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Mount Mazama: Explosion versus Collapse

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and

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University of Oregon
EUGENE

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BY WARREN D. SMITH AND CARL R. SWARTZLOW

CONTENTS

	Page
Introduction.....	1809
Distribution, character, and amount of erupted material.....	1812
Diller's "backflow" in Cleetwood Cove.....	1816
Shape and character of the crater.....	1817
Absence of extruded lava of recent date.....	1821
Materials of the rim.....	1822
Mechanics of collapse.....	1824
Records of some Pacific rim volcanoes.....	1827
Summary and conclusions.....	1829

ILLUSTRATIONS

Figure	Page
1. Cross section of Crater Lake.....	1810
2. Pumice areas.....	1813
3. Section in Wheeler Canyon.....	1815
4. Crater Lake east wall.....	1816
5. Hillman Peak area.....	1819

Plate	Facing Page
1. Crater Lake and a mine crater.....	1820
2. Erosion remnants.....	1821
3. Pumice and "backflow".....	1822
4. Mazama Rock.....	1823
5. Pit of Halemaumau, Kilauea.....	1824
6. Aniakchak Volcano.....	1825

INTRODUCTION

Crater Lake, situated close to the crest of the Cascades of southern Oregon, approximately in latitude 43° N, longitude 122° W, occupies an extensive crater, formed by the destruction of a mountain, which has been named Mount Mazama. The lake lies at an altitude of 6161 feet, approximately 16 feet lower than that recorded by early surveys, and is surrounded by a nearly circular rim, varying from 500 to 2,000 feet in height (Pl. 1, fig. 1). It has a shoreline of approximately 21 miles and is 6½ miles in diameter from west to east and about 4½ miles from north to south. The materials in the crater walls and the inclination of the

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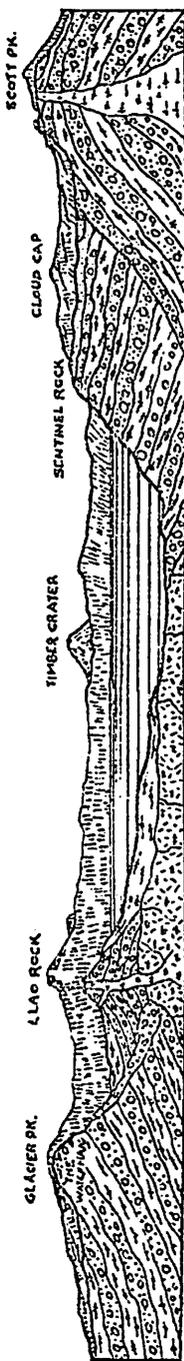


FIGURE 1.—Cross section of Crater Lake (adapted from Diller by Ira A. Williams)

back slopes indicate that, prior to the formation of the lake, there was a composite cone, 12,000 to 15,000 feet high, with a circumference comparable to that of Mount Shasta (Fig. 1).

The problem of the origin of Crater Lake excites the curiosity of thousands of visitors to this famous National Park. The explanation proposed by Diller in 1896, and questioned by some geologists before this, that the crater was a result of the collapse of Mount Mazama, has been generally accepted. Indeed, to the layman, there is no apparent cause to question this explanation, and, thus, the story is spread far and wide, that this is the only explanation. However, if one is permitted to wander at will about the crater's rim and to explore the back slopes of the mountain and study, point by point, the evidence submitted by Diller, it is soon apparent that some of his contentions are based on, or supported by, meager evidence.

It should be distinctly understood that this paper is not a condemnation of Diller's work. His paper is a work of outstanding merit, but he was denied some of the advantages available to present-day investigators. Deep road-cuts have exposed sections not visible in those early days, and a network of roads and trails has facilitated the exploration of all parts of the area.

It is in the light of the evidence obtained from recent exploration that a different explanation of the origin of Crater Lake seems justified. It is with the hope that other geologists will critically examine this evidence in the field that the writers present their case.

For the opportunity to study this problem rather intimately in the field, the writers are indebted to the National Park Service. While acting as ranger-naturalists at Crater Lake during the summers of 1934 and 1935, they were provided with every facility in time and transportation, to carry on research in this interesting problem. Smith prepared the manuscript except the part dealing with the mechanics of collapse. However, there was close

collaboration and agreement between the writers in all stages of field study and preparation of the paper.

In addition to the assistance rendered the authors by the staff of ranger-naturalists and rangers of Crater Lake National Park, we wish to acknowledge valuable suggestions from Professor William H. Hobbs, of the University of Michigan, and from Professors Ralph Leighton and O. F. Stafford, of the University of Oregon.

The Cascade volcanoes, of which Mount Mazama was one, are part of the so-called Pacific "Circle of Fire", and any interpretation of their history and activity should properly be considered in the light of other portions of this great ring of volcanic mountains. The writers, having had some experience with volcanoes in several sections of this Pacific Circle, offer these observations and interpretations as a contribution to Pacific vulcanology in general, and a radically different possible solution of the particular problem of Crater Lake.

In view of the very definite trend of opinion among some observers, especially geologists from abroad, away from the older, and hitherto generally accepted, "collapse" theory for the origin of Crater Lake, it will be necessary to discuss certain critical points bearing upon explosion versus collapse. Especially does this seem important in the light of observations in the field during 1934 and 1935.

The development of Mount Mazama, as sketched by Diller,¹ is accepted, but exception is taken to the last part of his report, in which he argued that, after the explosive activity culminating in the extrusion of pumice, the mountain was wrecked by a "subsidence which engulfed it."

Proponents of the collapse theory do not overlook the fact that vast quantities of pumice exist for a few miles in all directions (Diller said 20 miles), and it is not denied that this points to a tremendous explosion at that point, but they do overlook the fact that the pumice is scattered many times farther than this. In the opinion of the present writers, this explosion of pumice is the climactic episode in the history of the mountain. The subsidence theory postulates an unusual process, the undermining of the top of the mountain by liquid magma to such an extent that, finally, the great superstructure of the mountain could no longer support it, and it fell in upon itself, after which the material, in some mysterious way, became completely absorbed in the throat of the volcano.

The points that appear to be critical are the following:

1. Distribution, character, and amount of erupted material.
2. The so-called "backflow" of Diller, in Cleetwood Cove.
3. Shape and character of the crater itself.

¹ J. S. Diller and H. B. Patton: *The geology and petrography of Crater Lake National Park*, U. S. Geol. Surv., Prof. Pap. 3 (1902) p. 45-46.

4. Absence of molten material, which should have issued at some lower point, if the mountain had collapsed and the superstructure had been engulfed.
5. Glaciated surfaces about the rim.
6. Mechanics of collapse.

DISTRIBUTION, CHARACTER, AND AMOUNT OF ERUPTED MATERIAL

Although no detailed areal mapping of all of the fragmental material from the mountain has been made, it is manifest, even to the casual observer, that pumice and other fragmental material are widespread in the area, extending at least 80 miles to the east and about half that distance north and south of Crater Lake. In Sand Creek, Annie Creek, and other valleys radiating from the crater, this pyroclastic material is at least 200 feet deep (Pl. 2, fig. 2). Even on the Rogue River, 15 miles west of the center of the eruption, this same kind of deposit, at least 100 feet thick by actual measurement, has buried the former forest (Pl. 2, fig. 1). As other volcanoes in this region have been in violent eruption, it is impossible to determine at this time how much of the pyroclastic material came from Mount Mazama; the present study indicates that all of it came from Mount Mazama. Mount Thielsen, for instance, has erupted explosively, but, as nearly as can be judged from field examination, there is little, or no, evidence that it contributed any of the pumice to the region under discussion.

Of course, if one presupposes an eruption of Krakatoan magnitude, he would not need (nor could one expect) to find all the erupted material within range of the Park. Some of it, undoubtedly, would be carried great distances by lofty wind currents, far beyond the confines of the present Park. With the prevailing winds from the southwest for nine months of the year, one would expect, and does find, the bulk of this deposit to be northeast of Crater Lake.

However, Moore has furnished some fairly conclusive quantitative data, which, though not final, is more detailed than any other yet published. His article includes a clear, small-scale sketch map (Fig. 2) showing the distribution of pumice in the region. His pertinent final paragraph is as follows:

"Though much material has been washed from the area adjacent to Crater Lake, sufficient remains to show that the older pumice contained at least $8\frac{1}{2}$ cubic miles of material and the younger pumice at least $2\frac{1}{2}$ cubic miles. The distance traveled by the *nucées ardentes* and the amounts of material carried by them indicate that they were of tremendous size and force. Whereas those of the Pelée traveled 6 kilometers to the sea and those of the Valley of Ten Thousand Smokes $11\frac{1}{2}$ miles to the sea, these of Mount Mazama traveled 23-36 miles, carrying great masses of pumice boulders the whole distance. The succeeding eruption that furnished the granular

pumice hurled granules as much as an inch in diameter to distances of 80 miles and may have furnished the volcanic dust which settled in Baker and Wallowa counties and is there seen interbedded with the recent alluvium."²

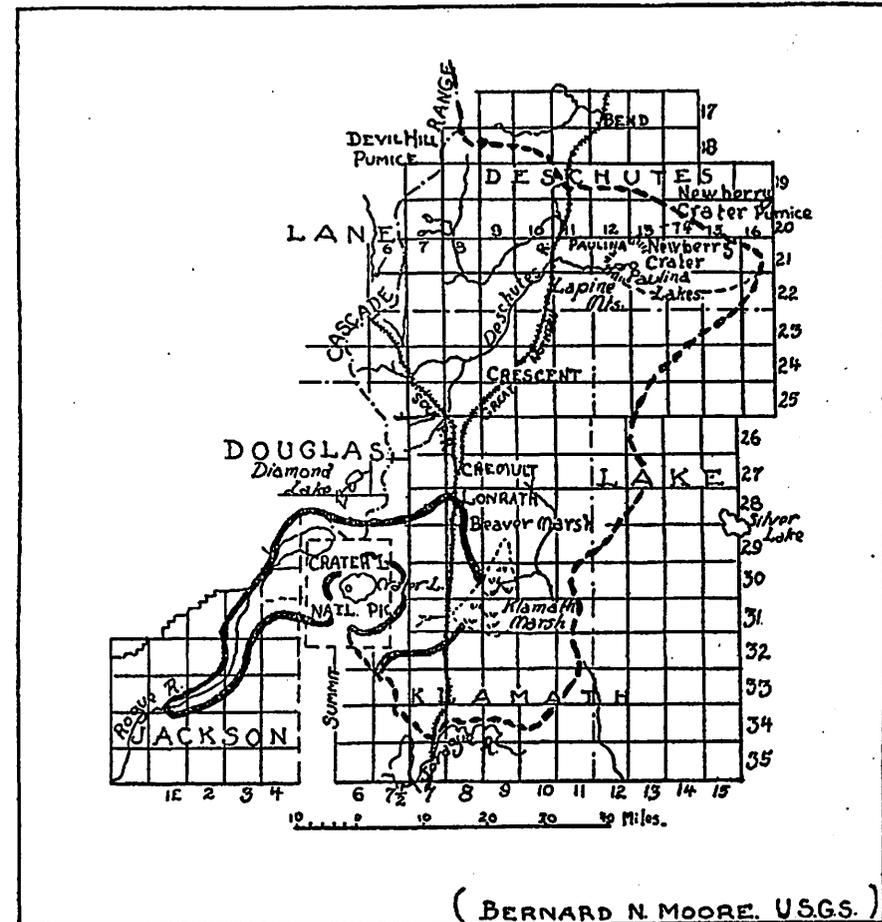


FIGURE 2.—Pumice areas (modified from B. N. Moore, U.S.G.S.)

Heavy line = older pumice
Broken line = younger pumice

The character of the material has, thus, been determined by Moore. It was probably deposited over the countryside during eruptions of the Pelean type, as he suggests.

During the summer of 1935, David Griggs, of Harvard University, accompanied one of the writers in an examination of a section in the

² Bernard N. Moore: *Deposits of possible nuées ardentes origin in the Crater Lake region, Oregon*, Jour. Geol., vol. 42, no. 4 (1934) p. 375.

Pinnacles area (Pl. 2, fig. 2) in Wheeler Canyon. The section as seen in the west wall of the canyon, about opposite the old east entrance ranger station, is given in Figure 3. The total section is made up of pyroclastics, approximately 225 feet thick, with some few feet of water-sorted material at the bottom, which apparently veneers volcanic material beneath. Much of the material filling in this and other canyons was thought by Griggs, who has studied similar deposits in the Valley of Ten Thousand Smokes, Alaska, to be typical sand-flow. The writers think that, although some of this undoubtedly is sand-flow, much of it fell as showers of ashes and coarse fragments. Typical sand-flow at Lassen seems not to resemble canyon fillings at Crater Lake.

The critical and interesting features revealed in this section are the pinnacles and the red horizon of much-oxidized material near the top of the section. The Pinnacles have been described by Diller and others. On August 16, 1935, hitherto unrecorded old fumaroles were discovered in the red horizon just beneath the later fine pumice, which masks most of the surrounding country. Many of the pinnacles are merely indurated tubes leading up to these vents. Oxidation as a result of fumarole action is the explanation for the conspicuous red band at the top of the gray tuff. At least a dozen of these fumaroles were found within a few square yards. These will be described in some detail in a paper by Griggs, now in the course of preparation.

Attention should be directed to two aspects of this pyroclastic material. First, although the fine pumice veneers most of the surfaces around Crater Lake—i.e., both in the valleys and on the hilltops—the coarser tuffs are either absent or inconspicuous on the higher land. This might be explained as due to subsequent erosion or to the fact that the deposit was, in part, of the nature of a sand-flow confined to the valleys radiating from the crater.

Second, these fumaroles further attest the high temperature of the deposit—i.e., much of it was clearly of *nuée ardente* origin. The writers find it rather difficult to visualize these conditions as part of the picture presented by the theory of collapse and engulfment.

Much has been made of the absence of large fragments, bombs, blocks, and other debris on the back slopes of Crater Lake. The alleged cleanness of these slopes is only apparent. As a matter of fact, field observations, especially in recent road-cuts, show great quantities of coarse debris, covered over, veneered, and completely masked by a heavy accumulation of pumice.

An especial point was made by Diller of the finer explosive material about the rim, which, he maintained, was of different composition from that making up the bulk of the mountain; he thought that there ought to

be more andesite fragments than appear on the surface. In this connection, it should be pointed out that much of the later extrusives was dacitic—in particular, the upper flows and pumice—and this would seem to indicate that the older andesitic fragments would naturally be covered over by the more-acid type of material of later extrusion.

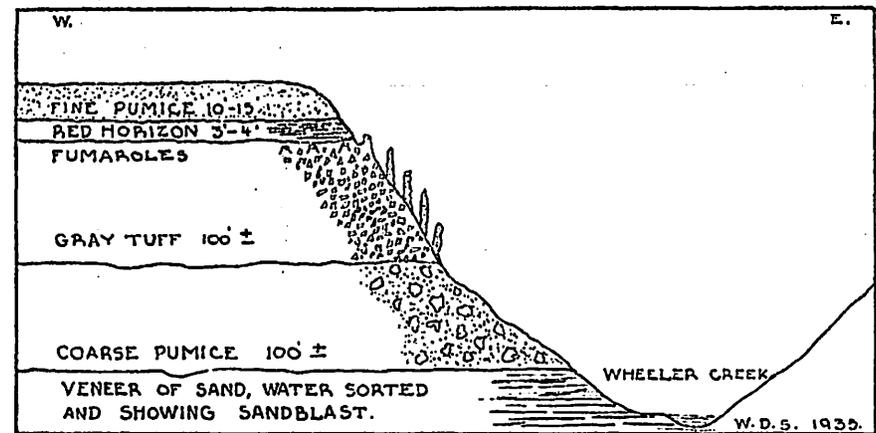


FIGURE 3.—Section in Wheeler Canyon

Examination of the coarser fragments in Wheeler (Fig. 3) and Annie creeks and other canyons radiating from Crater Lake reveals much andesitic material mixed with coarse, and even large chunks of, pumice. Just what is the proportion of andesitic to dacitic material cannot be stated at present.

Concerning the veneering of coarser fragments by the pumice, there is a rather pertinent paragraph in Charles E. Stehn's discussion of Krakatoa. He says:

"The solid rock of which the Danan was built up, products of the first eruptions in 1883 and of the recent explosions, which had been deposited here also, were hurled high into the air and distributed over the three islands.

"The heavier material fell first and formed the block horizon; the lighter pumice descended later. Thus the sifting filled up the spaces between the blocks and formed the last layer of the products of 1883."³

This account of the conditions of Krakatoa appears to agree closely with what the writers have observed at Crater Lake (Pl. 3, fig. 1). It explains what earlier observers apparently interpreted as absence of sufficient amounts of coarse debris, which seem to be demanded in a situation of the kind attendant upon an explosion of great magnitude.

³ Charles E. Stehn: *The geology and vulcanism of the Krakatau group* (1929) p. 29. Fourth Pac. Sci. Cong., Batavia, Java.

from the rim to the pit of Halemaumau, a distance of several miles, there is only a most superficial resemblance between the two.

The caldera of Kilauea is a veritable slag-pot, with fused material everywhere and evidences of peripheral faulting on all sides; it has, for the most part, vertical walls. Most of its history has been quite different from that of Crater Lake.

On the other hand, the crater (and this appears to be the correct term to use) of Crater Lake is a typical explosion orifice; there is relatively little peripheral faulting visible and no visible fusion within the crater.

Even Dutton had grave doubts about the lack of features to be expected in the case of a sinking mountain, to judge from the following:

"In the Hawaiian calderas the evidences of sinkage are conspicuous. They are not confined to the deeper floors of the pits, but are also seen in the partial subsidence of great blocks or slices of the walls immediately enclosing them, and in irregular sunken spots in their vicinity, also in the marks of powerful shearing or faulting action in the walls themselves. They appear to be correlated to the remarkable quiet habits of the Hawaiian volcanoes, to their habitual modes of eruption, and to the special structure of the volcanic piles, which do not rise in steep conical peaks, but are very broad and flat. At Crater Lake, neither in the walls themselves, nor in the immediate neighborhood back of the crest line, have any traces of sinkage been observed as yet. Nothing can at present be pointed out which suggests the Hawaiian mode of origin, beyond the fact that a vast crater is before us. The general structure and habits of the Cascade volcanoes are indicative of a more vigorous style of volcanic action than the Hawaiian."⁹

This statement of Dutton is repeated here, because many proponents of the collapse theory refer to Kilauea in their arguments. Evidently, they are unfamiliar with the conditions at Kilauea, or they overlook the significant features just pointed out (Pl. 5).

Atwood's studies⁹ have clearly and unmistakably shown how numerous have been the explosive actions of Mount Mazama in the past and how different this history has been from that recorded at Kilauea.

Furthermore, no one, to the writers' knowledge, has ever asserted that a vast superstructure over the present caldera of Kilauea ever existed and that it fell in. It exists as an orifice in the top of a low lava dome, in which the lava periodically rises and falls, and where only at long intervals, as a minor episode in the history of the mountain, have explosive extrusions occurred. This appears to be a very significant difference.

Of course, subsidence craters are not unheard of, though they are, as far as known, relatively scarce on the Pacific Rim.

Inasmuch as some proponents of the theory of subsidence of craters may

⁹ J. S. Diller and H. B. Patton: *The geology and petrography of Crater Lake National Park*, U. S. Geol. Surv., Prof. Pap. 3 (1902) p. 48.

¹⁰ W. W. Atwood, Jr.: *The glacial history of an extinct volcano, Crater Lake National Park*, Jour. Geol., vol. 43, no. 2 (1935) p. 142-168.

be tempted to cite, and have done so in oral discussions with the writers of this paper, the case of the well-known volcano of Mull, off the Scottish Coast, so admirably worked out by E. B. Bailey and his co-workers, it should be pointed out that this discussion is hardly pertinent here. Dis-

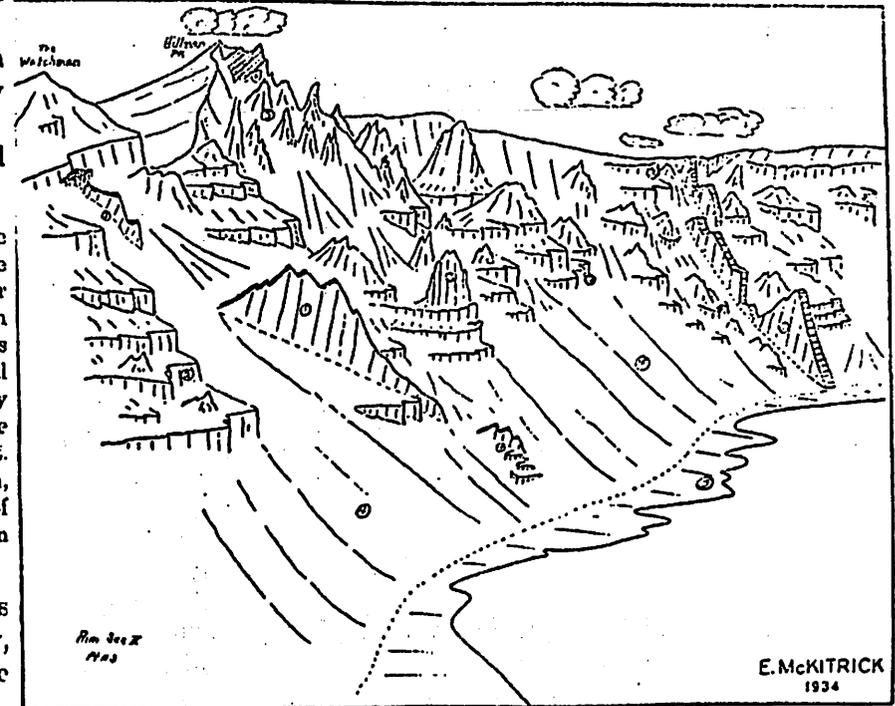


FIGURE 5.—Hillman Peak area

(Sketch after E. McKittrick.) 1. The Devil's Backbone—andesite dike; 2. Andesite flows; 3. Cemented fragmental material; 4. Talus slope; 5. Low fan deposits; 6. Agglomeratic flows.

section of the remains of Mount Mazama have not proceeded far enough to permit one to ascertain whether or not the deeper structures do resemble any of those found in Mull, and any such possibilities must remain purely conjectural.

That well-known student and photographer of vulcanism in many parts of the world, the late Tempest Anderson, Fellow of the Geological Society of London, visited Crater Lake sometime prior to 1903 and was convinced of the explosive origin of this crater.¹⁰

The present writers studied several collapsed areas in the basalts of the surrounding region, where it is evident that caving has taken place,

¹⁰ Tempest Anderson: *Volcanic studies* (1903). (London).

and the topography of the subsidence areas is totally unlike anything within the main crater.

Furthermore, nearly everywhere, but notably in Hillman Peak (Fig. 5), the ends of flows are turned upward or tend to turn upward. The high percentage of fragmental material within the rim and the subsequent explosive history indicated by the appearance of the three later cones would appear to be convincing evidence that subsidence could hardly have taken place on the scale suggested by Diller. Such procedure would, in the light of its previous and subsequent history of extrusion, seem unusual, to say the least.

One must bear in mind, of course, that the crater has been considerably modified by subsequent erosion and that the old walls have been cut back so that the present ones might conceivably present a somewhat different appearance from the former, with all the old fused material removed. However, there has not been much of this removal, or the slopes would be much lower. The comparative recency of the main action is obvious.

Still another point should not be overlooked—namely, the configuration of the bottom of the crater. As far as can be judged from the present soundings, the bottom of the crater does not have the configuration one would expect from subsidence, for the basin seems to be like one from which material has been scooped out, rather than one into which much debris has fallen. In other words, its configuration is not irregular enough. Whatever modification of the bottom contour may subsequently have taken place seems due almost entirely to the building of the later cones, Wizard Island and the other submerged ones that have no name.

If one disregards the subsequent extrusions that have been built up within the older cavity, created as a result of the wrecking of the mountain, he has to deal with an orifice that cannot easily be explained as due to subsidence. This particular basin, bowl, or crater, of which an accurate picture is available as a result of soundings and the slope of crater walls above the water-line, is strikingly similar to mine craters, produced during military operations. The walls of such craters tend to follow the characteristic catenary curve. Such craters, compared with photographs of large craters on the Western Front during the World War, present close similarity (Pl. 1, fig. 2). The dissimilarity to subsidence craters common in mining operations and the remarkable resemblance to explosive mine craters would seem good grounds on which to reject the collapse theory.

Conditions resulting from mine subsidence was the theme of a paper published several years ago by Rice.¹¹ His photographs and diagrams

¹¹ George S. Rice: *Some problems in ground movements and subsidence*, Am. Inst. Min. Metall. Eng., Tr., vol. 69 (1923) p. 374-393.



FIGURE 1. MODEL OF CRATER LAKE
Looking North. Mounts Thielsen and Bailey in distance.
(National Park Service)



FIGURE 2. MINE CRATER ON WESTERN FRONT
(The Times History of the World War)



FIGURE 3. SUN NOTCH, A BEHEADED GLACIAL VALLEY

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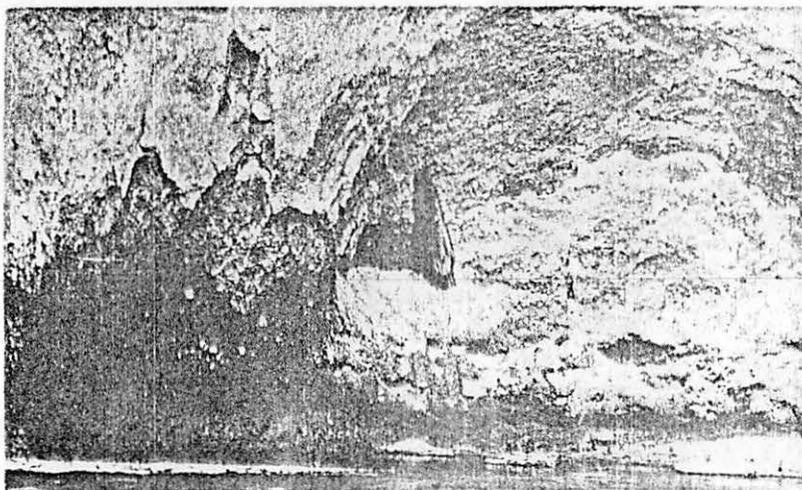


FIGURE 1. BURIED TREE IN PYROCLASTICS ON ROGUE RIVER

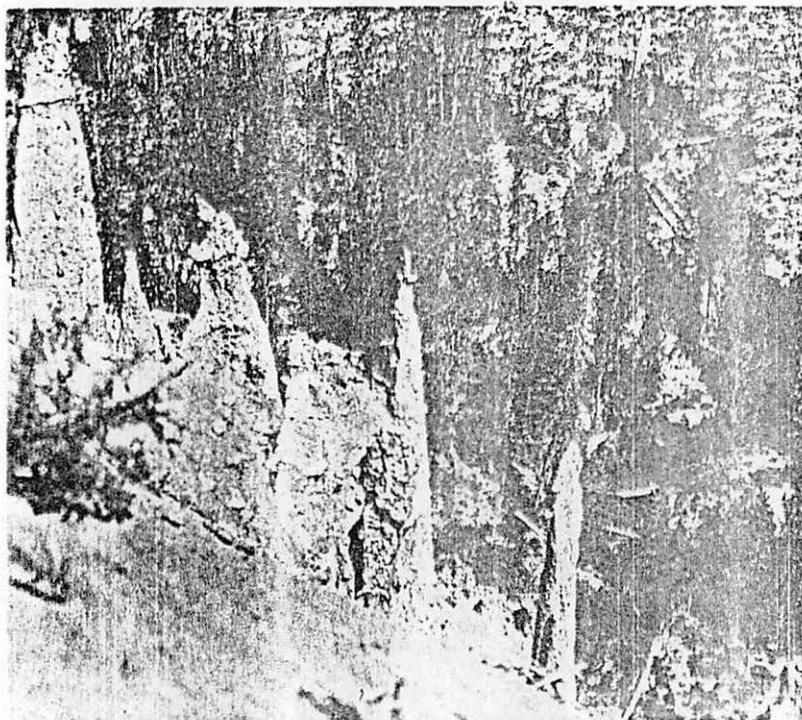


FIGURE 2. PINNACLES AND FUMARoles IN WHEELER CANYON

EROSION REMNANTS

throw considerable light upon this point and indicate some important features attendant upon subsidence, which appear to be totally lacking at Crater Lake. Of these, conspicuously absent are large areas of slumping and vertical slip walls, with one exception of a doubtful nature just under Garfield Peak.

It is interesting to note, in passing, that de Martonne says:

"The explosions which occur very frequently in volcanoes with acid lavas can take place in all volcanoes that for some time have ceased to throw out igneous material. The consolidated lava, in effect, plugs all the chimneys. When the pressure of the gas becomes too strong, the lava plug comes out, and the explosion pulverizes a great part of the mountain. Sometimes it lifts off only the upper part of the cone; sometimes it is opened up to the base, leaving only a fraction of the crown of the crater, which can be as much as 10 kilometers in diameter. Often, under the name of craters of explosion are designated those immense cavities that in the Azores are called calderas. Almost always one sees, after the explosion, one or more cones built up in the center of the caldera. Such is the case on the Isle of Reunion, where the adventitious central cone of Grand Brule has built up to a height greater than the wall of the caldera. A lake can fill the caldera, the accidental cone taking the form of an island. Such is the case of Crater Lake in Oregon in the western part of the United States, and Lago de Vico with the Monte Venere in Italy."¹²

Of course, it may be justifiably contended that this argument is weak, inasmuch as de Martonne had made no detailed study of the local situation. On the other hand, it would seem that his comparative studies of the forms of many volcanic craters in different parts of the world are not without some relevancy, particularly as Diller's observations were available to de Martonne, and he, undoubtedly, was familiar with them.

ABSENCE OF EXTRUDED LAVA OF RECENT DATE

Diller, true scientist that he was, admitted this very vital evidence as being completely lacking at the time of his work. Since his time, no recent flow has been discovered, such as one finds on the lower slopes of Mauna Loa and Kilauea, anywhere within reasonable range of Crater Lake, and, in the opinion of the writers, it is unlikely that one will be found.

During the field seasons of 1934 and 1935, the writers traversed, by car and on foot, many miles of country on all sides of the crater, both within and beyond the Park boundaries, but saw nothing except later pyroclastics, the older Miocene lavas of the Columbia River series, or the younger basalts of the adnate¹³ cones, Red Cone and Timber Crater, beyond the large crater, and nothing that could in any way be interpreted as later fused material that could have issued from openings in the side of Mount

¹² Emmanuel de Martonne: *Géographie physique*, vol. 2 (1925) p. 734-736.

¹³ Term used by Diller; parasitic might be more appropriate.

Mazama. The dike known as the "Devil's Backbone" is nearest to that kind of material, but it probably long antedated the final cataclysm. One might reasonably argue, at this point, that this magma may have issued from some opening in the side of old Mazama that is now concealed by the pumice accumulations. This is a legitimate point to raise, and, until the whole region is thoroughly explored and every stream channel studied with this in mind, one cannot dismiss this argument.

MATERIALS OF THE RIM

Diller has said:

"The area of the caldera, as marked out by the crest of the rim, is over 27 square miles, and its original volume, making some allowance for the subsequent refilling from the craters on its floor, is about 12 cubic miles. If to this we add 5 cubic miles for the part of the mountain above the caldera—and this is a conservative estimate—we get 17 cubic miles of material, for whose disappearance we have to account. If this material were blown out by a great explosion and fell equally distributed upon the outer slope of the rim within 3 miles of the crest, it would make a layer over 1,000 feet in thickness. This mass would be so conspicuous and composed of such fragmental material that its presence could not be a matter of doubt. There can be no question concerning its complete absence, for the surface of the outer slope of the rim exposes everywhere either glaciated rock, glacial moraine, or pumice, all of which are features which belonged to Mount Mazama before its destruction, and no trace of a fragmental rim, such as is referred to above, was found anywhere."¹⁴

The present writers wish to challenge several statements in this paragraph.

First, this blown-out material does not have to be found "within three miles of the crest." Even a superficial knowledge of East Indian and other Pacific volcanic eruptions would show the irrelevancy of this statement. Debris from Krakatoa fell to a depth of several inches on the decks of ships 1200 miles away in the Indian Ocean, and some of the finest ash went around the world.

Second, "and no trace of a fragmental rim, such as referred to above, was found anywhere." The only answer the writers can make to this is—if Diller could walk over some of the same territory today and see the new road-cuts, he would be amazed at the amount of fragmental material on the rim and back slopes. One feature, which Diller makes little of, and which seems to have tremendously impressed later observers, is the very considerable amount of fragmental material everywhere about the rim of the crater; not only the considerable amount, but the preponderance of it. At this point, one might properly ask, "Why are not Kerr and Sun notches (Pl. 1, fig. 3) old glacial valleys, formed before the cataclysm and later truncated, filled with debris from the mountain?" These valleys do

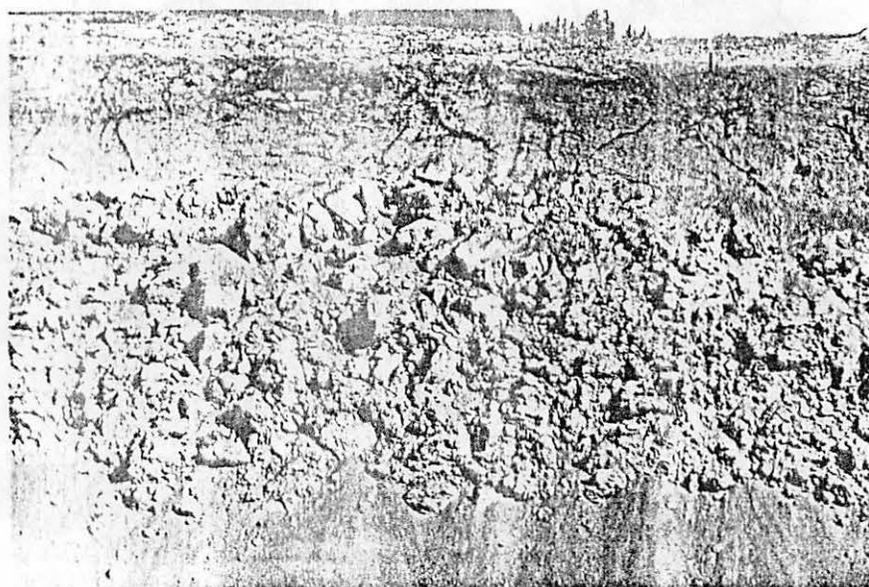


FIGURE 1. SECTION ON DIAMOND LAKE ROAD
Pumice veneering blocky débris.

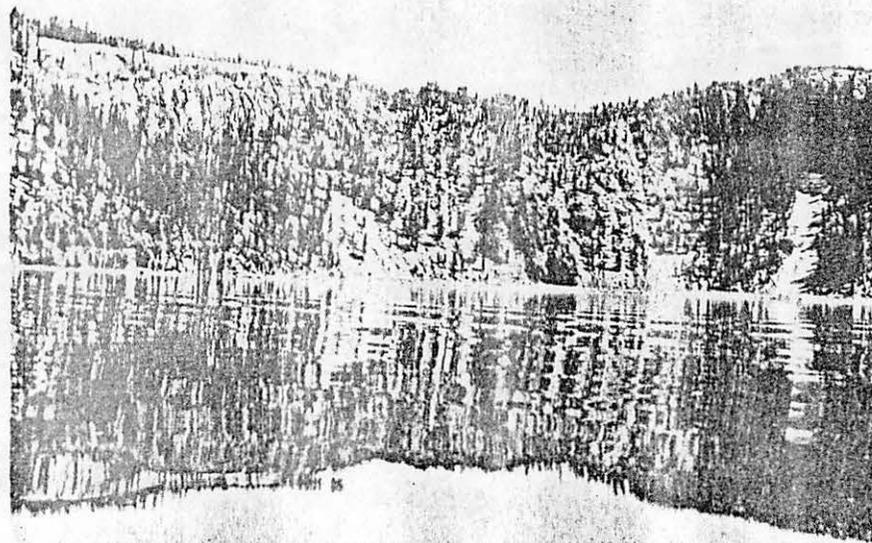


FIGURE 2. "BACKFLOW" IN CLEETWOOD COVE

¹⁴ J. S. Diller and H. B. Putton: *op. cit.*, p. 48.

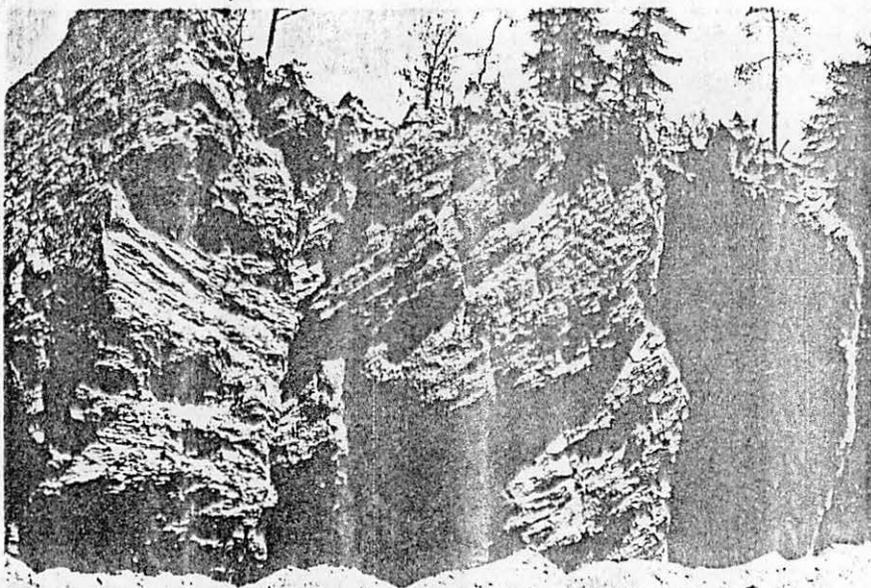
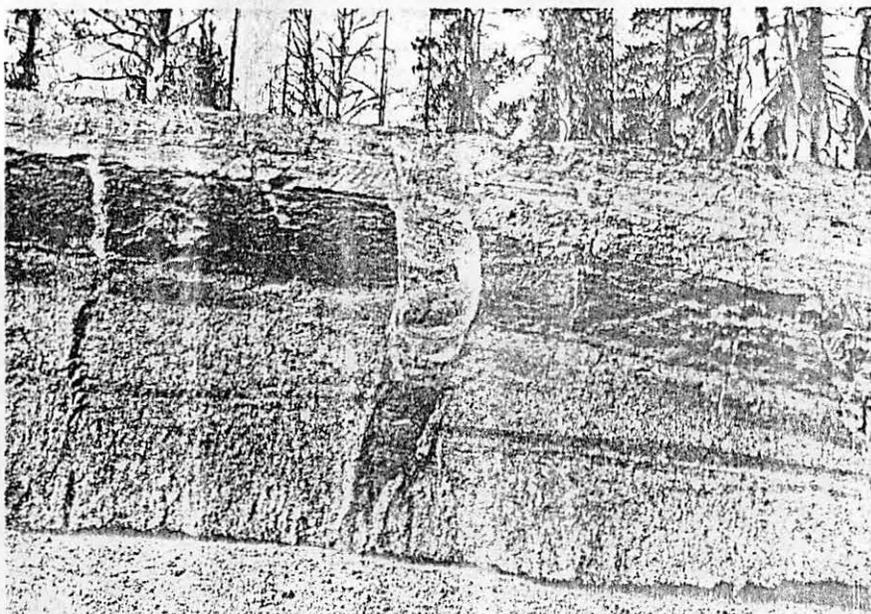


FIGURE 1. MAZAMA ROCK

FIGURE 2. BANDED PUMICE NEAR MAZAMA ROCK
Note the clastic dikes.

MAZAMA ROCK

contain a certain amount of pumice, but, if one remembers the direction of the prevailing winds in this region, and if he recalls the distribution of material during the recent Lassen eruption to the northeast of that mountain, he will have a satisfactory explanation, it would seem, for not finding these valleys completely filled. Furthermore, if the major explosion and disruption occurred when glaciers filled the valleys, subsequent melting of the ice would leave the valleys relatively free from debris of this kind.

Third, the statement . . . "there can be no question concerning its complete absence (fragmental material) for the surface of the outer slope of the rim exposes everywhere either glaciated rock, glacial moraines, or pumice, all of which are features which belonged to Mount Mazama before its destruction." The present writers do not find evidence for this view, in the face of the fact that pumice covers most of the glaciated surface and must have been the last event before the filling of the lake and the formation of Wizard Island and its sister cones within the crater. During the 1934 and 1935 seasons, the writers made some observations on the back slopes on the eastern side of the crater and were amazed to see the large masses of lava blocks, some larger than houses, in the region between Pumice Point and Skell Head. Mazama Rock is apparently quite severed from the rim and is only one of many such dislodged masses.

The whole eastern rim (Pl. 4, fig. 2) is covered with great layers of pumice, so that the coarser fragments are almost completely masked. On Llao Rock, farther to the north, the pumice blanket is at least 150 feet thick, and glaciated surfaces are relatively scarce, and have to be exposed by excavation; in some places, they are 60 feet below the surface.

W. W. Atwood, Jr., summarizes the glacial history of this ancestral mountain, as alternation of glaciation with great eruptions, indicating that explosive eruptions have repeatedly occurred in the history of the mountain.¹⁵ Is it not reasonable to assume that such have occurred in more recent times?

Although there are many good examples of glaciated surfaces in the area, they are, with a few exceptions, in isolated places, where they have been exhumed by the wind, or are partially buried by debris. They are generally inconspicuous. Compared with the many square miles where no glaciated surface is exposed, such surfaces are relatively scarce.

There is a preponderance of morainal material on the west side of the lake, but not about other portions of the rim. There is relatively little such material on the north and east sides, where the major portion of the eruptive material fell.

There is evidence, not yet conclusive, for thinking that some glaciation

¹⁵ W. W. Atwood, Jr.: *The glacial history of an extinct volcano, Crater Lake National Park*, Jour. Geol., vol. 43, no. 2 (1935) p. 142-168.

occurred after the destruction of Mount Mazama, indicated by cirques at the head of Munson and Castle creeks, which did not cut back through the rim of the crater. However, the main glaciation occurred before the wrecking of the mountain. In fact, there is good evidence for saying that there have been at least three epochs of glaciation on the mountain.

MECHANICS OF COLLAPSE

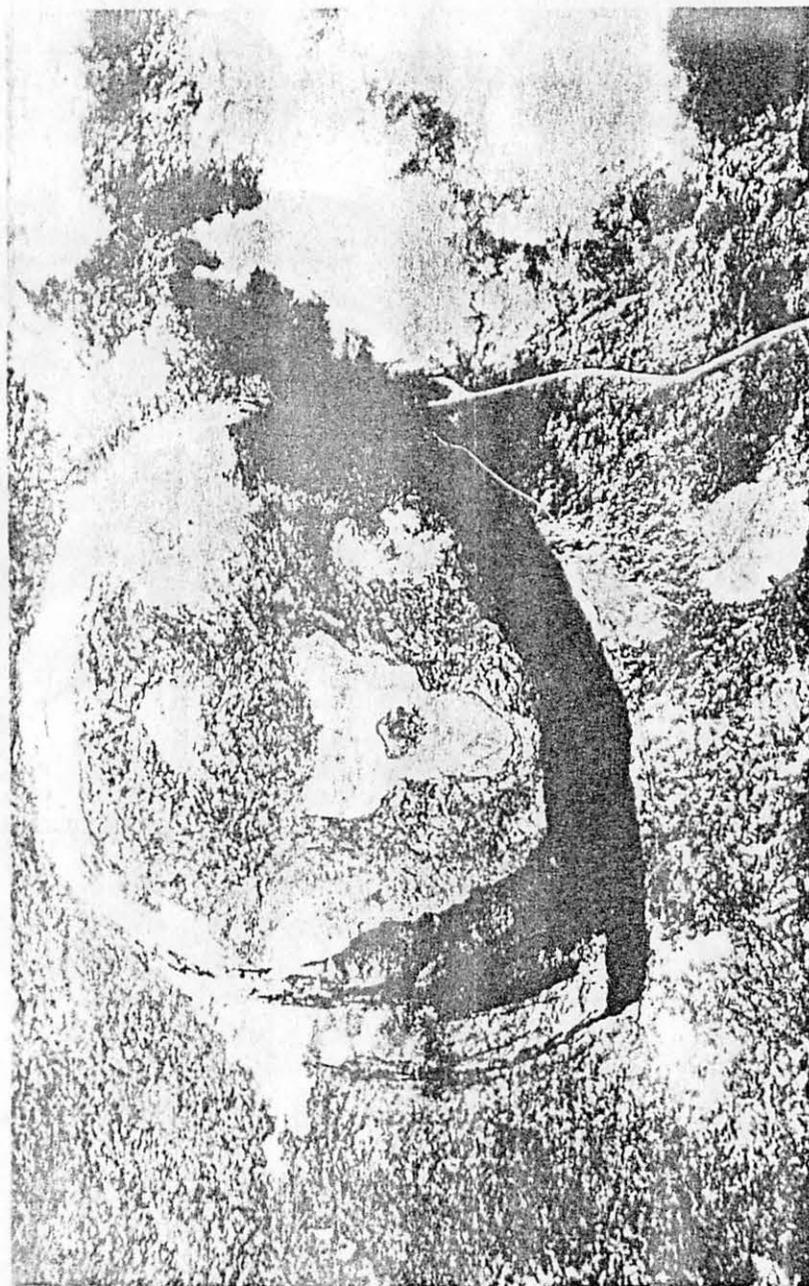
When the dominant forces in volcanic regions are acting outward, to suppose that a whole mountain, or seventeen cubic miles of it (Diller's own estimate), collapsed seems to be mechanically unsound, especially when that mountain's entire previous history, as far as one can judge from a study of its crater walls, has been one of extrusion. On this point, T. C. Chamberlin wrote to Bailey Willis, some years ago, as follows:

"In regard to the great pit of Crater Lake, my mind runs parallel to yours on general principles. I do not take kindly to the idea that the Earth melts its upper crust and swallows the product. I think the upper crust is a place of cooling, and only in exceptional cases, where there are gases to be burned or some special source of heat, does it seem likely that melting takes place. Moreover, if I read the signs aright, the interior is a place of high compression with predominant lateral stresses in the outer part, and the natural direction of liquefied rock is outward rather than inward. If anyone holds that a mountain has been melted and swallowed, he is under obligations to show how and why the natural order of things is reversed. No doubt it may be in some cases. I can understand that if there were an underduct that could lead the lavas away to some lower point periodically, and if there were much combustible gas coming up the throat of the volcano from the interior, it might melt the walls of the crater and cause them to fall in, and in time become liquid and be so discharged through the supposed outlet. But then, this is Kilauea reflected as you suggest. So, I do not see how I can part company with you even on the ground of exceptional action."

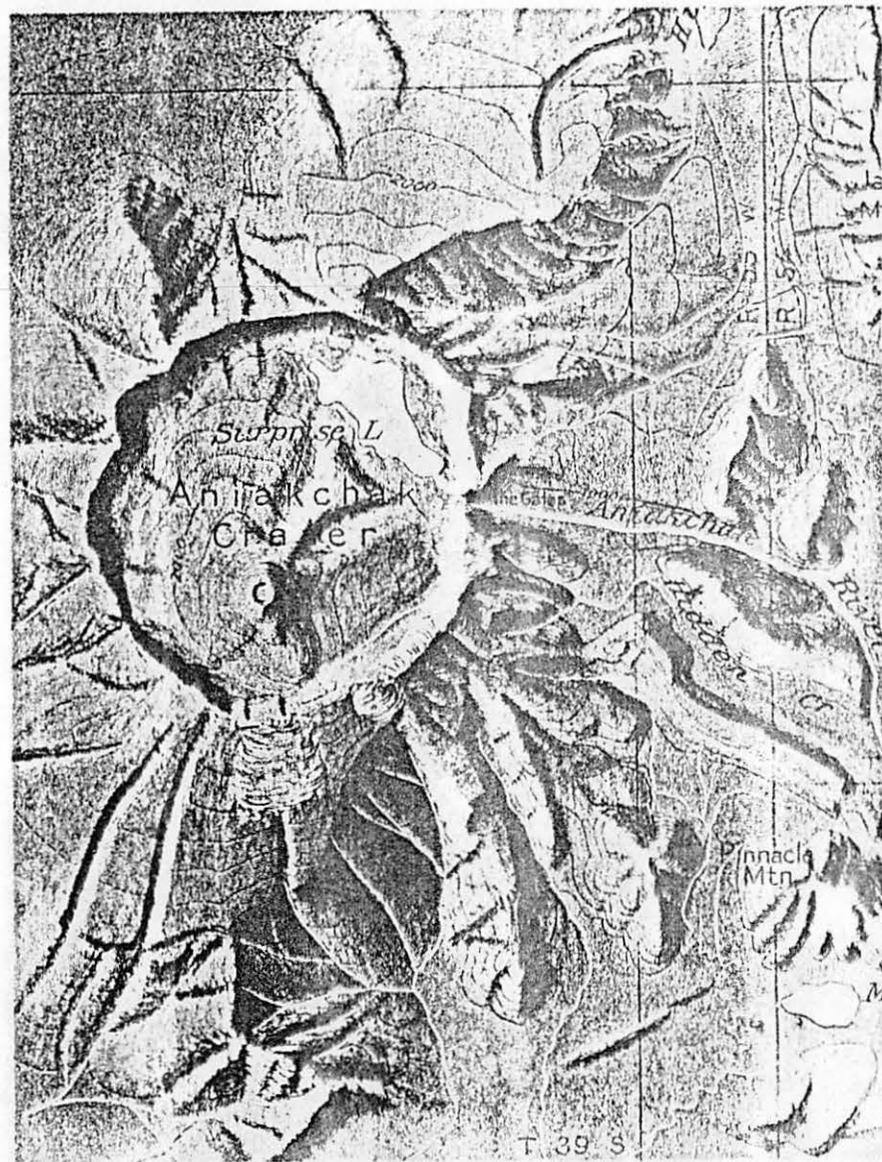
In considering the collapse theory, a number of problems present themselves; namely, the original height of Mount Mazama, the size of the crater and neck of the mountain, and the shape of the opening, vent, or receptacle into which the collapsed superstructure fell. These three points will be considered in detail. They involve many hypothetical situations, but, by comparing historic volcanoes with Mount Mazama, a series of data may be assembled, consistent with facts known to have been the case in other eruptions.

The height of Mount Mazama was first estimated by Diller to be about that of Mount Shasta, 14,161 feet. This figure is conservative, and 15,000 feet is a more common estimate.¹⁶ The quantity of material removed from the mountain during its destruction was estimated by Diller to be 17

¹⁶ Work during the field season of 1935 indicates that both these figures are too high and that 12,000 would be more nearly correct.



PIT OF HALEMAUMAU, KILAUEA
(Photo by Volcano Observatory, Hawaii)



ANIAKCHAK VOLCANO, ALASKA PENINSULA
(Photo by W. R. Smith, United States Geological Survey)

cubic miles. This comprised the upper 6,000 feet of the mountain and all of the present interior of the rim of Crater Lake. These estimates of Diller are generally accepted by investigators of the origin of Crater Lake, whether or not his theory of destruction is subscribed to. Any alternative that is proposed for the destruction of Mount Mazama, must account for these quantities. Certainly, a mountain of that magnitude must have been present to account for (1) the vast system of glaciers on Mount Mazama, probably as extensive as the system on Mount Rainier, (2) the size of the base of the mountain, (3) the angle of the slope.

The third point mentioned at the beginning, the shape of the receptacle into which the collapsed portion fell, is significant, because the depth of the hole would be largely dependent on the shape of the opening. However, there is no way of determining whether the opening was cylindrical, spherical, conical, or merely irregular.

At the present time, the rim rises above Crater Lake to a maximum height of nearly 2,000 feet. The sounding of the deepest part of the lake is, likewise, 2,000 feet. It is true that these are maximum figures, but they may be used with justification when one realizes that, after the destruction of the top of Mount Mazama, three volcanic cones were built up in the bottom of the lake. It may easily be supposed that this added material built up the bottom of the crater several hundred feet.

There is, then, a vertical distance of 4,000 feet from the top of the rim to the bottom of the lake. Mount Mazama rose 7,000 feet above the present crater rim, however, making a total distance of 11,000 feet from the top of the mountain to the bottom of the lake. But, below this, there must have existed an opening large enough to receive the 17 cubic miles of superstructure that is supposed to have collapsed. If the cross-sectional area of the neck of Mount Mazama is assumed to have been two square miles, an additional depth of $8\frac{1}{2}$ miles, or something over 44,000 feet, existed, making the total depth of the hole, from the top of Mount Mazama, about 55,000 feet. It seems patently impossible for such a cavity to exist in the earth's crust. The pressure and heat developed at such a depth would cause the closure of the opening long before that depth were reached.

There remains, then, the possibility that Mount Mazama collapsed into a huge irregularly spheroidal opening. But, again, an opening of 17 cubic miles, existing below 11,000 feet, is nearly as impossible a concept as the one required for the conditions already mentioned.

Another point to consider is the fact that, after the destruction of Mount Mazama, three cones were built up on the bottom of the crater. Two are covered by the lake, and the only one that may be studied, Wizard Island, is composed of basic andesite fragments. The island was

built up from the bottom of Crater Lake to a height of nearly 2,000 feet, and, as far as observations have gone, no other material has been found. If the neck of Mount Mazama had been choked with dacite, pumice, and andesite from the collapsed superstructure, at least some indication of these materials should be present in the ejecta comprising Wizard Island.

The possibility presents itself that the collapsed materials became fused at depth and were later ejected. The bulk of material comprising the upper part of Mount Mazama was dacite and dacitic pumice with subordinate quantities of andesite. Unless unusual magmatic differentiation took place, the andesite of Wizard Island would be less basic in character, owing to the assimilation of the acidic dacite.

If the remote possibility of fusion and differentiation of collapsed material did take place, the mechanics of such a condition are again antagonistic to the engulfment theory proposed by Diller. If sufficient heat were present to fuse all, or most, of the engulfed 17 cubic miles of rock fragments, there was far too much heat to allow an original opening large enough to receive the subsided materials.

It will, doubtless, be pointed out that it is unnecessary to stipulate a "hole" or cavity into which the mass of Mount Mazama would fall, but that, through the process of magmatic stoping the previously extruded matter would be slowly melted and assimilated and, thus, obeying the laws of hydrostatics, be re-absorbed and re-distributed in the magma reservoir. The writers do not believe there could have been a "hole," but, if solid collapse occurred, one must have existed. They fail to see just how and why the normal extrusive processes in the case of this type of mountain would be reversed. In the Kilauea type, a low lava dome volcano of very basic and very fluid lava, this would be expected, but not in the composite cone type, such as Mount Mazama.

There are two objections to the stoping theory: First, the absence of fused materials within the crater rim, and, second, the presence of caves, which are found almost exclusively in the andesite. Had the caves been formed by stoping instead of being simple flow cavities, there should be approximately the same number of caves in the dacite. Furthermore, if these caves were exposed to a stoping magma, it seems reasonable to assume that the magma would have filled the caves. Some geologists may advance the contention that these caves have been exposed during subsequent erosion, but the writers believe that the crater is a young physiographic feature and that there has been insufficient erosion to support this contention. The rim walls are steep and precipitous, the angle of repose of the talus is high, and the beach around the lake is exceedingly narrow, all attesting the youth of the crater.

In support of engulfment and resorption in the new magma of the

materials of the upper part of the mountain, further chemical and petrographic study is needed.

On this point, Ernest McKittrick, who worked on some phases of the problem, says:

"The evidence for this would be the same as that cited by Fenner¹⁷ in his study of Katmai; the presence of basic phenocrysts in siliceous pumice and the gradational stages in the digestion of older rock. He also points out the presence of banded or variegated pumice and attributes this to the solution of more basic rock in the new siliceous magma just prior to eruption. So far as I have observed, such features are lacking at Crater Lake, and in the petrographic study made by Patton, I do not recall his pointing out such features."¹⁸

Since Patton's study, accompanying Diller's paper, very little petrographic and chemical research on the rocks of this region has been made. It is hoped that David Griggs, who spent several weeks in the field during the field season of 1935, and who collected an extensive series of samples of lavas and pyroclastics, will follow this paper with the results of his petrographic studies.

The writers have given considerable thought to the possibility of gradual collapse by piecemeal stoping but have been unable to visualize this process in a mountain of this type. In volcanoes of the Kilauea type, this explanation seems reasonable, but not in one whose history, in the main, has been largely that of extrusion, much of it violent.

RECORDS OF SOME PACIFIC RIM VOLCANOES

The writers know of no volcano of the Pacific type that has certainly collapsed. In fact, they know of no mountain of any kind about the Pacific that has been engulfed, although Krijanovsky records a comparatively recent eruption in Kamchatka of the volcano Klyuchevskoi, one of the great but apparently little known volcanoes of the world.¹⁹ In this eruption, "the sharp summit collapsed into the crater, destroying the symmetry of its wonderfully regular cinder cone."

Since this article was first written, Howel Williams has described the Newberry craters in central Oregon and has presented apparently sound arguments for subsidence and engulfment at that place.²⁰ To the writers, however, conditions in the Newberry craters and their history appear markedly different from those at Crater Lake.

As evidence of the general rule among Pacific Rim volcanoes, and not

¹⁷ Clarence N. Fenner: *The Katmai region, Alaska, and the Great Eruption of 1912*, Jour. Geol., vol. 28 (1920) p. 580-606.

¹⁸ Personal communication.

¹⁹ N. Krijanovsky: *Volcanoes of Kamchatka*, Geol. Soc. Am., Bull., vol. 45 (1934) p. 529-540.

²⁰ Howel Williams: *The Newberry volcano of central Oregon*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 253-301.

the exceptions, one need merely to call attention to the following explosive eruptions within historic times:

- (1772) Papandayang, Java—9,000 feet elevation, 30,000,000,000 cubic feet of ejecta. Height of mountain reduced to 5,000 feet.
- (1815) Tamboro, Sumbawa, near Java—50 cubic miles of ejecta.
- (1882) Galoongan, Java—Explosion, no estimate of amount of material ejected.
- (1883) Krakatoa, Sunda Straits—5 cubic miles blown away.
- (1888) Bandaisan, Japan—Greater part of cone blown away.
- (1911) Taal, Philippines—Old volcano crater disemboweled by explosion and crater lake formed.
- (1912) Katmai, Alaska—Explosion, 4.75 cubic miles of ejecta.

The writers' attention has been called, in conversation with Father Bernard Hubbard, to Aniakchak volcano in Alaska. Walter R. Smith, of the United States Geological Survey, believes that Aniakchak attained its present condition through explosion.²¹ It has a remarkable resemblance to the crater of Crater Lake. The orifice of Aniakchak (Pl. 6) is similar in proportion and shape to Crater Lake; it lacks a large lake nearly filling it. Owing to a breach in the wall, most of the Aniakchak crater is now empty of water, though a small lake, Surprise Lake, does exist in the northeast quadrant. Near the south side is a single small secondary cone, built up subsequent to the great explosion, much as in the case of Wizard Island. By blocking off the lower portion of one of the panoramic views of this crater and coloring the lower portion blue to simulate the lake in Crater Lake, the likeness of it to Crater Lake is almost startling. Perhaps this proves nothing, but such physiographic resemblances may not be entirely fortuitous.

In Italy, New Zealand, and elsewhere are many crater lakes, some with secondary cones and some without, but all, as far as can be learned at present, formed as a consequence of explosive activity. Mercalli²² records a crater lake, similar in size and appearance to Crater Lake, on the island of Niuafou in the Tonga Archipelago. The physiography of this lake, 8 kilometers in diameter, is, judging from his excellent photograph, almost a duplicate of that of Crater Lake except for the presence of two islands instead of one. This crater lake is said to have been formed as a result of a violent explosion in 1886.

If one of the writers had not been familiar with the history of Taal volcano in Luzon, where an explosive eruption in 1911 and subsequent formation of a crater lake comparable in every way to Crater Lake

except in size, was witnessed, he might be willing to entertain such an unusual hypothesis as that of engulfment at Crater Lake as a possibility, perhaps, though not as a probability.

The eruption of Taal²³ was of the Pelean type; more than a thousand persons were asphyxiated by the exploding gases. After the major eruption, the floor of the old crater was found to be completely gone and a large steep-walled crater, not greatly unlike that of Crater Lake, excavated. It was about 260 feet deep, but in a few weeks it had filled with seepage water, and today a small crater lake exists where, prior to the eruption, one could walk over a fairly smooth floor.

SUMMARY AND CONCLUSIONS

Summarizing the preceding considerations, and others not elaborated in this article, the objections of critical importance to the traditional collapse theory seem to be the following:

(1) The distribution, character, and known quantity of volcanic ejecta within a reasonable distance of Crater Lake seem to indicate that explosion is the most acceptable explanation for the origin of the crater of Mount Mazama.

(2) The so-called "backflow" of Diller in Cleetwood Cove can be explained by faulting and slumping, in part, and also by the way the section was cut by the extrusion of material from the main vent. Even if this were a genuine "backflow", it would not disprove explosion.

(3) The shape and character of the materials of the crater are typical of known explosion volcanic craters. The shape of the crater at Crater Lake is remarkably like that of typical mine craters and quite unlike that of subsidence craters.

(4) Molten material of recent age, which might have issued at some vent lower down on the slopes of Mt. Mazama, has not been found.

(5) Glaciation of the surfaces about the rim has been overemphasized. Most of these surfaces have been completely concealed by pyroclastics, predominantly pumice.

(6) Known subsidence craters, like that of Kilauea, exhibit strikingly different features from those found at Crater Lake.

(7) Subsidence areas in the younger basalts outside the limits of Crater Lake show features in no way resembling what one finds within Mount Mazama's crater.

(8) All other volcanoes on the Pacific Rim, with possibly one or two exceptions, known to have partially destroyed themselves, have done so through explosion.

²¹ W. R. Smith: *Aniakchak volcano, Alaska Peninsula*, U. S. Geol. Surv., Prof. Pap. 132 (1925) p. 139-149.

²² G. Mercalli: *I vulcani attivi della terra* (1907) p. 79, pl. IX.

²³ W. E. Pratt: *Philippine Jour. Sci.*, vol. 6, no. 2, sec. A (1911) p. 63.

(9) The calderas of the Azores, of Italy, and of the Rhine region, all appear to be of similar origin and have hitherto been explained as caused by explosion.

(10) The great mantle of pumice and other ejecta about Crater Lake has masked the coarser fragments, which Diller thought ought to be more in evidence.

(11) Much of the finer ejecta from Mount Mazama may have been blown for hundreds, and even thousands, of miles from the crater; one cannot expect to find 17 cubic miles of such material all within a short distance of the mountain.

(12) The mechanics of the problem, for a mountain of the explosive type, such as Mount Mazama, seem to offer insuperable difficulties to the engulfment explanation.

(13) The closing stages of vulcanism, during which three newer cones of pyroclastic materials were built up within the giant crater, would seem to be quite at variance with general subsidence of the mountain.

(14) A probable post-Mazama period of minor glaciation and later erosion by streams have removed an unknown quantity of the fragments that formerly covered this area.

(15) None of the materials found on Wizard Island appears to be similar in composition or structure to those that formed the upper part of Mazama.

(16) The ejecta of Wizard Island are of a composition that seems to preclude the assimilation of acidic rocks with any other known material in the vicinity of Crater Lake.