THE VOLCANIC ACTIVITY AND HOT SPRINGS OF LASSEN PEAK

BY

ARTHUR L. DAY AND E. T. ALLEN

PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON

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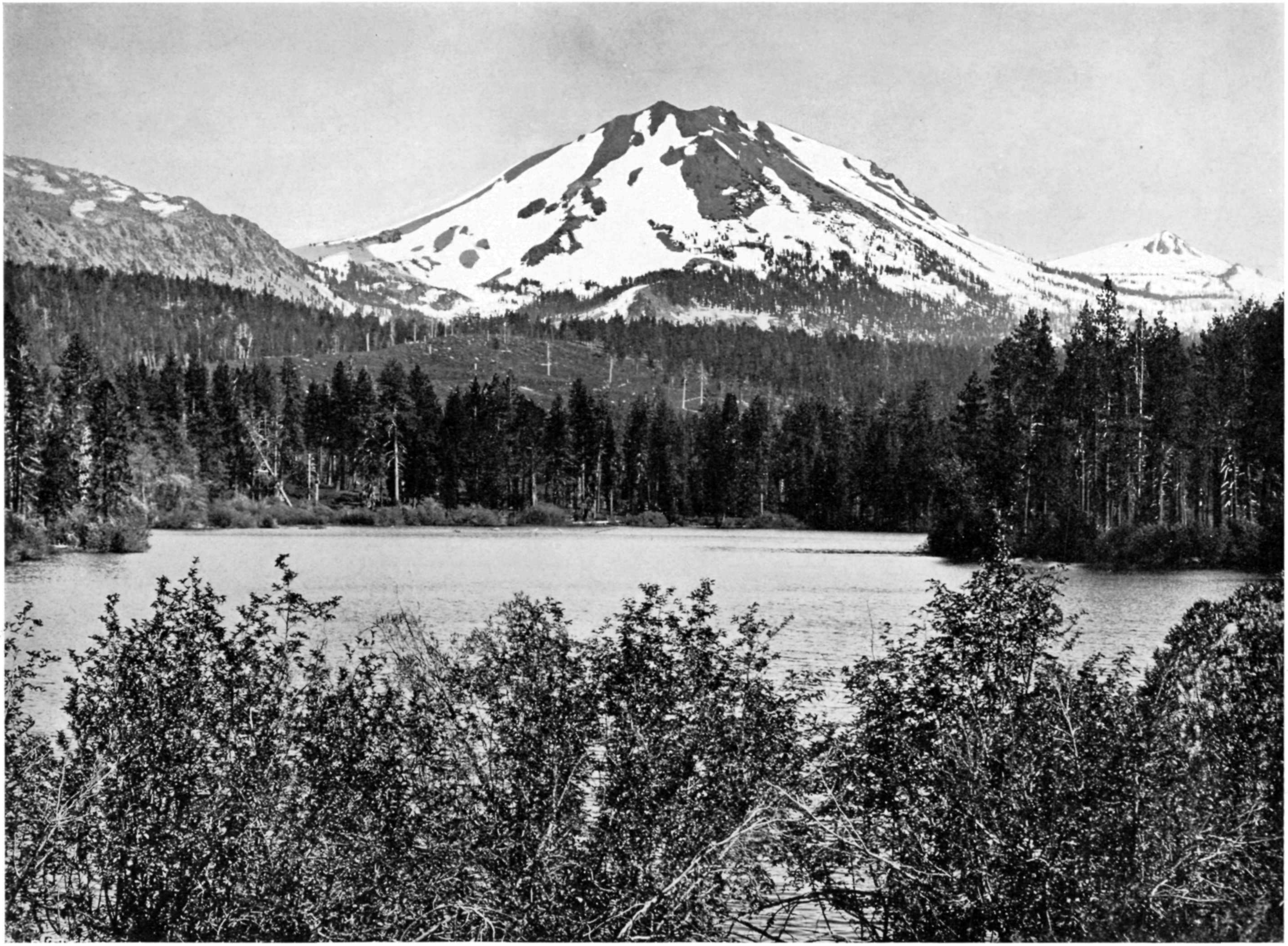

Lassen Peak in 1900. View from Manzanita Lake looking southeast. Photo Loomis.

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PREFACE

The Geophysical Laboratory was first attracted to the study of Lassen Peak by Mr. J. S. Diller, Geologist of the U. S. Geological Survey. Mr. Diller was on the ground during the early eruptions of 1914 and on his return to Washington expressed a wish that the Geophysical Laboratory should cooperate in the study of the outbreak because of the physical and chemical relations involved. It was agreed, tentatively, that the Geological Survey would undertake the necessary geological studies[1] and the Geophysical Laboratory the physical and chemical phenomena. Accordingly the authors made their first visit to the mountain in June, 1915, some four weeks after the culminating volcanic outbreak of that year. Except insofar as conclusions could be drawn from the visible consequences of the eruptive activity of the first year (1914) and the great catastrophic outbreak of May 19–22, 1915, we were therefore dependent upon others for many of the field observations.

We are accordingly under obligation first of all to Mr. J. S. Diller, of the U. S. Geological Survey, who visited the Mountain in 1914, 1915 and 1921, and cooperated with us throughout, then to the Supervisors and Rangers of the Forest Service who, although inexperienced in volcanic matters, were nevertheless men practiced in field observation, of excellent judgment and keen discrimination, and contributed very greatly to the record contained in the following pages.

Mr. A. Sifford, Proprietor of the Drakesbad Camp (seven miles southeast of Lassen Peak), Mr. Roy Sifford his son, and Charley Yori, who acted as guide in this region during both 1914 and 1915, not only provided all facilities and much camp comfort, but were able to contribute important details of personal observation and photographs, as did also the brothers George W. Olsen and Nelson Olsen of Chester, whose observations will be found in detail in the Appendix (page 176).

We were also fortunate in having the cooperation of Mr. B. F. Loomis, one time a professional photographer and now in the lumber business at Viola (7 miles northwest of Lassen Peak) whose splendid collection of photographs, some of them copyrighted, were unreservedly placed at our disposal, together with his diary. The frontispiece and many of the finest illustrations in this book are the work of Mr. Loomis.

Miss Alice Dines, Postmistress at Manton (15 miles west of Lassen Peak) kept an unceasing watch upon the mountain from the beginning to the end of its activity. Her observations will also be found in the Appendix (page 176).

Of the occasional visitors the authors wish particularly to acknowledge the assistance of Professor R. S. Holway of the University of California, who permitted the free use of his photographs and the record of his visit in June, 1915. Likewise the written (and photographic) record of the visits of Mr. W. H. Spaulding, President of the Great Western Power Company, and a group of friends, in 1914 and 1915,

[1] Not yet published.

and the photographs of Mr. Jack Robertson of San Francisco were kindly placed at our disposal. The photographers Mr. R. E. Stinson of Red Bluff, Mr. Chester Mullen of Redding, and Mr. E. N. Hampton of Mineral, also kindly permitted the use of excellent photographs, some of which are copyrighted.

To all of the above named individuals and many others who cannot be mentioned in so brief a space the authors feel under great personal obligation for the uniform courtesy shown in helping us to provide a complete record of this volcanic outbreak, the first of its kind in this country in our generation.

For the laboratory studies of volcano material collected during the eruptions the authors are most grateful for the indispensible cooperation of their colleagues Messrs. Aurousseau, Merwin, Morey and Shepherd, whose accurate work has thrown a flood of light on the whole problem of volcanic activity.

The study of the hot springs (Part II) is entirely the work of the authors, with the help on the ground of Charley Yori and Allen Raker, guides, who aided in every practical way during the years 1915, 1916, 1922 and 1923.

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PART I.

ERUPTION OF THE VOLCANO.

By Arthur L. Day and E. T. Allen.

INTRODUCTION.[1]

Lassen Peak, in the southeastern corner of Shasta County, California, is the southernmost expression of a great volcanic region, to which Mount Shasta, Mount Hood, and Mount Rainier belong. Volcanic activity in the Lassen region began in early Neocene time and has continued, with diminishing violence, to the present day. The period of most violent activity was concomitant with the upheaval of the Sierra Nevada, and some of the earlier lavas are intercalated with deposits of the Ione epoch. The earliest extrusions were of hornblende andesite, and the general course of eruption produced, in turn, pyroxene andesite, rhyolite, dacite, basalt, and, finally, quartz basalt. In detail the sequence is more complicated, some of the basalt flows being old, but, in general, they are the youngest lavas of the region. Some rhyolite flows have succeeded flows of dacite, but for the most part the former precede the latter.[2] The absence of augite andesite from the whole magmatic region to which Lassen Peak and the associated volcanoes belong is noteworthy.[3] Whatever may have been the course of differentiation, that of eruption has been from the production of intermediate lavas to that of extreme types, ending with a basic type; a sequence that was pointed out first by von Richtofen as that of Californian and other lavas,[4] and later by Iddings,[5] as the general law of succession of lavas. The activity of the whole comagmatic region of northern California, Oregon, Washington, and Idaho, has been so low within recent times that the field may be regarded as almost extinct. Lassen Peak and Cinder Cone, however, have shown activity within historic times,[6] Cinder Cone having extruded a flow of quartz basalt, perhaps no more than 200 years ago, and Mount St. Helens and Mount Hood are believed to have been the scenes of ash eruptions within historic times.[7]

The terrane through which the lavas of Lassen Peak have been erupted is worthy of comment. The extrusions rest upon the Chico formation (Cretaceous) of the upper part of the Sacramento Valley. Beneath the Chico are the Jura-Trias rocks, which in turn rest unconformably upon contorted Palæozoic formations. The Palæozoic formations contain both contemporaneous volcanic and transgressive igneous rocks of varied nature, some of the volcanic rocks, though metamorphosed, being similar to those of the Tertiary eruptions, though they may bear no magmatic resemblance to them. Chemically they are uninvestigated. The thicknesses of the various members of this Palæozoic and Mesozoic terrane are unknown, and

[1] By M. Aurousseau.

[2] J. S. Diller, Lassen Peak, U. S. Geol. Survey, Folio No. 15, 1895.

[3] Hague and Iddings, Notes on the Volcanoes of Northern California, Oregon, and Washington Territories, Amer. Journ. Sci., (3), 25, 222–235, 1883.

[4] F. von Richtofen, Principles of the Natural System of Volcanic Rocks, Mem. California Acad. Sci., 1, 39, 1868.

[5] J. P. Iddings, The Origin of Igneous Rocks, Bull. Phil. Soc. Washington, 12, 178, 1892; Igneous Rocks, 1, 257, 1909.

[6] A. L. Day, Possible Causes of the Volcanic Activity at Lassen Peak, Bull. Seismol. Soc. America, 12, 35–46, 1922; Journ. Franklin Inst., 194, 569–582, 1922. J. S. Diller, Lassen Peak—our most active volcano, Bull. Seismol. Soc. America, 6, 1–7, 1916; A late volcanic eruption in Northern California, U. S. Geol. Survey, Bull. 79, 1891.

[7] W. R. Jillson, Geogr. Rev., 3, 481–485, 1917; 11, 398–405, 1921.

though, for the most part, they consist of shales and sandstones, limestones appear to be abundant, especially in the Calaveras formation (Carboniferous) and in the Cedar formation (Jura-Trias).[1] There are abundant limestones in the Carboniferous of the Klamath Mountain section, one horizon 2,000 feet in thickness outcropping for 50 miles along the McCloud River, 50 miles to the northwest of Lassen Peak. The Trias of this district emerges from beneath the Lassen volcanic field along Cedar Creek, and contains one horizon of limestone 200 feet in thickness. The dip and strike of the Palæozoic rocks of the Klamath Mountains render it not improbable that they extend beneath the Mesozoic formations underlying part, at any rate, of the Lassen volcanic field,[2] but no alkaline rock, as possible evidence of assimilation of limestone (Daly), has been found in the region, with the possible exception of a boulder of hornblende basalt, found in a stream bed near the Great Bend of the Pit River on the extreme northwest of the Lassen sheet. The relations of this rock are quite unknown, and it can hardly be considered to belong to the Lassen suite of lavas. Nothing of its kind, chemically or mineralogically, is known from the field.[3]

The position of the Lassen group of vents with relation to the orography of the surrounding regions is significant. They lie at the northern extremity of the geosynclinal depression of the Sacramento Valley, which separates the mass of the Sierra Nevada from that of the Coast Range. The depression is partly filled with the flat-lying Mesozoic and Neocene sediments. The abundance of volcanic vents between the northern end of the Sierra Nevada and the Klamath Mountains is in accord with the tectonic weakness of such a regional structure.

Lassen Peak itself was the center of fairly extensive glaciation, which reached its maximum after the period of major volcanic activity. Some of the later lavas have flowed for long distances down valleys cut and glaciated into lavas of earlier age. Solfataric action has continued down to the present time, however, and in a consideration of the eruptions since 1914, which seem to be exceptional volcanic manifestations in many ways,[4] it is well to bear in mind that Lassen Peak itself has been relieved of its ice load in recent times. It is by no means impossible that some isostatic adjustment, consequent upon the relief of ice load, may have assisted the mechanism of the more recent outbursts.

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[1] U. S. Geol. Surv. Geol. Atlas, Lassen Peak Folio, 1895.

[2] J. S. Diller, Klamath Mountain section, California, Am. Journ. Sci. (4), 15, 342–362, 1903.

[3] J. S. Diller, Hornblende basalt in Northern California, Am. Geol., 19, 253–255, 1897.

[4] A. L. Day, Possible causes of the volcanic activity at Lassen Peak, Bull. Seismol. Soc. Am., 12, 35–46, 1922; Journ. Franklin Inst., 194, 569–582, 1922. J. S. Diller, Lassen Peak—our most active volcano, Bull. Seismol. Soc. Am., 6, 1–7, 1916.

CHAPTER I.

SEQUENCE OF EVENTS.

BEGINNING OF EXPLOSIVE ACTIVITY.

On June 1, 1914, the following telegram was sent by the local observer of the Forest Service at Mineral, California, to the central station in Sacramento.

MINERAL, CALIFORNIA, *June 1, 1914*.

STATE FORESTER, Sacramento, California.

Volcanic eruption of Mount Lassen occurred 5 p. m. May 30th. Crater 25 × 40 ft. with lateral fissures formed. Mud, boulders, and sand 1 to 2 feet deep thrown over an area 200 feet in diameter. Ranger Abbey examined eruption yesterday. Heavy volumes of steam rising this morning. Crater 1/4 mile from summit. No damage yet.

(Signed) W. J. RUSHING.

This brief message contains the first trustworthy record of the outbreak of an active volcano within the boundaries of the United States in the memory of men now living.

Lassen Peak (fig. 1), or Mount Lassen, as it is frequently called, lies in northeastern California near the southern boundary of Shasta County, something over 200 miles northeast of San Francisco and about 75 miles south by east from Mount Shasta. It forms the southern extremity of the Cascade Range, although from neighboring cities (Redding, Red Bluff), where views of Lassen Peak are obtained, it appears isolated and stands out quite conspicuously as the highest point in a small mountain group forming a portion of an older and much greater center of volcanic activity of which little now remains. Its height as given by the U. S. Coast and Geodetic Survey (1913) is 10,466 feet above the sea, but it is no more than 4,500 feet above the surrounding teriane. Its nearest neighbor, Brokeoff Mountain, is a part of the rim of the ancient crater of Lassen Peak, but its activity has long since ceased. Only a few feeble sulphur springs remain to indicate where the northern border of the active basin may have been.

Diller[1] calls attention to the fact that Lassen Peak is included within the great outpouring of basalt to the north, which forms one of the greatest lava fields in the world, including northern California, Oregon, Washington, Idaho, and a part of Wyoming, covering altogether some 250,000 square miles. Nevertheless, most of the exposed lava sheet immediately about Lassen Peak is andesite rather than basalt and suggests that we are here in a transition zone, just outside rather than within the great "plateau" basalt field. The present cone is made up of a rather dense dacite, not unlike the dacite of Mont Pelée (Martinique), and presumably

[1] J. S. Diller, Volcanic History of Lassen Peak, Science, N. S. 43, 727, 1916.

of high viscosity at the time of its eruption. The lava accordingly piled up about the opening and is insignificant in volume as compared with the great basalt outpourings to the northward, which were for the most part relatively fluid.[1]

It has been supposed that the last preceding period of activity of the present volcano brought to the surface the rough region known as Lassen Crags, just north of the peak, and that this eruption occurred at least 200 years ago.[2] Probably the most recent volcanic activity in the region occurred some 10 miles to the northeast, where a low cone (Cinder Cone) emerges somewhat abruptly from the plain and

Fig. 1.—June 9, 1914. One of the earliest eruptions of Lassen Peak. Photo Loomis.

reaches a height of about 620 feet, with an open summit crater rather more than 200 feet deep. From the side of this cone, at an elevation not much above the level of the surrounding plain, there emerged a flow of rough lava of aa type, covering more than 3 square miles and from 100 feet to 125 feet in thickness.

From Indian tradition the age of this flow has been assumed to be between 75 and 100 years, but an investigation of the age of adjacent trees[3] indicates that a somewhat greater period has elapsed since this flow occurred. So far as we have

[1] Cf. H. S. Washington, Deccan Traps and other plateau basalts, Bull. Geol. Soc. America, 33, 775–780, 1922.

[2] Diller, *loc. cit.*

[3] At the suggestion of the writer, Supervisor Merrill of the Forest Service cut down one of the trees growing about 3 feet from the flow and rooted in the ash. He counted more than 200 rings on the stump. See also J. S. Diller, A Late Volcanic Eruption in Northern California and its Peculiar Lava, U. S. Geol. Surv. Bull. 79, 20, 1891.

record, therefore, the only local volcanic activity during the past century, and perhaps the last two, has taken the form of steam fumaroles and hot springs in the ancient basin to the southwest of Lassen Peak (Supan's Springs) and in the valleys to the south and southeast of it (Morgan's Springs, Bumpass Hell, Devil's Kitchen, The Geyser, Boiling Lake, etc.).

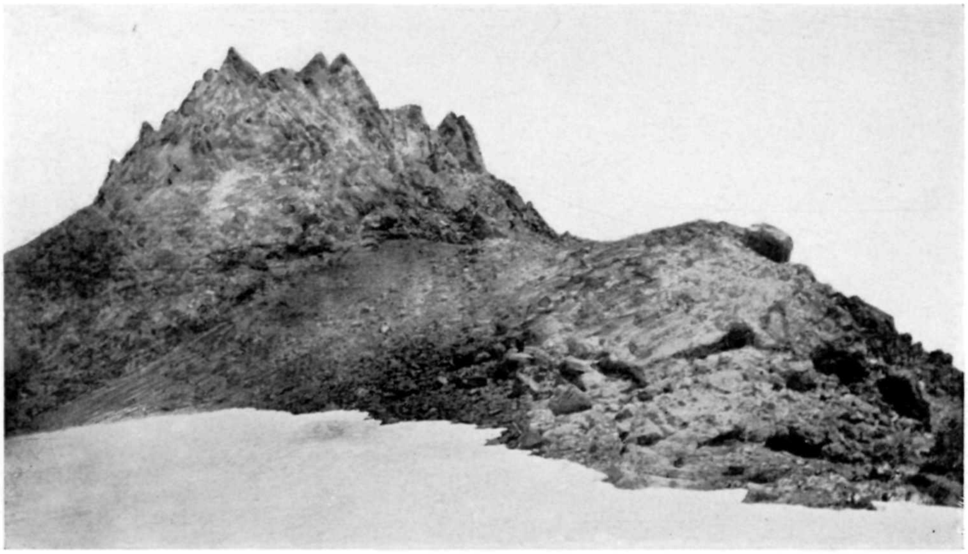


Fig. 2.—1891. Inside old crater looking southeast. Note deposit of snow in foreground. Photo Drew.

Fig. 3.—The bottom of the old crater with its pool of water draining westward through the western notch (left). Photo Yori.

The outbreak of May 30, 1914, referred to in the Forest Service telegram quoted above, came without premonitory symptoms of any kind having been observed. No change was noticed either in the temperature or in the activity of the neighboring hot springs, and no local earthquakes attracted especial attention. A lowering of the ground water so often observed at Vesuvius[1] as a conspicuous premonitory indication of impending eruptions was not noticed here.

The valleys surrounding Lassen Peak for a distance of 20 miles or more are occupied for the most part only in summer by cattlemen and lumbermen. The nearest point of observation during the winter season is probably the hamlet of Mineral, from which the telegram was sent and which is regularly used as a winter observation point by the Forest Service. The summer observation point at the summit of Lassen Peak itself was not regularly occupied before the forest-fire season (July).

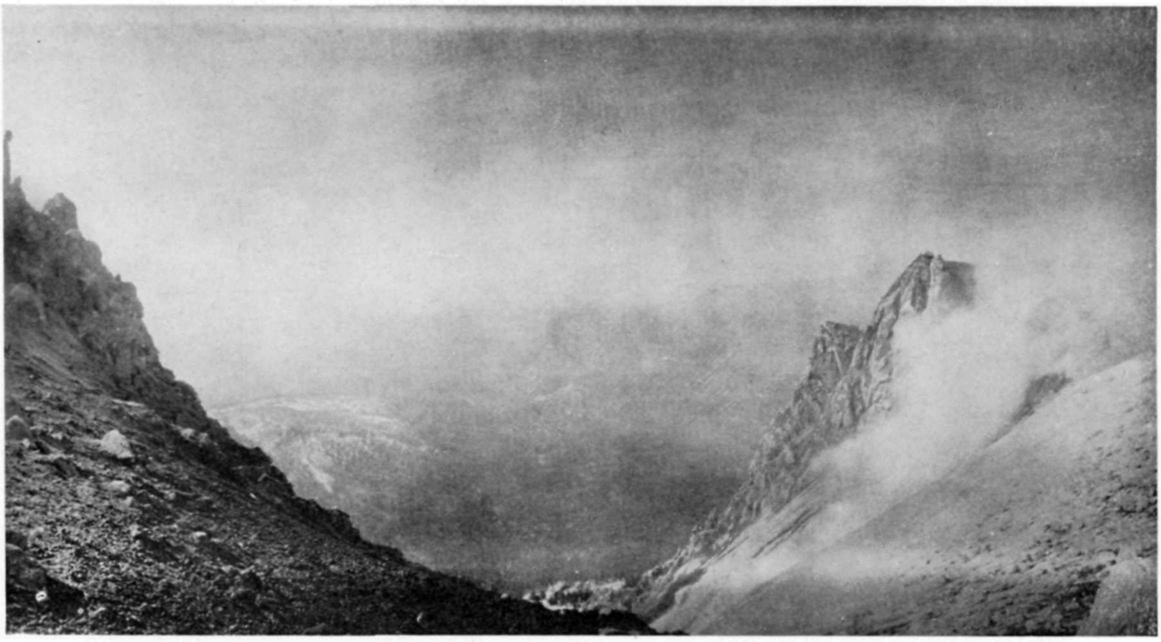


Fig. 4.—The western notch in the crater rim before the upheaval in May, 1915. Photo Olsen.

In the summer season Lassen crater was reasonably well known and was accessible to and occasionally visited by tourists before any sign of activity appeared. In appearance the crater was a smooth bowl with a floor of volcanic sand and lapilli, the lowest point of which was about 360 feet below the highest point of the rim upon which the Forest Service had built its shelter. A small pool of drainage water was usually to be found in the bottom of the bowl and the portion of the inclosing parapet which faced north, was never free from snow (figs. 2 and 3). The shape of the bowl itself was roughly oval, with the long axis nearly east and west, but it was not entirely symmetrical. The north and south sections of the inclosing rim retained approximately the original conical form but the east and west sections were broken by V-shaped openings (fig. 4), pointing to earlier explosive action and perhaps indicative of structural weakness in this azimuth. It is interesting to note in this connection that the general faulting of the region (see Diller) is in a nearly

[1]Joseph Prestwich, On the Agency of Water in Volcanic Eruptions, Proc. Roy. Soc. No. 246, 117, 1886.

east-and-west direction, and the earliest cracks reported from the present eruption were in this azimuth. No fumaroles or other signs of latent activity are known to have existed on the summit within the memory of those living near. Snow is reported to accumulate within the summit basin to a depth of 40 feet or more each

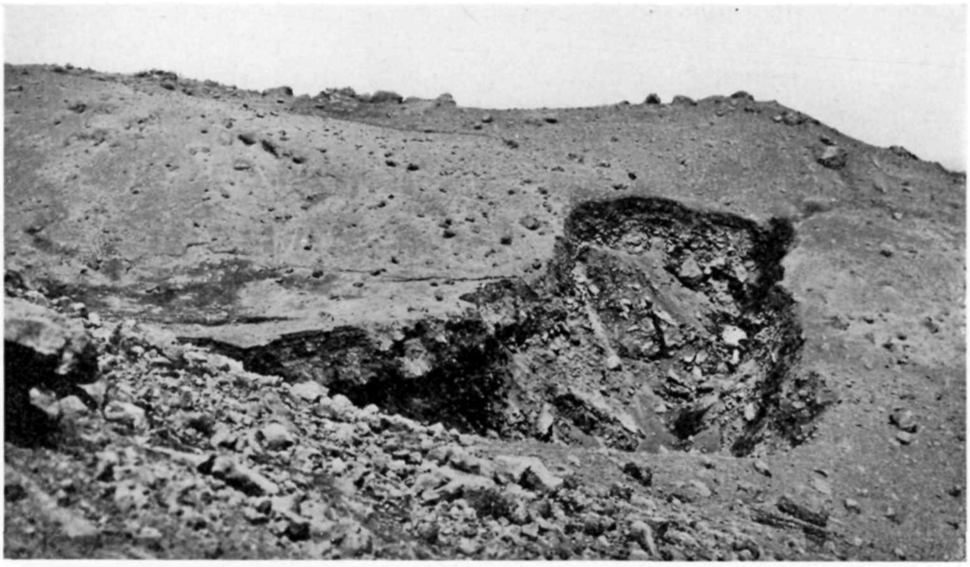


Fig. 5.—June 28, 1914. Explosion crater showing the "lateral fissures." Photo Holway.

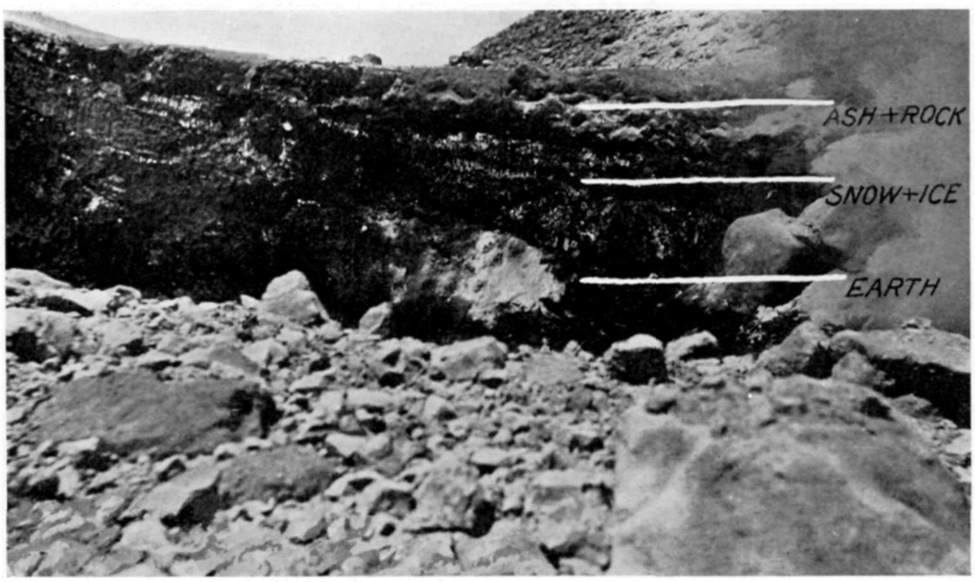


Fig. 6.—The first explosion crater showing the snow with ash and debris lying upon it. Photo Yori.

winter, and it may or may not be noteworthy that the time of the initial eruption corresponded approximately with the period of rapid spring melting of this accumulated snow, and that streams of water from this melting snow were reported to be pouring into the new crater opening in the very earliest announcements of the renewal of activity (see below).

Notwithstanding the sparsely inhabited character of the region, the first explosion appears to have been plainly seen (from Chester, 21 miles away). On the next day Mr. Harvey Abbey, of the Forest Ranger Service, made his way to the summit over snow and found an opening about 25 by 40 feet, obviously a small explosion vent on the inside of the crater bowl, between the small pool at the bottom of the bowl and the northwestern rim, rather less than half way up.

The early photographs of the explosion crater show plainly in section the snowbank through which the explosion occurred (figs. 5 and 6) and the accumulated debris of the explosion scattered over the top of the snow. It is obvious from these photographs that the lapilli and fragmentary ejecta thrown out by the explosion were cold, otherwise they must have melted their way into the snow upon which they rested. Steam and hot water within the explosion crater are reported by Ranger Abbey, but the solid material ejected was not hot.

Following the telegram above reported, the records of the Forest Service contain the following memorandum under date of June 2, which contains some further details:

At 4 a.m., May 31, Ranger Abbey left Mineral for the mountain, arriving on top at 9 a.m., traveling 14 miles over snow from 1 to 6 ft. deep. He found a new crater 25 × 40 ft. in extent and about 300 ft. from the top on the north side of the small lake. There were 2 lateral fissures about 100 ft. long extending from the crater. Hot mud, stones 18 inches in diameter, and sand had been thrown over an area 200 ft. in diameter to a depth of one to two feet [See fig. 6]. Ashes and fine sand were scattered over an area of about one mile across. A large quantity of hot water had run down the slope into the lake, cutting a channel in the snow. Large volumes of steam were being blown out, and there was a continual loud hissing. Large quantities of water from the snow were pouring into the crater, also sand, gravel, and boulders from the sides. Abbey approached to within 50 ft. of the brink, but owing to the caving bank it was unsafe to approach closer. The entire disturbance acts more like a geyser than a volcano.

(Signed) W. J. Rushing.

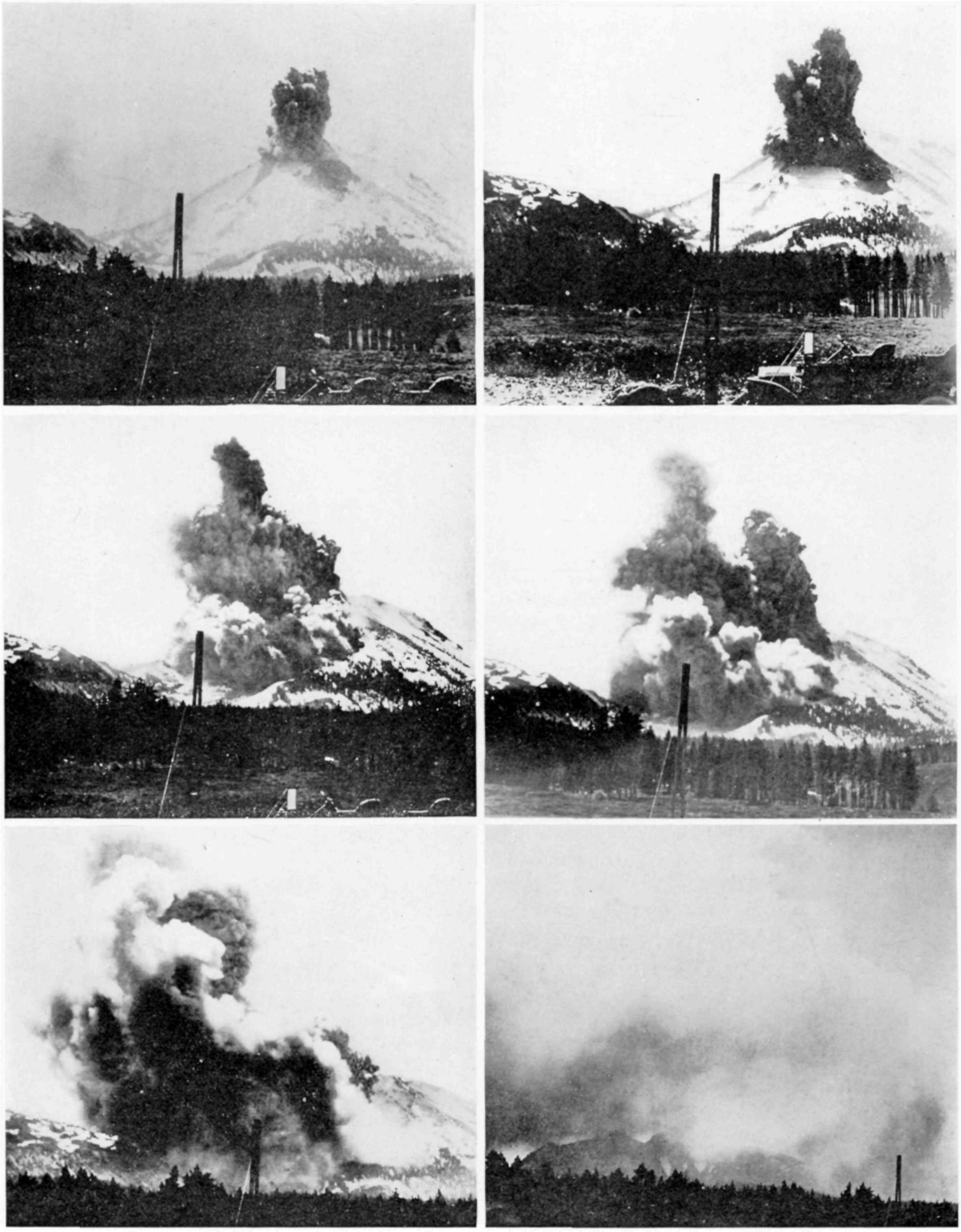
The following extract is taken from a letter addressed by the local supervisor to the district forester at San Francisco under date of June 9, 1914.

Such wild stories are being circulated concerning Mount Lassen that I am sending you the results of our observations to date.

Saturday, May 30, an outbreak occurred at 5 p.m. This was witnessed by Ike McKenzie of Chester, who was looking directly at it when it occurred. Abbey investigated it Sunday, May 31 . . . . (see telegram above). . . . The sand thrown out was granitic in character, sharp, and contained mica. No molten material was thrown out at all. At $8^h 5^m$ a.m., June 1, a second outburst occurred, throwing out large quantities of the same material. Some boulders weighing all of a ton were thrown out. The vent was enlarged to 60 × 275 ft. The fumes escaping were said by Boerker and Macomber to be arsenic [?], hydrochloric acid, and sulphur. Boerker, Abbey, and Macomber went up June 4, remained at the top in the lookout house over night, and came back June 5. . . .

We have watched it carefully and at no time have we been able to see any flame or indication of fire. . . .

(Signed) W. J. Rushing.



Successive views of the explosion of June 14, 1914, taken near Manzanita Lake. Photo Loomis.

For the next few days eruptions continued at the rate of about one every two days and were of increasing violence and duration. The fourth recorded outbreak, which occurred at 4^h30^m p.m. on June 8, continued for 40 minutes and was heavier than any which preceded it. On Friday, June 12, the ash cloud was very dense and poured out for 50 minutes or more. It was after this eruption that a visit to the summit showed that the explosion crater had increased to 400 feet in length and 100 feet across, the inner walls and bottom being formed of infallen talus.

Sunday, June 14, brought three eruptions, during one of which the ash cloud reached an elevation of 2,500 feet above the summit, and explosions of great power were reported. After the eruption of Friday, June 19, the explosion crater had grown to 600 feet in length and 100 feet across (fig. 7), evidently extending eastward along

Fig. 7.—June 20, 1914. Looking north. Explosion vent now 600 ft. long and 100 ft. wide. Photo Loomis.

a preexisting summit fault. During this period of development a considerable number of people visited the mountain and made photographs and observations of various kinds. One party was so unfortunate as to be caught in the midst of a severe outbreak (June 14, 9^h43^m a.m.), during which a member of the party suffered a broken shoulder from a falling stone, and all were obliged to bury their heads in the snow to avoid breathing the dust-laden air. The darkness within the cloud was reported to be intense for a period of 10 minutes or more, but suffocating gases were not encountered. (Plate I.)

In general during the summer of 1914 the eruptions continued to increase in violence. On July 15, for example, a very heavy eruption at 6^h5^m a.m. was reported which lasted 4 hours and was followed at 12^h5^m on the same day by the greatest disturbance thus far recorded. It lasted during the entire afternoon and vast quantities of dust were discharged. This period of activity (1914) probably culminated in the outbreak of Saturday, July 18, beginning at $5^{h}28^{m}$ in the morning. Of this, the record kept by the Forest Service states. "By far the most violent eruption to date. Ash, steam, etc., arose to height of 11,000 feet practically entire morning." This eruption is No. 24 of the Forest Service record (No. 30 of the combined record hereto appended, p. 176).

Following this outbreak the mountain was quiet until August 10, when a moderate quantity of ash was thrown out in the late afternoon and early evening. Under date of August 15, Forest Supervisor Allen reported to Mr. Diller of the Geological Survey that a tape measurement of the explosion crater showed it to be 600 feet by 209 feet. Other outbreaks followed during the summer, notably on August 21, when the entire crater appeared to be active and the smoke cloud reached a measured elevation of 10,560 feet above the summit. Following is an abstract from a letter from Supervisor Rushing dated August 27, 1914, describing the activity of this period:

> The eruptions of last week were considerably heavier than any formerly seen, and the eruption of August 19 was plainly heard by parties entering the Manzanita Chute [distant about 5 miles northwest of the mountain]. From the west end seven vibrations were felt by Ranger Bramhall at Jessen and Stuart's place in section 30, T. 31 N., R. 5E. [distant 5 miles northeast; reference is to Forest Service map of Lassen National Forest, 1913]. Rumblings and noises similar to rocks sliding have been heard by the lookout on Brokeoff Mountain [4 miles southwest] during all recent eruptions. There is only one crater so far as we can determine. . . . Rumors of new craters are caused by parties seeing the ashes or dust being blown by whirlwinds from different parts of the Mountain . . .

From this time on eruptions were of greater duration and heavily ash-laden, but apparently of more moderate violence. The total number of outbreaks recorded at the Forest Service observation stations during the year 1914 is 69 (from all sources 110). Of these, the first 17 (up to July 13) were sharp and short, none lasting more than an hour. The eighteenth eruption (July 15) lasted 4 hours, and of the following outbreaks up to and including the forty-ninth (September 30, 1914) but two are described as short, the average length being 3 to 4 hours. From the fiftieth outbreak (October 1) to the end of the year but one eruption (the fifty-third October 7) exceeded an hour in length, (see p. 176, *et seq.*).

CHARACTER OF EXPLOSIONS OF 1914.

The discussions of volcanic activity at Lassen Peak by newspapers and random observers have not served to set before us a very clear picture of the actual activity there as compared with other volcanic eruptions of historic record. The number of observers was actually small, by reason of the isolated location of the volcano, and the proportion of these who had seen volcanic phenomena before was almost negligible. It is, therefore, not surprising if the emphasis has occasionally been misplaced in the accounts which have come to us of the different phases of activity. By way of illustration, it will be recalled that a rather serious discussion took place in newspapers, in which one or two magazines of local circulation participated, as to whether Lassen Peak should properly be described as a volcano or a geyser, the latter apparently being suggested by one of the earliest Forest Service dispatches (p. 8), by the steam clouds, and by the report of streams of hot water within the crater basin. This point need never have been in doubt. Lassen Peak, both in the visible record of past activity and in the characteristics of the present eruption, is a true volcano.

The precise character of the explosions which occurred during 1914 can not be determined from information available on the ground. No report of fumes of sulphur or acid in the smoke cloud itself has come from any observer. During 1914 acid fumes in insignificant volume were twice reported on the mountain, once by the Forest Service and once by Mr. Diller of the Geological Survey, but neither of these reports was connected with the more violent phases of activity. Neither have

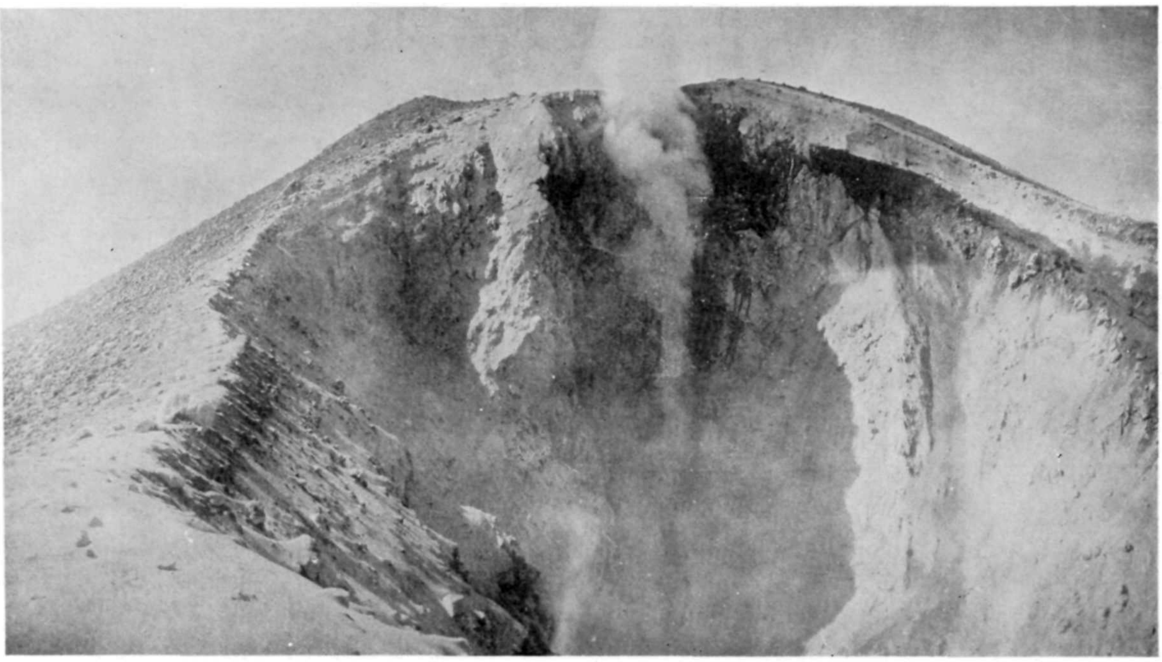


Fig. 8.—October 27, 1914. The explosion crater and its vertical rift. Photo Olsen.

any reports indicated the presence of incrustations or precipitated matter on the rocks exposed by the explosions. There was steam at all times, both in the explosion clouds and pouring from cracks and loose ejecta (fig. 8), both during and after the explosions. Practically all reports from visitors to the mountain, as well as photographs taken at the summit, confirm this. It would almost seem as though the explosions of the first summer were altogether of the steam-boiler type without the participation of fresh lava or more than insignificant quantities of the more active chemical ingredients common to the explosive volcanoes of the West Indies or the Mediterranean.

The absence of any evidence of continued high temperature on the mountain appears to confirm this conclusion, for all of the phenomena observed during the summer of 1914 could have been produced by exploding steam without attaining high temperatures locally. The further fact that most of the outbreaks were of low intensity and large volume also suggests the same interpretation. The single recorded observation of red-hot objects (Forest Service, see below) thrown out of the crater offers little to disturb this view. It is altogether possible, considering the volume of dust and heavier ejecta removed from the crater by the successive explosions continuing through several months, that for a few moments red-hot rocks should have become exposed and a few fragments ejected while still hot enough to show red, but the evidence in support of such a hypothesis is meager.

This question, whether or not liquid lava appeared in the crater in 1914 or red-hot rocks were thrown out, has been somewhat difficult to answer conclusively. The newspapers reported such occurrences very early, and isolated observers reported having seen such displays at night during the summer months. It is hardly possible to give full credence to such observations so long as they remain entirely isolated and lack all precision of detail. With the mountain under constant observation from all directions in a time like this, a real display of glowing lava or bombs would certainly find more than one observer when it occurred, and would leave unmistakable traces after its conclusion. The reports of the character of these displays are very incomplete, some reporting red-hot rocks and others brilliant white flashes. No one with whom the writer has talked has ever described a full flight of any hot object (in 1914), including its fall and landing, although the mountainside was in plain view to many observers (cf. observations of 1915, pp. 18,19).

A glow in the heavens at night was reported on one or two occasions from Chester, but this observation also is subject to a certain amount of reservation in view of the fact that the sunset during the summer months is behind the mountain. From Chester illuminated clouds are often seen in the west in the evening hours without any unusual significance being attached to them. Such a glow was not reported from other places, nor was it reported from Chester during the darkest hours of the night in 1914. The only authentic statement of reasonably positive character bearing upon this subject during this year is found in the Forest Service records.

SEPTEMBER 30, 1914.

Mr. R. B. HOLWAY,

Mr. Wade, the lookout on Turner Mountain [15 miles to the south], distinctly saw luminous bodies which appeared to him to be red-hot stones thrown out. He counted 17 distinct luminous bodies. The same phenomenon was seen by several parties at Chester. This is the first time that any forest officer has seen indications of fire or molten material although on at least two other occasions private parties asserted that they saw what appeared to them to be fire. The crater has opened up on the west side of the mountain for a considerable distance and considerable quantities of steam issue from its entire length.

(Signed) W. J. RUSHING.

No other incident of the kind appears in the records of the Forest Service. In reply to an inquiry from the Geological Survey upon this subject the following positive statement was received:

DECEMBER 14, 1914.

Mr. J. S. DILLER,

We have no record of anyone having visited the crater lately, so can not quote any proof of heat except as given by our Turner Mountain lookout as described in my letter of November 7. [Repeats information contained in letter addressed to Professor Holway on September 30, quoted above.]

The eruption upon November 18 was seen by me from near Reading, and I feel positive that there is a vent somewhere near the base of the mountain on the north side, although no one has verified this by finding a crater there. The crater on the west side near the top is much enlarged and the entire west slope of the mountain is discolored by volcanic dust.

(Signed) W. J. RUSHING.

In endeavoring to reach a proper conclusion regarding these occurrences, we should not overlook the fact that all these eyewitnesses were viewing volcanic phenomena for the first time. This is not primarily to question the available evidence, but rather to emphasize the need of bringing experience to bear on the interpretation of this evidence, for which purpose the introduction of trustworthy observations elsewhere may be profitably invoked. The observeıs reported bright objects in flight above the crater. It is a natural inference, but not a necessary consequence, that these moving objects were blocks of hot lava. Such witnesses as I had the good fortune to talk with afterward were uncertain about important details which were necessary to establish this conclusion. They were not sure, for example, whether the flying objects were red or white, nor did they observe that they fell to the ground. The record of the eyewitnesses during the year 1914 is confined to the observation of moving objects appearing to emerge with the explosion cloud from the crater, but which were not seen to leave the cloud or to fall.

In explanation of this may be placed a fact of common observation in all violent volcano outbreaks, that dust-laden clouds shot out at high velocity frequently develop electrical phenomena due to the friction of the dust particles in passing swiftly through the air. These electrical flashes are widely variable in color and behavior with the intensity of the explosion and the dust content, and at distances of 20 miles may easily have suggested more tangible objects.

To this we may perhaps add that during the year 1914 no volcanic ejecta showing evidence of recent heat were found, either on the summit or flanks of the mountain, despite a most diligent search. It is particularly noteworthy in this connection that all the early photographs of the crater show the ejecta lying on the surface of the snow, without sinking through it. There can be no question of red-hot rocks in that period. Neither were any fires started in the surrounding forest after the snow had melted, though dry leaves are kindled by contact at temperatures far below red heat. Such scanty evidence offers no very tangible ground for supposing that any of the explosions of 1914, violent and long-continued as they were during the summer months, reached down to a zone of red heat.

A still more positive and convincing proof of this is available which has not been cited hitherto. Charley Yori, who frequently served as a local guide in the Lassen Peak region, is thoroughly familiar with the seasonal appearance of the mountain, both before and during its period of activity. His report that the accumulation of snow on the summit was uncommonly heavy during the following winter (1914–15) is therefore entitled to full confidence and has been confirmed by other visitors. This observation bears directly upon the question of high crater temperatures during 1914. If red-hot lava had been exposed on the summit during the summer and autumn of that year, heavy snow accumulations upon it during the following winter would have been impossible. Indeed, in the winter of 1915–16, when moderately hot material did fill the crater, no snow accumulated within the area of activity.

During the winter opportunities for observation are rare and usually poor. The summit is surrounded by clouds and covered with snow. Except for explosions of sufficient power to penetrate above local clouds and so be observed at considerable distances, the reports of the winter of 1914–15 must be regarded as incomplete. There were no visitors to the summit before March, and there is no record of changes in the observed conditions there.

Although the explosions continued to occur at intervals of a few days through the autumn and winter of 1914, scattering ash and small fragments for miles to the eastward under the prevailing wind, the intensity of the explosions gradually diminished. In making comparisons of this kind, however, it should be borne in mind that there is no proper measure of the intensity of such explosions. The Forest Service, in default of other standards, based its estimates on the height of the dust cloud above the summit, but this is hardly a measure even of the volume of the blast, for the puffs vary, not only in intensity but in direction and in duration, and, furthermore, several new openings are believed to have participated in the winter activity. Within a period of 4 or 5 months during the winter season, probably no activity was observed from a point nearer than the Forest Service Station near Mineral, 15 miles to the southward. The number of outbreaks, however, was carefully recorded, in so far as they were visible in daylight.

CULMINATION OF EXPLOSIVE ACTIVITY, MAY 19–22, 1915.

In May the accumulated snows of winter begin to melt at this elevation. All observers agree that the quantity of snow on the mountain in the winter 1914–15 was uncommonly large.[1] The drifts in the bays, high up on the flanks of the mountain to the south and northeast, immediately adjacent to the peak, were probably not less than 50 feet deep. The crater conditions characteristic of the first stage of activity (first year) were last observed by E. N. Hampton on March 23, 1915, when an ascent to the summit was made and several photographs of the explosion crater were taken. From these photographs it appears that the new explosion crater had grown almost to the full size of the old crater bowl. It is described as nearly circular and about 1,000 feet in diameter.

Between this visit and the more violent activity of May following, certain other physical changes at the summit were indicated to observers at a distance, though just what these changes were and how they occurred, whether by continuous slow upheaval or as the result of successive explosions, it is impossible to say. Mr. B. F. Loomis,

[1] Records at nearby stations of the U. S. Weather Bureau are as follows: Snowfall at Chester (elevation 4,550 feet) 1911–12, 91.5 in.; 1912–13, 155.2 in.; 1913–14, 210.1 in.; 1914–15, 183.2 in. Snowfall at Inskip (elevation 4,975 feet) 1911–12, 151.6 in.; 1912–13, 232.6 in.; 1913–14, 233.7 in.; 1914–15, 250.4 in. Climatological Data for United States, Northeastern California, pp. 31, 33, U. S. Weather Bureau, 1916.

observing from Anderson, which lies to the west of the mountain, about 45 miles distant, was the first to detect a small black mass pushing up into the cleft in the rim on the western summit. Miss Alice Dines, postmistress at Manton (20 miles west), in a private letter June 8, 1916, writes of similar changes: . . . "the dark formation began to rise above the level of the mountain about the 16th or

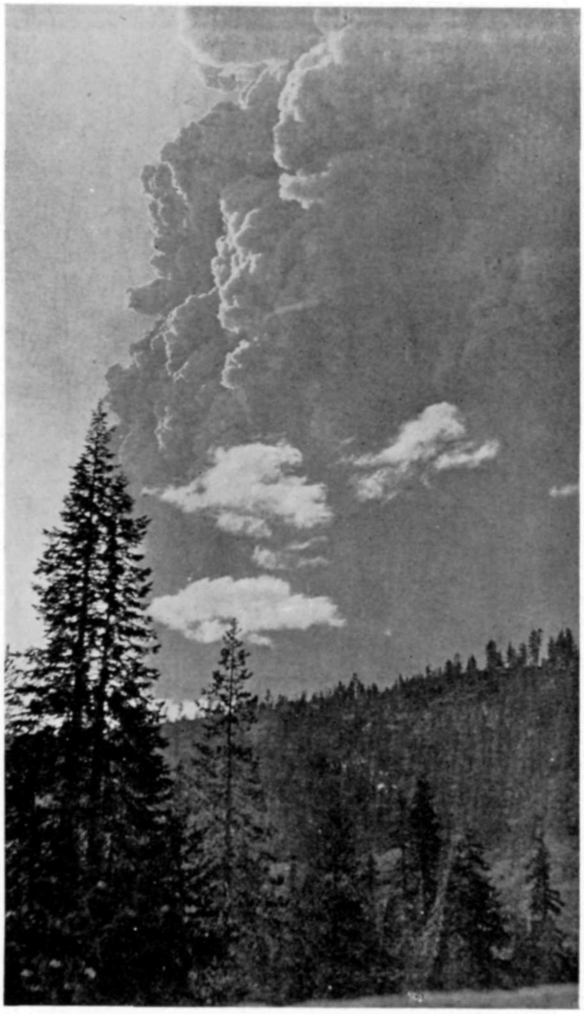


Fig. 9.—May 22, 1915. The great eruption seen from the east. Photo Yori.

18th of May, black during a clear day." This change appears not to have been noticed elsewhere and no observer hazarded the winter ascent in pursuit of further information. It would appear from these two bits of evidence, made by two independent and most faithful observers of occurrences at Lassen Peak throughout the eruptive period, that the crater had been partially filled from below before the great eruption of May 19 took place.[1]

[1] See also Appendix under May 19 "D", p. 182.

First Appearance of Glowing Lava.

On May 19 an eruption occurred which for volume and intensity probably overshadowed anything which had preceded, but which was but imperfectly observed because it occurred during the night. Mr. Olsen, from the leeward side of the mountain (Chester), says: "Lassen seen this afternoon the first time for six days. Was in eruption all the time it was visible. After dark a steady glow of light was seen shining on cloud of smoke for several hours."

Miss Dines, from her viewpoint on the opposite (windward) side of the mountain, enjoyed a more favorable view. She says "Mountain smoked all day. Fire lava seen on top at 9 p.m."

The first report from the Forest Service came in a telegram at 10^h30^m p.m. from ranger Seaborn at Jessen and Stewart's place to the northward of the mountain: "First indication of eruption was tremendous flood of mud, etc., down Hat Creek. Meadows covered."

G. R. Milford telegraphed on May 20 to Mr. Diller of the Geological Survey, Washington, as follows: "Lassen Peak in violent eruption 9^h30^m to 10^h30^m last night. Fire observed coming from crater. Incandescent ejecta roll down the mountainside. I observed the spectacle from Volta, 10 miles[1] from Lassen Peak. Many in Sacramento Valley saw the same."

This graphic telegram was later supplemented by a letter (November 17, 1916) to Mr. Diller, which we are permitted to quote practically entire:

> Ever since May of 1914, when Lassen Peak first showed indications of springing into life, and taking its place among the more or less active volcanoes of the world, reports have been circulated from time to time as to the observance of fire within and coming from the crater. These reports when thoroughly investigated, lacked substantiation and corroboration, both as to the hour the fire was visible and also as to its duration and magnitude. However, it was not until the night of May 19, 1915, that the observance of an eruption accompanied by fire of sufficient magnitude and duration was so generally noted and corroborated. On that date the writer was at the Volta plant of the Northern California Power Company Cons., this plant being located about 21 miles due west of Lassen Peak.
>
> About 9^h15^m p.m. word was sent in by telephone that Lassen Peak was in eruption and fire could be seen coming from the crater. In company with Mr. and Mrs. Chas. R. Milford, Miss Catherin Milford, Mr. C. E. Johnson, Mr. and Mrs. F. A. Dooley, Mr. and Mrs. Geo. Risley, the writer went to a point of vantage about 100 yards southeast of the power house, where an unobstructed view of the peak could be had, and there found that reports were true and that the mountain was in eruption and fire could be observed coming from the crater.
>
> Our attention was first drawn to the deep-red glow which appeared over the crater and was of sufficient intensity to illumine the entire outline of the mountain top. There was no moon, the heavens were clear, yet this glow was bright enough to be reflected in the dense clouds of steam and smoke arising from the crater. From time to time the glow seemed to change in brilliancy, now brighter, now dimmer—this variation due, no doubt, to the varying density of the clouds of steam and smoke issuing from the crater.
>
> As we continued to gaze at the wonderful spectacle, the glow commenced to increase in brilliancy, now brighter, now still brighter, until, behold, the whole rim of the crater facing us was marked by a bright-red fiery line which wavered for an instant and then,

[1] Obviously an error; Volta is 21 miles west of Lassen Peak. See Milford's letter following.

in a deep-red sheet, broke over the lowest part of the lip and was lost to sight for a moment, only to reappear again in the form of countless red globules of fire about 500 feet below the crater's lip. These globules, or balls of fire, were of varying size, the largest appeared at that distance (21 miles) about 3 feet in diameter, the smallest appeared as tiny red sparks. All maintained their brilliancy as they rolled down the mountainside until lost to sight behind the intervening range of hills.

These phenomena took place at intervals of about 8 minutes for a period of some 2 hours, and to the writer it appeared as though he were looking at a titanic slag-pot being slowly filled by molten slag in some smelter. The glow over the rim gradually increased in intensity until the pot's rim was brilliantly marked by the appearance of slag itself. Finally, the slag spills over the lip in a vivid red sheet and, as it runs down upon and into the slag dump, it breaks through the crust of older slag and appears against the background as splashes of deep-red molten material.

As stated earliest in this article we watched this re-occurring boiling-over, as it were, of the crater for a period of two hours, at the end of which the activity seemed to decrease. Concluding that the display for that evening was nearly at an end, we returned to the power house and made preparations for a trip on the morrow to Manzanita Lake, which lies almost at the foot of the mountain.

Next day proved a disappointment, as the sky was overcast and the peak was shrouded in dense storm clouds. Nevertheless we started, and arrived at the lake about 10 in the morning. At brief intervals the clouds would break sufficiently to permit us to see the peak, which was steaming and smoking in great volumes, indicating that the activity had immensely increased. We also observed that there was on the western slope a dark mass of matter appearing almost black. This mass appeared about 1,000 feet across and extended down the slope for possibly a distance of 2,000 or 2,500 feet. From our location this mass appeared like volcanic mud and must have been of a consistency greater than ordinary mud, as the surface still maintained its roughed, furrowed appearance.

Of direct observation of this eruption there is little more than is contained in this account, the mountain was shrouded in cloud and darkness, except from the west (windward) side, where the glow of incandescent matter was seen by the Milford party and by Miss Dines. Mr. Milford's record, considering the distance away, is clear and positive. Sufficient incandescent matter was visible at the summit to illuminate the summit outline and the smoke column above it at a distance of 21 miles, and some appearance of movement there was plainly visible. The incandescent mass which he describes to resemble a slag-pot overflowing at intervals of 8 or 10 minutes does not, upon close examination afterward, appear to have been a flow. There is no evidence of recent fluidity in the ejected material; it appears rather to be a shattered portion of the solid volcanic plug uplifted through the western cleft in the crater rim along with the general upheaval of the crater bottom. The bright spots which Milford describes as splashes of "deep-red" molten material were probably due to the breaking off of hot fragments revealing fresh red-hot surfaces which flashed out and then gradually cooled, while the separated fragment rolled down the mountainside. The lava is andesite of such extreme viscosity that no splash is possible at the deep-red temperature described. Neither does the form of the ejected material show any evidence of recent fluidity. Sharp edges are not rounded nor side walls sagged. The total surface of the triangular mass which Mr. Milford saw was about 1,000 feet long from the crater rim to the terminating point (fig. 10) and about 300 feet wide at the rim.

It also appears from Milford's letter that he does not believe the rumors of glow on the mountain and red-hot fragments thrown out before this date, that is, during the year 1914, to be true. Supervisor Merrill, of the Forest Service, who was stationed within view of the mountain throughout this period, told me that he was of the same opinion. There were violent and long-continued explosions discharging great quantities of ash which no doubt caused occasional electrical displays, but there is no tangible evidence of the appearance of incandescent matter in the crater until the night of May 19, 1915, nearly a year after the beginning of the outbreak.

Fig. 10.—July 20, 1915. The upheaval in the western notch. Photo Day.

Professor Ruliff S. Holway, of the University of California, appears to have been the first to visit the summit crater after (5 days after) this upheaval. Not only this fact, but his comment gains especial interest and weight from the fact that he is one of the very few experienced geologists who have studied this eruption on the ground. He says:

There were also many reports that the volcano had ejected red-hot boulders and molten lava. The writer examined the rocks in several of the localities credited with having received such deposits, but so far has found none differing from the characteristic rocks of the old crater. Nor were there found any rocks, old or fresh, bearing evidence of recent fusion. It seems very probable that molten lava has been near the surface, and it is quite possible that small quantities have been ejected. There are many reports from trustworthy people that "flames" have been seen. The writer, with a good field glass, watched until after dark the diminishing puffs of steam and dust of the eruption of June 16. Shortly after sunset he saw apparently most perfect flames shoot up from the crater's rim.

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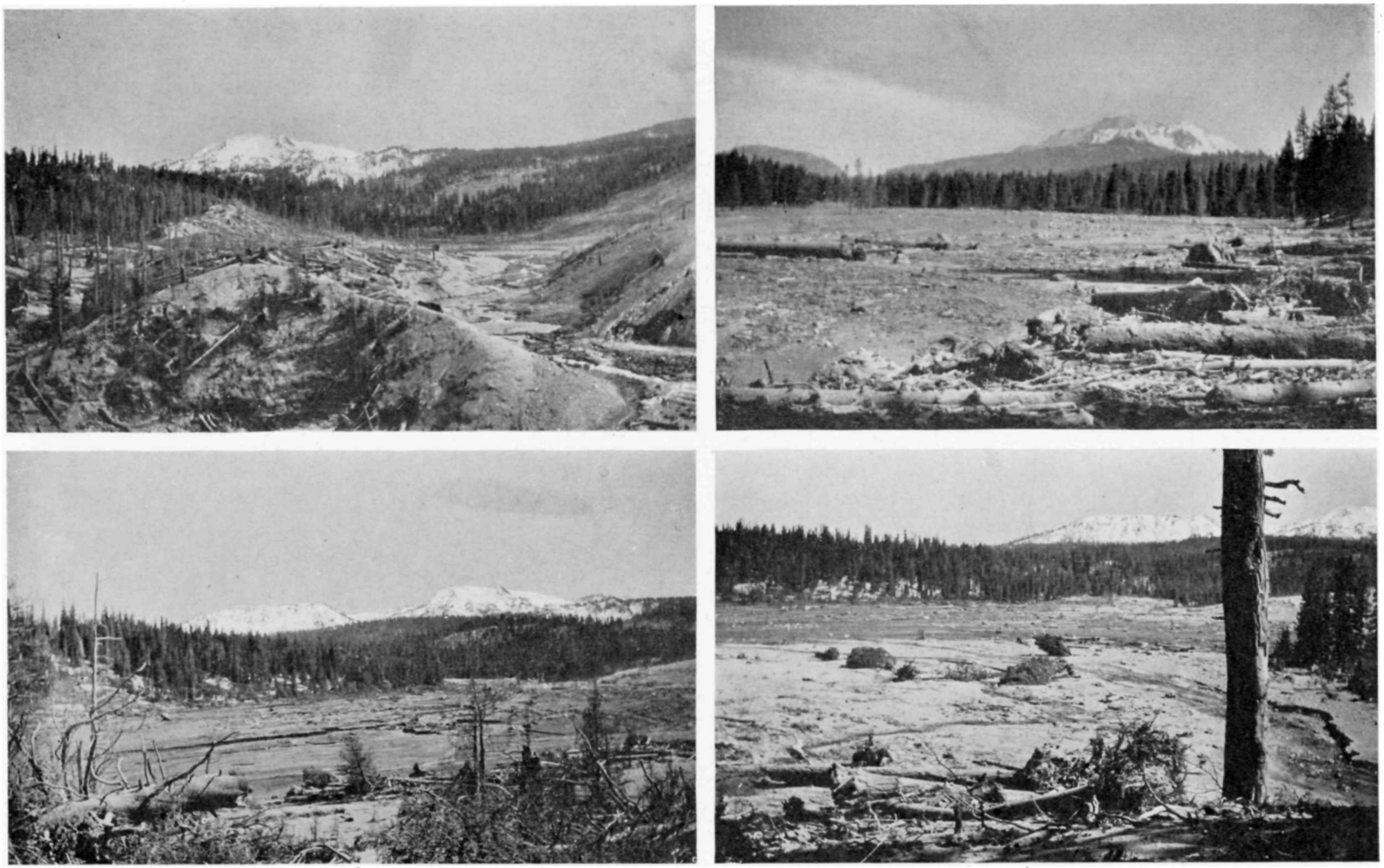

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Plate 2—Views of the mud flow, May 19, 1915, in Lost Creek and Hat Creek Valleys.

1. June 4, 1915, West Fork of Hat Creek.
2. May 27, 1915, Lost Camp. The buildings stood in the foreground prior to the mud flow.
3. June 4, 1915, Jessen Meadow from the lower end.
4. June 4, 1915, Jessen Meadow from the northeast corner where the mud flow crossed Lost Creek Divide.

Photo Seaborn.

PLATE 2

However, as the sun sank lower those apparent flames became entirely dark, except for the highest part of the column. A minute or two later the entire jet became wholly dark. There remain, however, reports of luminous objects and glows[1] seen 3 or more hours after sunset, for which the writer can not account.

FIRST HORIZONTAL BLAST AND MUD FLOW, MAY 19, 1915.

Some important features of this eruption, which Mr. Milford describes so graphically, were concealed by darkness and remained unsuspected until some time afterward. No one knew, for example, that there was also a horizontal blast which swept down the opposite (east) side of the mountain with sufficient power to carry everything before it. Not only were the snow and the forest trees swept away, but even the surface of the ground was swept clean. The primary results of this blast escaped observation for the moment, but the great avalanche of mud and water, boulders, and forest débris which resulted from it poured down the mountainside along the valley of Lost Creek, in part over the divide into Hat Creek, and thence around a sharp bend to the northward in an overwhelming flood which was reported by Ranger Seaborn (p. 16), 7 or 8 miles below. These parallel valleys, Hat Creek and Lost Creek, contained fertile meadows which were usually occupied by herdsmen later in the season. On the morning of May 20 these meadows were found covered to the depth of 5 or 6 feet with débris of this destructive flood, which the newspapers forthwith described as a flow from the crater itself. This erroneous conclusion was corrected by Professor Holway a week later, and by Loomis, who visited it 2 days after its occurrence. His résumé in the *Anderson Valley News* of March 17, 1922, is as follows:

It was on May 20, 1915, that the first great eruption of Lassen Peak occurred. An immense amount of hot water, steam, and hot rocks were thrown out on the east side. There were deep snowdrifts on the east side, and this mass of hot stuff melted the snow and the whole mass ran down the mountainside, taking everything before it. There was a heavy growth of timber there before the flood, but this was all swept away. A great part of this mud and water ran down Lost Creek, while the other part crossed over the divide and went into Hat Creek.

Four ranches were washed away by the flood. Nelson Stewart's place on Hat Creek, Adams's place on Lost Creek, and Lost Camp, and yet farther down the Perkiss place. The flood not only washed the land away, but left the places covered with logs and rocks everywhere. The Perkiss place was formerly a flat meadow, but now there are a hundred rocks or more from 5 to 10 feet in diameter where formerly there were no rocks at all. [Plate 2.]

[1] For example: "Nelson Olsen of Chester, who kept a notebook of happenings on the mountain, said he had moved his bed so as to see the mountain constantly from his window at night, but had only once (2^h30^m a.m., May 15, 1915) seen evidence of fire. He described the phenomenon as a series of flashes coming from the crater and shooting upward like Roman-candle balls. Several in number. Short flights. Lasted 5 minutes. In reply to a question whether they appeared white or red, he said white, and added that he thought at the time that they might be electric flashes, as they expired high in the air without returning to the ground." (Day, Field notes of May 13, 1916.)

"Charley Yori, the Lassen Peak guide, also of Chester, said he had heard from Olsen of the above observation and later, in the month of October, 1915, had seen flashes himself. Asked what they looked like, he said 'Lightning'." (Day, Field notes of May 13, 1916.)

"Miss Kelly, schoolmistress at Chester, said that she, in company with the driver of the Chester-Red Bluff stage (who was present and confirmed the observation) had seen unmistakable bright-red flashes on the night of October 29 or 30, which went out suddenly and were not seen to descend. I suggested that red-hot rocks would have to be very large to be seen at a distance of 25 miles and that if very large, could hardly 'go out suddenly'. She thought they might be electrical flashes." (Day, Field Notes of June 1, 1915.)

Wid Hall lived at Old Station on Hat Creek, 20 miles from Lassen. . . . Halls' folks . . . left the door open on leaving and the mud filled the house up to the window-sills. This loaded the house down and kept it from floating away.

Professor R. S. Holway, writing in the *Sunset Magazine* for August 1915, describes the occurrences in a similar way after a study of the situation on the ground. He says:

In this gorge the winds drift the winter's snows, making a huge snow field which lasts through the summer. During the period in which Lassen has been erupting ashes the wind has drifted them also into this same gorge, making the conditions ideal for a flood of mud and water.

Naturally this hot volcanic dust has melted the snow and caused mud flows. The writer has followed actually flowing mud on the side of the cone to the edge of the crater and found at the head of the flow dry dust wherever the rim was bare rock, and moistened dust where it rested on snow, thus disproving the current reports that mud flows really issued from within the crater itself. On the crater rim no mud seemed to have been ejected from the crater. The most reasonable theory for the big flood down the two creeks, the swiftness and power of which can scarcely be exaggerated, seems to be the following, viz., that on the accumulated mass of snow and volcanic dust in Lost Creek gorge there fell a mass of steam and dust from the eruption of May 20, a mixture which probably came in a blast directed downward by a sudden explosion.

Origin of the Mud Flow.

A second difficulty in establishing the mud flow as a direct outflow from the crater occurs when the attempt is made to follow the mud stream to its source. Instead of fixing by this means a connection between the mud flow and the crater, all trace of the mud flow is lost on the mountainside 1,500 feet or more below the crater rim (fig. 11). Although no eyewitness of its actual formation and progress has been found, a most careful search fails to reveal any tangible connection on the surface of the ground between the mud flow, now hard-baked and standing in its tracks, as it were, and the explosion crater. It has proved quite impossible to find support for the view that the crater sent forth this or any other mud flow, as such, during the eruption of May 19. W. H. Spaulding, who visited the summit on May 30, says: "The first reports were that the mountain had belched mud which had flooded Hat Creek Valley to the north and Lost Creek and Manzanita Lake to the south and west of the mountain. Our examinations showed no mud flow out of the mountain." Neither has the more or less obvious suggestion that the mud may have issued through a secondary opening near the foot of the mountain found any supporting evidence on the ground.

To an observer of this scene 4 weeks after the explosion occurred, when practically nothing was changed and yet the storm had cleared away, so that all parts of the field were accessible, the true course of events appeared obvious, even without the evidence of an eyewitness. Lost Creek has its source in a mass of snow and ice (fig. 11, left) which fills a great shallow bay on the outer (eastern) flank, reaching nearly to the summit of the mountain. Within this bay the snow accumulates to such depth in the winter season that all of the summer heat is normally inadequate to melt it away. (Compare snow deposit of 1916, Plate 5.) This year in particular we know that the volume of snow was very great, and even at the time of these observations (July 1) a small body of ice remained on the upper slope, sudplying the head-waters of Lost Creek. The great mass of snow which had filled this basin in May had, therefore, disappeared completely in one night, and in place of it we had the flood or mud flow. There is no other outlet for such a quantity of water on the one hand, and no evidence of any other source of the water necessary to the flow except the melted snow and the hot, ash-laden rain condensing from the steam explosions. Condensed volcanic steam, falling as hot rain charged

Fig. 11.—July 14, 1915. The northeast flank of the mountain where the horizontal blasts and the flood originated. Upper left, snow left after passing of horizontal blast. Upper center (dark), eastern end of the upheaved lid, fumaroles indicating continuation of fault. Lower right, beginning of mud flow. Photo Day.

with ash, bathed the summit and melted the adjacent snow, forming rivers of mud, not only in the valleys of Hat Creek and Lost Creek but upon the west, northwest, and north slopes also. One of these, accumulating in the Manzanita Lake drainage basin (northwest), covered many acres and reached the proportions of a considerable flood, though it caused no serious damage to the large forest trees in its track and so remained practically unnoticed.

It was, however, not the mud flow but a volcanic blast of terrific power (nuée ardente) and moderately high temperature, heavily charged with dust and rock fragments, delivered at a low angle in an east-northeast direction down Lost Creek Valley, which cleared the valley of its immense trees and indeed of every moveable object for more than 4 miles. When accompanied by ash and condensed steam from the cloud and directed upon the accumulated snow a torrent of fresh mud was an inevitable but secondary consequence.

There appears to be no need to base this deduction upon grounds of probability, for many direct observations of the effects of the horizontal blast are available. Before May 19 the valley of Lost Creek is reported by the Forest Service to have contained 5,000,000 feet of standing timber (original forest), much of which reached the diameter of 3 to 5 feet. After that date the bottom of the valley was swept

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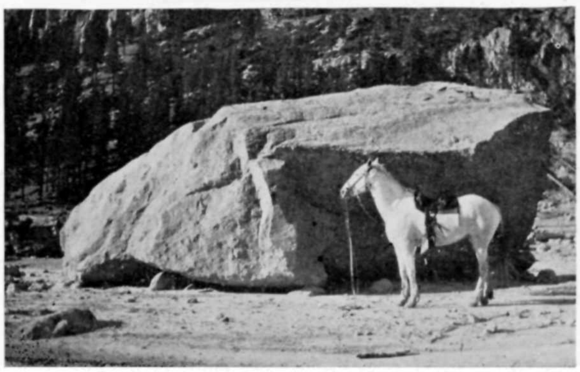

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Timber and boulders swept down Lost Creek by the mud flow of May 19, 1915.

Fig. 12.—June 4, 1915. Logs piled on the divide between Lost Creek and Hat Creek. Photo Seaborn.
Fig. 13.—July 18, 1915. Boulders and tree trunks, Lost Creek Valley. Photo Day.
Fig. 14.—June 4, 1915. Boulder from Lassen Peak carried for 4 miles by the mud flow of May 19, 1915. Photo Seaborn.
Fig. 15.—June 4, 1915. Log jam below Jessen Meadow. Photo Seaborn.

like a floor, and was left without stumps or roots to indicate its previous forest cover. It was hard to find even a pebble in that area greater than a few inches in diameter. In the lower reaches of the valley this floor still carries its covering of baked mud flow, sometimes 2 or 3, sometimes 5 or 6 feet deep, and it is only when one arrives at the far end of the devastated region that the disposition of the boulders from the summit and the timber which once covered the valley begins to be evident. Here are giant trees broken and twisted into fantastic groups, with here and there a boulder weighing up to 15 tons or more (figs. 12, 13, 14, 15). As stated above, this cleaning-out of the timber cover of the valley was not accomplished in the first instance by the mud flow, because the valley walls are clean far above any point reached by the mud. It requires hardly more than a glance, however, to show what the agent must have been, for higher up on the inclosing sides of the valley, a little at the side of the main axis of the blast, we find the forest trees down but not removed, and in particular we find them lying in parallel rows for nearly 2 miles, with their tops pointing uniformly away from the crater. It is quite possible to-day to ride a horse through these avenues of parallel trunks lying prostrate in faultless alignment, upon which a force must have been expended which did not distinguish between saplings of a few inches and the oldest giants of the forest.

Fig. 16.—July 14, 1915. View across Lost Creek Valley S to N showing the timber lying away from the blast and across the hillside. In the foreground the center of the path of the blast now swept clean. Photo Day.

One must not fail to note also that these parallel rows of trunks, as they line the inclosing walls of the valley, are not in the position of rest to which a tree trunk falling on a steep hillside would normally attain, namely, pointing down the slope. On the contrary, without exception, they lie along the contour lines in the position least stable of all (fig. 16). Even the force of gravity aiding the fall of the trees was quite powerless to dictate their position in competition with the force of the blast which laid them low.

Another interesting observation may be made in this outer zone at the side of the blast. Most of the trees which line these corridors were uprooted, but some were broken off a few feet above the ground instead. The standing stumps of such bear unmistakable, direct evidence of the bombardment which they received. Without exception, their bark is gone on the side toward the mountain, while fully retained on the protected side. Similarly, the exposed wood on the side toward the mountain is completely peppered with fine sand, oftentimes driven in for a considerable fraction of an inch. Indeed, as one nears the source of the outburst the intensity of this bombardment was that of a fierce sand-blast which rounded off the stumps themselves (fig. 17). The power of this blast was sufficient to carry away all the trees and the vegetation in Lost Creek Valley and those covering the divide between Lost Creek and Hat Creek to the eastward. It also con-

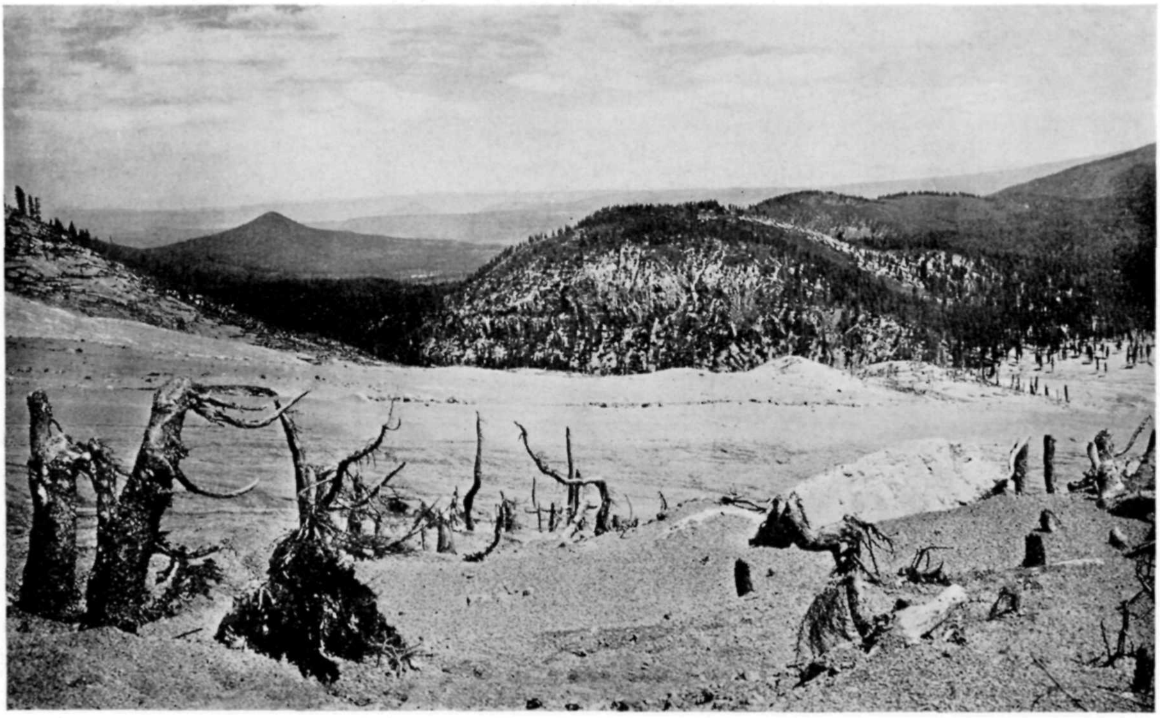


Fig. 17.—June 28, 1915. The path of the blast showing the sand-blasted trunks on the south border. Photo Day.

tinued on across the Jason Meadows and laid low most of the trees for perhaps half a mile on the far side of the divide. The total length of the devastated area in a straight line from the point of outbreak on the mountain eastward to its greatest extent is more than 4 miles. The area is in general fan-shaped (fig. 29) following the contour of Lost Creek Valley and widening out below to an extreme width of perhaps a mile and a quarter. On the boundaries adjacent to this area the trees are down, but were not carried away, and all the transition stages, down to comparatively insignificant damage, may be observed. Branches broken by falling rocks are found in all directions for 2 miles or more about the devastated area.

May 22, 1915. Lassen Peak and Lost Creek Valley after the first and before the second horizontal blast. Photo Loomis. Note the group of standing trees (right) which are down in subsequent views (Plate 4).

PLATE 3

SECOND HORIZONTAL BLAST, MAY 22, 1915.

There is trustworthy evidence that not all of the damage observed in the valleys of Hat Creek and Lost Creek was done by a single blast. There appear to have been two of these, the one just described, occurring on the night of May 19, and one accompanying the culminating eruption on the afternoon of May 22. The evidence of this is contained in a photograph of the mountain from Hat Creek Valley made by B. F. Loomis in the early afternoon of May 22, just before the greatest eruption occurred. In this photograph the effects of the first explosion and of the resulting flood are plainly shown, but a group of forest trees on the north side of Lost Creek Valley (on the right, Plate 3) is still standing in this picture, while

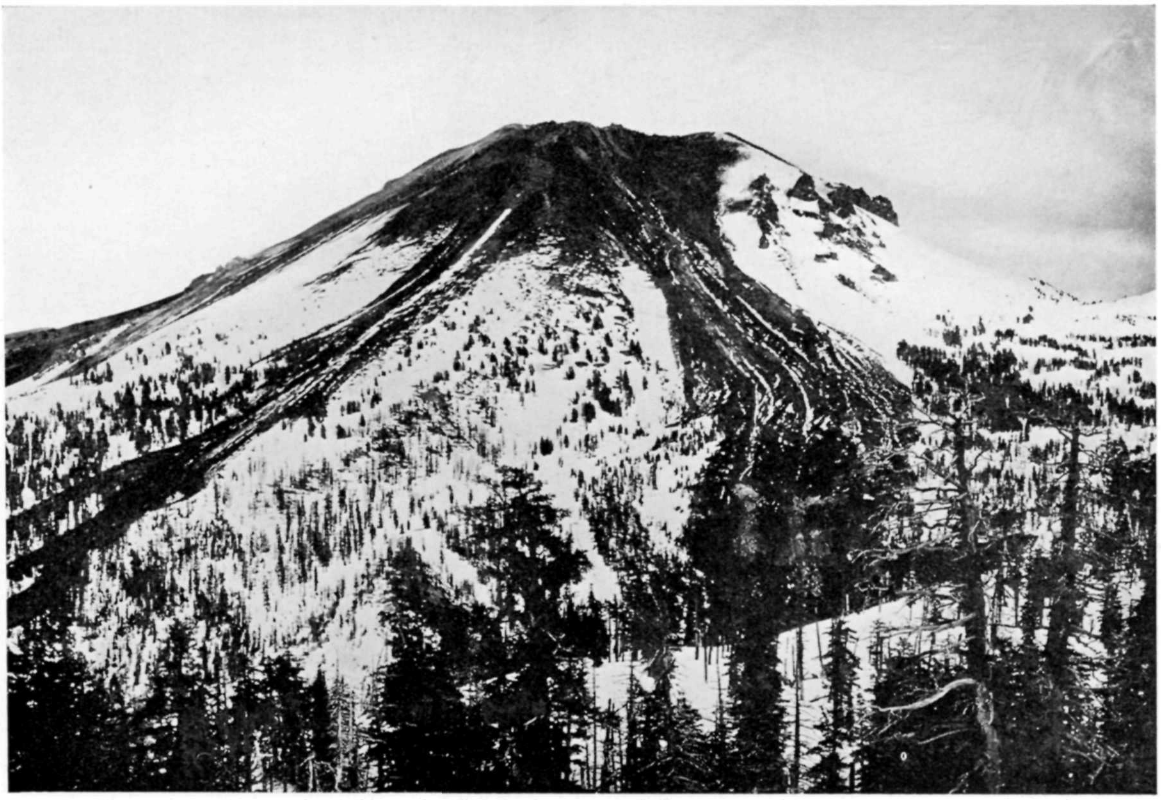


Fig. 18.—May 24, 1915. Minor mud flows on the north and west flanks of the mountain due to falling ash and condensed steam melting the snow. Photo Loomis.

in subsequent views they are down (Plate 4). No other essential change has been noted between this and the later views. There was a second flood accompanying the eruption of May 22, but the snow had been carried out by the earlier blast, so that the water causing the second flood must have been furnished almost entirely by the condensing steam from the explosions themselves. Further evidence of this is found in the fact that three other mud flows of secondary magnitude accompanied the eruption, on the west, northwest, and north sides of the mountain respectively, as shown in another photograph by Loomis, taken on May 24 (fig. 18).

Of these minor mud streams of May 22, which were witnessed by Loomis, he says (private letter April 20, 1922):

I have a photograph taken in the morning of May 22 which shows white snow to the summit and only one black streak on the west side, where a small mud flow probably went down in the eruption of May 19. In fact, the snow was white to the summit when the great eruption of May 22 began, and directly afterward we saw the streams start down the sides of the Peak . . . These mud streams did not start before the great eruption, nor afterward, but while the great eruption was on . . . It is unthinkable that water, either cold or hot, would flow over the crater rim in gentle ripples, while hot rocks and mud bombs were being hurled into the air a mile. But I know that hot water fell in the form of rain which started the mud flow, because nothing else could have done it.

Of the second great blast and accompanying mud flow down the east slope of the mountain following Lost Creek Valley, Loomis says (*Anderson Valley News*, Anderson, California, March 17, 1922):

On this second big eruption (May 22) a second flood went down Lost Creek, but not so large as the first one. Very little snow was left to be melted, so that the water from the crater (rain) was the greater part of the column of water that went down. Another frightful thing happened there to add to the damage caused by the flood. Hot steam flew out through that slit in the east side of Lassen, which blew down across the heads of Lost and Hat Creeks and blew down every tree for a space of a mile wide, and on the outer edge of this area the trees were burned to a crisp with the hot steam.

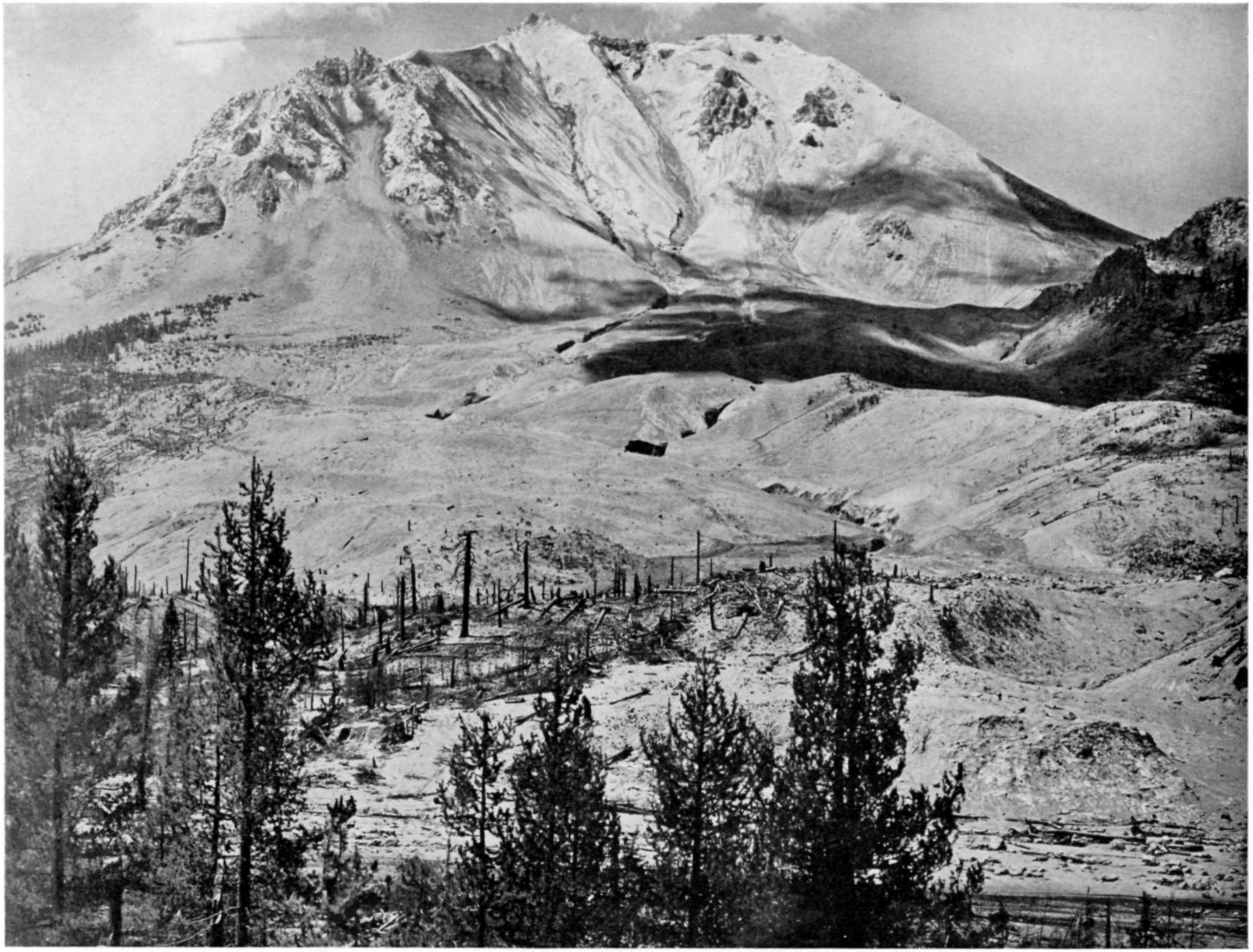
PERIOD OF SUBSIDENCE.

Following the great eruption of May 22, the volcano entered upon a period of gradual subsidence, interrupted at intervals by sporadic activity, but none of a magnitude comparable with the great eruption or even of the heavier eruptions of the previous year.

During June eight eruptions were recorded, all of short duration; during July, six, the last of which was fairly heavy and accompanied by rumblings which were heard several miles away. In September and October nineteen were recorded, two of which are reported to have been accompanied by bright flashes as though bombs were being shot high in the air, but which were probably electrical effects (page 19). During November and December there was but one eruption of consequence (November 13), and in the winter following no signs of activity were noted.

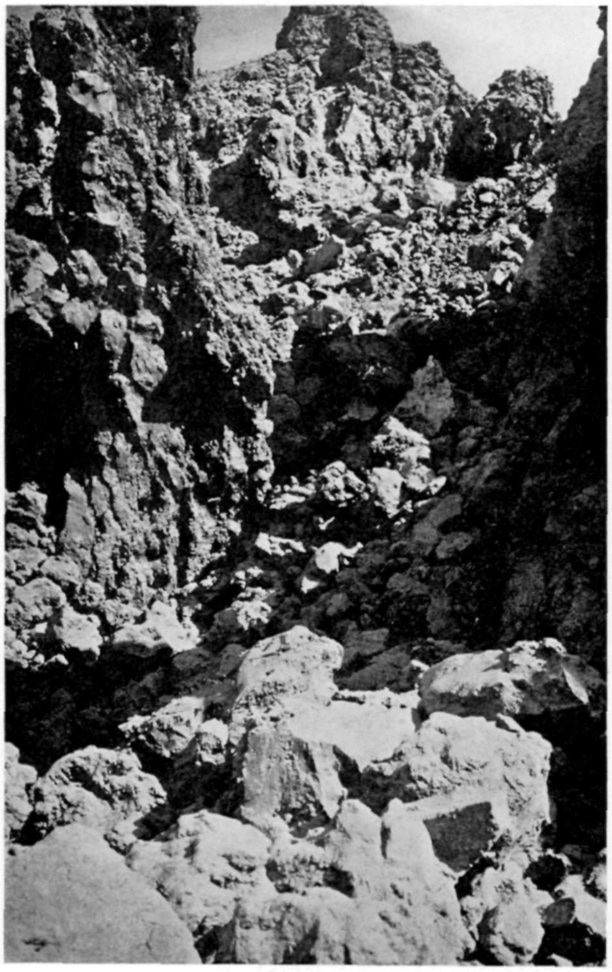
In view of the fact that the first outbreak occurred late in the month of May, during the period of most rapid melting of the accumulated snow of winter, and the maximum intensity of action was reached in the same month of the following year (1915) under like conditions, it was deemed of importance to make a trip to the mountain in May of 1916 in order to ascertain whether the snow conditions of this season could be definitely associated with the intensity of volcanic activity. Accordingly, the month of May and part of June following was spent on or near the mountain.

It may be said at once that so far as this primary purpose is concerned, nothing conclusive could be ascertained, for the reason that the major portion of the exposed plug on the summit remained warm enough to prevent any accumulation of snow



July 22, 1915. Lassen Peak from the northeast showing the devastated area after the blast of May 22, 1915. Photo Day. Note the absence of the trees on the right which are standing in Plate 3.

on it during the winter of 1915–16. At the time of our visit on May 22, the anniversary of the great eruption, there was no snow to be seen in the crater, except on the surrounding rim, and in consequence there was no surface water to be disposed of. Whether it is a consequence of this or not, there was also no activity observable during the period of our visit, save only a few fumaroles, notably on the northeast slope below the lid at the point of origin of the two great horizontal blasts of 1915.



19

20

Fig. 19.—July 26, 1915. The bottom of the summit crater after the great eruption of May 22, 1915. Photo Loomis.

Fig. 20.—July 15, 1915. Rift extending radially down the north flank of Lassen Peak after the great eruption of May 22. Photo Day.

During the remainder of the year (1916) only two eruptions of noteworthy magnitude appear to have been noticed (October 16 and 24). The year 1917 began with a serious show of activity on January 17, and in the month of May some powerful eruptions of several hours' duration were noted. The smoke cloud rose to a height of 12,000 feet on May 18 during an eruption of 6 hours' duration, and on May 19 and 20 activity was nearly continuous. It is of considerable interest to note that this brief resumption of sustained activity not only falls at the same period of the year as the initial outbreak in 1914 and the period of maximum activity in 1915, but also that considerable quantities of snow, accumulated during the previous winter, were again available (Plate 5). Eruptions followed this resumption of violent activity almost daily until the middle of June, when the extinction became practically complete. Smoke clouds were reported sporadically thereafter by the newspapers and by various observers, but it is not likely that any of these represented true eruptions. Indeed, many of them were nothing more than movements of dust under the action of the wind.

During this period of activity of May and June (1917), however, some explosions occurred of such violence as to displace large masses of material at the top of the mountain, and materially to change the appearance of the crater. So far as known, this is also the only period following the great eruption of 1915 when such displacements occurred.

Fig. 21.—July 7, 1922. Summit of Lassen Peak. Shallow 1917 crater. Photo Day.

At the close of the activity of 1915 there were two major centers of eruption—one within the old crater at the northeast corner of the crater bowl (fig. 19), developed by the activity of 1914 and 1915, the other outside the cone on the north, where a radial crack (fig. 20) several hundred feet in length opened some time during the period of maximum activity (May 19–22, 1915), from which most of the subsequent eruptions took their origin. In 1915 this crack was no more than a few feet wide, but during the activity of 1917 it increased in magnitude to a crater about 500 feet in diameter and possibly 300 feet deep, separated now by only a thin wall, probably less than 50 feet thick at any point, from the older inside crater above referred to. Indeed at the top 40 to 50 feet of this wall has been blown away so that the two craters are now nearly merged.

There is also a third center of activity which developed in 1917 within the periphery of the old crater rim, immediately to the west of the inside crater above referred to, and possibly 200 feet distant from it. This crater is both larger and shallower than the others, but around the margin of it are to be found the only fumaroles which persist at the top of the mountain. These are not seriously active

May 27, 1916. Same view as Plate 4, one year later. Note great accumulation of snow on northeast flank of mountain. Photo Day.

and the highest temperature noted among them during our visit of this year (July 1922) was 79°. This third crater is probably not more than 75 feet in depth below the general level of the upheaved plug, and lies immediately to the east of that portion of the western rim which is still standing (fig. 21). Through the courtesy

Fig. 22.—Lassen Peak from the air (northwest) showing all three summit craters.

Beginning at the arrow left:

(1) The outside rift (Fig 20) after its enlargement in 1917. This crater was the center of most of the activity subsequent to the great eruption of May 1915.

(2) The main crater in 1914 and 1915 (Fig. 19). Origin of the catastrophic eruptions of May 19 and 22, 1915.

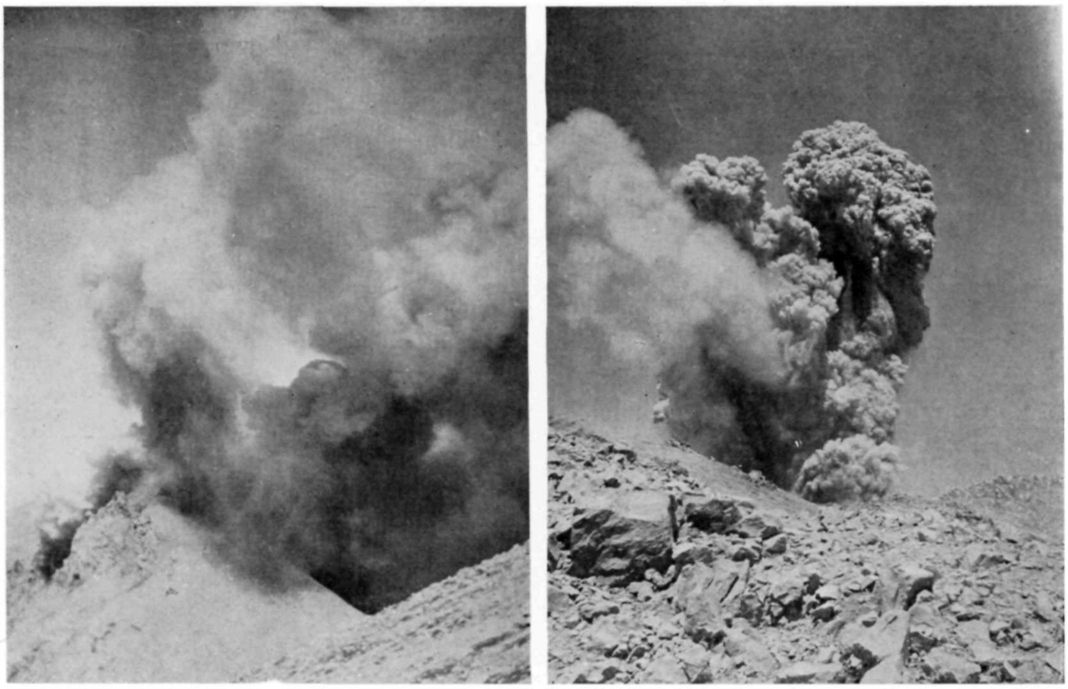
(3) A shallow summit crater (Fig. 21) developed in 1917. Photograph by U. S. Army Air Service. From National Geographic Magazine, Copyright 1924.

of the Army Air Service and the National Geographic Society it is possible to show the relation of the three summit craters of Lassen Peak which have survived from the eruptions of 1917. The photograph (fig. 22) is taken from the air above and to the northwest of the summit.

So far as may be ascertained from the present appearance of the summit, this entire period of activity is now closed. There are no signs to indicate its early return.

SUMMARY OF FIELD OBSERVATIONS.

Gathering together for purposes of discussion the various threads of evidence that have been followed thus far in their chronological sequence, we may divide the present activity into three periods: (1) the activity of 1914 and the early months of 1915, during which the culmination was approaching; (2) the devastating eruptions of May 19 and 22, 1915, including the upheaval of the crater floor which was the only lava movement recorded; (3) the slow subsidence from May 1915 through the year 1917.



23 24

Figs. 23, 24.—June, 1914. Explosions encountered on the summit by Robertson's party. Photo Robertson.

Considering these periods in this order, the first comprehends the long series of explosive eruptions that occurred at intervals of 2 or 3 days for almost a full year, the intensity increasing rapidly from the beginning in May to the late autumn and then diminishing during the winter season preceding the violent outbreak of the following May (1915). At the time of the first outbreak the crater bowl was filled with snow to a depth varying from 15 to 40 feet, and the rapid melting under the hot May sun was at its height. The initial eruption was explosive in character, sending up a cloud of "smoke" to a height of several hundred feet and scattering small fragments and miscellaneous débris from the bottom of the old crater to a distance of 200 feet or more in all directions. The succeeding explosions were characterized by violent outbursts of steam, some white and some black with their load of ash (figs. 23, 24), ascending to different heights from a few hundred to 11,000 feet above the summit and continuing from 1 to 4 hours. Stones from a few inches to 2 feet in diameter were scattered in all directions, reaching an extreme distance of 4 miles on the leeward (east) side of the mountain. The fine ash floated eastward under the prevailing wind for a much greater distance. The ejected rock fragments were cold and remained on the top of the snow without melting their way in. During this period the dust exerted no melting action upon the snow which it covered. After the first eruption the forest rangers noticed two cracks extending in general direction east and west from the explosive opening, and out of these cracks clouds of steam were exhaled. The snow adjacent to the cracks and to the explosion opening was melting and considerable quantities of water flowed into the cracks and so into the bottom of the explosion crater, where it disappeared in the talus without forming a pool.

Other eruptions, following the first at intervals varying from a few hours to 2 or 3 days, showed increasing intensity and duration, the explosion crater becoming rapidly enlarged as the explosions succeeded one another. The general direction of growth of the explosion crater was east and west, apparently following the initial cracks, which also correspond in general direction to the rift in the cone and to the faulting in the Lassen Peak region, since studied by Diller.

The period from July 13 to October 1 included all of the more powerful explosions of 1914, and the average duration of the activity was 3 to 4 hours. From October 1 to May of the following year explosions were less frequent and of only moderate violence. It is altogether likely that many of the explosions of this period escaped observation by reason of the short days and the winter clouds and snow.

Little information gathered in this period of activity appears to bear very directly upon its possible cause. That the explosions were steam explosions, in which neither chemical reactions nor extreme temperatures played any visible part, appears to be established. Evidence of heat on the summit and in the ejecta is almost entirely wanting. The explosions were for the most part of comparatively large volume and low intensity when compared with typical eruptions of Vesuvius, for example. This conclusion is equally true, whether it be based on the height of the explosion cloud or on the size and character of the ejecta. The explosion cloud was heavily dust-laden always, but it rarely rose to great heights, nor was it, in this period, ever observed to be hot or strongly acid either by persons coming in contact with it or from its effects on vegetation.

Similarly, the ejecta thrown out during this year were composed entirely of small rock fragments and lapilli. No heavy boulders were thrown beyond the crater rim, no bombs or fragments showing signs of recent fusion, and no fragments hot enough to melt the snow so long as there was snow where they fell. Later in the season when the forest carpet in the vicinity consisted of dry leaves of highly inflammable character no fires were set by ejected material.

This evidence, when brought together, plainly indicates that during the first year of activity (1914 and the winter of 1915) there were no evidences of chemical action, of high temperature, or of the development of great volcanic power. Neither was there during this period any dislodgment of any portion of the mountain structure beyond the original east-and-west rift, or of heavy boulders.

It is pertinent, and perhaps significant, to note that a considerable body of snow within the crater basin melted and disappeared in cracks leading down to the

Fig. 25.—Explosions in quick succession in summer of 1914. Photo Mullen.

center of activity during the early weeks of the eruptions. The water thus assimilated certainly participated in the steam explosions, but whether or not as a contributory cause will perhaps better be left to a later chapter for discussion. Diller, who has also commented[1] upon this fact, has discarded it as an essential factor in the activity, because the explosions continued (fig. 25), with generally increasing

[1] Unpublished communication.

violence throughout the summer months long after the snow had disappeared. This fact, however, may indicate merely that the explosions were not so simple a matter as pouring a mass of water into a hot cavern and witnessing the immediate explosion of it as steam. Indeed, if the operation of the volcano had been as simple as this we should not have had separate explosions at intervals of several days during the period of melting snow, but a more or less continuous discharge of steam (during the daytime at least) until all the snow was melted, followed by a cessation of activity until the following spring. The fact that no such simple mechanism was discovered in no wise disposes of the participation of water in the activity at Lassen Peak. Great quantities of water actually flowed into the explosion crater and its tributary cracks, as observed by the forest rangers and many others, and great quantities reappeared in the explosions. There is no evidence that the activity was damped thereby; on the contrary it increased

Fig. 26.—August 10, 1915. Summit, looking west along the southern edge of the upheaved plug. Photo Diller.

rapidly during this period, both in intensity and duration. The participation of the water in this activity therefore constitutes one of the chief problems offered by Lassen Peak during this eruption. It requires laboratory study for its elucidation, however, and will therefore be discussed more in detail on a later page.

SECOND PERIOD OF ACTIVITY, MAY, 1915.

As has been indicated in the preceding description, the first sign of the change in the character of the activity at the close of the first period was indicated by the observations of Loomis and Miss Dines a day or two previous to the great eruption of May 19 and 22. These observers noted (p. 15) the appearance of a black mass thrust up into the western notch on the summit, which suggested to them, and may well have been, an upheaval of the whole bottom of the old crater bowl (fig. 26), completely filling the explosion crater, which had grown during the previous year to occupy nearly the whole of this bowl. The last estimate of the size of the explosion crater reported it to be nearly round and about 1,000 feet in diameter (March

1915). Its depth was never measured, nor did any observer from June 1914 to March 1915 take note of any exposure of the solid bottom, other than the point of meeting of the talus from the surrounding walls. In other words, the explosion crater during the first period was always approximately an inverted cone, at first narrow and afterward broadening out as the explosions continued and removed the loose material out to the inclosing rim of the bowl. These explosions of the first period, then, apparently failed to reach solid rock, still less molten magma. The observations of Loomis and Miss Dines therefore offer the first clue to the appearance in action of the greater forces through which the volcano plug was lifted at least 300 feet, and perhaps much more than this,[1] and which found release afterward in the two mighty explosions of May 19 and 22, 1915.

These explosions were of very considerable intensity. The first (May 19) came in the night and so brought to view the only incandescent lava certainly observed on the mountain during its activity. By virtue of this observation we have a clue to the crater temperature while the activity was at its maximum. The second of the great explosions occurred during daylight and so enabled the Forest Service observers to estimate by triangulation the height of the dust cloud accompanying the blast (25,000 feet above the summit). Associated with each of these great explosions was one or more horizontal blasts of tremendous destructive power, suggesting the nuées ardentes of Lacroix at Martinique. These outbursts were heavily charged, both with dust and heavier detritus and with water vapor, which together were sufficient to melt completely the snow in their pathway and so to cause destructive floods which submerged the valleys of Lost Creek and Hat Creek to a depth of from 2 to 10 feet for some 20 miles. It will also be recalled that these blasts carried away or laid down in a single direction, pointing away from the mountain, standing timber up to 5 feet in diameter, far above any level reached by the flood; that they were hot enough to singe but not to fire the foliage of the evergreens, and that the flood material when allowed to settle yielded something like 90 per cent of solid matter (including pore-space). We shall consider these facts in some detail in the subsequent discussion.

Following this culminating outbreak a normal subsidence period ensued, covering altogether a period of about 2 years, in which the activity only once (May 1917) attained to any considerable intensity. The only noteworthy feature of this period for purposes of a discussion of causes is the date of the renewal of the violent explosions (May 18, 1917), which corresponds very closely to the date of the first outbreak (May 30, 1914) and to the height of the activity (May 22, 1915).

In type the present outbreak was a mild and but incipiently developed counterpart of the eruption of Mont Pelée (Martinique) in 1902. A great number of explosions occurred, causing violent displacements of old material within the crater and an eventual upheaval (May 1915) of the entire crater floor, but these disturbances did not lead to a lava flow, nor were they sufficient, as in the case of Bandai-

[1] 300 feet represents merely the difference in level between the bottom of the old crater bowl (before 1914) and the elevation of the top of the plug after the upheaval (May 1915). The depth of the débris overlying the solid plug before the upheaval is of course unknown. The amount of this débris scattered over the countryside during the hundred and more explosions of the first year, before the upheaval, would indicate that it was considerable.

san, to destroy or blow off the top of the mountain. There is also this further difference, that the violence of the explosions of Bandai-san was sufficient to relieve the pressure within the mountain in rather less than an hour, and the eruption had practically spent itself within that time. The explosions at Lassen Peak continued intermittently through nearly 5 years, no one of them being sufficiently violent to alter radically the shape of the mountain or to remove any considerable volume of matter from the crater basin (like the great Katmai eruption of 1912 for example, when about a cubic mile of the mountain top and crater basin was blown away). In point of violence, therefore, compared with the great explosions of history, Lassen Peak showed only moderate activity at any time, although during the second year there were two explosions (May 19 and 22) of sufficient violence to have overwhelmed a small city (like St. Pierre, Martinique) in case it had happened to be located in Lost Creek Valley. Accompanying the May eruption in 1915 there was an upheaval of the crater floor which penetrated through the rim, both east and west, for a total length of about 2,000 feet, and rising at its highest point some 300 feet above the original floor-level, but only random fragments, and these practically all at the eastern notch, were projected beyond the mountain top. A few of these boulders weighed several tons.

CHAPTER II.

CHEMICAL AND PHYSICAL RELATIONS (Laboratory Study).

CHEMICAL COMPOSITION.[1]

Perhaps no North American volcano has been so extensively studied chemically as Lassen Peak. Detailed field investigations, of somewhat limited scope, to be sure, have also been carried to a stage of admirable completeness. Unfortunately, however, little has been done in the detailed description of the volcanic products, and, although the materials are available and await use, an adequate petrological interpretation of the field has yet to appear. Several andesites and dacites and a number of pyroclastic products have been described,[2] and Diller has made a detailed study of the quartz basalt of Cinder Cone,[3] while Hague and Iddings provide some generalized descriptions of the lavas.[4] Desirable detail on the order of succession and the mineralogical and textural variety of the rock types, however, is lacking. Of the mineral phases produced we know practically nothing, the only mineral analysis being that of a plagioclase which contains glassy inclusions.

We possess now some 55 analyses of rocks from the Lassen field, of which 7 are tuffs and 5 are "secretions" in lava flows. The remainder consists of 6 rhyolites, 8 dacites, 14 andesites, 8 quartz basalts, and 5 basalts from the regional suite, together with 1 hornblende basalt, mentioned above, and 1 pumice, which are so exceptional in character and occurrence that in all probability they do not belong to the Lassen magmatic series at all. Nearly all of the analyses are of excellent quality, and most of them have been published by the United States Geological Survey.[5] They enable certain conclusions to be drawn.

If the analyses of the lavas be arranged and examined critically they are found to represent five well-defined groups, corresponding to the five types: rhyolite, dacite, andesite, quartz basalt, and basalt. The "secretions" demand separate treatment. The lavas, as Harker has shown,[6] form a graded series, but whereas he considered that the quartz basalts do not fit well into the serial arrangement, we find that in general they show divergence of serious magnitude only in being low in alumina and high in magnesia (the oxides chosen by Harker to demonstrate the exception). The only other notable difference is in their low water content. They fit the scheme, indeed, quite as well as the so-called "secretions," which are high in alumina and low in lime. The fact that the silica range of the "secretions" embraces that of the quartz basalts is suggestive of some relationship between them. Arrang-

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[1] With the co-operation of Mr. Aurousseau.

[2] U. S. Geol. Surv. Bull. 150, 1898.

[3] J. S. Diller, A late volcanic eruption in Northern California, U. S. G. S. Bull. 79, 1891.

[4] A. Hague and J. P. Iddings, Notes on the volcanoes of Northern California, Oregon, and Washington Territories, Am. Journ. Sci. (3), 25, 222–235. 1883.

[5] H. S. Washington, Chemical analyses of igneous rocks, U. S. Geol. Surv., Prof. Paper 99, 1917; U.S. Geol. Surv. Bull. 148, 191–200, 1897; Bull. 591, 169–175, 1915.

[6] A. Harker, The natural history of igneous rocks, 1909, pp. 125, 355, figs. 28, 110.

ing the lavas in the order of their silica percentages, the five types are found to be characterized by a well-defined silica range, and are generally separated by significant gaps. The rhyolite range is well separated from that of dacite and is unbridged. That of dacite is well separated from andesite. The andesite range is comparatively wide and overlaps that of quartz basalt, but it and that of quartz basalt are well marked off from true basalt. The "secretions" embrace the quartz basalt range and overlap that of andesite, but not that of basalt. The analyses for each type group of rocks were accordingly averaged and the results recalculated to 100 per cent, as shown in table 1.

TABLE 1.—AVERAGE COMPOSITION OF THE DOMINANT ROCK TYPES, LASSEN PEAK.

	1	2	3	4	5	6
SiO_2	73.73	68.41	60.89	56.25	55.34	51.24
Al_2O_3	14.05	16.02	16.90	16.79	18.80	18.17
Fe_2O_3	0.99	1.76	2.77	1.70	3.92	4.19
FeO	0.59	1.14	2.75	4.84	3.18	4.81
MgO	0.29	1.28	3.13	6.54	5.13	6.29
CaO	1.04	3.20	6.45	7.90	7.54	9.90
Na_2O	3.30	4.08	3.79	3.26	3.20	2.80
K_2O	4.23	2.60	1.65	1.31	1.22	0.73
H_2O	1.36	1.00	0.81	0.52	0.90	0.99
TiO_2	0.18	0.24	0.53	0.54	0.51	0.55
P_2O_5	0.04	0.10	0.15	0.17	0.10	0.17
MnO	0.08	0.09	0.11	0.13	0.12	0.15
BaO	0.11	0.06	0.04	0.03	Trace	0.01
SrO	0.01	0.02	0.03	0.02	0.04	Trace
Li_2O	Trace	Trace	Trace	Trace	Trace	None
Sum	100.00	100.00	100.00	100.00	100.00	100.00

1. 6 rhyolites. Silica range, 74.65 to 72.40 per cent.
2. 8 dacites (includes 2 "andesites"). Silica range, 69.51 to 67.89 per cent.
3. 14 andesites (includes 1 "dacite"). Silica range, 63.81 to 55.20 per cent. Water range of 12 analyses, 1.24 to 0.51 per cent.
4. 8 quartz basalts. Silica range, 57.59 to 54.56 per cent. Water range of 5 analyses, 0.42 to 0.27 per cent.
5. 5 "secretions" in dacites and andesites. Silica range, 58.97 to 53.35 per cent. All notably rich in alumina.
6. 5 basalts. Silica range, 52.95 to 47.93 per cent.

The serial relations are admirably shown by the average type values and have been plotted as a variation diagram (fig. 27). It is noteworthy, in comparing this diagram with the "smoothed" curves of Harker (another method of averaging, which should lead to identical diagrammatic results),[1] that the forms of the individual curves differ somewhat at the basic end. This is doubtless due to the fact that he has included in his diagrams the hornblende basalt, which we regard as extraneous. The figures for this rock and the pumice differ so greatly from those of the undoubted products of the Lassen field, that they must of necessity displace the average figures of basalt considerably. The mineral character and single occurrence of the hornblende basalt throw suspicion upon it, and the pumice is not only exceptionally silicic, but shows low alumina, and, contrary to expectation, high lime and reversed alkali values. Its water content is low (perhaps not a significant

[1] A. Harker, The natural history of igneous rocks, 1909, pp. 125, 355, figs. 28, 110.

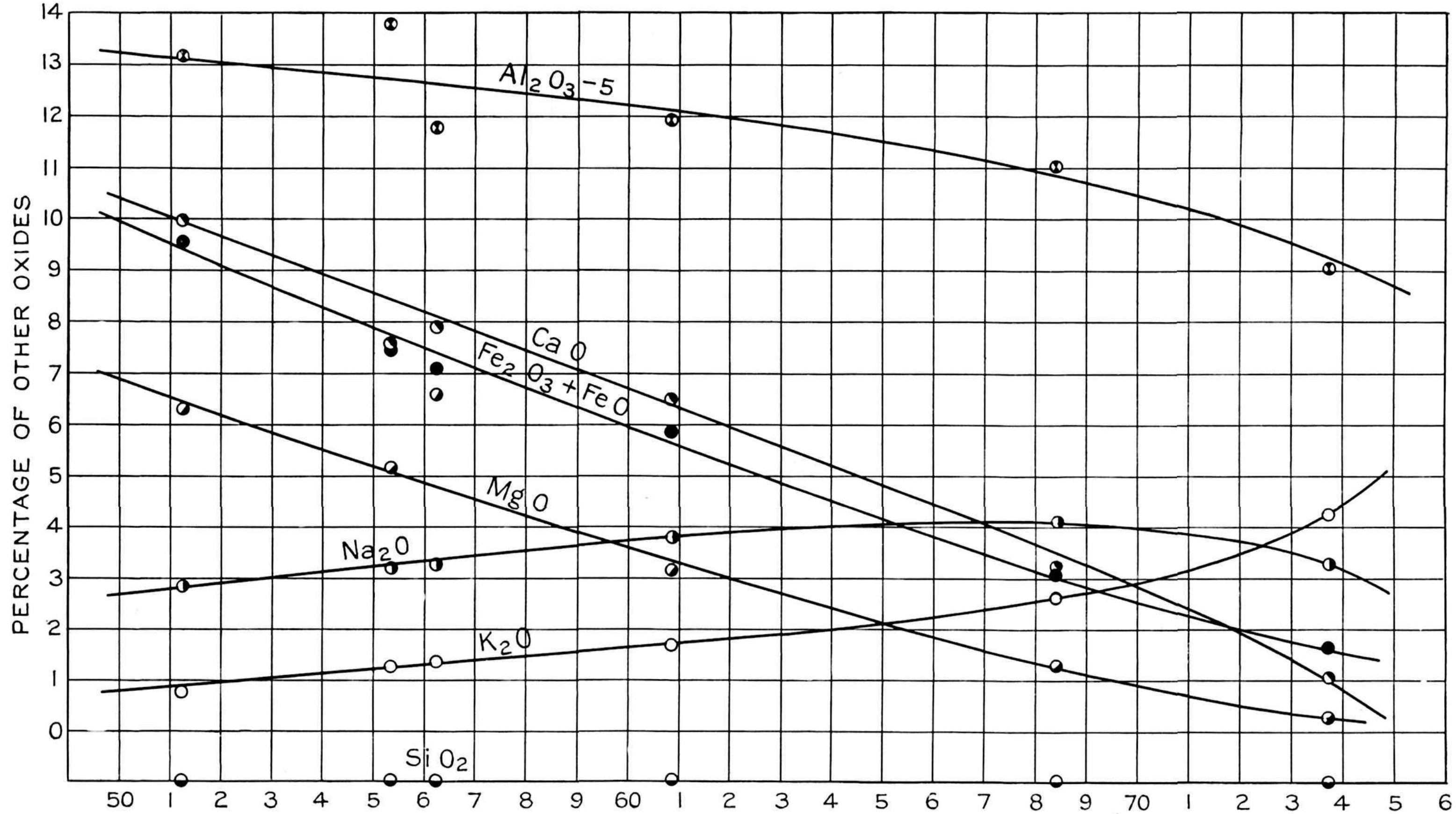


Fig. 27.—Curves showing the variations in the composition of the Lassen Peak Rocks. Constructed from the type averages of Table 1.

point) and it contains no manganese. In every way it is exceptional, and we exclude it from membership in the Lassen suite.

The Lassen rocks on the whole show some interesting individual features for the field, which link it with such areas as Shasta, Crater Lake (Oregon), and inferentially, with Mount Hood and Mount Rainier. It can hardly be doubted that these great volcanoes have all had a similar magmatic history and express similar processes in the production of their lavas.[1] The Lassen rocks are normally alkali-calcic, and only in the range of their minor constituents do they differ from similar andesites, dacites, etc., from other parts of the world. Their TiO_2 content is a little lower than usual. They contain notable amounts of BaO, especially towards the silicic pole, which preponderates as a rule over an ever-present but small amount of SrO. All contain traces of Li_2O, but ZrO_2 is present, where it has been sought, only in the smallest amounts, and P_2O_5 throughout the suite is in smaller amount than is usual. MnO is present in normal quantity. Cl, F, and S, if present, exist in quantities barely determinable by gravimetric methods. The values for H_2O deserve close inspection in relation to the last products of eruption (1915). Only in the quartz basalts do they fall below 0.50 per cent. In all the other rocks water is present, usually in amounts well above this value. These minor characters are also to be seen in the published analyses of rocks from Shasta and Crater Lake, Oregon.

The "secretions" do not fit the variation diagram. Diller regards them as products of early crystallization in the rocks in which they occur.[2] They are notably high in alumina, a little low in lime, and exhibit small but notable amounts of strontia. Their alkali content is close to that of the types of the suite.

Little can be said concerning the nature of the processes of differentiation in the Lassen field, except that from the diversity of rocks produced they must have proceeded nearly to completion. Hague and Iddings have published two interesting tables of analyses which suggest how crystallization affects the composition of the remaining magma. In a pumice from Shasta they give analyses of the rock, its hypersthene, feldspar, and glass; in a dacite from Lassen, the rock, the feldspar, and the glass are given.[1] In both examples the glass is highly silicic and the greater part of the potash is concentrated in it. We have calculated the analysis of the feldspar (which contains glassy inclusions) from the Lassen dacite. It is as shown herewith:

Quartz	16.08	
Alumina	0.50	
Orthoclase	5.00	
Albite	49.78	$=Ab_{64}An_{36}$
Anorthite	28.36	
Water	0.34	
	100.06	

[1] A. Hague and J. P. Iddings, Notes on the volcanoes of Northern California, Oregon and Washington Territories, Am. Journ. Sci. (3), 25, 222–235, 1883.

[2] U. S. Geol. Surv. Bull. 150, 1898.

These interesting results suggest that towards the silicic pole the process has proceeded from the basic side to the production of silicic types. The "glass" of the dacites may well correspond to the composition of the rhyolites. This early chemical work is an attempt at phase analysis, and merits attention.

PRODUCTS OF RECENT ACTIVITY.

The recent activity of Lassen Peak has been characterized by the eruption of ash, the evolution of steam, and on May 19 to 22, 1915, by the filling of the crater with lava from below (the uplifted plug). We propose to examine critically the material extruded in this latest upheaval on external, internal, and experimental grounds, in order to ascertain if it presents any evidence on the mechanism of the recent activity.

From the general considerations of the preceding sections, Lassen Peak may be interpreted as an old and dying volcano. It has extruded the products characteristic of a very well-differentiated magma, and its greatest period of activity has long since passed. Occasional outbursts of no great violence may still be expected, the most likely product of which would be comminuted ash due to attrition in the choked vent, with a moderate discharge of steam and rising gases. If magmatic material in sufficient quantity to produce a lava flow still exists beneath the cone, the recent history of Cinder Cone, and the stage of differentiation attained, would lead one to expect the eruption of a lava resembling the products of the later stages of activity, a rock of more extreme type than the extrusions of the opening or most active phases (andesite)—a quartz basalt or even a normal basalt would not be astonishing. The behavior of the Cinder Cone suggests that it is not improbable. Lassen Peak itself consists of dacite on the northeast, which embraces the crater, of pyroxene andesite on the southwest, with normal basalt on the lower flanks all around, and an area of rhyolite on the low western flank. A mile north of the crater is a very small area of quartz basalt.

The real products of the recent eruption, however, differ considerably from what might have been expected. The ash is andesitic, or dacitic, in composition, while the uplifted and shattered plug is an andesite of somewhat variable composition, exhibiting three significant physical modifications, having in the main the chemical composition of some of the old andesitic or dacitic rocks which form the northeastern part of the upheaved mass and the inclosing crater of Lassen Peak itself. The composition of the ash and of two forms of the lava which now fill the crater, together with an analysis of the youngest dacite of the region (according to Diller), are given in table 2.

The ash, dust, and pumice of the recent eruptions covered the country to the northeast of Lassen Peak. That analysed by Shepherd was collected from the Hat Creek "mud flow" in June 1915. It was air-dried, that is, it remained in a screw-capped glass jar until analysed in 1923. The analysis (No. 2 of table 2) shows no peculiarities except a slightly higher amount of silica than would be expected from the composition of the lava. Physically this mud flow consists of fine ash, mixed with fragments of two modifications of the andesite of the new lava. These coarser fragments were removed by passing the material through a 28-mesh sieve. Of the

TABLE 2.

	1	2	3	4	5
SiO_2	63.86	66.45	63.21	64.16	68.72
Al_2O_3	16.07	16.19	17.15	16.87	15.15
Fe_2O_3	1.56	2.66	1.30	1.46	1.16
FeO	2.31	1.12	3.00	2.77	1.76
MgO	2.11	1.86	2.96	2.60	1.28
CaO	4.94	4.55	5.23	4.96	3.30
Na_2O	3.59	4.06	4.12	4.09	4.26
K_2O	1.91	2.03	2.10	2.29	2.78
H_2O+	0.81	0.68	0.31	0.13	0.74
H_2O-	1.47	0.39	0.04	0.05	
CO_2	....	....	none	none	....
TiO_2	0.45	0.39	0.48	0.55	0.31
ZrO_2	0.04	0.01	0.02	trace	....
P_2O_5	0.12	0.16	0.16	0.12	0.09
Cl	....	....	0.02	n.d.	....
F	....	....	p.n.d.[1]	p.n.d.[1]	....
S	0.84	0.09	0.03	0.02	....
Cr_2O_3	....	....	none	none	....
MnO	0.05	0.10	0.07	0.08	0.11
BaO	0.03	....	0.07	0.07	0.07
SrO	....	....	....	....	0.03
Li_2O	trace	....	....	....	trace
Sum	100.16	100.33	100.27	100.22	99.76
Less O	....	0.04	0.01	....	....
Sum	100.16	100.29	100.26	100.22	99.76

NORMS OF 3 AND 4.

	3	4
Quartz	15.18	17.28
Orthoclase	12.23	13.34
Albite	34.58	34.58
Anorthite	22.24	21.13
Diopside	2.26	1.63
Hypersthene	10.00	8.57
Ilmenite	1.06	1.06
Magnetite	1.86	2.09
Apatite	0.34	0.34
Water	0.35	0.28
Sum	100.10	100.30
Symbols	I(II). 4″.3.4.	I(II).4.3.4.
Name	Yellowstonose	Yellowstonose

1. Andesitic ash, Lassen Peak, September 1914. U. S. Geol. Surv., Prof. Pap. 99, p. 259. W. C. Wheeler, analyst.
2. Andesitic ash. Hat Creek mud flow, eruption of 1915, Lassen Peak. E. S. Shepherd, analyst.
3. Pyroxene andesite (dacitic). Dense, glassy variety. The crater, Lassen Peak. Eruption of 1915. Collected by E. T. Allen, June 1922. M. Aurousseau, analyst.
4. Pyroxene andesite (dacitic). Pumiceous variety. The crater, Lassen Peak. Eruption of 1915. Collected by E. T. Allen, 1922. M. Aurousseau, analyst.
5. Dacite. East end of Chaos, northwest base of Lassen Peak. The youngest dacite of the region. J. S. Diller, U. S. Geol. Surv., Bull. 150, p. 218, 1898. W. F. Hillebrand, analyst.

[1] Present—Not determined.

remaining portion about half, by volume, passes through the 125-mesh bolting cloth without further grinding. Microscopically this powder is distinguishable from the powdered andesite (vesicular variety) only in the obvious presence of slightly more quartz. It is a mixture of glassy material containing small crystals of feldspar and pyroxene, broken grains of feldspar phenocrysts, and occasional grains of magnetite and shreds of biotite. Apparently this material is merely comminuted andesite (vesicular variety) from the lava in the conduit. In passing, it may be noted that the grains of magnetite and shreds of biotite appear identical with the biotite-magnetite relations in the andesite. The main mass of the "mud flow," as well as the great quantities of ash and pumice which covered the country to the northeast, seem to have been of this material. The ash of 1914 agrees more closely with the andesite of the volcano plug (1915) in composition, the differences in the two analyzed samples of ash being due perhaps to the sorting effect of the atmosphere. The presence of so large an amount of free sulphur in Wheeler's sample is of no particular significance, in view of the fact that we do not know its local origin, but the differences in the iron values are interesting. Wheeler's sample is practically a comminuted form of the andesite. The Hat Creek sample suggests a preponderance of magnetite.

The andesite of the lava of 1915, which partly filled the crater and intersects the rim on the western side,[1] is a dacitic rock, an andesite containing insignificant amounts of free quartz, a little biotite, and a little pyroxene. It is very variable in composition and shows three distinct physical modifications—a dense andesite, a pumiceous, and a bread-crust variety. The crater was rifted east and west[2] and the 1,000-foot tongue of lava, which transgresses the rim, occupies the western notch of the rift. From the general nature, disposition, and appearance of the lava it is the top of a mass of material (the "plug") which has risen in the vent to the level of the old crater rim, convex in general form, crusted and solidified above, and capable of viscous movement below. In expanding to fill the larger diameter of the upper part of the crater and the rift on the west, the upper crust has been cracked and fissured vertically as the viscous lower portions pushed it upward.

The modification of this lava, which we term the dense, glassy andesite, is a black rock, containing abundant glistening phenocrysts of plagioclase. It has a smooth fracture. The color is the neutral-gray M of Ridgway. With the white plagioclase phenocrysts, which range up to 8 by 15 mm. in size, a little free quartz, a rare flake of biotite, and an occasional phenocryst of pyroxene, perhaps 7 mm. long, may be seen. Apparently rolled into it are occasional inclusions from which the lava has more or less pulled away. One specimen shows a wrinkled surface and an abortive, laminated mass-structure which suggests its having been rubbed along a colder or more rigid mass, or that the nearly rigid material has been fractured; otherwise it resembles all the specimens of the dense material in showing flow while in an almost rigid condition, which came little short of fracture. All of the dense,

[1] J. S. Diller, Lassen Peak—our most active volcano, Bull. Seismol. Soc. Am. 6, 1–7, 1916.

[2] A. L. Day, Possible causes of the volcanic activity at Lassen Peak, Bull. Seismol. Soc. Am., 12, 35–46, 1922; Journ. Franklin Inst. 194, 569–582, 1922.

glassy material examined is shattered throughout in a peculiar manner; a network of minute cracks divides the mass into cells about 0.5 cm. in diameter. While not noticeable on first inspection, a smooth or polished surface, when wetted, will in drying show the cracks distinctly. The fracturing is not pronounced enough to prevent cutting 4 mm. slices of the rock, but it is quite definite. The feldspar phenocrysts are all shattered and easily broken out, and those of pyroxene are fractured. Apparently the dense, glassy andesite occurs chiefly near the source of the extrusion, or in angular blocks thrown out and scattered about the mountain-top. Dr. Fenner (in 1919) found one piece, apparently of this material, showing the transition from dense to vesicular structure on the top of Cinder Cone, 10 miles distant from Lassen Peak. In all respects it suggests flow under pressure while in a viscous, almost rigid state. Whether any portion of the upheaved plug now exposed was actually viscous during the eruptive period 1914–17, or the fragments showing indications of viscous movement belong to an earlier period of activity, it is not possible to say with certainty on account of its shattered and disconnected condition. As far as is known, however, all of the newly erupted material consists of one or another phase of this parent andesite, or dacite.

Microscopic examination shows the dense andesite to be variable in composition. It may contain from 40 to 60 per cent of glass, according to the specimen examined. An estimate of the amounts of plagioclase, biotite, pyroxene, and quartz occurring as phenocrysts gave the respective proportions 15 : 3 : 2 : less than 1. Magnetite, in minute grains, is the only noteworthy accessory.

The plagioclase is partly fragmentary and mostly rounded. It shows successive reaction surfaces and irregular zoning with less and more calcic material alternating. The more calcic material often penetrates along a fracture line through a zoned crystal. The narrow outer zones of the phenocrysts are sharply marked and notably more calcic than the neighboring inner ones, but they show resorption. The range of composition, as determined by refractive indices on powder, varies between $Ab_2\,An_1$ and $Ab_3\,An_2$. None of the phenocryst feldspar is as calcic as some of that of the ground-mass.

The biotite is always surrounded by a border of reaction products [1] and for the most part is decomposing, as might be expected in a conduit plug which may have been reheated several times. This decomposition results in the grains of magnetite noted in the ash of the Hat Creek mud flow, and explains the ferrous-ferric ratio of the analysis of the ash. Biotite separated from the rock magnetically showed optical characteristics, undoubtedly due to loss of volatiles and partial oxidation (as will be explained below). It gave $\gamma = 1.68$ to 1.70, with $2E = 10°$ to $40°$, and showed varying degrees of reddening. The pyroxene is near diopside in composition, having $\alpha = 1.675$, and $\gamma = 1.715$. It usually occurs in granular aggregates as though shattered. A few grains of quartz occur, their corrosion being the only point of interest.

The ground-mass is a brownish glass in which both plagioclase and pyroxene needles are abundant, but orthoclase is absent. Most of the plagioclase needles are

[1] Cf. H. S. Washington, The magmatic alteration of hornblende and biotite, Journ. Geol., 4, 257–282, 1896.

more calcic than any of the phenocrysts, reaching Ab_2An_3 in composition. The glass is brownish by transmitted light and full of minute microscopic crystals. It is highly siliceous, with a refractive index varying greatly over short distances from 1.485 to 1.500, and is thus notably inhomogeneous.

The composition of the rock is stated in table 2. It is the most silicic of the andesitic group of rocks from Lassen Peak. It has a lower water content than any rock other than quartz basalt which has been analyzed from that field, with the exception of its own vesicular modification. The water was determined by the Penfield method, and was checked by a more elaborate method (exhaustion of the water on heating the powder *in vacuo*, with subsequent absorption by P_2O_5). The results were in the closest accord. The ferric ratio[1] is 0.281, and the gas-content is 10.6 c. c. per gram, at 1200° C. (see p. 48). Volatile constituents seem to be present in the Lassen rocks in amounts not determinable with certainty by gravimetric methods. Cl and S were determined in this rock, on large portions, blank determinations being made at the same time. The results merely prove the presence of these constituents but can not be accepted as an accurate measure of the amounts present. The results of gas analysis, given below, afford a much more reliable appraisal.

The petrological study of this rock, then, shows it to resemble the rocks of which the crater region of Lassen Peak is built. Chemically it resembles certain dacitic rocks, which have been analyzed, from the northwest base of the mountain.[2] As a volcanic product it represents material which is in anything but a state of equilibrium, judging from the condition of the biotite, the nature of the plagioclase phenocrysts, and the variable composition of the glass. Physically also it has suffered a great amount of shattering and movement. It is just the kind of mass which would be expected from an old conduit lining and plug, slowly forced upward after being shattered and locally heated by ascending gases or otherwise.

The second modification of the new lava is a pumiceous or vesicular andesite, much lighter in color than the dense, glassy variety. It apparently forms the interior portions of the blocks on the cracked and fissured, crusted and expanded surface of the new lava filling the crater. Its vesicular character, and consequent lighter color, and its rough, hackly fracture, distinguish it from the dense andesite. In places the vesicles show a rough alignment due to movement of the mass. Microscopically it resembles the dense form very closely, and has not been given such detailed optical study. The glass is lighter and more uniform in color, and less variable in index than is the dense variety. The chemical composition of this rock is stated in table 2. It parallels that of the dense variety closely, though it is slightly more silicic. It is lower in water content than any rock from the Lassen region (excluding the quartz basalts) which has been analyzed. Its ferric ratio is 0.362, and the gas content 7.8 c. c. per gram at 1200° C. Thus there is more ferric iron and less gas than in the dense variety.

[1] The ferric ratio is the ratio of Fe_2O_3 in the rock to the total amount of iron in the rock reckoned as Fe_2O_3. It will be used here as a thermal index.

[2] A. Hague and J. P. Iddings, Notes on the volcanoes of Northern California, Oregon, and Washington Territories, Am. Journ. Sci. (3), 25, 222–235, 1883. U. S. Geol. Surv. Bull. 591, 169–175, 1915.

The third modification is a dense, gray, glassy outer layer found upon some blocks, both dense and pumiceous. We refer to it as the bread-crust variety. It is usually about 3 cm. in thickness and merges gradually into the normal dense or pumiceous form. As it is obviously the same material as the latter a complete analysis was not made. The biotite calls for comment. A flake 5 mm. from the outer surface of a specimen of the bread-crust variety was decidedly biaxial, with γ greater than 1.67. Within the vesicular portion of the specimen, about 30 cm. from the surface, a flake showed $\gamma = 1.67$. The glass of the bread-crust is decidedly clearer and lighter in color than that of the dense variety. It is not vesiculated, however. The ferric ratio of this variety is 0.480, and the gas content 9.5 c. c. per gram at 1200° C. The bread-crust variety seems to have had the most drastic natural reheating. Its ratio and gas content are higher than those of the pumiceous variety, and suggest that it has been affected by rising gases under oxidizing conditions.

WATER CONTENT OF CONDUIT LAVA.

It has been stated above that the conduit lava is strikingly low in water content. This applies to all three modifications and has been verified in several ways. With the exception of the quartz basalts, the Lassen volcanic rocks are all significantly richer in water than the new lava. The various water determinations are stated below. Those from the rock analyses were carried out by the Penfield method; only one check by the P_2O_5 method was made (p. 44); the values from the gas analyses, determined upon 150 grams of rock, which was broken into lumps, and hence free from the plus error due to adsorption of water shown by powders, are produced here, calculated to weight per cent.

Rock.	On rock powders.		Rock fragments—gas analysis.
	Penfield method.	P_2O_5 method.	
Dense andesite	0.35	n.d.	0.150
Pumiceous andesite	0.18	0.183	0.113
Bread-crust andesite	n.d.	n.d.	0.133

It is evident that the bread-crust variety contains more water than the pumiceous, both being lower in water than the dense andesite. Results to date show that a similar relation holds true between bread-crust and pumice from Martinique. The bread-crust contains considerably more water than the corresponding andesitic pumice. This general poverty in water content in comparison with other rocks of the Lassen region is appropriate evidence in support of the hypothesis that the lava which was pushed up to fill the crater is an old rock which has been reheated. The higher water content of the bread-crust surface may be due to surface exposure to H_2O (gas) at high temperature and pressure (see pp. 76 and following).

GAS CONTENT OF CONDUIT LAVA.[1]

The gas content of rocks has been investigated by various students, and the previous work well summed up by Chamberlin in his "Gases in Rocks." Unfortunately none of these investigators has given any special attention to the relation between the composition of the rock and the gases obtained from it. Nor has any one of them except Gautier remembered that H_2O is a regular, and perhaps the most important, constituent to be determined. The gas content of the material of the 1915 eruption of Lassen Peak was examined in connection with a general study of this problem of the gases in the rocks which is now in progress. The results are tabulated in table 3.[2] About 150 grams of rock, preferably obtained from the interior of a specimen, in order to avoid accidental contamination, were placed in a silica tube which had been heated and exhausted of its own gases before the specimen was introduced.

TABLE 3.

(Volume percentage composition of total gases. Andesite, Lassen Peak eruption of 1915. Basalt from Kilauea.)

	Dense.	Pumiceous.	Bread-crust.	Aa.	Pahoehoe.
CO_2....................	1.959	1.187	2.071	6.80	5.673
CO.....................	0.503	0.310	0.623	3.83	0.601
H_2.....................	1.187	0.210	0.412	6.18	1.085
N_2.....................	0.029	0.116	0.577	1.31	0.269
A......................	0.0003	0.018	0.003	0.01	0.003
SO_2....................	n. d.	n.d.	0.009	0.26	0.404
S_2.....................	0.123	0.215	0.882	n.d.	1.384
Cl_2....................	0.129	0.428	0.297	0.26	0.404
F_2.....................	n.d.	n.d.	1.524	n.d.	n.d.
H_2O....................	96.067	97.519	93.658	80.17	90.580
Total gases per gram of rock, at 760 mm. and 1200° C.............	10.6 c.c.	7.8 c.c.	9.5 c.c.	9.8 c.c.	5.4 c.c.

The first feature to attract attention was the obvious presence of considerable amounts of fluorine. This showed itself by etching the glass tubes next to the furnace. Unfortunately, in only one analysis was a reasonable attempt at its determination possible. In the absence of data on other rocks too much emphasis must not be laid upon this fluorine content, which may be due in part to the biotite. One has the impression, however, that the amount is much too great to be accounted for in this way alone.

In general, the volume of gas per gram of rock is the first matter of interest. If these quantities be calculated on a weight per cent basis they are insignificantly small, but expressed by volume at 760 mm. and 1200° C. (the temperature at which

[1] With the co-operation of E. S. Shepherd.

[2] Table 3 gives the volume percentages of gases obtained by heating the rock *in vacuo* to about 1200° C. It must be remembered that carrying out computations to the third or fourth decimal place is not evidence of great precision in the analytical work, but a result of including in the computation about 0.2 gm. H_2O which is weighed as such. Similarly the halogens and sulphur (except SO_2) have to be determined gravimetrically and included in the computation. In general, the fixed gases amount to about 10 c. c., which are passed over into the apparatus and analyzed. When computed to 760 mm. and 1200° C., the water vapor usually amounts to about a liter, so that the other constituents, if they are to be expressed at all, must be given in decimals.

all the volatile constituents of the rock would exist as gases), they may be used, together with the rock analysis, in any discussion of the composition of the material. In the case of the new lava of Lassen Peak it will be noted that the dense andesite and the bread-crust variety show about the same gas content, while the pumiceous portion has lost an appreciable amount of its gas. The relation is similar to that of the Hawaiian lava given in table 3 for comparison. The halogens run higher in the pumiceous and bread-crust varieties, that is, in the modifications supposedly most subjected to reheating in the conduit. Hydrogen seems to be definitely higher in the original, dense andesite, and, in a general way, it might be said that the supposed reheating has been accompanied by some slight oxidation of the volatile matter. A similar relation seems to exist in the gases of the Hawaiian lavas.

It was most astonishing to find fluorine ranking with CO_2 as a major volatile constituent.[1] While it would be unwise to infer too much from this one measurement, apparently the fluorine content was high in the other two varieties also. Mr. Perret, in his volcano studies in the Mediterranean region, has noted that the initial stages of an eruption are usually characterized by predominant halogens, whereas the declining stages show sulphur compounds predominant.[2] This observation is in accord with what we have so far observed. At Kilauea, where the halogens are minimal, it was found in the 1912 gas collections, which involved about 1,000 liters of gas, that fluorine was about twice as abundant as chlorine, while at Mount Katmai, Alaska, it was found to be only about one-fourth as abundant. Of course, in ordinary field observations a distinction between fluorine and chlorine is not feasible, and it is possible that fluorine has frequently been overlooked. It combines so readily, and its compounds are so easily obscured or removed, that it may prove to have been present in many places without attracting the attention which it merits.

It is within the bounds of probability that fluorine will prove to be not only a significant factor in the mineralogical composition of the plutonic rocks, but also that its presence or absence may give some hint as to the nature and past history of petrogenic processes. For the present it will suffice to note that the renewal of volcanic activity at Lassen Peak was accompanied by an appreciable quantity of this elusive element. The actual amount of gases present in these rocks after they have reached the surface is of course not great in weight per cent; on the other hand, the *volume* of gas which these rocks can yield when heated is significant. In the above analyses it appears that there is *still* available, for each kilo of rock, some 10 or more liters of gas (total volatile matter, including water). Presumably this is only a small portion of the gas content of these lavas when below the surface.

[1] Since the above was written a similar high fluorine content has been observed in the gases from the Martinique lavas.

[2] The observations are in general accord with those of Sainte-Claire Deville at Etna (1857) and elsewhere, Fouqué at Santorini (1865), and other observers. For the literature see: F. W. Clarke, The data of geochemistry, U. S. Geol. Surv., Bull. 695, 255–284, 1920; and F. von Wolff, Der Volkanismus, 635, 1914.

FERRIC RATIO IN CONDUIT LAVA.[1]

Determinations of FeO, Fe_2O_3, and SiO_2 were made on the three varieties of the andesite, before and after treatment for the extraction of the gases. The results are shown in table 4. SiO_2 was determined (to the first place of decimals) in order to ascertain if the fused rock made any appreciable attack upon the silica tube, which it evidently does not, and also as a test of the uniformity of the samples. The iron values are taken from the rock analyses for the dense variety. For the other samples the determinations were made on special portions by the method of decomposition with hydrofluoric acid. The samples varied, as might be expected, within narrow limits. In order that the values might be compared directly, the figures from the actual determinations have been recalculated on the basis of an average value of 4.82 per cent of total iron expressed as Fe_2O_3. The ferric ratio, of course, is not affected by the recalculation.

TABLE 4.—FERRIC RATIO IN THE CONDUIT LAVA, LASSEN PEAK, 1915.

Treatment.	SiO_2	Fe_2O_3	FeO	Total Fe as Fe_2O_3	Ferric ratio.
Dense, glassy andesite.					
(1) None	63.2	1.30	3.00	4.63	0.281
(2) 780° C. for 5 hours in steam and CO_2	62.7	1.57	2.70	4.57	0.343
(3) 1260° C. for 3 hours *in vacuo*	63.4	1.73	2.90	4.95	0.349
Pumiceous andesite.					
(4) None	64.2	1.75	2.77	4.83	0.362
(5) 1260° C. for 4 hours *in vacuo*	63.3	1.79	2.75	4.85	0.369
Bread-crust surface of pumiceous andesite.					
(6) None	64.1	2.34	2.28	4.87	0.480
(7) 1260° C. for 4 hours *in vacuo*	64.2	1.78	2.73	4.82	0.369
RECALCULATED VALUES, ASSUMING AN AVERAGE OF 4.82 PER CENT FE AS FE_2O_3.					
(1) None	63.7	1.35	3.12	4.82	0.281
(2) 780° C. for 5 hours in steam and CO_2	63.7	1.65	2.85	4.82	0.343
(3) 1260° C. for 3 hours *in vacuo*	63.7	1.68	2.83	4.82	0.349
(4) None	63.7	1.75	2.76	4.82	0.362
(5) 1260° C. for 4 hours *in vacuo*	63.7	1.78	2.73	4.82	0.369
(6) None	63.7	2.32	2.25	4.82	0.480
(7) 1260° C. for 4 hours *in vacuo*	63.7	1.78	2.73	4.82	0.369

SUMMARY STATEMENT OF THE CHANGES IN THE FERRIC RATIO.

Rock variety.	Untreated.	780° C. in steam and CO_2.	1260° C. *in vacuo*.	Gas-content in c. c./gm. at 1200° C.
Dense	0.281	0.343 (5 hrs.)	0.349 (3 hrs.)	10.6
Pumiceous	0.362	....	0.369 (4 hrs.)	7.8
Bread-crust	0.480	....	0.369 (4 hrs.)	9.5

In recalculating the average values (2) was excluded, being a small sample, unduly rich in phenocrysts and poor in glass. The values obtained from the determinations on (2) were, however, raised to the average value, on the assumption that the relations of FeO and Fe_2O_3 would be the same as in the other samples.

[1] With the co-operation of M. Aurousseau.

For this particular material the ratio, as stated above, suggests the attainment of equilibrium after the rock has been heated for some hours in a neutral atmosphere, or *in vacuo*. The results obtained are in accord with the other evidence in showing that, of the three varieties of material, the dense andesite has suffered least in the natural process of reheating. Treated in the laboratory its ferric ratio approaches that of the pumiceous variety, which itself is but little affected by laboratory treatment.

THERMAL STUDY OF CONDUIT LAVA.[1]

MINERAL CHANGES ON HEATING.

Biotite and glass are the constituents of the rock most sensitive to thermal treatment. The first studies were confined to the stability of biotite when heated through a range of temperature, both in air and in a neutral atmosphere. Heated in air a biotite from granite ($\gamma = 1.64$) began to lose weight at 500° C., even in an hour's time. At 650° C. it had become reddish and decidedly biaxial, with $\gamma = 1.69$. This decomposition occurs in two ways; one is by loss of volatile matter, the other by oxidation. The oxidation is the chief factor in the development of biaxiality, reddening, and the increase of γ. The biotite of the dense andesite, as stated above, also showed decided reddening with a high value for γ; that of the bread-crusted variety shows the same characters but in a decreasing degree from the outer surface of the crust inward.

In a neutral atmosphere[2] biotite persists fairly well at 850° C. but shows increasing decomposition with further rise in temperature. Above 900° C. there is fairly rapid decomposition with the formation of magnetite. The clearing of the glass proceeds with increased rapidity as the temperature rises above 850° C. Thus, 15 minutes at 1050° C. yields a clear, nearly colorless glass. Changes in the biotite and glass are indicated in the experiments detailed in the following section. Plagioclase and pyroxene are but little affected at these temperatures during such short periods of exposure, though material subjected to a higher temperature shows a little less pyroxene.

In the dense, glassy andesite the biotite always shows partial decomposition, with the formation of reaction rims, and on reheating to temperatures above 840° C. it decomposes with increasing rapidity, even in the short exposures here employed. Unless, therefore, the effect of pressure upon the stability of biotite is considerable, it seems reasonable to suppose that this lava could not have been heated above 850° C. at any time after it approached the surface; otherwise, in the large blocks, which would have remained hot for some time after reaching the surface, a complete breakdown of the biotite would be expected. From the condition of the biotite, and the phenomenon of glass-clearing, we may reasonably infer that we are here dealing with a relatively low-temperature eruption so far as surface phenomena are concerned.

[1] With the co-operation of E. S. Shepherd and H. E. Merwin.

[2] For rocks and minerals relatively low in ferrous iron this atmosphere was provided by steam and CO_2 obtained by passing a slow current of CO_2 through boiling distilled water and passing the mixture over red-hot copper before it came in contact with the minerals (or rocks), which are placed in a silica tube.

BENDING (FLOW) TEMPERATURE OF DENSE ANDESITE.

For the purposes of this study, small prisms were cut from the dense andesite and were heated for varying lengths of time in the neutral atmosphere mentioned above. Such prisms of dimensions of about 5 × 10 × 50 mm. were supported at first at both ends and allowed to sag in the middle; in later experiments they were supported by one end and at an angle of about 45° in order to get a somewhat sharper indication of softening.

(*a*) *Below 700° C.*—Very little change occurs in the time available for a laboratory experiment.

(*b*) *770° to 780° C. for 5 hours.*—No change was noted, even on a polished surface of the prism.

(*c*) *840° C. for 3 hours.*—A polished surface showed minute warping and the glass, which was originally brownish, had become much clearer.

(*d*) *930° to 970° C. for 1½ hours.*—A prism 50 mm. long, supported at one end, had bent about 10°, swelled appreciably owing to the beginning of vesiculation, and the glass was perfectly clear and colorless. The biotite was unoxidized, but the time interval was short and the biotite was completely inclosed in the glass.

Fig. 28.—A prism of dense Lassen andesite, supported at two points and heated to 1040° C. for 15 minutes. Note the sag at ends and center. Photo Snapp.

(*e*) *1040° C. for 15 minutes.*—A prism supported at both ends sagged, swelled, and developed a glazed surface (see fig. 28). The glass was colorless in thicknesses which, in the original, were decidedly brownish.

(*f*) *1050° to 1100° C. for 42 hours, closing with several hours at the lower temperature.*—The glass formed is clear, except as stained by the dissolving biotite, all of which has decomposed, leaving spicules of magnetite and brownish streamers of color. No evidence of recrystallization was observed.

(*g*) *1260° C. for 4 hours.*—Shows only solution effects. The glass is brownish, with relatively few crystals embedded in it. The index of refraction of the glass reached 1.530. The feldspar phenocrysts, while reduced in size and corroded, were not fused and, if anything, were more shattered than before.

Such results obtained from the thermal study of biotite will eventually be of general application when the series of minerals known as biotite has been more thoroughly investigated and the thermal behavior correlated with composition, etc. It must be emphasized, however, that the behavior of the dense glassy andesite from Lassen Peak, as studied here, is peculiar to that particular rock. No inference can yet be made, from its behavior, concerning the behavior of other andesites, even if chemically resembling it. For example, the andesites, dacites, and pumices of Mont Pelée, Martinique, are now being studied in the same way. They bear a general resemblance to the Lassen Peak rocks, but their behavior on thermal treatment is quite different. Whereas the dense andesite from Lassen begins to soften at about 850° C., a similar rock from Mont Pelée does not do so until about 1200° C. A glassy basalt from Kilauea crystallizes on reheating after which it does not again soften at the low temperature at which it first flowed from the crater (from 1100° C. down to 600° C.); furthermore, the gas content of the Lassen rock can hardly be accepted as typical of the gas content of similar andesites in general.

GENERAL EFFECTS OF HEATING TO 1260° C.

All three modifications of the rock, when heated *in vacuo* for 3 or 4 hours, in order to pump off the gases, yield identical products. The mass becomes vesiculated and the crystals of the ground-mass go into solution, though the phenocrysts do not do so noticeably. The glass reaches an index of 1.530 rather uniformly. It is brownish in color, with relatively few crystals embedded in it. The biotite disappears completely. The ferric ratio of the product tends to approach the value 0.369, strongly suggestive of the attainment of a condition of equilibrium. The actual values for the ferric ratio after this treatment are:

Variety.	Value for ferric ratio.	Hours heating.
Dense, glassy variety.....	0.349	3
Pumiceous variety.......	0.369	4
Bread-crust variety......	0.369	4

It is to be noted that the ferric ratio of the pumiceous variety was 0.362 before treatment in this way, and we may infer that it has already had, in nature, a thermal treatment comparable with that given it in the laboratory. The ratio for the dense variety has increased on treatment, the time of heating being less than with the others, while that of the bread-crust has actually decreased. The last, being a surface modification, would have been subject to oxidizing conditions in nature, while the pumiceous interior of the same blocks would be relatively protected. We conclude that the three modifications represent the same original material, each having been subjected to its own peculiar conditions of thermal alteration.

SOME CONCLUSIONS FROM LABORATORY STUDIES OF THE CONDUIT LAVA.

The lava extruded during the 1915 eruption of Lassen Peak is an andesitic or dacitic rock. It is variably brecciated, and the glass of the ground-mass is variable in amount and composition within narrow limits and over short distances.

The plagioclase phenocrysts show several periods of alternating resorption and growth, with concurrent shattering. The larger pyroxenes have been shattered and the biotite has begun to decompose. These features indicate repeated reheating and cooling under differential stresses without the attainment of thermal equilibrium. The greater basicity of the feldspar of the ground-mass and the vanishing quartz indicate changes in composition other than those due to gradually falling temperature in a melt having the composition of this rock as a whole.

Specimens of this lava heated under suitable laboratory conditions give a general idea of the temperatures which may have operated at the surface during the doming-up of the massive conduit lava. Under laboratory conditions 850° C. seems the lowest temperature at which the material could be deformed without considerable fracturing. On the other hand, the biotite in cracks in the surface rock and the unvesiculated character and opacity of the glass indicate a prevailing temperature lower than this.

It should be remembered also that the material tested in the laboratory had presumably lost the major portion of the volatile matter, which exerts a considerable influence on the viscosity of lavas, from which it is proper to infer that the figures obtained in the laboratory represent maximum temperatures, and that the actual temperatures, if they differed from these, would have been lower rather than higher.

This lava of 1915 does not seem to have been a new magma erupted through an old conduit. It seems rather more like an old conduit lining, which had been fissured and reheated by a fresh influx of juvenile gases from below until finally it acquired sufficient mobility to allow it to be forced upward by pressure. The eruption of both pumiceous and dense lava together favors this hypothesis of irregular reheating along cracks in part of the old conduit lining.

Whatever the source of energy, the mass ultimately acquired a sufficient fluidity to permit it to reach the surface, where some of it was too cold to expand into pumiceous form, while the more highly heated portions continued to expand and contributed to the enormous amount of ash which spread over the surrounding country. It seems probable that the upward movement of the crater plug may have been an abortive attempt at spine formation, but the power behind it was released prematurely through a weak spot in the eastern crater wall.

It appears therefore to be a clear conclusion from the mineral content and physical relations within the conduit lava, which alone afford a proximate clue to conditions within the volcano, that the eruption was in singular measure a low-temperature phenomenon.

"A careful re-examination of this mass of 'dense glassy andesite' and associated material in May 1923 shows that rock of this type is exposed over an area of only a few hundred square meters. It is split vertically into large, often monolithic, blocks with the rifts decidedly widened at the top. These rifts are smooth fractures except near the bottom of a few of them, where the surfaces are rough for a vertical distance of a meter or so upward from the lowest point accessible, as though formed by the pulling apart of a pasty mass. This (lowest) portion of the block is slightly vesiculated and the glass cleared to some extent but not reddened.

"In the western notch this dense rock gradually gives place to a coarse breccia of red dacite, similar to the top of Lassen Peak, in a matrix of red, vesiculated andesite. This material (the westerly two-thirds of the crater mass) is a jumble of broken blocks which individually show flow textures, though they are not oriented in any particular direction. On the other hand, the mass which forms the northeast corner of the crater is composed of large, shattered, monolithic blocks of glassy andesite which have obviously been pushed up along the old crater wall. It is significant that these blocks did not bend over and their sides are not warped appreciably, even where they overhang. Some of the horizontal cracks (2 to 10 cm. wide) between such blocks were found filled with ash, loose fragments of old dacite, and even thin plates of glassy andesite, the whole scarcely at all compacted. There were no fingers of lava between the fragments filling these cracks. One thin plate of glassy andesite was bent but was not vesiculated nor had the glass cleared. Certainly none could have been very hot.

"No evidence was found to support any interpretation of the phenomenon as a lava flow,[1] at least not in the usual sense of that expression. It has neither top, bottom, nor sides, while the material of the western end is appreciably less intimately related than that near the source, though grading irregularly into it. If, however, we accept the hypothesis that the 1915 upheaval merely brought up the old plug or conduit lining, all of the observed facts fit together without difficulty." (Memorandum by E. S. Shepherd, 1923.)

[1] Cf. Professor Holway, p. 18.

CHAPTER III.

FIELD EVIDENCE OF TEMPERATURE RELATIONS.

HORIZONTAL BLASTS.

It would be a matter of very great interest and of no little importance in interpreting the mechanism of the eruption to fix the temperature of the two horizontal blasts of May 19 and 22, but as there were no eyewitnesses, so also no thermometer was available to record the temperature attained. It is significant that except in one small area no fire was started by the blasts, although on all sides the foliage of the standing evergreens was found scorched and brown. Around the blasted area both standing trees and smaller undergrowth seemed completely dead, but as the summer advanced it appeared that they were not so, and most of these trees attained to complete restoration of their foliage before the following winter. Both leaves and branches were somewhat blackened at the most exposed points, but nowhere was the appearance as if the branches themselves were burning and so contributing to the heat. Rather they appeared to be scorched or singed, as though by momentary exposure to heat which either was not sufficiently high or was of too short duration to set the trees on fire.

On the borders of the devastated zone small trees and bushes which were partly embedded in snow suffered no damage below the snow line from the passing blasts. The exposed portion above the snow was either carried away or completely blasted, indicating more definitely high velocity and high temperature. Toward the center of the area everything was carried away root and branch and no trace of snow or of vegetation remained.

The single area in which fire was started was a steep hillside forming a part of the boundary of the Lost Creek basin, exactly facing the mountain at a distance of about 3.5 miles and a little to the north of the axis of greatest intensity of the blast. (See Sketch Map, fig. 29.) The second blast (May 22) must have struck against the broadside of this steep hill and have been so far checked in its progress that the vegetation upon the hillside endured a considerably longer exposure to its heat than in those areas over which it merely passed by. Elsewhere the momentary passage of the blast was wholly insufficient to kindle dead leaves, splinters, and small twigs, but on this opposing hillside these were set on fire and somewhat charred. Both the extent and intensity of the fire appear to have been small, which is explained in part by Forest Ranger Seaborn, who reports that the fire was soon quenched by rainfall (probably condensation from the steam cloud). It is also possible that the second blast was considerably hotter than the first, but, finding no inflammable material left in the track of the earlier blast, no fire was kindled except at this comparatively remote point. To judge by the appearance of this hillside 3 or 4 weeks afterward, the fire must have been altogether insignificant, for the depth of penetration into the dead leaves which lined the hillside was small and dead leaves on the pine trees were only charred at their outer extremities, the fire being insufficient even to burn up all of the exposed dead foliage (fig. 30).

Of course, the effect of such a hot blast depends upon two factors, the temperature and the time of exposure. If the time of exposure were extremely short the temperature might be very high and still cause no fire. On the other hand, an exposure of even 2 or 3 minutes to a much lower temperature might kindle such

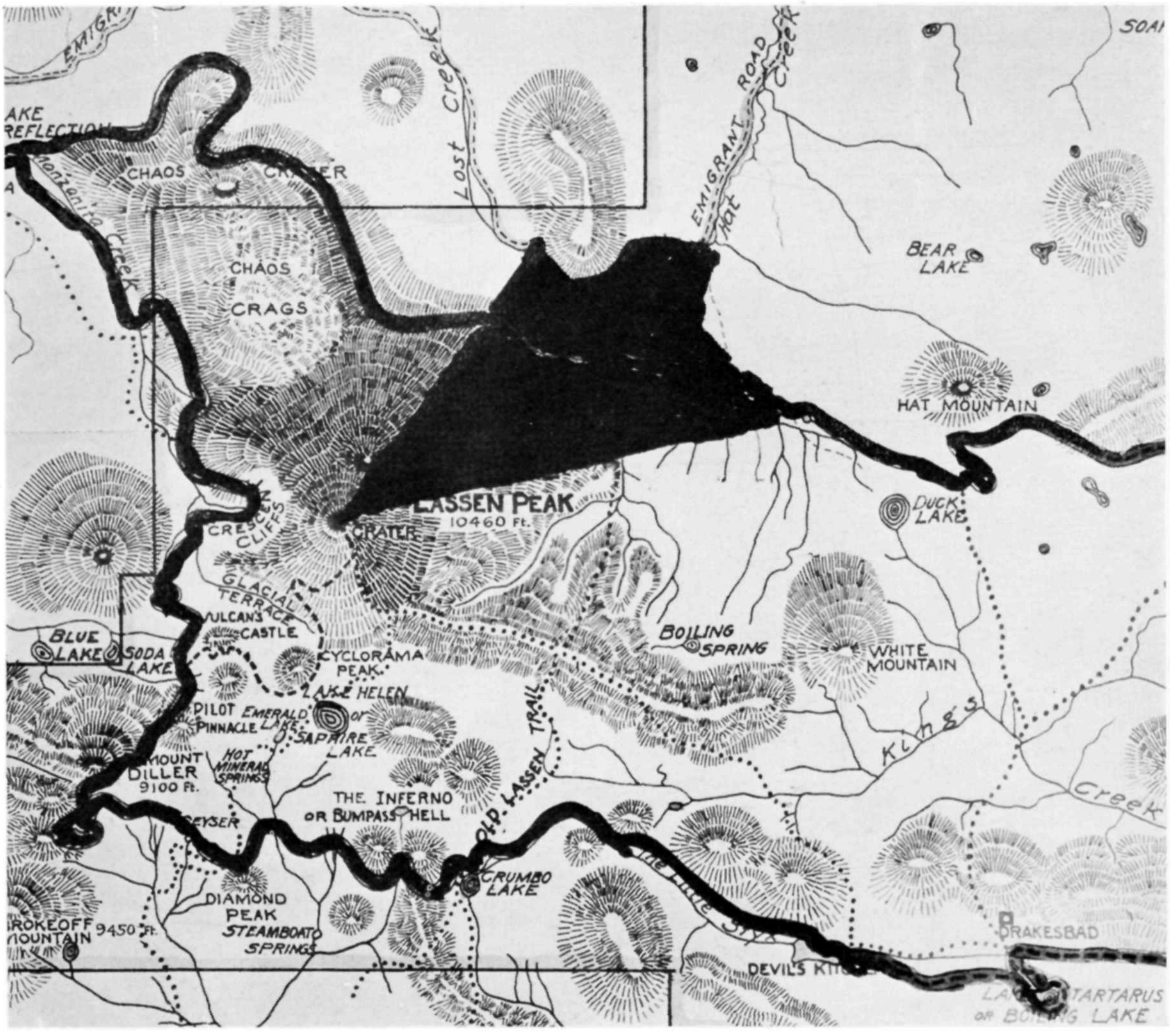


Fig. 29.—April 28, 1922. Sketch Map showing a portion of Lassen Volcanic National Park. Devastated area shown in black. 2 miles = 1 inch (approximately). (Courtesy of Mr. M. E. Dittmar, Secretary, Lassen Volcanic National Park Association.)

vegetation immediately. In a crude laboratory test it appeared that about 160° C. for one minute would blast pine foliage in the same manner as the foliage was blasted along the boundaries of Lost Creek, but a higher temperature (and a shorter time of exposure) may have prevailed during the period of destruction there and still fall far short of the temperatures appropriate to red heat in the crater (600° minimum). It also happened that the portion of the devastated zone nearest to the source of the blast was also the most barren, so that immediately adjacent to the mountain the temperature of the blast might have been as high as 300° or 400° C. without finding material upon which such a temperature could have left evidences of burning. In the center of the track of the explosion no snow was found by Loomis and his party, who visited it before the second blast on May 22. On the adjacent hillside the snow was more or less protected by a cover of rocks and small stones, projected by the earlier explosions, which blanketed the regions to the north and south of the devastated zone to a depth varying from 2 feet down to a few inches. These stones nowhere melted their way through the snow and so could not have been hot at the time when they alighted. Even on the summit the explosions had covered the snow surrounding the explosion crater to the depth of several feet with rocks and ash without melting it, except in the case of a few very large boulders weighing several tons, which penetrated through the snow (fig. 31). Their mo-

Fig. 30.—July 7, 1915. Green pines blown down and charred at base of Jessen Mt. on Lost Creek, May 22, 1915, by a hot blast from Lassen Peak. Photo Diller.

mentum must have accomplished most of this result, for they appear to have had no excess heat through which to melt any considerable body of the surrounding snow. The solid ejectamenta, therefore, contributed little of the heat which melted away the snow. This observation also is of some importance in considering the extent to which hot magma became exposed during this eruption.

It appears from the evidence bearing upon the temperature of the blast, as observed upon the snow and vegetation remaining along the borders of the zone of destruction, that we must abandon any thought of extremely high temperature or else assume that the velocity of the blast, even upon its outskirts, was still so great as to prevent combustion.

As we approach the source of the horizontal outburst just below the upheaved lava "lid" at the summit, we have to consider the situation from a different viewpoint. No momentary blast, however hot, can be assumed to have carried away such an accumulation of snow as existed in the bay of the mountain itself by melting

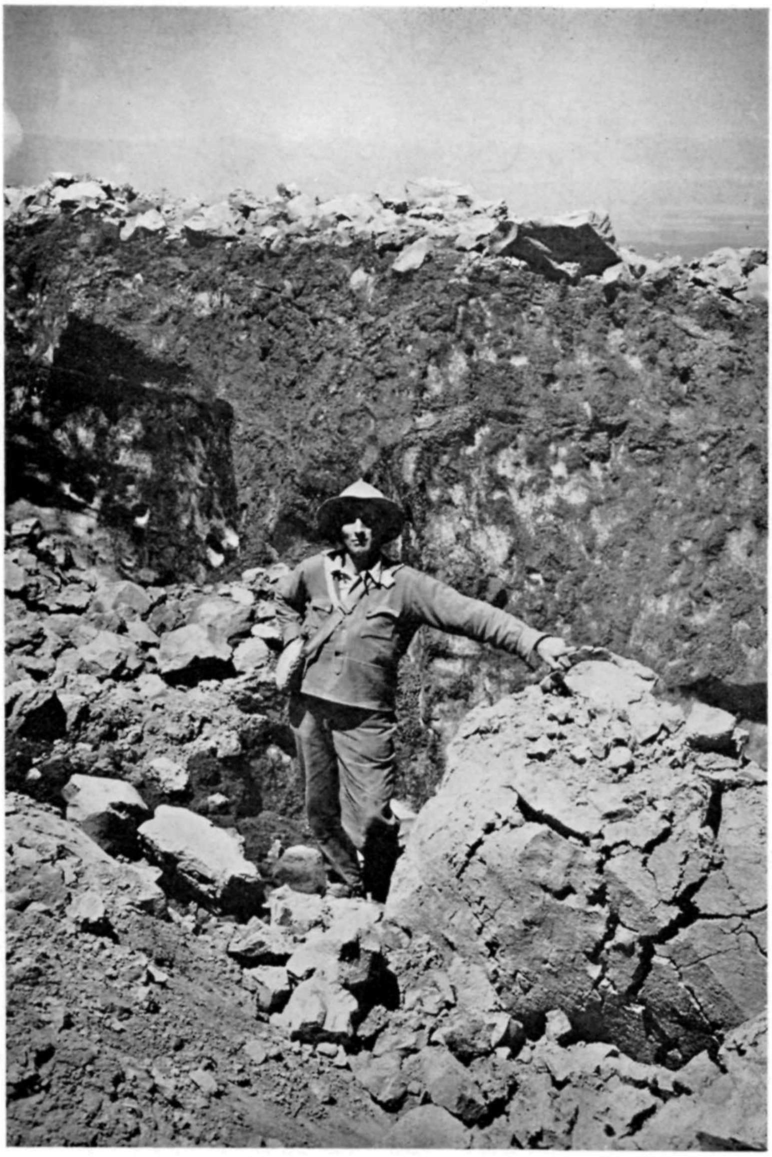


Fig. 31.—June 28, 1915. Bread-crusted boulder imbedded in the snow on the summit showing that *the boulder was cold when it fell.* Note also smaller rocks and debris lying on the snow. Photo Day.

from the top downward, for we know that under normal exposure to the sun an entire summer does not suffice to do this. Either the snow was cleared away mechanically by a very low-angle blast of extreme velocity, which conclusion finds support in the fact that the whole valley was swept clear of vegetation, root and branch, as well as the snow; or near the mountain there must have been continued or repeated outpourings of hot vapors of lower intensity but of reasonably long duration. There is some little difficulty with either assumption considered alone. A downward blast of extreme violence might carry away the snow, even though it were a hundred feet deep, but if so this snow must have been scattered rather than melted, and so would have caused no such flood. If, on the other hand, a considerable outpouring of hot gases at low velocity be assumed, the flood is accounted for, but not the destruction to the trees.

There must have been at least one blast of sufficient intensity to carry out all the vegetation in the valley for a distance of 4 miles, and *in addition to this* the accumulated snow on the mountain slope near the source of the blast must have received sufficient heat to melt it completely, except for the comparatively small residue of ice remaining in the photograph (fig. 11). That the destructive horizontal blast was of extremely high temperature or of long duration seems impossible, for the reason that at its borders there is no evidence of fire (with the single exception above noted). To account for the great body of snow melted, some supplementary agency must therefore be sought. Either the great horizontal blast was followed by hot gas exhalations of low velocity for several hours thereafter, or, as seems to the authors much more probable, the condensation of superheated steam from the volcano cloud, which certainly did continue for several hours, falling on the snow to leeward of the mountain, furnished the major portion of the heat which melted the snow and caused the floods. The fact that both of the great floods (the night of May 19 and the afternoon of May 22) appeared to leeward of the mountain accords with this view. The further fact that a flood occurred on May 22 at all, after all the snow had been carried out on the 19th, probably admits of no other explanation than this.

The heavy body of ash contributed materially to the immense quantity of solid matter which the first flood carried down,[1] but not to the heat of melting. It seems most probable, therefore, that the first violent blast blew down most of the trees in Lost Creek Valley and the flood of hot ash-laden rain, mingled with the snow, carried the trunks within its reach, together with the boulders, out of the valley along the line of Lost Creek and Hat Creek and stranded them among the standing timber below. The fact that they were carried around a sharp bend to the northward, about 3 miles from the explosion center, indicates this mode of transportation. The large boulders, both those remaining in the crater and those detached by the explosion and sent down the mountain to be distributed by the flood waters, were of andesite and were readily identified as a part of the original summit cone, though some of them were moved for a distance as great as 4 miles (see photograph, fig. 13). These boulders were not new lava, nor were any of them of a temperature higher than the probable temperature of the flood which bore them to their present resting-place, as may be seen from the fact that wood in contact with them was not blackened. Several of these boulders weighed many tons each (fig. 14).

[1] Forest Ranger Seaborn reported that a bucket filled from the flood and allowed to stand over night showed only 10 per cent in depth of clear water in the morning, indicating a very large content of solid matter.

LAVA TEMPERATURE AND "FLOW."

It has already been pointed out that few or no experienced observers of volcanic phenomena were witnesses of either of the two great eruptions. It is therefore necessary to build a somewhat hypothetical structure out of the actual observations of individuals with little experience in such matters, and such studies as could be made on the ground and in the laboratory after the eruptions had ceased.

In making such a composite analysis Mr. Milford's direct observation (p. 16) is of importance. From the statements of his party, which included a number of people, it is perfectly clear that red-hot material appeared at the surface on the night of May 19, probably for the first and last time during this eruptive cycle. The report says explicitly that both the lava and the glow were "deep-red" or "vivid-red," which probably fixes a temperature between 600° and 750° (see pp. 49, *et seq.*). The report further says that at intervals of 8 or 10 minutes molten material flowed out of the western notch in the crater rim like slag out of a crucible, but observations on the ground show no evidence of recent fluidity, and laboratory studies show that the rock is solid and not liquid at those temperatures, so that this particular conclusion must be modified. Under high pressure in a closed chamber with a considerable percentage of water still in solution, the magma might conceivably be somewhat mobile at 750°, but immediately the pressure is relieved at the surface the excess of water will escape and the residual silicate become immediately rigid. Boulders, some of them probably red-hot, did break off at the point observed and rolled down the mountain in the direction indicated. It would therefore seem more likely that the material which reached the surface was solid throughout all of the events observed. The Milford party, after all, was 21 miles away. Lassen andesite would require to have a temperature above 900° to flow under its own weight in the open air, unless ejected by force in the form of an emulsion, and above 1250° to "splash" in the manner indicated in Mr. Milford's description. Such a flow (at 1250°) would be white-hot and of blazing brilliancy, and not deep-red, as the Milford party saw it. Moreover, it would contain no biotite; indeed, all the crystals of the ground-mass would be converted into glass. On the other hand, the breaking away of boulders from a solid mass at a temperature between 600° and 750° (red heat) certainly would lay bare fresh bright-red surfaces. Presumably one of these surfaces belonged to the rock which rolled down the mountain, while the place from which it broke away remained behind and slowly cooled to blackness. Flashes of this kind, some moving and some still, appear to offer a rational explanation of what the Milford party witnessed. This accords well with the observed red heat and with the present formation of the mass on this (west) side of the mountain (fig. 10).

After the summit crater had been filled (figs. 26, 32, 33) by the eruptions of May 19 and 22, the exposed rocks over much of the upheaved area (the volcano plug) are uniformly reported by observers (Howell, Spaulding, Yori) to have been hot. Heated air rose from the cracks and the radiation from the surface appears to have been uncomfortable enough to prevent the Spaulding party from venturing out upon the debris which filled the crater, but when the writer visited the summit, 3 weeks later, no such limitation was experienced; it was quite possible to walk without discomfort over any portion of the newly upheaved mass. Some of these rocks, particularly the largest boulders, on the southern margin of the plug, were too hot for the unprotected hand when pressed against them and held there, but were not otherwise uncomfortable. The northern half of the plug was cold or nearly so. In one crack on the south side a thermometer thrust into the ash to the depth of a foot showed a temperature of 150° immediately, and no doubt would have gone somewhat higher but for the limitations of the thermometer. A week later a temperature of 250° was measured by Shepherd in a similar crack. No evidence of combustion was found upon the summit nor was any smell of sulphur or other of the usual volcano gases found there, except for a faint trace of hydrochloric acid,

Fig. 32.—July 26, 1915. View in the Summit Crater of Lassen Peak after the upheaval (on or about May 19, 1915). Photo Loomis.

barely detectable in one or two places. Against this, however, it should be borne in mind that Spaulding's party, one week after the great explosion, reports odors of sulphur and strongly acid gases at the summit. But when one recalls that strongly acid fumes, when judged only by the effect upon breathing, probably indicate a concentration no greater than 0.5 per cent by volume with air, and this at the source itself, the quantity of acid gases given off must have been insignificant, even during the period of maximum activity.

These observations bring into the foreground a point which has been considered already (pp. 52, 53) but which is the subject of some difference of opinion. The newly erupted material on the west side of the mountain extends beyond the old rim of the crater about 1,000 feet, ending in a narrow point. Diller has described this as a lava stream flowing through the notch in the crater rim. He says (private letter Oct. 3, 1922): "It is my opinion that the lava erupted from Lassen Peak, May 19, 1915, really formed a lava stream, broken to solid fragments on the surface of the flow, but stiffly viscous, slowly flowing beneath, thus enabling it to move down the slope gently from the overflowing top of the volcanic vent over the bed of the old crater lakelet, whose drainage it followed to the rim of the old crater, where it broke over the steep western slope, forming the wonderful spectacle seen by Mr. Milford." It is probable that he found support for this view in Milford's observations discussed above. He has not called attention to features of the flow itself which point to this conclusion, beyond comparing its general appearance with the nearby flow of Cinder Cone, which, however, is a quartz basalt and presumably

Fig. 33.—July 15, 1915. Another view of the upheaved floor of the crater showing details. Photo Day.

more fluid than Lassen dacite or andesite. Its silica content is given as 56 per cent compared with 68 per cent for the dacite (p. 37). There is also abundant evidence of high temperature at Cinder Cone which is not found at Lassen Peak. Perhaps it should be emphasized, in view of the fact that a surface flow has been explicitly insisted upon by a geologist of such long experience, that a careful examination of the new lava on the west side of the mountain does not reveal surface evidence of recent flow. Neither do the deep, gaping crevices yield indications of fluidity near the surface. In appearance it suggests nothing but boulders and debris. (see fig. 33). A highly viscous lava, such as this, if sufficiently hot and flowing to its present position en masse, would rather have advanced in great rounded lobes like heavy sirup filling a spoon or like the acid lavas of Lipari. Nothing of this formation is suggested here. Lassen dacite is in fact solid at red heat and not liquid, but supposing it to have been above red heat and fluid enough to move through the notch under the action of gravity, it is difficult to see how a flow could possibly have taken the present form.

A supposition that the lava upheaval was really much hotter than the surface evidence has indicated has been offered by Diller (personal communication) in support of his belief that the spur on the western slope is a true liquid flow and indeed is indispensable to such a conclusion. The supposition, however, encounters a number of difficulties already pointed out as follows:

1. The lava in the western notch was found to be cold when we visited it, 4 weeks after the eruption, at the time when the eastern portion was still hot, as noted above. It therefore appears not to have been one of the hotter portions of the upheaved area, which could be assumed to be more mobile because superheated.

2. The words of Professor R. S. Holway, of the University of California, an experienced observer (quoted on page 18), who visited the crater only 5 days after the upheaval occurred, are important in this connection: "Nor were there found any rocks, old or fresh, bearing evidence of recent fusion." E. S. Shepherd has reached the same conclusion (p. 53).

3. The single assured case of viscous conduit lava *in situ*, offered by Diller in support of his contention (Plate 6, No. 2), was not found in the western notch, but at the opposite end of the crater. It is, in fact, located at the summit of a steeper slope (fig 35) than the western notch and much nearer the center of activity, nevertheless it shows no tendency to flow from its point of emergence down the slope.

4. Unaltered biotite is found everywhere in Mount Lassen andesite (dacite). In the laboratory this biotite becomes biaxial and suffers partial dehydration when exposed to the air at 650°; when exposed in an atmosphere of steam and air it begins to show oxidation and turns reddish brown a few degrees above 800° (cf. p. 49). At neither of these temperatures is dacite fluid enough to move under its own weight. If dacite actually emerged into the air at a temperature above 800° the biotite would certainly be quickly altered. Nothing of this has been found on the dacite surfaces thus far studied.[1]

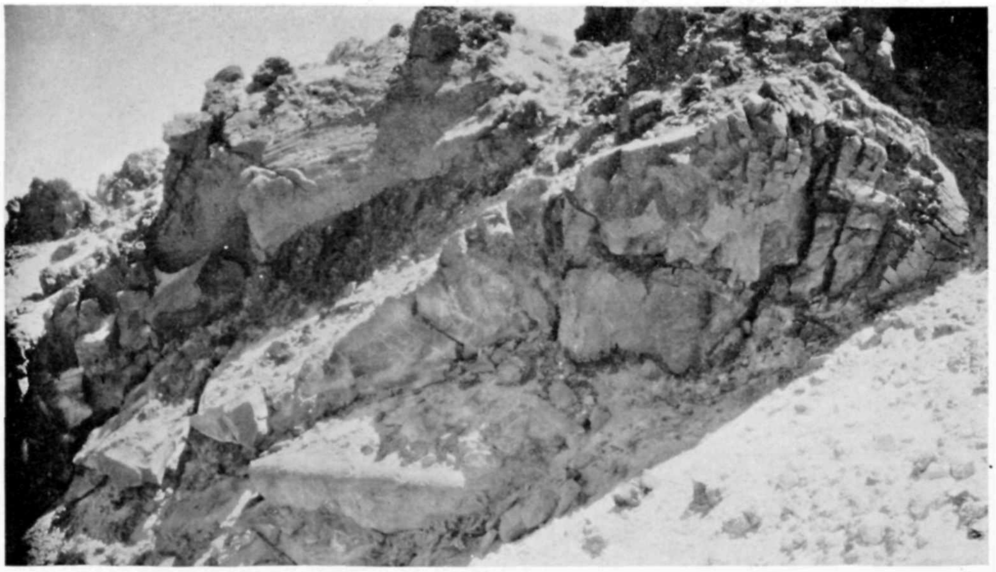
5. At the point where Diller has indicated that the lava "broke over the rim" there has been a considerable settling of the new lava since the upheaval in 1915. The general contour of the surface was then convex to an observer looking down upon it from either side (north or south). It is now distinctly concave, as may be seen from figure 34, the concavity extending entirely across the western notch. There are of course no bench marks through which to attempt a measurement of this depression, but it may be estimated at from 25 to 30 feet. Whether this settling has significance here or not may be a matter of opinion, but to us it has seemed more probable that the solid surface of a viscous plug might, after upheaval, settle more easily than a stream-flow over an old and cold bench.

It therefore appears from field studies, no less than from the laboratory studies already cited, that this exposed tongue of lava was moved to its present position after solidification of its surface, not before. It could not have *flowed* through the notch to its present position under any conditions of which we have any present indication.[2]

If this spur of lava did not reach its present position by flow it must have been pushed up from below along with the rest of the volcano "plug," and this assump-

[1] Except in the bread-crust bombs, page 71.

[2] See also p. 51 *et seq.*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2


3

(1) A part of the exposed eastern end of the volcano plug.
(2) An instance of flow structure in situ cited by Diller (p. 62).
(3) (Center) A large block from the original plug (solid) tilted outward 90° by the upheaval. Photo Day.

tion seems to accord well with the form of the spur and with the east-and-west faulting of the crater, concerning which other evidence has been adduced.

For example, supervisor Rushing, of the Forest Service, writes to Professor Holway under date of September 30, 1914 (before the upheaval) as follows: "The crater has opened up on the west side of the mountain for a considerable distance and considerable quantities of steam issue from its entire length." (p. 12). Again in a letter to J. S. Diller, December 14, he says: "The crater on the west side near the top is much enlarged and the entire west slope of the mountain is discolored by volcanic dust." (p. 13).[1] W. H. Spaulding in the (unpublished) memorandum of

Fig. 34.—August 14, 1923. Looking west across the upheaved area eight years later. Note the concave sky-line. (cf. fig. 26) Photo Day.

his visit to the mountain on May 30 (after the upheaval) has offered a similar view; he says of this western spur: "It appeared that the mountain had been cleft and that a tremendous fissure extended down into the mountain about 1,000 feet. The whole west half of the mountain appeared shattered." Finally, Loomis and Miss Dines reported (pp. 14, 15) that the western notch was already filled by a black mass thrust up into it before May 19.

There is also evidence that the east rim of the bowl was similarly broken through by the same upheaval, furnishing some of the great blocks which were subsequently carried down Lost Creek Valley with the flood. The form of the upheaved mass from east to west is also such as would be given to a volcano plug, solid above but viscous below, rising in an open funnel.

[1] See also accurate description by Olsen following a personal visit on Oct. 10, 1914. Appendix p. 178.

On the eastern slope, a little to the south of Diller's viscous extrusion (Plate 6, No. 2), there is also to be found a great lava block from the easternmost end of the plug, which has been tilted outward 90° from the position in which it originally solidified, as may be plainly seen from its structure (Plate 6, No. 3). Outward tilting is rather to be expected when a shattered plug emerges at the funnel rim. Both the eastern and western notches gave opportunity for such outward tilting, and evidences of it are abundant.

The total area of the upheaved portion of the summit is about 2,000 feet in length by about 800 feet in width in the widest part. The western end is sharply pointed, while the eastern end is truncated, perhaps by breaking off over the steep precipice which forms the eastern rim, but more likely by the emergence of the horizontal blast at this point. These fragments were carried several miles by the flood. The general form of the upheaved area is that of the explosion crater which it fills, plus the additions east and west along the fault and tapering out toward the west end. Being generally convex upward, it is deeply cleft at several points where it was broken up during the operation of upheaval in an open funnel. In short, it has the usual appearance of a volcanic plug, without complicating features, shoved upward 300 feet or more, after which the motive power appears to have found release at the side rather than through the top in the fearful explosions of May 19 and 22. There is no record of any upward movement of the mass after the latter date. The appearance of the upheaved region is well shown by photographs (figs. 26, 32, 33).

MECHANICS OF UPHEAVAL OF PLUG AND OF HORIZONTAL BLASTS.

It is desirable to endeavor to correct a misunderstanding which appears to have arisen regarding the present appearance of the upheaved structure and of the rocks freshly exposed thereby. Rock fragments showing inclusions and local flow structures in nowise establish the fact that these inclusions were acquired, or that any of this flow structure was formed during the present eruption. A volcanic plug, from its very nature, must be made up of these features and little else. These should be clearly distinguished, however, from flow structure *in situ*, of which Messrs. Diller and Paige were fortunate enough to find an isolated case (Plate 6, No. 2), just beyond the northeast end of the upheaved area. Other observers, so far as known, have found flow structure only in fragments now entirely disconnected from the parent magma, that is to say, in material which obviously came to its present position after complete solidification.

In view of the temperature of the upheaved material, and the fact that it was simply elevated 300 feet or thereabouts, while retaining undisturbed its continuous connection with the magma below, it is probable that there is a continuous and fairly rapid increase in temperature downward in this upheaved mass. Attention has already been called to a dust-filled surface crack in which, 5 weeks after the great eruption, a thermometer indicated 250° C. Volcanic dust is a very poor conductor of heat, so that this temperature, persisting very near the surface for weeks after the eruption occurred, may very well confirm the observation of red heat during the eruption, and the inference of a steep temperature gradient downward. It is of course a matter of accident along this gradient whether 300 feet of elevation would be sufficient to expose any viscous material or not. That viscous material was there, immediately below the solid plug, appears to be unquestioned by anyone. The top of the plug, however, stopped in its movement about at the level of the crater rim and so very little opportunity was given for the appearance, still less for the outpouring, of the viscous material which pushed it up. The exposure at the northeast end, where the steep slope, aided by the explosions, broke off the easternmost portion of the rim and exposed the plug, is therefore probably the only tangible evidence of its structure below the surface which will be found.

There is some danger of confusing an otherwise clear picture with a multitude of details, some of which find different interpretations in the hands of different observers, and so do not strengthen the picture at all. To us the features of lava movement found in the western notch are not to be appraised as an expression of viscous flow during this eruption, but as most excellent evidence of the east-and-west faulting of the summit crater, which afforded relief to the excess pressure within the mountain, and perhaps prevented its demolition, (1) by "loosening" the plug, and (2) through the release of confined gases (mainly steam) in horizontal blasts from beneath the plug at the east end. Something of this was seen at Martinique in 1902, but elsewhere mechanisms of this kind are relatively rare. The viscous extrusion *in situ* observed by Paige and Diller may be of value as evidence that viscous lava did actually reach the surface during this eruption, but the strength of the evidence is somewhat impaired by the fact that it appears to bear no obvious relation to the present activity. That it came to its present position through viscous flow is unquestioned, but if, after examining Plate 6, No. 2, we shift our viewpoint somewhat in order to bring this extrusion into perspective with the crater rim, it will be found outside the hot zone of present activity. There is also undistorted lava exposed between this extrusion and the present center of activity, as may be seen from figure 35. This feature loses some of its significance, therefore, from its outlying position. It may very well be a product of some earlier eruption rather than of this one. On the other hand, it does strengthen our picture of the mechanism of the upheaval to find evidences of viscosity at the deepest point within the plug which came to be exposed during this eruption (fig. 35, foreground).

It will be recalled that the horizontal blast to the eastward really came out from beneath the "lid" because the containing vessel (the rim) yielded at this point. The explosion which released the pressure beneath carried away 200 feet or more of the thinnest portion of the rim, and the lava plug is therefore exposed in vertical section in this area alone. This vertical section (roughly triangular, about 200 feet wide and 75 feet deep, see fig. 11) of the east end of the plug appears not to have been examined by earlier observers because of its inaccessibility, but during the summer of 1923 a special effort was made to reach the bottom of it. This effort was rewarded with evidences of viscous flow at the point where, in the opinion of the writers, it is most important to find it. Figure 35 (foreground) will permit one to see, as well as the unfortunate afternoon light permitted, the curved contours at the base of the portion of the plug now exposed.

It may be of interest to advance a further hypothesis which may account in part for the shattered condition of the surface of the plug. All of the explosions previous to May 19 were out of the main crater and generally vertical, except in so far as they were influenced by the direction of the wind. On May 19 there was a horizontal blast from a different point and on the 22d another, both of terrific violence, as is shown by the uprooting and laying down of all the forest trees for a distance of more than 4 miles in the direction taken by the blast.

Fig. 35.—Another view looking northwest across the exposed eastern end of the volcano plug. At the top of the picture (right) may be seen Mr. Diller's example of flow in situ (Cf. Plate 6, 2). Just to the left of it and projecting up between it and the crater (adjacent notch) is a similar outcrop of *undeformed* lava. In the foreground viscous movement is indicated in several places. Photo Day.

The upheaval above noted probably began just before May 19. The point of greatest weakness in the inclosing cone was on its northeast side, where but a very thin wall inclosed the plug, the outside slope being extremely steep at this point and probably faulted. Also, the apparent center of the most violent explosive activity preceding the upheaval at the summit is near this side of the crater bowl.

It would therefore seem possible to infer that the upheaval of the old plug was tantamount to lifting the "lid," from beneath which the two side explosions then took place by tearing away some 200 feet of the shell of the old crater bowl which was thinnest at that point. The violence of these explosions was sufficient to shake up and break up the lid without being quite sufficient to blow it off the mountain. It may be likened to a train of dynamite which is laid for the purpose of blasting out a roadway. The explosions are not planned to be sufficiently violent to blow the rocks completely out of the roadway, but only to break them up so as to facilitate their subsequent removal. The rocks forming the present surface of the volcanic plug appear to have been loosened in some such manner as this, while the maximum violence of the explosion developed sidewise from underneath the lid at the point which proved weakest. Viewing this side of the mountain from the valley below, a point can be clearly seen (fig. 11) which may very well have been the source of this blast. It lies just at the bottom of the exposed section of the "lid," with a fault extending downward from it. This intersection of the lid with the rift in the mountainside probably indicates the locus of greatest structural weakness. Also, when this point was first seen by the authors, some 4 weeks after the explosion, steam was still issuing from the rift for several yards below the lid, and in May 1916 these fumaroles could still be seen.

There is some reason for believing that the horizontal blast of the afternoon of May 22 did not follow absolutely the same direction as that of the 19th. The trees laid down by the first blast were in the central floor and the southern slope of Lost Creek Valley. The trees on the northern slope of the valley were still standing after this blast, but not after that of May 22. Both groups of trees lie with their trunks pointing directly away from the same point in the mountain, namely, the exposed end of the lid. It would appear, therefore, that both blasts emerged from the same point, but the second took a slightly more northerly course than the first.

Also, we may not overlook the fact that on both the occasions when these blasts were directed down Lost Creek Valley there were terrific vertical explosions also; whether at the same moment, or shortly before or after, may not be known, for there was no witness of either of the two horizontal blasts. Neither are there any photographs of the vertical blast of May 19, which occurred in the night. The vertical blast of May 22 was photographed from all directions over the entire countryside, the volcano cloud being one of the most magnificent spectacles which it is ever the fortune of students of volcanoes to observe. It ascended to a height of about 25,000 feet above the summit in volutes of the heavy cauliflower type in an otherwise clear sky. Although very spectacular in appearance, the violence of these explosions was not sufficient to modify the form of the volcano or to dislodge any considerable portion of its structure. Unlike the great eruption of Vesuvius in 1906, when the crater rim was lowered several hundred feet, and the eruption of Katmai in Alaska in 1912, when the shape of the cone was radically altered by the scattering of a cubic mile or more of the summit crater and its contents, these two explosions merely served to shake up the top of the plug and to tear away a section of the thin eastern rim, scattering boulders and smaller fragments about the mountain for a distance of several miles, accompanied, of course, by a great volume of ash, as in the case of all the previous explosions. These blasts, vertical and horizontal, served to relieve the major concentration of energy developed by Lassen Peak during this period of activity.

VOLCANIC BOMBS AND BRECCIA.

On the saddle between Lassen Peak and Lassen Crags to the northward of Lost Creek Valley there were found a considerable number of small fragments which have been described as volcanic bombs because of the evidence of recent heat which they carry. That these fragments were thrown out during the eruption of May 22 there appears to be no doubt. Their total volume is insignificant. They were of two kinds: (1) a sort of breccia of coarsely pumiceous material containing numerous inclusions of fragmentary, unaltered dacite (fig. 36); (2) the "bread-crust" bombs.

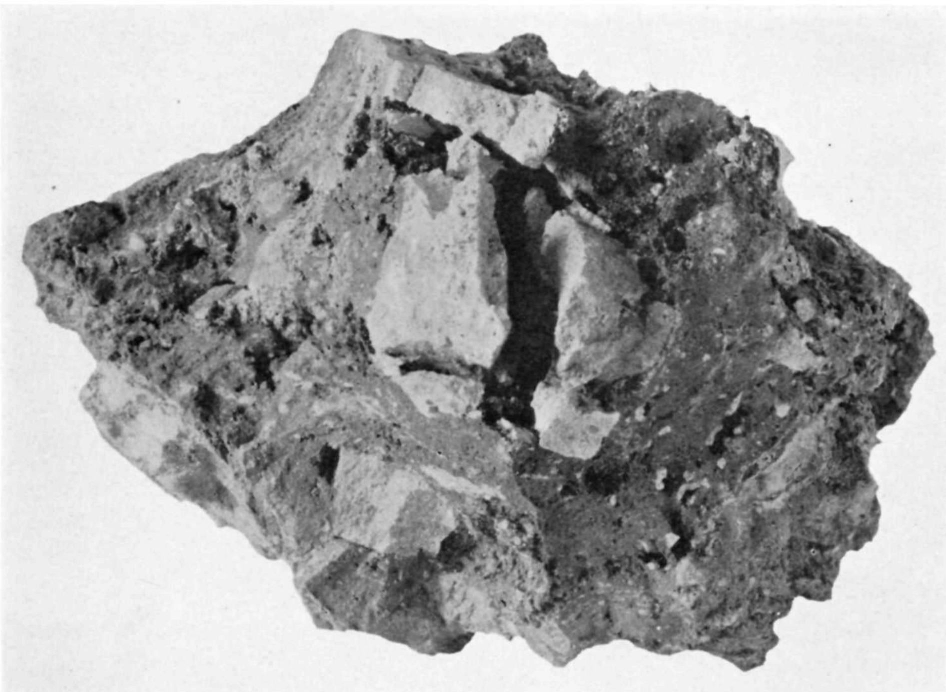


Fig. 36.—Pumiceous material containing dacite inclusions. Photo Snapp.

The pumiceous material in appearance is hard to align with any other ejecta discharged during this entire eruption, neverthelesss it is quite common along the path of the horizontal blast. It is a very light pumice, sometimes hardly more than a foam, containing large bubbles and showing plain traces of superheating. No other comparable material, either ancient or recent, has been found on the mountain in so far as we are aware. In color the pumice varies from dark purple at the center through many shades of gray to yellow on the outside, representing possibly the variable effect of oxidation at the time when the superheating occurred. The specimens are often irregularly banded dark and light, often indicating turbulent movement in the liquid state. Inclusions of pumice and scoriaceous matter are numerous.

These brecciated masses vary in size from 2 feet in diameter down to small fragments of a few inches, and none were observed to have had their form altered in any way through the force of the impact, except where breakage has occurred, and none appear to have been altered or to have had their surface configuration determined in any way by their flight through the air. These facts would appear to warrant the conclusion that they were no longer fluid at the time when they were thrown out. Perhaps the fact that no material has been found on the summit from which these could have been detached, contains some further support for this conclusion. Notwithstanding this, local observers, even including Loomis and Diller, are of the opinion that in these fragments we have direct evidence of fluidity during this eruption. To us it seems to be the same problem over again which confronted us in studying the summit material, for there is no doubt whatever that this material was once fluid, but on the other hand no evidence has been found that it was fluid during this particular eruption.

BREAD-CRUST BOMBS.

The second group of fragments is found associated with the first within a small area of a few acres on the northeast shoulder of the mountain, perhaps a half mile distant from the crater bowl. They have the surface appearance of bread-crust bombs, but in no case do they show the symmetrical forms or figures of rotation indicating that they were thrown out as liquid masses whose figure was then determined during flight. Neither is there among these fragments any evidence of splash or other deformation at the time of impact. Nevertheless the surface is a true bread-crust surface (fig. 37), and perfectly fresh as though it solidified but yesterday.

Johnston-Lavis, who first defined bread-crust bombs, plainly confined his definition to liquid ejecta, of which the general form was more or less determined during flight, and accordingly approximated to some figure of rotation, the surface being quickly chilled while the interior was still liquid, giving the bread-crust appearance which obviously suggested the name. Mercalli a year later adopted the term and applied it to a great number of bombs which had figured in the Italian eruptions. The type is more or less familiar to all students of volcanoes. Hans Reck has brought together a great many records of observations of these bread-crust bombs and has sought to clarify the definition in an elaborate treatment published as an "Ergänzungsband" in the *Zeitschrift für Vulcanologie* in 1915 (q. v). It remained for Lacroix in his discussion of the ejecta from Mont Pelée to recognize a new group which belongs in this classification, but which had not hitherto been included. This group includes random fragments of solid material which have been superficially reheated by gas combustion or otherwise, causing the surface to soften while the interior remains solid and unaltered. The surface melting serves to develop contraction cracks characteristic of the bread-crust surface, which may even open up and become rounded on the edges if the exposure is long-continued. Such bombs retain the random form of the original fragment, which is of course unaffected by flight through the air.

This second group of fragments found on the northeast slope of Lassen Peak is of this type; some are somewhat larger than the brecciated fragments above described, but are scattered about promiscuously among these. They are for the most part confined to this area and have only occasionally been found elsewhere on the mountain. Unlike the pumiceous fragments such bread-crusted surfaces are found on some of the larger fragments at the summit of the mountain, showing possibly the local development of considerable heat at certain points. Inasmuch as none of these bread-crusted surfaces at the summit appear to have been reheated in their present position, we are obliged once more to admit a reasonable doubt whether the bread-crust surface was acquired during this eruption or some earlier one.

At the time when these bombs were first found Lacroix's description of this type had not come to the attention of the authors, but it was perfectly clear that

Fig. 37.—July 17, 1915. Bread-crust bomb about four feet long, northeast slope of Lassen Peak about one-half mile from crater. Photo Day.

they were different from the types discussed by Reck and others as bread-crust bombs on account of their generally angular shape and the absence of any influence upon their form due to flight through the air. In other words, they were evidently solid fragments at the moment of ejection and not liquid fragments, so that although bread-crusted on the surface they differed fundamentally from the hitherto recognized bread-crust bombs. Accordingly, some study was made of these in the laboratory, and in particular the effort was made to produce the bread-crust surface on Lassen Peak dacite which had been sent on to Washington for the purpose. Upon these fragments there was no difficulty in producing a bread-crust surface after an exposure of 2 hours to a temperature of 1000°. Presumably a considerably longer exposure to a somewhat lower temperature would have produced the same results on larger masses.

These bread-crusted surfaces by reason of their extremely fresh appearance and the absence of contact fracture, such as might have been expected in the violence of the explosion through which they passed, may possibly have been produced during this eruption. If this conclusion is adopted, there is indication here of the local development, presumably in very small areas, of a temperature somewhat higher than the red heat noticed and reported by Milford on the west slope of the mountain. A red heat such as he describes would not be adequate to produce bread-crust surfaces on this dacite so far as the laboratory experiment reveals the conditions under which the bread-crusting must have occurred. Some 200° additional temperature above red heat are necessary to produce the bread-crust effects here observed. On the other hand, the very small quantity of such bread-crusting which has appeared at the surface will perhaps indicate that these more highly heated regions, if they occurred during this eruption at all, are restricted to a few small openings, presumably in the deepest part of the crater floor. The ash and smaller fragments discharged by this eruption have been found to contain little glass or even rounded crystalline fragments.

Dr. H. E. Merwin has made a microscopic examination of fragments and thin sections of the bombs, the results of which we may incorporate here:

1. Very vesicular breccia with dark andesitic matrix inclosing various vesicular and porphyritic rhyolites and andesites. Some of the fragments, especially the denser ones, are very loosely held, others have blended and flowed with the matrix. The appearance suggests that the matrix was formed in part by a fluxing of the most basic fragments of an original, less consolidated breccia. The glass of the matrix is more basic than the inclosed fragments—as determined by refractive index.

I have not found more than traces of *quartz* in the matrix, but it is abundant in some of the inclusions. *Biotite* scales are scattered sparsely in the matrix and inclusions, and it is found in some of the typical andesites of the region.

Andesine is abundant as phenocrysts and in the ground-mass.

2. Bomb which is very vesicular but only obscurely brecciated. This has a denser bread-crusted surface, contains very little quartz but much feldspar, and is speckled sparsely with biotite. The biotite scales in the bread-crusted surface seem unaltered. One crack was observed to have divided a biotite flake along a cleavage and the sharp edges of the biotite remain.

3. Bomb which is dense and aphanitic, and decidedly bread-crusted. This is a typical dacite with considerable quartz and andesine as phenocrysts. Nothing in the rock powder examined indicated resorption of quartz, but slides have not been studied.

The phenocrysts from the interior of bombs are almost exclusively fragments of plagioclase crystals. Some show two stages of growth interrupted by a period of resorption or fracturing; most of the larger phenocrysts were fractured also during the solidification of the bomb. Original flakes of biotite are largely altered to dark, very fine-grained aggregates which appear to consist of magnetite, pyroxene, feldspar, and glass. The cause of the alteration is not apparent. Quartz is almost lacking.

CHAPTER IV.

SOME INFERENCES CONCERNING THE CAUSES OF ACTIVITY.

Now that we have brought together the facts of observation, both those which may be obtained from eyewitnesses of the phenomena and those which may be directly inferred from conditions which are visible on the ground, we may appropriately inquire about the relations below the surface which determined the mechanism of the eruption, and perhaps also the particular conditions which may have precipitated it.

The essential facts thus far determined show this eruption to have been rather different in character from the established types best known in the literature of the subject. It may therefore not prove practicable to determine by direct analogy with a well-known type the probable relations obtaining in this eruption, but over against this limitation we may set the fact that laboratory and theoretical studies of rock formation have advanced somewhat farther in recent years, and have afforded information regarding the behavior of the fluid magma and the crystallization of rock from it, which has not been known long enough to find particular application to the earlier eruptions. Upon this information, limited though it is at present, we may profitably draw freely for the elucidation of our problem.

Viewed as a whole, the recent eruption of Lassen Peak can not be accounted a volcano problem offering great complications. The phenomena as observed followed a reasonably consistent course to a climax without serious interruption of continuity and without the intervention of unique occurrences like the appearance of the spine in the crater of Mont Pelée. The climax itself lasted but 3 days and was without catastrophic complications of a character to blind observers to the normal course of events, or to interfere with a reasonably direct deduction, both of the proper sequence and of the order of magnitude of the manifestations which occurred.

The closing phases following upon this climax have indicated nothing more than a gradual dying down of the active forces without developing any features of especial interest. The facts which may be regarded as established, upon which attention has been mainly concentrated in the foregoing pages, are these:

1. A period of the order of magnitude of 200 years had elapsed since the last previous activity of Lassen Peak, which undoubtedly gave time for a considerable accumulation of energy beneath the plug which sealed the orifice. During recent years no fumarole or other sign of latent activity has been visible on the mountain, so that the volcano may be regarded as having been completely sealed. Also, we may not overlook the fact that the hot zone approaches close to the surface in this region, as is evidenced not only by the activities of the volcano itself, but also by the continuous activity of the near-by hot springs, of which there are several groups extending along the south front of the mountain and to the southeastward for a

distance of 10 miles (see Part II). This is also the major zone of faulting, as has been shown by the detailed studies of the geology of the region recently undertaken by Diller (unpublished).

2. The lava forming the plug of Lassen Peak, as well as the inclosing cone, is dacite of somewhat variable composition, which does not differ from the neighboring andesite in chemical content, but does differ from it frequently in mineral composition in that it usually contains small quantities of free quartz. The composition of this dacite and its relation to andesite are in this particular very like the correspond-

Fig. 38.—May 22, 1915. A view of the great eruption from Mineral, 12 miles south of Lassen Peak. Photo Hampton.

ing lavas participating in the latest eruption of Mont Pelée (1902), which have been studied in great detail by Lacroix.[1] It will be worth while to recall in this connection that Lacroix's conclusion was that the dacite appeared wherever conditions were favorable for slow crystallization, while the andesite may have resulted from more rapid cooling.

[1] A. Lacroix, *LaMontagne Pelée et ses Éruptions*, 1904.

3. The volcanic phenomena throughout the recent period of activity have yielded no evidence of high temperatures, near the surface at least, nor of the participation of any considerable quantities of the chemically active gases such as are commonly found in the volcanoes in which temperatures are high. In the absence of evidence of oxidation of any of the participating components, whether gaseous or other, it may fairly be assumed that there was no chemical activity of a kind to add heat to the system. The explosions, so far as direct observations can determine their character, were primarily of steam, more or less laden with ash (figs. 39, 40) from the crater bowl or produced by attrition in the conduit. None

Figs. 39, 40.—The great eruption of May 22, 1915, viewed from Mineral 12 miles south. Photo Hampton.

was violent enough to change the form of the cone or even to dislodge any considerable sections of it. The highest temperature indicated either by indirect or by direct observation was a moderate red heat which can not have been more than 700° or 800°. Very locally there may have been slightly higher temperatures if the brecciated fragments and the little group of bread-crust bombs were formed during this eruption, but this conclusion is open to question. There was no conclusive evidence of glow on the mountain except on the night of May 19 during the short culmination of the activity, nor were red-hot fragments certainly observed on any other occasion. There were also no more than two or three occasions when chemically active gases were certainly detected, and then only in small quantity and for short periods. No evidence was found of the destruction of foliage by gases, as is so frequently seen at Vesuvius, where acres of trees and smaller plants are sometimes completely blasted in a few hours' exposure to a smoke cloud so cold that it will not even rise but "rolls" down the mountainside.

4. The two great floods and the minor mud flows, which are so conspicuous among the visible evidences of activity, and in consequence have played such a considerable part in the descriptions of the eruption of Lassen Peak in the newspapers and popular literature, may be dismissed as secondary effects, due to the condensed steam falling upon a great body of accumulated snow and set in motion by hot horizontal blasts from the mountain.

5. The only lava movement en masse occurring during this eruption period was the lifting of the lava plug forming the old crater floor into a position nearly level with the crater rim, an elevation of at least 300 feet, following the faulting of the summit cone which began at or before the first eruption in 1914 and continued to grow under the stress of the explosions until the plug was lifted to fill both the rift and the explosion crater. Whether in lifting the plug, a movement taking place entirely within the cone, liquid lava from below would become exposed is of course entirely a matter of accident. The upward movement stopped when the crater floor had reached the level of the rim, so that the liquid lava could not become exposed unless the plug should be shattered or the cone itself yield to the force of the explosions at some point of weakness. The cone did yield at three points: (1) Along the fault-line on the northeast side, where the two horizontal blasts emerged, but this opening appears to have come just under the "lid" which closed down upon it immediately afterward, so that its precise position can only be inferred from local fumaroles. It is near this point, however, that an instance of recent flow *in situ* was found. There is also an opening (2) on the north front of the cone extending radially down the mountain for several hundred feet from a point very near the summit, through which a considerable number of the later explosions were seen to emerge, but no evidence of heat concentration or of liquid lava has been seen there. The third opening is the rift in the western rim which was filled when the plug was lifted. All of these openings are in or about the crater rim and so gave no opportunity for the release of fluid lava from beneath the plug.

6. So far as available observation goes, all the explosions recorded, both vertical and horizontal, were steam explosions, so that water appears to be the only volatile ingredient with which we have to deal seriously as a possible participating cause. Ground-water levels were high and a number of streams of considerable size have their sources high up on the mountain. The annual rainfall at the nearest comparable station (Inskip) is upwards of 80 inches. The accumulation of snow in the crater bowl was melting rapidly at the beginning of the activity in May 1914 and, except for the small portions blown out during the explosions themselves, contributed directly to the water content of the volcano. This supply of snow was exhausted during July 1914 and a new and uncommonly large accumulation replaced it during the following winter. Following the two winter seasons (1913–14,

1914–15), therefore, a great amount of meteoric water undoubtedly reached the volcano hearth (as steam) directly through cracks in the plug (crater floor).

Bringing this evidence to bear upon the problem of the actuating forces, we have to consider the relation between water and the characteristic andesite lava at temperatures below 1000°. Thus far we have considered only facts of direct observation or of immediate inference therefrom. It is now necessary to make assumptions to which a reasonable degree of probability can be assigned. The first is that we are dealing with a cooling system, that is to say, a mass of magma which is receiving no new heat, as for example by chemical action during the eruption. Energy accumulated during two centuries under a perfect seal is finding release, not at once, but gradually over a period of several years. What conditions and relations are competent to accumulate and localize this energy in a slowly cooling system and to release it explosively in this manner?

Beneath the plug there is undoubtedly a considerable mass of liquid magma in which some crystallization has taken place, inclosed within a cone of the same material. We have little information upon which to base an appraisal of its condition at the temperature now prevailing in it, except that the solidified lava now exposed still contains some glass and also free quartz, the latter of which has been shown (Lacroix, op. cit.) to indicate a very slow crystallization of the andesite magma.

The presumption is, further, that the movement of the plug at this comparatively low temperature, through upthrust of liquid magma from below, is positive indication that the water content of the liquid lava is large, otherwise there is little possibility of fluid movement in a magma of this composition. This is further established by direct inference from the immense quantities of water given off during the explosions throughout all phases of activity, and is otherwise logical because of the high level of the hot zone in a region of considerable rainfall. It is logical also because a lava high in silica will probably carry in solution more water than a basic lava,[1] and also because all volatile ingredients, other conditions being equal, tend to be driven off by heat, and therefore the lower the temperature the greater the possible content of volatile matter (in this case water) in the magma.

G. W. Morey has recently published a paper in which these questions are considered in some detail.[2] Almost all of this bears upon the question here under discussion, and considerable citations from it will therefore be permissible. He says, for example, of the solubility of molten lavas for water vapor the following:

It is now a demonstrated fact that water vapor under a pressure of one atmosphere is appreciably soluble in liquid silicates at their melting-points, and that the amount of water dissolved at this pressure will produce an appreciable lowering of the melting-point. . . . If the initial pressure of water vapor is increased, more water will be dissolved and freezing will begin at a correspondingly lower temperature.

The solubility of water in a silicate melt at a given pressure of water vapor will depend largely on the temperature, and it is to be expected that the solubility will increase with

[1] See below.

[2] G. W. Morey, Development of pressure in magmas as a result of crystallization. Journ. Wash. Acad. Sci. 12, 219, 1922.

decreasing temperature, for the same reasons that gases are more soluble in cold water than in hot water. If an undercooled silicate mixture, that is, a mixture which had remained liquid although it had cooled below the temperature at which crystallization should have taken place, were to come into contact with water vapor, . . . it would probably take up a much larger quantity of water than at a high temperature.

The evidence which has led Morey to these conclusions is partly derived from general laws of solutions which have now received abundant verification and partly from actual experimentation with molten salts and silicates. They may therefore be accepted as bearing directly upon our problem and offering information of fundamental importance. We conclude from it at once that the highly siliceous magma beneath the plug almost certainly contained great quantities of water in solution, and that its mobility at this relatively low temperature was directly the result of this water content. A high-silica magma without water is ultraviscous.

If it is desirable to offer direct geological evidence to supplement that of the laboratory upon the capacity of a highly siliceous magma to carry water in solution, it will be borne in mind that some obsidians and pitchstones, of whose analyses we have a record, are found to contain 10 per cent or more of water,[1] while average andesites, according to Washington's table of analyses, contain no more than from 1.0 to 1.5 per cent of water. Pitchstones and obsidians are really liquid magma which has cooled down under such extraordinary conditions that true freezing (crystallization) did not occur. Any readjustment of relations leading to equilibrium between the volatile and non-volatile elements of such a magma was therefore prevented, and we have in these unusual masses a trustworthy picture of a liquid magma before the volatile elements are driven out by subsequent reactions.

From the evidence of the laboratory, therefore, as well as from natural occurrences, the conclusion is justified that the Lassen Peak magma was fluid at such low temperature because of the amount of water in solution in it, and the fact that movement occurred at all at these temperatures is direct evidence of high water-content.

So far as this conclusion is concerned it is immaterial whether the water is an original constituent of the magma, or is meteoric water acquired in the usual way through contact with water-bearing strata, or is meteoric water reaching the volcano hearth through cracks in the crater floor under a head determined by the elevation of the crater basin.

The last source alone would probably be inadequate to provide all or even a considerable proportion of the water given off in the 300 or more explosions constituting the present activity of Lassen Peak (pp. 176, *et seq*), but it may not be neglected as one of the sources of the great quantity of water that participated in and was indeed responsible for the activity. The water was undoubtedly supplied from all the three sources mentioned. The point of chief interest here is not a distribution as between available sources of supply, but the establishment of adequate sources for the tremendous quantities given off.

[1] Cf. J. W. Judd *et al.* The Eruption of Krakatoa and Subsequent Phenomena, p. 36. (Rept. of Krakatoa Com. Roy. Soc. London 1888.)

Suppose we consider now the effect of the progress of crystallization in a magma of this type under the conditions above described. This is the major subject of discussion in Morey's paper, from which we may therefore appropriately quote further:

At temperatures near that at which crystallization begins, a liquid silicate mixture containing but a small amount of volatile component may exert but a comparatively small vapor pressure, but as crystallization proceeds with falling temperature the pressure of the volatile components will increase at a rapid rate, so rapid that a pressure many times the original pressure may result from the crystallization of but a small proportion of the non-volatile material.

The logic of this conclusion is direct and inevitable, for as the magma crystallizes the volatile ingredients are crowded out, and if they are then confined in a closed space their pressure will increase rapidly until relieved by rupture of the inclosure or otherwise. This accounts at once for the gradual accumulation of energy in such a closed volcanic hearth, where the only operative cause required is a sufficient water content and the gradual cooling and crystallization of the magma contained therein. Morey illustrates this by a number of laboratory studies beginning with the behaviour of crystallizing potassium nitrate and water, the progress of which can be followed in detail, he says:

As the mixture cools, crystallization proceeds, the water content of the liquid increases, and its vapor pressure rises. Reference to figure [41] A or B[1], shows that at the time crystallization begins the liquid composition is 99 per cent KNO_3, 1 per cent H_2O. When the water content has doubled, the pressure has increased from 1 atmosphere to over 6 atmospheres, a six-fold increase. When the water content has again doubled, reaching 4 per cent, the pressure has risen to almost 11 atmospheres. If the mixture be contained in a flask which can withstand a pressure of only 10 atmospheres, the flask will burst as the result of the pressure developed by cooling the mixture.

[1] Figure 41.

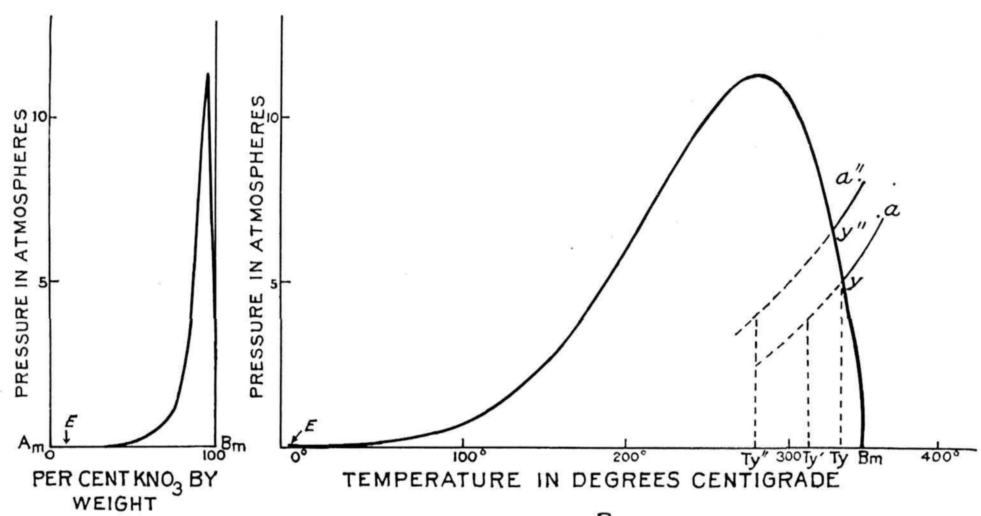


FIG. 41.—Diagrams showing change of pressure, temperature, and composition of the univariant equilibria between solid, liquid, and vapor phases in the binary system H_2O-KNO_3.

A further example, illustrating, from the experimental results, the development of a fairly high pressure in a silicate system as the result of cooling, may be found in the same system [$H_2O-K_2SiO_3-SiO_2$]. The eutectic between $K_2Si_2O_5$ and SiO_2 lies at the remarkably low temperature of 520°. If a mixture of K_2O, SiO_2 and H_2O, containing 9.1 per cent of H_2O, with the other ingredients in the molecular ratio $SiO_2/K_2O=4.26$, be cooled from a high temperature, the vapor pressure of the mixture will fall as the temperature falls. The mixture will not begin to freeze until it has cooled to 500°, when crystals of quartz and the ternary compound $KHSi_2O_5$ will separate. The vapor pressure of the solution at this temperature is 160 atmospheres. On further cooling the substances continue to crystallize and the pressure increases rapidly. When the temperature has fallen 20°, to 480°, the water content has increased to 10.2 per cent, and the pressure to 180 atmospheres. When the temperature has fallen to 420°, the water content has increased to 12.5 per cent and the pressure to 340 atmospheres, more than double the pressure at 500°.

It is of interest to consider what would happen if the mixture were to cool without crystallizing, say to 420°, and then begin to crystallize. . . . On the assumption that the drop in pressure for the 80° drop in temperature from 500° to 420° in the solution is the same as the drop in pressure of water from 348° to a temperature 80° lower, the vapor pressure of the supercooled liquid at 420° will be 59 atmospheres. If the mixture containing 9.1 per cent water were to cool, without crystallizing, from 500°, its saturation temperature, to 420°, its pressure would fall from 160 atmospheres to about 50 atmospheres. If at this lower temperature it should begin to crystallize, the pressure would suddenly rise to that of the solution in equilibrium with quartz and $HKSi_2O_5$ at 420°, or 340 atmospheres.

It is evident, then, that as a magma containing water and other volatile components cools, with consequent crystallization, the pressure will rapidly rise from its initial value, and as the cooling continues the pressure will increase until the temperature of maximum pressure has been reached, or until the pressure is relieved by escape of the volatile material. In the first case, which is that in which the liquid cools under a crust of sufficient weight and strength to withstand the internal pressure, the liquid will solidify as an intrusive mass.

If the vent is a fairly open one, enormous pressures probably will not be developed and the escape of the water as steam may be comparatively quiet; . . . It may well be that in both these cases the activity is the result of the release of volatile material consequent on crystallization, and the rate of release of the volatile material may be regarded as a measure of the rate of crystallization in the parent body.

In the last paragraph of this discussion lies a clue to the character and development of the present eruptive activity which we may not overlook. If the rapidity of release of water from the magma is proportional to the rate of crystallization and the increasing pressure of this water vapor is the explosive agent, the appearance of outbreaks at intervals of 2 or 3 days during the entire summer and autumn of 1914 is readily explained. If the explosions had been due only to water from without, pouring into rifts in the crater floor, and exploding as steam on reaching the hot zone, no such periodicity extending into the summer and autumn would have been possible. Considering the explosions to be due to a more or less regular release of water vapor from a crystallizing magma, to which any outside water is merely contributory, then explosions may be expected to occur as often as the accumulating pressure within overcomes the resistence of the envelope. Usually it may be assumed that the inclosing crater wall will withstand the expanding force of the volatile ingredients released by the magma, and the outbreaks will then depend solely upon the fortuitous resistance of the conduit and its contents to the accumulating pressure from below. Morey, in his subsequent treatment, recognizes the cumulative character of this operation and its direct bearing upon the eruptive period. He says:

> Conditions may be such that a much greater pressure must be developed before the gases are able to force their way to the surface. It may be assumed that eruptions will then take place at less frequent intervals.

Such accumulating pressures may find release in a single explosion, like Bandaisan, or explosions may come intermittently over a considerable interval of time, as happened at Mont Pelée or in the case now under consideration, where explosions continued to recur over a period of more than 4 years. Indeed, so far as the theory is concerned it is direct, competent, and appears to require no modification beyond the local limitations imposed by varying composition of the magma, the water supply, and the physical resistance of the structure. When a conduit is once opened consecutive explosions at longer or shorter intervals from the same opening are likely, for the probability is small that the volcano hearth will be laid wide open by a single explosion, or the accumulated pressure otherwise completely discharged in the first outbreak. Where a considerable body of magma participates and the more fluid portions have access to the opening a lava flow may result, following somewhat the same mechanism as a soda-water bottle when the entire content is violently discharged through a too abrupt relief of the pressure. Or an open stand of fluid lava may accumulate in the conduit, discharging its gas content by quiet bubbling, with or without occasional overflows, as at Vesuvius before the outbreak of 1906 and at the present moment, or as at Kilauea usually. All these conditions find a ready explanation through the same mechanism, with but slight modifications of local mechanical details.

With very great volcanoes, such as Mauna Loa in Hawaii or Etna in the Mediterranean, the point where the structure fails under the cumulative pressure is usually not the summit crater, but some other point lower down, where weakness has developed through fissuring or some other mechanical defect, or because of the solvent action of the magma boring from within. In these cases the hydrostatic pressure of the overlying column in the conduit is probably added to that developed in the crystallizing magma below. There is evidence at Mauna Loa that the whole mountain becomes distended as the pressure develops prior to a catastrophic release; also that there is some segregation due to gravity in the great magma chamber, for outbreaks at or near the summit release either gas alone or a light emulsion, while outbreaks at lower levels are flows of heavy lava containing little gas. The difference in level between the summit crater and the recent lava outpourings at Mauna Loa is about 7,000 feet.

All these are but instances of local limitations impressed upon the pressure reservoir, which have the effect of varying rather radically the visible phenomena of volcanic outbreaks without in any way affecting the application of the simple theory here offered to account for the continuing source of pressure, so long as the crystallization of the magma remains incomplete. The limiting condition at Lassen Peak, and from a theoretical viewpoint its most interesting feature, was the uncommonly low temperature at which the more violent phases developed. It is altogether conceivable that, if the temperature had been but a little lower, ultra-viscosity would have spread its inert mantle over the whole system and no movement would have occurred, however remote the solution was from a condition of equilibrium. Perhaps the Obsidian Cliff of Yellowstone Park is as good an illustration as can be found of a frozen system in which equilibrium was never reached.

There is still another phase in the theoretical consideration of this subject which may have a bearing on conditions at Lassen Peak, though experimental evidence is limited by the fact that no flow occurred and no sample of lava, which certainly represents the present stage of development within the magma basin, has been collected. We quote again from Morey:

> It might be that, if the crust were of sufficient strength, a fairly large proportion of the liquid magma would crystallize before a pressure had been built up of sufficient magnitude to cause an eruption . . . In such a case, in which a considerable amount of crystallization has taken place, the non-crystallized material ejected will represent the "mother liquor" remaining after the segregation of those minerals which are the first to crystallize under the conditions prevailing. These may be the femic minerals, in which case the mother liquor will be enriched in the more salic minerals, quartz and the feldspars, and the water content will be correspondingly increased.[1]
>
> The tendency for the heavier femic minerals to differentiate by settling will be great, especially since the density difference between the femic and salic minerals will be increased by the presence in the salic melt of the accumulated water.

To make appropriate application of this indication would lead us out upon broader ground than is contemplated in the direct consideration of the outbreak at Lassen Peak. It will be recalled, however, that Diller definitely included Lassen Peak, geologically, within the great region of basaltic overflow extending through portions of five states in the great Northwest. Lassen Peak is one of the few remaining active vents in this entire region, and therefore, presumably, contains the last vestiges of residual magma. Aurousseau has also characterized this lava as "well differentiated" (p. 40). Very probably this segregation, to which Bowen first called attention in the paper to which reference has been made, is responsible for the depletion of basalt (the femic minerals) in the residual magma in this great volcanic basin, and the persistence of salic residues still fluid because of their high water content.

A final and very short paragraph may properly concern itself with the assignment of a possible cause to this particular outbreak. Of course, the ultimate cause is to be sought and found in the accumulation of sufficient pressure to break down the overlying resistance of the plug which closed the original conduit. This may be due either to the continuity of pressure development in the manner indicated, which finally equaled and overcame the overlying resistance; or it may happen that this resistance was broken down or weakened through the operation of some extraneous cause, thereby giving an opportunity for release to the accumulated vapor pressure within. There is some indication that the latter explanation is the true one. The fact that cracks over 100 feet long and in the general direction

[1] N. L. Bowen, Later stages of the evolution of the igneous rocks, Journ. Geol. Suppl., vol. 23, No. 8, 1915.

of the summit fault were noticeable immediately after the first explosion and were reported in the very first telegram announcing the inception of activity, (p. 3) appears to warrant the consideration of such a possibility.

Whether these two cracks represented the first outbreak of a cumulative pressure, or an earthquake disturbance which weakened the volcano plug, is a question to which, probably, no direct answer can be given. It is a fact, however, that the first explosion was insignificant in point of magnitude and altogether inadequate to account for the cracks. If it had represented the first outbreak of enormous pressure accumulated through 200 years or more of slowly crystallizing magma then breaking through the crust for the first time, a catastrophic explosion would be expected and the explosions following would be weaker; or a long pause might ensue, for the volcano hearth itself would probably be laid open.

If on the other hand the first opening represented a weakening of the plug from without, the resistance of which then required to be broken down and the opening enlarged from within, successive explosions of progressively increasing magnitude would seem to be a natural consequence. If the latter conclusion is followed, the water, which entered the cracks after the first and subsequent explosions, may have been a very definite contributing cause, for a considerable influx of water from without might cause a considerable increase of fluidity locally, and so precipitate activity in a more or less inert mass. Morey says of this phase of the subject in his theoretical exposition:

> If an undercooled magma were to come into contact with percolating waters, or the vapor generated thereby, as previously explained, a similar introduction of water at a low pressure might take place. Introduction of this water might of itself induce crystallization in virtue of the lowered viscosity of the resulting magmatic solution, and it is conceivable that the result would be a sudden and violent outburst of steam and ash, at a comparatively low temperature.

If the weakening of the inclosing plug came from without and water was admitted to contact with the outlying portions of a magmatic mass in which reaction had practically ceased and a condition of suspended activity in an ultraviscous magma had supervened, then the relation indicated by Morey might be realized. The influx of water-vapor from above into the outlying portions of an incompletely crystallized magma might then have the effect of decreasing viscosity in the still fluid portion and promoting crystallization, and might cause an explosion which would be followed by others in increasing intensity as greater bodies of magma were affected by the more favorable conditions. This mechanism seems to offer a more logical explanation of a series of explosions of progressively greater intensity, and approaching a culmination after several months, than any other which has been suggested.

To those who are accustomed to draw upon experience with solutions of salts in water for precedents of convenient application here, a word of suggestion may help to clear up certain misgivings which can hardly fail to come to mind in following the demonstration just offered. Undercooling in salt solutions is rare and can hardly occur in contact with crystals of the stable solid phase. Because of the great viscosity of silicate solutions (magmas) undercooling is there the rule, and furthermore, the rate of reaction is often extremely slow, so that equilibrium throughout any considerable mass of magma can not be expected to follow shifting conditions, nor indeed, in a magma considerably undercooled, to be approached at all within a limited time. By way of illustration note the percentage of glass revealed by the microscopic study of the Lassen Peak rocks (p. 43). This glass is undercooled magma in continuous and intimate contact with the crystalline phases *throughout the mass.* When Morey considers the case of an undercooled magma at 700° or 800° to be radically altered by the advent of water vapor, he pictures phenomena of common occurrence in the study of rocks of high silica content. Such an andesite magma containing several per cent of water may be in intimate

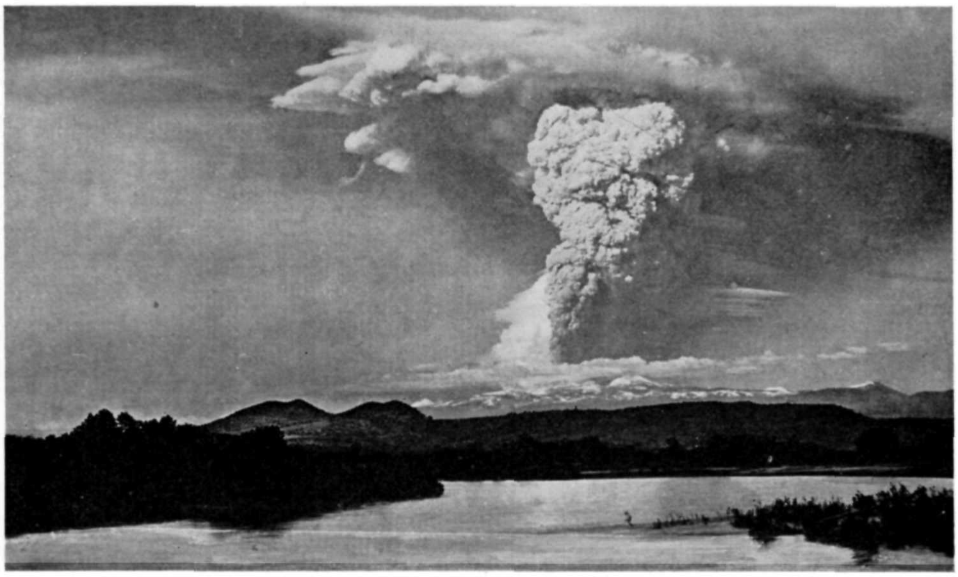


Fig. 42.—May 22, 1915. View of the great eruption from Red Bluff, 45 miles southwest. Photo Stinson.

contact with the crystalline phases at these temperatures and yet be very far removed from equilibrium. Undercooling might indeed be accounted to be the normal condition of such a system when inclosed within a competent reservoir, and inertness its most apparent characteristic.

Suppose additional water vapor under appropriate pressure to be introduced into such a system. The solubility for water of the liquid portion (magma) is greater at these low temperatures and increased fluidity of the magma is its immediate consequence. But with increased fluidity comes an increased reaction-rate, a more rapid approach toward equilibrium through crystallization, to which may correspond an enormous increase in the vapor tension (see curve, p. 78). In a volcano reservoir, with vast quantities of surcharged magma potentially available, such a discharge of water vapor may precipitate an avalanche of crystallization and consequences of catastrophic proportions.

If this reasoning is admitted, no natural agency need be invoked to explain this type of volcanism, which does not find its place among the well-established laws of the behavior of solutions. Ultraviscosity may provide a cloak beneath which slow-moving changes may proceed unobserved for long periods of time, and these may develop a potential of enormous proportions before conditions favorable to its discharge (equilibrium) occur, but there appears to be nothing in this special case, except its magnitudes, which is in any way foreign to our usual thinking, and these will give us no concern, provided only we have the courage to follow the reasoning through to the logical outcome.

After establishing the validity of such reasoning we shall not overlook the facts, nor set them aside as mere coincidence, that (1) streams of water from the melting snow in the crater basin were observed to be pouring into the first explosion crater and adjacent cracks at the beginning of the activity in May 1914; (2) a very unusual winter accumulation of snow in the crater preceded the culminating outbreak in May 1915; (3) following the great eruption in 1915 and the upheaval of the crater floor which formed a part of it, the rocks in the crater remained warm throughout the winter following and were found to be quite bare of snow in May 1916—whether from lack of a new supply of water to diminish the viscosity and so to give fresh impulse to the crystallization, or for some other reason, there were no eruptions in May 1916 or thereafter in that season; (4) after the surface rocks at the summit had cooled and the winter snows again accumulated there (1916–17), the period of spring melting (May 1917) was again marked by violent explosions which opened a new explosion crater some 600 feet wide and deep.

Since the summer of 1917 the opening has remained sealed, so far as trustworthy observations at the summit have been reported.

When the remarkably low temperature of all the observed phenomena is recognized and the consequent high viscosity which characterized the only lava movement observed during the entire eruptive cycle, it is hardly possible to conclude that the volcano hearth itself can have had a high temperature. If it had not, then undercooling and an extremely slow rate of crystallization is indicated, which may have required an influx of surface water to precipitate violent phenomena.

PART II.

THE HOT SPRINGS OF LASSEN NATIONAL PARK

By Arthur L. Day and E. T. Allen.

INTRODUCTION.

In the course of the investigation of the recent eruption at Lassen Peak some interesting observations were made in 1915 on the hot springs of that vicinity. The possibility of studying certain genetic conditions for the formation of sulphide minerals was suggested by what appeared to be the precipitation of pyrite in one of the hot-spring areas. The next year observations were continued with this purpose in view, and collections were brought home for laboratory study. As the investigation developed, the original purpose broadened in scope, and when, after the interruption of the war, the work was taken up again the reed of more complete evidence on a number of points became obvious. Accordingly, the field was revisited in 1922 and again in 1923.

CHAPTER I.

OBSERVATIONS AND EXPERIMENTAL WORK.

LOCATION OF SPRINGS.

The hot springs described in this paper are found in northeastern California. They occupy adjacent portions of Plumas, Shasta, and Tehama Counties and, with the single exception of Morgan's Springs, all are included within the limits of the Lassen National Park. This region, which has but recently (1916) been established a national park, is comparatively little known, because it lies remote from the main lines of travel and is still traversed only by rough trails, but it abounds in attractions both for the scientist and nature lover—magnificent scenery of mountain, meadow, lake, and stream, a wonderful forest of great conifers, and volcanic phenomena of high interest, including Lassen Peak and many groups of hot springs.

GEOLOGIC RELATIONS OF HOT SPRINGS.

The region about Lassen Peak is covered by thick lava flows, almost exclusively dacite and andesite. There is a small area of basalt along the west side of Bumpass Hell, as one of the largest hot-spring areas is called, but elsewhere the dacite is uppermost. At the Devil's Kitchen this reaches an estimated thickness of 1,200 feet. Below it lies an andesite flow of unknown thickness. The hot springs all occur in the dacite areas.

A more significant relation is the association of the springs with a system of faults.[1] According to Mr. J. S. Diller, of the U. S. Geological Survey, to whom we are indebted for these geological observations, there exists between the Sierra Nevada and the Klamath Mountains "a group of features, mainly faults" which parallel the Lassen volcanic ridge. It is in this structural belt "which has aligned the volcanoes" that all the hot springs of the region occur. The faults are generally, if not always, normal faults. As we approach the Sierra these faults penetrate to shallower depths and hot springs are no longer found.

HOT-SPRING GROUPS.

There are at least eight groups of hot springs in the Lassen region, occurring at intervals of a few miles. Their alignment, as Mr. Diller points out, suggests that they follow two intersecting fissures; the Geyser, Boiling Lake, Drake's Springs, Devil's Kitchen, and Bumpass Hell on the one; Mill Creek Springs, Supan's Springs, and Morgan's Springs on the other. Our observations included all but the last group, but most of the work was done on the Boiling Lake, Devil's Kitchen, and Bumpass Hell. So far as the different groups have been studied their essential characteristics are the same.

[1] Bunsen (*Liebig's Annalen*, 62, 1, 1847) points out that practically all the springs, geysers, and fumaroles of Iceland lie along a northeast-southwest line, without regard to mountains or valleys.

Geyser.

The Geyser is the name applied to the principal spring of a small group which occurs in a deep, narrow ravine about 10 miles southeast of Lassen Peak, Like each of the three following spring groups, it is situated in Plumas County, California. Ranged in an irregular line at the head of the ravine are three connecting pools, each about 25 feet in diameter, the Geyser itself being first in order. The ravine at this point is but little wider than the Geyser pool. The temperature of the pools varies from 20° or 30° up to nearly boiling temperature, which at this elevation (5,700 feet by the aneroid) is not far from 94° C. Two of the pools have been observed at times to spout jets of water to a height of 5 to 8

Fig. 43.—The Geyser. Southernmost pool, July, 1922. Photo Day.

feet, at other times the action is inconsiderable (fig. 43, Plate 7). A small cold stream flows down into the ravine in the spring of the year, but dries up in late summer. Along the little stream, which drains the hot pools, thermal activity continues for a short distance in the form of insignificant fumaroles. From a point at the top of the ravine a narrow lava flow, like a windrow in form, can be followed northwestward almost to the Boiling Lake.

Boiling Lake or Lake Tartarus.

The Boiling Lake (elevation 5,750 feet) is an oval basin of hot water, 200 yards in its largest diameter, set in a beautiful evergreen forest, 7 or 8 miles southeast of Lassen Peak (figs. 44, 45, Plate 8). Except at the lower (northwest) end, its banks are steep and from 15 to 75 feet in height. The basin-like form of the depression and the associated thermal phenomena suggest the site of an ancient crater (Diller). There is a very small cold stream flowing into the lake from the south and an outlet of warm water, slightly larger, at the northern end. During the summer both dry

1

2

3

The Geyser. Northernmost Pool. (1) June, 1916, Temperature 30°, No spouting. (2) June, 1915, Temperature 93°. (3) July 1922, Temperature 94°. Photo Day.

up completely (fig. 44). Gas bubbles rise from time to time at various points on the surface. In spring and summer the temperature averages about 50° C.; our observations varied from 46° to 52°. The lake is pale green in color and choked with a fine cream-colored mud which makes it appear quite shallow. Clinging to the muddy bottom of the outlet, and occasionally in slight amounts to the earth about the borders of the springs, is found a green growth which in all probability consists of algæ, to which the greenish color of the lake is perhaps due. Algæ were not noticed in the other hot-spring areas, except in Drake's Springs; if present at all they must be scarce.

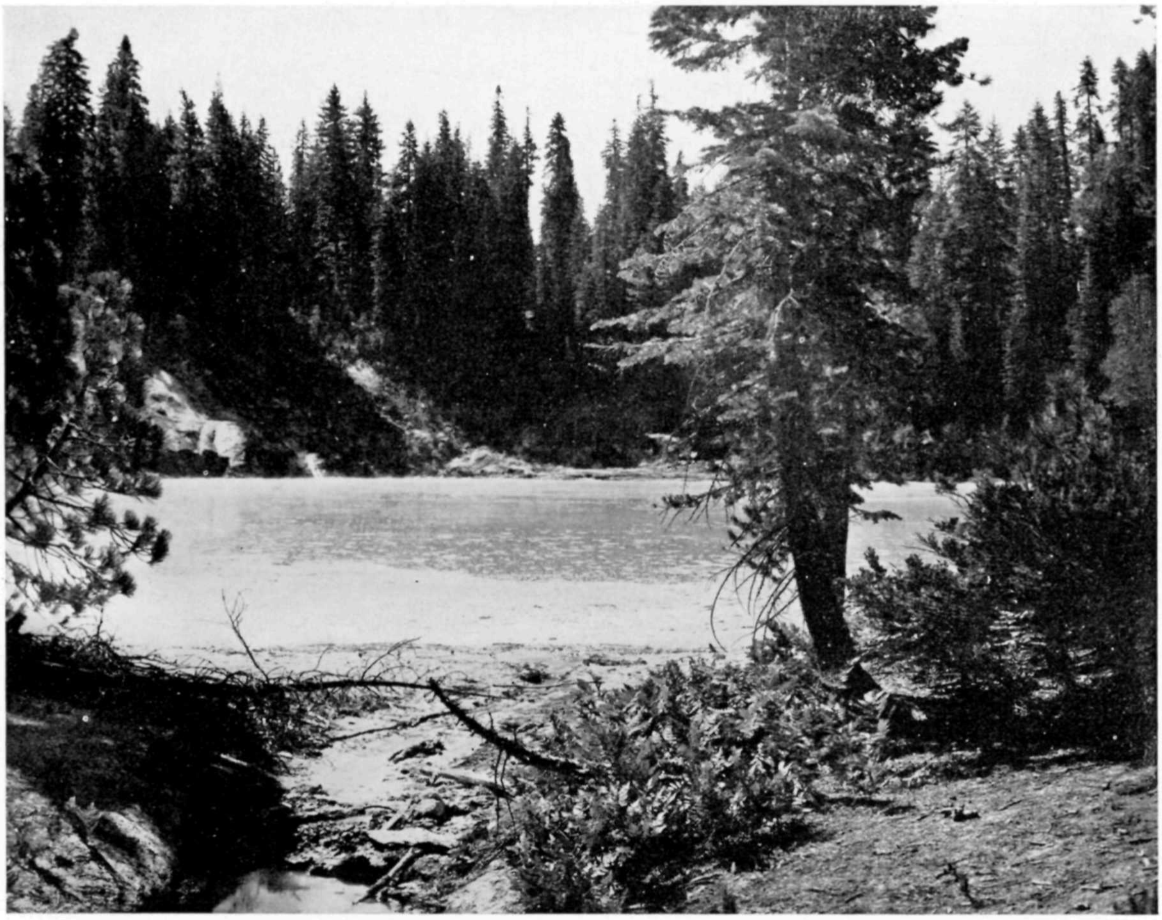


Fig. 44.—July 23, 1915. Boiling Lake (Temp. 50° C) surrounded by a beautiful evergreen forest. Outlet (then dry) in the foreground. Pyrite crystals abundant in the bed of the stream. Photo Day.

The lake is almost completely encircled by a chain of small springs and mud pots, most of which are near the boiling temperature. They generally occur close to the shore. Some are found on the bank up to 30 feet above the water, some are spread out over a low-lying delta at the inlet, and some of the mud pots are submerged or surrounded by the lake at high water (fig. 46, Plate 9).

As a result of the action of thermal waters, the shores of the lake for a maximum distance of some 50 yards at the northwestern end are of bare earth—a thoroughly decomposed lava colored reddish by oxide of iron.

Fig. 45.—May 19, 1916. Boiling Lake looking northwest. Lassen Peak in the background. Photo Day.

DRAKE'S SPRINGS.

Three-quarters of a mile north of Boilir g Lake in the close vicinity of Warner Creek is a small group of springs (elevation, 5,500 feet) which differ in appearance from all others in the region. As a consequence of the lower temperatures and probably also other conditions prevailing here, the waters are choked with a bright-green vegetable growth, contrasting strongly with the barrenness of the other spring areas. The highest temperature we have observed at any time in these springs is 62° C. Besides a number of seepages, there are a very few well-marked springs, all quite small and practically all on the slope which runs down to the south bank of Warner Creek. The easternmost spring is the largest and hottest.

The mineral content of Drake's Springs is of similar character to that of all the rest, so far as the salts are concerned, but they are small in quantity and there

PLATE 8

May 19, 1916. Boiling Lake. The outlet at high water. Photo Day.

is no free acid and apparently no hydrogen sulphide. These qualities adapt the waters to bathing purposes, and chiefly for this reason a summer camp has been located here for several decades. The camp, which belongs to Mr. A. Sifford, has always been our stopping-place, as it forms the most convenient base for all points of interest in the Lassen region.

Fig. 46.—May 26, 1916. Springs on the bank of Boiling Lake. Pyrite crystals abundant in the clay banks. Photo Day.

DEVIL'S KITCHEN.

The site of the Devil's Kitchen (elevation about 5,800 feet) is a deep, narrow valley through which flows a swift, cold stream about 15 feet in width and 1 or 2 feet deep, called Warner Creek. The active area, which is approximately 550 feet by 1,300 feet in extent, is about 1.5 miles west of Drake's Springs and 6 miles southeast of Lassen Peak. The south wall of the Kitchen is precipitous and several hundred feet in height. There are also high banks on the north side of Warner Creek below No. 27 (see map fig. 47) and at either end of the area. On these steep slopes there is almost no sign of thermal activity, but many mud pots and hot springs are scattered over the irregular floor of the Kitchen. In the immediate vicinity of the springs the ground is practically always bare of vegetation, but pines,

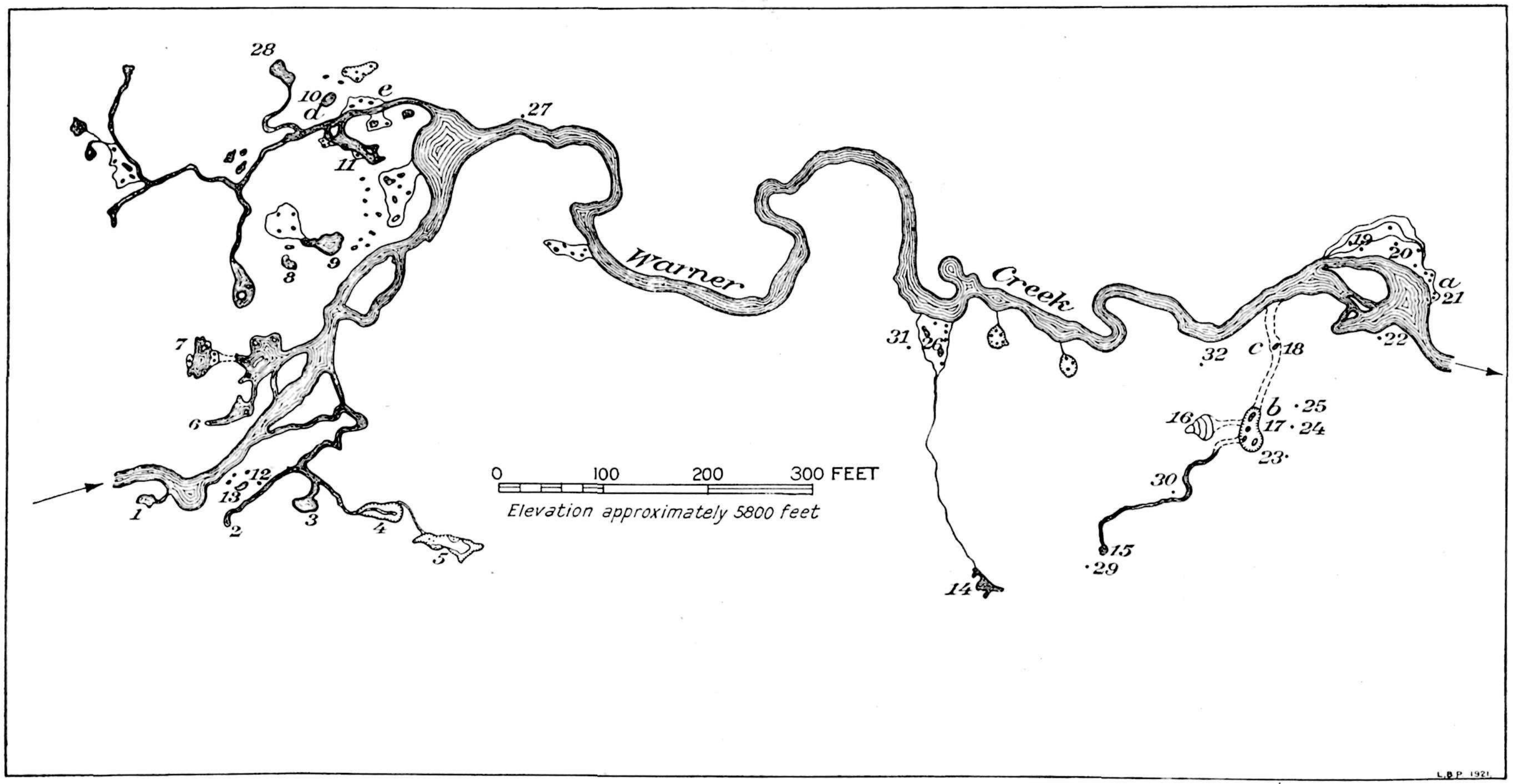
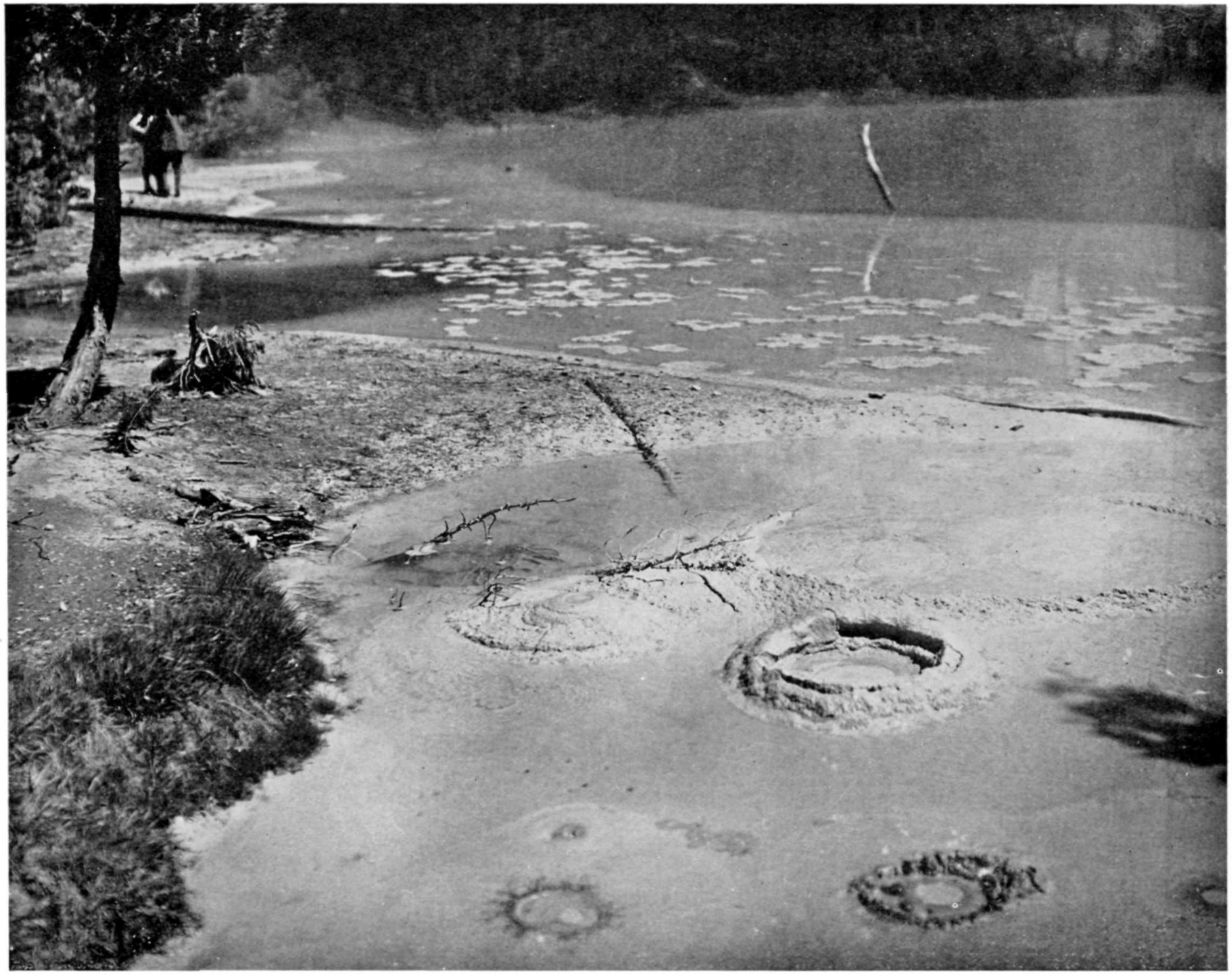


Fig. 47.—Sketch Map of "Devil's Kitchen" area, six miles southeast of Lassen Peak. Numbered and lettered springs referred to in the text.



May 19, 1916. Mud pots on the shore of the Boiling Lake (high water). Photo Day.

PLATE 9

cedars, etc., are distributed over the area wherever conditions are favorable, and north of the creek beyond a barren border strip the ground is forested. Thermal activity reaches its greatest intensity at the two ends of the area, especially the eastern, where there are several strongly spouting springs and well-marked fumaroles (figs. 48 and 73). The temperatures are no higher than at the Boiling Lake, but the thermal activity as measured by the volume of hot water is considerably greater.

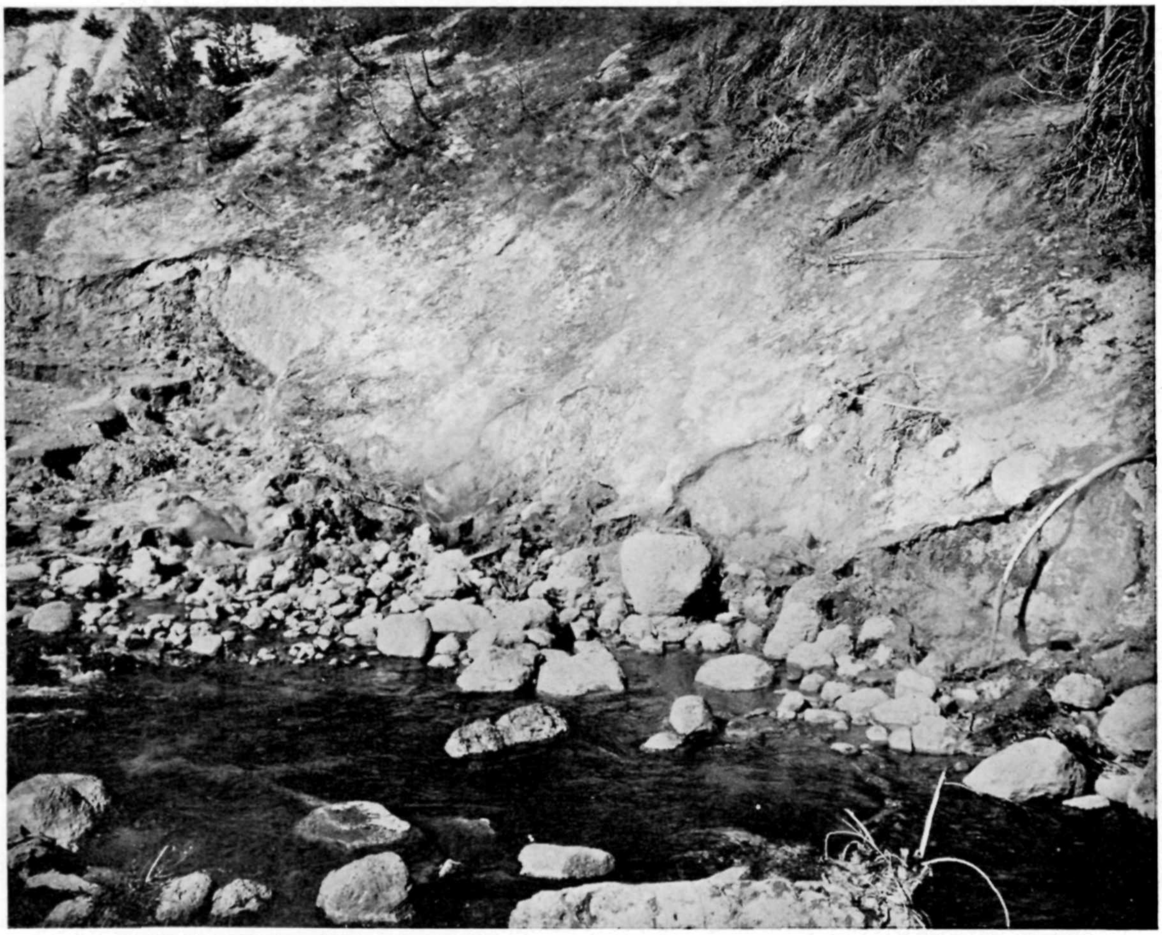


Fig. 48.—July 21, 1915. Four steaming springs at the foot of a high bank, east end of Devil's Kitchen. Warner Creek in the foreground. Photo Day.

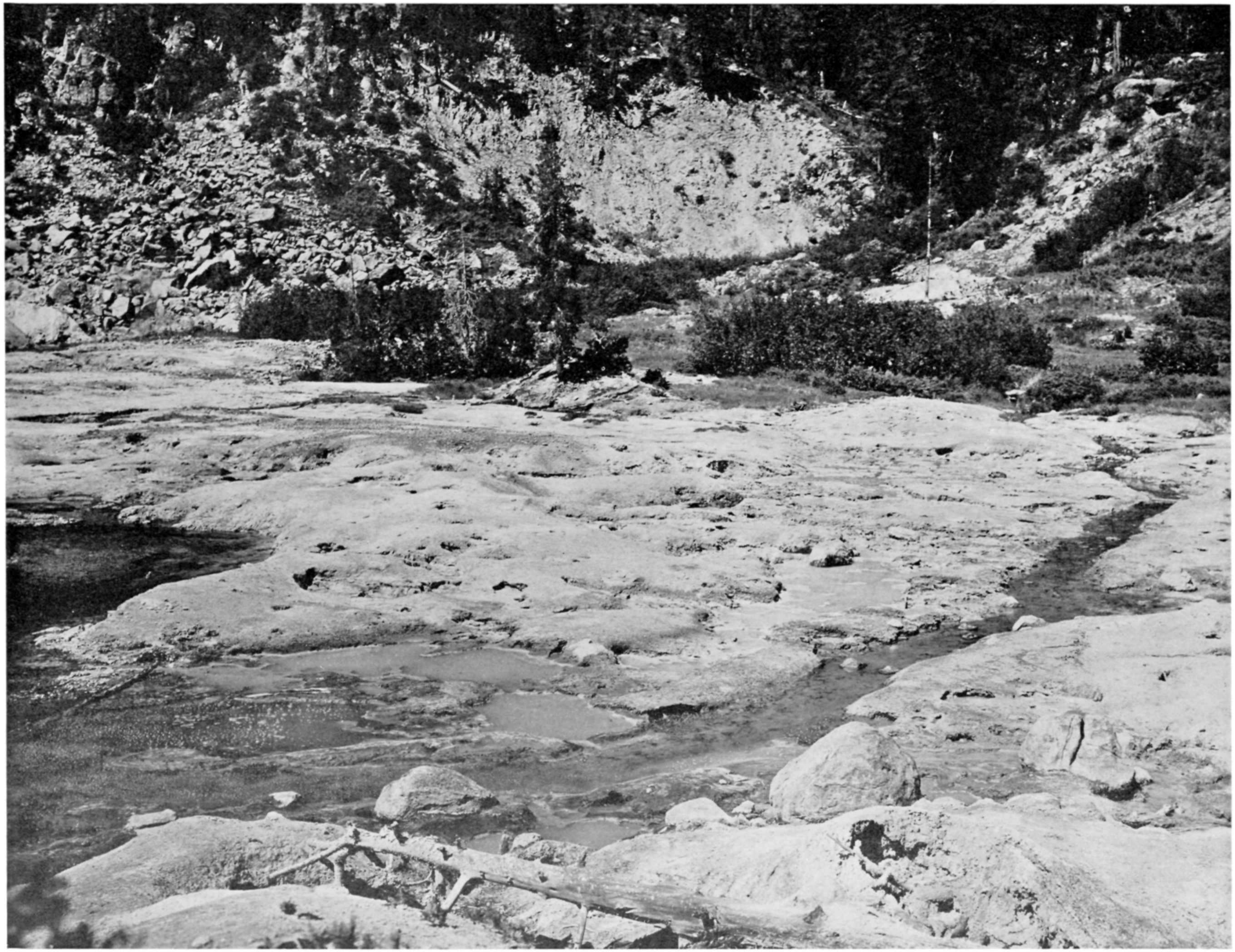
In outward aspects there are other differences between the two areas. A number of pools in the upper end of the Devil's Kitchen are colored yellow with precipitated sulphur, while free sulphur is hardly noticeable at the Boiling Lake. There are also pools in the Devil's Kitchen covered by a dark scum which has proved to be pyrite. In the flats near Warner Creek the ground has been reduced by the action of the hot waters to a fine, hot, sticky mud which dries out and becomes baked into a thin crust, through which one may easily break with serious results (Plate 10).

Bumpass Hell.

Bumpass Hell, 2 miles due south of Lassen Peak, is a crater-shaped basin 500 by 1,400 feet in area, lying high up among the mountains (elevation about 8,000 feet) and almost absolutely devoid of vegetation (figs. 49, 55, Plate 11). Quite the most picturesque of any of the hot-spring areas, its barren ground, sulphur cauldrons, boiling fountains, and disagreeable odors form a striking contrast to the wooded slopes by which the traveler approaches it and the magnificent mountain scenery visible from the rim of the basin. Thermal action here, if not more intense than in the other areas, has been at least decidedly concentrated. Rock decom-

Fig. 49.—View of Bumpass Hell (looking west) taken in 1891. Activity greater than at the present time. Photo E. R. Drew.

position at the surface is thorough. It not only covers the ground of the entire basin, but extends to adjacent peaks and slopes. Thus the long, steep slope, which is traversed by the little stream forming the outlet of the basin, has been similarly decomposed for a distance of several hundred yards and many small fumaroles and springs of high temperature are still active there. The surface of the slope which rises to the southeast of Bumpass Hell, the steepness of which is indicated on the map (fig. 50), has also been similarly transformed. A glance at the map shows that the eastern portion of the floor of the basin is quite irregular, rising in barren mounds among the pools (fig. 55). The ground of Bumpass Hell, more especially the western part, is undermined, sounds hollow to the tread, and is easily broken through. One of the most conspicuous features of this area is the large size and the comparatively small number of the pools. Another characteristic is the prevalence of free sulphur, which occurs as a precipitate in some of the pools (figs. 52, 61, 62), and which, in the form of needles, lines many small fumaroles on the western side. Mud pots are found in considerable number, but not so many as in the Devil's Kitchen. One of them on the north side (No. 17, fig. 50; fig. 77) is conspicuous for its size, about 20 feet in diameter.



July 21, 1915. East end of the Devil's Kitchen showing disintegration of the ground by thermal action. Photo Day.

PLATE 10

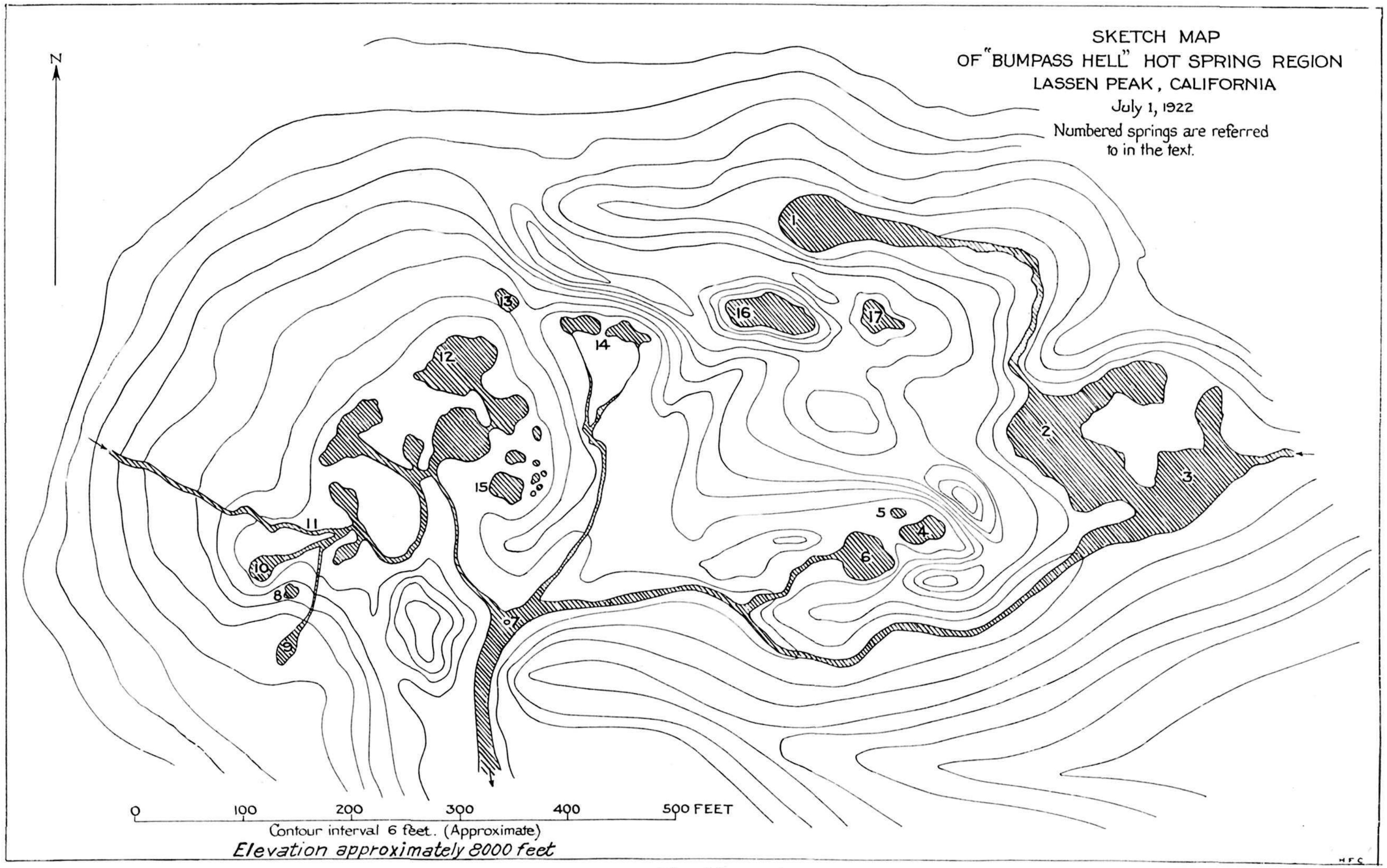

SKETCH MAP
OF "BUMPASS HELL" HOT SPRING REGION
LASSEN PEAK, CALIFORNIA
July 1, 1922
Numbered springs are referred to in the text.
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
0
100
200
300
400
500 FEET
Contour interval 6 feet. (Approximate)
Elevation approximately 8000 feet

Fig. 50.

Temperatures at Bumpass Hell usually approach the temperature of boiling water for that elevation, 91° to 92°, but one vigorous roaring fumarole (No. 8, fig. 50) showed in 1916 a maximum temperature of 117.5° C., and in 1923 was still considerably above the temperature of boiling water.

Rising above the northeastern rim of the basin is a lava flow that forms a considerable ridge which can be followed by the eye for some distance as one approaches Bumpass Hell by the usual trail along King's Creek.

Fig. 51.—July 10, 1915. Large shallow pool, bright brown color, considerable gas evolution (center), pyrite scum (right). Photo Day.

SUPAN'S SPRINGS.

In the nearly straight line from Boiling Lake, Devil's Kitchen, and Bumpass Hell is another small hot-spring area in Mill Creek Valley, known locally as Supan's Springs. It lies nearly 3 miles to the west of Bumpass Hell and about 4 miles southwest of Lassen Peak. The surrounding topography suggests that it may represent a residual trace of the great crater basin which preceded Lassen Peak, of which Brokeoff Mountain is the most conspicuous remnant. In appearance Supan's Springs resemble most closely those of the Devil's Kitchen. They include small mud pots and a number of small springs, some turbid and some clear, as in

Plate 11—July 10, 1915. A portion of Bumpass Hell looking southwest. Photo Day.

PLATE 11

the case of the Devil's Kitchen, but the drainage basin is much smaller and the stream which flows through the valley is insignificant. This is perhaps partly due to the very steep grades, which carry away the water much more rapidly than in any of the basins heretofore described.

The temperatures are substantially identical with those found in Bumpass Hell, the maximum (91.6°) being equivalent to the boiling temperature of water corresponding to the elevation. The soil is much decomposed (fig. 53), the ac-

Fig. 52—July 10, 1915. Large sulphur cauldron (No. 4; fig. 50), Bumpass Hell. No outflow. Little gas. Photo Day.

cumulations of sulphates being greater in this valley than in any other part of the region. Formerly considerable deposits of pure sulphur existed here, but in so far as they were exposed to plain view they have been carried away in sporadic mining operations. There are no surface evidences of large deposits and presumably the region would not repay commercial exploration for sulphur.

Some 200 yards above this group of springs is a spring somewhat larger than any of the others, to which is sometimes given the name Upper Supan's Spring. The hillside is so steep at this point that the action of the spring has produced a slight embayment of the hillside so as partially to roof over the active basin. The basin itself is about 6 feet in diameter and contained no more than 4 or 5 inches of water in August 1923. This pool was slightly turbid, gray in color, and was boiling quite violently over the entire surface, which was probably caused entirely by the escape of steam through it. There was no indication of other gases and no samples were taken.

If one follows up the valley from Supan's Springs directly toward Lassen Peak one may notice an ancient basin in which are only 2 or 3 small springs, slightly sulphur-colored and in part surrounded by vegetation (fig. 54). These are probably the highest springs in the valley which feed Mill Creek, and so perhaps they might be called its source. The contours of the basin suggest one of the last centers of ancient activity, of which nothing more remains than these feeble hot springs. There is little of interest to note about this group of springs, save only that they are north of the line upon which all of the hot-spring regions thus far described are located. It is therefore natural to conclude that they are not con-

Fig. 53.—July 1923. Supan's Springs, lower group, showing the effects of thermal action. Photo Day.

nected with the major east-and-west fault of the region, but with a north and south fault leading to the extinct center of former volcanic activity. The volume of water in the springs themselves is negligibly small, the largest being no more than 2 or 3 feet in diameter and a few inches deep, the exact dimensions being partially concealed by small boulders and vegetation. It should be said, however, that the entire basin, even in August, was saturated with water, indicating that the drainage follows small seepages without being localized into springs.

Morgan's Springs.

Morgan's Springs were not visited during any of our expeditions to Lassen Peak. They lie several miles to the south of the major fault to which our studies were directed, and at a much lower level (on Mill Creek), thus indicating to us that they were perhaps not closely related to the sources of the volcanic activity which it was our chief interest to study. The following description, taken from Waring's[1] account of Morgan's Springs, is here quoted, in order to complete the account of the known hot springs of the region. They occupy a small meadow which forms the floor of a narrow valley where "about 25 springs and pools are scattered for a distance of 600 yards along Mill Creek." The meadow is a part of Morgan's ranch.

Most of the springs are quiet pools of small flow, less than 5 feet in diameter and relatively shallow. A number of them contain thick algous growths and several deposit native sulphur. Others rise in areas where hard deposits of siliceous and calcareous materials have formed. Three or four springs steam and sputter from vents on the banks of the creek. One of the northernmost of these springs seems to have a true geyser action for it issues in a shallow basin 3 feet in diameter in which water is said to come to a state of vigorous ebullition and then to subside about once a day. During a period of 41 hours the

Fig. 54.—July 1923. Mill Creek Hot Springs. Probably the last vestige of activity in the old Lassen Peak crater southeast of Brokeoff Mountain. Photo Day.

condition of this spring was noted five times as follows: At the beginning of the period in active ebullition, discharge about 15 gallons a minute, temperature above 93° C.; two hours later quiet, no overflow, temperature 86° C.; at 16 hours and at 25 hours later, in active ebullition, overflowing; at 41 hours quietly overflowing, about five gallons per minute.

Waring says that—

The siliceous deposit at Morgan's springs is thought to be the largest spring deposit of this material in the state. . . . The slopes on each side of the meadow are covered with pyroxene andesite of Miocene or Pliocene age, but a cemented conglomerate is exposed along the creek in the meadow where the springs rise. The cementing material is siliceous and has probably been deposited by the hot water.

Some of the above features obviously differ considerably from any that have been observed in the other spring areas. The waters also, so far as they have been

[1] Springs of California, U. S. Geol. Survey, Water Supply Paper 338, p. 138, 1915.

examined, are exceptional in containing a preponderant amount of chlorides and in their high concentration (p. 110). Waring suggests that the chlorine may be derived from the sediments of the Chico formation, outcrops of which were discovered by Diller 20 miles to the west and southwest. The highest recorded temperature which has been observed in Morgan's Springs is 95.6° (Diller). This indicates that the area is lower than any of the other hot-spring basins described in this book.

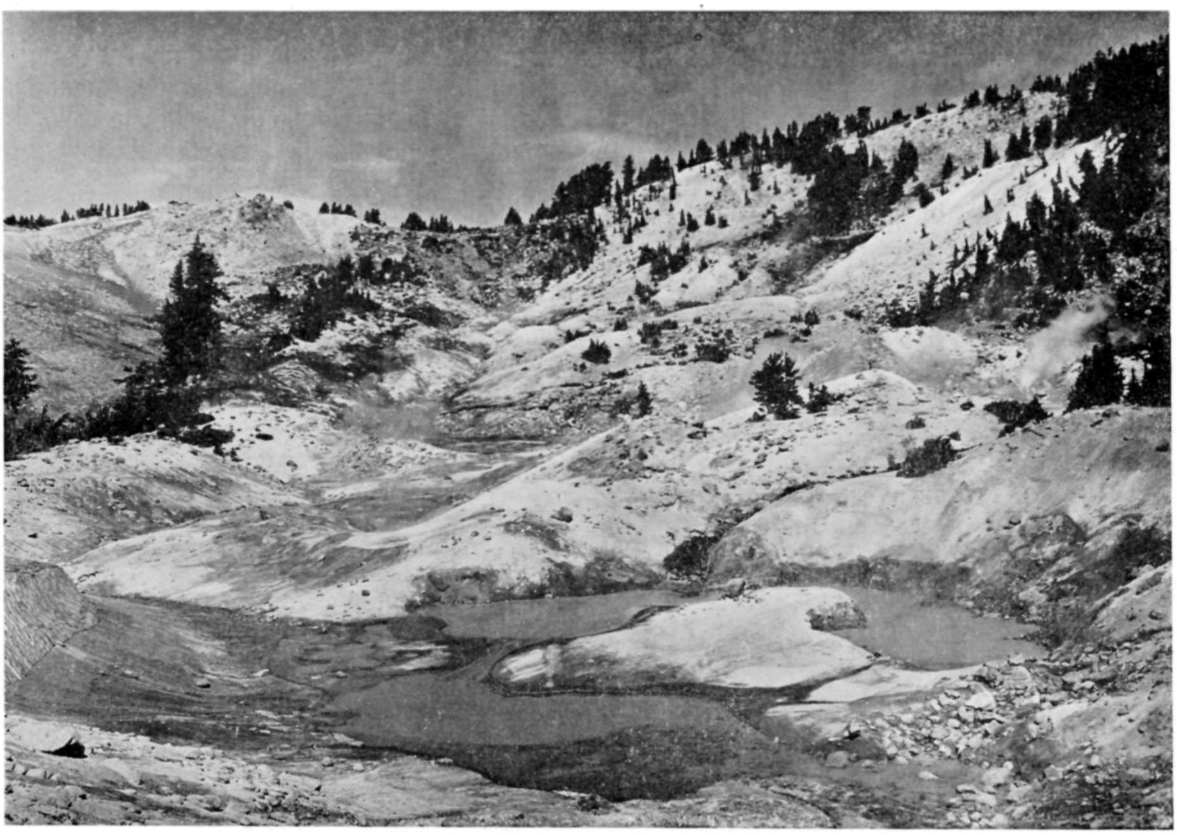


Fig. 55.—July 10, 1915. General view of Bumpass Hell hot springs, looking west. (Cf. Fig. 49). Photo Day.

Types of Springs.

The hot springs of the Lassen region are chiefly of the solfataric type and are, so far as one may depend on descriptions, duplicated in many parts of the world. They resemble closely the acid springs in the Norris Basin of the Yellowstone Park. At first sight the visitor is impressed by the diversity in appearance which the springs present. In size, amount, and color of sediment, and in physical activity the differences are in fact very great. Individual spring pools range in size all the way from a diameter of 50 feet or more down to insignificant dimensions. Though they have never been gauged, it is obvious to an observer that the discharge, even from the largest springs, is quite small, and some have no visible outlet at all.

One of the best-defined types and perhaps the most striking is the spouting or pulsating spring. The pool may vary greatly in size, but the spring is characterized by one or more jets of water which spurt spasmodically and, with considerable regularity at intervals of a second or so, to a height varying from a few inches to 5 or 10 feet. The volume of the fountain also varies considerably. Sometimes it is dome-shaped, but usually it is like a jet from a nozzle. The height to which the same fountain may play differs greatly at different times and it may even cease altogether (Plate 7). But such springs are not to be regarded as geysers of irregular period, as they are not characterized by eruptions which appear and disappear suddenly. In fact, there are no geysers in the Lassen region.[1] The spouting in these springs naturally keeps the water stirred up and they are usually muddy, though an outlet of sufficient size helps to keep them clear of sediment.

Fig. 56.—July 10, 1915. Large mud pot in Bumpass Hell. Inactive since 1915. Photo Day.

MUD POTS AND MUD VOLCANOES.

The essential characteristics of a mud pot seem to be a very limited water supply, a relatively large supply of heat, and the lack of any visible outlet (figs. 56, 57, 58 and Plate 9). The mud it contains is generally thick and pasty, though it varies considerably; in fact, all degrees of consistency down to slightly turbid

[1] With the possible exception of the single spring in the Morgan group described above.

water, are found in the various springs. Some of the mud in the mud pots is unquestionably a product of chemical action on the spot, but in some places a part of the mud is probably transported. Thus all about the Boiling Lake occur mud pots issuing from the sediment which is probably transported to the shores at high

Fig. 57.—June, 1922. Mud pot in the Devil's Kitchen (No. 10, Fig. 47). Bursting gas bubble in the foreground. Very thick mud. Photo Day.

Fig. 58.—July, 1923. Boiling Lake, Mud pot active below the lake level (foreground), others drowned. Very low water. Photo Day.

water. Some of this was probably formed by thermal action at various points on the lake bottom, and some has been carried into the lake through the outlets of other hot springs.

A *mud volcano* differs from a mud pot much as a spouting spring differs from a quiet hot spring. When the water of a mud pot dries out sufficiently the escaping steam throws out clods of mud, which in falling build up a cone inclosing a crater just as spouting lava does. The pressure of the steam must obviously be equal to the work required. Thus a very large and rather active mud pot in the Devil's Kitchen (No. 10, fig. 47; fig. 57) has never within the time of our observation built up walls of any considerable height because, though the mud is constantly spluttering, the pot is unusually deep and wide, while the steam pressure is not proportionately great. The result is that most of the mud drops back into the pot and comparatively little falls on the rim (fig. 58). In consequence of a wet season, a mud volcano sometimes slumps in, forming a mud pot again, for mud pots have been found at points where in drier times mud volcanoes had been observed. In 1916 a number of mud volcanoes were to be seen both at the Boiling Lake and the Devil's Kitchen; in June 1922 all had disappeared and their sites were occupied by mud pots. In August 1923 all these and many other smaller ones had once more built up mud cones.

These three forms, spouting springs, mud pots, and mud volcanoes, are the most distinctive types of hot springs which we have to consider. The differences in the color of the spring sediments are also of a striking character, but when we come to the study of the chemical nature of the sediments and the physical character of the thermal activity we shall find that all this manifold diversity is but the manifestation of the same process due to the same fundamental forces, modified here and there by local influences most of which are of secondary importance.

CHAPTER II.

FIELD AND LABORATORY WORK.

WORK IN THE FIELD.

The field work included detailed observations of the springs and their relationships, the preparation of maps of the three most important spring areas, measurements of temperature in the springs and of ground temperatures in some areas, approximate measurements of heat carried away from one of the basins by outflowing water, and the collection of waters, salts, sediments, and gases for laboratory study.

Maps.

Local outline maps (1 inch to 100 feet) of Lake Tartarus (fig. 59), the Devil's Kitchen (fig. 47), and Bumpass Hell (fig. 50), were made for the purpose of indicating the location and the relation of the springs studied and providing possible identification which might permit of further study. It must be recognized, of course, that these springs are situated in a region of very active and very variable surface drainage, partly due to the heavy accumulation of winter snow, and also one in which the temperature is high enough to bring about active metamorphic changes, so that shifting in the observed locations of springs and occasionally complete loss of identity may be expected.

Our observations in 1922, six years after two of the maps were prepared, proved them to be of great help in carrying out the investigation. Essential changes in that time had been comparatively few, but some there were which were incontestable and of special interest. The areas mapped were roughly surveyed with a compass and all distances were measured. The maps are therefore to scale. Letters on the maps refer to points observed by J. S. Diller in 1921, the numbers to points studied by the authors.

Temperature Measurements.

Temperature measurements were made with a maximum mercurial thermometer protected by a brass cage. As there was no reason for high accuracy it is unnecessary to give details. The results are recorded in Table 1.

The highest temperatures in each area are close to the temperature of boiling water for the elevation. They are usually a little lower—a fact which presumably means that the influence of escaping gases on the temperature is greater than that of dissolved salts. The temperature fluctuations in some springs are much too great to be accounted for by variations in the barometer. It will be noted also that there are some springs and pools with a temperature much below that of boiling water and rarely a cold pool. Fumarole temperatures, with a single exception (Bumpass Hell, No. 8), were practically the same as the maximum temperatures found in the springs.

TABLE I.—TEMPERATURES IN THE HOT SPRINGS OF THE LASSEN NATIONAL PARK.[1]

THE GEYSER.

[Elevation about 5,700 feet. Average boiling-point of pure water for this elevation about 94.0° C.]

Locality.	Date.	Temp.
		° C.
North pool	May 17, 1916	32.8
Do	July 11, 1915	94.3
Do	June 25, 1922	92
Do. (boiling steadily 3 to 5 feet high)	Aug. 9, 1923	95.5
Middle pool	May 17, 1916	37.2
Southwest pool	Do	23.1
Do	June 25, 1922	93
Do. (spouting occasionally 10 feet)	Aug. 9, 1923	93.7
Small fumaroles west side of outflow	May 17, 1916	89.3
Do	Do	89.7
Cold inflow from north:		
At top of ravine	June 25, 1922	8
Near bottom of ravine	Do	44
Both dry	Aug. 9, 1923	....

THE BOILING LAKE OR LAKE TARTARUS.

[Elevation 5,750 feet. Average boiling-point of pure water for this elevation about 94.0° C.]

Locality.	Date.	Temp.
		° C.
Outlet of lake; water turbid	May 15, 1916	49
Do	May 19, 1916	49
Do	May 26, 1916	50.8
Do	June 8, 1916	49.0
Do	June 15, 1922	46.0
Do	July 9, 1922	52.5
Do. dry. (Lake temperature near outlet)	Aug. 9, 1923	51.8
Muddy pool heated by spouting springs:		
No. 1, by fallen tree	May 26, 1916	92
Do	June 8, 1916	90.5
Do	June 30, 1922	93.5
Do	June 17, 1922	92
Do	July 9, 1922	93.8
Do. (much enlarged)	Aug. 9, 1923	93.3
No. 1, south end	June 17, 1922	93
Do	June 30, 1922	94.5
Do	July 9, 1922	94.5
No. 2. Very small	May 15, 1916	91
Do	May 19, 1916	91.7
Do	June 8, 1916	93
No. 2 (?)	June 19, 1922	93
Do	July 9, 1922	94.2
Do. (very low; 3 openings)	Aug. 9, 1923	93.4
No. 3. Very small	June 8, 1916	92.3
Do	May 19, 1916	89.7
No. 3 (?)	July 9, 1922	88
Do. banks caved in	Aug. 9, 1923	90.1
No. 4. Spouting spring	May 15, 1916	93.2
Do	May 19, 1916	87
Do	June 16, 1922	93.3
Do. steam only; no water	Aug. 9, 1923	....
No. 5. Mud springs	May 15, 1916	88
Do	May 19, 1916	80
Do	June 8, 1916	89.2
No. 5. Different orifices	June 16, 1922	82.5 to 91
Do	June 30, 1922	85.5 to 94
Do. (muddy)	Aug. 9, 1923	90.0
No. 6. Mud volcano	May 19, 1916	82
Do	June 16, 1922	80.5 to 90
Do	June 19, 1922	87.7, 91.5
Do	July 9, 1922	93.5
Do. (mud clods, banana size, thrown 10 feet)	Aug. 9, 1923	86.3
Two mud pots west of No. 6	June 16, 1922	70 and 92
Do. (active 2 feet below lake level)	Aug. 9, 1923	92.9
No. 7. Mud volcano	May 19, 1916	93
Do	May 26, 1916	90
Do	June 8, 1916	93.9
Do	June 15, 1922	90
Do	June 30, 1922	93
Do	July 9, 1922	92
Do	Aug. 9, 1923	93.3
No. 8. Lake border	June 17, 1922	93
Do	July 9, 1922	93.2
Do. (many steam openings; little water)	Aug. 9, 1923	89.9
No. 8. On promontory above lake	June 17, 1922	92.7 to 94
Do	July 9, 1922	94
No. 9. Mud pot in lake	June 30, 1922	93
Do	July 9, 1922	93
Do. (dry; steam only)	Aug. 9, 1923	....
No. 10	June 16, 1922	89 to 94
Do	June 30, 1922	92 max.
Do. only 2 inches deep; scattering bubbles	Aug. 9, 1923	90.8
No. 11	June 16, 1922	83
Do. 3 steam openings; no water	Aug. 9, 1923	94.8

[1] The variation in the observed barometric pressure at a nearby station of the U. S. Weather Bureau was 12.7 mm. during the period of our first visit (1916). This would cause a variation of about 0.6° C. in the boiling-point of water.

TABLE I.—*Continued.*

DRAKE'S SPRINGS.

[Elevation about 5,500 feet. Average boiling-point of pure water for this elevation about 94.0° C.]

Locality.	Date.	Temp.	Locality.	Date.	Temp.
		° *C.*			° *C.*
Few steps NE. of bath house	July 14,1922	52	Slope south of Warner Creek:—*Continued.*		
Slope south of Warner Creek:			Between last two, but nearer bath-		
East end	July 5,1915	51.5	house	July 14, 1922	43.0
Do	July 9,1915	53	Soda-spring, effervescent, 0.75 mile west		
Do	June 6,1916	57.6	of Drake's Springs in meadow	May 16,1916	26
Do	July 14,1922	62	Do	June 6,1916	26.8
West end	Do	43.5	Do	July 14,1922	29
Middle	Do	50.5			

THE DEVIL'S KITCHEN.

[Elevation about 5,800 feet. Average boiling-point of pure water for this elevation about 94.0° C.]

Locality.	Date.	Temp.	Locality.	Date.	Temp.
		° *C.*			° *C.*
No. 1	July 5,1915	94	No. 12	June 3,1916	81
Do	May 20,1916	91	Do.; feeble activity; invaded by		
Do	June 3,1916	78	stream	Aug. 17,1923	72.2
Do	June 20,1922	47 and 56.5	No. 13	May 25,1916	92
Do. two different points	Aug. 17,1923	92.9, 93.8	Do.; white mud, 3 inches below		
Hot rivulet flowing into No. 1	June 20,1922	83	normal	June 20,1922	91.5
No. 2	May 20,1916	40	Do	Aug. 17,1923	91.8
Do	Aug. 17,1923	93.3	No. 14 pool	June 8,1916	79
No. 3	July 5,1915	91	Do	May 20,1916	80
Do	May 20,1916	91	Do	June 21,1922	43.5
Do	June 3,1916	92	Do	Aug. 15,1923	58.8
Do	June 8,1916	90	Do.; separate pool	June 21,1922	78
Do	June 20,1922	82	Do.; mud-pot on margin	Do	91
Do. larger and more violent than			Do	Do	92.2
formerly	Aug. 17,1923	91	Do	Aug. 15,1923	93.2
No. 4. Hot stream depositing pyrite	May 20,1916	80.5	No. 15	May 20,1916	88
Do	June 20,1922	83	Do	June 3,1916	92.6
Do. no pyrite visible	Aug. 17,1923	88.2	Do	June 8,1916	93.1
No. 5	May 25,1916	82	Site of 15; steam hole	June 21,1922	94
Do	June 8,1916	82	Do.; insignificant	Aug. 15,1923	....
Do	June 20,1922	84	No. 16	June 3,1916	92
Do. (1) slightly turbid; boiling;	Aug. 17,1923	88.4	Do	June 8,1916	92
(2) sulphur-yellow pool	Do.	92.8	Do.; stream just above terrace;		
Hot turbid spring just above No. 5	June 20,1922	92.5	source under rock	Aug. 15,1923	75.1
No. 6	July 5,1915	91	No. 17	May 20,1916	89.8
Do. (?)	June 20,1922	71	No. 18	Do	90
No. 7	July 5,1915	85	Do	June 8,1916	93
Do	June 1,1916	83	No. 18; new spring very close to old site	June 21,1922	85
Do. west border	June 20,1922	65.5	No. 19	May 20,1916	83
Do. slightly turbid (some pyrite)	Aug. 17,1923	82.9	Do	June 8,1916	90
Pool 5 feet west of No. 7	June 20,1922	80	Do.; near old site	June 20,1922	92.5
No. 8	June 1,1916	62	Do.; very active	Aug. 15,1923	92
Do (?)	June 20,1922	88.5	No. 20	May 20,1916	92.3
Do.; gray pool; water low	Aug. 17,1923	79.1	Do.; near old site	June 21,1922	94
No. 9	June 20,1922	85 and 88	Do.; activity insignificant; terraces		
Do.; east end	June 28,1922	86	dry	Aug. 15,1923	92.9
Do.; activity about normal	Aug. 17,1923	87	No. 21	May 20,1916	91
No. 10. Largest mud pot	July 5,1915	94	Do.; near old site	June 21,1922	84
Do	June 8,1916	94	Do.; (nearly dry)	Aug. 15,1923	90.4
Do	June 1,1916	93	No. 22	June 21,1922	93
Do	June 20,1922	93	Do.; very active	Aug. 15,1923	92.8
Do.; low	Aug. 17,1923	92.6	No. 23	June 21,1922	93
No. 11. Sulphur-yellow pool	June 1,1916	90	Do.; very active	Aug. 15,1923	93
Do	Aug. 17,1923	83.8			

TABLE I.—*Continued.*

THE DEVIL'S KITCHEN—*Continued.*

Locality.	Date.	Temp.	Locality.	Date.	Temp.
		° *C.*			° *C.*
No. 24	June 21,1922	93	No. 28	June 28,1922	82
Do.; very active	Aug. 15,1923	92.5			
No. 25	June 21,1922	92	Do.; thick black scum; little bubbling	Aug. 17,1923	56
Do.; very active	Aug. 15,1923	93	No. 29. Big fumarole	June 20,1922	94
Steam hole near No. 24 and No. 25	June 21,1922	94	Do.; dry, no activity	Aug. 15,1923	....
No. 26	Do	79, 92.5, 93.5	No. 30. Dry steam fumarole (noisy)	Do	94.1
			No. 31. Active	Do	92.1
Do	Aug. 15,1923	94			
No. 27	June 20,1922	92.5	No. 32. New pool (milky; pyrite scum; no outlet)	Do	77
East two of three mud pots	Do	91.5, 92.5			

BUMPASS HELL.

[Elevation about 8,000 feet. Average boiling-point of pure water for this elevation about 91.5° C.]

Locality.	Date.	Temp.	Locality.	Date.	Temp.
		° *C.*			° *C.*
No. 1	July 3,1922	12	No. 11 stream. *Continued.*		
No. 2, NW. corner	Do	55.5	Do.; east of No. 6, 4 feet away	Aug. 10,1923	55.1
No. 3, east end	Do	59	No. 12 spring on border of pool	July 3,1922	50
No. 4; sulphur pool; opaque	June 5,1916	85.5	Do	Do	87.5
Do	July 3,1922	84 to 85	Do	Do	90
Do.; no outflow; 18 inches low	Aug. 11,1923	84.4	Do.; water very low	Aug. 10,1923	89.3
Fumarole 15 feet NW. of No. 4	July 3,1922	92			
No. 6	Do	34.6	No. 12. New fumarole; inaccessible; very noisy	Do	....
Do.; pool low; no outflow	Aug. 11,1923	55	No. 13. Large fumarole	July 3,1922	91
Do.; near hot south bank	Do	86.3			
Black mud-pot NE. of 6	Do	89.8	Do.; very noisy; little water; inaccessible	Aug. 10,1923	....
No. 7, at outlet	July 3,1922	42.5	No. 14	June 5,1916	91
Do.; volume small	Aug. 11,1923	41.2	Do.; western pool	July 3,1922	91.5
Do.; eastern branch	July 3,1922	47.5	Do.; active steam and water spray	Aug. 11,1923	93.1[1]
Do.; western branch	Do	34.5	Do.; eastern pool	July 3,1922	90
No. 8, fumarole	June 5,1916	117.5 max.[1]			
Do	July 3,1922	86	Do. doubled in breadth N–S since 1922	Aug. 11,1923	89 (S. side)
Do.; (temp. above range of thermometer)	Aug. 10,1923	110.+[1]			
No. 9	July 3,1922	88.5	Do. eastern pool (continuous steam and water spray 3 to 8 feet)	Do	94.1[1]
Do	Aug. 10,1923	84.6	No. 15	June 5,1916	85
No. 10	July 3,1922	63	Do	July 3,1922	57
Do.; (more active; temp. in 5 places)	Aug. 10,1923	89.4, 89.8, 92, 92.5[1], 92.2	Do	Aug. 10,1923	60
			2 mud pots just south of No. 15	July 3,1922	91.5
			Do	Do	92.5[1]
			Mud pots, now become turbid springs (1)	Aug. 10,1923	90
			Do.; (2)	Do	85.5
No. 11, stream	July 3,1922	19	No. 16. More water than in 1922	Aug. 11,1923	91
Do.; east of No. 6	Aug. 10,1923	88.5	No. 17. Black muddy pool	Do	89.8

MILL CREEK SPRINGS.

[2 miles south of Lassen Peak just inside the oldest crater rim east of Brokeoff Mountain. Elevation 7,950 feet. Average boiling-point of pure water for this elevation about 91.5° C.]

Locality.	Date.	Temp.	Locality.	Date.	Temp.
		° *C.*			° *C.*
2 boiling springs; sulphur precipitate	July 16,1915	68	Big fumarole, water in bottom: *Continued.*		
Strongly boiling spring; dark precipitate	Do	90.2	Do	Aug. 11,1923	91.1
Do.; no precipitation	Aug. 11,1923	90.8			
Big fumarole, water in bottom:			Dry fumarole; sulphur deposits and probably ferric salts	July 16,1915	88.6
In steam	July 16,1915	89.2			
In water	July 16,1915	90.8			

[1] Note that these temperatures are above the boiling point of water at this elevation.

TABLE 1.—*Continued.*

SUPAN'S SPRINGS.

Locality.	Date.	Temp.	Locality.	Date	Temp
		° C.			° C.
LOWER SPRINGS:			UPPER SPRING:		
No. 1. Shallow pool bubbling rapidly....	Aug. 11, 1923	91.6	Fountain 5 feet high.............	Aug. 11, 1923	85.0
No. 2. Small turbid spring............	.....Do......	87.4	Pool below fountain..............	.....Do......	83.5
No. 3. Do.; brown sediment...........	.....Do......	86.2			
No. 4. Large mud pot................	.....Do......	63.8			
No. 5. Mud volcano in canyon; bright blue, terraced...............	.....Do......	91.2			

OTHER FIELD TESTS.

Tests with lead-acetate paper showed that while hydrogen sulphide was widely distributed, only very small quantities were escaping from the springs. The papers were usually browned very slowly. These tests also indicated that the gases do not rise uniformly from the whole spring surface, but chiefly if not entirely from certain points. In making this test, by the way, the paper should not be dipped into the water, but held just above it; otherwise, so minute is the amount of gas actually dissolved in the water that the reagent may be washed away before any effect is

TABLE 2.—HOT SPRINGS OF LASSEN PEAK REGION.

[Unpublished observations by J. S. Diller, 1921. Springs may be identified by the letters, figs. 59 and 47.]

No.	Description.	Date.	Temp.
	Western belt:	1921	° C.
1	Morgans. Biggest; 2 miles north of stage road. Vigorously boiling...............	June 19	95.6
2	Do...	June 22	95.6
3	Morgans. Biggest; old steam bath in meadow by creek; no hot water seen.........	June 19	91.7
4	Morgans. Big Mill Creek, 50 yards NW. of old steam bath......................	...Do.....	89.4
5	Supan's Big Boiler, 1 mile NW. of Supan's cabin; vigorously boiling; elevation 7,675 feet, not accessible at that time....................................	June 21	....
6	Supan's Big Boiler, as No. 5, but water low; all steam.........................	Aug. 14	68.9
7	Bumpass Hell, west side. Steam only; hissing.................................	Aug. 13	88.9
8	Bumpass Hell, west side. Boiling mud pot by No. 7............................	...Do.....	88.3
	Eastern belt:		
9	Geyser, boiling vigorously...	July 10	93.9
10	Tartarus Lake, 100 yards west of inflow; slow boiling..........................	June 9	81.1
11	Tartarus Lake; boiling mud pool by inlet (forenoon)...........................	June 10	91.7
12	Tartarus Lake; boiling mud pool by inlet (afternoon)...........................	June 11	90.6
13	Taratrus Lake; at slide 40 yards east of inlet; hissing steam.....................	June 13	88.9
14	Tartarus Lake; west side near mud cone..	June 14	47.8
15	Tartarus Lake; outlet..	...Do.....	47.2
16	Do...	June 28	50.6
17	Drake's Springs. East spring of line south of creek..............................	June 13	51.7
18	Do...	June 14	51.7
19	Do...	July 10	58.9
20	Drake's Springs. West spring of line south of creek..............................	June 14	47.8
21	Do...	....Do....	43.9
22	Do...	July 10	44.4
23	Devil's Kitchen, east end; sputtering spring, left edge of creek....................	June 11	93.3
24	Devil's Kitchen, east end; hissing spring, steam..................................	...Do.....	92.8
25	Devil's Kitchen; east end; middle; vigorously boiling.............................	...Do.....	93.3
26	Devil's Kitchen; near head, 150 yards northeast of falls, near-by mud pot...........	...Do.....	93.3
27	Devil's Kitchen; near head; big mud pot..	June 12	93.9
28	Devil's Kitchen; near head; clear pool 50 yards; nearer falls; vigorously boiling......	June 28	81.7

noticeable. Certain gases issuing from fumaroles and ground cracks were found by the same test to contain considerably more hydrogen sulphide. Tests with sensitive litmus paper proved that most of the waters were slightly acid or neutral; only a very few were slightly alkaline.

Tests At Camp.

After the water samples had cooled in the collecting bottles they were filtered before sealing[1] for shipment. To avoid oxidation the filtering was done as rapidly as possible in large funnels covered wich glass plates, or if the samples were quite muddy they were left to settle, siphoned off, and afterwards filtered. The water from mud pots (or mud volcanoes) was obtained by squeezing the mud in "muslin" bags, in which most of the sediment was retained while the thinner product squeezed out was filtered again the usual way. Half a dozen bottles of mud were sometimes required for a single bottle of water. For the washing of bottles and other vessels at camp the supply of water was fortunately remarkably pure.

In order to obtain as nearly as possible the composition of the waters as they issued from the ground, ferrous iron and free acid were determined at the camp.

DETERMINATON OF FERROUS IRON.

For the ferrous-iron determination a filtered portion of water was acidified with sulphuric acid and titrated with standard permanganate. An exact determination would of course have demanded a removal of any hydrogen sulphide before the titration. Fortunately for our primitive facilities, the amount of this gas retained in the spring waters was rarely enough to impart to them the slightest odor, and a comparison of the amount of ferrous iron with the total iron found later in the laboratory at Washington, proved that the total iron was nearly always equal to the ferrous iron or in slight excess over it; in other words, that the iron was all, or nearly all, ferrous—a conclusion in excellent accord with the facts of field observation. In the few cases where the ferrous iron found was slightly greater than the total iron the reason is evident, and it is justifiable to regard the iron as all ferrous (see page 113).

DETERMINATION OF FREE ACID.

Another change in composition of the waters, which might naturally occur after collection and before they came to be analyzed, was an increase in free acid due to hydrolysis of ferric salts which might result from oxidation. The free acid was therefore determined at camp. For this purpose the waters were titrated with dilute sodium carbonate with the use of methyl orange as indicator. The method would have been satisfactory had not the standard alkali taken been unsuitably dilute. On this account the errors are greater than they would have been with sufficient laboratory facilities at hand.

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[1] An excellent method of sealing samples of this character is to melt Khotinsky cement around the carefully dried stopper of the bottle. An alcohol blow-torch is best adapted to field work.

WORK IN THE LABORATORY.

The Waters.

A few remarks will be necessary in regard to water analyses. In some cases when the bottle was opened a precipitate of ferric oxide was found clinging to the walls. In this event the total volume of the water was measured and the iron as well as SO_4 in the precipitate was determined, so that corrections might subsequently be applied. Since boric acid has been regarded by geologists in the past as of some critical importance in judging of the origin of spring waters, the determinations of this constituent were made with unusual care. Chapin's method [1] was used. A measured volume of water was first evaporated to dryness on the steam bath with a slight excess of sodium hydroxide. The residue was transferred with 15 c. c. water in successive portions to the distilling flask and acidified with hydrochloric acid. After a small excess of acid had been added, 15 grams of anhydrous calcium chloride were put in and the boric acid was distilled and titrated as Chapin recommends. A blank was then carefully made in a similar manner. It amounts under such conditions [2] to about 0.7 mg. B_2O_3. A very little boric acid appeared to be present in practically all the waters, though the quantities found in many cases were so small as to make this uncertain. A sample of lava from the region also gave 0.03 per cent B_2O_3 by the same analytical method.

Lithium was tested for in one sample from each of the three principal hot-spring groups. Only 100 c. c. water was taken. The mixed alkali chlorides, separated in the usual way, were tested spectroscopically. No lithium was observed.

The same waters all showed traces of *manganese* when tested colorimetrically with ammonium persulphate and silver nitrate.

The percentages of *carbon dioxide* given in the tables represent *total* carbon dioxide both free and combined. The amount of the *free* gas, however, was doubtless negligible in waters of this temperature range.[3]

Small quantities of the water samples, generally 100 c. c., sometimes 200 c. c., were taken for the analytical determinations. The inconvenience of transporting large samples practically precluded the use of larger portions. Errors were thus multiplied by 5 or generally by 10. So far as we can see, however, the results are accurate enough for all uses to which they are likely to be put. The results are stated in milligrams per liter, not reduced to parts per million.

PECULIARITIES IN THE COMPOSITION OF THE WATERS.

In composition all the hot-spring waters from the Lassen region (see table 3) which we have examined, though they vary considerably in concentration, namely, from 0.11 gram to 1.59 grams per liter, show striking similarities. They are without exception *sulphate waters almost entirely free from chlorides.* The sulphates are those of *the common rock bases, with the exception of alumina,* which, in four-fifths of the samples, varies from 0 to 0.2 mg. per 100 c. c., the amount used in analysis.

[1] Journ. Amer. Chem. Soc., 30, 1687, 1908.

[2] E. T. Allen and E. G. Zies, Journ. Amer. Ceram. Soc., 1, 763, 1918.

[3] At the time the analyses were made it was believed that practically all the carbon dioxide was in the form of *bicarbonate*. It is now known that *carbonate* is present in at least some of the alkaline waters.

In other words, four-fifths of the waters examined are virtually free from alumina. The more acid waters contain more alumina.

In considering the *condition of the iron* in the waters it will be noticed that the water from the Boiling Lake contains only *ferric* iron, while, with a single exception, (No. 23, table 3), the springs and similar pools contain *almost no ferric* iron. The volume of gases escaping from the lake appears to be relatively small, and their

TABLE 3.—COMPOSITION OF HOT-SPRING WATERS IN MILLIGRAMS PER LITER.

	Sample No.	Map No.	H	NH_4	K	Na	Ca	Mg	Fe″	Fe‴	Al	SO_4	Cl	SiO_2	CO_2	B_2O_3
BOILING LAKE.																
Water of the lake from near the foot[1]	1	.....	7.5	none	([2])	10	7	4.8	none	26	8	514	trace	84	.....	0.7
Water of the lake from the west side[1]	3	.....	6.7	.....	([2])	20	12	4.4	none	27	9.6	516	.....	106	.....	.....
Water of the lake from near the head[1]	2	.....	7.1	.....	([2])	10	9.3	4.5	none	27	14.0	516	.....	72	.....	.....
Vigorously boiling spring near head of lake. Waters collected May 19, 1916	13	4	2	9.7	6	22	44	18	18	none	1	258	trace	111	.....	.....
The same spring. Water collected, June 8	131	4	.....	.....	6	20	30	8	29	none	none	291	trace	123	.....	none
Black mud spring boiling vigorously.	128	1	none	19.3	7	31	54	33	197	none	2	775	trace	265	.....	0.7
Black mud spring	15	5	none	19.3	6	26	23	none	26	9	2	269	trace	202	.....	0.6
Mud volcano	125	7	0.57	none	1.8	5.5	14	8	104	4	2	322	1	68	.....	0.7
DEVIL'S KITCHEN.																
Mud volcano, largest in the basin	362	10	none	2.8	14	38	29	none	45	6	1.9	248	6	222	.....	1
Mud volcano, extremely active	331	13	trace	3.8	12	58	10	5	153	none	1.5	422	4.0	213	.....	none
Black mud spring	23	18	none	50.6	10	37	61	17	6	75[3]	none	527	trace	212	.....	.....
Vigorously boiling spring	21	21	acid[3]	8.8	9	22	16	5	36	none	2.5	244	trace	89	.....	1
Small spring, high level	37	15	.38	2.8	4	12	9	2	4	3	2	95	1.7	74	.....	1
Violently boiling spring, faintly alkaline	31	1	none	none	4	16	9	3	none	none	none	36	trace	45	.....	1
Violently boiling alkaline spring	29	3	none	.....	5	23	21	9	none	none	none	58	1.0	63	72	0.6
Small quiet spring, May 20, alkaline.	22	19	none	.....	11	55	24	3	none	none	none	95	none	217	97	2.0
Same as 22, collected June 8	221	19	none	.....	8	33	14	1	none	none	none	78	none	218	55	.....
Large pool fed by springs	30	5	7	2.6	9	43	38	14	30	none	10	617	trace	167	.....	1

[1] These samples of lake water were collected by Mr. Sifford in the autumn of 1915.

[2] Sodium and potassium not separated; all alkali chloride calculated as NaCl.

[3] This is probably an error (see p. 113).

TABLE 3.—*Continued.*

BUMPASS HELL.

	Sample No.	Map No.	H	NH_4	K	Na	Ca	Mg	Fe''	Fe'''	Al	SO_4	Cl	SiO_2	CO_2	B_2O_3
Very large, violently boiling spring....	60	14	7	15	13	29	7	4.5	17.5	5	28	681	2	236	.....	4
Hot pool filled with precipitated sulphur............	62	15	none	128	4	33	7	2	4	4	none	419	trace	138	.....	84
Largest hot pool, filled with precipitated sulphur....	64	4	4	39.6	2	21	5	trace	29	9	32	613	trace	224	.....	21
Large pool covered with a scum of pyrite...........	63	6	8.9	11.4	13	42	37	25	51		23	1010	trace	358	.....	.....
DRAKE'S SPRINGS.[1]																
Easternmost spring south side of Warner Creek....	400	.....	none	.....	10.5	34.6	53	13	none	none	none	152	.....	136	20	.....

[1] The analysis of this slightly alkaline water is not complete; the acid radicals are insufficient to balance the basic elements. The determinations were repeated and found essentially correct. Also, the alkalinity of the water was determined by a very weak hydrochloric-acid solution and found to be equivalent to the carbon dioxide found when reckoned as all in the form of bicarbonate. Unfortunately the water sample was insufficient for further investigation.

reducing or protecting influence is probably insufficient to prevent atmospheric oxidation.

The maximum amount of ferric iron found in any of the other samples, with the exception just noted, is 9 mg. per liter, or 0.9 mg. in the volume usually taken for analysis. A careful scrutiny of the results indicates that these values for ferric iron, which of course represent the difference between the values for the total iron and the ferrous iron, are within the limits of error. In the collection of the samples the bottles were filled with water, stoppered as tightly as possible, and the stopper tied down with a cloth hood. The samples were not opened until cold. No appreciable oxidation could have taken place in this time. In the subsequent filtration the waters from the mud volcanoes were exposed for a longer time to the air and under conditions more favorable for oxidation than the other samples, yet no more ferric iron was found in them. Thus in No. 125, which was taken from mud volcano No. 7, Boiling Lake, only 4 mg. of ferric iron per liter was found, and in No. 362 and No. 331, waters from mud volcanoes No. 10 and No. 13, Devil's Kitchen, 6 mg. and 0 mg. respectively were found. Still more significant is the analysis of No. 64 of the water from spring No. 4, Bumpass Hell. This water contained enough hydrogen sulphide to impart to it a distinct odor when cold, and when the ferrous iron was determined at the camp the iron was doubtless all in the ferrous condition, yet the maximum amount of ferric iron, 9 mg. per liter, was found. Thus, while laboratory methods now in vogue are quite competent to decide a question of this sort, the primitive camp facilities under which some of the work had to be done leave us in doubt whether the spring waters generally contain no ferric iron at all or only a very little. The latter view is in better accord with field evidence, for, as previously stated, the volcanic gases contain only a small amount of hydrogen sulphide and they rise here and there from occasional points of the surface, not uniformly over the whole pool, and furthermore the waters are hot, only slightly acid at the best, and often more effectively exposed to the air by spouting. All these conditions favor oxidation. Indeed, if there is no oxidation at all it is not easy to explain the formation of pyrite which other facts support. Oxidation and reduction involving small amounts of iron are probably following each other continually at the surface of the spring pools.

The analysis of sample No. 23 from spring No. 18, Devil's Kitchen, presents a different case from the rest; 75 mg. of ferric iron were found in this water and only 6 mg. of ferrous iron. The spring from which it was taken was a *black mud* spring which was shown by microscopic examination to contain a quantity of minute pyrite crystals, some as small as 0.01 mm. diameter, and while these might slowly oxidize in the spring or during filtration, all previous experience indicates that *ferrous* salt, not *ferric*, would be the principal product. This conclusion is supported by the analysis of samples Nos. 15 and 128. Both these waters were from black mud springs and the ferric iron found in them was 9 mg. and 0 mg. respectively. The result in question is therefore doubtless incorrect and is probably affected by some crude error in the determination of ferrous iron at the camp.

We conclude, then, that the iron, one of the principal constituents of the waters, is nearly all in the ferrous state.

REACTION OF THE WATERS.

None of the waters of these hot springs is very far from neutrality. Of those analyzed 6 were practically neutral, 4 were alkaline,[1] and 8 were acid. The acidity ranged from 19 mg. to 436 mg. H_2SO_4 per liter, that is, from 0.002 to a trifle over 0.04 weight per cent. As SO_4 is practically the only acid radical present it is permissible to state the results in this simple form. Qualitative tests in the field indicated that most of the waters were slightly acid.

SALT INCRUSTATIONS.[2]

Among the solid products collected about the hot springs were soluble salts, patches of which appeared at times here and there on the dry ground in all the hot-spring areas. The patches were never very large; generally not more than a few square yards in extent and perhaps 0.5 inch in thickness. In 1916 some patches were found in all the areas[3] visited and the amounts increased as the season advanced, but in June and July 1922, when the snow lingered late and the ground in consequence was wetter at the same period, scarcely any were to be seen. As a

[1] Waring (Springs of California, p. 142) cites a single analysis of one of the springs of the Morgan group which was made by F. M. Eaton (1909–1910). He designates the pool from which the water was taken as "about 3 feet in diameter in an area of hard siliceous deposit 45 yards west of the creek edge and 50 yards north of the eastern log bath house." The analysis in parts per million follows: Na 1416, K 122, Ca 90, Mg trace, Al + Fe 2.2, SO_4 102, Cl 2342, CO_3 25, BO_2 present, SiO_2 200. It may be pointed out that this water is very similar to one of the slightly alkaline waters found in the Devil's Kitchen and to the sample from Drake's Springs with the addition of an excess of sodium chloride.

[2] The microscopic examination was made by H. E. Merwin.

[3] Except Drake's Springs, where the ground is covered with vegetation.

result of these observations the salt patches were at first supposed to bear a very simple relation to the dryness of the ground, but later observations (August 1923) showed that even in very dry times the salts may not occur at all (see p. 157). Usually these salts formed fibrous aggregates, varying in color from white to yellow, according to the percentage of ferric iron they contained. All the samples were collected in May and June 1916.

No. 43 was found under a small rock in the Geyser ravine, on the west side of the little stream and a few steps below the lowest pool. A small fumarole issued here. The product was white and mixed with siliceous residue.

Fig. 59.—Sketch Map of the Boiling Lake (Tartarus) showing location of the springs in June, 1916.

No. 150 was from the delta at the south end of the Boiling Lake on the bank of the stream which forms the inlet (fig. 59). This bank was riddled by fumarolic action. When kicked to pieces by the foot it revealed pockets of fluffy, fibrous salt at various depths. The sample analyzed was scraped from the surface. Another sample collected in 1915 from the bank at the southeastern corner of the lake showed a similar composition, but was yellower and contained more ferric iron.

No. 26 was collected in the lower end of the Devil's Kitchen a few steps north of No. 17 (fig. 47). This salt patch was much thicker at some times than at others, a variation doubtless depending on the weather.

No. 61 was found at Bumpass Hell, some yards up on the southern edge of the basin, east of No. 9 (fig. 50). This patch was comparatively thick and extensive, and had a curious, disagreeable, persistent odor resembling fertilizer. Sample No. 26 had a similar odor.

Besides the above samples we collected several from the summit of Lassen Peak which are products of fumarolic action and which are interesting to compare with those from the hot-spring areas.

No. 53 was scraped from the rocks in the middle of the crater, where it formed a thin, closely coherent coating. A small amount was obtained from three different spots, all of which appeared to be similar. The salts were all of deep-orange color (due to ferric chloride) and hydrochloric acid in process of volatilization was detected along adjacent cracks.

No. 51 and No. 52 were collected on different dates from the eastern rim of Lassen Peak, 175 feet below the highest point of the summit and some distance to the north of it. The spot where sample No. 52 was collected was near a fumarole which was then (1916) very active, issuing from a fissure under a rock about 50 feet east of the crater's edge. No. 51 was found in the same general vicinity. By 1922 this fumarole had entirely disappeared, but tenuous wisps of steam, which were all but invisible, still escaped from various parts of the crater and a slight odor of hydrochloric acid was still detectable in some places.

ANALYSIS OF THE SALTS.

As the salts could not be obtained free from insoluble matter they had first to be dissolved and filtered. In the earlier portion of the work the solutions were evaporated to "dryness" on the steam-bath and the residue was ground in a mortar, but the material so prepared was probably not always homogeneous, for the analyses of several samples proved unsatisfactory. In such cases the work was repeated in a manner better suited to the nature of the material. A solution was first prepared from a suitable sample and measured portions were taken for the various determinations. Homogeneity was thus assured, gain or loss of water by the salt during weighing was avoided, and since the composition of the *soluble portion only* was required, the percentage of each constituent was calculated on the basis of the total thus found. The equivalence of acids and bases furnished sufficient proof of satisfactory analytical work. The details of analysis require no description except in the case of Nos. 51 and 52 from Lassen Peak, which are of a character so unusual that a laborious examination was necessary. As salts of similar nature probably occur elsewhere in volcanic regions, the analytical procedure, which is not to be found in the textbooks, is recorded here.

DETERMINATION OF PENTATHIONATE.

The singular behavior of some of the salts was first revealed in the attempt to separate the insoluble matter from one of the samples; the filtered solution when evaporated on the water-bath gave off sulphur dioxide. It should be stated in this connection that the salts originally showed a decidedly acid reaction. Still more curious was the formation of a yellow precipitate with silver nitrate and the precipitation of "manganese dioxide" when the acidified solution of the salt was treated cold with permanganate. These reactions indicate *thionates*, but do not decide whether one or all four thionates are present, nor do they exclude sulphite, thiosulphate, or sulphate. As the thionates are not generally known, and as our information concerning them is thus more liable to be in error, preparations of all of them were made for the purpose of studying their reactions qualitatively and quantitatively. About half a dozen tests (already known) were found useful in the investigation.

(1) The unknown *when evaporated to dryness* gave free sulphur and sulphur dioxide. All the thionates except dithionates respond to this test as do also the thiosulphates.

(2) With permanganate in the cold the acidified solution of the unknown gave a brown precipitate. This reaction is given by the same compounds as reaction 1.

(3) When the unknown was boiled with a solution of *mercuric cyanide* a black precipitate was obtained. This reaction is characteristic of all the thionates except dithionates. It is characteristic also of the thiosulphates.

(4) With *mercurous nitrate* the unknown gave at first a yellow precipitate, which gradually turned black. Pentathionates and tetrathionates behave similarly, while trithionates and thiosulphates give black precipitates. This test therefore indicates pentathionates, tetrathionates, or both, but does not exclude dithionates and perhaps not trithionates, at least in small amounts.

(5) With *iodine solution* and excess of soluble bicarbonate, one sample of the unknown absorbed no iodine, another sample only a trace. This test excludes sulphites and thiosulphates with certainty.

(6) With *ammoniacal silver nitrate solution* the unknown gave a black precipitate. This proves the presence of pentathionate with the possible presence of dithionate, tetrathionate, and trithionate, which do not react with the reagent. Small amounts of pentathionate may be detected in this way in the presence of large quantities of tetrathionate, though the solution must be cold. Thus 1 mg. of the pentathionate radical S_5O_6 may be detected in about 140 c. c. of solution. Tetrathionate does not respond to the reagent in a concentration of 1 gram of the radical S_4O_6 in 1.3 c. c. water, even after one hour.

(7) When the unknown was boiled for some minutes with a few drops of *cupric sulphate* solution no precipitate was obtained. Under these conditions a soluble trithionate gives a black or dark-brown precipitate, said to be cuprous sulphide. The test is moderately delicate. Thus 5 c. c. of a solution of potassium trithionate containing 0.1 mg. of the salt per cubic centimeter gave a plain test after boiling for a few minutes. The test was also obtained by boiling down to half its volume 5 c. c. of the above solution, to which had been added 1 gram of alum to make it comparable in composition to the unknown. But 50 c. c. of a trithionate solution containing the same amount of salt, 0.5 mg., did not respond to the test with copper sulphate, even when boiled down to a very small volume. From this we may conclude that the unknown contains only a very small amount of trithionate, if any.

As a result of all the tests we find that pentathionate is certainly present, tetrathionate and dithionate may possibly be present, as well as a very small amount of trithionate. It should also be remembered that none of the tests exclude sulphate. To determine whether the doubtful radicals were present or absent quantitative experiments were necessary. Dithionates were excluded in two ways. First the dilute solution of the unknown was boiled with bromine. This oxidizes all soluble thionates *except dithionates* to sulphate. In the resulting solution all the sulphate, including of course any which was originally present, was precipitated as barium sulphate and eventually filtered off. The filtrate containing excess of barium chloride was then evaporated to dryness with concentrated nitric acid. In this way all dithionate is transformed into barium sulphate; 1.6 mg. of $BaSO_4$ was found. Again another portion of the unknown was precipitated with mercuric cyanide. The precipitate thus formed from either tetrathionate or pentathionate consists of mercuric sulphide and free sulphur. The reactions are represented by the following equations:

$$(1)\quad K_2S_5O_6 + Hg(CN_2) + 2H_2O = 2KCN + HgS + 2S + 2H_2SO_4$$

$$(2)\quad K_2S_4O_6 + Hg(CN_2) + 2H_2O = 2KCN + HgS + S + 2H_2SO_4$$

After filtering off the precipitate all the sulphur in solution will be in the form of sulphate unless dithionate is present. The sulphate was precipitated as before, and in the filtrate from it dithionate was sought in the same way; 1.3 mg. $BaSO_4$ was found. These two quantities, 1.6 mg. and 1.3 mg. $BaSO_4$ represent, approximately at any rate, the solubility of barium sulphate under the present conditions, and it is safe to conclude that no dithionate is present. The results therefore narrow down the possible sulphur compounds in the salts from Lassen Peak to tetrathionates, pentathionates, and sulphates. The two thionates, though relatively stable under the field conditions prevailing where the salts occurred, are very unstable in solutions of oxidizing agents and alkaline reagents, especially when hot, and these facts caused a great deal of trouble in their determination. In the interest of accuracy many attempts were made to remove the sulphates as well as the iron and alumina before the thionate was determined, but the instability of the latter proved an insurmountable obstacle. The best method of procedure found was to separate first the soluble salts from rock residue and free sulphur by means

TABLE 4.—ANALYSES OF SOLUBLE SALTS, PRODUCTS OF FUMAROLIC ACTION IN THE LASSEN NATIONAL PARK.

No.	43.	150.	26.	61.	51.	52.[1]	52.[2]	53.[3]
Locality. . .	Geyser.	Boiling Lake.	Devil's Kitchen.	Bumpass Hell.	Lassen Peak, NE. summit.	Lassen Peak, NE. summit.	Lassen Peak, NE. summit.	Lassen Peak, middle of crater.
Al.	12.40	10.70	10.93	8.93	8.76	8.10	10.42	13.28
Fe'''.	.63	1.28	trace	1.01	. . . . .	. . . . .	. . . . .	1.38
Fe''.	trace	.11	8.93	7.23	5.60	4.04	3.11	.27
Ti.	. . . .	.02	.09	.11	.04	.19	.11	. . . . .
Mn.	.06	.07	.01	.03	. . . . .	. . . . .	. . . . .	.04
Mg.	1.78	3.10	.06	.91	1.77	1.72	1.94	2.53
Ca.	1.12	.44	none	.10	2.26	1.51	none	1.00
Li.	. . . .	present	. . . .	trace	. . . . .	. . . . .	. . . . .	trace
Na.	1.51	2.68	.28	.41	1.83	1.77	2.13	3.02
K.	.49	.42	.25	.37	.57	.61	.55	.07
(NH_4). . . .	.57	.04	.07	.06	. . . . .	. . . . .	. . . . .	. . . . .
H.	. . . .	. . . .	.19	cal. .26	.04	cal. .21	.25	. . . . .
Cl.	none	none	none	none	none	none	none	20.74
SO_4.	81.51	81.14	79.19	80.58	77.32	72.09	78.93	57.63
S_5O_6.	none	none	none	none	1.80	9.77	2.94	none
S_4O_6.	none	none	none	none	probably none	probably none	probably none	none
S_3O_6.	none	none	none	none	none	none	none	none
S_2O_3.	none	none	none	none	none	none	none	none
SO_3.	none	none	none	none	none	none	none	none
B_2O_3.	none	none	none	none	none	none	none	none

[1] Analysis of the original salt. It was intermixed with about 2 per cent of free sulphur.
[2] Analysis of the salt obtained by extracting original with water and evaporating on the steam bath.
[3] This analysis is defective but is included to show the general character of the mixture.

of cold water, and then to analyze the solution. Probably the best method we have of determining the two thionates, either alone or together, is by weighing the precipitate from a given quantity of salt thrown down by mercuric cyanide and then to ascertain the ratio of mercuric sulphide to free sulphur in the precipitate. Reference to the above equations shows that the precipitate from tetrathionate contains 1 mol free sulphur: 1 mol mercuric sulphide, while that from pentathionate contains 2 mols sulphur: 1 mol sulphide.

In practice the ratio was determined by transforming all the sulphur in the precipitate to barium sulphate and finding its weight. The following is the most satisfactory of the results:

Weight of $HgS + xS$ from a given amount of solution=0.0474 gram.
Weight of $BaSO_4$ from the sulphur of the precipitate=0.1129 gram.

$$\frac{0.0474}{0.1129} = \frac{HgS + xS}{(1 + x)BaSO_4} \cdot x = 2.04.$$

From this and other determinations it was concluded that no more than a few tenths of 1 per cent of tetrathionate could be present and probably none at all.

After the pentathionate had been thus determined, the total sulphur was obtained by the oxidation of the pentathionate to sulphate by bromine and the subsequent precipitation of all sulphate as barium sulphate. The sulphate *originally* present was then determined by difference.

The analyses of all the salts, both from Lassen Peak and from the hot-spring areas, are included in table 4. All are characterized by the metals commonly occurring in rocks, of which aluminum is the principal one, as contrasted with the salts dissolved in the spring waters, where aluminum is usually almost entirely lacking. Of the acid radicals present sulphate is predominant in every case and is exclusively found in the salts from the hot-spring areas. The salts from within the crater of Lassen Peak contain a decided quantity of chloride, while Nos. 51 and 52 from the vicinity of the large fumarole, though chiefly sulphates, are, as we have seen, remarkable for the presence of a notable amount of pentathionate.

MICROSCOPIC EXAMINATION.[1]

A number of the salts were examined microscopically. By means of the optical constants and the chemical composition together, it was possible to identify a number of the minerals present.

No. 61 consisted largely of *halotrichite* $FeSO_4.Al_2(SO_4)_3.24H_2O$ in fibrous forms with lesser amounts of *voltaite*, a hydrous potassium ferroso-ferric sulphate of undetermined formula, and *alunogen* $Al_2(SO_4)_3.18H_2O$. The sample also contained considerable material too fine to identify.

No. 26 contained considerable *halotrichite*, with some *voltaite* and *alunogen*.

No. 52 is largely *alunogen;* it also contains *pickeringite*, $MgSO_4.Al_2(SO_4)_3.22H_2O$, but no *voltaite*[2].

No. 51 consists of *halotrichite* or *pickeringite* (the optical properties are nearly identical) and very little else. In neither No. 51 nor No. 52 could any material be detected with a refractive index as high as that of any known thionate. The substance which was detected by chemical analysis was therefore presumably present in syrupy films spread over the surface of other crystals. *Halotrichite* and *alunogen* have been reported by Hague[3] from the neighborhood of certain acid springs in the Yellowstone Park.

[1] By H. E. Merwin.
[2] The formulæ are taken from Dana's Mineralogy.
[3] Arnold Hague, Origin of thermal waters of the Yellowstone Park, Bull. Geol. Soc. Amer., 22, 116, 1911.

THE SEDIMENTS.[1]

All the springs contain more or less mud, which varies from the finest sediment to coarse fragments of altered lava in process of disintegration. Where the springs have an outlet much of the finest material is naturally carried away by flowing water, but where conditions favor its retention, as they do in the mud pots, the chief constituent of the sediment is kaolin. The few cases where precipitated sulphur was abundant form the only exception to this rule which has been observed by the authors. On the bottoms of some springs was found a segregation of the heavier and more coarsely crystallized minerals, especially residual magnetite, pyrite new and old, and possibly residual quartz. Perhaps a more thorough dredging would reveal a certain amount of segregation everywhere in the lowest layers of the sediments, but the conspicuous examples of it thus far observed have been in springs where sorting seems to have been favored by flowing water. The sediments are colored, according to the minerals they contain, gray, black, yellow, and rarely brown or white.

The glassy and fine-grained ground-mass of the rock fragments is often thoroughly altered, while magnetite grains and quartz, feldspar, and pyroxene phenocrysts are still fresh. These altered ground-masses contain widely varying proportions of kaolin, opal, alunite, and pyrite.

Opal was found in every sediment examined. Usually it appeared intimately aggregated with kaolin, etc., but in some instances (Bumpass Hell) it was found in small separate grains. In a few springs, as at No. 5 (Devil's Kitchen) and No. 6 (Boiling Lake), many small, well faceted, doubly-terminated *quartz* crystals were present. It could not be determined whether they were derived from the surrounding rocks or were a product of the thermal waters.

The chief constituent of the sediment of nearly all the springs is a clay-like material, kaolin, which may consist of one or all of the recognized clay minerals, *kaolinite* ($Al_2O_3.2SiO_2.2H_2O$), *halloysite*, or *leverrierite*. The mud of Boiling Lake is of the same character.

Some years ago a sample of this mud was collected by J. S. Diller and analyzed in the laboratory of the U. S. Geological Survey[2] by W. C. Wheeler. This analysis, cited in table 5, shows that the mud approaches kaolinite in composition; the differences are satisfactorily accounted for by the admixture of small amounts of opal and rock débris.

TABLE 5.—MUD FROM LAKE TARTARUS, CALIFORNIA.

[Analysis by W. C. Wheeler.]

	Found.		Cal. for kaolinite.
SiO_2	47.51		46.5
Al_2O_3	34.08		39.5
Fe_2O_3	1.17		.....
FeO	.52		.....
MgO	.28		.....
CaO	.08		.....
Na_2O	.21		.....
K_2O	.11		.....
H_2O-	1.89	13.49	14.0
H_2O+	11.60		
TiO_2	.65		.....
ZrO_2	.09		.....
P_2O_5	.81		.....
S	.63		.....
MnO	tr.		.....
BaO	.05		.....
SrO	not det.		.....
Li_2O	tr.		.....
	99.68		100.0

In general, the kaolin is in the aggregates already described, as though it had been formed in place during the alteration of rock ground-mass or feldspar. The thoroughly air-dried clay varies considerably in optical properties. It usually possesses an indefinite birefringence, and refractive index measurements vary from 1.51 to 1.56.

[1] All the microscopic work was done by H. E. Merwin.

[2] Private communication from George Steiger, chief chemist.

Alunite, $K_2O.3Al_2O_3.4SiO_2.6H_2O$, in small rhombohedra was found in many of the sediments. Generally it occurs in very small quantities. More was found in certain springs of Bumpass Hell, but the amount was nowhere considerable.

Sulphur.—Some springs, more especially certain ones in Bumpass Hell, contain much precipitated sulphur, imparting to the sediment a yellow color which is sometimes very decided. No. 4, Bumpass Hell (fig. 52), is the most conspicuous spring of this character. A sample of the water was collected in 1916, but the sediment was not so carefully examined as that of a sample more recently collected by J. S. Diller (1921). The latter sample contained about 96 grams of sediment per liter, having approximately the composition[1] 64 per cent sulphur, 17.6 per cent opal, 15 per cent kaolin, 3.3 per cent alunite, and a very little pyrite.

Fig. 60.—July, 1923. A warm pool in the Devil's Kitchen near No. 10, Fig. 47. On the surface floated a black scum of finely divided pyrite. Photo Day.

Small amounts of sulphur occur in many pools and streams of the hot-spring areas (figs. 61, 62). A very little is found in the mud of the Boiling Lake, and in the upper end of the Devil's Kitchen (south side) it may be seen depositing on rocks and banks. The fumaroles of Bumpass Hell are often lined with needles of sulphur, and the same was true of the cracks along the eastern rim of the crater of Lassen Peak not long after the eruptions, but with the complete extinction of fumarole activity there the sulphur has disappeared. The crystals were always orthorhombic. At one time the hypothesis that some of this sulphur was a primary volcanic emanation proved appealing, but more careful observations have made this quite improbable, for it never appears where its presence can not be easily accounted for as an oxidation product of hydrogen sulphide; and furthermore, in the collection of gases from many fumaroles, sulphur was never noticed as a condensa-

[1] Based on microscopic examination and several chemical determinations.

tion product, as it should be if it were a constituent of the gases. At the Sulphur Banks, Hawaii, where the gases have a temperature of about 96°, the water condensed from them resembles milk, though the sulphur vapor forms but a few thousandths of 1 per cent of the total volume of the gases.

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Fig. 61.—July, 1923. Another view of sulphur cauldron (Fig. 52), at Bumpass Hell. Greater gas evolution with lower water level (no outlet) and higher temperature. Photo Day.
Fig. 62.—July, 1923. A group of quiet sulphur pools (Fig. 50, No. 15) Bumpass Hell. Photo Day.

Pyrite is very generally distributed at the Geyser, Boiling Lake, Devil's Kitchen, and Bumpass Hell; elsewhere it has not been sought for. It was first found in 1915 in the mud at the outlet of the Boiling Lake. The next year, when a more careful survey of the region was made, pyrite was found in practically all the hot springs and mud pots, but it was most noticeable in the beds of the little streams which form the outlets of the springs (fig. 63). The amount of the mineral, however, was so small and the crystals generally were so minute that it might easily have been overlooked by an observer intent upon the larger features of the district.

Some of the pyrite was so coarse or so characteristic in color as to leave little doubt of its identity in the mind of a close observer, but much of it was too fine-grained to be recognized by the unaided eye. One of the most interesting occurrences

Fig. 63.—May 20, 1916. Stream in Devil's Kitchen showing pyrite crystals (dark areas) in furrows on the sandy bottom (looking down through the water). Photo Day.

of it was in the form of dark scums on the surface of certain hot, quiet pools (e. g., No. 9, Devil's Kitchen, and No. 6, Bumpass Hell), where in reflected sunlight it appeared as beautiful mirrors of brass-yellow color (figs. 60 and 64). It is easy to get such a mirror by boiling finely ground pyrite in a vessel of water (phenomenon of flotation), and the color of the mirror is distinctly different from a similar mirror of marcasite.

The black and gray muds of many springs had been suspected to be colored by pyrite, but only the microscope was competent to decide the question. Dispersed through these sediments were found minute aggregates of an opaque, lustrous mineral, from 0.01 to 0.03 mm. in diameter, which, from their association with larger aggregates and separate crystals of pyrite, permitted the conclusion that they also were pyrite. The sediment contained no other material which could have imparted to it a gray or black color.

COLLECTION OF THE GASES.

The gases were collected over the hot spring water in a glass tube with the upper end closed, the lower attached to a glass funnel. There are some details about the apparatus which are perhaps worth noting, since by their application

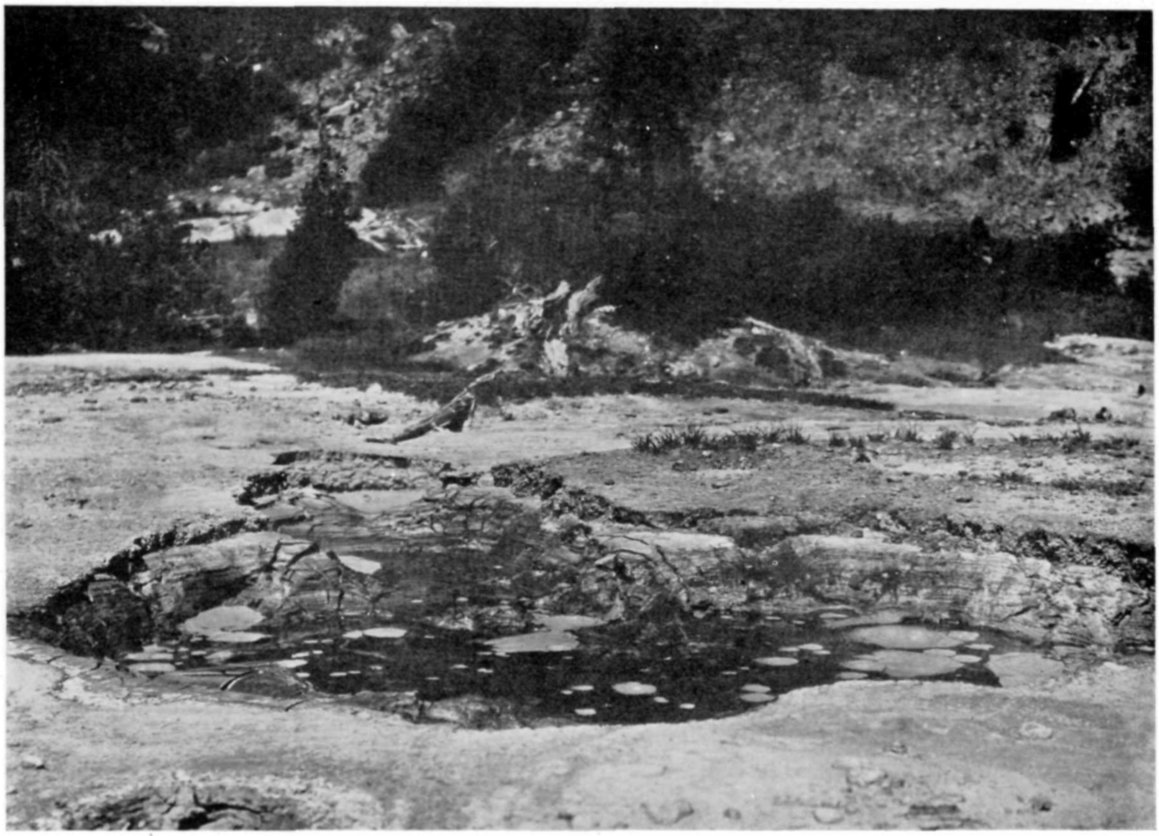


Fig. 64.—July 2, 1915. Hot pools in the Devil's Kitchen (No. 9, Fig. 47) showing scums of pyrite reflecting light like bronze mirrors. Photo Day.

air is effectively excluded and gases may be collected from difficultly accessible spots. The collecting tubes were half-liter cylinders, about 40 cm. long and 4.3 cm. outside diameter. The cylinders at each end were drawn down to tips about 9 mm. outside diameter, one tip closed, the other open. To the open tip the funnel is attached by heavy-walled rubber tubing securely wired. A 10-cm. funnel with stem cut down to a length of about 3 cm. is quite satisfactory. The collecting tube is conveniently handled by a clamp attached to a light pole, which carries the line for releasing the catch (described below) and another line for holding the funnel upright after filling the apparatus with water and during the operation of lowering it into the pool. By using a jointed pole its reach may be extended so as to collect gas in otherwise inaccessible places (figs. 65, 66).

To prevent any access of air after the tube is filled with gas and before it is removed from the water, the rubber connection between tube and funnel is tightly closed by a strong spring clamp, specially devised for the purpose. The clamp is slipped over the connection and fastened to the collecting tube before the funnel is attached. The jaws of the clamp are held open by a catch while the tube is filling and closed at the end of the operation by simply releasing the spring catch with a cord. The funnel may then be safely detached and the rubber connection filled with water, most of which is immediately displaced by pushing in a glass plug. The plug is carefully wired in and the tube sealed off after reaching the camp.

Fig. 65.—June, 1922. Collecting gases at Bumpass Hell. Spring 14, Fig. 50. Photo Day.

If the water of a spring is not too muddy it is naturally best to use it in filling the apparatus; otherwise any convenient hot water may be taken. Gas solubility counts for little in waters near the boiling-point. To collect gases from mud pots is not quite so easy. Where the mud is thick the funnel must be held in position or it will rise and let in air. In one case where the mud was very thick the tip of the collecting tube was completely clogged by it and collection proved impossible. Several gallons of water were therefore poured into the pot and left to stand some hours till the water was hot; collection then proceeded without trouble. A little care is required in sealing a tube filled from a mud pot, because the tip is sure to be smeared with mud, but if the operator works slowly the mud dries out gradually, and the sealed joint will not crack.

ANALYSIS OF THE GASES.

Samples of volcanic gases for analysis have usually been transferred from the collecting tube to the measuring burette, saturated with moisture as they occur in the field. To what extent the results are affected by this procedure when the gases contain hydrogen sulphide, as those from Lassen Park usually do, has never been ascertained, but the mercury is blackened and the measuring burette fouled by it. To avoid the error so caused, the gases under discussion were pumped through an ample supply of phosphorus pentoxide and measured *dry* [1]. The hydrogen sulphide was then absorbed by lead dioxide. The residual gas was subsequently transferred to a burette containing a drop of water and was measured again in the saturated state. The difference between the two volumes, when reduced to standard conditions, is obviously the volume of the hydrogen sulphide. The subsequent operations of analysis can then be carried out with absorbent *solutions* instead of dry absorbents and much time saved thereby. By pumping out the contents of the collecting tube through phosphorus pentoxide (one bulb of which is renewed after each operation), the soluble gases, which would otherwise be partly retained in the

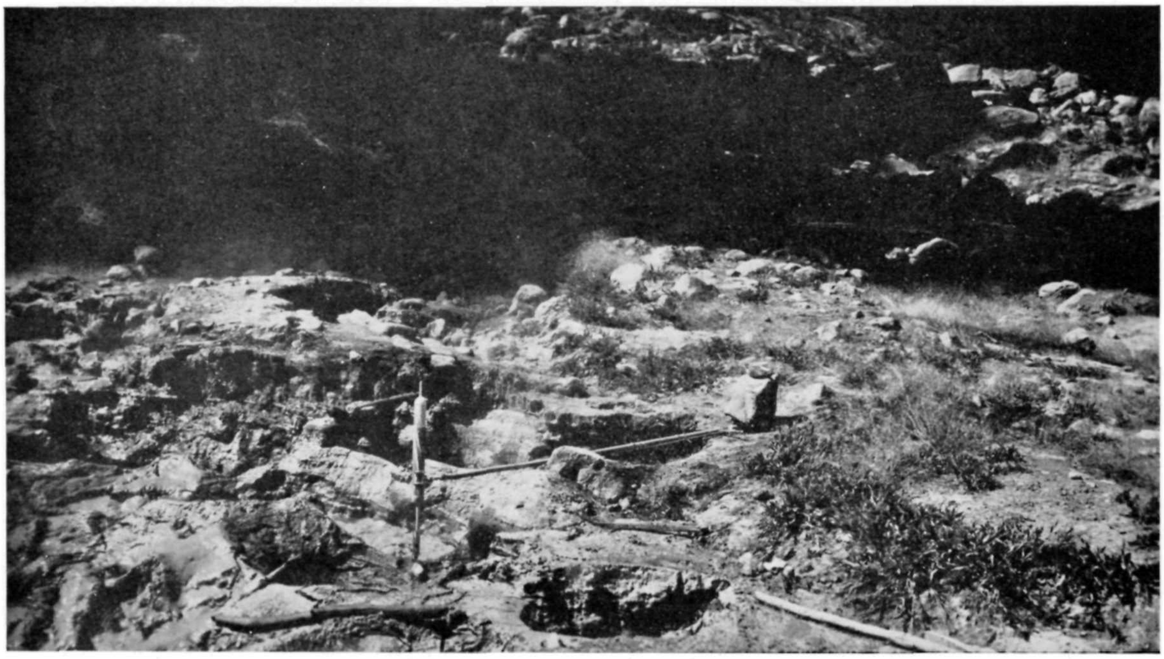
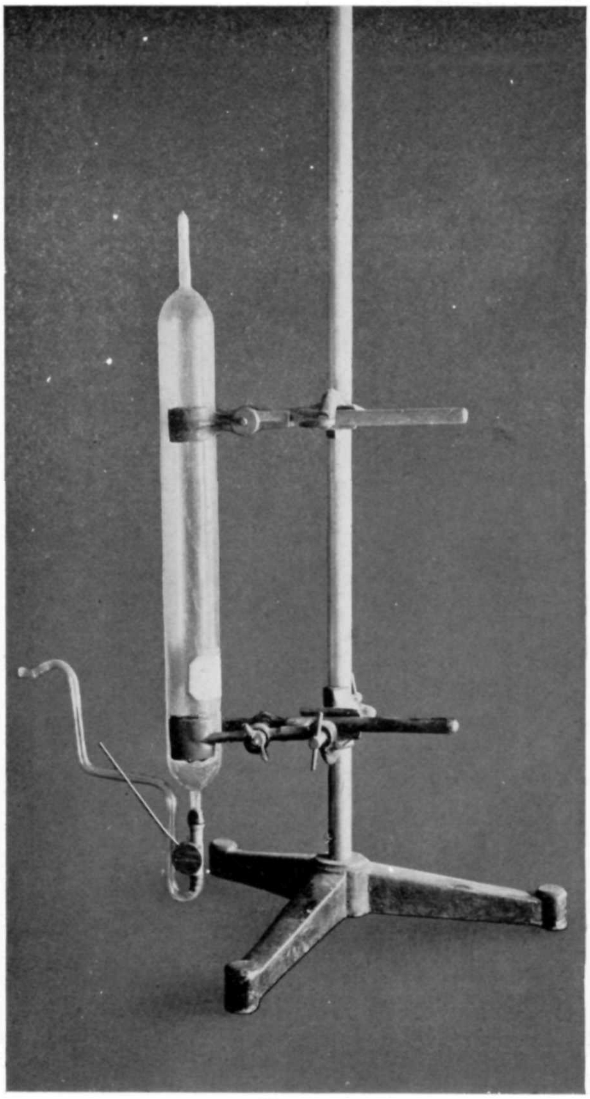


Fig. 66.—June, 1923. Collecting gases at the mud springs of Boiling Lake. Photo Day.

water which wets the inside of the tube, may be completely removed. In practice the tip of the tube is connected to the drier by cementing each to the ends of a crushing-screw which is immersed in mercury (fig. 67). The tip can thus be broken without access of air. The method has been employed by E. S. Shepherd for volcanic gases, but as his samples contained no hydrogen sulphide the subsequent procedure was necessarily different. To avoid any reaction with moist hydrogen sulphide, the steel crushing-screw was plated with platinum. The gases were first pumped into a dry burette, the mercury of which was carefully protected from the moisture of the outside air (fig. 69). About 95 c. c. was usually taken for analysis. After volume, temperature, and pressure had been measured, the gas was transferred to a

[1] Dried gases containing hydrogen sulphide up to about 9 per cent have been stored over mercury for days and no decomposition within the limits of error has ever been noticed. Slight blackening is sometimes seen. Whether or not this is due to a trace of moisture has not been ascertained. These observations apply to periods of a few days up to a week or two with smaller amounts of hydrogen sulphide.

mercury pipette containing a pellet of lead dioxide.[1] The pellet was attached to a platinum wire, the lower end of which formed a spring. When pellet and wire are pushed through the inlet tube of the pipette the spring is capable of holding the wire and pellet in any desired position. The leveling-bulb is then attached and securely wired to the inlet tube and the mercury is introduced (fig. 68).



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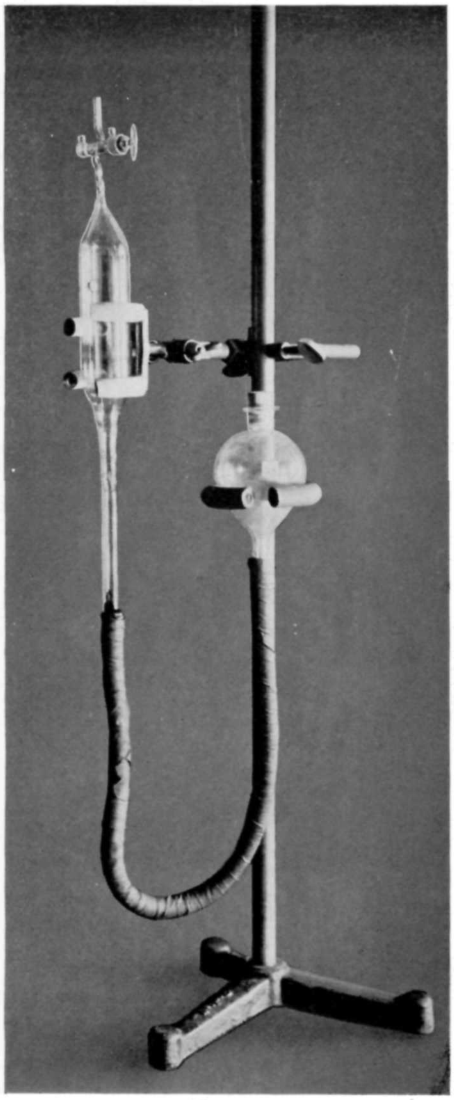

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Fig. 67.—Device for removing the gas from the collecting tube. Photo Snapp.
Fig. 68.—Pipette for absorbing hydrogen sulphide. Photo Snapp.

[1] The cylindrical pellet, 8 mm. in diameter by 5 mm. in thickness, was made by compressing the powder (free from PbO) with a drop of water at a pressure of 2,000 kg. At first the pellets were moistened with phosphoric acid, but this is unnecessary under our conditions and it fouls the mercury somewhat. Other investigators have used for the absorption of hydrogen sulphide balls of manganese dioxide or lead dioxide made up with oil and moistened with phosphoric acid. According to Bunsen, who was apparently the first to use the method, the ball, if not properly made, will absorb more indifferent gas than the amount of the hydrogen sulphide present.

See Bunsen, *GasometrischeMethoden*. Braunschweig 1877 p. 111; Christensen, *Tiddskr. Phys. and Chem.*, 28, 226, 1889; Thorkelsson, *Memoires de l'Academie royale des Sciences et Lettres de Danemark*, 8, 181, 1910.

If the pellet is floated on the mercury it of course rises to the top when the gas is driven out of the pipette and retains a little gas clinging to its surface. This gas is difficult to dislodge, but when the wire is used the air is easily detached by the simple expedient of squeezing the rubber tube and thus agitating the mercury. It is wise to use a fresh pellet for every determination of hydrogen sulphide, since the surface becomes coated with the reaction products and with a film of mercury. It seems to be a limitation of the method that a pellet dense enough to prevent absorption of other gases will not absorb a great deal of hydrogen sulphide. If the hydrogen sulphide is large in amount there would be no objection to using two

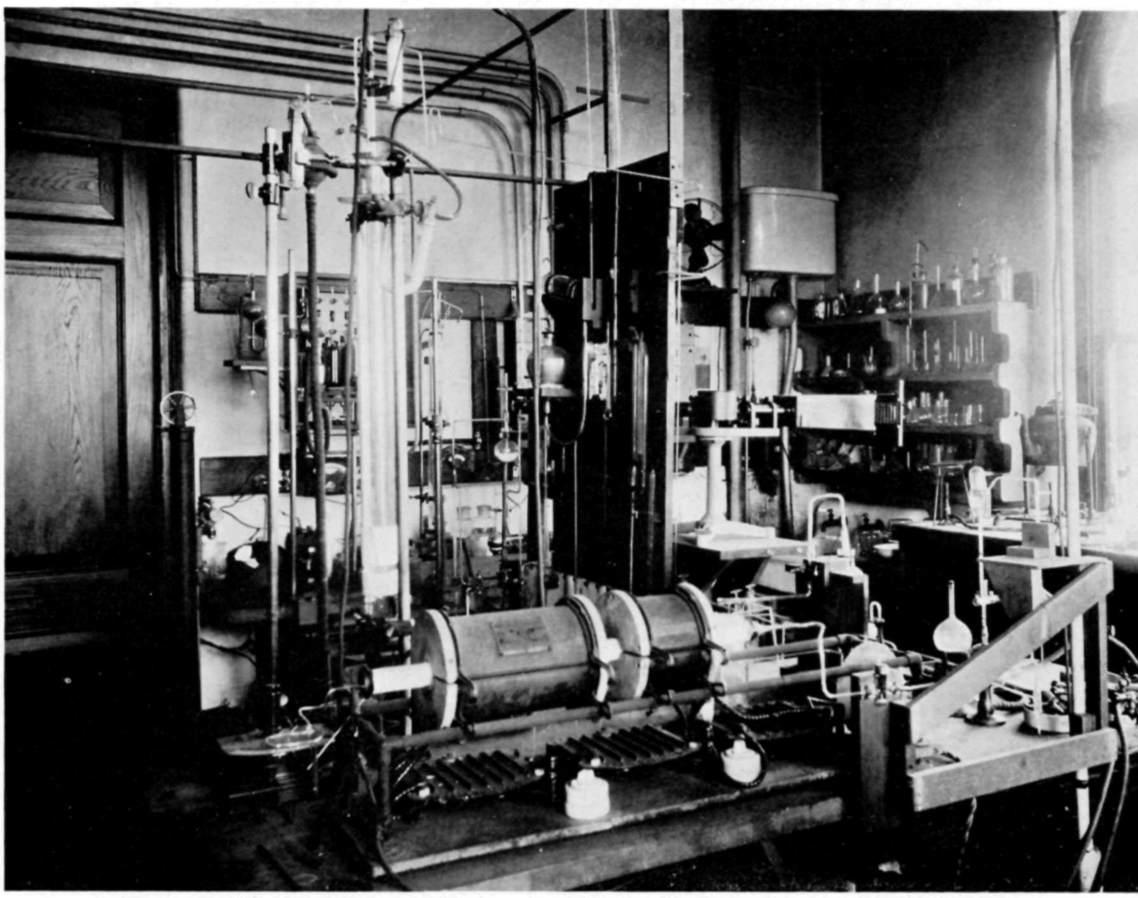

Fig. 69.—Apparatus for analysis of gases. "Dry" burette at left. Apparatus for removal of nitrogen from the inert gases in the foreground. Photo Snapp.

pellets at once. The hydrogen sulphide is rather rapidly absorbed and experiments proved that the absorption is complete. After an hour the residual gas is transferred to the "wet" burette and measured again, together with temperature and pressure. Perhaps it is hardly necessary to say the burettes were both filled with mercury and water-jacketed. The gases were transferred in both cases through a capillary connection which was first exhausted and filled with mercury, so that no gas was lost and no air gained. No appreciable amount of carbon dioxide, nitrogen, or oxygen, and probably no other gas present except the sulphur gases, is absorbed by the compressed pellet, but there was a constant error of about 0.3 c. c., not yet accounted for, involved in the transfer of gas from one burette to the other, whether the pellet is present or not. When this error is corrected the results are good. Thus in a synthetic mixture of hydrogen sulphide and carbon dioxide 3.84 per cent

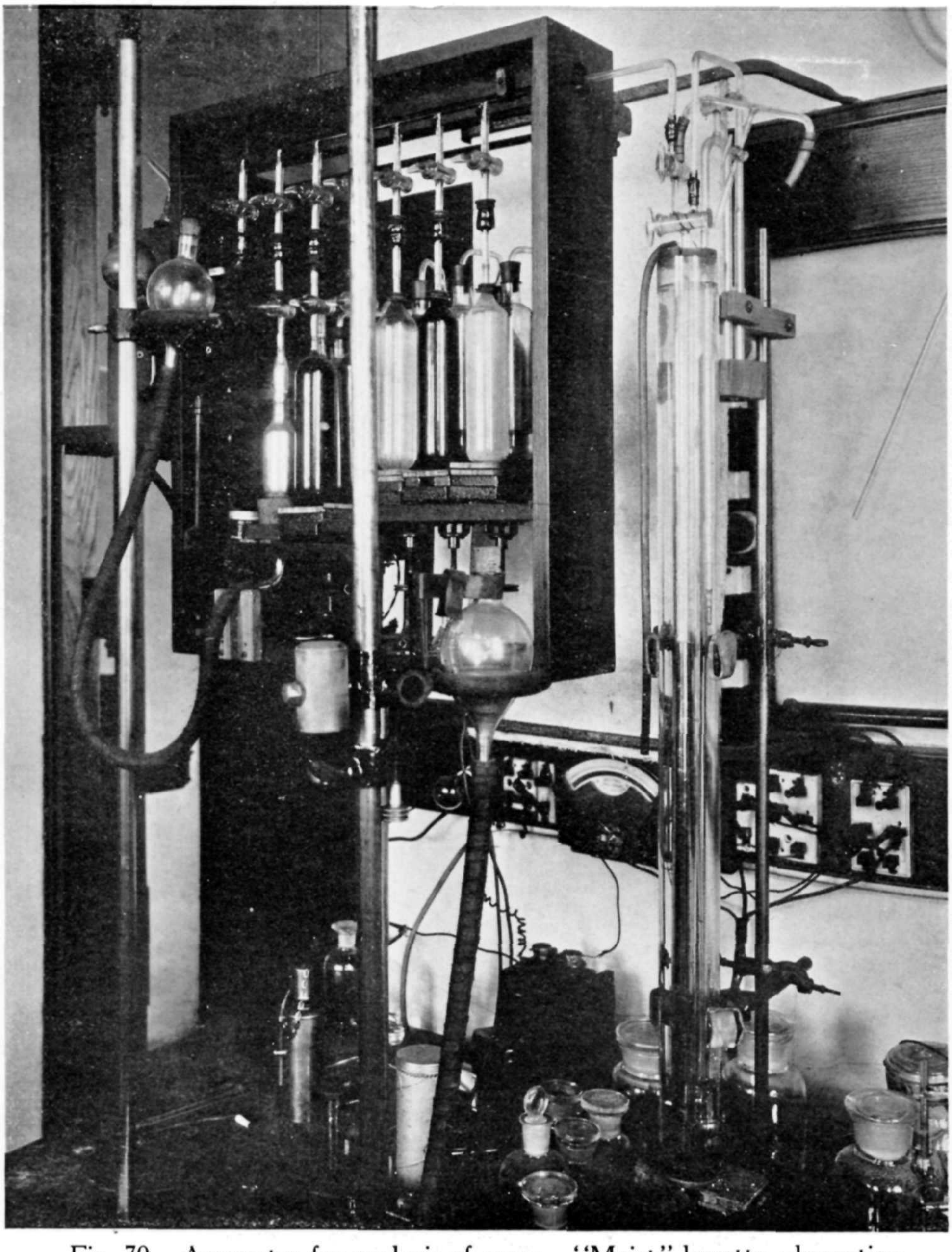

Fig. 70.—Apparatus for analysis of gases. "Moist" burette, absorption pipettes and combustion pipette. Photo Snapp.

and 3.92 per cent H_2S was found. In a second mixture of the same gases the results were 8.94, 8.88, 8.84, and 9.15 per cent.

The "wet" burette was connected on the one hand to a compensator and on the other to an apparatus specially constructed on the Orsat principle, the pipettes of which were joined to a "manifold" made from a capillary 1 mm. in inside diameter. The connections to the burette were made with Khotinsky cement, insuring absolutely tight joints without too much rigidity. The pipettes were also sealed to the apparatus (fig. 70) in the same way, thus permitting the ready renewal of the reagents. The combustion pipette [1] has already been described. Perfectly tight stopcocks intervened between each pipette and the capillary manifold. In practice it is necessary to attach the leveling-bulb of the burette to a cage, which slides vertically on a smooth, greased rod and which can be clamped to the rod in any position and afterwards leveled with an adjusting screw by the aid of the compensator.[2]

The absorbents, in order, were caustic potash for CO_2, alkaline pyrogallol for O_2, and acid cuprous chloride for CO. Combustions were made over mercury with pure electrolytic oxygen.

The agreement between duplicate analyses is all that could be desired, the differences in measurement ranging generally from 0 to 0.1 c. c. Criticism is often made of such gas-absorption methods on theoretical rather than experimental grounds, and we are satisfied that when the operator takes pains to displace each gaseous constituent from the capillaries and to absorb it completely the errors are very small.

For the determination of the so-called rare gases the measured residue of nitrogen, etc., is transferred to a mercury gasholder which is then sealed to an exhausted absorption apparatus of the usual type where the gas is passed in succession over phosphorus pentoxide, hot copper oxide, hot metallic calcium, solid caustic potash, and phosphorus pentoxide again (fig. 69). The gas is circulated several times through the train; finally the unabsorbed gas is pumped into a small capillary measuring tube carefully calibrated, in which the volume can be read to about 0.002 c. c. A spectrogram of the gas is then taken for comparison with standards (fig. 71). In the identification of the rare gases the authors take pleasure in acknowledging their indebtedness to Dr. E. G. Zies, whose previous experience made his aid of great value.

Criticism may very properly be made of the use of an Orsat apparatus for the determination of the rare gases if a high degree of accuracy is required, for the capillaries are filled before the analysis with nitrogen, argon, etc., obtained by absorbing the oxygen (and CO_2) from a sample of air. If the gas to be analyzed contains nitrogen and the rare gases in proportions different from those in the air, it is obvious that the residue tested for rare gases will not contain them in their original proportions. The error increases of course as the residue becomes smaller in volume and as the percentage of rare gases diverges from that in the air. The difficulty can be overcome by taking a second sample for rare gases and removing all other constituents by solid absorbents in an evacuated system. For reasons which will appear presently the procedure was unnecessary in the present case.

[1] Allen and Zies, A chemical study of the fumaroles of the Katmai region, National Geographic Soc., Contributed Technical Papers, Katmai Series, No. 2, p. 125, 1923.

[2] When the mercury levels are approximately the same before the stopcock of the compensator is opened, the inflow of gas to the compensator or outflow of air from it is negligible.

COMPOSITION OF THE GASES.

The gases are not only all of the same general character, but they are singularly constant in composition for natural gases. An inspection of table 6 shows that there is a preponderant quantity of carbon dioxide in every instance. The limiting values for carbon dioxide are 89.8 per cent and 96.4 per cent, the average 93.4 per cent. Nitrogen ranges from 2.2 per cent to 10.2 per cent, with an average of 5.5 per cent. Hydrogen averages 0.60 per cent, hydrogen sulphide 0.60 per cent, and there are traces of marsh gas and very small amounts of oxygen. The average percentage of oxygen is 0.10 and about one-third of the samples contain none at all.

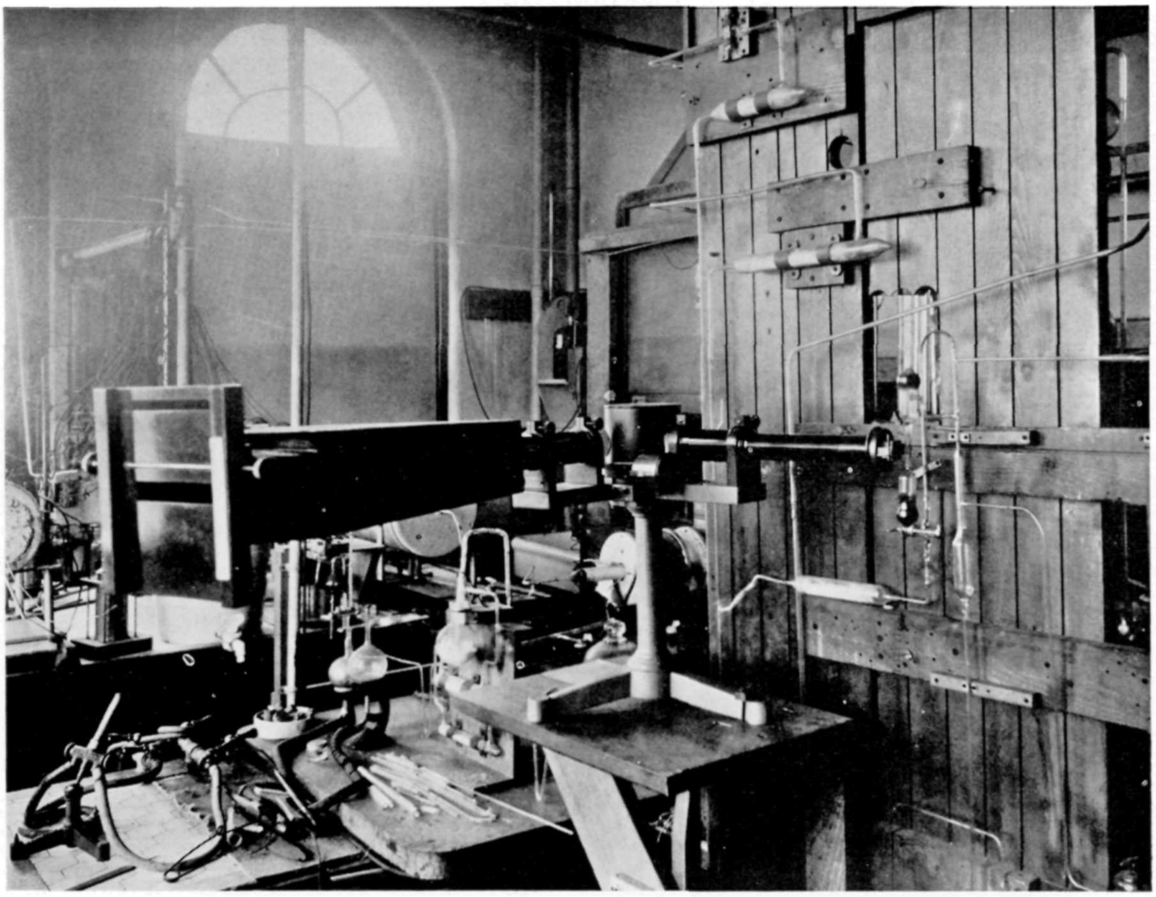

Fig. 71.—Apparatus for photographing spectra of the inert gases. Photo Snapp.

Many of these results are within the limits of error of the measuring apparatus used in the work and are perhaps to be accounted for in this way. It is quite unlikely that oxygen leaked into the collecting tube in any part of the process, nor is oxygen ever to be regarded as a primary volcanic gas. Its escape from a hot magma or batholith along with reducing constituents like the sulphur gases is highly improbable. There are, however, reasons for believing that the oxygen of the air becomes mingled with the volcanic gases near the surface of the ground, indeed, this is much the most satisfactory way of accounting for the sulphuric acid which is so generally distributed in fumarole regions (p. 138). Usually no doubt the

Table 6.—Gases from the Hot Springs of Lassen National Park.

Boiling Lake.

	No. 8. Pulsating spring on promontory 15 feet above lake.	No. 1. Pulsating spring on edge of muddy pool.		No. 5. Small group of mud springs.		No. 6. Mud pot on edge of lake.
		Sample *a*.	Sample *b*.[1]	1st Spring.	2d Spring.	
Temperature, ° C	93°	93°	93.3°	83°	91°	90°
Composition:						
CO_2	93.50 (with H_2S)	91.80 (with H_2S)	91.90	88.15 (with H_2S)	90.90 (with H_2S)	92.90 (with H_2S)
H_2S			2.00			
CO	none	none	none	none	none	none
CH_4	.25	.10	.20	.25	.20	.20
H_2	.10	.25	.40	1.25	.85	1.00
N_2[2]	6.15	7.80	5.55	10.20	8.06	5.90
A	......	.10	......	......	.09	......
O_2	none	.10	.05	.20	.10	.10
	100.00	100.15	100.10	100.05	100.20	100.10
$\frac{A}{A + N_2}$	......	1.45	......	......	1.39	......

[1] Sample collected in August 1923, the others collected in July 1922.
[2] Where argon is undetermined it is included with nitrogen.

DEVIL'S KITCHEN.

	No. 18.	No. 23.	No. 14.	No. 26.	No. 27.	No. 28 (North end.)	No. 11 (East end.)	No. 9 (East end.)	No. 3.	No. 1.	No. 9.[1]	No. 24.[1]
	Mud pot.	Vigorously spouting spring in hot pool.	Hot spring on edge of pool.	Pulsating spring in bed of hot steam.	Mud pot.	Spring on edge of pool covered with black froth.	Mud pot.	Muddy spring covered with a mirror of pyrite.	Hot spring in clear pool, vigorously spouting at times, alkaline.	Slightly turbid pool, bubbling all over, alkaline.	Hot pool with floating mirror of pyrite.	Fountain in the area of recent outbreak.
Temperture °C.	85°	93°	91°	93.5°	92.5°	61°	....	92.5°	91° in 1916 83° in 1922	65°	86°	93°
Composition:												
CO_2....	91.70	92.10	90.20	91.90	96.15	95.75	95.65	93.65	92.20	90.10	93.20	89.80
H_2S....	.55	none	.50	trace	.80	.35	.40	.25	.55	.45	1.95	none
CO....	none	none	none	....	none	none	none	....	....	....	none	none
CH_4...	.20	.20	.20	.20	.15	.15	.20	.15	.20	.20	.20	.20
H_2.....	.45	.80	.90	.50	none	.40	.25	.30	.30	.80	.30	.30
N_2[2]....	7.12	6.51	8.20	7.05	2.86	3.35	3.55	5.70	6.42	8.27	4.25	9.00
A......	.08	.09	....	....	.04	....	.....	....	.08	.13	....	....
O_2.....	none	.30[3]	.05	.20	none	none	none	none	.20	.10	none	.55[1]
	100.10	100.00	100.05	99.85	100.00	100.00	100.05	100.05	99.95	100.05	99.90	99.85
$\frac{A}{A+N_2}$....	1.07	1.43	....	....	1.29	....	.....	....	1.31	1.57	....	....

[1] Collected in August 1923.
[2] Where argon is undetermined it is included with nitrogen.
[3] The care which was taken in the collection of these samples suggests that the gas contained air which entered near the surface of the ground.

Bumpass Hell.

	No. 4. Simmering pool, yellow with precipitated sulphur.	No. 9. Spouting spring, muddy.	No. 10. Pool of slightly turbid water bubbling over whole surface.	No. 12. Hot spring within the border of a hot pool.	No. 14, (western pool.) Muddy pool heated by spouting springs.	No. 14, (eastern pool.) Muddy pool heated by spouting springs.	No. 16, (eastern end.) Slightly turbid pool in big slumphole.	No. 17. Very large mud pot.
Temperature, ° C.	84–85°	88.5°	63°	87.5°	91.5°	90°	......	......
Composition:								
CO_2.........	95.05	94.80	93.80	95.40	93.05	93.70	96.40	94.70
H_2S.........	.55	.60	.60	.55	.55	.40	.50	.60
CO.........	none	none	none	none	none	none	....	none
CH_4........	.15	.15	.15	.15	.20	.15	.15	.15
H_2.........	.30	1.15	1.20	.95	.45	1.05	.65	.95
N_2[1].........	3.85	3.25	3.75	2.90	5.38	4.60	2.20	3.50
A...........	.05	......	......	......	.07	......	......	.05
O_2..........	.10	none	.35	.05	.25	.10	.10	.05
	100.05	99.95	99.85	100.00	99.95	100.00	100.00	100.00
$\frac{A}{A + N_2}$.....	1.23	......	......	......	1.31	......	......	1.31

[1] Where argon is undetermined it is included with nitrogen.

reducing gases remain in excess, but occasionally an excess of oxygen may creep in. Such a situation would be most likely to arise where the ground was seamed or otherwise rendered more pervious than elsewhere. It is a significant fact that several samples of gas collected by two different persons along a line of recent subsidence in the Devil's Kitchen should all contain distinctly more oxygen than the average, namely, 0.3 per cent in sample No. 23, 0.55 per cent in No. 24, and 2.85 per cent in No. 25. The analysis of No. 25 has been omitted from table 6.

From their composition alone the gases might have been adjudged to be volcanic,[1] but any possible doubt of the fact should be dispelled by the circumstances of their occurrence, while the constancy of their composition indicates that they are all derived from the same batholith. The gases exhaled from a magma in the earlier stages of volcanism usually contain more carbon dioxide than any other gas except steam. In the last stages represented by these hot springs the carbon dioxide remains, while the chemically active constituents like the sulphur gases[2] and the halogen acids have been partially removed by reactions within the magma which result from falling temperature, or reactions with the mineral substances with which they come in contact on their way to the surface. Any very soluble gases like SO_2, HCl, and HF would, if originally present and not otherwise removed, remain behind in the spring waters. Not until the waters became alkaline (p. 164) would the carbon dioxide be retained by formation of carbonates and bicarbonates, the amount of it taken up depending on the degree of alkalinity of the waters. Only four alkaline springs were found in the Lassen district, and these all contained very little bicarbonate. Gases collected from two of them were only a little below the average in carbon dioxide.

TABLE 7.

	In 100 parts of natural gas.	
	Soffione Casotto.	Soffione Tini.
Sulphuretted hydrogen	2.070	2.000
Carbon dioxide	92.800	92.000
Methane	1.400	1.900
Hydrogen	2.600	2.400
Oxygen	0.050	0.200
Nitrogen	1.048	1.455
Argon	0.021	0.029
Helium	0.010	0.014

In the endeavor to reach an understanding of the relations which volcanic emanations at various stages of activity bear to one another, it will be well to cite here the analyses of two gases from the Larderello region in Tuscany, by R. Nasini[3] and his associates (table 7). Although they were collected from *fumaroles*, which,

[1] For the composition of volcanic gases in general, see E. T. Allen, Chemical aspects of volcanism, Journ. Franklin Inst. 193, 29–80, 1922. Appendix.

Hague regards the gases from the Yellowstone hot springs as of surface origin (Bull. Geol. Soc. Amer., 22, 117, 1911).

[2] Bunsen states that the H_2S in the gases of Krisuvik varies much more than the CO_2 because of the chemical action of the former on the rocks of the region (*Ann. chim. phys.*, 38, 266, 1853).

[3] *I soffioni boraciferi* etc. Rome, 1906, p. 82.

judging from the context of Nasini's account, possessed a temperature of about 180° C., the gases bear a remarkable resemblance to those from the Lassen springs, differing chiefly in the somewhat higher percentage of marsh gas and the presence of helium.

Some of the geysers of Iceland,[1] according to Thorkelsson, are giving off gases which consist almost exclusively of nitrogen and argon. As the waters of geysers are almost invariably alkaline, the original carbon dioxide may have been entirely absorbed and retained in the water as carbonate and bicarbonate, or partially transformed into other less soluble carbonates like those of calcium and magnesium. But if so, what has become of the unabsorbed gases like hydrogen or marsh gas, or were none of these contained in the original gases? The nitrogen and argon are regarded by Thorkelsson as of atmospheric origin. The solfataric districts of Iceland give off gases much richer in hydrogen[2] and hydrogen sulphide than those of the Lassen Park, but without a detailed knowledge of the Iceland springs it would be unwise to venture any explanation of the difference.

TABLE 8.—ANALYSES OF GAS FROM THE HOT SPRINGS AND GEYSERS OF THE YELLOWSTONE NATIONAL PARK.

[By F. C. Phillips.]

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
Carbon dioxide	1.32	27.88	18.80	82.85	83.69	44.18	94.65	92.57	98.67	98.68	51.74	77.99
Oxygen	3.50	6.25	11.25	1.53	1.57	6.26	0.60	1.74	0.66	0.06	3.71	0.23
Hydrogen	0.10	0.25	0.71	1.82	0.59	4.02	1.10	0.70	0	0.17	0	2.16
Methane	0	3.28	0	trace	3.80	trace	0.91	trace	0	0	0	0.30
Hydrogen sulphide	0	0	0	0	0	0	0	0	0	0.46	0	0.96
Nitrogen	95.08	62.34	69.24	13.80	10.35	45.54	2.74	4.99	0.67	0.63	44.55	18.36
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

I. Artemesia Geyser, Upper Geyser Basin.
II. Asta Spring, Hillside Group, Upper Geyser Basin.
III. Bottomless Pit, Chain Lake, Upper Geyser Basin.
IV. Fissure Group, Ebony Springs, No. 33, Lower Firehole Basin.
V. Fountain Geyser, Lower Firehole Basin.
VI. Coral Spring, Norris Geyser Basin.
VII. Echinus Geyser, Norris Geyser Basin.
VIII. Cleopatra Spring, Mammoth Hot Springs.
IX. Sulphur Spring, Mammoth Hot Springs.
X. Mammoth Hot Springs.
XI. Blue Glass Spring, Shoshone Geyser Basin.
XII. Taurus Geyser, Shoshone Geyser Basin.

The gases from some hot springs and mud pots consist almost wholly of marsh gas. Of its origin we have as yet but meager evidence, and must content ourselves here with pointing out what appears to be a general rule and a rational one, that the preponderant constituents of hot-spring gases CO_2, $N_2 + A$, and CH_4 are in the chemical sense all comparatively inactive at low temperatures. A decided exception to the rule is found in the analyses of gases from the hot springs of the Yellowstone Park by F. C. Phillips (table 8).[3] Most of these analyses contain oxygen in

[1] *Memoires de l'Academie royale des Sciences et Lettres de Danemark*, 8, 252, 1910.

[2] See Thorkelsson's tables. The hydrogen in these gases may have been augmented by the action of a part of the hydrogen sulphide on the *tin* collecting tube used (op. cit., p. 215).

[3] These analyses, which were found in the archives of the U. S. Geological Survey, are published by permission of the Director of the Survey. They were made in the eighties by Professor Phillips and would doubtless have appeared in Hague's monograph of the Yellowstone Park had he lived to complete it.

very unusual quantities, and one would be inclined to suppose that air crept in either during the collection or in the course of the analysis of the gases. In a private communication to the authors Dr. Walter Harvey Weed, who collected the gases, states that the method used was discussed with the late Professor Hallock, who was interested in the investigation, and that it was concluded by them that no air could have gotten in during the collection. Except for the oxygen, many of these gases are strikingly similar to those from the Lassen district.

A larger body of evidence, carefully worked out on the ground, will be needed before it will be possible to give a complete account of the changes through which volcanic gases pass in the course of their history.

Considering now the ratio of argon to nitrogen in the gases under discussion, it was explained above (p. 129) that the method employed in analysis was subject to error when the gases to be analyzed were related in a different ratio from that in the atmosphere. The results show that the ratios are not far from the same; the average of the determinations for $\frac{A}{A + N_2}$ is 1.33, while that in the air is 1.18. Considering the small quantities of gas (2.2 to 10.2 c. c.) taken for analysis, these differences are believed to be within the limits of experimental error.

Our conclusion is that the nitrogen and argon present are probably chiefly of atmospheric origin. We say *chiefly* rather than *entirely* because a *portion* of the gas might be magmatic and might contain a somewhat larger percentage of argon, while the total amount in the gas handled would be too small to enable us to settle the point by the method used.

Finally, there is another point of importance not revealed by the analyses, but legitimately inferred from sound knowledge. All volcanic gases, with few exceptions, whether collected from molten lava or from fumaroles, contain more steam than any other gas and, though much of this steam may be of surface origin, the unaltered igneous rocks when heated almost invariably give off more steam than all other gases put together. It follows that the gases which escape from volcanic hot springs should also have been accompanied by water in relatively large amount when they emerged from the batholith which originally contained them.

CHAPTER III.

CHEMICAL EFFECTS OF THE HOT WATERS AND GASES

CHEMICAL CHANGES IN THE SPRINGS.

The character of the spring sediments, the composition of the waters, the gases, and the lavas [1] of the region, when correlated with observations in the field, constitute a very satisfactory body of evidence for the interpretation of certain chemical changes which are in progress in these springs. There are two principal processes. The first is the formation of pyrite.

Formation of Pyrite.

The peculiar feature in this occurrence of pyrite is the great number of minute detached crystals completely bounded by crystal planes, not the incompletely developed fragments which would be left by the disintegration of a rocky matrix inclosing it. The Lassen lavas sometimes contain a few scattered grains of pyrite, but not such crystals as are found in the springs. The latter could result only from the formation of pyrite from the waters themselves. The occurrence of the microscopic aggregates, which occur in the black sediments previously described, suggests a first stage in the process. There is another point of almost equal weight. The conditions in the springs are strikingly similar to those found in the laboratory to be essential to the formation of pyrite, namely, the coexistence of ferrous salt, hydrogen sulphide, and sulphur.[2] The sulphur is not always observed in the springs, but contact with atmospheric oxygen is all that is necessary for its liberation from hydrogen sulphide. This may take place directly or through the intermediate agency of ferric iron:

$$(1)\quad 2FeSO_4 + H_2SO_4 + O = Fe_2(SO_4)_3 + H_2O$$

$$(2)\quad Fe_2(SO_4)_3 + H_2S = 2FeSO_4 + H_2SO_4 + S$$

Oxidation of some hydrogen sulphide by the ferric iron in the lavas during the process of their decomposition by the acid waters, which will be explained presently (p. 138), is also entirely probable.

The formation of pyrite is not to be regarded as confined to the springs alone. The presence of similar conditions below ground should lead of course to the same results.

There is an interesting fact about the pyrite samples collected in the hot springs and hot streams to which we wish to direct attention. The crystal forms in them were not distributed haphazard. In some samples the cube was developed almost to the exclusion of other forms, in other samples the octahedron. The pyritohedron was also observed, but not commonly. The conditions which determine

[1] For analyses of many lavas from Lassen National Park, see F. W. Clarke, U. S. Geol. Survey Bull. 419, 139, 1910.

[2] Allen, Crenshaw, Johnston and Larsen, Am. Journ. Sci. (4) 33, 169, 1914. See also Amer. Journ. Sci., 38, 371, 1914.

the crystal form constitute of course a very obscure problem, but here we have pyrite in the making under conditions which vary from place to place sufficiently to determine what crystal form shall develop. It ought to be possible for the crystallographer to find out what these differences are, or at least to gain important information on the subject.

Absence of Marcasite.

Marcasite has not been found in any of the hot-spring areas under discussion. In experiments made in this Laboratory several years ago[1], *some* marcasite was always found mixed with the pyrite when the solutions from which the minerals crystallize were *acid*. The *amount* of the marcasite decreased with decreasing acidity and no experiments were tried with a degree of acidity as low as that in these natural waters. The conclusion from the laboratory experiments was that some marcasite is always formed when the disulphide of iron crystallizes from acid solutions. This now appears to have been too sweeping. Nevertheless, marcasite is sometimes a product of hot-spring waters. In the Katmai region, Alaska,[2] marcasite was found in boiling hot springs (temperature 97° to 98° C) under circumstances which left no room to doubt that it was formed by the waters; it occurred in thin botryoidal crusts deposited on pumiceous material in the beds of the springs. Unfortunately the composition of the waters was not ascertained, but there is good reason to believe they contained free acid, for the fumaroles in the vicinity commonly emitted hydrochloric and hydrofluoric acids. So far as its *amount* is concerned, pyrite forms but a very small portion of the sediments; the importance of its occurrence lies in the bearing which the observations may have on the conditions of formation of a widely distributed mineral.

Origin of Sulphuric Acid.

Another chemical process which is going on in the springs is of a more general character, involving the major part of the sediment. This is the decomposition of the lavas by the hot waters; but before discussing that it will be necessary to consider the formation of the sulphuric acid which occurs as normal or acid sulphates in all the springs, without exception.

Sulphuric acid appears to be an active agent of decomposition in all solfataric areas. Various explanations of its origin have been given, all of which depend on the oxidation of some sulphur-bearing substance, primary or secondary. To be sure, the acid has been detected[3] in that portion of fumarole gases which is absorbed by water, especially gases which contain sulphur dioxide, but this is almost certainly the product of atmospheric oxidation. Whether it is formed near the surface of the ground and carried along as a spray or whether it is the result of oxidation in the course of the collection of the gas is a matter of doubt.

[1] Effect of temperature and acidity in the formation of marcasite (FeS_2) and wurtzite (ZnS); a contribution to the genesis of unstable forms. E. T. Allen, J. L. Crenshaw and H. E. Merwin, Am. Journ. Sci. (4), 38, 393, 1914.

[2] Allen and Zies, A chemical study of the fumaroles of the Katmai region, Nat. Geog. Soc., Contributed Technical Papers, Katmai Series, No. 2, p. 97, 1923. The many deposits of fine disseminated marcasite in the pumice of Lake Rotorua, New Zealand, may also be a product of solfataric action. (See Park, Geology of New Zealand, p. 178, 1910.)

[3] Journ. Franklin Inst., 193, 29 (Appendix), 1922.

Park[1] attributes the sulphuric acid and sulphates in the hot springs of New Zealand to the oxidation of pyrite. A steady supply of acid from this source for a long period of time would demand a large body of pyrite. It is conceivable that such a body might be formed during an earlier (fumarole) stage of volcanic activity, and that subsequent oxidation might ensue as a result of the waning emanation of hydrogen sulphide, bringing the formation of pyrite to a close in some places and allowing access of air.

Bunsen[2] regarded the sulphates in the Icelandic hot springs as an oxidation product of secondary sulphur dioxide by air or by ferric iron. The sulphur dioxide was supposed to be formed by the chemical action of sulphur vapor on the ferric oxide in the basaltic rocks of that region. Bunsen's hypothesis does not apply satisfactorily to the facts observed in the Lassen district, for sulphurous acid is never found in the vicinity of the springs, while if it were a primary emanation some of it ought surely to escape oxidation and make its way to the surface.

Sulphuric acid, together with hydrogen sulphide, may be formed by the action of water on elementary sulphur. At 100° the action is negligible, for satisfactory determinations of the vapor pressure of sulphur have been made by volatilizing it in a current of steam at that temperature. At 250°, and possibly as low as 200°, the action is rapid enough to account for such amounts of sulphuric acid, free and combined, as are found in the springs under discussion. It is doubtful whether such temperatures exist in this region at depths accessible to ground water, but a more important objection to accepting the hypothesis is the conclusion already reached on the basis of several facts that sulphur is not a primary emanation here (p. 120). Small amounts of sulphuric acid may arise here and there in these hot-spring areas from the oxidation of secondary pyrite, but to account for a continuous supply of the acid for any considerable period of time, the oxidation of hydrogen sulphide constitutes the most probable explanation, because this gas is constantly escaping from the springs and is generally distributed in all the areas.[3]

The oxidation may be accomplished either by ferric iron or by air or by both. The oxidation of hydrogen sulphide to *sulphur* by either reagent is the reaction best known to the chemist, but oxidation to *sulphuric acid* has also been established. Stokes[4] found that hot dilute ferric chloride oxidized about one-third of the sulphur in hydrogen sulphide to sulphuric acid. Experiments made in this laboratory indicate that if the gas reacts with ferric *oxide* rather than ferric salts, at a temperature of 140°, the sulphur forms pyrite but no sulphuric acid. In this case some preliminary oxidation of the hydrogen sulphide with air would be necessary before the formation of sulphuric acid by ferric iron in the silicates could proceed. As further evidence for these reactions some experiments by Deville and Dumas may be cited. Deville[5] observed that a mixture of hydrogen sulphide, steam and air, corresponding to the gases of many volcanic fumaroles, with rock fragments, in a

[1] Geology of New Zealand, p. 178, 1910.
[2] *Liebig's Annalen*, 62, 10, 1847; *Ann. Chim. Phys.*, 38, 272, 1853.
[3] Drake's Springs may be an exception. No gases were observed to escape from these waters and the odor of hydrogen sulphide was not noticed, but more careful observations would be needed to settle the question.
[4] Bull U. S. Geol. Survey, 186, p. 19; see also Gmelin-Kraut. 6th ed., I, pt. 2, p. 219.
[5] *Compt. rend.*, 35, 261, 1852; *Jahresb. der Chemie*, p. 919, 1852.

few months formed sulphates of the alkalies and alkaline earths, while Dumas[1] found that sulphuric acid was gradually formed when hydrogen sulphide and air are brought into contact with some porous substance at 40° to 50° and more rapidly at 80° to 90°.

The evidence thus goes to prove that hydrogen sulphide may be and probably is *directly* oxidized to sulphuric acid under the conditions prevailing in the hot-spring basins, but not all of it necessarily changes in this way. The free sulphur often observed at the surface of the ground is most probably an oxidation product of hydrogen sulphide by the better-known reaction ($H_2S + O = H_2O + S$), for it is commonly found where the conditions obviously favor oxidation. Thus it was noticed in several places incrusting rocks over which a thin sheet of warm spring water was flowing (fig. 72); it was found in needle-like crystals lining fumaroles and

Fig. 72.—June, 1923. Sulphur bearing pools at Supan's Springs. Photo Day.

ground cracks where hydrogen sulphide was issuing; in fact wherever it occurred the sulphur was readily accounted for in this way.

Sulphur, whatever its origin, doubtless contributes its share to the sulphuric-acid supply, for while stable in dry air, in moist air[2] it slowly oxidizes. In this region the warmth of the ground would of course be a contributing factor to the oxidation.

Chemical Decomposition of the Lavas.

The chemical decomposition of the lavas is of interest in several respects; it involves the formation of kaolin and is intimately related to the origin of the springs. The foregoing data enable us to interpret the process with comparatively little hypothesis. The active agents are hydrogen sulphide and especially sulphuric acid. When sulphuric acid decomposes a silicate the final products are free silica and the

[1] *Ann. chim. phys.*, 18, 502, 1846.
[2] Maly, *Monatshefte Chem.*, 1, 205, 1880; see also Gmelin-Kraut, 7th ed., vol. I, pt. 1, 377, 1907.

sulphates of the metals contained in the silicate, and these products are found in all the springs. With them occur two other products of intermediate composition, namely, *kaolin* and *alunite*. Kaolin, $Al_2O_3.2SiO_2.2H_2O$, contains silica still unliberated and alumina as yet unchanged to sulphate. Alunite, $K_2O.3Al_2O_3.4SO_3.6H_2O$, contains no silica, but it requires more sulphuric acid to transform its bases into normal sulphates; it is a basic sulphate.

SIGNIFICANCE OF THE OCCURRENCE OF KAOLIN.

Kaolin is well known to geologists as a decomposition product of certain silicates, especially plagioclase feldspars, by the action of cold dilute sulphuric acid, which commonly originates in such situations from the atmospheric oxidation of pyrite. In the springs of the Lassen National Park kaolin is the product of *hot* dilute sulphuric acid on the rock silicates, or some of them.

Lindgren [1] contrasts the formation of *kaolin* with that of *sericite*, the former as a product of *cold descending* waters, the latter as a product of *hot ascending* waters. Observations in the Lassen region show pretty clearly that it is not the *temperature* nor the direction of flow, but the *chemical nature* of the water which is of vital importance. Kaolin is the product of acid waters, whether cold or hot; where sericite is formed the waters are presumably alkaline. When the waters are acid, temperature may determine which of the clay minerals (kaolinite, halloysite, leverrierite) is found, but some clay mineral not sericite is formed in both cases.

A knowledge of the limiting conditions which determine the formation of the different clay minerals would be very useful in problems of this character, but an investigation of the subject is at present unpromising on account of the low capacity for crystallization of these minerals.

SIGNIFICANCE OF THE OCCURRENCE OF ALUNITE.

Kaolin, though comparatively refractory, is slowly decomposed by hot sulphuric acid,[2] the final products being silica and aluminum sulphate. It would therefore not be formed if the concentration of the acid were sufficiently high.

In composition alunite is a connecting link between kaolin and aluminum sulphate, but this of course does not necessarily give the key to its formation. It may follow kaolin as a product of further action by sulphuric acid, or it may be a precipitate subsequent to the formation of the soluble sulphates. The complex aggregates of alunite with opal and kaolin which are found in the sediments suggest rather that the three substances are contemporaneous products of the action of sulphuric acid on feldspars or volcanic glass.

In some places in this district alunite has been deposited in a comparatively pure state. Thus, a mound about 15 feet high, bordering the pool in the Devil's Kitchen marked No. 1 on the map, consists of alunite, at least on the surface (fig. 73). J. S. Diller discovered some years ago considerable amounts of this mineral at Supan's Springs. At present no explanation for its segregation can be offered.

[1] Economic Geology, 10, 89, 1915; see also Mineral Deposits, p. 305, 1913.
[2] Alexander Sabeck, *Chem. Centralblatt*, p. 779, 1902.

SILICA THE FINAL RESIDUE OF ROCK DECOMPOSITION.

With the possible exception of Drake's Springs, where a copious vegetable growth conceals the ground, the lava in all the hot-spring areas has been more or less completely decomposed by chemical action. Alteration has been most complete at Bumpass Hell, where practically every foot of the ground (Plate 12) has been bleached and disintegrated. A sample of the product from the surface of the hill adjoining the area on the southeast proved to be nearly pure opal with a little unchanged quartz and pyroxene (Merwin). It contained 94.79 per cent SiO_2, 3.05 per cent H_2O, 1.18 per cent Al_2O_3, etc., and very small amounts of other oxides. In the sample the banded structure of what was doubtless originally lava could be

Fig. 73.—June, 1923. Spouting Spring in the Devil's Kitchen (No. 3, Fig. 47). White alunite mound in background at the right. Photo Day.

plainly seen. This silica is obviously an example of lava decomposition with acid, and there is no reason to doubt that the acid has the same origin as that which occurs in the springs, namely, the oxidation of hydrogen sulphide and secondary sulphur by atmospheric oxygen and ferric iron. This general decomposition implies a wider distribution of gases, either past or present, than the observer might at first suppose. It is quite probable that these hot springs were preceded by a more active stage of volcanism in which hotter gases were emitted in greater volume than now, and that when the thermal activity declined it became extinct in some places. This is the normal course of change in fumarole regions.

Even to-day volcanic gases are probably slowly permeating the ground and escaping outside the spring and fumarole vents, for there are numerous barren areas in the spring basins that show no visible sign of present activity at the surface, where steam and abnormal temperatures are found but a few feet below it. Thus, in July 1922 a temperature of 94° was found only 2 feet below the surface at a

July 10, 1915. Spouting Spring (No. 14, Fig. 50) at Bumpass Hell. Photo Day.

PLATE 12

distance of 130 feet from the Boiling Lake (northwest end) and farther still from any active vent. The ground was bare, but no visible steam or water was escaping from it. Exploration both at the Boiling Lake and the Devil's Kitchen revealed many similar spots. The instance cited is unusual only in the greater distance of the place from an active vent. If the steam in these places is volcanic, or partly volcanic as we conclude, it must be accompanied by other volcanic gases, including hydrogen sulphide. The latter would become at least partially oxidized, for wherever the gases find egress, air will gain access unless the gases are escaping under high velocity, which is never the case except in well-defined vents.

That the decomposed lava of the barren ground in the hot-spring basins has gone chiefly to silica, like that at Bumpass Hell, has been inferred from the uniformity in its appearance. The subject deserves further study, but there is other evidence bearing on it. Thus, the salts which occur in places on this barren earth have invariably proved to contain more alumina than any other base, as do the

Fig. 74.—June, 1922. Western half of pool No. 14 Bumpass Hell. (Cf. Plate 12.) Photo Day.

lavas from which the salts were derived. The *complete* decomposition of the lavas by sulphuric acid would result in the liberation of silica and the formation of salts of the same character.

These salts are quite certainly not a product of the evaporation of spring waters, as was thought at first, for most of the springs contain hardly any alumina. Only the most acid waters, like those of No. 6 and No. 14 (Bumpass Hell, figs. 65, 74) and No. 5 (Devil's Kitchen), could yield such salts, and then only on condition that, through some chemical reaction, the acid hydrogen in them could be nearly all replaced by an equivalent of aluminum. There can be little doubt that these salts and the decomposition process which gives rise to them are the result of fumarole action. An illuminating bit of evidence on the point was found at the Geyser, where an insignificant fumarole was emerging from under a rock. A highly aluminous salt mixture (No. 43, table 4), mingled with opal and rock débris, occurred about the orifice of the fumarole, *but no kaolin*. The salts collected on the summit of Lassen Peak, which are of the same character so far as the bases are concerned, must be assumed to form by fumarole action, for there are no hot springs there.

TWO TYPES OF LAVA DECOMPOSITION CONTRASTED.

In the Lassen spring basins, therefore, two types of lava decomposition appear to be in progress, the one producing *kaolin* and some silica *without aluminum sulphate*, the other producing *silica with aluminum sulphate*. In the fact that kaolin is decomposed by strong sulphuric acid into silica and aluminum sulphate, the key to the difference is doubtless to be found. If the acid forms in a place where sufficient water is percolating, its concentration is kept down to such a value that the decomposition of feldspars, volcanic glass, and possibly other minerals is incomplete. The intermediate and comparatively stable compound *kaolin* results, and this, as we have seen, generally occurs in the springs, together with very dilute acid. It would not be surprising if the fine sticky mud of the low and wetter portions of the Devil's Kitchen and Bumpass Hell should also prove to contain kaolin, but observations have not been extended to these points.

On the other hand, if sulphuric acid forms in nearly dry ground it will accumulate by progressive oxidation of the sulphur gases and the concentration may reach comparatively high values—probably in the form of sirupy films. It is under such conditions that this more complete type of rock decomposition occurs, as field observations indicate.

It may be questioned by some whether sulphuric acid ever occurs in nature otherwise than in very dilute condition. Some mineral specimens collected by the authors in a fumarole area of Sonoma County, California, and recently examined by Dr. Merwin and ourselves, have an important bearing on this point. One of them consisted of a lower hydrate of magnesium sulphate and some free sulphuric acid. While the heptahydrate, epsom salt, is ordinarily obtained from water, this hydrate crystallizes from a certain concentration of free sulphuric acid. The other specimen contained two acid ammonium sulphates. The simpler one, NH_4HSO_4, will not crystallize from an aqueous solution containing less than about 30 per cent free sulphuric acid. Mr. Augustus Locke recently brought to this Laboratory a mine specimen from Arizona in which was identified an *acid* ferric sulphate, $Fe_2O_3.4SO_3.9H_2O$. The salt occurred close to a layer of pyrite and was undoubtedly formed by its oxidation. The same salt was obtained artificially by Posnjak and Merwin[1] from solutions containing not less than about 45 per cent free sulphuric acid. The statement assumes that an equivalent amount of SO_3 is in combination with Fe_2O_3 as $Fe_2(SO_4)_3$.

It should be noted that the majority of the salts collected in the Lassen Park contain free sulphuric acid, or are acid salts (table 4). These facts constitute good evidence that sulphuric acid of comparatively high concentration may occur in nature under favorable conditions, doubtless for a limited time and probably in the form of sirupy films in dry ground.

[1] Journ. Amer. Chem. Soc., 44, 1991, 1922.

These films of acid and the salts they form are doubtless washed down into near-by springs or outlets in the wet season. Whether the amounts which accumulate at any one time and place are great enough to change materially the composition of the waters is a question. The table, as has been pointed out, shows water analyses which are relatively high in acid and alumina.

Formation of Pentathionate.

Pentathionate, which was found in the salts from the eastern rim of the Lassen Crater, has been reported in nature but once before; it was discovered by McLaurin [1] in the water of the crater lake on White Island in the Bay of Plenty, New Zealand. Its formation at Lassen Peak is not entirely clear, but there is little doubt that it is the decomposition product of the lava by the two sulphur gases, hydrogen sulphide and sulphur dioxide. Both gases were proved to occur there in 1916, and it is by the interaction of the two gases at low temperatures that pentathionic acid has been prepared.[2] Moreover, no thionates were found in the salts from any other locality, nor was any sulphur dioxide found elsewhere. The gases from a large and active fumarole, occurring close by the spot where the salt sample was found, were collected by pumping approximately 100 liters of gases through an absorption train filled with solid barium hydroxide. The analysis was made by E. S. Shepherd on the principle of the difference in solubility between sulphite and sulphide of barium: that is, the soluble sulphur was reckoned as hydrogen sulphide, the insoluble as sulphur dioxide. Similar gases were collected on the south rim of the crater by Shepherd in 1915. The reader will note that the analyses account only for those gases *retained* by the barium hydroxide, which form a very small part of the whole, but all the sulphur and halogen gases are doubtless included.

Table 9.—Gases soluble in $Ba(OH)_2$. Per cent by volume.

Fumarole on Lassen Peak, east side of crater of 1914; collected in June 1916.		Fumarole on south side of old crater; collected by E. S. Shepherd, June 1915.	
CO_2	0.096	CO_2	0.040
SO_2	.054	SO_2	.005
H_2S	.005	H_2S	.004
HCl	none		
HF	none		

While the two sulphur gases react with each other at low temperatures, there is good ground for assuming that they may coexist at high temperatures. The gases, as they issued from the fumaroles, had an overpowering, pungent odor like sulphur dioxide. Of course, there was no means of testing for hydrogen sulphide in its presence. If one is inclined to be skeptical of the coexistence of the two gases in the same fumarole, it is at least certain that hydrogen sulphide was issuing from ground cracks close by, as it was recognized by the odor and by the lead-paper test.

[1] McLaurin, Proc. Chem. Soc., 27, 10, 1911; see Clarke's Data of Geochemistry, Bull. U. S. Geol. Survey, 695, 195, 1920.
[2] Wackenroder, *Liebig's Ann.* 60, 189, 1846; Debus, *Liebig's Ann.* 244, 76, 1887.

What must remain unexplained for the present are the conditions of temperature, etc., under which the thionate was formed. At low temperatures in the presence of water, thionic acid, as well as much sulphur, is obtained by the commingling of the gases. At ordinary temperature the products are supposed to be sulphur and water, but possibly a certain amount of some thionic acid is also formed. Pentathionates are unstable, but much less so in the presence of free acid. In accord with this fact sample No. 52, which contained acid salts, showed no diminution in the amount of thionate after 18 months.

It will be seen in table 4 that these peculiar salts from Lassen Peak, like those from the other localities, contain more sulphate than any other acid radical—a fact indicating that here also oxidation of the sulphur gases is an important process in the genesis of the salts.

Sulphur dioxide, upon which the formation of pentathionate probably depends, has been previously regarded as a product of higher temperatures than hydrogen sulphide, as it probably was at Lassen Peak in 1916. Bunsen [1] states that hydrogen sulphide followed sulphur dioxide in Iceland after the eruption of 1845, but whether this is indicative of surface oxidation of the hydrogen sulphide in the earlier and hotter stages of volcanic activity, or a change in the nature of the primary gases, remains unsettled.

Significance of Hydrochloric Acid in the Crater Gases.

Contrasted with the very slight amount of chlorides in the hot-spring waters and the salts of the hot-spring areas was the occurrence in 1916 of salts rich in chlorine in certain parts of the Lassen crater. These salts, as has been already remarked, were quite obviously derived from volcanic gases escaping from adjacent crevices in the lava and responding to tests for hydrochloric acid. The gases possessed the characteristic odor, reddened blue litmus, and reacted with silver nitrate in the usual way. The salts were in all probability formed by the reaction of the acid and lava rather than by sublimation. Neither the salts nor the gases were anywhere copious. This occurrence was strictly confined to the crater; in the fumaroles outside the rim from which gases were taken (p. 145) no hydrochloric acid was found.

According to Bunsen, the evolution of hydrochloric acid as a volcanic gas is dependent upon a "shallow hearth." [2] When the hearth sinks he believes that the acid reacts with the wall rock, forming non-volatile compounds. At Katmai, where hydrochloric acid is generally prevalent, it occurs in larger quantities in the hotter fumaroles and almost dies out at 100°.[3] This is probably a consequence of the fixation of the acid in the walls of the fumarole at the lower temperatures.

At first thought a similar explanation appeared to apply to the distribution of hydrochloric acid at Lassen Peak. The acid was found in the gases of the crater, where the climax of activity and doubtless the hottest temperatures were represented, while chlorides [4] were not found in the hot-spring areas which are typical

[1] *Ann. chim. phys.*, 38, 274, 1853.

[2] *Ann. chim. phys.*, 38, 262, 1853.

[3] Allen and Zies, Nat. Geog. Soc., Contributed Technical Papers, Katmai Series, No. 2, p. 150. 1923.

[4] For the relation between chlorides in hot-spring waters and magmatic hydrochloric-acid gases see p. 164 *et seq.*

of a declining stage of volcanism. But the facts as a whole do not support this view. The fumaroles on the outside rim of the crater were giving out hotter gases in 1916 than the gases in the crater where the hydrochloric acid was found, and in 1922, when the highest temperature in the crater was 79° C. and only the faintest wisps of steam were discernible, hydrochloric acid could still be detected in the gases.

The distribution of hydrochloric acid at Lassen Peak is not, therefore, well accounted for by assumed temperature differences in the magma or magmas where the gas originated, and at the present time there is no satisfactory explanation for it.

TABLE 10.—THE RATIOS $\frac{Ca}{Mg}$ AND $\frac{Na}{K}$ IN THE HOT SPRING WATERS.

No.	$\frac{Ca}{Mg}$	$\frac{Na}{K}$	No.	$\frac{Ca}{Mg}$	$\frac{Na}{K}$
1	0.9	...	37	2.9	5.2
2	1.2	...	60	0.9	3.8
3	1.6	...	62	2.1	[14.]
13	1.5	6.4	63	1.1	5.5
15	∞	7.5	64	∞	[18.]
21	2.0	4.2	125	1.0	5.0
22	[5.0]	8.5	128	1.0	7.5
221	[9.0]	7.1	131	2.3	5.8
23	2.1	6.4	331	1.2	8.1
29	1.4	7.7	362	∞	4.6
30	1.6	8.1	400	2.5	5.6
31	1.9	7.0			

UNIFORMITY OF ROCK DECOMPOSITION.

The analytical determinations on the spring waters throw some additional light on the processes of rock decomposition. The molecular ratio $\frac{Ca}{Mg}$ in the waters, reckoned from the results in table 2, shows a rough approximation to constancy (See table 10). In three waters, 15, 64, and 362, where no magnesium was found, the ratios are erratic, and the same is true of two of the alkaline [1] waters, but otherwise the variation for natural waters is slight. The limits are 0.9 and 2.9.

The $\frac{Na}{K}$ ratios, with two exceptions, also vary within comparatively narrow bounds, namely from 3.8 to 8.5. The exceptional ratios belong to waters from springs without visible outlet, in which an unusual amount of potassium had precipitated as alunite. F. W. Clarke [2] has compiled about 20 analyses of dacites and andesites from this region. From his figures, omitting one peculiar analysis, we reckon the average $\frac{Ca}{Mg}$ ratio for the dacites as 1.2 and the limits 0.3 and 1.9. The average ratio for the andesites is 1.7, with 1.2 and 2.0 as the limiting values.

[1] Analyses 22 and 221 of spring 19, Devil's Kitchen (table 3).
[2] U. S. Geol. Survey. Bull., 419, p. 139. 1910.

The $\frac{Na}{K}$ ratio averages 2.6 in the dacites, with 1.4 and 4.0 as the limiting values, while the average for the andesites is 3.6, with 1.5 and 5.5 as limiting values.

Comparing the ratios deduced from the water analyses with those deduced from the rock analyses, the former are seen to agree somewhat better with the andesite ratios. The $\frac{Ca}{Mg}$ ratios are remarkably close; the $\frac{Na}{K}$ ratios are higher in the waters than they are in the andesites, though the difference between the

Fig. 75.—July 2, 1915. Eastern end of the Devil's Kitchen showing encrusted ground and sulphur pools. Photo Day.

limits in both cases is about the same. The precipitation of potassium as alunite in the waters would of course raise the ratios. The amount of alunite in the sediments is always small, though more may be precipitated below ground.

The remarkable fact about these ratios is that they approach as closely as they do to similar ratios in the lavas. This agreement does not imply any uniformity in the rate at which the rock is decomposed. Of course, the various minerals in the rock must decompose at different rates, and the varying concentration of the salts in the spring waters shows that the acid concentration also must vary in different parts of the field. What the results do imply is that the decomposition process does not proceed in definite stages, but that fresh rock must be continually exposed to chemical action. If the decomposition products kaolin and silica effectually incrusted the surface of the lava, it is obvious that the ratios would eventually depart widely from those in the original rock. It might be expected that as the exposed surface of the more refractory minerals, quartz, pyrite, magnetite, and pyroxene, increases as a result of rock disintegration, the ratios would undergo a vital change. They probably do change somewhat. The lavas, however, are tolerably homogeneous in the mass, consisting largely of volcanic glass, which is rather rapidly altered. Surfaces of the refractory minerals also are exposed from the start, and the increase in the surface exposure is apparently too small to affect the results vitally.

While the ratios under discussion agree a little better with those in the andesites than with those in the dacites, these rocks are not sufficiently unlike in composition to warrant any conclusion as to which of the two supplies most of the bases found in the waters.

CHAPTER IV.

ORIGIN OF HOT SPRINGS AND THEIR RELATION TO IGNEOUS ACTIVITY.

SOURCE OF HEAT IN THE HOT SPRING AREAS.

Volcanic Heat.

The observations which have been presented in the foregoing, in so far as they bear on the origin of the heat of the springs, may be summarized as follows: While the volume of hot water discharged from the Lassen hot springs is small, the heat-supply, compared to the supply of water, must be large, for a great number of the springs are boiling hot, many are spouting jets of hot water to heights of 1 to 3 feet, and a few at times send up jets to heights of 5 or 10 feet (Plate 7). Some fumaroles in the same areas pour out considerable volumes of steam. One roaring fumarole at Bumpass Hell in 1916 showed a maximum temperature of 117.5°, though all other fumaroles tested had a temperature about equal to that of boiling water for the elevation. The geologic observations, as we have already found, show that the region is volcanic, and has been recently active, that the spring areas were originally covered with lava flows, and that they are ranged along fault lines, while the alignment of springs also suggests local cracks in several areas.

In entire accord with these facts is the almost universal occurrence of volcanic gases in the springs. The uniform character of the gases throughout the region, so far as they have been investigated, is indicative of a common source. That the source is a hot, underlying magma or batholith will hardly be questioned by a student of the subject, for all igneous rocks, which at an earlier period of their history were magmas themselves, give off similar gases when heated. While the evidence all appears very clear and consistent, there are some other sources of heat which should be discussed.

Radioactivity as a Source of Heat.

While the radioactivity of the gases and waters of the Lassen springs has not been investigated, tests of this kind have been made in Iceland by Thorklesson[1] and in the Yellowstone Park by Schlundt and Moore[2] with decisive results. The amount of the emanation in both these famous hot-spring areas is considerable; in the Yellowstone it is as great as that of well-known European localities, but no connection is found between the amount of it and the temperature of the waters. In fact, the cold waters of the Yellowstone were slightly more radioactive on the average than the hot waters. Thorkelsson started out with the hypothesis that the source of the heat was radioactivity, but both he and Schlundt and Moore came to the conclusion that radioactivity had nothing to do with it. As a result of other

[1] *Memoires de l'Academie royale des Sciences et Lettres de Danemark*, 8, 199, 1910.
[2] U. S. Geol. Surv. Bull. 395, 1909.

investigations it has not been found that mineral deposits which are particularly radioactive are associated with local high temperatures. This evidence is so definite and conclusive that further investigation along the same line appears unpromising.

HEAT DEVELOPED FROM CHEMICAL PROCESSES.

Some are inclined to attribute to oxidation or to other chemical processes, which are supposed to be in progress near the surface of the ground, a part or all of the heat supply of hot springs. In the foregoing (pp. 137, 140) the evidence has been presented for two principal chemical processes occurring both in the springs and also presumably below ground. The most important as regards the amount of the products is the decomposition of the rocks by sulphuric acid. In a general way the following expression may serve to represent this process:

$$a \text{ Silicates} + b \text{ sulphuric acid} = c \text{ sulphates} + d \text{ kaolin} + e \text{ silica}$$

The other product, alunite, will be for a moment neglected. This expression is not a true equation, for the reason that a small amount of water is absorbed from outside the system in the formation of kaolin, but the assumption that it is an equation is sufficiently near the truth for the purposes of this calculation. The method of calculation simply takes account of the soluble products found in a given volume of hot-spring water, from which can be estimated approximately the quantities of the other products involved in the chemical process considered. The resulting equation is then treated as a thermal equation. Although it is not possible to determine all the chemical coefficients accurately and the thermal data are not entirely complete, it is quite possible to estimate the order of magnitude of the aggregate heat effect satisfactorily.

We select as an example one of the most favorable cases, that of a boiling spring of the highest concentration. The soluble matter in a liter of it consists of 0.4 gram of sulphates, equivalent to 0.15 gram of rock bases (Na_2O, K_2O, FeO, etc.), some free acid which had not had time to act on the rock, and a very little ammonium sulphate which is assumed to have been derived from ammonia in the magmatic gases. Included in the 0.15 gram of rock bases are a few centigrams of alumina, which is usually very low in these waters. For the sake of simplicity we shall assume that all the alumina in the original rock is transformed into kaolin. At the same time, to insure a liberal estimate of the heat quantity, the heat of formation of the aluminum sulphate actually found will be taken account of.

As to the composition of the rock from which these sulphates were derived, many of the dacite-andesites,[1] the lavas in which all the hot springs occur, have been analyzed. The silica and alumina in them average about 60 per cent and 17 per cent respectively. Now, bearing in mind that kaolin contains about 40 per cent of alumina and 46.5 per cent of silica, we have approximately:

$$0.7 \text{ gram silicates} + 0.3 \text{ gram sulphuric acid} = 0.4 \text{ gram sulphates} + 0.3 \text{ gram kaolin} + 0.28 \text{ gram silica.}$$

[1] F. W. Clarke, U. S. Geol. Surv., Bull. 419, 139, 1910.

The total heat effect we have to consider is the sum derived from two processes: h_2, the heat produced in the decomposition of the rock as represented above, and h_1, the heat produced in the formation of the acid which decomposes the rock. The formation of the sulphuric acid involves some speculation. In our opinion it is most probably formed by the oxidation of hydrogen sulphide brought up in the magmatic gases. Whether it is formed from hydrogen sulphide or sulphur, the order of magnitude is the same in both cases. This question has already been discussed in another connection (see p. 138). The total quantity of the sulphuric acid from which the sulphates in the spring water are derived is 0.695 gram per liter, of which about half in this case remains undecomposed:

$$h_1 = 0.695 \times 1.38 = 0.96 \text{ kg. cal., or } 0.695 \times 1.45 = 1.0 \text{ kg. cal.,}$$

where the factors 1.38 and 1.45 are simply the heats of formation in kilogram calories of 1 gram of acid. We will call h_1, therefore, 1 kg. cal.

Some of the thermal data required for the calculation of h_2 are wanting, but values have been chosen which are within the limits of probability. As a basis for the selection we have the heats of formation of a few synthetic silicates, all of which vary from 2 to 3 kg. cal. per gram. Inasmuch as heats of formation in general have similar limits, it is quite unlikely that the values either for the primary silicates or for kaolin are exceptional. The other data are known. From these we have:

$$h_2 = 0.7 \text{ gram [silicates]} + 0.3 \text{ gram [sulphuric acid]} = 0.4 \text{ gram [sulphates]} + 0.3 \text{ gram [kaolin]} + 0.28 \text{ gram [silica].}$$

or in kilogram calories:

$$h_2 = -7 \times 2.0 - 0.3 \times 2.15^1 = 0.95^2 + 0.3 \times 3.0 + 0.28 \times 3.0 - 0.6.$$

$$h_2 = 0.6 \text{ kg. cal.} \qquad h_1 + h_2 = 1.6 \text{ kg. cal.}$$

The terms of this equation are all of a very small magnitude and the alteration of any of them or several of them by large percentages could not make any important change in the magnitude of the result. Again, though no account has been taken of the heat of formation of alunite, the amount of this mineral in any spring sediment examined has always proved slight as compared to the kaolin.

The temperature of the hot spring, the products of which are under discussion, was about 91° C. If the temperature of the ground water is taken as 10° C., it is obvious that the aggregate heat effect from the processes considered would be $\frac{1.6}{81}$, or about 2 per cent of the heat required to raise the temperature of the ground water to boiling. In this discussion we have taken one of the most favorable cases. In most springs the mineral content is much smaller and the corresponding heat effect therefore much less.

The rate of rock decomposition, as we view the matter, is not rapid enough to yield a heavily mineralized water nor any considerable portion of the heat. If it is contended that there may be other chemical processes which have been left out of

[1] The equation of course involves the heat of formation of sulphuric acid *from the elements*. This is somewhat greater than the heat effect of the oxidation of the sulphur gases, H_2S, or S_8.

[2] This figure includes a small heat effect from the neutralization of ammonia.

discussion, we can only say there are none of which we have evidence which could contribute any important quantity of heat. There is the formation of pyrite, but the amount of it in the sediments is too small to have any important bearing on the problem in hand.

If we assume that mineral veins are in process of formation in the conduits, through which the volcanic gases ascend, we must admit that the rate of formation, judging by what is known of geological processes in general, is probably fully as slow as the decomposition processes we have discussed.

Fig. 76.—July 2, 1915. Western end of the Devil's Kitchen close to Warner Creek. Steam indicates the location of hot springs. Photo Day.

It is therefore concluded that chemical reactions, not only those in progress near the surface of the ground, but any which may be in progress in the zone of deposition, are a minor factor in supplying heat; for the major part we must go back to the original heat of the magma.

Heat Carried Away by Surface Water.

Any attempt to estimate the amount of heat dissipated by a hot-spring valley of the character and extent of the Devil's Kitchen must be of the crudest, but even so such an attempted estimate can not fail to have a certain amount of interest. The area included within this basin is roughly 1,300 feet long by 500 feet wide, though the hot springs themselves are more or less concentrated in about half of that area. As may be seen from the map (p. 92), the valley is drained by a single stream (fig. 76), which follows a winding pathway through it. On July 1, 1922, a rough estimate showed the volume of inflowing water in this stream to be about 30 cubic feet per second, the outflowing water at the east end to be about 36 cubic feet per second, a gain of perhaps 15 per cent, which was of course contributed from the various springs, both hot and cold, and the seepage water draining in from the steep sides of the valley. The gain in temperature from inlet to outlet was about 6°. From these figures one may roughly calculate the total heat received and carried out by the stream alone to be of the order of 500,000,000 kg. cals. in each 24 hours. To this a considerable quantity must be added for the loss by evaporation over the porous surface of the ground, the hot springs, and the main stream.

August 17, 1923, represented a nearer approach to mid-season dryness than any other visit we were privileged to make there. The total intake water in the main stream was then about 25 cubic feet per second, and the corresponding quantity at the outflow about 24 cubic feet per second, that is, in the main drainage channel the inflow and outflow from the Devil's Kitchen was substantially equal, indicating materially smaller accessions of surface water in passing through the hot-spring area and presumably also considerably increased evaporation. Against this we may set the fact that the temperature of the inflowing water was 11.8°, while the temperature at the outlet was 19.2°, an increase of 7.4° during the period of flow through the basin. Very roughly these numbers indicate about 400,000,000 kg. cals. of heat carried away by the stream on August 17, 1923, compared with 500,000,000 on July 1 of the previous year. Inasmuch as the heat actually contributed to the basin from below is presumably substantially constant this diminution in the heat carried away by the stream is to be supplied by the increase in the loss by evaporation. This would seem to be a reasonable analysis of the conditions, but the undetermined losses by radiation and evaporation deprive the figures of any considerable quantitative significance. In spite of this fact the figures are interesting.

SOURCE OF THE WATER.

SURFACE WATER.

The Lassen springs occur in small natural drainage basins in a country where, judging by the records of the U. S. Weather Bureau for neighboring stations, the mean annual precipitation must be above 40 inches.[1]

[1] Estimated from data contained in a private communication from Mr. P. C. Day, climatologist, U. S. Weather Bureau, which were as follows:

	Elevation.	Precipitation.
	feet	*ins.*
Canon Dam	4,570	42
Greenville	3,600	45.5
Butte Valley	4,020	49.5
Chester	4,550	36.0
Westwood	4,000	33.0

Considering the higher elevation of the slopes which drain into the hot-spring areas, the above estimate is conservative.

In April and May the snow lies deep on the mountain slopes, the valleys are watered by perennial streams, and sometimes cold pools occur associated with the hot ones. In all the areas there are pools much cooler than the hot springs, which are best accounted for by the presence of surface water. At the Geyser, the Boiling Lake, the Devil's Kitchen, and Bumpass Hell indubitable cooling effects (Plate 7, No. 1) can at times be traced to cold streams which, when swollen by the melting snows, encroach directly on hot springs and pools, and while this fact does not prove that meteoric water finds its way into the springs beneath the ground, there is obviously a considerable supply very close at hand.

SEASONAL CHANGES IN THERMAL ACTIVITY.

In our earlier visits to the Lassen Park we gained the impression that the springs were responsive to seasonal changes, but the recorded evidence left much to be desired. In 1922, therefore, more systematic observations were undertaken. Since the Boiling Lake and the Devil's Kitchen were the most conveniently located hot-spring areas, the observations were practically confined to them. Work was begun at the Boiling Lake on June 15, when the higher slopes were completely covered with snow. At that time the lake and springs were full of water; even some of the mud pots contained small pools of water in their craters, while others were partially or wholly submerged by the lake. By July 9, when most of the snow had melted, the small cold stream flowing into the lake had dried up completely and the discharge from it had almost ceased. Within the same interval the water-level of the springs—most, if not all of them—had fallen a foot or more. The fall was particularly noticed in Nos. 1, 4, 8, 11, and the springs of group 5. A small hot pool (80° C.) close to the cold inlet had dried up completely. During these weeks there had been little change in the temperature of the springs. With one exception (No. 1) their pools are very small and the heat was apparently sufficient to keep them boiling, even at high water.

In August 1923, only the larger springs contained water, the smaller ones had shrunk to the proportions of feeble steam fumaroles. The mud pots likewise showed the effects of a greatly reduced water supply; they had become considerably deeper and more violently active (volcanic), though the amount of the participating material (mud) was much smaller (fig. 77).

At the Devil's Kitchen similar changes were noticed, though they were not so carefully followed. However, in 1922 the volume of the steam in the *fumaroles* of the east end of the Kitchen waned decidedly as summer advanced.

In the mud pots, too, obvious changes were seen with the advancing season. At the Boiling Lake the water in Nos. 6 and 7 dried out perceptibly, the temperature increased a little, and sputtering became more active. A bit of former evidence now became clear. On May 25, 1916, the mud volcano, No. 13, Devil's Kitchen, was sputtering quietly. On June 8 it was in active eruption, throwing mud in all directions to the height of 10 or 12 feet, while the muddy ground all about it was obviously drying out and mud cracks appeared. If the water supply falls off while the heat supply keeps up the effect is naturally a more violent boiling. The thick mud offers greater resistance to the passage of steam and other gases which, in overcoming it, produce a miniature eruption. At that time we had no opportunity to follow the process further, but a continued reduction in the water supply should logically produce a steam jet or little fumarole, the steam of which may not be visible under ordinary weather conditions.

These later stages have actually been observed both in 1922 and 1923 in other localities in this region. Certain small mud pots at the Boiling Lake (west of No. 6) displayed considerable activity early in our visit (1922), but declined later and finally appeared extinct.

Hot springs pass through transition stages of activity similar to the mud pots, which very naturally find explanation in variations in the supply of surface water. Thus at times some springs spout to a much greater height than at others. (cf.

Fig. 77.—June, 1923. Large mud pot at Bumpass Hell (Fig. 50, No. 17). Active at the bottom. Color, battleship gray. Photo Day.

Plate 7). Variations of this character have been noticed at the Geyser, at the Devil's Kitchen (No. 3), and at Bumpass Hell (No. 14). The phenomenon has not been studied with the same detail as the activity of the mud pots, but in August 1923, when the ground was drier than it had been at the time of our previous visits, a larger number of springs were spouting.

VARIATION IN THERMAL ACTIVITY IN DIFFERENT YEARS.

In restricted localities within the hot-spring areas decided differences have been observed in different years. Thus in 1922, and particularly in 1923, one of the most active spots at the Boiling Lake (fig. 59, No. 8), was on the promontory at the foot of the slide on the northeast end. Within an area of perhaps 10 yards square were more than a dozen springs in which muddy water was boiling violently to the height of several inches. Neither in 1915 nor in 1916 had any springs been observed here. At the Devil's Kitchen there was a similar and much larger area in the northwest corner. The activity must have been very slight there in 1916, for it passed unnoticed, while in 1922 there were a large number of boiling springs and mud pots, some of them violent. On the same (north) side of Warner Creek and east of No. 10 many mud pots, which in 1916 were seemingly extinct, showed considerable activity in 1922 and 1923. Bumpass Hell offers an interesting case (Plate. 13).

We attribute the differences to a greater supply of surface water in 1922 and 1923 during the time of our observations. Differences of this sort may possibly be caused by variations in the total annual precipitation, but the differences under discussion are apparently conditioned by the rate of melting and the eventual disappearance of the snow. Comparison of the weather records indicates that more snow fell in the winter of 1916 than in 1922, but in the latter year the snow lingered late. In consequence of this our arrival in the Park was postponed a full month beyond the time when we began work in 1916. The amount of snow still unmelted and the tardy appearance of the spring flowers evinced the lateness of the season. The large volume of water at the Boiling Lake at that time has already been mentioned (p. 155). At the Devil's Kitchen Warner Creek was brim full, many small rills were pouring over the high southern wall of the basin, some of the springs were obviously affected by inflowing surface water, and the flats near the brook level between the points marked 3 and 10 on the map were quite muddy and the footing less secure than usual.

SALT PATCHES AS AN INDICATION OF THE STATE OF THE GROUND.

In May and June, 1916, salt patches were found in all the hot-spring areas. Some of them appeared and visibly increased as the ground dried out. The same course of development was observed in one place in the Devil's Kitchen in 1922, but in that year hardly any patches were seen, and these were of the scantiest character. From these facts the inference was drawn that the appearance of the salts depended on the moisture in the ground, and that as a corollary the latter season was wetter than the former. But in August 1923, when other convincing facts led to the conclusion that the ground was drier than it was on either of our former visits, *no salts at all were observed.* A further consideration of the matter makes it quite improbable that the salts remain indefinitely in the ground of any particular area, merely moving up and down in response to variations of the weather. In very dry times there is too little moisture to move them at all, while in wet seasons they are probably washed down into some near-by hot spring or into some outlet stream. The formation of more salt and its subsequent deposition at the surface will depend on the amount of volcanic gas that permeates the area in any particular time (p. 141) and on a proper distribution of ground water to maintain just the right degree of moisture, for neither the flow of gas nor the flow of water through the same section of ground can be at all constant. Both are bound to change in a region where disintegration and slumping are in active progress and where the difference in the water supply from early spring to midsummer is so great. The presence or absence of salts can not, therefore, of itself be regarded as an index of the amount of moisture in the ground, but the evidence which precedes this discussion is still valid and indicates that in June and early July 1922 the ground was wetter than at the time of our former visit, while in August 1923 it was drier.

RECENT OUTBREAK OF THERMAL ACTIVITY.

Some time between 1916 and 1922 a new outbreak of thermal activity occurred in the east end of the Devil's Kitchen (figs. 78, 79). At the earlier date the activity in this locality was chiefly on the left bank of Warner Creek. On the right bank

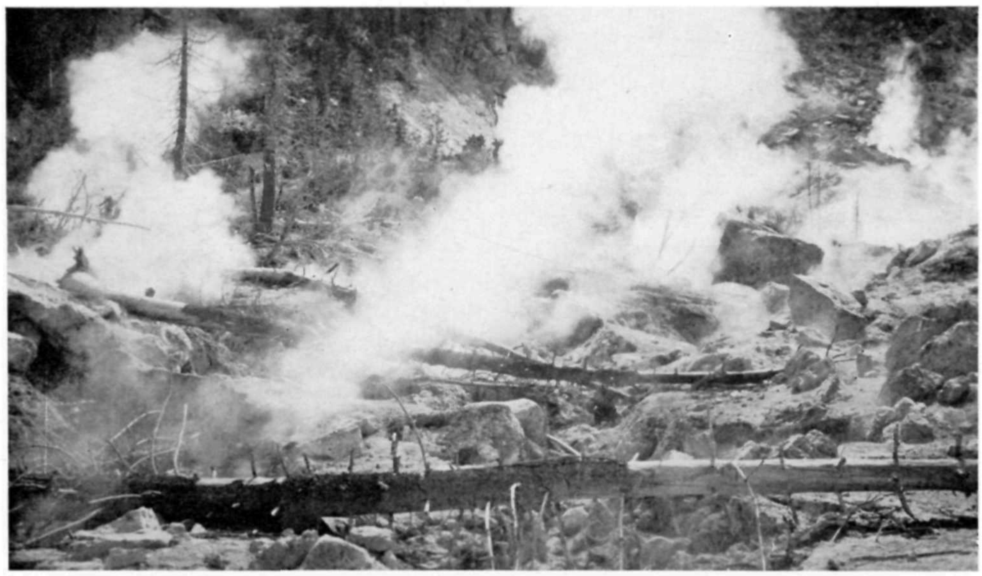

Fig. 78.—June, 1922. Fresh outbreak of thermal activity in the Devil's Kitchen. Photo Day.

Fig. 79.—The same region in July, 1923. All of the central portion of the picture has settled 8 to 10 feet. Photo Day.

there was a small hot stream (fig. 80)—a mere rill formed by the discharge of several insignificant hot springs flowing down from No. 15 and emptying into the creek, and a single fumarole. In 1922 the stream had disappeared and its place was occupied by a deep furrow, from the bottom of which several large active fumaroles (fig. 78), occurring at intervals, poured out a considerable cloud of steam. The temperature in all the fumaroles was practically that of boiling water at this spot, namely, 94°. About 25 feet to the southeast, close up to the steep, high bank bounding the Kitchen in that direction, there now appeared a deep trench approximately parallel to the bank, from which issued the most active hot springs in the whole region. Both furrows and trenches were obviously formed by intersecting slump holes which were especially well marked. Each hole in this trench was partially filled by a hot muddy pool emptying into the next below. Into the uppermost pool throughout the time of our stay in 1922 a rill of cold water was flowing, yet the temperature of the pools close to the springs never varied more than a degree or two from the boil-

Fig. 80.—May 20, 1916. Wonderful magenta terraces colored by oxide of iron. Obliterated by the new outbreak at the Devil's Kitchen (1923). Photo Day.

ing-point. The surface of the lowest pool was constantly stirred by pulsating jets of hot water. In No. 24 appeared a dome-shaped fountain of considerable volume (probably 2 feet high and 2 feet across), spasmodically leaping, splashing, and roaring. The uppermost spring (No. 23) was the most spectacular (fig. 81). It took the form of a noisy jet of steam and hot water shot out of a large nozzle, from which it emerged at an angle with a pulsating motion, dissipating itself in a cloud of steam at a distance of 5 or 10 feet. The subsidence which formed the seat of this new activity was evidenced by the form of the depressions and by the uprooting of good-sized trees (figs. 78, 79).

During the same period (1916–1922) a decided decline occurred on the opposite bank of the creek, where in 1916 there had been a line of small, vigorous hot springs and a good-sized and quite active fumarole (fig. 47, No. 20). The ground along the north bank of the creek at that time was riddled by chemical action and afforded a very uncertain footing (fig. 75). In 1922 all had changed materially. Spring No. 19 could no longer be located. A shallow depression containing boiling water was found where No. 20 had been. No. 21 apparently still existed, but was much less active than formerly. The bank was generally firmer and drier and some incrusting salts were observed. In August 1923, No. 23 was still active as a roaring jet of steam but carrying little water, while No. 24 had become reduced to a shallow, turbid pool showing but a fraction of the activity of the year before. Both the steam jet and the springs showed the temperature of boiling water, while the ground about the springs was unpleasantly hot and dry. The undermining of trees and slumping of the ground had progressed farther into the south bank, probably during the previous spring, for the cold inlet stream was now dry. Both these pools and others to the north were now considerably deeper than in 1922.

Fig. 81.—June, 1922. Spouting spring in Devil's Kitchen (No. 23, Fig. 47). A jet of hot water and steam 8 or 10 ft. in height. Photo Day.

Changes of a character similar to these have been observed elsewhere. Hague[1] says of the Yellowstone Park: "New springs are continually reaching the surface and old ones are becoming extinct." Within a short time one of the largest geysers in the Park has broken out.

A comparison of these changes to the rejuvenation and decline of activity in volcanic craters, where great fluctuations in temperature are known to take place, is naturally suggested. While of course the temperature of spring waters is limited by the boiling-point, the acquisition of a new store of energy by the batholith from which the heat of the springs is derived is a possibility.[2] However, a more plausible

[1] Bull. Geol. Soc. Amer. 22, 114, 1911.

[2] Thus the temperature of the famous Solfatara of Pozzuoli near Naples rose about 70° C. in a period of about 50 years (1856–1905). See Wolff, *Vulkanismus*, vol. I, p. 600, 1914.

explanation of the phenomena described is found in the changes which may occur along the paths by which hot water and steam reach the surface. The ground of these areas is gradually disintegrating under the influence of thermal action into products which are slowly carried away by flowing water; the ground is undermined and the surface portions slump in. These are observed facts. That steam should slowly cut for itself new passages to the surface, that slumping should dam up old channels and divert the water to new paths or should open up new apertures, seems not improbable.

The data are probably insufficient for a detailed explanation of the changes in the Devil's Kitchen, but what we have are suggestive. The new outbreak and the decline of earlier activity may be intimately connected, for both spring groups probably derive their water supply from the same collecting ground—the long steep slope to the south. Springs 19 to 21 lie near the creek level and the new springs are on the slope above mentioned at a higher elevation. There are one or two hot springs rising in the bed of the creek between the two groups. The *decline* appears to be certainly due to a local interruption of the water supply of springs 19 to 21, for ground temperatures in that vicinity are still high, reaching a maximum of 94°, at depths of 1 to 3 feet. If the two groups of springs derive their supply from the same source, the slumping in of the ground at the higher elevation may bring most of the water to the surface and thus impoverish the other group.

In the two preceding sections we have endeavored to account for variations in the volume of water observed in different years in the two localities which have been most closely studied. Two factors appear to be responsible for these variations—a change in the total volume of water and a change in its distribution; but to decide in each case which is the cause of the observed variation would probably necessitate a close and continuous observation of the phenomena such as we have not been able to give.

FLUCTUATIONS IN THE COMPOSITION OF THE WATERS.

G. A. Waring in his "Springs of California" [1] gives a brief description of the hot-spring areas in the Lassen Park. He publishes two analyses of the waters made by F. M. Eaton of Oakland, California, which, so far as we know, are the only ones ever made of the waters of this region excepting our own. The analyses are worth quoting (see table 11). The first water sample is "from a large pool in the centre of the area" (Devil's Kitchen). This description agrees well with pool No. 5 (see fig. 47), an analysis of the water of which is given in the table for comparison. The discrepancy in composition between the two is very striking; the soluble salts are 1.12 gram (Eaton's result) and 0.79 gram (our result), respectively. It is possible that Eaton may have referred to pool 9 instead of pool 5, the water from which was not analyzed by us, but it is noteworthy that none of the waters in the Devil's Kitchen which we did analyze were so concentrated in soluble salts as the waters of pool 5.

Eaton's second sample was from Bumpass Hell Springs. This may seem to the reader entirely indefinite, considering the size of the area, but anyone who has

[1] U. S. Geol. Survey, Water Supply Paper 338, pp. 140–143, 1915.

visited it will recognize that there is one pool, No. 14 (Plate 12), now divided into two, which, on account of its size and its activity, is more impressive than any other. The comparison of Eaton's analysis with our analysis of the water from No. 14 shows that the soluble salts are 0.24 gram (Eaton's result) and 0.81 gram (our result), respectively. There is only one other pool which it is at all likely anyone would select as representative of Bumpass Hell, namely, No. 4 (figs. 50, 52), but here also the difference, though smaller, is quite beyond the limits of analytical error.

Table 11.—Comparison of Analyses of Spring Waters in Devil's Kitchen and Bumpass Hell.

[Samples taken several years apart.]

Locality.	H.	NH_4.	K.	Na.	Ca.	Mg.	Al.	Fe''.	Fe'''.	SO_4.	Cl.	SiO_2.	B_2O_3.
Devil's Kitchen Springs, hot pool near the center of the area. (Analysis 1909–10 by F. M. Eaton)........	10	......	9.7	41	20	11	50	11		963	trace	286	......
Pool 5 (fig. 47) Devil's Kitchen. (Analysis 1916, the authors)...	7	2.6	9	43	38	14	10	30	none	617	trace	167	......
Bumpass Hot Springs. (Analysis 1909–10 by F. M. Eaton)........	0.37	......	14	16	8.9	5.1	53	1.4		141	trace	124	......
Spring 14 (fig. 50) Bumpass Hell. (Analysis 1916, the authors)....	7	15	13	29	7	4.5	28	17.5	5	681	2	236	4
Spring 4 (fig. 50) Bumpass Hell. (Analysis 1916, the authors)....	none	128	4	33	7	2	none	4	4	419	trace	138	84

This evidence admittedly leaves much to be desired, but interpreted according to our best judgment it indicates fluctuations in composition which are in accord with all the rest of the evidence in supporting a variable rather than a constant flow of water from the springs.

Altogether, the evidence for the surface origin of water in the Lassen springs is so convincing to an observer that if the hypothesis of juvenile or magmatic water had never been proposed the entire adequacy of the simpler theory to account for *all* the water would probably never have been questioned.

The Presence of Magmatic Water.

Nevertheless there are reasons for concluding that a *portion* of the water in these springs is magmatic—reasons so cogent that the conclusion appears almost inescapable. We have already found in the presence of the volcanic gases in the springs evidence of a hot magma from which the heat arises. We have concluded that a hot magma must of necessity give off volcanic gases as well as heat, because all igneous rocks, which once were magmas themselves, give off similar gases when heated. *Furthermore, heated igneous rocks almost invariably give off more steam than all other gases put together.*

Hot magmas in all probability always give off magmatic water, and any hot spring which gives off volcanic gases should also contain some magmatic water.

A possible step in the direction of estimating the amount of it would be to determine the ratio of the gases to the total water in the springs, and then to compare this ratio with that of the gas to the steam in fumaroles and the ratio of gas to water in rocks. An intimation of the order of magnitude of the magmatic water might be arrived at in this way.

RELATION OF HOT SPRINGS TO THE MAGMA.

Views of Other Investigators.

As regards their view of hot springs, geologists divide into two schools. One school has held the perfectly definite conception that hot springs are produced by meteoric water circulating under the influence of gravity through hot ground. Many of this school would probably admit that some of the volatile products as well as the heat were derived from a deep-seated source. The other school, approaching the subject from a study of the mineral veins and their relation to the igneous rocks, has held that the water, or some of it, was juvenile, though their ideas of how this water is conveyed to the surface do not appear to have been clearly worked out.

Hague [1] concluded that the hot waters of the Yellowstone springs were of surface origin, and Bunsen [2] reached the same conclusion regarding the hot springs of Iceland, though the latter qualified his statement by the admission that some of the water there was derived from the heated rocks. This is doubtless true of a zone which lies between the batholith and the zone of ground water. In the latter the decomposition products, kaolin, alunite, and silica, would contain more water than the mass of most igneous rocks from which they were derived. In that case water would be withdrawn from the general supply.

Thorkelsson [3] is less specific in his statements than Hague or Bunsen. He concludes that the alkaline springs of Iceland contain at any rate considerable atmospheric water, but avoids further speculation.

More recently Schneider [4] has published an important contribution to this subject. His observations prove in a convincing manner the close relation of ground water to the Icelandic hot springs. At Krisuvik, for instance, where hot springs, mud pots, and solfataras occur together, the spouting springs are rendered more active by stopping up the solfataras. If the springs are stopped up by turf, the mud volcanoes respond by greater activity, while if the surface waters above the solfataric field are dammed up, steam replaces the water jets and the mud volcanoes cease their activity. At Cape Reykjanes, Schneider states that the geysers are strongly affected by the ebb and flow of the tide. Schneider believes that *all* the water of hot springs is atmospheric and that they contain nothing juvenile except the volcanic gases, which, as a follower of Brun, he regards as anhydrous.

Respecting the hot springs of New Zealand, it is the view of Park [5] that both alkaline and acid waters have a common origin, and this is quite probably mag-

[1] Hague, Bull. Geol. Soc. Amer. 22, 121, 1911.
[2] Bunsen, *Liebig's Annalen*, 62, especially 1–5, 1847.
[3] Thorkelsson, *Memoires de l'Academie royale des Sciences et Lettres de Danemark*, 8, especially p. 260, 1910.
[4] Schneider, *Geolog. Rundschau*, 4, 65, 1913.
[5] Park, Geology of New Zealand, pp. 178, etc.

matic. On the other hand, there are well-known facts difficult to explain on that hypothesis, notably the phenomena of the great geyser of Waimangu and its relation to Tarawera Lake.[1]

THE MAGMATIC WATER

Some new light on the subject, we believe, is to be gained by considering hot springs as one of the phases of volcanism and closely related to the fumaroles. Hot springs and fumaroles often, if not generally, occur together. There are fumaroles in some of the hot-spring areas under discussion, notably at Bumpass Hell and the Devil's Kitchen. Whether the one or the other occurs is no doubt a question of the relation of heat supply to water supply.[2] Any magmatic water which a fumarole may possess must find its way to the surface as steam. That fumaroles actually do contain magmatic water follows from the behavior of an igneous rock when heated. Occasionally also field evidence may indicate that the water of a fumarole is *entirely* magmatic. This is true of the well-known fumarole[3] at the foot of the cone of Etna. As the temperature of a fumarole falls the exhalation of steam continues. Not until it reaches the critical temperature, strongly modified as it is by the soluble matter in the magma, would it be possible for the water to condense, and not then unless the pressure were sufficiently great. The experimental studies of G. W. Morey [4] indicate, however, that the vapor pressure of water in the magma would be so reduced by the soluble matter that a pressure sufficient to condense the water would only serve to drive it back into the magma. In other words, if water is to leave the magma at all, it must do so as steam. If one is inclined to argue that some important factor has been omitted from the discussion, invalidating this conclusion, he finds himself confronted by the necessity of explaining how liquid water is raised to the surface. A force adequate to do this has so far not been suggested. Of course, the hydrostatic pressure of a column of colder water from the surface would be equal to this work, but probably few if any geologists believe that unbroken columns of water penetrate down far enough to reach a batholith. As to the means by which magmatic water reaches the surface, another line of reasoning has led us previously to the same conclusion.

ACID AND ALKALINE SPRINGS.

Fumaroles commonly contain some acid[5] gases, H_2S, SO_2, HCl, HF, as well as CO_2, while hot springs may be either acid or alkaline. The presence of these gases is satisfactorily explained as the result of a hydrolysis of sulphide and halide molecules in the complex magma or batholith by the agency of steam. The volatile acid products of the reaction are continuously carried off in the gaseous phase of

[1] MacLaren, Geol. Mag. 3, 511, 1906.

[2] Wolff says (*Vulkanismus*, p. 627) that a decline in temperature changes fumaroles into hot springs This is not a necessary consequence. In the Katmai region, Alaska, many *extinct fumaroles* have resulted from this cause. The formation of a hot spring is of course also dependent on topography and ground structure which determine at what points water shall come to the surface.

[3] This fumarole, the Fummarola o Vuccaloru, gives off an enormous volume of steam after 9 months of rainless weather (observation of 1914). Its location (less than 1,000 feet below the summit) and the structure of the mountain also lead to the view that its water can not be meteoric.

[4] Journ. Wash. Acad. Sci. 12, 219–230, 1922.

[5] Occasionally also fumarole gases are alkaline from the presence of ammonia or ammonium carbonate.

the system and may thus continue to be given off for long periods. If, however, it were possible for a magma or batholith to give off *liquid* water, the solution should always be alkaline, for we know that the principal reaction of an igneous rock with water at 100° is the hydrolysis of the silicates, a reaction which should move nearer to completion at the higher temperature of the batholith. This reaction is obviously favored by the solubility of the alkali hydroxides, though it would doubtless be unimportant if the water were given off by the batholith in the form of steam on account of the slight volatility of the hydroxides. Acid elements, like the halogens, sulphur and carbon would be carried off by liquid as well as by gaseous water, but in the water solution they would take the form of salts—halides, sulphides and carbonates or bicarbonates. The halides are neutral, the sulphides, carbonates, and bicarbonates are alkaline. We have reason to believe that a magma, and in a lesser degree a batholith, contains more sulphur, and in some instances more halogens, than an ordinary igneous rock, but that these elements should ever reach such a proportion as to be capable of neutralizing completely all the alkali from the hydrolysis of the silicates, much less that they should by any conceivable reaction give rise to free acid, is quite beyond the bounds of probability.

On the other hand, *acid* springs are the logical successors of acid fumaroles, if we suppose them to be formed by ground water which serves to condense the volcanic steam and acid gases arising from a batholith. Springs which contain free hydrochloric acid, like some in the Yellowstone Park, or possibly hydrofluoric acid in certain instances, are thus accounted for, while springs which contain free sulphuric acid can only be explained by supposing that an oxidation of the original sulphur gases (H_2S, S, SO_2) occurs after they come into contact with air in the zone of ground water. This phase of the problem has already been discussed. Waters of such an origin may emerge from the ground still acid, or their character may be changed as a consequence of their subsequent history.

Whatever the origin of the acid, it will attack the rock as soon as it comes in contact with it, decomposing it in a manner already explained (p. 140), and the decomposition will proceed as long as the contact continues or until the acid is exhausted, for no igneous rock can remain in equilibrium with an acid spring-water. The bases in the rock gradually neutralize the acid and eventually, unless the rock is entirely free from alkalies, the hydrolysis of the alkali silicates will produce an alkaline water. Bunsen [1] convinced himself of this years ago, when he heated an acid spring-water of Iceland with the powdered rock of the region. When the two were heated for some hours in a sealed tube at about 100° C. the solution became alkaline in consequence of the formation of sodium and potassium hydroxides. Incidentally the iron was of course precipitated. In a natural spring-water the caustic alkalies would always be transformed into carbonates or bicarbonates and the alumina as well as the iron would be precipitated.

From a chemical point of view, then, an acid spring-water, the rock it traverses, and the decomposition products of the rock constitute a system in process of change, and the composition of the water where it emerges from the ground will depend on a number of conditions.

[1] *Liebig's Annalen*, 62, 52, 1847.

Still holding the chemical viewpoint, we see that the problem involves the speed of the reactions, and that these depend on the physical and chemical nature of the rock, the temperature, and the time of contact between rock and acid. If the rock is rich in volcanic glass, like that in the Lassen Park, or in feldspathic minerals, the acid will be neutralized much faster than by a rock composed chiefly of pyroxenes and amphiboles. Where the rock is cracked and seamed its active surface is obviously increased, and the speed of reaction thus promoted, while the influence of variations in temperature is obvious. The time of contact between rock and acid depends not only upon the length of the path which the spring-water traverses in its journey beneath the ground, but also upon its rate of percolation, which in turn varies with the topography and rock structure.

In other respects the acid hot spring is not comparable with the chemical systems ordinarily studied in laboratories; the waters move from point to point, laving successive portions of rock, and finally leave the field before equilibrium can be established. Moreover, the supply of acid is continually renewed and, according to our hypothesis, continually, though probably not regularly, reduced in concentration as the waters percolate. If the acid supplied to a particular spring is relatively small in quantity, and this will depend in the present case not only on the concentration of hydrogen sulphide in the volcanic gases, but on the conditions which favor its oxidation and on the proportion of surface water diluting the gases, so much the greater will be the chance that the water of the spring as it issues from the ground will be alkaline. Local differences in the volcanic emanation, like local differences in the composition of a rock, may occur in the same field, or changes in the composition of the original gases may arise from reactions with the rock as the gases move through a zone of diminishing temperature toward the surface.

For the sake of simplicity we have considered the formation of the acid and the attack of the acid on the rock as separate processes, but it is practically certain that the two go on together. If this is the case, the rate of the former reaction must be the greater.

Variations of the above character in conditions beneath the ground may thus result in both acid and alkaline springs in the same area.

COEXISTENCE OF ACID AND ALKALINE SPRINGS.

Acid and alkaline springs occur together in the Lassen district, but the number of the latter must be small, as only four have been found, all but one in the Devil's Kitchen, and these are only slightly alkaline. These four are lowest in SO_4 of any springs in the region, only one slightly acid spring containing so small a quantity. From this we may infer that the cause of the alkalinity, or rather the principal condition favoring it, is a local limitation of the acid supply. The outstanding fact is that the waters are especially dilute in this strong acid radical. The cause of this is attributed to the presence of a larger quantity of surface water to a given amount of volcanic gas, rather than to any considerable variation in the composition of the latter.

None of these springs so far as observed is depositing any siliceous sinter, as geysers invariably do.[1] The reason for this is unknown, and we shall not hazard a guess until the subject has been more thoroughly studied.

Acid and alkaline springs occur together in all the great hot-spring regions of the globe. Bunsen[2] says that in Iceland the alkaline springs are the most widely distributed and form the majority of the warm and hot springs of the island. Hague[3] says of Yellowstone Park: "The volume of the siliceous alkaline waters far exceeds that of the acid type. On the other hand the latter occur more widely distributed." According to Park:[4] "The waters which rise to the surface in the region about Lake Rotorua are alkaline, acid, or neutral."

TIME RELATION BETWEEN THE ACID AND ALKALINE SPRINGS.

If our hypothesis of origin is correct, the waters of the few alkaline springs in the Lassen Park are acid at some point or points nearer their source, and in the process of rock decomposition they have become alkaline by the time they have reached the spring vents. The close relationship of these springs to the acid springs in composition and in the character of their sediments, as well as the absence of other important differences, lead to the conclusion that all are of the same age.[5]

It is interesting to consider how other investigators have handled this problem. Bunsen concluded that the alkaline springs of Iceland are later in development than the acid springs. His conclusion is based on chemical evidence. Elementary sulphur is apparently regarded by Bunsen as the only original sulphur gas in the volcanic emanations there. This he supposes to have reacted along with steam on the ferric iron of the pyroxenes in the rocks, with formation of pyrite and sulphur dioxide, as previously explained in another connection (p. 139). In the course of time sulphur dioxide is succeeded by hydrogen sulphide which results from the action of steam on the pyrite previously formed. Bunsen gives observations in support of his statement that sulphur dioxide is characteristic of an earlier phase of volcanism and that it is later succeeded by hydrogen sulphide. His explanation, however, implies that steam was not present in the earlier stage. Neither evidence of this fact nor any reason why it should be true are accorded us. Bunsen says:

In consequence of these changes the acid reaction of the water with which the rocks are impregnated is converted into an alkaline reaction resulting from the formation of alkali sulphurets at the cost of the now solely reacting sulphuretted hydrogen . . . With the disappearance of the acid reaction begins the action of carbonic acid on the rocks and the formation of alkali bicarbonates. The latter dissolve silica, which is the cause of the formation of geysers.

Discussing the relation of acid and alkaline springs in the Yellowstone Park, Hague[6] affirms:

The ascending waters in their circuitous course penetrate fresh seams and cracks in unaltered rock which slowly widen under the disintegrating influence of aqueous vapor.

[1] Some springs in the Morgan group apparently form an exception, but these were more distant from the volcanic center, and have not been studied by the authors.

[2] *Liebig's Ann.* 62, 7, 1847.

[3] Bull. Geol. Soc. Amer. 22, 116, 1911.

[4] Geol. of New Zealand, 178, 1910.

[5] For the reason previously given no positive statement can be made about Morgan's Springs.

[6] Op. cit., p. 118.

Finally the thermal waters following these cracks issue at the surface as hot springs and pools. These early waters are usually acid in composition and deposit ferric and aluminous salts. Occasionally they set free sulphur derived from the decomposition of hydrogen sulphide. In time the openings through which they flow become broader, the waters themselves, free from hydrogen sulphide, become clearer and neutral and at last issue as siliceous alkaline waters.

While little account of chemical changes is taken in this exposition, one important idea stands out clearly; the alkaline character of certain of the springs of the Yellowstone Park, as well as their greater size, is a natural result of prolonged rock decomposition.

On the other hand, Park[1] believes that the hot acid waters of New Zealand were originally alkaline and that they have subsequently become acid through chemical changes occurring near the surface of the ground. He says:

Shafts and bore holes put down in the pumice and rhyolite, which constitute the great bulk of the rocks in this area, have shown that the alkaline waters come from a deep-seated source while the acid waters have quite a superficial origin. This has led to the erroneous conclusion that all the waters have not a common origin.

On p. 181 he says:

Of the genesis of the ascending alkaline waters nothing is known at present. It is not improbably magmatic.

On p. 180 we read:

The hot, ascending, alkaline, chlorinated waters become partially or wholly oxidized into sulphates by contact with the decomposing iron sulphide with formation of free sulphuric and hydrochloric acids and the liberation of sulphuretted hydrogen and sulphurous acid. In this way the ascending alkaline waters that happen to come in contact with masses of pyrites become oxidized in the superficial layers of the pumice and rise to the surface as neutral or acid springs, according to the degree of oxidation they have undergone.

Whether in this instance there is sufficient ground for supposing that the acid waters of this region are derived from the oxidation of pyrite is not clear from Park's statement. Evidence in general is certainly against it. However, the views of Park probably accord with the views of many economic geologists in that they regard acid waters as the result of a transformation of alkaline waters of much deeper origin. At the famous Steamboat Springs, Nevada, the authors observed *acid salts* at the surface of the ground within a few inches of alkaline hot-spring waters. Apparently they were the product of oxidation of hydrogen sulphide which had escaped from the waters. At Sulphur Bank, on the shore of Clear Lake, California, the deeper ground waters have been shown to be alkaline, while nearer the surface hydrogen sulphide and sulphur oxidize to sulphuric acid, which has been changing the rocks to silica. In neither case did we observe alkaline waters changing to acid waters, although the possibility is not excluded.

Pursuing further the theory which we have advanced regarding the relations of acid and alkaline springs, it becomes clear that if the volcanic gases are condensed under conditions unfavorable to the oxidation of sulphur gases, the water would

[1] Geology of New Zealand, 178–181, 1910.

become alkaline in the first stages of rock decomposition, unless the gases contain halogen acids. If the water were alkaline in the begining there is the possibility that it might become subsequently acid. But if, as observations in many different places seem to indicate, alkaline waters are characteristically low in sulphur, it would be only in the very first stages, if at all, that the water could be acid; the amount of sulphur would be insufficient to make it acid at any subsequent time, even if the sulphur were completely oxidized. The problem is one that calls for detailed observation in many localities, but at present the weight of the evidence clearly inclines the student of the subject to the conclusion that the acid hot springs constitute a stage of volcanism, logically following the acid fumaroles, and that the alkaline springs develop subsequently as a necessary result of the processes of rock decomposition.

Speaking generally, *all* volcanic hot springs in the lapse of time should become alkaline as a result of the gradual decline in the amount of sulphur gases and halogen acids in the volcanic emanations as the temperature of the batholith falls.[1] A *uniform* decline would not, however, explain the coexistence of acid and alkaline springs in the same area.

Hague's argument that the alkaline springs of the Yellowstone are older because they are larger is a plausible one, but no reason is given for the change in the chemical character. The large springs discharge a much greater volume of water, however, and there is some reason to conclude that a larger proportion of it is meteoric than is true of the acid springs. It is known that geysers fill with cooler water after an eruption, and it is easier to explain the heating of large amounts of surface water (p. 170) in a given area than to explain the condensation of great quantities of magmatic steam. The effect of dilution on the acid gases is, as we have found, to favor the formation of an alkaline water.

There is another reason for concluding that in the order of development the alkaline springs follow the acid springs, as Bunsen and Hague believed. The products of the acid hot spring are all soluble or easily washed away, while an alkaline hot-spring often deposits about its mouth a hard, compact, siliceous sinter quite refractory toward natural acid waters. If, therefore, the acid springs succeed the alkaline springs, there ought to be many instances of acid springs about which the surviving sinter tells the story of an earlier alkaline age. But no facts of this sort are on record, so far as we are aware.

This conclusion should not be understood to imply that *all* alkaline springs of volcanic origin must be originally acid, either in place or time. According to our interpretation, that would depend on the nature of the volcanic gases. If, when the springs came into existence, the gases contained none of the strongly acid constituents like the halogen acids, nor constituents which, like the sulphur gases, give rise to strong acids through oxidation, the waters would obviously never acquire an acid character, and the processes of rock decomposition would be from the first of quite a different nature. Whether this case actually occurs in nature or not we

[1] This statement supposes that the chemically active gases disappear before the steam. It is supported by a considerable body of evidence.

are unable to say. Thus we find logical grounds for the conception that volcanic hot springs may be originally alkaline, or originally acid, changing later to alkaline, but no basis for the conclusion that volcanic springs originally alkaline become acid by later development.

SUBSTANCES OF SECONDARY ORIGIN IN VOLCANIC HOT SPRINGS.

It has been concluded from cogent evidence that the bases in the Lassen spring-waters are derived from the lavas through which they percolate, but from the nature of the gases which escape from the springs and the close relation which the springs bear to the fumaroles it appears equally certain that the sulphur is derived from the volcanic gases. It has also been implied in the discussion that the sulphur, halogens, and other volatile elements in all volcanic spring-waters are similarly derived, but in view of the great diversity of conditions which prevail in the earth's crust it would be unwise to maintain that this is an invariable rule. If waters supplying hot springs traverse sedimentary strata in which soluble salts, such as sulphates and chlorides, have been segregated, they will naturally dissolve and remove a portion of such salts.

In this connection it may perhaps be inquired why, if igneous rocks contain sulphur, chlorine, etc., these elements should not find their way into the hot-spring waters by leaching as well as by volatilization. The reply is that whatever is capable of passing into solution in the course of the decomposition process would necessarily become a constituent of the water, but the amount would be generally small. For example, only about a gram of lava would be required to supply all the bases in a liter of any of the waters of the Lassen Park, and this amount would not contain more than a few milligrams of sulphur.

THE MEANS BY WHICH HEAT IS CONVEYED TO THE SURFACE.

If we accept the view that the Lassen hot springs contain magmatic water and that this water rises from the magma as steam, it is clear that the condensation of the steam would supply a relatively large amount of heat. Only when the magmatic steam is very hot, where it meets the ground water, does its specific heat become comparatively important. Of course, the other volcanic gases participate in the heat convection, but since their amounts are probably very small when compared with steam, their heat capacities being only about half as great as that of steam (except in the case of hydrogen and marsh gas which are insignificant in the Lassen gases), and especially since they do not undergo a change of state, their contribution to the heat supply is negligible. On the assumption that all the heat in the hot springs is brought up by magmatic steam and that none is lost to the surroundings, some estimate of its limits in the springs and fumaroles can be made. The highest temperature found in the Park, was, as previously stated, 117° C. The temperature of the magmatic steam is therefore at least as high. The boiling point of the springs in this particular locality (Bumpass Hell) is 91°. Taking the temperature of the surface water as 10°, from which it varied little during the time of our visits, a simple calculation shows that 1 kg. of steam in condensing would heat about 6.9 kg. of surface water to boiling if no heat were lost to the surrounding ground, and that the resulting mixture would contain about 12.5 per cent of magmatic water. Under the above conditions this would be the lowest possible amount a boiling spring could contain. If the temperature of the magmatic steam were 100° hotter, the heat supply would be increased about 10 per cent, but the magmatic water in the mixture would be lowered thereby less than 1 per cent of the total weight.

Assuming that the heat of the springs is derived from magmatic steam, it is obvious that the above figures for the percentage of magmatic water would have to be raised in consequence of the loss of heat to the ground through which the waters percolate. After a time an equilibrium would be established in which this loss would be equivalent to the heat loss from the surface of the ground outside the springs. At present this quantity is impossible to estimate. Temperatures at the very surface in the hot-spring areas here under discussion seem to be near the normal, except close to the borders of the pools. A few feet below the surface the ground is often quite hot for long distances from the springs. In such cases steam always seems to be present. We are inclined to the conclusion that the heat lost in this way is less than that carried off by the hot water. Still, the very large area of the surface through which heat escapes, when compared to the area of the springs themselves, is a factor which may raise the heat loss to an unsuspected magnitude.

But there are facts which are difficult to explain by the assumption that volcanic heat is transmitted to the surface *entirely* by magmatic steam. For example, there is strong evidence that the fumaroles of the Katmai region, Alaska, carry with the magmatic gases much steam originating from surface water. Gases from very hot fumaroles carry sometimes as much steam in proportion to the other gases as those several hundred degrees lower in temperature. To assume that the heat is supplied entirely by the magmatic steam would lead to an absurdly high initial temperature of the gases and of the magma. But if the water is not all magmatic one must assume some other source of heat to vaporize the surface water.

Only one other means for the transfer of heat from a batholith to the surface has yet been suggested, so far as we are aware, namely, conduction through the rock. It is difficult to see how heat could be conducted through the rock fast enough to keep up the temperature of boiling springs. If it is possible at all it must be accomplished by the circulation of the water through a labyrinth of cracks and crevices, which brings a given volume of water into contact with a very great surface of rock, for rock is a poor conductor of heat at the best, and shattered rock, such as would be expected in the upper strata of the earth's crust in hot spring areas, especially poor.[1]

Some recent experiments of Professor Jaggar[2] offer good evidence that at least in these upper strata it is not chiefly by conduction that heat is transferred. In 1922 Jaggar sunk several drill holes in or near the crater of Kilauea. One of these was bored in the bottom of the crater itself within a mile of Halemaumau, where a high temperature gradient was expected. At a depth of 80 feet a temperature of 62° C. was found. As a matter of fact, there was no gradient at all in the completed shaft; the temperature was equalized by a rising stream of volcanic gases.[3]

[1] Thorkelsson believes that "the transmission of heat from the interior of the earth takes place almost exclusively by means of convection of hot water and steam through fissures in the crust of the earth." *Mem. de l'Acad. roy. de Danemark* 8, 263, 1910.

[2] Bull. Hawaiian Volcano Observatory 10, 27, 63, 75, 97, 111.

[3] That the gases from this particular bore hole were volcanic is an assumption. They have not been analyzed. The gases at the Sulphur Banks are certainly volcanic.

The maximum temperature found in any of the bore holes (at Sulphur Banks outside the crater) was the boiling-point of water, 96° for that altitude.

The gases here are mostly steam, 96 to 97 per cent in the samples analyzed, which for reasons previously stated (p. 162) is doubtless partly magmatic. But much of it is certainly surface water, for the rainfall there is abundant and the lava is remarkably porous.

Jaggar's experiments therefore tend rather to confirm our ideas of heat convection by steam, and they suggest further that surface water as well as magmatic water may have a part in the transfer. Percolating ground water receives heat from magmatic steam which rises through crevices cutting the path of the former. Very narrow cracks offer a ready passage to the steam, but are less accessible to liquid water. We may suppose, however, that some surface water finds its way through and into a zone where it is not stable, but where the temperature may or may not be much above boiling according to varying conditions in different places. For every point in the path of the percolating ground water there is of course a depth below which gravity can not bring it again to the surface. If the water falls below this depth it will continue to fall until it is vaporized, when it will again rise. In this way another portion of heat may be transferred from the rock to the surface water. This process seems the more likely to happen because it is difficult to believe that fractured rock which permits the passage of steam would not also give access to some liquid water, though in particular cases it is possible that the pressure of escaping steam might practically prevent it. One limitation to the transfer of heat by this means is obvious. Since the heat is withdrawn from the rock for the most part by a change of state in the water, it can not be operative below the depth which liquid water can reach. From the magma or batholith up to that level it would seem that heat conduction must afford the only means of transferring heat except that of magmatic steam. As to the reheated fraction of ground water which may be instrumental in the transfer of heat, it is clear from the previous discussion that only a comparatively small proportion would be required to heat all of the remainder to boiling, even if there were no magmatic steam at all.

The minimum limit to the amount of magmatic water which a boiling spring may theoretically contain is therefore subject to two corrections. In so far as heat from the magmatic steam is lost to the surrounding ground, the limit must be raised, while in so far as ground water is vaporized and thus participates in the convection of heat, the limit must be lowered. At present we can not estimate the magnitude of either correction, but we are inclined to the view that the latter is the greater. Whenever the magmatic water in a spring falls below the minimum limit in question the temperature of course would fall below boiling. On the other hand, if the amount of the ground water diminishes, the spring will boil more and more violently as the proportion of magmatic steam increases. Spouting will result, and since the temperature can not rise as long as liquid water remains, the new accession of heat will be chiefly expended in evaporation, until finally, when the steam has reached a sufficient excess, a fumarole will result. This phenomenon has been observed both in mud pots and in hot springs. The transformation of certain boiling springs at the Boiling Lake into fumaroles in midsummer of 1923 is an especially illuminating observation (p. 155).

It is a very interesting fact that nearly all the fumaroles in the Lassen Park have almost the same temperature as the hottest springs, which is practically that of boiling water for the elevation. There are many such fumaroles at Katmai, at Kilauea, and no doubt elsewhere. The most satisfactory explanation of this phenomenon is that there is *liquid* water in contact with the steam of these fumaroles, equilibrium with which controls the temperature as it does in the boiling process. In some fumaroles we had ocular evidence of the fact, and there was other evidence in certain instances. The maximum amount of magmatic steam which such a fumarole can contain will depend of course on the conditions. Assuming, as before, that the magmatic steam where it meets the ground water has a temperature of 117°, that the temperature of the surface water is 10°, and the boiling-point 91°, we calculate that an amount of ground water (supposing it to evaporate) equal to about 2 per cent of the weight of the steam would be required to cool it to 91°, and the mixture of course would contain nearly the same percentage of steam of surface origin. Only a small excess of surface water would theoretically be required to maintain the boiling temperature. The amount of surface water required to cool the steam to the boiling-point varies considerably with the initial temperature of the latter, since steam is not condensed in the process. If the steam were 100° hotter (217°) the surface water required would amount to 9.7 per cent of the weight of the steam and there would be 8.8 per cent steam of surface origin in the vapor mixture. If we take into account the fact that the ground would aid in the cooling of the steam, we see that the surface water required would be somewhat less than these limits. But if, as we believe probable, surface water participates in the convection of heat, probably a larger correction in the opposite direction would be required. Fumaroles of the temperature of boiling water are therefore likely to contain less magmatic water—perhaps much less than the theoretical upper limit. From a physical standpoint there would be no essential difference between a fumarole of this nature and a boiling hot spring except in the relative amounts of the liquid and vapor phases. So long as conditions permit water to flow from the vent the phenomenon would be called a spring. In the fumaroles the water level, where there is one, must be below ground, but the level may be rising or falling, or practically constant, with the water flowing out at a level lower than the orifice.

The hypothesis of heating by magmatic steam implies that the amount of magmatic water in springs and fumaroles varies from place to place and from time to time in the same spring. The limits are not ascertainable at present, but the discussion indicates that they are wide apart. In the time of melting snow, at any rate, all the evidence goes to show that ground water is in large excess, and it is altogether probable that the amount decreases with the advancing season, but as the fumaroles themselves may contain much steam of surface origin, only a theoretical upper limit to the amount of magmatic water can be set, and this may be much above the actual.

In view of the fact that much has been said in the foregoing pages regarding the participation of meteoric water in the activities both of the volcano and of the adjacent hot springs, it is appropriate to consider briefly how such waters reach the centers of activity; what is the manner and what the limitations, if any, of their circulation.

In the consideration of this question capillary forces continue to be invoked as they have been always since Daubrée showed that these forces under given conditions were competent to move water against the opposing force of gravity or an adverse gas or vapor pressure. In point of fact, these "given conditions" prescribe limitations which are absolutely prohibitive to any extended application of the principle to such geological phenomena as those here considered. This has been conclusively shown by Johnston and Adams [1] and plainly indicated by Kemp[2] and by Osmond Fisher [3] much earlier. Capillarity is strictly a force of surface tension; "a column of liquid can be supported *only when there is a free* liquid surface within the capillary." [4] "Capillary action can be made to do great things, . . . But it can not cause a liquid to flow continuously through a tube, however short; for, if it could, it would give us perpetual motion." [5] Moreover, the surface tension diminishes as the temperature rises, and of course vanishes when the surface vanishes at the boiling temperature. It is therefore of no service in accounting for the access of water to a volcano conduit or to a boiling spring. It is perhaps of importance in facilitating the surface evaporation of ground waters in a hot-spring area.

Johnston and Adams have also considered the magnitude to which capillary forces can attain in support of the geological speculation that the penetration of water into deep-seated rocks can be accounted for in this way. The principle invoked is that the pressure developed by capillarity increases as the pore spaces diminish in size. They discover at once that such pressures are "insignificant in comparison with the hydrostatic pressure except for very fine pores," and as soon as the pores are fine enough (0.1 μ or 0.01 μ in diameter), the amount of water which could flow through them, assuming a total pore-space of 10 per cent, would be respectively 0.15 or 0.0015 c. cm. *per year* for each centimeter of surface.

Johnston and Adams leave no doubt of the conclusion to be drawn from this full and complete investigation of the matter; they say in their résumé (op. cit. p. 15):

> Capillary forces are effective only when there is a surface of separation within the pores; moreover, they diminish steadily with rise of temperature and vanish at the critical point of the liquid. Calculation shows that the effects producible at any considerable depth are, in comparison with the pressure due to the hydrostatic column, insignificant except in pores of such fineness that the amount of water which could flow through them is infinitesimal.

This conclusion leaves the movement of meteoric water in the ground, and so its approach to centers of volcano and hot-spring activity, subject primarily to the action of gravity and the local temperature relations. The penetration of liquid water to considerable depths is therefore dependent upon the existence of actual cavities, or structural discontinuities, and is limited in depth, so far as can be inferred from our present knowledge, to the zone in which such structural discon-

[1] John Johnston and L. H. Adams, Observations on the Daubrée experiment and capillarity in relation to certain geological speculations, Journ. Geol. 22, 8, 1914.

[2] J. F. Kemp, Rôle of Igneous Rocks in the Formation of Veins, Trans. Am. Min. Eng. 31, 177, 1901.

[3] Osmond Fisher, Physics of the earth's crust, 2d. Ed., p. 143, 1889.

[4] Johnston and Adams, op. cit.

[5] Osmond Fisher, op. cit.

tinuities can occur—sometimes described as the "zone of fracture." Above the boiling-point or critical temperature the penetration of water vapor is governed entirely by the mechanics of gas pressure and movement and the solubility or chemical activity. The observations presented in the preceding pages contain abundant evidence of the solubility of water vapor in silicate solutions (magmas) and of the enormous pressures which may be developed locally under given conditions (p. 72 *et seq.*).

All of these observations tend definitely to restrict in depth the zone in which both hot-spring and volcanic activity can occur and bring us more and more definitely to the conclusion that these phenomena are subject to local rather than general conditions and have no far-reaching subsurface connections or very deep-seated origin.

CONCLUSION.

As a result of this investigation in the Lassen National Park it is concluded that the hot springs in this locality are chiefly fed by surface water which drains the basins in which they lie, and that the variation in the volume of the water locally and seasonally accounts for the variation in volume and partly for the variation in temperature which we find in the springs. Another portion of water is derived from an underlying batholith. Arising in the form of steam along with other volcanic gases though clefts in the rock, it is condensed by the ground waters and becomes mingled with them. The amount of this magmatic water varies in different springs and at different times in the same spring, not so much because of inconstancy in the emanation as because of variations in the volume of ground water. In the time of melting snow the magmatic water is in general small in amount. It increases as the ground water diminishes. The final stage which is sometimes actually realized is a fumarole. The fumaroles of the Lassen region, whether persistent or otherwise, have almost always a temperature close to that of boiling water for the elevation. This is interpreted to mean that there is liquid water below ground in contact with the steam.

Some of the heat, perhaps the larger part of it, is derived from the magmatic steam. Another portion conveyed by conduction through the lower depths of the rock is carried through the upper strata by the evaporation of a fraction of the ground water in a manner which has been explained. This process may become relatively important where the quantity of ground water is especially great.

Whether the spring waters descend throughout their whole course, or whether they ascend in the latter part of it as artesian waters, we do not know, but according to our view the *liquid* water is moved by gravity alone and comes from no greater depth than that to which the ground water penetrates, while the mineral content, excepting the volatile portion or portions formerly volatile, is all derived from the rock above that level.

The hot springs of acid character are closely related to fumaroles which give off sulphur gases or in other localities halogen acids. The alkaline springs are a later development from acid waters in the process of rock decomposition. Under favorable conditions the acid is exhausted and the further action of hot water on the rock (hydrolysis of alkali silicates) gives the water an alkaline character.

APPENDIX.

List of Observed Eruptions of Lassen Peak 1914–1917.[1]

Observers.	*Stations.*
F—Forest Service	Summer, Brokeoff Mt., 4 miles west; Winter, Mineral, 15 miles south.
O—George W. Olsen	Chester, 20 miles east.
D—Miss Dines (Postmistress)	Manton, 20 miles west.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1914		*Minutes*	
1	F, O	May 30	5^h p.m.	10	Heavy. H. Abbey reports size of crater 25 by 40 feet.
2	F, O	June 1	8^h a.m.	15	Heavier.
3	F	" 2	9^h30^m a.m.	30	Very heavy.
4	F, O	" 8	4^h30^m p.m.	40	Heavier.
5	F	" 9	10^h30^m a.m.	30	Heavy, steam darker.
6	O	" 12	10^h45^m a.m.		
7	F	" 12	3^h45^m p.m.	50	Heavy, steam very dark. Size of crater 40 by 100 feet.
8	F, O	" 13	6^h a.m.	30	Heavy. Ashes fell at Mineral.
9	O	" 13	3^h45^m p.m.		
10	F	" 14	6^h a.m.	?	Unconfirmed. Reported by Red Bluff.
11	F, O	" 14	9^h43^m a.m.	30	Heaviest yet. Altitude of smoke 2,5000 ft.
12	F, O	" 14	6^h45^m p.m.	15	Medium. Size of crater 450 by 125 feet.
13	F	" 19	8^h15^m p.m.	15	Medium. Altitude of smoke 2,000 feet. Size of crater 600 by 150 feet.
14	O	" 22	7^h30^m p.m.		
15	F	" 29	3^h a.m.	?	New snow covered by layer of ash.
16	F, O	" 30	11^h06^m a.m.	....	Heavy. Series of slight eruptions followed first. Continued to 5 p. m. Altitude 2,800 feet.
17	F, O	July 1	5^h30^m a.m.	50	Heaviest yet. Altitude 5,900 feet.
18	O	" 1	2^h20^m p.m.		
19	F, O	" 2	6^h50^m p.m.	30	Very heavy.
20	F	" 6	3^h30^m a.m.	30	Reported by Red Bluff. Heavy steam and smoke from entire length of crater.
21	F	" 13	3^h07^m p.m.	40	Medium. Air calm. Thin column steam rose to height of 1,800 feet. Little ash visible. West end of crater
22	F	" 15	6^h05^m a.m.	4 hours.	Very heavy. Of long duration, 4 hours.
23	F	" 15	12^h05^m p.m.	Entire afternoon.	Greatest disturbance yet, exceeding previous eruptions in intensity and duration. Great amount ash thrown. Height, 8,910 feet.
24	F	" 16	12^h30^m p.m.	Intermittent through early hours.	Very heavy. Volcanic dust fell at Mineral.
25	F	" 16	4^h30^m a.m.	Several hours.	Heavy eruption.
26	O	" 16	6^h a.m.		
27	O	" 16	12^h M		
28	F	" 17	6^h a.m.	Several hours.	Heavy eruption. Volcanic ash fell at Mineral.
29	F	" 17	11^h47^m a.m.	Several hours.	Heavy eruption.
30	F, O	" 18	5^h28^m a.m.	Entire morning.	By far most violent eruption to date. Ash, steam, etc., rose to height of 11,000 feet.
31	F, O	Aug. 10	5^h30^m p.m.	Continued after dark	Medium. Small quantity of ash thrown out.
32	F, O	" 19	7^h24^m a.m.	4 hours, 30 minutes.	Very heavy. Huge clouds of ash thrown out. Height 10,500 feet.
33	O	" 20	5^h a.m.		
34	F, O	" 21	11^h10^m a.m.	1 hour, 40 minutes.	One of the largest eruptions to date. Entire crater active. Height 10,560 feet.
35	F, O	" 22	8^h40^m a.m.	....	Heavy ash column shot up obliquely instead of vertically as in all former eruptions. Altitude, 7,590 feet.
36	F, O	" 22	12^h40^m p.m.	1 hour, 20 minutes.	Heavy. Entire crater active. Height 5,940 feet.
37	F, O	" 22	4^h35^m p.m.	55 minutes.	Medium. Short duration. Altitude 6,000 feet.
38	F, O	" 23	6^h33^m a.m.	1 hour, 53 minutes.	Medium. Height 5,610 feet.

[1] Collected by J. S. Diller.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1914		*Minutes*	
39......	F, O.....	Aug. 23	7^h43^m p.m.	Continued after dark.	Larger than morning disturbance. Height 5,940 feet.
40......	F, O.....	Sept. 5	12^h23^m p.m.	4 hours.	Medium. Full-length crater active. Height 5,600 feet. Size of crater 605 by 208 feet. (C. H. Lee's measurement).
41......	F........	" 5	4^h25^m p.m.	1 hour, 35 minutes.	Medium. Larger quantities of ash than morning eruption. Height 4,950 feet.
42......	F, O.....	" 6	$11^h\ 4^m$ a.m.	3 hours, 55 minutes.	Medium. Entire crater active. Height 5,920 feet. (Crater reported to have widened considerably in west end.)
43......	F........	" 7	10^h30^m p.m.	Continued indefinitely thru early morning hours.	Very heavy. Wind negligible, column dust ascended to great height. Rumblings awakened lookout on Brokeoff Mountain.
44......	F........	" 8	8^h a.m.	Had not reached normal when second eruption took place.	Very slight. Began subsiding almost immediately after first outburst.
45......	F, O.....	" 8	9^h55^m a.m.	Normal had not been reached when third eruption of day took place.	Medium. Began subsiding immediately after outburst.
46......	F........	" 8	10^h25^m a.m.	Normal not reached	Medium. Slightly more ash thrown out than two preceding eruptions.
47......	F........	" 8	11^h35^m a.m.	1 hour, 50 minutes.	Heavy. Ash clouds enveloped mountain. Entire crater active.
48......	F, O.....	" 9	4^h20^m a.m.	....	Medium.
49......	F, O.....	" 9	3^h p.m.	Continued after sundown.	Considered one of the largest eruptions to date. Heavy fall of ashes in Mineral and Lyonsville.
50......	O........	" 10	5^h a.m.		
51......	O........	" 11	4^h30^m a.m.		
52......	O........	" 15	8^h p.m.	....	At 8 p.m. on Sept. 15, people in Warner Valley heard rumbling noises and felt a slight earthquake. Not noticed at Chester.
53......	F........	" 16	3^h p.m.	Unknown.	Mt. obscured by clouds. Only indication of eruption was fall of ashes at Viola. Storm cleared on 18th, disclosing 3 new vents on west slope, undoubtedly caused by eruption of 16th.
54......	F........	" 19	3^h10^m a.m.	Short.	Medium.
55......	O........	" 20	12^h30^m a.m.	....	The ground here was white with the dust from the eruption at 12.30 a.m., the only time it has fallen here (Chester).
56......	F........	" 20	3^h a.m.	5 hours.	Very heavy. Accompanied by terrific rumblings, followed by heavy vibrations. No change noted in vents.
57......	F, O.....	" 20	11^h35^m a.m.	3 hours.	Heavy. Rumblings and detonations heard at Mineral for first time. Ashes fell at Mineral. No change noted in vents.
58......	F, O.....	" 21	$6^h\ 5^m$ a.m.	....	Probably most violent eruption to date. Ash practically obscured sky from Mineral viewpoint. Vent nearest top on west slope considerably enlarged. Equal volumes of steam from both sides of mountain. No mutterings heard or earthquake felt at Chester.
59......	F, O.....	" 29	7^h15^m p.m.	Unknown.	F — "Very heavy. Luminous bodies hurled high into air. Substantiated by Turner Mt. Lookout and other eyewitnesses. Demolished lookout house. Estimated length of crater 900 feet. Considerably widened. Becoming more rounded with each eruption." O — "The only time I saw light was a flash of light that looked as tho it might have been an explosion of gases or an electric flash. This is the only eruption I have seen at night."
60......	F........	" 30	10^h p.m.	3 hours.	Heavy. Ashes fell at Hall's Flat.
61......	F, O.....	Oct. 1	5^h15^m a.m.	1 hour.	Heavy.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1914		*Minutes*	
62......	F, O.....	Oct. 1	7^h a.m.	2 hours.	Medium.
63......	F, O.....	" 1	12 M	1 hour.	Medium.
64......	O........	" 1	4^h40^m p.m.		
65......	O........	" 6	6^h10^m a.m. to 11^h30^m p.m.	....	Estimated height of column 8,000 feet. Color at first very dark, later, turning almost white.
66......	F......	" 7	6^h20^m a.m.	4 hours.	Very heavy.
67 & 68	O........	" 10	?	....	Made a trip to the top of the Mountain Oct. 11. The crater is much wider and deeper than at my last visit July 19. I guessed the crater to be between 400 and 500 feet wide and 700 and 800 feet long and 150 and 200 feet deep. Forest outlook house demolished by large quantity of stones blown out since Sept. 15. The crater has cut through the West Butte and there is a large crack extending down the west side of the Mountain for several hundred feet, emitting steam constantly.
69......	O........	" 15	3^h a.m.		
70......	O........	" 15	9^h30^m p.m.	....	Fire being seen at this eruption but not by myself.
71......	O........	" 16	4^h30^m a.m.		
72......	F........	" 17	Between 8 p.m. & Midnight.	Unknown.	Unknown. Observed by parties in vicinity of mountain.
73......	F, O.....	" 22	11^h30^m a.m.	2 hours.	F—"Very heavy. Air at Mineral darkened by heavy fall of ash." O—"Rumbling plainly heard here at Chester but no earthquake felt. Yori says, Oct. 22, biggest eruption. He ascended Lassen Peak soon after and states that the ashes were so hot he could not remain long at one place and that the dog's feet were burned. He took a photo of the new crater on the N. E. side at the head of Lost Creek."
74......	F, O.....	" 23	6^h15^m a.m.	1 hour.	F—"Heavy. Snow on all sides of mountain covered by ash."
75 & 76	O........	" 23	6^h10^m p.m.	....	"There were numerous flashes of light seen at this eruption. There seems to be no doubt as I have talked to several eyewitnesses whom I believe to be reliable and all are positive that it was light from the volcano and not from the rays of the setting sum. Unfortunately I did not see this eruption."
77......	O........	" 27	1^h50^m p.m.	....	Oct. 26, ascended the mountain and found the crater quite a bit deeper.
78......	O, D.....	" 28	2^h p.m.		
79......	F, D.....	" 30	1^h30^m p.m.	20 minutes.	F—"Occurred during storm. No further details."
80......	O, D.....	" 31	11^h50^m a.m.		
81......	O........	Nov. 1	6^h p.m.		
82......	O........	" 2	8^h45^m a.m.	15 Minutes.	
83......	O........	" 2	$9^h\ 5^m$ a.m.	10 Minutes.	
84......	F, D.....	" 2	10^h10^m a.m.	30 Minutes.	F—"Medium." D—"Smoke . . . south."
85......	F........	" 2	12^h10^m p.m.	30 Minutes.	Medium.
86......	F, O, D..	" 2	4^h20^m p.m.	20 Minutes.	F—"Medium." D—"Smoke . . . south."
87......	O........	" 3	2^h15^m a.m.	....	Seen by a neighbor.
88......	O........	" 4	?	....	Steaming or smoking nearly all day.
89......	D........	" 10	4^h25^m p.m.		
90......	O........	" 11	?	....	Heavy clouds of steam rising from the crater all day but not like the regular eruptions.
91......	O........	" 12	3^h p.m.	....	Same as on Nov. 11, with small eruption at 3 p.m. Did not rise above the mountain. Drifted north.
92......	F........	" 16	10^h10^m a.m.	30 Minutes.	Slight.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1914		*Minutes*	
93......	O........	Nov. 18	2^h50^m p.m.	....	Small eruption. *Note.*—Since Nov. 26 (letter of Dec. 7) there has been a heavy fall of snow in the high mountains, I should judge about 4 feet, there being 2 feet at this place (Chester). During this time (Nov. 26 and Dec. 7) I have seen Mt. Lassen but twice. On Nov. 30 the clouds cleared away and Lassen was plainly visible for several hours, and it was completely covered with ashes showing that there had been a heavy eruption within the last 24 hours, otherwise it would have been white. At that time there were two or three feet of snow on the high mountains. Dec. 4 it was partly visible for a short time. At that time it was white.
94......	F........	" 18	4^h10^m p.m.	20 Minutes.	Medium. Several parties viewing eruption from different angles declared disturbance came from north slope of mountain.
95......	D.......	" 20	....	....	Eruption at night.
96......	F........	Dec. 3	During afternoon.	Unknown.	Medium.
97......	F........	" 11	3^h30^m p.m.	Unknown.	Reported as heavy snowstorm on mountain at time of eruption.
98......	F........	" 12	11^h45^m a.m.	30 Minutes.	Slight.
99......	F, O.....	" 12	4^h45^m p.m.	40 Minutes.	F—"Medium." O—"Rays of setting sun colored this eruption but nothing like fire was noticed."
100......	F........	" 13	10^h30^m a.m.	....	Medium.
101......	O........	" 15	?	....	At daylight steam rising from a point not seen before, seemingly about one-fourth mile down the slope of the mountain, steaming quite heavily all morning.
102......	O........	" 15	1^h p.m.	....	Two jets of steam; one from the crater and one from the north crater—narrow column rising several thousand feet.
103......	O........	" 16	?	....	Steamed quite heavily all day from north crater.
104......	O........	" 17	11^h a.m.	....	Charles Yori, at Drakesbad, heard rumbling noises in the direction of Lassen Peak.
105......	O........	" 18	3^h to 4^h p.m.	....	Small eruption. Clouds rise several thousand feet. Column narrow like smokestack, and extends far into southern sky.
106......	O........	" 18	?	....	Steamed all day from the north crater and all afternoon from both craters.
107......	O, D.....	" 24	11^h45^m a.m.	....	O—"Eruption from north crater accompanied by rumblings distinctly heard at Chester. Cloud very dark colored at beginning, getting lighter in about 20 minutes. Duration about 3 hours, height 10,000 feet." D—"Lasting one-half hour. East side new crater."
108......	O........	" 27	7^h a.m.	....	Lassen was white with the new snow last night, and quite a cloud of steam rising from new crater. By 8 p.m. it was obscured by fog or cloud until afternoon, when it cleared. The snow was covered with ashes and quite a cloud of steam rising from new crater.
109......	O........	" 29	....	....	Lassen steamed very heavy all forenoon and until about 2 p.m. Heavy cloud of steam hanging over the mountain for 2 hours about midday.
110......	O........	" 31	....	....	Lassen steamed quite heavy for 2 or 3 hours in afternoon, from north crater.
		1915			
111......	D.......	Jan. 2	4^h55^m p.m.	10 minutes.	Erupted from southeast. Smoke—north.
112......	F........	" 13	6^h a.m.	Unknown.	Heavy.
113......	D.......	" 17	5^h30^m a.m.	½ hour.	Black Smoke. Smoke—north.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1915		*Minutes*	
114......	F........	Jan. 17	6^h30^m a.m.	Unknown.	Medium.
115......	O........	" 17	8^h a.m.	15 or 20 minutes.	The first eruption of Lassen Peak seen from Chester this month occurred at 8 a. m. from center of mountain. Duration 15 or 20 minutes. Did not rise to any great height but drifted to southwest in quite a heavy cloud.
116......	F........	" 18	6^h a.m.	Unknown.	Medium.
117......	O........	" 18	8^h a.m.	....	Small eruption at 8 a.m. from center.
118......	O........	" 18	1^h15^m p.m.	1 hour.	Quite a heavy eruption; height 5,000 feet duration 1 hour, steaming quite a bit all afternoon. Cloud drifting clear across the western sky.
119......	F........	" 19	5^h p.m.	Short.	Slight.
120......	D........	" 21	6^h30^m a.m.	1 hour.	Went about 1,000 feet. Smoke—north.
121......	O........	" 21	8^h10^m a.m.	....	Cloud not rising above top of mountain but drifting west or southwest.
122......	F........	" 22	6^h a.m.	Several hours.	Heavy.
123......	O........	" 23	6^h a.m.	20 minutes to ½ hour.	Two eruptions, one about 6 a.m., only the cloud seen at 6:30; cloud drifted in N.E. direction. This eruption was of medium size, duration was from 20 minutes to one-half hour.
124......	F, O, D..	" 23	9^h15^m a.m.	O, D reports one hour, F reports several hours.	F—"Medium." O—"Quite heavy, duration about 1 hour. Cloud went several thousand feet high, drifted N.E. The rumbling was plainly heard at Drakesbad and Warner Valley, northeast of Chester." D—"Large volume of smoke lasting 1 hour." Smoke—southeast.
125......	F........	" 25	10^h20^m a.m.	Several hours.	Medium.
126......	O........	" 26	12^h10^m a.m.	....	Loud rumbling noise heard in direction of Lassen Peak, 12.10 a.m. It being cloudy no eruption could be seen.
127......	D........	" 26	10^h25^m a.m.	....	Black smoke. Smoke—north.
128......	D........	" 26	2^h40^m p.m.	....	Black smoke.
129......	F........	Feb. 5	Late in afternoon.	Unknown.	Unknown. Snow darkened.
130......	F........	" 6	Early morning.	Unknown.	Unknown.
131......	F, O, D..	" 11	6^h50^m a.m.	Several hours.	F—"Heavy. Ash cloud reached high altitude." O—"Eruption." D—"Smoked all a.m."
132......	F, O, D..	" 12	About 5 a.m.	Several hours.	F—"Heavy." O—"Eruption." D—"Smoked all a.m."
133......	F, D.....	" 12	12^h55^m p.m.	Several hours.	F—"Very heavy eruption occurred." D—"Large eruption. Thousands of feet high."
134......	O........	" 20	12^h30^m a.m.	....	Rumbling heard in direction of Lassen Peak at 12.30 a.m.
135......	F........	" 26	6^h a.m.	Short.	Medium.
136......	O, D.....	Mar. 11	7^h40^m a.m.	½ hour.	O—"Medium intensity, duration 30 minutes." D—"Black smoke. Smoke—north."
137......	F........	" 12	7^h30^m a.m.	Short.	Medium. Bumpass Hell in an eruptive state just previous to and during eruption. Witnessed by Abbey from near Brokeoff. Crater appeared from Brokeoff to have lengthened considerably in direction of Lookout House.
138......	O........	" 14	....	....	Eruption some time during night. Mountain covered with dust this morning that was white last night.
139......	F........	" 19	5^h a.m.	Could not be determined.	Very heavy eruption. Falling ash caused hazy atmosphere in vicinity of mountain for greater portion of day. Steam could be seen from Red Bluff issuing from vents on side.
140......	F, O, D..	" 20	5^h30^m a.m.	35 minutes.	F—"One of the heaviest eruptions. Conditions similar to those of previous day prevailed."

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1915		*Minutes*	
140......	F, O, D..	Mar. 20	5h30m a.m.	35 minutes.	O—"Heavy eruption, 10,000 feet, duration 35 minutes." D—"Largest yet. Crimson clouds of smoke. As sun was rising reflections were beautiful and wonderful. Never to be forgotten by those who witnessed the grand phenomenon. Black smoke. Ashes fell from 9 a.m. to 10 o'clock. Ashes reached Paynes Creek and the Black Buttes."
141......	O........	" 20	6h30m a.m.	20 minutes.	Medium eruption, duration 20 minutes.
142......	F, O.....	" 20	7h50m a.m.	Until 5 p.m.	F—"Medium." O—"Heavy eruption lasting until 5 p.m."
143......	F........	" 21	4h30m a.m.	Short.	Medium.
144......	O........	" 21	5h30m a.m.	Short.	
145......	O, D.....	" 21	10h15m a.m.	O—15 minutes. D—1 hour.	D—White Smoke.
146......	F, O, D..	" 21	3h p.m.	F—Short. O—2 hours. D—1 hour.	F—"Medium." O—"Column rising about 10,000 feet."
147......	O........	" 21	9h30m p.m.	About 30 minutes.	
148......	D........	" 21	10h p.m.	....	Twenty-one eruptions at night about 10 o'clock.
149......	O, D.....	" 23	....	....	O—"Lassen in light eruption all day. Column not rising above mountain, but rolling over and drifting northward." D—"Crater smoked all day."
150......	O........	Apr. 4	....	Nearly all forenoon.	Light eruption nearly all forenoon. Obscured by clouds after 11.30 a.m.
151......	D........	" 5	6h p.m.	½ hour.	Smoke—south.
152......	O........	" 6	7h15m a.m.	2 hours.	Medium sized eruption at 7:15 a.m. lasting two hours.
153......	O........	" 8	....	....	Eruption some time last night just before dark. The east side of Lassen was white with new snow this morning at 7.30. When fog cleared up the north half of the east side was covered with dust. This evening after sunset two columns of steam were rising from the top of Lassen several hundred feet. This forenoon from 11 to 12 a large column of steam was rising from Bumpass'. Charles Yori reports quite a heavy fall of ash at Drakesbad, sometime during the night of the 12-13th.
154......	F, O.....	" 15	6h30m p.m.	F—Short. O—Continued until dark.	F—"Heavy." Crater visited by Hampton and Kaul Mar. 23, 1915. Apparently no great increase in size. O—"Heavy column rose several thousand feet high, continued until dark."
155......	O........	" 16	4h a.m.	Until 5.30 a.m.	The time of beginning not known, only estimated.
156......	O, D.....	" 16	1h30m p.m.	O—Most of the afternoon.	O—"Cloud drifting this way, fumes quite strong here, no dust fell to amount to anything." D—"Resembled horns. Smoke—south."
157......	F, O.....	" 16	5h50m p.m.	F—Short. O—Continued until dark.	F—"Medium." O—"Cloud drifting southeast."
158......	O........	" 17	....	....	A small amount of ash fell last night.
159......	F........	" 26	3h p.m.	Short.	Medium.
160......	F........	" 27	3h30m p.m.	Unknown, storming	Heavy. Volcanic dust fell at Manton.
161......	O........	" 27	5h30m p.m.	30 minutes.	Heavy, duration about 30 minutes.
162......	D........	" 30	....	....	Ashes fell at dusk filling hair of E. Z. Williams and Alice Dines who happened to be working in flower garden. Very cloudy. Eruption not seen. We held out paper and caught one-half teaspoon of ashes in about 10 minutes. Ashes fell at Cottonwood, Shasta County this time. Eruption happened during a storm.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1915		*Minutes*	
163......	O........	May 2	....	....	Eruption in morning. Time of beginning not known. Seen at 5:30 a.m.
164......	O........	" 3	....	....	Eruption first seen at 1 p.m. and at intervals all afternoon until 7 p.m., when it was covered by cloud. Was cloudy all afternoon but cleared up enough to see the mountain several times, and every time it was in eruption.
165......	O, D.....	" 4	....	....	O—"Eruption lasting all day." D—"Black smoke. Cloudy day, only visible a few moments at 3 p.m. Smoke—south."
166......	O........	" 5	....	....	In eruption all day.
167......	O........	" 6	....	....	In eruption all day.
168......	F, O.....	" 7	During morning.	Unknown, storming.	F—"Reported by Ranger from Mineral." O—"In eruption all day."
169......	O........	" 13	8h30m a.m.	....	Lassen in eruption at 8.30 a.m., was visible only for a short time, cloudy. This was the first time that Lassen had been seen since the 7th. Cloudy all the time.
170......	D........	" 14	2h40m p.m.	....	New crater. Large eruption. Smoke—east. Large crater first visible from here 9 a.m. Fire seen for first time by 8 persons. I telephoned to all having phones so hundreds saw the fire, which lasted all night and was seen just before daybreak at intervals of 15 minutes, ½ hour, and ? hours.
171......	O........	" 15	....	....	Light seen on top of Lassen at 2.30 a.m.
172......	F........	" 17	Evening.	Unknown.	Various parties on all sides of mountain reported glow above crater on clouds.
173......	F, O, D..	" 19	10h30m p.m.	Unknown.	F—"First indication of eruption was tremendous flood of mud, etc., down Hat Creek. Meadows covered." O—"Lassen seen this afternoon the first time for six days. Was in eruption all the time it was visible. After dark a steady glow of light was seen shining on cloud of smoke for several hours." D—"Mountain smoked all day. Fire lava seen on top at 9 p.m. A few days previous to this a change was noticed in mountain. A black-like wall appeared coming in middle crater getting higher every day. It looked from here wedge-shaped and was seen from north to south of crater and mountain. After this it spilled over on west side and still remains there."
	F........	" 22	During morning.	Long. In eruption up to time of large eruption.	Abbey reported mountain in continual eruption all morning. From point 3 miles distant, mountain appeared flattened on top. Abbey's report.
174......	F, O, D..	" 22	4h30m p.m.	About an hour.	F—"Terrific eruption. Incomparable with any former eruption. Evidences of ejecta such as hot mud, hot rocks, and pumice. Heated boulders fired drift wood several miles from crater. Several new fissures on mountain side, especially on north and east slope." O—"Lassen seen today first time since 19th. Was in light eruption all day. At 4.45 p.m. there was an eruption by far the heaviest ever seen, lasting about an hour. Column of steam reached a height of about 30,000 feet." D—"Eruption was largest, grandest ever seen. Went 1,000 feet high. Large volume of smoke first drifted over Manton but turned and smoke and ashes drifted to Nevada. Many people hitched their horses preparing to leave. Among those who were ready to depart were: Mrs. Kate Stull, R. L. Pruden and family, E. L. Tulbright and family." NOTE.—No earthquakes ever felt at Manton.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1915		*Minutes*	
175......	F, O.....	May 30	$5^h\ 8^m$ p.m.	40 minutes.	F—"Ordinary volume. Steam issued from north slope of peak quite heavily laden with ash. Main crater full of boulders. Floor of crater appears shoved upwards." O—"Medium sized eruption at 5.10 p.m."
176......	O........	" 31	5^h15^m a.m.	....	Medium sized eruption at 5.15 a.m.
177......	F........	" 31	9^h30^m a.m.	30 minutes.	Medium. Emission from crater on north slope. Main crater quiet.
178......	O........	June 1	10^h30^m p.m.	....	Heavy eruption at 10.30 p.m.
179......	F........	" 10	During night.	Unknown.	Unknown. Mountain unusually active following morning. Heavy volumes steam from crater low down on west slope.
180......	O........	" 12	3^h p.m.	....	Eruption at 3 p.m. Light continued until dark. *Note.*—I am not certain that anything was seen from Chester between June 12 and Aug. 25, 1915. On the night of July 13, 1915, ashes fell at Drakesbad so that we could write our names on porch railing in the morning. A small *puff* of steam seen in forenoon of Aug. 8, when J. M. Howells and I went up Lassen Peak. Steam drifted northeast. J.S.Diller.
181......	F........	" 16	8^h30^m a.m.	20 minutes.	Medium.
182......	F........	" 16	1^h15^m p.m.	20 minutes.	Medium.
183......	D........	" 20	3^h a.m.	....	Was an eruption. Two distinct shots of fire ascended with black smoke. I was just returning from a dance. It was witnessed by G. D. Cronemiller and my cousin, Otto Daily.
184......	F........	" 23	10^h44^m a.m.	20 minutes.	Medium. Entirely from crater on north slope.
185......	F........	" 26	4^h10^m a.m.	Short.	Medium. Witnessed and reported by lookouts.
186......	F........	July 2	9^h20^m p.m.	Of long duration.	Very heavy. Ash clouds of unusual density.
187......	F........	" 3	8^h10^m p.m.	20 minutes.	Slight.
188......	F........	" 13	9^h40^m p.m.	20 minutes.	Medium.
189......	F........	" 27	4^h30^m a.m.	1 hour.	Heavy. Eruption from north crater. Bumpass Hell and other hot springs unusually active. Increased volumes of steam from crater on top.
190......	F........	" 28	2^h50^m p.m.	Several hours.	Heavy. Eruption from north crater. Rumblings distinctly heard at Big Springs.
191......	F........	Aug. 6	7^h a.m.	Continued until midnight.	Quake felt at summit of Brokeoff at 11 a.m. Direction N. and S. Heavy eruption.
192......	F........	" 8	9^h50^m a.m.	All day.	Very heavy eruption.
193......	F, C.....	" 25	5^h25^m p.m.	2 hours.	F—"Heavy. Rumblings heard by Brokeoff Mountain lookout. Altitude 12,870 feet. Huge jagged boulders cover location of former crater." O—"Heavy eruption at 5.25 p.m. lasting 2 hours. Altitude 10,000 feet."
194......	F, O.....	" 27	8^h30^m a.m.	F—50 minutes. O—1 hour.	F—"Medium." O—"Medium eruption at 8.30 a.m. Duration about 1 hour.
195......	F, O.....	Sept 1	7^h25^m a.m.	30 minutes.	F—"Medium. Altitude 3,630 feet." O—"Medium eruption at 7.30 a.m. Duration 30 minutes."
196......	F........	" 3	9^h a.m.	20 minutes.	Slight.
197......	F, O.....	" 18	9^h a.m.	6 hours.	F—"Heavy. Unusually active until 3.30 p.m. Rumblings heard by Brokeoff lookout. Steam and sulphur fumes constantly being emitted from many fissures." O—"Heavy, lasting until 6 p.m. Heavy until noon; light the remainder of time."
198......	F, O.....	" 20	9^h30^m a.m.	35 minutes.	F—"Heavy." O—"Heavy eruption. Duration 30 minutes."
199......	F, O.....	" 23	9^h45^m a.m.	35 minutes.	F—"Medium." O—"Medium. Duration 35 minutes."
200......	F, O.....	" 26	$2^h\ 5^m$ p.m.	F—45 minutes.	F—"Slight. Nearby observers state boulders 8 inches in diameter hurled about 100 feet.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1915		*Minutes*	
200......	F. O.....	Sept. 26	2^h 5^m p.m.	O—30 minutes.	Lassen has developed 3 distinct new craters on northwest portion of mountain. These are located on summit of mountain directly west of old crater; are circular in shape, and are at present the outlet of most material thrown out. O—"Light eruption. Duration about 30 minutes."
201......	F, O.....	" 27	2^h50^m p.m.	20 minutes.	F—"Medium. Very deep rumblings heard by Brokeoff lookout." O—"Medium. Duration about 20 minutes."
202......	O........	" 30	5^h p.m.	....	Light eruption at 5 p.m.
203......	O........	Oct 2	11^h p.m.	....	Earthquake felt at 11 p.m. two shocks, light, no sounds.
204......	O........	" 6	12^h30^m p.m.	About 20 minutes.	Medium eruption at 12.30 p.m.
205......	F, O.....	" 14	10^h45^m a.m.	F—30 minutes. O—All day.	F—"Medium. Slight fall of snow on Lassen October 13. Prospect Peak lookout reports the eruption issued from new fissure on north slope." O—"Light eruption lasting all day."
206......	F, O.....	" 15	2^h45^m p.m.	1 hour, 30 minutes.	F—"Medium. Rumblings heard by Prospect Peak lookout. Eruption from above-mentioned fissure." O—"Steaming all day quite heavily at times."
207......	O........	" 16	....	....	Steaming all day quite heavy at times.
208......	F, O.....	" 17	10^h45^m a.m.	1 hour.	F—"Medium. Rumblings heard by Prospect Peak lookout. Also heard by Harvey Mountain lookout. Eruption from above mentioned fissure." O—"Steaming quite heavy from daylight until 10.50 a.m. when there was quite a heavy eruption. All the eruptions from the 14th to the 17th (inclusive) seemed to come from a new fissure on the north slope."
209......	O........	" 19	....	....	Visited the summit of Mt. Lassen. Found but few changes since July 25, date of last visit. Visited the new fissure and found it steaming quite heavy. The steam was quite full of dust and sand; it had collected around the opening.
210......	O........	" 24	2^h p.m.	....	Light eruption at 2 p.m.
211......	O, D.....	" 25	7^h30^m p.m.	O—30 minutes. D—20 minutes.	O—"Medium eruption at 7.30 p.m. Light flashes and bombs seen shooting from the crater." D—"Moonlight. Very pretty in moonlight. Smoke—north."
212......	F, O.....	" 30	7^h30^m p.m.	F—Unknown. O—30 minutes.	F—"Heavy. Glow over crater and luminous bodies reported seen by various parties." O—"Heavy eruption 7.30 p.m. Large flashes of light and bombs shot high above top of mountain lasting 4 or 5 minutes, the eruption lasting about 30 minutes."
213......	F........	" 31	11^h40^m a.m.	20 minutes.	Heavy.
214......	F........	Nov. 1	12^h25^m p.m.	Short.	Slight.
215......	F........	" 10	8^h30^m a.m.	Short.	Medium.
216......	O........	" 13	11^h40^m a.m.	About 40 minutes.	Heavy eruption. The cloud from this eruption went about 11,000 feet high. "*Note.*—This was the last eruption seen from this place up to Dec. 31, 1915."
217......	F........	" 22	Early morning.	Mountain in eruption all day.	Reported by Manton and Shingletown residents. No particulars.
218......	D.......	Dec. 25	....	....	Mountain smoked at 5 p.m. Smoke drifted to south.
219......	D........	" 29	6^h a.m.	....	Eruption about 6 a.m. Smoke west to south. Smoked all day. Mountain hid by large volume of smoke settling down on it.

Note.—No record of eruptions *between Dec. 29, 1915 and Sept. 24, 1916.*

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1916		*Minutes*	
220......	D.......	Sept. 24	7^h a.m.	All day.	Steam at intervals.
221......	D.......	Oct. 4	Between 6 and 7 a.m.	?	Black smoke, heavy, ascending into clouds.
222......	D.......	" 5	5^h35^m p.m.	....	Small eruption of white steam.
223......	D.......	" 16	9^h a.m.	Entire day.	Largest eruption of the summer. Smoke settled around mountain.
224......	D.......	" 24	6^h p.m.	1 hour.	Very largest this year. White and black smoke drifted south over Brokeoff Mountain. Sulphur fumes reached Manton at 9 p.m. Smell very strong like sulphur and something rotten. Smoke went thousands of feet in the air.
225......	D.......	" 25	a.m.	....	Steaming quite heavy this morning.
226......	D, O.....	Nov. 1	4^h p.m.	½ hour.	Very large eruption. Smoke rolled out but went down in strong wind to north.
227......	O.......	" 2	....	....	Steam rising at intervals all day.
228......	O.......	" 8	9^h a.m.	....	Heavy.
229......	O.......	" 9	4^h40^m p.m.	....	Heavy.
230......	D, O.....	Dec. 17	4^h30^m p.m.	....	Medium (O); white steam came straight up (D)
231......	D, O.....	" 20	All day.	All day.	Steam, heavily all day and drift south.
232......	D.......	" 28	7^h a.m.	5½ hours.	White steam came in great volumes.
		1917			
233......	D.......	Jan. 1	....	All day.	White steam.
234......	D.......	" 3	....	All day.	White steam, small quantity.
235......	O.......	" 15	4^h p.m.	1½ hours	Medium.
236......	D.......	" 16	3^h30^m p.m.	1 hour.	White steam.
237......	D, O.....	" 17	9^h45^m a.m.	All day.	D—"Large eruption of black smoke. Ashes fell on Brokeoff. Rumblings heard 15 miles at Crookes. None heard at Manton." O—Medium heavy growing lighter to little steaming at dark.
238......	D.......	" 18	a.m.	....	Strong sulphur at Crookes' place, 15 miles.
239......	D.......	" 20	4^h20^m p.m.	1⅔ hours.	Smoke drifting south.
240......	D, O.....	" 30	7^h a.m.	....	D—"Great quantities of white steam." O—"New snow covered with dust on N, ¼ of east side of mountain."
241......	O.......	Feb. 1	....	....	Another night eruption, covering entire east side of mountain.
242......	O, D.....	" 3	7^h a.m.	All day.	O—"Steamed slightly." D—"White steam, great quantity until noon."
243......	O.......	" 18	9^h a.m.	1 hour.	Medium heavy cloud went several thousand feet high.
	O.......	Mar. 8	2^h a.m.	....	Two light earthquake shocks. No eruption.
244......	O, D.....	" 16-20	....	....	O—"Steaming quite heavily whenever visible."
	D.......	" 21	....	....	D—"Mountain more active. Eruption during night of 21st, covering snow with dust."
245......	D, O.....	" 22	11^h30^m a.m.	¾ hour.	D—"Eruption large. Jet black smoke drifts south." O—"Smoke rose 3,000 feet."
246......	D, O.....	Apr. 5	2^h25^m p.m.	½ hour.	D—"Largest of this year. Must have gone up 1,000 feet before black smoke drifted south. Ashes fell to south." O—"Clouds go several thousand feet high. This is the heaviest eruption I have seen since big one May 22, 1915."
247......	D, O.....	" 6	8^h15^m a.m.	3 hours.	D—"Black smoke drifted south. Ashes." O—"Continues medium about 30 minutes."
	O.......	" 8	11^h30^m a.m.		One slight earthquake shock.
248......	D, O.....	" 15	6^h a.m.	1 hour.	D—"Smoke rises thousands of feet in air." O—"Medium. Small column rising several thousand feet."
249......	O.......	" 18	11^h a.m.	¾ hour.	
250......	D.......	" 19	2^h10^m p.m.	....	Smoke went up into clouds.
251......	D.......	May 4	7^h10^m a.m.	....	Very large. Smoke went thousands of feet in the air.
252......	D.......	" 4	1^h p.m.	2 hours.	Very large. Smoke went thousands of feet in the air.

No. Eruption.	Authority.	Date.	Time.	Duration.	Intensity and Remarks.
		1917		*Minutes*	
253......	D........	May 4	10^h30^m p.m.	....	Black smoke drifts south. Eruption large, half-way down mountain side as big eruption.
254......	O........	" 9	6^h45^m p.m.	30 minutes.	Medium.
255......	O........	" 13	6^h45^m a.m.	30 minutes.	Heavy. Large volume of dust and steam.
256......	D, O.....	" 18	12^h45^m p.m.	6 hours.	O—"Very heavy. Clouds rising 10,000 to 12,000 feet. accompanied by loud rumblings lasting until darkness obscured view."
257......	O........	" 19	....	All day.	O—"Steaming heavily all day—quite large after sundown. Rumblings heard from 3 to 5 p.m."
258......	D, O.....	" 20	6^h a.m.	All day.	O—"Steaming all day quite heavy. Rumblings heard during afternoon."
259......	O........	" 21	10^h a.m.	30 minutes.	Medium.
260......	D, O.....	" 22	7^h20^m p.m.	½ hour.	D—"Black smoke lasting ½ hour." O—"A steady glow of light seen on summit at 9 to 10 p.m.
261......	O........	" 29	....	....	Eruption during night. Ashes fell at Feather River Meadows.
262......	O........	" 30	6^h15^m a.m.	45 minutes.	Heavy.
263......	D, O.....	" 31	11^h a.m.	1 hour.	D—"Large. Smoke to south." O—"Heavy."
264......	O........	" 31	5^h10^m p.m.	30 minutes.	
265......	O........	June 1	3^h p.m.	30 minutes.	Medium.
266......	O.......	" 2	10^h a.m.	30 minutes.	Heavy.
267......	D........	" 2	1^h20^m p.m.	....	Large. Smoke went high in the air.
268......	O........	" 3	8^h a.m.	30 minutes.	Medium.
269......	D........	" 3	1^h30^m p.m.	....	Black smoke went high in the air.
270......	D........	" 3	4^h20^m p.m.	....	Small eruption—white steam.
271......	D, O.....	" 3	5^h55^m p.m.	15 minutes.	Small eruption—white steam.
272......	D........	" 3	$7^h\ 7^m$ p.m.	15 minutes.	Small column high in air.
273......	O........	" 3	8^h20^m p.m.	15 minutes.	Small.
274......	D, O.....	" 4	7^h10^m a.m.	40 minutes.	D—"Large. Black smoke thousands of feet in air."
275......	D, O.....	" 4	10^h a.m.	20 minutes.	O—"Light."
276......	D........	" 4	1^h40^m p.m.	30 minutes.	Smoke high in air.
277......	D, O.....	" 4	6^h50^m p.m.	30 minutes.	O—"Heavy."
278......	O........	" 6	7^h40^m a.m.	1 hour.	Heavy smoke rising about 10,000 feet.
279......	D........	" 6	7^h a.m.	1 hour.	Black smoke large.
280......	D........	" 6	1^h p.m.	20 minutes.	
281......	D, O.....	" 8	2^h30^m p.m.	2 hours.	D—"Terrible eruption. Smoke went north." O—"Heavy. Four hours."
282......	D........	" 8	6^h40^m p.m.	15 minutes.	Small, white eruption.
283......	O........	" 10	1^h p.m.	All afternoon.	Medium.
284......	D, O.....	" 21	2^h20^m p.m.	1 hour.	Light. Smoke went north.
285......	O........	" 27	6^h15^m a.m.	....	Medium.
286......	D, O.....	" 29	3^h p.m.	1 hour.	D—"Large. Black smoke drifted north 1 hour." O—"Medium."
		1918			No eruptions reported for 1918.
		1919			
292......	D........	Jan. 9	3^h p.m.	1 hour.	Small smoke—evaporated short distance above mountain.
293......	D........	" 10	....	1 hour.	Small smoke—evaporated short distance above mountain.
294......	D........	Apr. 8	5^h30^m a.m.	....	Black smoke drifted south until 7 a.m.
295......	D........	" 9	6^h a.m.	....	Small quantity of white smoke drifting south.
		1920			
296......	D........	Oct. 24	8^h a.m.	10 hours.	Quantity of black smoke rising rapidly and drifting south.
297......	D........	Oct. 30	7^h a.m.	12 hours.	Small smoke arising slowly disappeared at summit of peak.
		1921			
298......	D........	Feb. 7	7^h a.m.	5 hours.	Great clouds of white steam issuing from eastern fissures.

Note.—The newspapers of Red Bluff and Redding in the Sacramento Valley have reported a number of eruptions during the years since 1917 that appear to have been cloud banners about Lassen Peak rather than eruptions of steam. The latest eruption seen by G. W. Olsen, the observer at Chester, was Aug. 23, 1917.

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