THE MONO CRATERS, CALIFORNIA*

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THE Mono Craters are a unique series of obsidian domes and coulees south of Mono Lake, in eastern California. From an undulating, pumice-covered plain their steep slopes rise nearly 2700 feet above the surrounding country and reach an altitude of 9169 feet at the summit of the highest dome. Were the range not dwarfed by the neighboring Sierra Nevada, "it would be far-famed for its magnificent scenery as well as for its geological interest."[1]

The Mono Craters present many features of interest. Their relationship to the lacustrine record of Mono Lake and the glacial history of the eastern Sierra Nevada is important. Added interest to the problem is afforded by the water tunnel under construction by the city of Los Angeles, which passes beneath one of the larger domes at the south end of the chain. This tunnel is to convey water from the Mono Basin into the drainage of the Owens River and, by the present aqueduct, to Los Angeles. The work has been impeded by the large quantity of water encountered in the tunnel and the presence of carbon dioxide (see Fig. 16). On the other hand, there is the fortunate circumstance that the tunnel line passes through an area suitable for the determination of the age of the craters. All the important rocks of the region crop out, and in this area the glacial and volcanic records overlap.

Descriptions of the Region

One of the first and most interesting accounts of the craters is contained in the journal of William Brewer,[2] assistant on the Geological Survey of California:

> July 8 [1863] Hoffmann 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

*The field work was done in the summer of 1936. Dr. Ian Campbell of the California Institute of Technology and Dr. Catherine Campbell gave much assistance by a critical reading of the manuscript and by a trip into the field. The Los Angeles Bureau of Water Works and Supply extended many courtesies in connection with the tunnel operations. Dr. Eliot Blackwelder gave valuable information on the glacial history of the region.

[1] I. C. Russell: Quaternary History of Mono Valley, California, *U. S. Geol. Survey, 8th Ann. Rept., 1886–'87*, Part I, 1889, pp. 261–394; reference on p. 378.

[2] W. H. Brewer: Up and Down California in 1860–1864: The Journal of William H. Brewer, Professor of Agriculture in the Sheffield Scientific School from 1864 to 1903, edited by F. P. Farquhar, New Haven, 1930, p. 416.

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.

A similar, although less personal, description was given by Whitney,[3] the first to comment on the presence of granite fragments on the summits of the craters, which he rightly interpreted as accidental ejecta. Whitney believed that the granite blocks had been torn from the solid-rock foundation underlying the craters. Joseph LeConte[4] considered the fragments, many of which are rounded, to be derived from the glacial drift rather than from the bedrock. The rounded fragments are found most frequently on the summits of the craters nearest to Mono Lake.

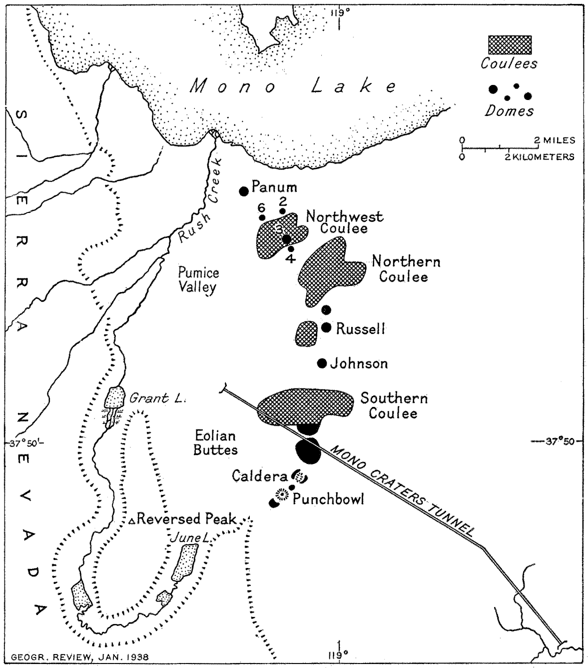

FIG. 1—Index map of the Mono Craters.

The most important contribution to the knowledge of this area is the report based on the reconnaissance survey of I. C. Russell and W. D. Johnson,[5] a work that sets a standard difficult to equal. More recently the volcanoes have been described by Williams[6] and Mayo.[7] Williams describes the origin of two of the Mono Craters in relation

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[3] Geological Survey of California, J. D. Whitney, State Geologist: Geology, Vol. 1, 1865, pp. 454–455.

[4] On the Extinct Volcanoes about Lake Mono, and Their Relation to the Glacial Drift, *Amer. Journ. of Sci.*, Ser. 3, Vol. 18, 1879, pp. 35–44.

[5] Russell, *op. cit.*; see also his "Volcanoes of North America," New York and London, 1897, pp. 217–225.

[6] Howel Williams: The History and Character of Volcanic Domes, *Univ. of California Publs.*, *Bull. Dept. of Geol. Sci.*, Vol. 21, 1931–1932, pp. 51–146; reference on pp. 73–79.

[7] E. B. Mayo, L. C. Conant, and J. R. Chelikowsky: Southern Extension of the Mono Craters California, *Amer. Journ. of Sci.*, Ser. 5, Vol. 32, 1936, pp. 81–97; E. B. Mayo: Sierra Nevada Pluton and Crustal Movement, *Journ. of Geol.*, Vol. 45, 1937, pp. 169–192.

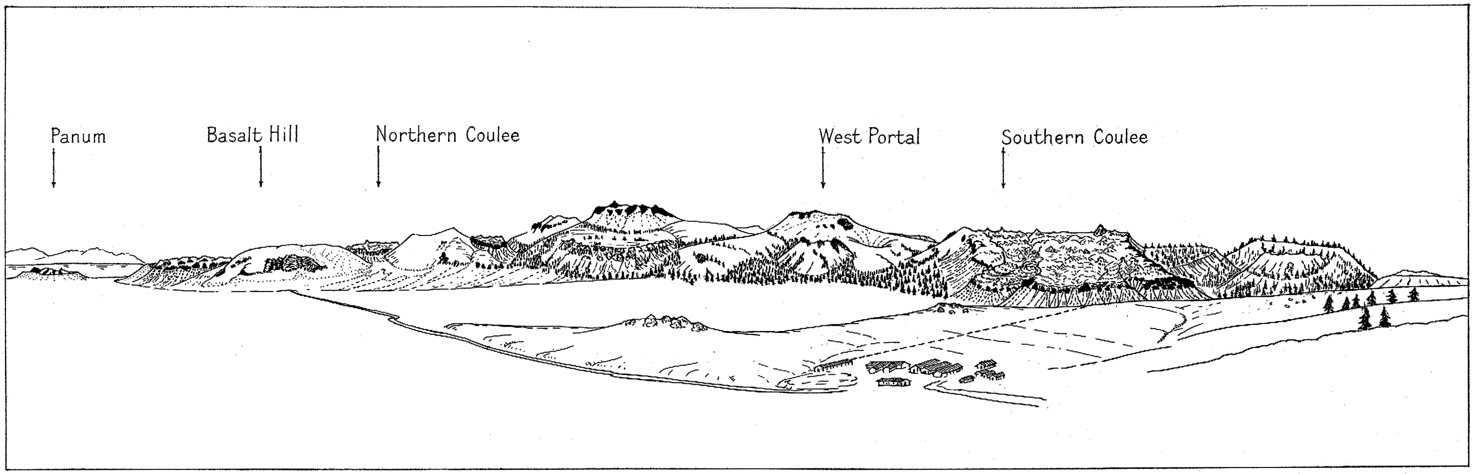

FIG. 2—Panorama of western side of Mono Craters.

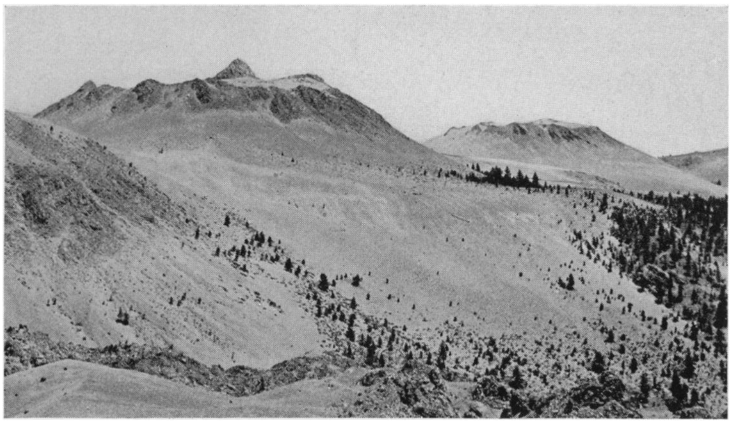

FIG. 3—The southernmost two of the three central obsidian domes at the summit of the Mono Craters.

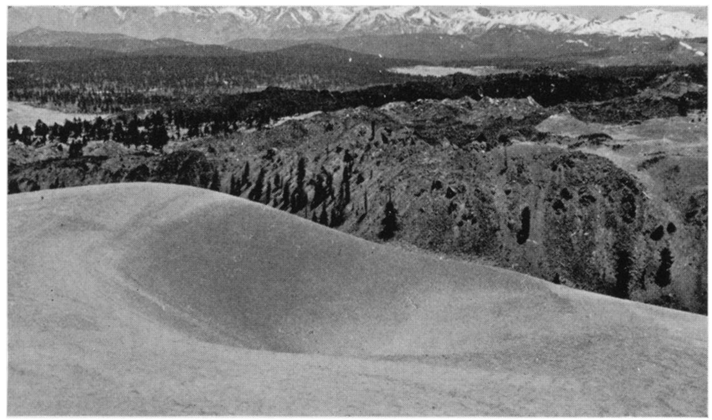

FIG. 4—Explosion pit near summit of Mono Craters. Steep slope of the Southern Coulee in middle distance; Sierra Nevada in the background.

to the general problem of the character of volcanic domes. Mayo's first paper, which appeared after the writer's field work had been completed, deals with the southern extension of the Mono Craters, outside the area investigated.

The Volcanic Forms

The craters are a group of obsidian domes and stubby obsidian flows, known as coulees. Both the domes and the coulees are ranged in a curved line, convex eastward. The chain is divided into three nearly equal parts by two of the larger coulees, which have their longest dimension at right angles to the axis of the chain. The northern coulee is confined to the east side of the range; the southern is divided almost equally between the east and west sides.

The highest elevations are near the center of the range, where three nearly equal, turret-shaped domes dominate the group. Of these three, the two southern domes are somewhat larger and more recent than the northern. The central dome of the trio is the highest peak in the Mono Craters.[8]

North of the Northern Coulee the craters consist of five distinct obsidian domes and two coulees. The northernmost of the domes stands by itself on the plain south of Mono Lake and is about one mile north of the main range. This crater, a nearly perfect example of a steep-walled obsidian dome encircled by a collar of lapilli, is known as Panum. According to Russell[9] "Pa-num" meant "a lake" in the Pa-vi-o-osi language.

South of the Southern Coulee are six obsidian domes and four large explosion pits. The explosion pit marked on the map (Fig. 1) as the Caldera has destroyed an earlier dome.

Sequence of Eruptive Forms

A study of the Mono Craters shows that most of their volcanic features are part of a definite sequence, a sequence of eruptive forms beginning with an explosion pit and ending with a steep-faced flow, or coulee. In the following sections the ideal eruptive sequence will be first described and then illustrated by examples drawn from the Mono Craters.

The near approach of an obsidian dome to the surface is heralded by explosions that produce a shallow, conical depression with flaring walls and shaped much like a large shell hole. This explosive episode

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[8] None of these prominent domes are named, in spite of the fact that they are conspicuous elements of the landscape. The names of Russell and Johnson are suggested by the writer for the central (9169 feet) and southern of these domes respectively. It seems particularly appropriate to have the highest peaks of the chain commemorate the pioneering achievements of I C. Russell and W. D. Johnson in mapping and describing this region.

[9] Quaternary History of Mono Valley, p. 382.

is succeeded by the rise of a stiff, cylindrical, and essentially solid column of obsidian, which builds a dome in the floor of the explosion pit. If the obsidian continues to ascend, it eventually spills over the rim of lapilli encircling the explosion pit and forms a blocky, steep-faced coulee. This eruptive sequence is illustrated by the block diagrams of Figure 5. Separate outpourings may coalesce to make a fissure flow, as happened, for example, in the Northern and Southern Coulees.

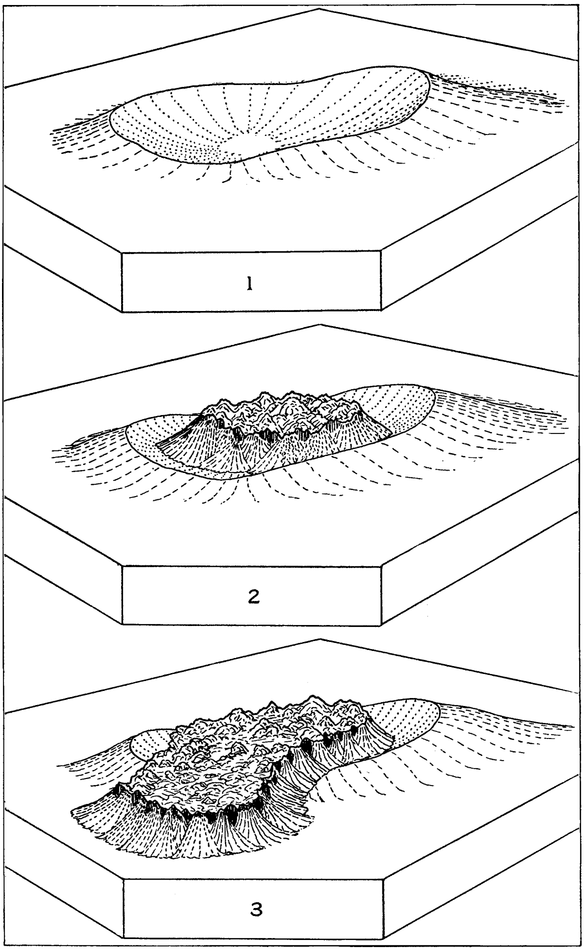


FIG. 5—Morphological development of an obsidian dome and coulee.

As a rule the explosions are strongest at the beginning of an eruption and decrease in intensity as the dome expands. The rise of the dome is one of the last events in the history of a vent. When the dome is emplaced, the conduit is sealed and the likelihood of renewed explosive activity is small. The one important exception in the Mono Craters is the deep crater known as the Caldera at the south end of the chain. This steep-sided double crater occupies the center of an obsidian dome destroyed by an explosion.

Explosion Pits

The explosion pit formed in the early stages of a domical eruption contains no visible obsidian protrusion. The pit is usually a conical depression, with sides that may slope as much as 38°. The material forming the walls and rim consists of unconsolidated, silvery-gray pumice and lapilli. Pellets or fragments of jet-black obsidian are abundant, and accidental ejecta as much as a foot or even more in diameter are frequently found. Two nearly complete explosion pits are near the summit of the range between the southernmost of the three central domes and the Southern Coulee.

The Devil's Punchbowl, near the Bishop-Reno highway, is a small but nearly perfect example of an explosion pit in a slightly more advanced stage in the eruptive cycle. This pit has a diameter of 1200 feet and a depth of 140 feet. At the bottom is a small obsidian plug. The base of this incipient dome is 250 feet long, and it rises 40 feet above the floor of the crater.

Obsidian Domes

A dome is formed by the continued rise of an obsidian column above the floor of an explosion pit. Panum Crater is an excellent example. The crater has three rather distinctive parts: a central, steep-sided obsidian dome; a deep moat encircling it; and an outer ring of lapilli, heaped up in the early, explosive phase. Panum resembles the second of the block diagrams in Figure 5. To give a quantitative picture of a typical obsidian dome, some of the more important dimensions of the crater are listed below.

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

The top of the dome is a chaos of slender spires, crags, and loosely piled, angular blocks of brown pumiceous obsidian. Few structural 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 block accumulations show a tendency toward a crescentic arrangement, and that the dome is crossed by a deep fracture from north to south on the east margin.

The flow banding in the spires is nearly vertical but shows a tendency to fan outwards in the larger pinnacles. The spires have nearly perpendicular sides, are penetrated by numerous joints, and tend to disintegrate into cairnlike accumulations of loose blocks. The highly shattered condition of the obsidian is the primary cause of the great number of angular blocks that mantle the surface of the dome and mask its sides as talus. When the spires rise above the dome, they collapse into piles of razor-edged stony obsidian. The talus is formed in the same way. The obsidian pushes outwards to the margin of the dome and, when unsupported, slides down to form a sloping blanket of debris.

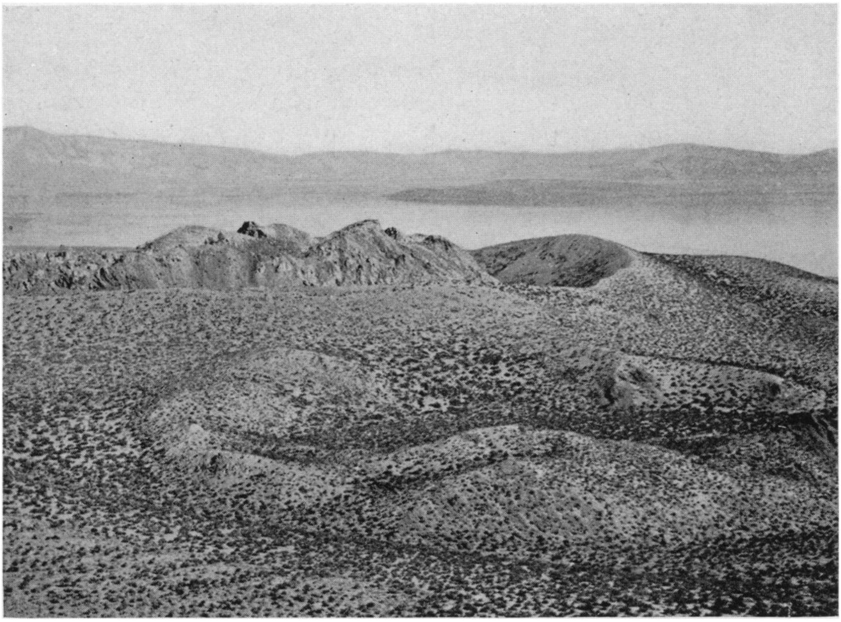


Fig. 6

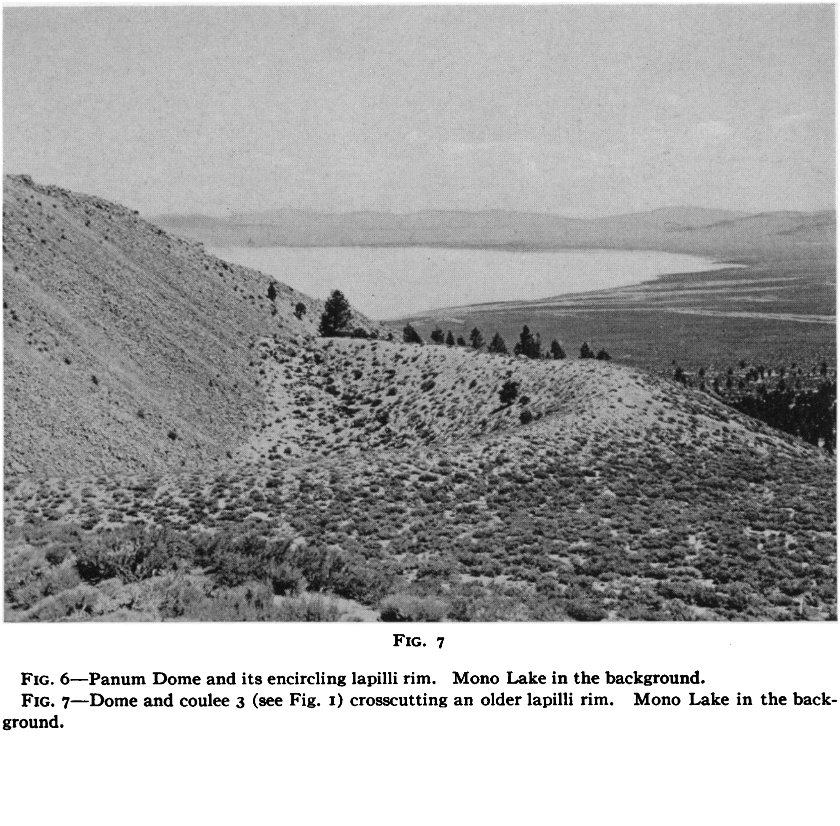


Fig. 7

Fig. 6—Panum Dome and its encircling lapilli rim. Mono Lake in the background.

Fig. 7—Dome and coulee 3 (see Fig. 1) crosscutting an older lapilli rim. Mono Lake in the background.

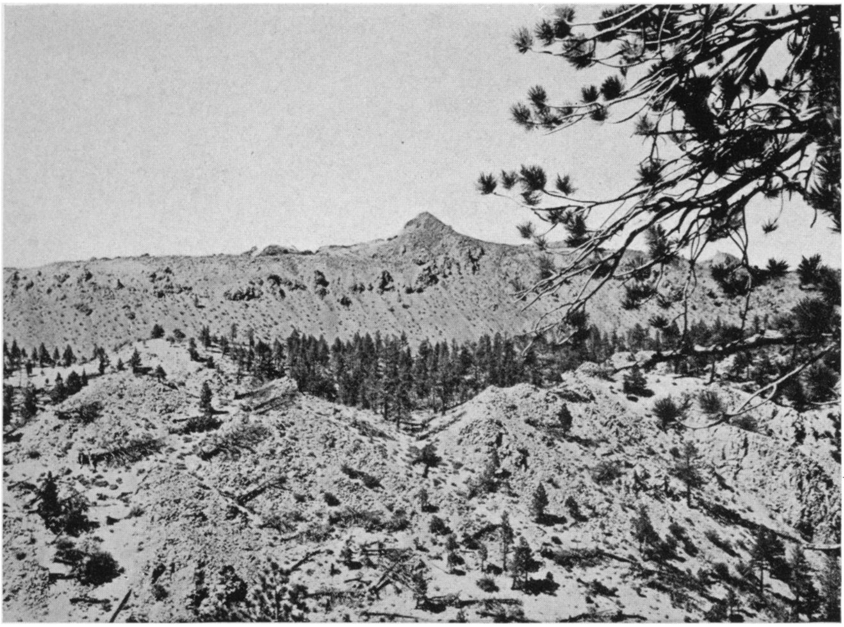
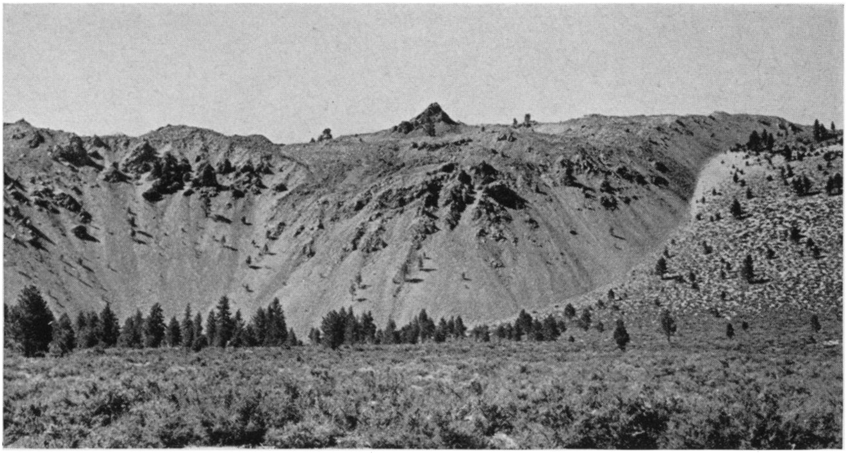


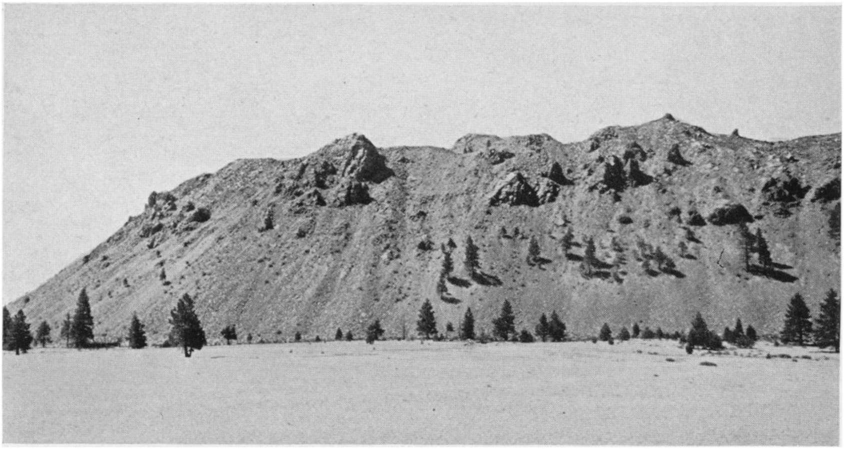
Fig. 8

Fig. 9

Fig. 8—One of the principal spines on the axis of the Southern Coulee. The almost vertical wall of this flow forms a barrier across the chain of craters.

Fig. 9—Pinnacles on the upper surface of the Southern Coulee. The distant ridges at the base of the Sierra Nevada are lateral moraines of the June Lake Glacier.





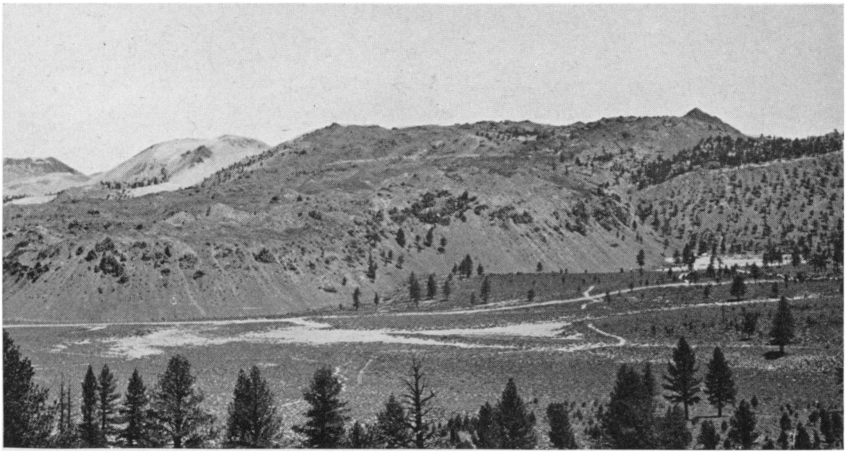


Fig. 10 (top)—The north wall of the Northern Coulee showing the nearly perpendicular side of the obsidian flow.

Fig. 11—The eastern end of the Northern Coulee showing the pinnacle encrusted upper surface, and talus slopes masking the lower part of the flow.

Fig. 12 (bottom)—The western end of the Southern Coulee. The low ridge crossed by the obsidian is a lateral moraine of the June Lake Glacier.

FIG. 13

FIG. 14

FIG. 13—Small explosion pit on the north wall of the Caldera. This is the crater which reveals the internal structure of an obsidian dome (compare Fig. 15).
FIG. 14—Dry, pumice-floored lakes east of Mono Craters.

The dominant rock type of Panum Dome is purplish-brown pumiceous obsidian. On fresh surfaces the rock is light silvery gray, and in many places the laminated appearance due to the alternation of vitreous obsidian and pumice is pronounced. Every gradation is found from jet-black obsidian, with a pronounced conchoidal fracture, to vesicular pumice. The familiar black, vitreous form of obsidian is comparatively rare. It seems to have been intruded into the fractures of the already solidified stony obsidian and reaches the surface in tonguelike extrusions. This black form shows the best fluidal banding.

Williams[10] sums up the origin of Panum Dome in the following concise statement:

> 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.

Coulees[11]

Most coulees are formed by the expansion of an obsidian dome beyond the confines of its tuff ring. This stage is illustrated by the third diagram of Figure 5. One of the best examples is the dome and coulee indicated as number 3 of Figure 1. This dome cuts across the edge of the crater of lapilli and continues down the east side of the range as a stubby obsidian flow (Fig. 7).

The most important of the coulees are the two that divide the range into three parts. They are about the same size, but the Northern Coulee has an approximate volume of 0.13 cubic mile of rock and the Southern 0.16 cubic mile. The Southern Coulee is the greatest single outpouring of obsidian in the range.

Neither of these flows seems to have issued from a single central vent. The obsidian reached the surface through several outlets, now marked by prominent spines, and moved down the slope in a viscous, nearly vertical-faced flow. These flows are sharply limited and show little tendency to spread, even at the terminus. The sides and end of the coulee are marked by loose, angular obsidian blocks in the talus

[10] *Op. cit.*, p. 78.

[11] The use of the term "coulee" for a lava flow has become less familiar than its meaning as a steep-sided stream valley, such as the Grand Coulee, in Washington. It has seemed desirable to revive the first usage for these steep-fronted obsidian flows. Russell recognized the validity of this meaning. "Coulee" is defined in Webster's New International Dictionary, 2nd edit. (unabridged), 1934, p. 605, as "a stream or sheet of lava." The word is derived from the French *couler*, "to flow."

below a parapet of minaretlike obsidian spines ranged along the upper rim. As the flow moved forward and solidified, fragments detached along the numerous fracture planes in the spines tumbled down to form the talus apron. This process was described by Russell.[12]

The extreme ruggedness of the coulées 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 coulées was also due to the viscid condition of the glass composing them. In flowing down the side of the craters the lava descended slopes that must have had an inclination of fifteen or twenty degrees, but only in the case of the greatest eruptions did the viscid streams reach the plain at the foot of the cones. In no instance did they continue their course for a considerable distance after leaving the abrupt slopes. . . .

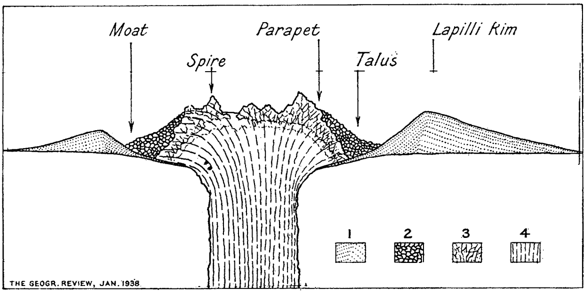


FIG. 15—Structure of a typical obsidian dome. Key: 1, ash and lapilli; 2, talus; 3, brown, pumiceous obsidian; 4, black obsidian, grading downward into rhyolitic phase.

Had the lava been more liquid, the ends of the coulées 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, having a height of from two to three hundred feet. Before the edges of the coulées were broken and defaced by weathering, they must have been approximately 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.

THE CALDERA[13]

This large explosion pit (Fig. 16) gives a nearly complete cross section of the internal structure of an obsidian dome. The crater consists of a large, flat-floored bowl open at the west end and a small, deep-throated explosion pit blasted out of the north wall of the main vent. The total length of the Caldera is 2000 feet, the width 1700 feet, and the depth 360 feet. The satellite crater, shown in Figure 13,

[12] Quaternary History of Mono Valley, p. 383.

[13] R. A. Daly: Igneous Rocks and the Depths of the Earth, New York and London, 1933, pp. 163–171; H. T. Stearns and W. O. Clark: Geology and Water Resources of the Kau District, Hawaii, *U. S. Geol. Survey Water-Supply Paper 616*, 1930, p. 46.

Stearns differs with Daly in the use of the term "caldera." Daly (p. 164) would restrict it to explosive craters and call forms produced by subsidence "volcanic sinks." According to Stearns, the term may be used "in its generic sense as meaning a circular or amphitheater-shaped depression on a volcanic mountain. Instead of including in the definition the process by which the depression was formed, an adjective can be placed before the term when it is wished to indicate the process. For instance, 'explosion caldera' can be used for a caldera formed by explosion, and 'collapse caldera' for one formed by subsidence." In his classification this particular crater would be an explosion caldera.

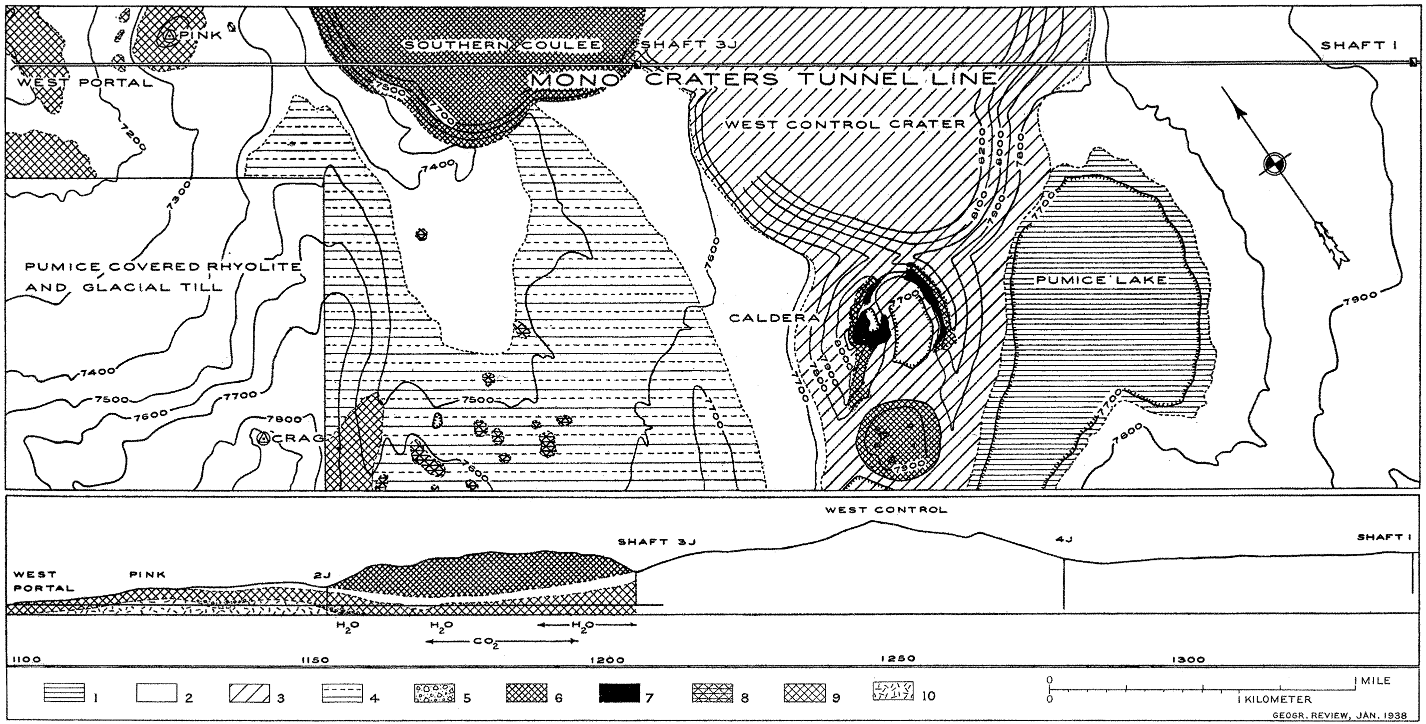


FIG. 16—Map and cross section of area surrounding the western end of the Mono Craters tunnel. Key: 1, pumice lake bed; 2, pumice-mantled surface; 3, pumice-covered domes and lapilli rings; 4, pumice-covered glacial till; 5, boulder clay; 6, obsidian; 7, intrusive obsidian; 8, Black Butte basalt; 9, west portal rhyolite; 10, tunnel granite. Contour interval 100 feet.

is 800 feet long, 700 feet wide, and 320 feet deep on the north side and 50 feet on the south side.

Russell[14] apparently favored subsidence for the origin of this crater. However, evidence for the engulfment of a dome in the area now occupied by the Caldera is not clear-cut. More likely the crater is a large explosion pit that destroyed an earlier obsidian dome. The tops of the obsidian cliffs forming the walls of the Caldera are buried beneath 30 to 50 feet of volcanic ash. The secondary crater is clearly explosive, and it differs from the larger depression only in size. There are no peripheral faults, partly collapsed segments, etc. Lastly, the sheaf-like structure of the dome (at a middle point in the crater wall the flow lines radiate outwards like the top of a sheaf of grain) is not particularly conducive to subsidence.

The pale rhyolitic obsidian in the lower part of the vent, because of its presence in the interior and conduit of the dome, has been called "intrusive obsidian." It cooled with relative slowness and acquired a near-rhyolitic texture. The vesicular obsidian near the surface is highly fractured and, almost immediately upon solidifying, disintegrated into blocks.

Structure of an Obsidian Dome

The internal structure of the Mono obsidian domes would be a matter of conjecture were it not for the section revealed in the Caldera. Figure 15 is a diagrammatic cross section of a dome based on the internal arrangement seen in the Caldera and the surface pattern of Panum. The explosions that cleared the path the obsidian followed to the surface built the rim of lapilli. The expansion of the obsidian into the tuff bowl caused the sheaf-like pattern of the flow banding. Quickly congealed blocky obsidian overlying the more slowly cooling rhyolitic obsidian of the interior covered the upper surface of the dome with spires and cairns.

It is difficult to interpret the structure of an obsidian dome because of the complex manner of its growth. Some sections solidified before others. Fluid obsidian often penetrated fractures in the already solid crust. Mayo points to Cloos's comparison of this arrangement with a river delta.[15]

> In such an analogy the congealed portions between the eruptive channels are comparable, in a sense, to the sediments of a delta. The viscous material ascending the channels corresponds to the distributaries, and the magma column beneath the dome represents the river.[16]

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[14] Quaternary History of Mono Valley, p. 382.

[15] Hans Cloos and Ernst Cloos: Das Strömungsbild der Wolkenburg im Siebengebirge, *Zeitschr. für Vulkanologie*, Vol. 11, 1927–1928, pp. 93–95; reference on p. 95.

[16] Mayo. Conant, and Chelikowsky, *op. cit.*, p. 97.

THE AGE OF THE MONO CRATERS

The tunnel now being constructed beneath the craters furnishes valuable information about their age. The tunnel has not yet pierced the large obsidian dome that lies in its path, but it has already passed beneath the Southern Coulee. The oldest rock is the granite of the two buried ridges near the west portal. This granite was glaciated in the early Pleistocene. The boulder clay of this glaciation occurs in the saddle between the ridges and is overlain by several hundred feet of rhyolitic tuff. This tuff, which crops out in the vicinity of the tunnel and in the Eolian Buttes, was glaciated by the earlier of the two most recent glaciations, the Tahoe stage of Blackwelder. The glacial moraines of this stage are indicated near the center of the map (Fig. 16). The Tahoe glacial till is partly covered by an unglaciated basalt flow surmounted by numerous spatter cones. The basalt was glaciated one mile to the southwest by the Tioga (Wisconsin) ice.[17] In the area east of the highway, shown on the map between the lateral moraines of the Tahoe stage, the basalt is partly buried under pumice-covered Tioga outwash.

The eastern of the Tahoe lateral moraines is partly covered by the obsidian of the Southern Coulee. The steep slopes of this lava flow are not cut by any of the former shore lines of Mono Lake, though it extends into the area occupied by the lake water.

East of the craters are numerous pumice-floored depressions that are dry lakes. The dry lake shown on the tunnel map is more recent than the southernmost of the Mono Craters, for its shore line cuts their eastern flank. This lake existed in the late Pleistocene or early Recent. Since the disappearance of its waters on the surface the water table has been lowered about 300 feet.

To summarize, the age of the Mono Craters is late Pleistocene. Explosive activity began during the high stand of Mono Lake, as is shown by the pumice interstratified with the lake deposits. No shore lines cut the more recent craters, particularly the lapilli cone of Panum, which extends to less than 150 feet above the present lake level. The Southern Coulee covers one of the earlier lateral moraines of the June Lake glacier. The explosion pits at the southwest end of the craters were formed by eruptions through the floor of one of the late-Pleistocene lakes east of the craters. Pumice hurled from the craters covers the surface of the moraines of the last glaciation. In spite of the recency of eruption, no signs of activity can be seen in the craters today. There are hot springs on one of the islands in Mono Lake, and to the south in the drainage basin of the Owens River are a few more, but these are unrelated areas.

[17] Eliot Blackwelder: Pleistocene Glaciation in the Sierra Nevada and Basin Ranges, *Bull. Geol. Soc. of America*, Vol. 42, 1931, pp. 865–922; reference on pp. 891–892.