain Explosion Pits

Five hundred feet south of the End Crater is the northermost of two small explosion vents at the base of Deer Mountain. While these two maaren are not on the trend line of the Mono Craters they are clearly part of the same volcanic province, and have participated in the same period of activity. They occupy a critical position; for they not only serve as a connecting link between the Mono and Inyo Craters, but also indicate something of the structure of Deer Mountain as well.

The surface of Deer Mountain is buried beneath a surficial covering of pumice which effectively conceals the rock structure, except at the very summit where granite and a scattering of metamorphic rocks crop out. At the western base of the mountain, horizontally bedded rhyolite is exposed in the eastern wall of both explosion pits. The shape of the mountain, with a gently sloping eastern side, an abrupt western one, and a linear pattern for the base of the western escarpment is suggestive of a fault block.

The evidence is far from conclusive, but when the distribution of rocks in the mountain, and the presence of explosion pits at the base are considered, the idea of a

Figure 53

Main explosion pit at base of Deer Mountain. Arroyo draining into it on left side. End Crater in background.

fault paralleling the western side of the mountain does not seem to be an untenable hypothesis.

As stated before, these explosion pits bridge the gap between the Inyo and the Mono Craters. The Mono Craters are ranged along a curving arc, with the convex side facing eastward, or away from the Sierra Nevada. Near the middle of the bow the axis of the range trends North-South. At the southern end this trend has changed to ENE, and the Punchbowl

Craters prolonged would strike into the Sierra Nevada on a course paralleling the south side of June Lake.

The Deer Mountain explosion pits and the Inyo Craters show less curvature in their trend, and follow a north-south line which intersects the Mono Craters at their western extremity at End Crater. Whether the two volcanic axes actually intersect could not be determined, but the evidence is quite strong that they do. The distance separating the explosion pits from either the Mono or the Inyo Groups is slight, the period of eruption seems to have been identical in both groups, and the lava appears to have come from either the same or closely related sources.

The two explosion pits are steep-walled, elliptical depressions, oriented along a north-south line. No obsidian domes appear within them, and they belong to the pre-intrusive stage of the eruptive cycle. The walls of the pits are made of sloping ash, lapilli and accidental ejecta. The non-explosive products reach the greatest size found in any of the craters, and in the smaller pit are over ten feet in length. These exceptionally large fragments are rhyolite, and have been blasted from the sides of the pit by the explosions. Rhyolite forms the eastern wall of both pits and is the typical block jointed West Portal variety. It is through this volcanic cover that the gas column responsible for the _maaren_ was forced to drill its way to the surface.

The northern of the two pits is on the southern side of the Punchbowl-Benton road. An elliptical pit with a breadth of 1800 feet measured on its axis, it has a north-south orientation. The pit, 180 feet deep, has the highest wall on the eastern side. The western wall is lower, and is composed entirely of lapilli and ash, in distinction from the steeper eastern side along which a 50 to 60 foot cliff of rhyolite crops out.

The western side of the crater has been breached by a deep arroyo which permits the water accumulating in the Pleistocene lake basin to the west to drain into the pit. As a consequence, the lake floor is now being dissected by the trunk arroyo and its branches, while at the same time the floor of the crater is building up and has also become quite flat.

This has a significant bearing on the problem of the crater's age. As mentioned above, the eastern side of the crater is higher than the western, and is built entirely across the floor of the Pleistocene lake that paralleled the southern side of the Punchbowl craters. It looks very much as if the lapilli wall had been built high enough on this side to act as a barrier across the lake. The western rim, being on the windward side, was less successful, and was unable to keep the water of the cut-off portion of the lake from spilling over the lowest part of the lapilli rim and from cutting an arroyo through it into the crater. If this interpretation is valid, it means that the series of lakes on the eastern and southern side of the Mono Craters was in existence at the time of the last outburst of activity and that this last activity occurred during late stages of the Wisconsin (Tioga) glaciation.

The southernmost of the two pits is closer to the base of Deer Mountain and is so secluded in the trees that it might readily escape notice. It is smaller than its neighbor, with a diameter of 400 feet and a depth of 50 feet . It is a double pit, with a small northern and larger southern depression. These are probably indicative of two explosions with the last and most violent, the one responsible for making the southern section.

As was also true of the northern crater no obsidian is to be seen in place. All the walls, save the western one are cloaked in pumice; and it is a nearly vertical cliff 30 feet high made of rhyolite. This rock occurs in large blocks bounded by widely spaced joints and has readily succumbed to the force of the explosions which cleared the pit. Many large blocks of rhyolite litter the floor of the crater as well as the slopes about the rim. Some of these fragments hurled some distance up the crater wall are more than 4 feet in diameter.

To recapitulate; (1) These craters represent one of the final phases in the volcanic record of the Mono Craters. (2) They are probably contemporaries of the late Pleistocene or early Recent Lakes which formed a nearly continuous chain to the east and south of the craters. (3) The explosion pits are important as a link between the Inyo and the Mono Craters, (4) and they may also indicate the presence of a fracture of considerable magnitude at the foot of Deer Mountain.

The Inyo Craters

The Inyo Craters are closely related to the Mono Craters in their similar position along a fracture system at the base of the Sierra, in their identical time of eruptions, and in the consanguinity of their rock types. The Inyo Craters are a group of tuff cones, and unusually well developed obsidian domes, which center about Glass and Deadman Creeks, west of the highway at Crestview Station. With the exception of the northernmost two, the group was not investigated.(16)

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(16) After this study was completed the following article on the Inyo Craters was published:

E. B. Mayo, L. C. Conant, and J. R. Chelikowsky, "Southern Extension of the Mono Craters, California." Amer. Jour. of Science, Vol. XXII, No. 188. p. 81-97, August, 1936.

These authors show that the two systems of craters are related, as was pointed out in the preceding section dealing with the Deer Mountain explosion pits. Wilson and the North Inyo Craters in this paper are equivalent to Crater 1 and 2 in their terminology.

The two northern craters are of special interest because of their nearness to the Mono Group, and because they are exceptional examples of obsidian domes without tuff rings. In this respect they resemble Crater 3, except that both are larger, more isolated, and several times more impressive. Both are west of the highway, and the northernmost, Wilson Dome, is so close that the road would pass through its center if it did not swerve around its base to avoid it.

Wilson Dome

This dome is named for the triangulation station of "Wilson" on its summit at an altitude of 8494 feet. The dome is a nearly perfect circle at its base with a diameter of 2300 feet. It rises abruptly in a craggy peak, flanked by talus, and stands 450 feet above an undulating and forested plain about its base. It is 5500 feet due south of the southern Deer Mountain explosion pit, and 8600 feet south of the End Crater. The dome is a spectacular sight in its isolation, and it is rather difficult to tell with which group it is allied.

Figure 54

Wilson Dome

Russell considered it as separate from the Mono Craters although Williams (17) describes it in a section dealing

(17) <u>op. cit.</u>, (Univ. of Calif. Bull., Vol. 21) p. 78

with the Mono Craters, as follows:

"Immediately to the south of the highway, separated from the main group of the Mono Craters by a broad, pumice-strewn flat, rises another dome, already mentioned as devoid of traces of an earlier tuff cone. This dome excels in the distinctiveness of its structures, for although the lower half is mantled by long slopes of talus, the top bristles with solid pinnacles in which the attitude of the flow-planes can be readily seen. Except toward the periphery, the banding dips steeply inward or is vertical, but marginally it has a low inward dip, lies flat or even dips outward at small angles. In this dome also the concentric structure is emphasized by many short, arcuate ridges of blocks, in addition to which there are straight ridges that run between the summit pinnacles in dike-like fashion, suggesting the rise of lava along fissures. Notewrothy, too, is the fact that several of these straight ridges are aligned parallel to the trend of the Mono Craters. The impression given by the surface of the dome is, therefore, of obsidian having risen along a series of more or less rectilinear and crescentic fissures, reaching its maximum elevation at the intersections of the fissures where it formed summit spines."

The writer agrees with this statement, with the exception of the trend of the summit ridges in a direction parallel to the Mono Craters. If any parallelism is present, it is primarily crescentic. Most of the obsidian is heaped in cairn-like piles of jagged blocks. Some of these suggest a rude north-south orientation which might be considered as paralleling the trend of the Inyo Craters, but this apparent effect may or may not be of significance.

The North Inyo Crater

The North Inyo Crater is a large obsidian dome and almost circular coulee, with no indication of an earlier explosion pit in evidence. It may be considered as an obsidian dome which has sprawled out sluggishly in all directions away from its center in the absence of any restraining influence.

This obsidian outpouring has a maximum breadth of slightly more than a mile, and rises 500 feet above its base. It stands about one mile due south of the Wilson Dome, and is an almost equal distance west of the highway from which it is rather effectually screened by the forest. The crater is completely encircled at the top by an abrupt, overhanging parapet above the steep talus. The summit stands at a nearly uniform elevation, although it rises in all directions from the periphery towards the center. No words, however, can convey an impression of the chaotic irregularity of the upper surface. The jagged crests, cairns, ridges and depressed areas in their

Figure 55

Surface of North Inyo Crater.

extraordinary freshness more nearly simulate a lunar landscape. It is a harder task to cross the surface of this dome than either of the two coulees.

One reason for the extreme ruggedness of this dome is the relatively greater amount of black, vitreous obsidian. This rock type, as in Panum, shows every gradation from a pure glassy variety, into a gray pumiceous, flow-banded form. About the edges of the flow, the attitude of the obsidian is almost horizontal, and it is often inclined outwards. Spines and pinnacles are common; in fact, unusually perfect examples of all the features described for the Mono Domes and Coulees are present on this dome.

Figure 56

Horizontal flow-banded obsidian in parapet of North Inyo Crater.

The Wilson and North Inyo Domes are among the most recent of the eruptions in this region, and are probably equivalent to Panum and Crater 2 at the northern end of the Mono Craters. Both Wilson and Inyo Craters rest on the pumice which covers the surface of the entire area, including the glacial deposits, and as a consequence have no volcanic ash deposited on them.

Related Volcanic Rocks

Closely associated with the Mono Craters, although not an integral part of them are two volcanic rocks. These are the rhyolite flows which center about the West Portal camp, and the craggy basalt which rises through the bed of the eastern branch of Rush Creek Glacier. The rhyolite is especially significant as the foundation for the Mono Craters, and is the most common rock type revealed in the West Portal branch of the Mono Craters Tunnel. The basalt is of interest because of its intimate connection with the glacial record. The complete investigation of the related eruptive rocks is outside the province of this paper, but it is a problem which the author hopes to take up in the future.

The West Portal Rhyolite

The West Portal Rhyolite crops out in the Eolian Buttes, and along the crest of the ridge occupied by "Crag" triangulation station, and in a number of isolated pinnacles at "Pink" triangulation station. It is also the dominant rock exposed in the tunnel as far as Heading 1 had been driven up to August 1, 1936.

The rhyolite in surface exposures is a pinkish rock although light gray phases are not uncommon. It is divided into large blocks by well-defined vertical joint planes. There is a rude indication of a layered structure, but the vertical joints are the dominant type of fracture. Where the rock crops out in an exposed position, particularly where it is attacked by the wind, it forms fantastic crags and isolated pinnacles, often fluted by wind erosion. It was for this reason that Russell applied the name Eolian Buttes to the prominent ridge between West Portal and the highway.

The rhyolite has an aphanitic ground mass, often quite tuffaceous. It contains numerous inclusions, many of which are lenticulat shreds of obsidian, while others are pumiceous fragments of rhyolite. Most of these inclusions show a parallel orientation, and are practically horizontal.

They are particularly noticeable underground. Many gas vesicles are present and give the rock an unusually porous texture for rhyolite. These cavities are sometimes quite large (2 to 3 inches) and are generally lens shaped. In many exposures the rock has a distinctly agglomeratic texture, and is a loosely bound mixture of rhyolitic mud with angular fragments cemented in it. The visible minerals in embedded phenocrysts are quartz, sanidine, hornblende, and various ferromagnesium minerals.

The age relationship of the rhyolite is of particular significance. In a road cut on the main highway, a few feet south of the branch road leading to West Portal Camp, the rhyolite may be seen resting upon glacial till. The same phenomenon is also visible in the tunnel where the rhyolite rests upon a boulder clay. There also is little question that its upper surface has been glaciated, particularly in the vicinity of "Crag" triangulation station. Also, the rhyolite below "Red Butte" in the Eolian Buttes has been cut by the high-level shorelines of Lake Mono. The conclusion which may be drawn from this evidence is that the rhyolite was extruded during an interglacial epoch, and probably during a comparatively early one.

Black Butte Basalt

This basalt is named for the prominent reddish-black double butte which rises near the middle of the former bed of the eastern fork of Rush Creek Glacier. The basalt crops out in a series of small knob-like tumuli in the low area between the lateral moraines occupied by "Crag" and "Long Ridge" triangulation stations to NW and SE, and the highway and the Southern Coulee to NE and SW.

Figure 57

Basalt Crag in trough of Rush Creek Glacier.

These basaltic tumuli in the central part of the Rush Creek glacial trough penetrate glacial till. There is no indication of their glaciation as in the case of the breached cone north of June Lake. The outlines of the basalt crags are jagged and irregular, are not covered with glacial erratics, and only a comparatively thin layer of pumice is spread over them. Russell[18] considered them post-glacial.

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(18) op. cit., (8th Annual Report) p. 345.

The basalt is black, aphanitic, comparatively free from inclusions, and rather dense rock without many vesicles. It grades upwards near the surface of the lava into a reddish brown and finally brilliant red, scoriaceous variety with numerous cavities.

Where the tumuli have been opened up for road material the basalt is the scoriaceous variety, and is a loose clinkery mass brilliant red in color, and more closely resembling furnace slag than a lava flow.

This basalt may be a correlative of the Basalt Hill at the northern end of the Mono Craters. It is impossible to tell with certainty because of the distance separating the two exposures, but the resemblances between the two occurrences are greater than the differences.

SYSTEMATIC PETROGRAPHY

The rocks of the Mono Craters present few petrographic problems. They are almost exclusively volcanic glasses, either pumice or obsidian, and contain few determminable minerals. The related volcanic rocks are comparatevely simple rhyolites and basalts. The microscopic appearance of the various types of obsidian will be first discussed; than a description of the petrography of the Black Butte Basalt, the West Portal Rhyolite, and the Tunnel Granite will follow.

Mono Craters Obsidian and Pumice

Every gradation from frothy, silvery-gray pumice to jet black obsidian may be found, not only throughout the chain of Mono Craters, but also within the limits of a single vent. In general, the more pumiceous varieties occur most frequently, and except for Panum Dome, obsidian in the familar black, vitreous form is rare. The most common rock type is a purplish-brown pumice, with small (1-3 mm) phenocrysts of sanidine scattered through the groundmass. On unweathered surfaces this groundmass is silvery gray, and is composed of silky glass fibers. There is frequently more pore space than the glass, penetrated by tube-like gas channels. Flow structure is well developed, and is best indicated by the parallelism of the sanidine phenocrysts.

Pumiceous obsidian

The typical pumiceous form of obsidian consists basically of a clear, wholly isotropic glass. The glass was flowing turbulently at the time it solidified. The long glass shreds, pores, trichites, etc. preserve the complex pattern of whorls and eddies in the viscous fluid before it congealed. Some indication of the intricate designs to be found are indicated in Figure B, Plate IV. This example is from obsidian with a relatively small pumice content. Rocks that contain less obsidian have correspondingly more intricate textures.

Sanidine is the most abundant phenocryst, and may occur in large, isolated, embayed and corroded crystals, or in swarms of minute, parallel microlites. The larger variety is early crystallizing, has a weak conchoidal fracture, and about the same birefringence as quartz. The trichitic groundmass swirls about these larger phenocrysts in distinct eddies. Some plagioclase, with narrow twining striations, occurs, and is oligoclase. A few rounded grains of pyroxene are present, and very little magnetite. Opacite is abundant, and forms dark, dusty concentrations and spotted areas that are difficult to identify.

In some thin sections trichites are comparatevely rare, in others they are abundant. As is to be expected, there is every gradation from obsidian to frothy pumice, even within a single specimen. Long foils of yellow-brown biotite are fairly common where the trichites are most numerous. There is some evidence that the trichites may be incipient biotite crystals. At least the two are in fairly close association. The larger trichites are dark brown to opaque, and tend to form wavy clusters with a parallel orientation.

Platy Pumiceous obsidian

One of the characteristic rocks of the later obsidian domes and coulees is a grayish, platy form of pumiceous obsidian. The platy habit is so well developed that the rock simulates a schist or slate in the perfection of its rock cleavage.

The groundmass of this form of pumice is a brownish glass, and is less shredded by gas inclusions than the block variety. The gas vesicles are more oval in cross section that thread-like. Concentrations of opacite, cumulites, and acicular trichites are scattered through the groundmass. Occasionally the glass is double refracting, but whether this is due to a greater number of these crystallites, or is the result of strain could not be determined.

Swarms of feldspar microlites are distrubuted through the groundmass, and are mostly sanidine. Many of these skeleton crystals are interpenetrating twins. The majority of the microlites are narrow, prismatic crystals without distinct terminations. The more important phenocrysts are sanidine, embayed quartz, resorbed flakes of biotite cut normal and parallel to the cleavage.

The percentage of these minerals determined by inspection is,

Glass	80%
Feldspar microlites	11
Sanidine phenocrysts	5
Biotite	3
Quartz	1

which may be compared with the percentage determination for pumiceous obsidian from the Inyo Craters by Mayo (19).

(19) op. cit., (Amer. Jour. Sci.) p. 86.

Glass	73%
Plagioclase	14
Sanidine	6
Dark red biotite and basaltic hornblende	4
Quartz	3

Intrusive obsidian

The intrusive variety of obsidian is found in the walls of the secondary crater on the west side of the Caldera. It is a pale gray to pink rock with an aphanitic ground mass enclosing euhedral glassy sanidine phenocrysts. The texture of the ground mass is transitional between obsidian and rhyolite. It is made of yellowish-brown glass, interpenetrating quartz and feldspar microlites, and might be called microcrypocrystalline. The rock is either a partially crystallized obsidian, or a hyalorhyolite. It is grouped with the other varieties of obsidian because of the close genetic relationship.

The most unusual feature of the ground mass is the presence of large spherulites which flow lines in the ground mass penetrate without interference; an indication of their late origin. Most of them are bordered by a dark rim of opacite, the interiors are lighter colored than the outside area. Many spherulites show two or more periods of growth, with a less well developed outer rim and a distinct inner kernel. The spherulites are made of straight, radiating fibers, probably of tridymite and feldspar.

Sanidine is the most important phenocryst. It has two, and possible three, occurrences. The first is in the numerous microlites scattered through the ground mass; the second, in a few large corroded phenocrysts; and the third, in a great number of small spherulitic bodies which are later than the large spherulites mentioned above. They have sharp boundaries, and appear to be gas cavities filled during a late stage in the solidification of the rock. Between crossed nicols the cavity fillings have an extinction closely resembling the pseudo-uniaxial cross of chalcedony. They also show much the same type of aggregate structure, and about the same, or slightly lower, birefringence (0.005). In some cavities, several nuclei have developed, and the radial fibers growing from separate centers interfere with each other. At times a single crystal is surrounded by a fringe of radial fibers. These spherulites occasionally seem to be micropegmatitic, and may include free silica. If this is the case, these smaller spherulites, formed in the last phase before consolidation, are intergrowths of feldspar (probably sanidine) and tridymite. Occasional microlites of biotite penetrate the spherulites.

The next important phenocryst is biotite, both in long narrow crystals and partially resorbed flakes. No large crystals of quartz were detected, but it is probably present as intergrowths in the ground mass and the spherulites.

Obsidian

The black vitreous variety of obsidian is sparingly represented in the Mono Craters. Aside from short flows on the surface of the coulees and Panum Dome, its most important occurence is in the form of accidental ejecta in the lapilli covered areas. It is uniformly black, has an excellent conchoidal fracture, and is translucent in thin flakes. The rock is composed of clear glass, completely isotropic, and almost entirely free of any crystalline substances. A few crystallites are found occasionally, and are either unidentifiable globulites, or skeleton crystals of feldspar. Several flakes of reddish brown biotite may be encountered. The gas cavities in the dense obsidian are minute, and almost circular in contrast to their attenuated form in the pumiceous varieties.

In slightly pumiceous obsidian there is a marked increase in the quantity of trichites. The ground mass is crowded with a multitude of short, hair-like fibers oriented in one direction. There may be also an increase in the size of the feldspar microlites, and they are recognizable as sanidine.

Composition

Had these rocks been permitted to crystallize, they would probably have formed rhyolite. This is shown in their composition by their relatively high silica content. The refractive index for the obsidian of the Inyo Craters, as determined by Mayo[20] ranges from 1.490 to 1.496±0.002, which gives a silica value of 72 - 74%.

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(20) Op. cit., (Amer. Jour. Sci.) p. 86.

Published analysis for rhyolitic obsidian and pumice form the Mono Craters confirm these values.

The two obsidian analyses are high in silica, low in lime, and have the relatively large amounts of soda and potash expectable in a rhyolite. The low silica content of the pumice is somewhat surprising. Albite, orthoclase, and oligoclase might have formed at the expense of quartz, had the rock been allowed to crystallize, and produced a trachyte or keratophyre.

	A	B	C
SiO_2	74.05	67.39	73.84
Al_2O_3	13.85	15.99	12.47
Fe_2O_3	) tr.	.56	.32
FeO	)	1.99	.90
MgO	.07	.77	.25
CaO	.90	1.63	1.08
Na_2O	4.60	4.74	2.88
K_2O	4.31	4.80	5.38
H_2O	2.20	2.06	2.76
	99.98	99.93	99.88

A. Scoriaceous obsidian. Analyst, T. M. Chatard
8th Annual Report, p. 380

B. Rhyolite pumice)
C. Rhyolite obsidian) Analyst, T. Melville, U.S.G.S., Bull. 150, pp. 148-152, 1898.

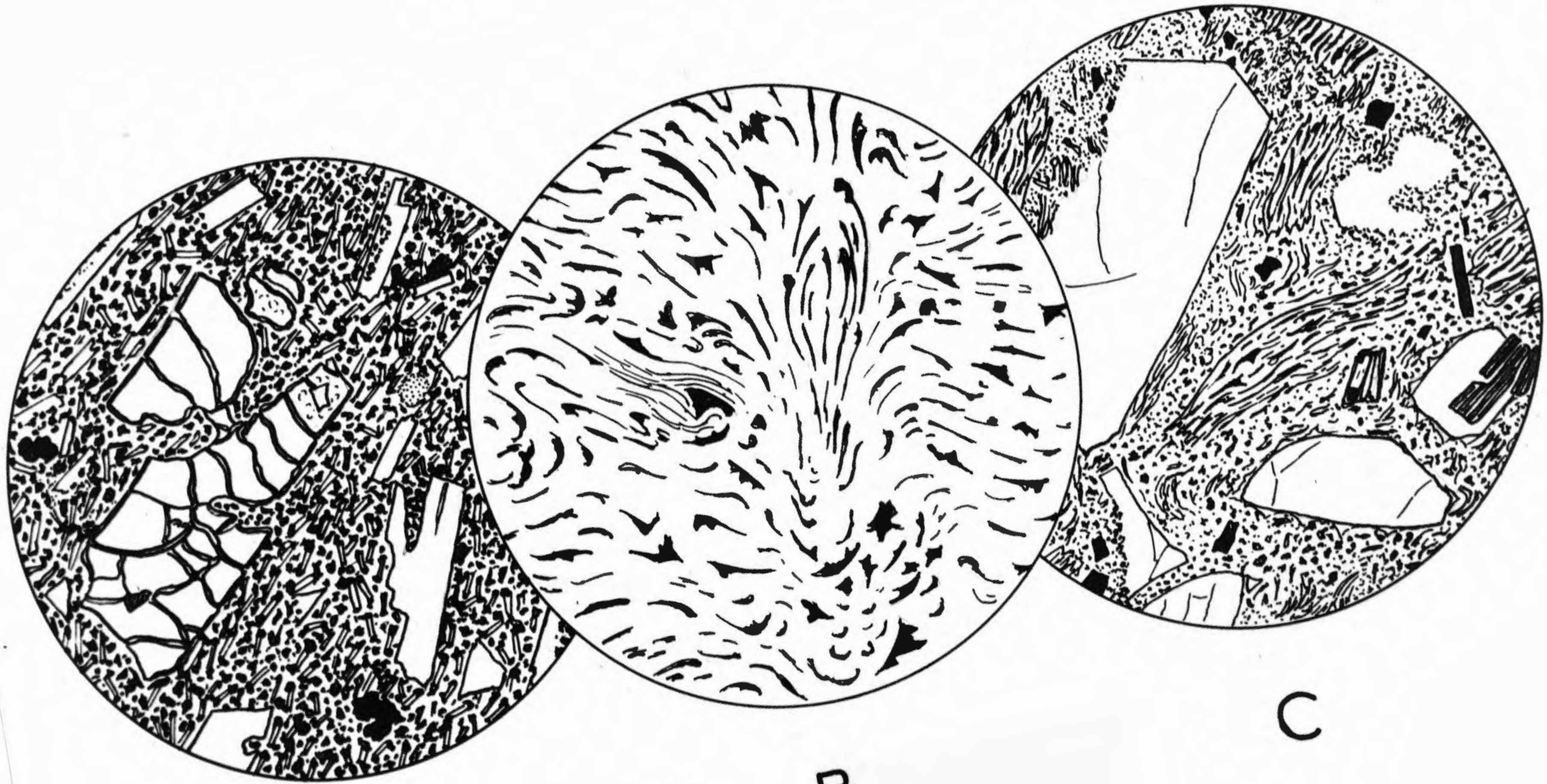
Plate III

A. Black Butte Basalt from the type locality. Phenocrysts of olivine and augite are set in a microlitic ground mass.

B. Pumiceous obsidian from Panum Dome.

C. West Portal Rhyolite from "Pink" triangulation station. Sanidine and biotite phenocrysts are set in a cryptocrystalline ground mass. The large glass inclusions are a characteristic feature of this rock.

Plain light



A B C

Related Rocks

None of the related rock types were studied in detail, as they are outside the main problem of the Mono Craters. Their primary interest centers about their relationship to the glacial record.

Black Butte Basalt

The Black Butte Basalt crops out in the former trough of Rush Creek Glacier, and a related type is found in Basalt Hill in the Central Lapilli Area. The rock is almost uniformly black, with an aphanitic ground mass in which plagioclase phenocrysts may be recognized. In the tumuli, the basalt grades into a brilliant red, scoriaceous phase at the surface.

No scoria is found in Basalt Hill, and the rock is quite dense, although occasionally riddled with vesicles. This is the rock J. P. Iddings identified for Russell as a hornblende andesite in the following description [21] ;

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(21) op. cit., (8th Annual Report) p. 379.

"The glassy, microlitic ground mass carries many small porphyritic crystals of reddish-brown hornblende and fewer of light brown hypersthene, augite, and reddish-brown mica with those of plagioclase feldspar. The hand specimen shows large glassy plagioclase feldspars."

Under the microscope the rock from Basalt Hill has a hyalopilitic to diabasic texture, with minute microlitic feldspar disseminated through the ground mass, which also contains interstitial glass. Moderate sized phenocrysts are numerous. For the most part, they are reddish brown biotite, olivine, augite, plagioclase, and magnetite. The plagioclase phenocrysts are lath-shaped, usually discrete, are zoned, and are medium labradorite (Ab). Magnetite is arranged in parallel bands through some of the plagioclase crystals. The plagioclase is twinned according to the Carlsbad and albite rules, with pericline twinning rare. Calcite is the only important secondary mineral, and is aboundant in some areas of the rock. The feldspar is fresh and unaltered.

The coarser ground mass of the basalt at Black Butte has less well developed eutaxitic texture, and is composed of small plagioclase and augite microlites. The darker color of the ground mass is due to the greater quantity of magnetite. This mineral is distributed through the rock in dusty, euhedral grains. The basalt from this locality is shown in Figure A, Plate IV.

The phenocrysts are more prominant than at Basalt Hill, and this is particularly true of the olivine. The labradorite laths are larger, show more zoning, and occasionally have a poikilitic texture. The characteristic prismatic, reddish-brown biotite of the Basalt Hill locality is superseded by faintly pleochroic rounded and resorbed flakes. The Black Butte variety of basalt shows fewer secondary changes, and no calcite was observed.

The West Portal Rhyolite

The greatest interest attached to the West Portal Rhyolite is its occurrence in the Mono Craters Tunnel. It is exposed for more than a mile in the tunnel, as well as in numerous outcrops in the Eolian Buttes.

At the surface the rock is usually pink, underground a nearly uniform greenish-gray. The most striking characteristic is the great number of lenticular obsidian inclusions. These are isotropic, flamboyant bands which bend around the angular phenocrysts. They are roughly parallel, and are elongated in the direction of flow. Some of them are shown in Figure C, Plate IV. The glass inclusions are usually pumiceous, and contain tube-like gas channels.

The ground mass of the rhyolite has a felsitic texture, and is made of yellowish-brown material. This seems to consist of a microscopic intergrowth of cryptocrystalline quartz and feldspar.

The phenocrysts are a prominent feature, and are large and euhedral. Most of them are clear sanidine, with a conchoidal fracture, rather difficult to distinguish from quartz. Quartz is present, but is not important among the phenocrysts. Most of the sanidine is twinned according to the Carlsbad law. Some polysnthetic twinned feldspar was found, and is oligoclase, averaging Ab . Biotite flakes are not numerous, some magnetite is included, and an occasional crystal of augite is encountered.

The most noteworthy features are; the numerous glass inclusions, the dark microcryptocrystalline ground mass, and the large sanidine phenocrysts.

The Tunnel Granite

With the exception of a small outcrop on Deer Mountain, no granite crops out in the area surrounding the Mono Craters. It is found in accidental ejecta, and in glacial erratics, but these occurrences are of minor importance. The only significant exposure is the one in the Mono Craters Tunnel between Stations 1114 00 and 1151 00.

The rock is a binary granite, is medium grained, and is usually mesocratic. It ranges from aplitic to coarsely crystalline. The essential and variental minerals are; orthoclase, quartz, oligoclase as calcic as Ab , and muscovite intergrown with biotite. The muscovite is clearly the later of the two. The brown biotite has altered to greenish chlorite along cleavage planes. The minor accessories are apatite, magnetite, and zircon. No hornblende was found, and is not to be expected in the presence of muscovite.

The granite has been weathered, as might be anticipated from its position in the tunnel. The surface of the plagioclase feldspar has been almost completely kaolinized.

GEOLOGY OF THE MONO CRATERS TUNNEL

between

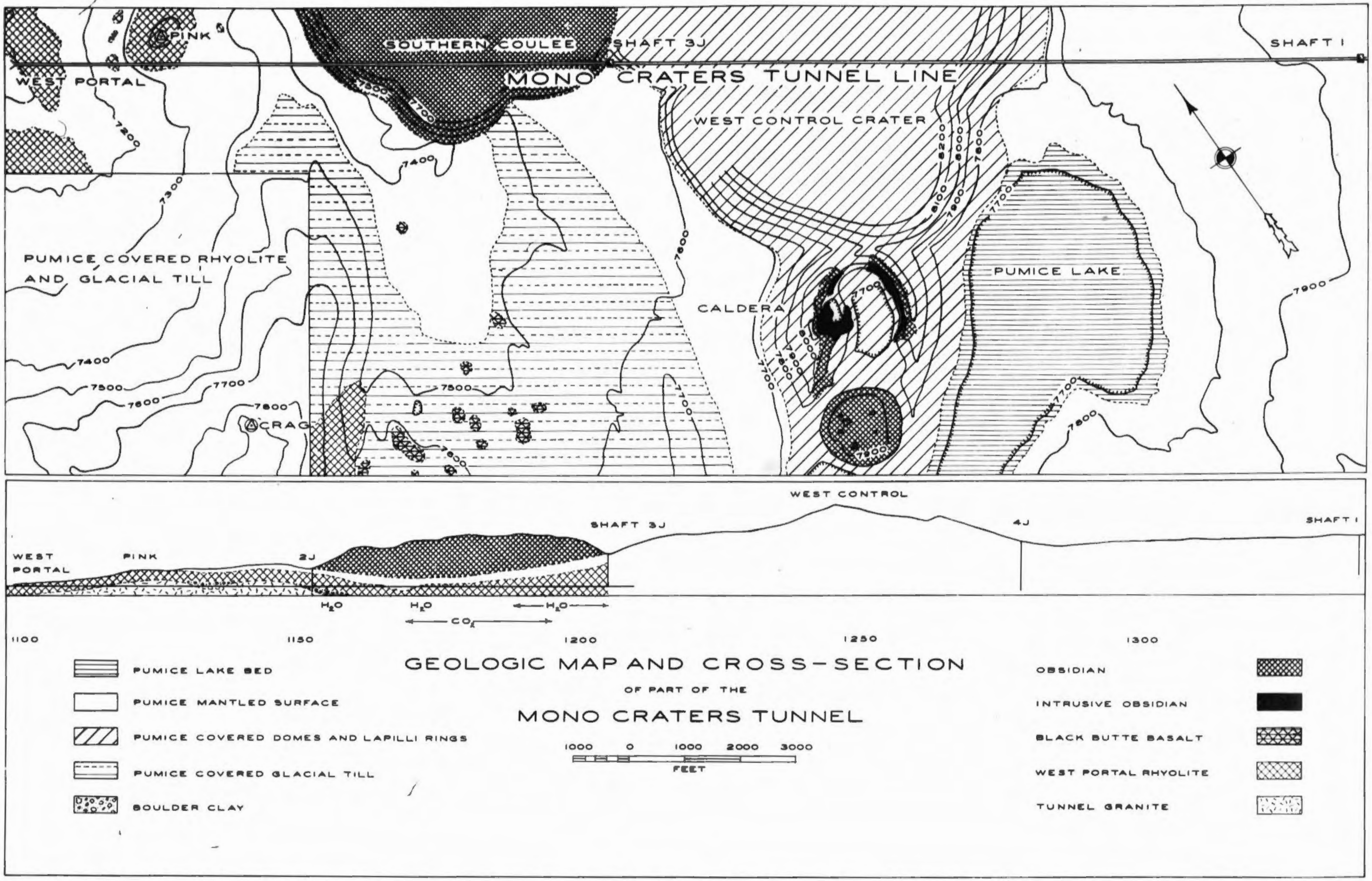
SHAFT 1 AND WEST PORTAL

The Mono Craters Tunnel is part of the Mono Basin project of the Los Angeles Bureau of Water Works and Supply. The tunnel will carry water from the Mono Basin to the headwaters of the Owens River where it will be impounded in a reservoir at Long Valley. The water will be supplied by the streams which flow down the east slope of the Sierra Nevada and empty into Mono Lake. The most important of these is Rush Creek, and an earth fill dam will be built across it on the terminal moraine at the lower end of Grant Lake.

It is expected that the project will cost more than $9,000,000. Work was started on December, 1934; by July, 1936 about 30,000 feet of tunnel had been driven, and the section between East Portal and Shaft 2 was holed through. The projected tunnel has a total length of 59,811.70 feet (approximately 11½ miles), and a gradient of 0.0005 per cent. In addition to the two portals, it was planned to sink two shafts to the tunnel line and to drive headings in opposite directions. Shaft 2 was finished with a depth of 299.1 feet, and the tun-

Plate IV

Geologic Map and Cross-section of the Mono Craters Tunnel



GEOLOGIC MAP AND CROSS-SECTION
OF PART OF THE
MONO CRATERS TUNNEL

nel between it and East Portal was completed. About 4,000 feet have been driven at Heading 4 towards Shaft 1.

Shaft 1

Shaft 1 has been a more difficult problem. Sinking ceased in it February, 1936, and no further progress had been made by August 1, 1936. When the shaft reached a depth of 763 feet, a large volume of water broke in, and, in one instance, surged up 200 feet. At the present time a series of lateral drifts driven from the shaft in opposite directions are joined by cross drifts to form a square with the shaft in the center. This is an attempt to tap a "watercourse". The flow of water has not increased appreciably and averages 500 G.P.M.

The lower section of the shaft is in water-saturated boulder clay. This deposit consists of sub-angular boulders, cobbles, and gravel set in a clay matrix. There is no apparent sorting, and little stratification is evident. The deposit is glacial till, with some glacio-fluviatile material included. The till belongs to one of the older glaciations, and probably can be correlated with Blackwelder's Sherwin Stage. The top of the glacial deposit is approximately 500 feet below the collar of the shaft, and is overlain by 470 feet of so-called "Rhyolitic tuff", and 30 feet of pumice at the surface. It was not possible to examine these uppermost pyroclastic deposits as they have been sealed off.

The Tunnel between West Portal and Shaft 1

Heading 1

The tunnel has not yet reached the central axis of the Mono Craters. Heading 1 has been driven about 12,000 feet from West Portal, and no work has been started on Heading 2, westward from Shaft 1.

Two great difficulties have hindered the driving of the West Portal section. These are, 1.) the large volume of water entering the tunnel, and 2.) the presence of CO_2 and SO_2 gases in quantities great enough to overcome the men.

Work stopped at Heading 1 for several months while an auxilary shaft was sunk at Drill Hole 3J. This shaft, with a blower installed at the surface, was completed at the depth of 535.5 feet. When the heading was reopened, an advance of 11 feet was made. As an even greater concentration of CO_2 and SO_2 was encountered, driving ceased. The tunnel is to be lined with corrugated sheet-iron to keep out the water, supposedly bearing the CO_2. The water will be led off to the sump through a covered ditch beneath the tracks.

Plate IV shows the geology of the surface area between Shaft 1 and West Portal, and a cross-section of the tunnel between West Portal and Shaft 3J. In the sections to follow, the geology of the tunnel will be described before the surface geology along the route.

Tunnel Geology from West Portal to Shaft 3J

The opening for the West Portal is at Station 1097+00, and was made in weathered, tuffaceous West Portal Rhyolite. This is a strongly fractured rock in its surface exposure, and has been weathered to a depth of more than 50 feet along joints.

1097+00 to 1115+00 (1868' from W.P.) The West Portal Rhyolite is exposed in the tunnel throughout this distance. The rhyolite retains the pinkish color of its surface exposures in the Eolian Buttes. A grayish phase is dominant about Station 1100+00. The rhyolite is markedly agglomeratic at Station 1115+00, and remains so up to the end of the exposure. The rhyolite is weathered throughout the length of this section, and at the eastern contact is 180 feet below the surface. There is reason to believe that much of this weathering occurred between the Tahoe and Sherwin glacial stages, as it was covered by drift after the Tahoe glaciation.

Two fracture zones with large angular blocks are found at 1109+00 and 1112+00. No water enters this section, for this part of the tunnel is above the water table.

1115+68 to 1133+32 (3632') The rock exposed between these stations is a binary granite, and will be named the "Tunnel Granite". It is a medium grained rock with little visible quartz, an abundance of biotite, some muscovite, and a sugary texture. The western half of the exposure is prevailingly leucocratic, and the rock is aplitic. In the eastern part of the section, the rock becomes increasingly melanocratic, and at the same time coarser grained.

The granite has a blocky fracture, with three well-defined joint systems. Near the center of the exposure the rift is almost horizontal. The tendency of the back to spall off in tabular blocks has made the granite more difficult to support than was anticipated.

The western contact of the granite with the rhyolite slopes approximately 8 degrees west, and the eastern nearly 11 degrees east. The granite is weathered at both contacts. The western is covered with a tuffaceous, mud-flow phase of the rhyolite.

1133+32 to 1138+00 (4100') This part of the tunnel exposes a section of boulder clay. It is an unconsolidated deposit of angular, block-like boulders set in a matrix of plastic clay. The boulders are completely unsorted and unstratified.

One large one spans the tunnel from one side to the other, a distance of 11 feet, and is 5 feet broad. What the height, or total breadth might be is impossible to determine.

Most of the boulders are dark plutonic rocks and appear to be dioritic and gabbroic rather than granitic types. This dominance of darker rocks is characteristic of the older tills in this area. The surfaces of the boulders are unweathered, and although no striae are visible many boulders seem to have had their surfaces smoothed. This till underlies the West Portal Rhyolite, which has been glaciated.

1138+00 to 1151+00 (5400') Between these points the same type of blocky biotite granite reappears that was exposed on the opposite side of the boulder clay. The western contact of the granite dips 6 degrees west, and the eastern 8-9 degrees east. The granite is slightly darker than in the first exposure, but there is no essential difference between the two occurrences.

The granite exposed in the tunnel at both localities is a buried continuation of the eastern ridge of the Eolian Buttes. This is the ridge, occupied by "Crag" triangulation station, that forced the eastern branch of

Rush Creek Glacier to divide. The subsurface crest of the eastern ridge is outlined on the map by the 7400 foot contour. The western branch follows a line between "Crag" and "Pink" triangulation stations.

1151+00 to 1151+43 (5443')	A thin (8-10 foot) bed of boulder clay overlies the granite, and in turn is covered by pinkish-brown tuffaceous rhyolite. The eastern contact of the boulder bed dips 9-10 degrees east.
1151+43 to 1208+00 (11,100')	From Station 1151 to the gas bulkhead at Station 1208, the only rock exposed is West Portal Rhyolite, except for gray, unconsolidated pumice between Stations 1166+77 and 1171+00. This material, the consistency of loose sand, is bone dry, and rests on the

weathered surface of the rhyolite. In relation to the ground surface, it is under the lowest part of the trough occupied first by the Rush Creek Glacier, and later by the Southern Coulee. The pumice occurs where the inclination of the rhyolite surface carries it below the tunnel grade. The pumice dips 18° east at 1166+77 and 18° - 19° west at 1171+00.

The West Portal Rhyolite in this 5600 foot section of the tunnel, when wet, is a lead gray to dark grayish-green color. The ground mass is aphanitic. Fresh phenocrysts of sanidine sparkle brilliantly when they catch the light. The most unique feature in the appearance of the rock is the multitude of parallel, lens-shaped inclusions of jet black obsidian. These are horizontal and are the only visible evidence of flow banding in an otherwise unusually uniform effusive rock.

The rhyolite is penetrated by many fractures. Most of these are closed, but near the western end of the tunnel a number are open and have a width of 2-4 inches. Although there are no large faults, almost all the fractures have slickensided walls. In many places the rhyolite is broken into large, angular, separate blocks which tumble down when unsupported. These shattered areas are sometimes 100 feet or more wide, and have been a hindrance in the progress of the tunnel.

The tunnel passes and continues beneath the western slope of the Southern Coulee at Station 1153 until Shaft 3J is reached. Water is first encountered at 1154, and the rhyolite shows the greatest degree of fracturing in the section under the coulee. In fact, the only fault with any significant displacement is at Station 1154+85, almost directly beneath the west parapet of the coulee. This fault strikes N 53° W and dips 84° SW. The slickensides on the fault plane are vertical.

Fracture Zones

The most prominent fracture in the tunnel is the fault mentioned above. Its strike almost parallels the tunnel line, which it crosses at an angle of 2-3 degrees, and it is exposed for a distance of 173 feet.

Another important fracture zone, at Station 1158+00, is related to the fault at 1154. Both fracture systems have a parallel trend, and are under the western margin of the coulee.

1164+00 and 1173 to 1176+00 — The rhyolite is broken into large angular blocks at both these localities, and is penetrated by many joints with iron stains along their walls. Both fractured areas at 1164 and 1173 are identical, as they are on opposite sides of the pumice section between 1166 and 1171. These fractured areas are in the former weathered surface of the rhyolite before its burial by the pumice. The fracture zone from 1173 to 1176 is the larger of the two, and has been almost completely lagged. This zone is important, for the first high concentration of CO_2 was encountered here, especially at Station 1175.

1189+00 to 1194+00 — Between 1189 and 1176 the rock is fractured almost the entire distance. At 1189 the rhyolite is broken into large blocks, exceptionally difficult to keep in place. There is a strong flow of water through all the joints, and much of it issues in jets between the separate blocks. The frequency of shatter zones increases between 1194 and the heading. The rocks are strongly fractured at 1193, 1199, 1202, and 1208.

These fractures probably formed at the time the rhyolite solidified, and are not the result of stresses applied by an external force. They are accentuated by the load of 700-800 feet of obsidian overburden. It is likely that these water bearing fractures will be encountered as long as the tunnel remains in West Portal Rhyolite.

Water

In addition to the highly fractured rock and the gas in the tunnel, the large volume of groundwater has hampered the driving of Heading 1. The quantity of water averages 4500 G.P.M., although it has risen above 5000 G.P.M. at times. All the water is pumped to West Portal, as the gradient of the tunnel is eastward. On one occasion the supply of water proved too great and work stopped until the tunnel was bailed out with auxilary pumps.

Water is first encountered at Station 1154, where the tunnel intersects the water table. This point is directly beneath the foot of the talus slope on the western side of the Southern Coulee. The water table rises beneath the coulee, until at Shaft 3J its surface stands at an altitude of 7245 feet, or 180 feet above the tunnel line. The water enters the tunnel through fractures in the rhyolite. The unbroken rhyolite is relatively impervious.

A curious feature in the distribution of ground-water in the tunnel is its absence in the pumice area between 1166 and 1171. Water is abundant on either side of this section, but is absent in the pumice. The tunnel is floored with dry powdery dust, and the walls have had to be lagged. The lack of water is due to the rapidity with which it sinks through the sieve-like pumice. The water table rises in the direction of Shaft 1. At Shaft 1 water was encountered at an elevation of 7451 feet, 400 feet above the tunnel grade. There is reason to believe that an increase in the volume of water may be expected as Heading 1 is advanced.

Carbon Dioxide

The problem of determining the actual source of the carbon dioxide in the tunnel is extremely interesting. The tunnel is is West Portal Rhyolite in the section where the gas has caused so much difficulty. This rock is middle Pleistocene in age, is deeply fractured, and has been exposed at the surface during the last two glaciations. Besides, the openings in the rhyolite are filled with water in the area from which the CO_2 comes.

Analyses of this water show that it contains CO_2. It is evident that the CO_2 is escaping from the water and may be seen bubbling through it where it collects on the tunnel floor. There is a high concentration of CO_2, about the main pumping station where a large volume of water stands in the sump. A visible fog, consisting in large part of CO_2 in mechanical suspension with water vapor is spread over the water surface.

The CO_2 is found in the section of the tunnel underneath the Southern Coulee. It may be anticipated that it will also be encountered under the West Control Crater. The source is not known, but the gas issues from the water filled joints in the West Portal Rhyolite. It may well be that the carbon dioxide is derived from this rock. Although the rhyolite has been exposed at the surface for nearly half the Pleistocene, a considerable residue of carbon dioxide may still be trapped. It is doubtful that the CO_2 percolates downward from the obsidian.

Surface Geology of the Mono Craters Tunnel Line between West Portal and Shaft 1

The area penetrated by the Mono Craters tunnel is a particularly critical one. This is the region where the glacial and volcanic records overlap, and the various events in the history of the craters may be successfully interpreted.

The surface distribution of the glacial deposits, and the various volcanic rocks is shown on the geologic map of the tunnel route (Plate IV). The tunnel line passes beneath the Southern Coulee, and on its present course will penetrate the center of the West Control Crater.

The surface of the entire area is covered with pumice derived from explosions in the Mono Craters. It was the last deposit to accumulate, and covers the glacial till. The pumice lake east of the Caldera existed during the last part of the latest glaciation. The fact that a lake existed with so porous a floor indicates that the water table then stood at an altitude of nearly 7800, instead of the present level of 7500 feet.

The glacial deposits of this area are the lateral moraines of the east branch of Rush Creek Glacier. The ice was divided by the Eolian Buttes and formed a horseshoe around them. The two lateral moraines of the eastern lobe are on both sides of the depression between the Caldera and "Crag" triangulation station. The Southern Coulee rests upon the eastern moraine. The moraines belong to the first part of the last glaciation, and in Blackwelder's terminology are in the Tahoe Stage.

The Black Butte Basalt crops out in the floor of the depression formerly occupied by the ice. Since the basalt is not glaciated, and penetrates glacial material, it is obviously younger than the Tahoe Stage. However, the same basalt has been glaciated a short distance northeast of June Lake. In short, the Black Butte Basalt was erupted during the time between the Tahoe and Tioga glaciations.

The West Portal Rhyolite has been glaciated, and the lateral moraines of the Rush Creek Glacier cover it in the Eolian Buttes. In the tunnel between stations 1133+31.57 and 1138+00, the rhyolite rests upon still older glacial till. This older till is probably Sherwin, although there is some possibility that it may be still older. The West Portal Rhyolite was erupted in the interglacial stage between the Tahoe and Sherwin glaciations.

The Tunnel Granite, the oldest rock in the area, is the foundation for the volcanic and glacial deposits. The granite in the tunnel is the buried extension of the ridge on the west side of June Lake.

The sequence of events in the geologic history

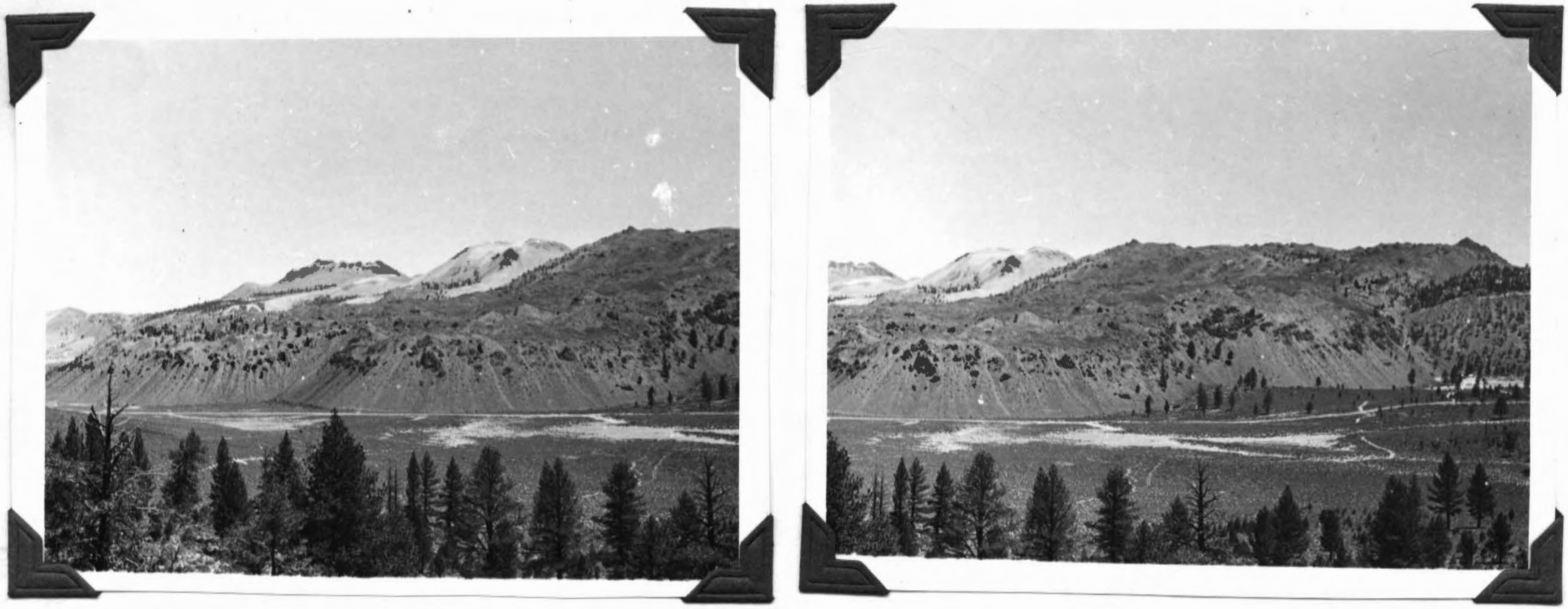


Figure 58

The Southern Coulee may be seen covering the eastern lateral moraine of the Rush Creek Glacier in the right half of the photograph. The small white spot at the base of the coulee, beyond the moraine, is Shaft 3J. The tunnel route passes under the coulee from Shaft 3J to the left margin of the picture.

of the southern end of the Mono Craters, as shown on the surface and in the Mono Craters Tunnel is as follows:

	Glacial Record	Volcanic Record
		Outpouring of Southern Coulee
Pleis-tocene	Pumice Lake	Eruption of the Caldera and the Punchbowl Craters
	Tioga	
		Black Butte Basalt
	Tahoe	
		West Portal Rhyolite
	Sherwin	
Jurassic		Tunnel Granite

SUMMARY AND CONCLUSIONS

Age Succession of the Mono Craters

Not only is it a difficult problem to determine the position in time of the Mono Craters as a group, but also the eruptive succession within the Craters is often hard to decipher. That the main activity took place in the Pleistocene is clear from the overlapping of the glacial and volcanic records, but how far back into the Pleistocene it extends is impossible to tell from the Craters themselves. The record of the earliest eruptions is buried by the later ones. That the volcanoes were active during the high stand of Lake Mono is shown by pumice layers intercalated with lascustrine deposits.

The close of the eruptive period falls near the end of the Pleistocene, and may extend into the early Recent. Its recency is shown by: 1) Pumice from these craters rests on the surface of moraines of the last recessional stages of the latest glaciation. 2) No shorelines cut the loosely consolidated lapilli ring of Panum Crater or girdle the steep face of the Northern Coulee. 3) The Southern Coulee rests directly upon the lateral moraine of the Rush Creek Glacier. 4) The Craters of the Punchbowl Series, and particularly the Explosion Pits were in eruption at the time the pumice lakes were in existence. 5) Streams have had no opportunity to furrow the slopes of the craters, which show no appreciable degree of either weathering or erosion. 6) Fumarolic stains are still fresh and unaltered.

This evidence indicates that the eruptions of the Mono Craters began to be important some time after the middle Pleistocene, and continued unabated until the close of the Epoch. The whole episode endured geologically for only a very brief time. The rapid rate at which domes, erupting in historic times, have been built bears out this supposition.

The order of events within the range is not a simple matter to work out. There has been no uniform progression of activity in one direction, as in the case of the Hawaiian or Samoan volcanoes; but rather a kaleidoscopic shifting from one vent to another. Furthermore several vents appear to have been active concurrently, and the span of time involved is so short that no significant differences in the amount of weathering or erosion are discernible.

In general, as Russell pointed out, the central part of the range appears to be the oldest, and last activity has been centered about the extremities. For the most part this is a valid generalization, but there are a number of notable exceptions. The most important deviations from the rule are the large coulees, which are very recent, and yet are located nearer the center of the chain than many older vents. On the other hand one of the oldest vents, Crater 6, is at the northernmost limit of the main group of craters.

The greatest difficulty to correlate the summit craters in an orderly sequence is the presence of the two coulees. These extend across the range, are recent features, and have buried the surface on which they rest. It is impossible to compare the succession of vents in the Central Area with those of either the Northern or the Southern ones. For that reason, the subjoined table of the succession of events should be considered as merely tentative. The order of the eruptions is listed from the most recent to the oldest, and each subdivision of the range is treated as an independent unit.

RELATIVE AGES OF THE MONO CRATERS

NORTHERN AREA	CENTRAL AREA	SOUTHERN AREA
Panum (1)		Wilson & North Inyo Domes
Crater 2		
Crater 3		Explosion Vents
Crater 4		
. . . . Northern Coulee	. . . . Southern Coulee	. . . .
	Johnson Explosion vents	Central Dome
	Mono and Johnson Domes	Punchbowl
	Mono Explosion vents	Caldera Explosion
Northwest Coulee (5)		Southern Craters
		Caldera Dome
Crater 6.	Russell Dome	End Crater
Northern Lapilli Area	Older domes and coulees	
	Black Butte Basalt	
	West Portal Rhyolite	

The Origin and Character of the Mono Obsidian Domes

It becomes apparent when a study is made of the Mono Craters that the majority of their volcanic features fit into a definite, recognizable sequence; a sequence of eruptive forms that starts with an explosion pit and ends with a coulee. Although this succession may not go to completion, and some phases occasionally may be lacking, the regularity with which a very definite order of events is repeated is surprising. In the sections to follow the eruptive sequence in an ideal case will be described, as well as the morphology and structure of the various volcanic forms.

Order of Eruption

The first phase of the type of eruption exhibited by the Mono Craters is usually an explosive one. The near approach of an obsidian dome to the surface is heralded by a series of explosions which produce a shallow, conical depression, shaped much like a gigantic shell-hole. The explosive phase is succeeded by the upwelling of a stiff, cylindrical column of obsidian to form a dome. Should the obsidian continue to rise it will eventually spill over the lapilli rim and form a blocky, steep-fronted coulee. Separate outpourings may coalesce to make what is virtually a fissure eruption, as for example, in the Southern Coulee.

Explosive eruptions may continue throughout this history, and are rarely violent enough to destroy much of the dome. As a rule, the most violent explosions are the first, and their intensity wanes as the dome expands. The appearance of the dome may be considered one of the last episodes in the history of a particular vent. When the dome is emplaced the conduit is sealed, and there is little likelihood of renewed activity.

Rate of growth

With the exception of the 1912 eruption of Novarupta, described by Fenner (22) no other eruption of an obsidian dome within historic time seems to have been described.

(22) C. N. Fenner, "The Katmai Region, Alaska, and the great eruption of 1912." Journal of Geology, Vol. 28, pp. 587-591, 1920.

Novarupta reached an altitude with the year of eruption of 200 feet above its 800 foot wide base. Williams [23] cites several examples of the growth of a number of famous domes.

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(23) <u>op. cit.</u>, (Univ. of Calif. Bull., Vol. 21) p. 141-142.

"After two years' growth, the dome of Santa Maria, Guatemala, had a maximum diameter of 1200 meters and a height of 500 meters, while at one period it rose as much as 100 meters in a single week. Within a year and a half, the dome of Mount Pelee attained a diameter of about 1000 meters and a height of some 400 meters, despite the fact that it suffered repeatedly from disastrous explosions. In one day it increased its height by 25 meters. Tarumai rose 100 meters during the first four days, and 200 meters within the first two weeks, when its basal diameter was 420 meters. The dome of Galunggung, Java, was 130 meters high and 400 meters wide at the end of three weeks, while Graham Island grew to a geight of 65 meters and attained a circumference of 3700 meters within the same period. Finally, the recent domes, McCulloch Peak and Metcalf Cone, in the Bogoslof

Islands, were each elevated about 150 meters above the sea and had a basal width of more than 600 meters, ten months after they first appeared."

By comparison with these rates of growth, although none of these are obsidian domes, a dome as large as Panum, with a height of 230 feet, might well require less than a week for its construction. Much less than a month would suffice for Wilson Dome, with an altitude of 450 feet if the rate at which Santa Maria grew is not far from the average. Mono Dome, which is slightly more than 2000 feet above Pumice Valley, would require less than a year if it grew at the rate of Mount Pelee; and the likelihood is that it would exceed Mount Pelee's rate, as it probably grew more quietly. Actually the dome may have required less time than a year for it is superimposed on an older dome and coulee. That these estimates are not unreasonable is borne out by the length of five years which Williams suggests for the construction of the much larger dome of Mount Lassen.

Morphology

In this section the characteristics of a typical lapilli cone, obsidian dome, and coulee will be described.

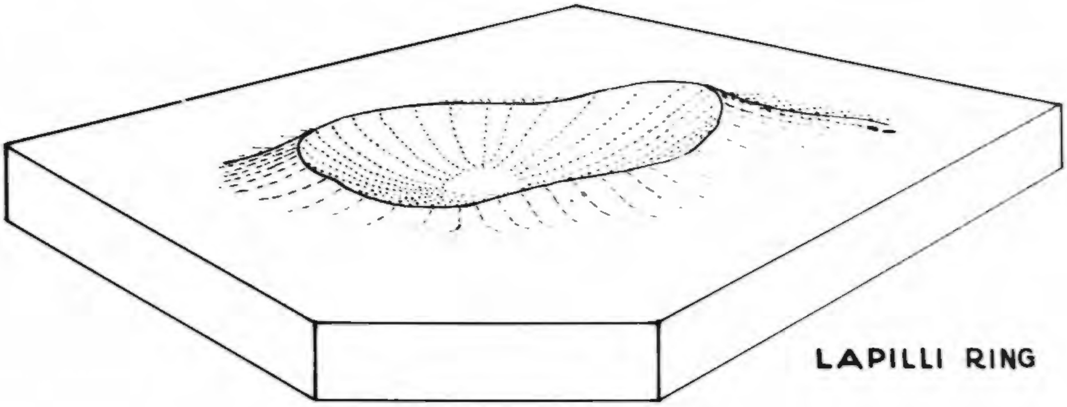
Lapilli Cones

The average lapilli cone is a nearly circular depression, with steep walls that slope down in all directions to form a conical pit. Frequently the apex of this cone lies beneath the level of the surrounding country. The inner wall is usually steeper than the outer, and stands at an angle between 35 - 38 degrees. The direction of the prevailing wind exerts a strong control over the distribution of ash outside the crater. The rim is higher on the leeward side, and usually has a long "tail" or windrow pointing away from it down wind.

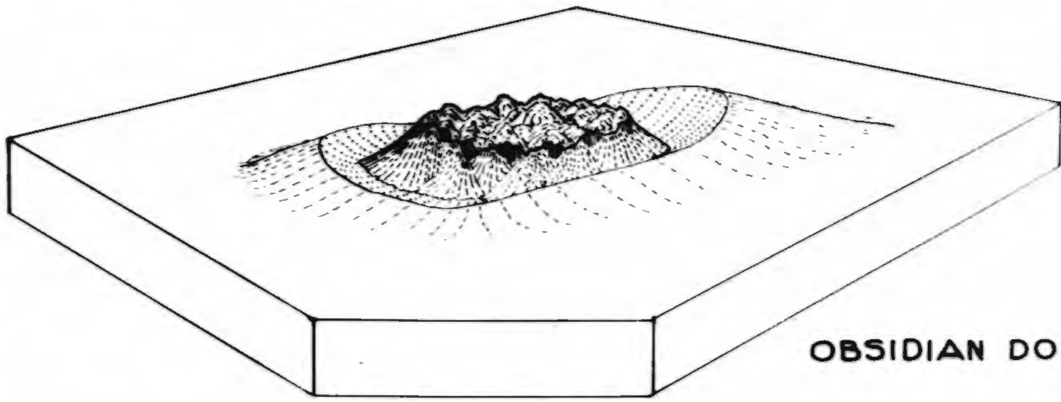
Most of the material visible in both the walls and rim of the lapilli cone is volcanic, and has the same composition and origin as the material in the obsidian dome. For the most part it consists of frothy, silvery-gray pumice and angular fragments of black, vitreous obsidian. This

Plate V

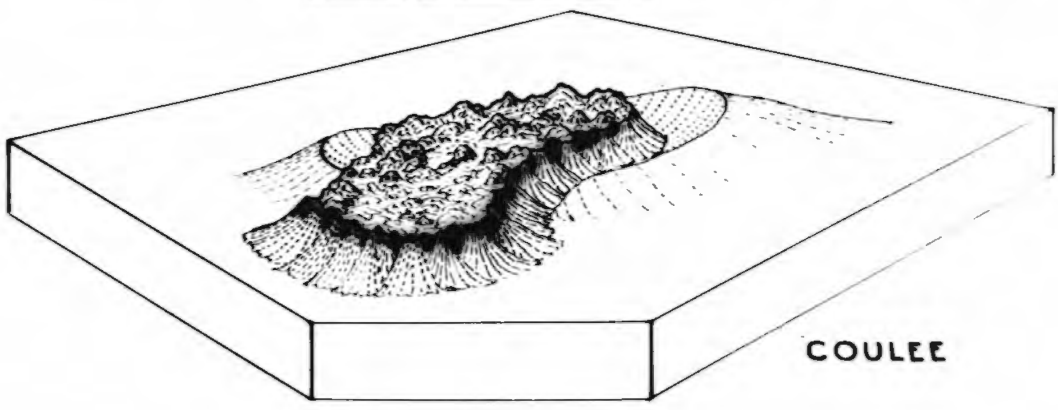
Morphologic Development of an Obsidian Dome



LAPILLI RING



OBSIDIAN DOME



COULEE

material has obviously been derived from the same source as the dome which will later occupy the floor of the pit. Of less quantitative importance, but greater interest, are the angular fragments of the country rock which have been blasted to the surface. None of these "accidental ejecta" give any indication in their appearance of the vicissitudes they have endured, and are not fused nor altered. Nor for that matter, do any of the glaciated fragments show striae.

Obsidian Domes

The typical obsidian dome would probably have a nearly cyclindrical shape if the talus cover were to be stripped away. The ground pattern is usually circular, and the exposed sides are nearly vertical. The visible section of an obsidian dome may be divided into three separate units; the upper surface, the parapet, and the talus slope.

The upper surface is a region of crags, spines, pinnacles, and heterogenously jumbled accumulations of sharp-edged obsidian blocks. As a rule there is little recognizable pattern, and few generalizations are valid for this area on all domes. If anything, the more recent spines are most likely to be near the periphery, and the central part is often depressed below the level of the outer rim.

The spines are strongly jointed, and this jointing is their undoing in the course of time. They break down into cairn-like accumulations of angular blocks (breche d'ecroulement). Occasionally these blocks may become autobrecciated if they are recemented by obsidian injected into the numerous interstices, (breche d' epanchment). In the surviving pinnacles the outer margins are frequently slickensided, and along the edges of crevices are glazed where remelting by streaming gases has occurred.

The Parapet is the nearly vertical outer wall overlooking the talus slope. It often bristles with precariously balanced spines, which are poised on the brink of destruction. It is in this area that most of the vitreous obsidian occurs, and here it usually has a very gentle dip either towards or away from the point of issue. The vitreous form of obsidian underlies the blocky variety.

The Talus Slope is made up of the large, angular blocks which have tumbled down the slope as the obsidian pushing out at the parapet has become overbalanced. These ubiquitous talus slopes are as much a primary feature as the spines on the summit of the dome. In other words, their growth is as rapid as the dome itself, and it is extremely unlikely that at any stage in the history of an obsidian dome was it free from the mantle of its talus cone.

Coulees

The coulees are nothing more than expanded obsidian domes. In their formation the obsidian in a rising dome spills over the top of the levee built up about the vent, succeeds in filling a section of the moat, and eventually cuts across the lapilli rim. This extremely viscous, dry, and gas impregnated lava soon solidifies, and on cooling becomes strongly jointed. Along these joint planes the lava rapidly separates into blocks, and it is probably as a jumbled chaos of blocks that it advances. Very little fluid lava appears on the surface of these flows except for a few short lived, narrow tongues of obsidian which may occasionally dart among the interstices of the slowly tumbling blocks. The flow maintains an essentially vertical front in its advance. As the parapet moves forward, it is continually collapsing to build up a sloping talus apron, which screens the advance of the main body of the flow. The coulees at no time resemble the Hawaiian pahoehoe, but are like the block lava of the 1928 eruption of Mount Etna which pushed forward in smoking piles of angular fragments to overwhelm everything in its path.

The external appearance of a dome and coulee is identical, with the single exception of the greater size, and the lobe-like shape of the latter. The coulee has a pinnacle encrusted upper surface, a steep parapet, and a apron of talus about its sides and front. The pinnacles are most abundantly clustered about the margins, the interior of the coulee is likely to be a chaos of ridges of obsidian blocks, depressed areas, fissures, fumarolic vents, and spines.

In both the Northern and Southern Coulees, the obsidian apparently has issued from several vents along the central fissure, and has coalesced to from these distinctive flows. The evidence is also clear that the coulees have been built up by a number of closely spaced, but separate outpourings, rather than by a single extravasation of obsidian.

Structure

The internal structure of a typical obsidian dome would lie entirely in the field of inference, if it were not for the ideal cross section providentially revealed in the walls of the Caldera. In every other dome the structure is completely masked by the talus, and by the debris of collapsed pinnacles scattered over the upper surface.

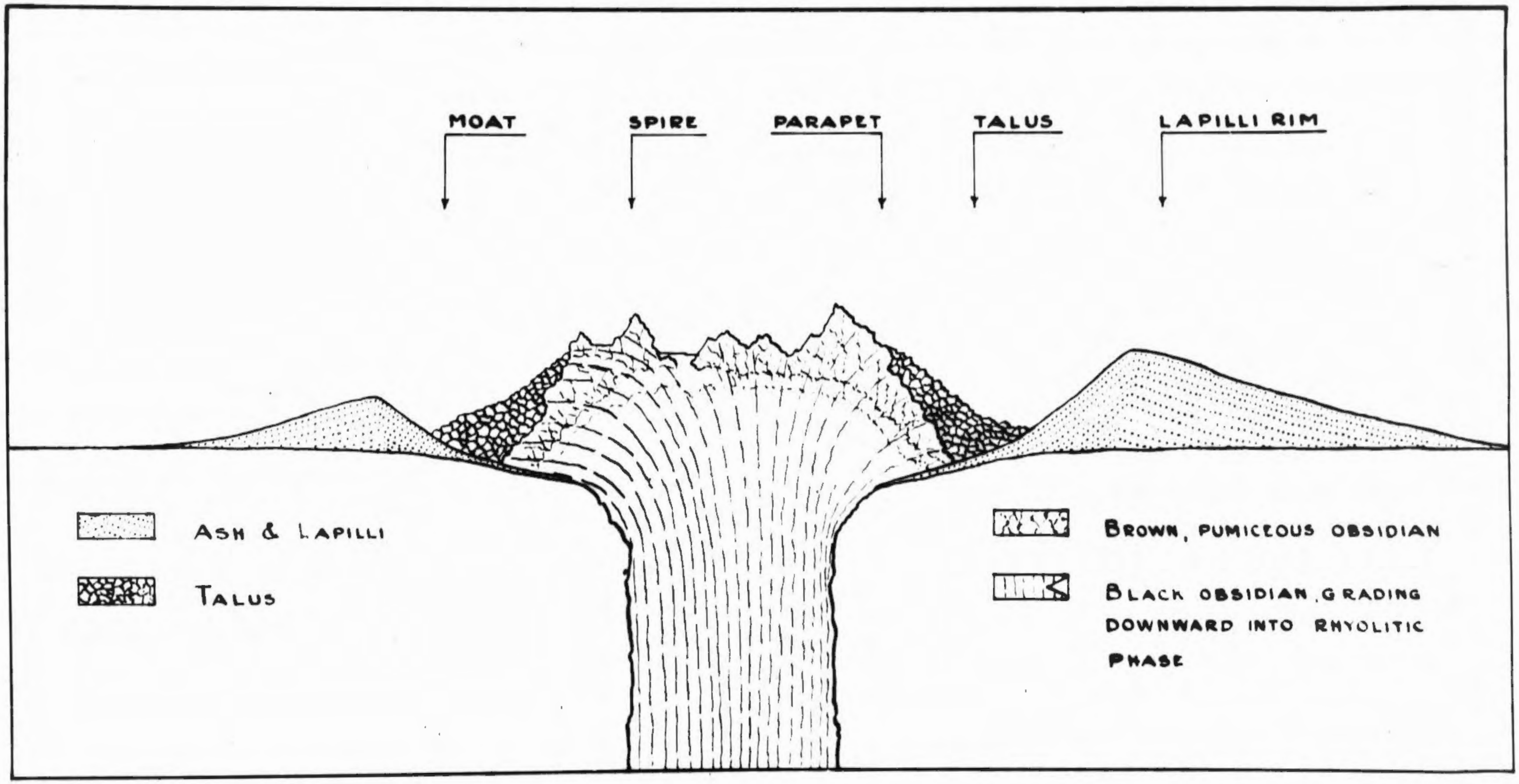
The evidence is strong that the obsidian in the Mono Craters has risen along a fracture in the earth's surface. Presumably this fault is contemporary to the one responsible for the escarpment behind Leevining, or to the one west or Deer Mountain. The obsidian has reached the surface through narrow pipe-like conduits, rather than along fissures in the sense that the term is employed for the Columbian or Icelandic eruptions.

In the formation of a typical obsidian dome, the lava column rising through a narrow conduit, expands into the bowl prepared for it by the earlier explosions. As the lava rises, it builds up a levee which serves to confine the still ascending column. In the source of time this uniform expansion in all directions from the central column produces the sheaf structure shown on Plate VI. Flow banding in the obsidian near the outer margins usually dips outwards at a gentle angle, somewhat closer to the center it may be horizontal, and nearest to the interior of the dome, the inclination increases until it becomes vertical.

The solidified lava contracts rather sharply on cooling and developes a strong system of joints. This jointed lava soon separates into blocks, and presumably at all times forms a solid, blocky crust over the rising magma column below. Locally along fractures, or where the fluid obsidian ascends more vigorously it succeeded in elevating this solidified cover in polyhedral columns or spines.

Plate VI

Structure of a typical Obsidian Dome



CROSS-SECTION OF OBSIDIAN DOME

The line of demarcation between the blocky and the vitreous forms of obsidian is usually distinct. The block lava forms early and usually solidifies at a time when the gas content of the lava is still high. A frothy texture develops even though flow banding is distinct and large phenocrysts of sanidine have crystallized. The black vitreous form solidifies near the end of the domical intrusion, when the vapor tension is less, and thus develops a uniformly glassy texture. That gases still play an important role is shown by the large spherulites and lined cavities which are found occasionally. Whenever an opportunity affords, the still fluid obsidian forces its way through the interstices between the blocks.

The black, vitreous form of obsidian forms a "Cooling surface" between the pumiceous, block variety on the top of the dome, and the more slowly cooling "intrusive obsidian" in the neck. This last form shows a strong development of fluidal banding, and is almost gradational into rhyolite.

The problem of the mechanism responsible for the rise of such viscous lava to the surface is extremely difficult. Especially when the quantity of obsidian represented in some of the domes and coulees of the Mono Craters is considered and the height to which it has ascended.

Williams[24] makes the following concise statement:

(24) op. cit., (Univ. of Calif. Bull., vol. 21) p. 146.

"The propelling force in domical protrusions seems to be the pressure of volatiles. Sufficient gas is left in the magma, even after long periods of explosive activity, to urge it to the surface, and as crystallization proceeds this gas pressure is increased at a rapid rate. Once pressure is released so that the gases are able to escape from solution, their upward streaming may itself provide adequate propulsion. The rise of so many domes is attended by periodic explosions, owing to a regular accumulation of vapor tension, that we must attribute an important, and often a major role, to the crystallization of subjacent magma."

Conclusion

The Mono Craters are a unique series of obsidian domes, coulees, and lapilli cones on the southern shore of Lake Mono. They have a length of slightly more than ten miles, and are grouped along a curving fracture which roughly parallels the main trend of the Sierra Nevada. The range is divided into three nearly equal parts by two prominent obsidian coulees, the largest outpourings of obsidian in the chain.

There has been a shift of activity from the central part of the range towards the two extremities, but there are numerous exceptions to this generalization. The central section of the range is the highest, and is dominated by three truncated, conical domes. The northern section embraces six centers of volcanic activity, including one of the most complete domes in the series, the somewhat isolated obsidian dome and lapilli collar of Panum. The southern section includes a number of closely related explosive pits and domes grouped about a distinctive crater, the Devil's Punchbowl.

The principal rock types in the Mono Craters are the frothy lapilli in the explosion vents; the gray, pumiceous, sanidine-bearing obsidian of the older domes; the purplish-brown, also pumiceous and sanidine bearing variety of the more recent domes and coulees; the familiar black, vitreous type of obsidian which is characteristic of the "cooling zone"; and lastly the near-rhyolitic variety of "intrusive obsidian" found in the deeper parts of the volcanic conduits. Associated with the obsidian of the Mono Craters are two older volcanic rocks, the West Portal Rhyolite and the Black Butte Basalt.

The volcanic vents in the Mono Craters, in the typical case, pass through an orderly sequence in which the period of activity commences with a series of explosions, ash and lapilli are hurled out of the vent and a funnel-shaped explosion pit is formed. The explosions are succeeded by the appearance of obsidian in the floor of the lapilli cone. In time the essentially solid obsidian has risen high enough to form a dome. Should a sufficient volume of obsidian reach the surface, the dome expands beyond the confines of its lapilli ring, and a coulee is produced. In brief, the sequence progresses from an explosion pit through a domical stage, to be completed by a short, steep-faced flow or coulee. Explosions of waning intensity may occur during any of the later stages in the sequences. Reasoning by analogy from the eruption of similar domes during historic times, there is good reason for believing that these obsidian protrusions may have been built in a short period. The highest may have required little more than a year, and Panum may have been constructed in a week or less.

The essential element in determining the internal structure of the average dome is a narrow central vent from which the rising obsidian issues. Upon the removal of the restraint imposed by the constricted walls of the conduit, the lava expands in a sheaf-like form, with gentle dips near the periphery and vertical ones in the interior. The obsidian solidifies almost immediately upon its arrival at the surface, and pushes up as a stiff cylinder with essentially vertical sides.