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VIOLENT MUD-VOLCANO ERUPTION OF LAKE CITY HOT SPRINGS, NORTHEASTERN CALIFORNIA

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ABSTRACT

During the night of March 1 and 2, 1951, an inconspicuous group of hot springs and small mud volcanoes in northeastern California burst into spectacular eruption, unequalled by other known mud volcanoes. The eruption cloud of steam, gases, and mud particles rose several thousand feet in the air and distributed fine debris to the southeast for a distance of at least 4 miles. More than 20 acres of the hot-spring area was intensely disturbed and greatly modified by the eruption, estimated to involve at least 6 million cubic feet or 300,000 tons of mud. Several days after the eruption, the area was barely active. The eruption appears to be unique in the history of the springs.

The hot-spring system is in deep fine-grained clastic sediments immediately east of the Surprise Valley fault bounding the Warner Range. The sediments of the spring area are saturated with near-neutral hot saline water. Previous temperatures and geothermal gradient of the area were probably high.

Mud volcanoes exist in similar physical environment near Gerlach in Washoe County, Nevada, and on the southeast shore of Salton Sea, Imperial County, California. Other mud volcanoes occur in acid thermal areas and are characterized by abundant volcanic gases and near-surface alteration by sulfuric acid; their eruptions involve only surficial material and not underlying competent bedrock.

Eruptions in deep fine-grained basin sediments are attribured to unstable or metastable temperature-depth relations existing in many high-energy thermal systems. Vapor pressure at depth may equal or exceed hydrostatic pressure. Great energy is stored in a thermal system of this type, but ordinarily is released slowly.

A mud-volcano origin is possible for some eruption deposits classed as phreatic or cryptovolcanic. Although near-boiling hot springs are considered phases of volcanism, true volcanic eruptions are distinct from mud-volcano eruptions. The former derive their energy directly from new volcanic rocks or magma, but the latter are caused by sudden release of energy stored in near-surface hydrothermal systems and do not involve direct release of energy from new volcanic magma. The energy of true volcanic eruptions, however, may be increased by release of energy from previously existing hydrothermal systems, for example in the Rotomahana phase of the great Tarawera eruption of 1886 in New Zealand.

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Introduction

An extraordinary eruption of an inconspicuous group of hot springs occurred March 1, 1951, in Surprise Valley in the northeastern corner of California. No similar activity of comparable magnitude is recorded in geologic literature. The eruption was of a type best described as a mud volcano and was distinctly not a geyser nor true volcano.

The hot springs are located in sec. 23 and 24, T. 44 N., R. 15 E., about 2 miles north of Lake City and half a mile east of the front of the north-trending Warner Range. The springs were formerly so inconspicuous that they had no formal name. In this report they are called the Lake City hot springs.

The author first visited the scene of activity with R. G. Reeves, of the U. S. Geological Survey, on March 6, 1951, about 4½ days after the eruption started. On September 16, 1951, he revisited the area with G. A. Thompson and C. H. Sandberg, of the Geological Survey, and William Wise, of Carson City, Nevada.

DEFINITIONS: The terms mud pot and mud volcano have been used by several authors (Veatch, 1857; Day and Allen, 1925, p. 103; Barth, 1950, p. 113) to describe certain features of hot-spring areas, but the terms have not been clearly defined. The term mud pot is used to indicate a depression containing a fluid mixture of mud and water that is generally being agitated mildly by gases or steam. The term mud volcano is applied to those thermal features that erupt mud, either quietly or violently. The distinction between mud pots and many mud volcanoes is slight; a small change in type of activity may change one into the other, as Day and Allen (1925, p. 103) have indicated. Some of the mud volcanoes described in this paper, however, were not mud pots in the past nor are they likely to be in the future.

Although mud volcanoes are distinctly not true volcanoes, the comparison is appropriate in many ways. Most mud volcanoes propel blobs or clots of mud upward from a central crater by violent flow of gases and water vapor through mud in the floor of the crater. Mud falling outside the crater accumulates to form a cone comparable to a pyroclastic cone. A less common type of mud volcano is formed by quiet extrusion on the surface, unaccompanied by vigorous activity of gases. Some are comparable to shield volcanoes and to pahoehoe and aa lava flows.

Mud volcanoes of very different origin are associated with oil deposits of many regions, but are not likely to be confused with mud volcanoes of thermal areas.

Acknowledgments

Information on the first day of the eruption has been acquired largely from Mr. Joe Parman and Mr. Lloyd A. Rogers, editor of the Alturas Plaindealer, who visited the springs the morning following the eruption. Permission to use photographs taken by Mr. James Souther of Alturas is gratefully acknowledged. Particular appreciation is extended to Prof. Fred Humphrey of Stanford University, to whom the author is indebted for the sketch map of the eruption area. The author is also grateful to his associates for assistance and advice.

Lake City Hot Springs

Previous Activity

Little is known about the Lake City hot springs before their eruption in 1951. Waring (1915, p. 122–123) describes them briefly as

> 'Hot springs near southwest side of Upper Lake. At points about 2 and 3 miles, respectively, north of Lake City, hot water rises in meadowland that borders Upper Lake. The quantity of flow and the temperature of the water are rather indefinitely known, as the water rises in tule-grown areas."

In a later report by Stearns *et al.* (1937, p. 118), a spring listed as California No. 14 is described as "near southwest side of Upper Lake, 12 miles north of Cedarville." Temperature is listed as 120° F (49° C) and discharge as 5 gallons per minute. The data on temperature, discharge, and number of springs are derived from some other source than Waring's earlier paper, and are of doubtful reliability. Of particular interest, in view of the lack of reliable data, are pre-eruption air photographs of the U. S. Forest Service (photos DEM-33-90 and -91, taken September 20, 1946). These photographs indicate a hot-spring area three-fourths of a mile long and as much as 800 feet wide, but only the central part contained many hot springs. Large pools and the cones of several mud volcanoes can be distinguished. The pre-eruption sketch map of the area (Fig. 1) has been constructed from these photos.

Although the temperatures of the springs were not known, some springs were reportedly hot enough for hog scalding and were therefore definitely hotter than the 120° F (49° C) reported by Stearns *et al.* (1937, p. 118). No direct evidence is available to indicate whether they had recently been at or near boiling, but near-boiling springs are believed to have existed in the inaccessible central portion of the marsh. The existence of small mud volcanoes, recognizable in the air photographs, is evidence that temperatures were at least periodically close to boiling.

According to other local reports, the springs have been quiet and inconspicuous since the area was first settled, although occasionally one of the mud volcanoes would erupt mildly and throw mud out on its banks. The 1951 eruption, however, was a very unusual and probably even a unique event in the life of these springs. No evidence on the ground or in the photographs indicates that comparable activity has occurred in the past.

Geologic Setting

Northeastern California has had a long and complex volcanic history extending through most of the Tertiary and Quaternary periods (Russell, R. J., 1928; Anderson, C. A., 1941; Powers, H. A., 1932). The Warner Range consists dominantly of gently dipping flows and agglomerates bounded on the east by a major fault of the basin-range type. This fault is about half a mile west of the Lake City hot springs. I. C. Russell (1884, p. 449–450) and R. J. Russell (1928, p. 466–467, 470) have discussed the fact that hot springs occur along the fault but neither author specifically mentions the Lake City springs.

The depth of alluvial fill under the springs and elsewhere in Surprise Valley is not known. A well a few miles south of Lake City and within a mile of the Warner Range was drilled through 835 feet of lacustrine sediments without reaching bedrock (R. J. Russell, 1928, p. 436).

Hot Springs of the Region

In the eastern half of Modoc County Stearns *et al.* (1937, p. 118–119, Pl. 15) have identified 18 springs and spring groups. Three of these groups discharge water at or near boiling, a fourth yields boiling water from wells, and two others, not including the Lake City group, are about 65° C in temperature. All these high-temperature springs are believed to owe their heat and very probably a part of their water supply and mineral content to volcanism (White and Brannock, 1950, p. 567–572; Brannock *et al.*, 1948, p. 216–222).

Table 1 shows the chloride content, pH, and specific conductance of water samples collected from the Lake City hot springs, compared with selected samples from other areas.

The Lake City springs are similar chemically to many of the other thermal waters.

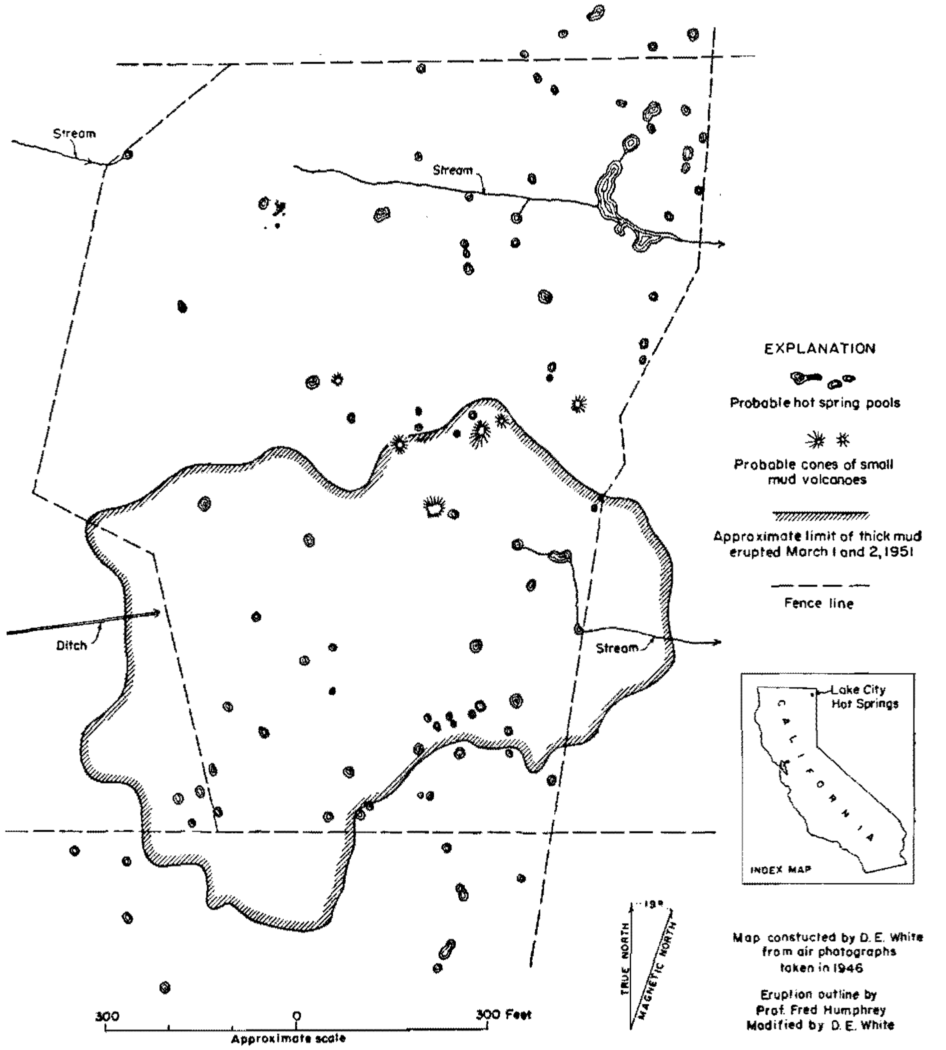

FIGURE 1.—PREERUPTION SKETCH MAP OF CENTRAL PORTION OF LAKE CITY HOT SPRINGS, SHOWING OUTLINE OF ERUPTION AREA

Map constructed from air photographs of September 20, 1946, U. S. Forest Service, with eruption outline by Prof. Fred Humphrey.

Eruption of March 1 and 2, 1951

The following account of the eruption of the Lake City hot springs was obtained from Mr. and Mrs. Joe Parman, on whose farm most of the activity occurred, and from Mr. Lloyd Rogers, editor of the weekly *Alturas Plaindealer*. Rogers and photographer James Souther arrived at the springs about mid-day of March 2 while the activity was still moderately strong. Their report and photographs of the eruption appeared in the Thursday, March 8 issue of the *Alturas Plaindealer*.

Apparently without warning on the night of March 1 at about 11.30 p.m. a large part of the spring area erupted, perhaps not en masse but at least in major part. Because of the darkness of the night, little could be seen, but the accompanying noise has been described as "terrific" and as a "grumbling and roaring sound accompanied by a loud whistling similar to rapidly escaping air." The erupting springs were said by some witnesses to have formed a "tornadolike cloud with a long tail that reached down to the mud volcano." While this cloud was forming, the noise increased in volume and a series of tremors led many to believe an earthquake was occurring. The column of gases and mud was estimated to rise at least a mile in the air, drifting to the south and southeast under the influence of a strong wind.

Oddly enough, Parman and his family were asleep when the eruption started and were awakened only when friends telephoned from Lake City, about 2 miles to the south. However, the wind was blowing strongly to the southeast, and the springs are located nearly half a mile southeast of the Parman farm. The noise was so loud in Lake City that the local fire department was alerted in the belief that an explosion had occurred. A hail of frozen particles consisting largely of mud were falling on the town, and pellets about the size of peas were later reported from farms as far as 4½ miles from the spring. The local residents believed the pellets were erupted or blasted for those great distances. The eruption column, however, must have risen to considerable heights because of its contained steam and hot gases, and resultant low density, and not primarily because of explosive violence of the eruption. Evidence was later found to indicate that large blocks and boulders were erupted several hundred feet in the air. The mud pellets presumably formed fro n freezing water vapor, incorporating small particles of mud.

The activity is described as being greatest soon after the initial eruption, continuing very strongly but with decreasing vigor during the night. Early the next morning Parman found steam from vents rising perhaps 100 feet in the air. The fumarole discharge consisted almost entirely of vapors, but a little mud was being thrown nearly as high. The first known photographic record of the activity was obtained by Mr. James Souther about noon of March 2. Figure 1 of Plate 1 shows four small late-phase mud volcanoes in a much larger depression that was one of the major vents during the initial violent activity. Four or five other major vents, one of which is shown in Figure 2 of Plate 1 to be steaming with great vigor, were distributed in an area later determined to be nearly 700 feet long and as much as 700 feet wide. (*See* Fig. 2.) All surface and near-surface material in this large area of about 10 acres was completely churned up and thoroughly redistributed. Most of the activity had been localized in the major mud-volcano craters, each of which was 60–200 feet in diameter and was bounded by mud walls of ejected debris. Souther's photographs indicate that by noon of March 2 the activity in each large crater consisted of vigorously boiling mud pots and fluid mud volcanoes, occasionally blurping pellets and clots of mud to a height of 10–20 feet. At this time the eruption was essentially completed, but activity continued on a decreasing scale for several days.

Activity and Observations on March 6, 1951

Area nearly quiescent.—Nearly all activity had ceased by the morning of March 6, a little more than 4 days after the eruption started. The flow of energy from the thermal system was probably near its absolute minimum since the system first came into existence and may not be so low again until the system becomes extinct.

Masses of mud, still wet, hot and dangerous in many places, surrounded the disturbed area and rose up to 15 feet above the adjacent flat eastward-sloping alluvial plain. (*See* Pl. 2, fig. 1.) The previously existing springs apparently had discharged essentially on this plain.

Very little steam or vapor was rising from the springs. Nearly all mud-volcano craters, large and small, were drained of water though the bottoms of the deepest were below the surrounding plain, which was saturated with water. A small creek with a flow of about 3 second feet was discharging into the crater in one of the few

TABLE 1.—PARTIAL ANALYSES OF THERMAL AND METEORIC WATERS FROM LAKE CITY REGION AND OTHER MUD-VOLCANO AREAS

Springs	Description	Date	Temp. (°C)	Estimated discharge (gpm)	Cl (ppm)	pH	Specific conductance, K × 10^6
Lake City	Preserved spring vent NE part of area	3/6/51	38	None	216	6.81	1,888
Lake City	Eruption crater, north-central part	3/6/51	49	None	224	6.38	1.825
Lake City	Boiling pool, NW part	9/16/51	96	None	212	7.77	1,680
Lake City	Boiling pool, east-central part	9/16/51	97.5	10–15	212	7.63	1,680
Lake City	Discharge from east-central part of area	9/16/51	Warm	100	202	7.83	1,745
Lake City	Artesian well ¼ mi. ESE of springs	9/16/51	21	¼	76*	....	....
N. end Lake City Group	About ⅜ mi. N of main group	9/16/51	55	None	233	6.67	1,855
Calif. No. 16†	12 mi. NE of Cedarville, SE of Lake City	9/16/51	65.8	50	212	7.96	1,645
Calif. No. 15†	2 mi. N of No. 16	9/16/51	87	40	228	7.76	1,630
Cedar Plunge	Erupting well E of Cedarville and SSE of Lake City	9/16/51	84	100	184	8.42	1,430
Kelly hot spring	About 35 mi. SW of Lake City	9/17/51	96.5	400	164	8.49	1,275
Kelly hot spring	Artesian well 500 ft. E of spring	9/17/51	28.9	½	4	8.51	265
Gerlach, Nev.	Geyser pool, border Black Rock Desert	8/6/47	94.7	50	2,136	7.13	6,850
Gerlach, Nev.	Mud volcano, inactive, 500 ft. to NE	8/6/47	27	None	4,500	6.29	15,740
Gerlach, Nev.	Hughes well, ½ mi. SE of springs	8/6/47	61.3	15	1,996	7.27	6,600
Gerlach, Nev.	Well ¾ mi. E of springs	8/6/47	21	Flowing	2,004	7.18	6,600
Salton, Calif.	Perpetual spouter, largely steam, near mud volcanoes	4/12/48	100.2	Small	69,560	6.97	130,600
Salton, Calif.	CO_2 well N of abandoned dry-ice plant	4/12/48	39.8	30–40	12,960	6.33	34,300
Salton, Calif.	Thermal well, Mullet Island	4/13/48	72.9	Periodic small discharge	59,720	5.83	115,500
Salton, Calif.	Salton Sea	4/13/48	Cold	....	14,320	7.96	40,850
Norris, Yellowstone	Phillips Cauldron	9/28/47	93.8	None	12	3.40	1,233

TABLE 1.—*Cont.*

Springs	Description	Date	Temp. (°C)	Estimated discharge (gpm)	Cl (ppm)	pH	Specific conductance, K × 10⁶
Norris, Yellowstone	Acid pool about 200 ft. NW of Norris drill-hole site	9/28/47	"Boiling"	Slight	12	1.86	6,105
Norris, Yellowstone	Congress Pool 100 ft. NW of acid pool	9/28/47	61	None	672	1.98	6,625
Boiling Lake, Lassen	Mud volcano	6/25/47	94.7	None	4	3.49	1,005
Boiling Lake, Lassen	Acid spring	6/25/47	94.4	Small	4	3.02	963

* Sample bottle broken, only sufficient quantity for chloride analysis.
† Numbers after Stearns *et al.* (1937, p. 118).

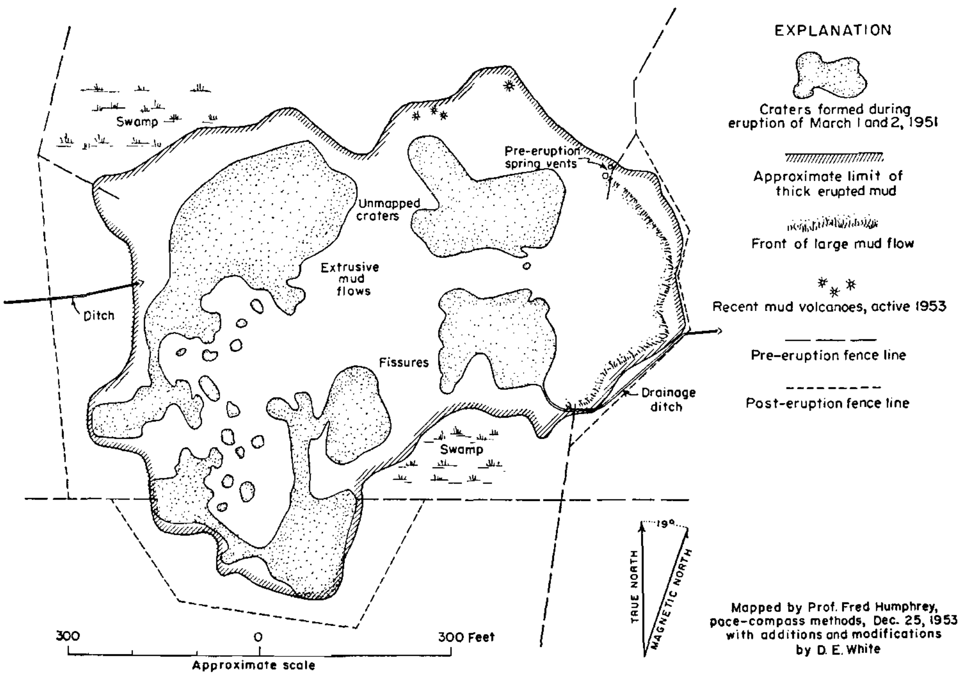

FIGURE 2.—SKETCH MAP OF ERUPTION AREA
Mapped by Prof. Fred Humphrey, pace-compass methods, December 25, 1953, with additions by White.

places where the bounding mud wall was insignificant. The creek water was disappearing underground, and no water was flowing out of the eruption area. One small mud pot in the western part contained a little water and was bubbling gently at a temperature of 47° C. A group of small mud pots in the northwestern part of the disturbed area was a little hotter, with temperatures of 60° C. Still farther to the northwest where the superficial layer of erupted mud had thinned to a foot or so, the most extensive activity of the area was taking place. This is believed to be an original part of the spring group not directly involved in the eruption, but its activity may have been in part induced in some complex way by the eruption.

The ground was hot, and so boggy that it could not be crossed safely, but many small hot pools and steaming vents were visible from the comparatively safe, well-drained mud embankments. No well-established pools lined with spring deposits were seen.

Major mud volcanoes.—The eruption area contains six large depressions or craters, very irregular in outline, and ranging from about 60 to 200 feet in diameter. These are surrounded by mud embankments generally rising 5–15 feet above the crater floors. These large depressions are believed to be the main vents for the initial and most violently active mud volcanoes. Mud walls are insignificant on the west sides of two southwestern craters and in two other depressed areas on the south side of the active area. These are probably craters of subsidence resulting from the eruption of mud and removal of support.

Fissures in mud embankments.—The mud embankments near several large depressions were cut by open fissures and cracks as much as 50 feet long and a foot wide. Some were at least 5 feet deep and were probably considerably deeper in spite of their occurrence in water-soaked mud. The fissures were concentrically arranged around at least one of the large depressions and probably resulted from settling of the over-steepened mud walls after activity had ceased. On March 6, vapor was rising quietly from many of the fissures, and in a few places considerable steam was flowing. The highest temperatures found in the area were measured in these fissures. Vapor from one vent discharged at 75° C, and steam escaping from a second vent under slight pressure had a temperature of 97.2° C (Pl. 2, fig. 2). The latter temperature is slightly above theoretical boiling point for the altitude of the springs (about 95.5° C at an altitude of approximately 4600 feet).

Small mud volcanoes in major craters.—Smaller mud pots and mud volcanoes are distinct from the larger depressions. These smaller features have a somewhat random distribution, but a large proportion are in the crater depressions of the large mud volcanoes. The small features are later than the depressions in which they occur and were active during the declining phases of the eruption. (*See* Pl. 1, fig. 1.) They were not over 5–15 feet in diameter and, because they formed in the soupy mud of the depressions, their cones are low and gently sloping. Larger mud volcanoes of this type probably existed during intermediate stages of activity but were not preserved.

The large mud volcanoes were probably deep, steep-sided craters during their maximum activity. When activity decreased, steep walls could not be maintained in soft water-saturated mud. The crater floors were probably built up considerably by collapsing and inflowing mud walls and by strong agitation of small mud volcanoes.

Intermediate mud volcanoes.—Other mud volcanoes of intermediate size, as much as

PLATE 1.—MAJOR MUD-VOLCANO VENTS ABOUT 12 HOURS AFTER THE ERUPTION STARTED

FIGURE 1.—A MAJOR MUD-VOLCANO CRATER SURROUNDED BY ERUPTED MUD EMBANKMENTS AND CONTAINING FOUR SMALL ACTIVE MUD VOLCANOES

The large crater is about 100 feet in diameter and was a center of intense activity the night of March 1 and 2, 1951; photographed by James Souther about noon, March 2, 1951

FIGURE 2.—VIGOROUSLY STEAMING CRATER OF A MAJOR MUD VOLCANO

Mud-erupted embankment, nearly water-saturated, in foreground; distance to edge of crater about 30 feet; photographed by James Souther about noon, March 2, 1951

PLATE 2.—ERUPTION AREA AFTER MAJOR ACTIVITY HAD CEASED

FIGURE 1.—FENCE BURIED BY ERUPTION DEBRIS ON THE SOUTHEAST BORDER OF THE ACTIVE AREA

Near source area for much of the mud flow of Figure 2 of Plate 4; fence poles about 5 feet high; photographed by White, March 6, 1951

FIGURE 2.—OPEN FISSURES IN ERUPTED MUD EMBANKMENT

Adjacent to a major mud volcano to the right of the photograph; probably caused by subsidence toward the crater. Temperatures as much as 97° C measured in these fissures. Photographed by White, March 6, 1951

FIGURE 1

FIGURE 2

MAJOR MUD-VOLCANO VENTS ABOUT 12 HOURS AFTER THE ERUPTION STARTED

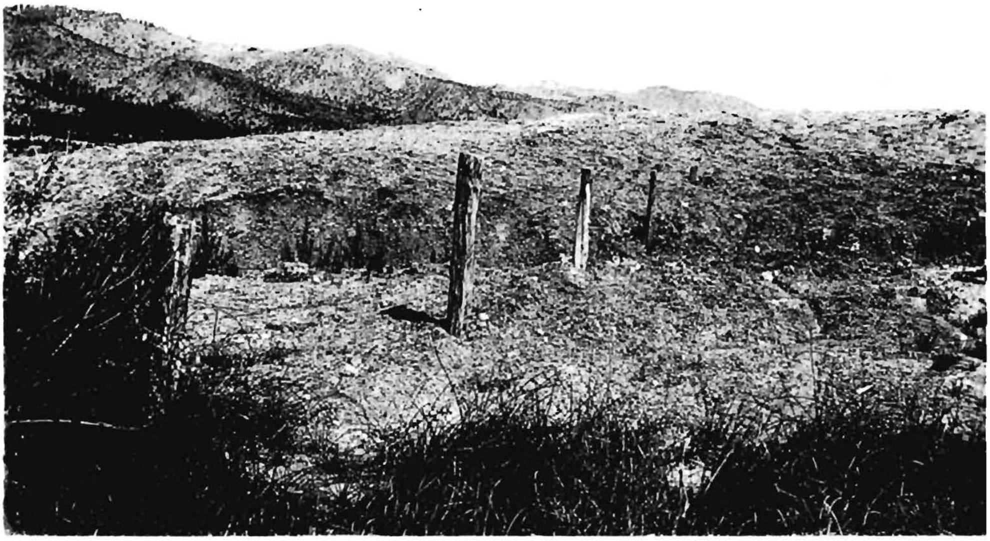

FIGURE 1

FIGURE 2

ERUPTION AREA AFTER MAJOR ACTIVITY HAD CEASED

FIGURE 1

FIGURE 2

MUD-VOLCANO CRATERS AND SMALL MUD FLOWS

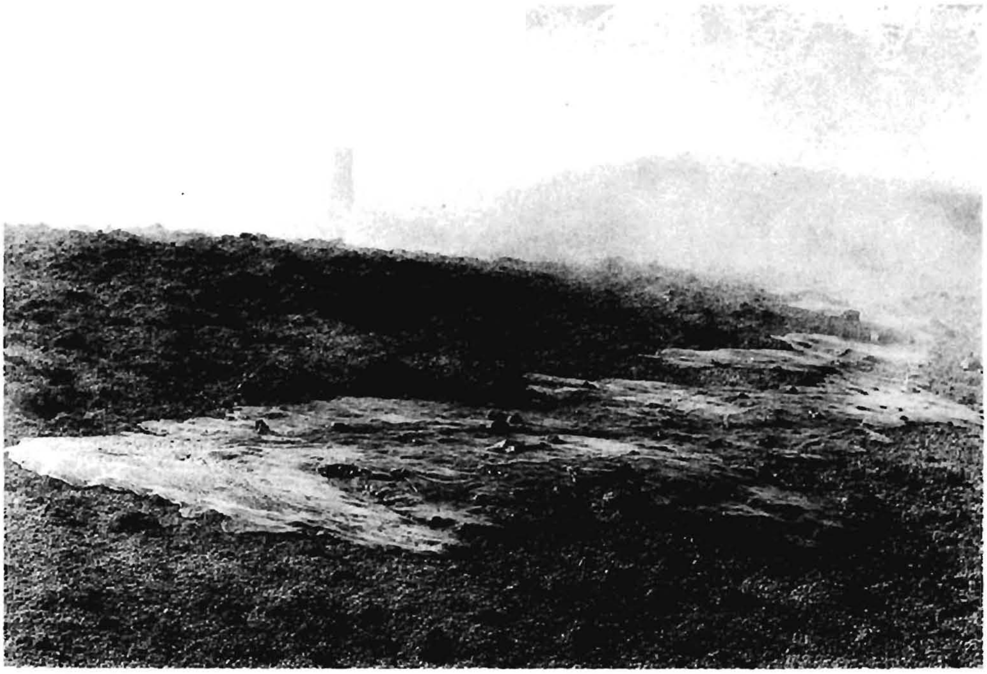

FIGURE 1

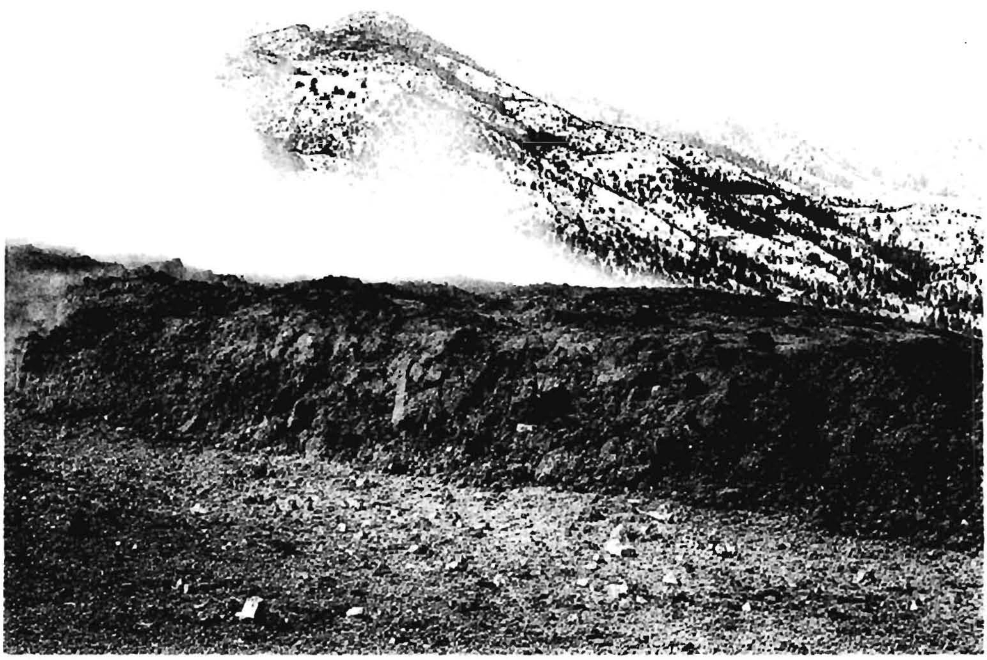

FIGURE 2

LARGE AND SMALL MUD FLOWS

25–30 feet in diameter (*see* Pl. 3), are irregularly distributed on the accumulations of mud separating the large depressions. In general their cones are high; inner as well as outer slopes are steep. The difference in altitude between crater floor and cone summit is as much as 15 feet, but 5–10 feet is more common. These mud volcanoes may grade into the major mud volcanoes, but the ones that have been preserved apparently formed after the most violent activity had ceased and are more closely related in time to the small mud volcanoes in the major craters. The differences between the small and intermediate types are believed to result principally from differences in the fluidity of their environment. Those in the major craters were erupting very fluid mud because water was concentrating in the depressions; only the latest of this type were preserved. On the other hand, the mud embankments containing the mud volcanoes of intermediate size were relatively high in altitude and were drained of excess water.

One mud volcano on an embankment was particularly instructive. Its cone was 7 or 8 feet in diameter, and the steep inner slopes revealed a cross section of the mud embankment. The lower part was brownish gray and coarse in texture without stratification, and had many randomly distributed stones and mud fragments or clots as much as 6 inches in diameter. The upper 2 feet was characterized by a gray color and a much finer texture, without conspicuous fragments other than small stones and mud clots that were probably semifluid when erupted. The contact between the two types of deposit is relatively sharp. The lower mud is believed characteristic of most of the disturbed material resulting from the more violent early phase of activity. The upper layer was deposited as a mantle on the lower mud by small mud volcanoes after the gross features of the area had been determined and the activity was tapering off. This particular mud volcano was distinctly later than the lower mud and apparently erupted through a part and perhaps all of the upper layer.

Areas of subsidence.—The large craters were formed primarily by the explosive eruption of mud. At least parts of some craters, however, are believed to have formed by subsidence because mud was removed from below by the extensive eruption. The three southwestern craters shown on Figure 2 are adjacent to the pre-eruption ground surface, with little or no intervening mud embankment. The scarcity of splatter near the western and southern borders of these craters is the principal evidence suggesting subsidence.

A swampy area southwest of the major mud flow (Fig. 2) appears to be about 1–2 feet lower in altitude than the ground surface to the south

PLATE 3.—MUD-VOLCANO CRATERS AND SMALL MUD FLOWS

FIGURE 1.—LATE-STAGE MUD FLOWS OR EXTRUSIVE MUD VOLCANOES, IN SOME RESPECTS RESEMBLING LAVA FLOWS

The pancake-shaped "pahoehoe" type of flow in the foregound was erupted from a vent under its center. Mud flows immediately beyond the observer were erupted from a single vent to the right of the photograph and are similar in some respects to aa lava flows. The crater-pocked embankment in the middle distance lies between major mud volcanoes.

FIGURE 2.—MUD-VOLCANO CRATERS OF INTERMEDIATE SIZE

Mud embankment formed by major mud volcanoes to right and left of photograph; craters of intermediate size were probably active after the most intense eruptions had ceased. The large angular block held by the observer consists of a ramifying network of calcite veins cutting a matrix of mud. This was the largest erupted fragment found in the area; photographed by White, September 16, 1951.

PLATE 4.—LARGE AND SMALL MUD FLOWS

FIGURE 1.—MINOR FLUID LATE-STAGE MUD FLOW

Still in motion when photographed by James Souther about noon, March 2, 1951; probably situated near the source area of mud flow of Plate 4, fig. 2; height of fence post about 3 feet

FIGURE 2.—SOUTHEAST BORDER OF MUD FLOW THAT MOVED EASTWARD FROM THE ERUPTION AREA AFTER DEEP ACCUMULATION OF ERUPTED DEBRIS

Flow is about 6 feet thick near border and 15 feet near center; rocks and mud pellets in foreground were erupted at least 300 feet from source vents; photographed by James Souther.

(Pl. 2, fig. 2). A small, general subsidence may have occurred here.

Small mud flows or extrusive mud volcanoes.—The mud volcanoes previously described are comparable in many ways to true pyroclastic volcanoes except for obvious differences in scale, temperature, and composition. Small mud flows or mud volcanoes of an extrusive type constitute a very late phase of the activity. These resemble extrusive lava flows unaccompanied by marked explosive activity. Figure 1 of Plate 4 shows a very fluid flow, photographed while still in motion. A somewhat more viscous flow of the same type was erupted from a vent in the central part of the disturbed area (Pl. 3, fig. 1). The flow was similar to a pahoehoe lava flow, spreading out on all sides from its vent to form a smooth-topped "pancake" about 15 feet in diameter and only a few inches high on its borders. This mud flow is very similar in general form to the "lily-blossom" pahoehoe lava, illustrated by Stearns and Macdonald (1946, Pl. 26A, p. 83) from Hawaii, and is also comparable in miniature to the pancake-like flow of recent dacite obsidian about half a mile north of Medicine Lake (Anderson, 1941, p. 372–373).

Another mud volcano, shown in the same photograph, erupted mud resembling an aa lava flow in some physical properties. The surfaces of its compound flows were rough with abrupt flow fronts 6 inches to a foot in height. These "aa" flows had moved farther from their vents and down steeper slopes than the "pahoehoe" flow, and they appeared to be initially more viscous. The original water content of the two contrasting types could not be determined, but presumably the differences resulted at least in part from a higher water content in the "pahoehoe" flow. The water content of the mud flow shown in Figure 1 of Plate 4 was very high.

The more-fluid mud flows were extruded through mud accumulations that were semisolid, and from the surface of which excess water had already drained. Compaction and settling of semisolid mud may have produced extrusion of entrapped masses of more-fluid mud that could rise and flow out at the surface because of its lower density. Eruption of the mud flows appears to be one of the late phases of activity. This is illustrated by the still-moving mud flow photographed about mid-day of March 2 after most of the explosive activity had ceased and is also supported by the fact that no exploded rocks or mud clots were found on the surfaces of the mud flows.

Large mud flow.—A much larger mud flow of different origin formed and moved eastward from the eruption area during or soon after the climax of activity (Pl. 4, figs. 1, 2). Viscous mud accumulated to a considerable thickness adjacent to the large mud volcanoes on the east and moved eastward down slope under the influence of its own weight. The photograph shows a jumbled irregular mass of mud blocks near the flow front, which indicates that the surface was broken up and disturbed during the last stages of movement in a manner strikingly comparable to that of block lava flows. The flow is approximately 320 feet wide at its base, and it advanced an average of 140 feet east of its base line. The average thickness of mud in the flow is about 12 feet, and its total volume is approximately 500,000 cubic feet. Its mass is nearly 30,000 tons, with an assumed density of 1.8.

Airborne eruption debris.—Blocks and fragments of mud and rocks as much as a foot in diameter have a significant distribution around the area. These fragments are most abundant on the east, southeast, and south sides of the eruption area and are as much as 300 feet from the nearest major center of activity. None were found lying on the surface of the latest mud near the small mud volcanoes. Few if any fragments were erupted on the surface of the large mud flow after movement had ceased, although blocks of comparable size are contained in the large mud flow and are abundant within the thicker accumulations of mud. The evidence clearly indicates that the large fragments were erupted into their positions during the most vigorous early activity. Blocks that fell near the main centers presumably were concealed under later deposits.

A block falling 300 feet from its source was probably erupted to a height of at least 100 feet and perhaps 200–300 feet, although precise estimates cannot be made without a knowledge of their trajectories. Many of the blasts may have been inclined to the east or south, because even a very strong wind probably could not account for the existing distribution of large fragments 4–6 inches in diameter.

Character of fragments.—A variety of fragments was erupted. Mud, more or less indurated, is by far the most abundant, but most mud "blocks" were broken down into smaller fragments before or during impact. Fragments that were collected and identified are: (1) A large block about a foot in length, consisting dominantly of ramifying calcite veins. (*See* Pl. 3, fig. 2.) Adhering material proved that the veins had been deposited in cracks in fine clastic sediments. (2) Well-sorted sandstone consisting of rounded to subrounded grains of volcanic rocks cemented by zeolites and a little celadonite and clay minerals. The zeolites are largely heulandite(?), but stilbite(?) is also present. The volcanic fragments are almost unaltered, but a little feldspar has been replaced by zeolite. (3) A fine-grained aggregate of clay minerals (largely hydromica) and probably zeolite. (4) Fine-grained clays consisting mostly of hydromica but with considerable montmorillonite. Diatoms and zeolites are absent. (5) Fine-grained clays, largely montmorillonite, and clastic silicate grains, as well as a little zeolite cement. Diatoms are abundant, and most if not all are not the common hot-spring types. (6) Opaline masses with concretionary forms. The abundance of diatoms within the concretions and in the white powdery border material suggests that the concretions probably formed by introduction of opal into diatomite. Some of the diatoms are similar to types considered by the present author to be characteristic of hot springs, but so many other species are present that the diatomite is probably unrelated to hot springs.

Magnitude of the eruption.—The total volume of mud and hot water directly involved in the eruption is impossible to determine accurately. The eruption area measures about 600 by 500 feet. The average depth of the disturbance is unknown, but is at least 10 feet and probably 20–100 feet. If a depth of only 20 feet is assumed, the total volume is 6 million cubic feet and the mass, with an assumed density of 1.8, is approximately 330,000 tons.

Observations, September 16, 1951

The Lake City hot springs were visited again on September 16, 1951. The activity was greater at that time than it had been 5 days after the eruption. Water levels had risen almost to the levels of the surrounding fields, largely filling the major crater areas. The many small mud volcanoes in the large craters were submerged. Water was boiling vigorously in a number of pools and in two of these the intensity varied from time to time. One boiling pool in the east-central part of the area discharged into a larger nearby pool at rates estimated to range from 10 and 15 gpm. (*See* Table 1.) Although not a true geyser because it did not discharge intermittently, the pool was gradational between ordinary hot springs and true geysers.

Temperatures of 90°–97.5° C were not uncommon in the hot-spring pools in contrast to the maximum of 60° C measured in springs of the same area on March 6.

The muddy ground was almost as treacherous as in March, and many places were even more dangerous because of the higher water levels and poor drainage.

The total surface discharge from the hot-spring area was at least 100 gpm, in contrast to March 6 when about 1000–1500 gpm of surface water was flowing into the area and none was being discharged, presumably because the craters were being filled.

Observations, December 25, 1953

Professor Fred Humphrey of Stanford University visited the Lake City hot springs on December 25, 1953, and to him the author is most indebted for the following observations and for the post-eruption sketch map shown in Figure 1.

On December 25, 1953, the general activity probably equalled that of mid-September, 1951. The large craters were flooded with warm and hot water, and considerable vapor was being evolved. The stream from the west was flowing at an approximate rate of 150 gpm. At the western edge of the mud embankment, it disappeared under the mud and could be heard cascading downward for at least a few feet. The ditch cut through the southeastern mud embankment to drain the area was discharging warm water at an estimated rate of 200 gpm.

Small mud volcanoes had formed during the preceding two years, probably in the fall of 1953. Four small cones are shown in Figure 2 on the northern fringe of the eruption area. The crater of the eastern cone is about 4 feet in diameter; the cone rises about a foot above the general surface and is surrounded by a ring of mud about 18 feet in diameter. This mud volcano is very near the former location of a conspicuous mud volcano shown on the pre-eruption 1946 air photos. The three new western mud volcanoes have craters about 2 feet in diameter; the cones rise about 6 inches above the nearby ground, and they are surrounded by mud rings approximately 10 feet in diameter. The fresh appearance of the mud indicates very recent activity, with no intervening heavy storm.

Other Mud-Volcano Areas

General

Activity similar to the Lake City hot spring eruption and comparable in magnitude has not been described from other areas. Most mud pots and mud volcanoes are relatively small and feeble in comparison with the Lake City mud volcanoes. The small mud volcanoes active during the late phases of the eruption are similar in energy relations to most mud volcanoes elsewhere.

Gerlach Hot Springs, Washoe County, Nevada

General description.—Mud volcanoes are found at Gerlach hot springs, about a mile northwest of Gerlach in northwestern Nevada. The spring area is approximately 1000 feet long and 200–300 feet wide. The environment is similar in many ways to that of the Lake City group of springs: (1) They are situated in a similar topographic position, about a third of a mile from the Granite Range and in the basin of the Black Rock Desert. (2) The range front is believed to be a fault scarp. (3) The spring group is elongated normal to the trend of the range front. (4) Fault scarplets are absent in the immediate vicinity of the springs. (5) The water table in the immediately surrounding area is at or very near the ground surface. (6) The springs emerge from probable deep-basin fill consisting dominantly of fine-grained lacustrine mud and silt.

Salinity in the Gerlach hot waters is high but only slightly higher than samples of warm and cool well waters near Gerlach. Ground water of the area obviously contains salines (Table 1) of the Black Rock Desert, a large playa lake and formerly a major arm of Pleistocene Lake Lahontan.

The only spring of the group with appreciable discharge is a pool about 20 feet in diameter at the southeastern end of the belt. It ordinarily discharges at a rate of about 50 gpm and at a temperature of 95° C, and is said to "boil up" periodically 1–4 feet above the general water level in geyserlike action.

Mud pots and mud volcanoes.—Many mud pots and mud volcanoes occur from 250 to 1000 feet northwest of the discharging pool. The ground surface rises gradually in the same direction toward the scarp on the front of the Granite Range. The altitude of the northwestern pool is about 15 feet higher than that of the geyser pool. The water table, as indicated by levels in the various pools, also rises to the northwest but less rapidly than the ground surface. In the northwestern pools the water levels are about 6 feet below the general land surface but were probably higher before trenches were cut to drain this part of the area.

Mud volcanoes are concentrated in the northwestern and particularly in the central parts of the belt. During the writer's visits no mud volcanoes were actively erupting mud. In fact, all appeared inactive or extinct, except that in some, gases were bubbling quietly through water in the crater floors. Temperatures in 1947 ranged from near air temperature to as much as 91° C. Evidence for recent activity in 1951 was found for only two mud volcanoes. One consisted of a pile of gray mud, only 5 or 6 feet in diameter, rising a foot above the surrounding grass-covered surface in a cone-shaped mound. The vent for the mud consisted of a summit crater about a foot in diameter. Mud near the crest of the cone was still damp, and fresh mud coated surrounding vegetation. Reportedly the small mud volcano had erupted the previous night, September 14, 1951, to a height of about

10 feet. The eruption column either was not vertical or a strong wind was blowing from the east, because mud was strewn to the west 10 or 15 feet.

Another larger mud volcano had also erupted since the previous rain. A pool 10–12 feet in diameter was surrounded on the north, east, and south by mud embankments as much as 3 feet high, and mud pellets were found more than 15 feet from the pool. The mud was light gray and dry. The pool was relatively cool, but fresh-looking mud coated all surrounding vegetation except to the south and had definitely been erupted after the most recent rain.

Other much larger mud pots and mud volcanoes exist in the area, but the magnitude or recency of activity is not known. At the time of the 1947 visit, a resident stated that he once saw one of the mud volcanoes erupt clots of mud to heights of at least 100 feet, an estimate similar to those made for the Salton mud volcanoes.

The Gerlach mud volcanoes are characterized by sporadic and apparently unpredictable intervals of activity separated by very much longer intervals of quiescence. Apparently a vent may have only a single period of eruptive activity and may then become extinct.

Salton Area, Imperial County, California

General relations of hot springs and rhyolite domes.—A group of hot springs, mud pots, and mud volcanoes are located near the southeast edge of Salton Sea not far from Niland, California (Le Conte, 1855; Veatch, 1857; Mendenhall, 1909; Waring, 1915; Kelley and Soske, 1936). The thermal features are closely associated with five relatively recent extrusive volcanic domes of pumiceous rhyolite, obsidian, and pyroclastic pumice. These domes rise 100–150 feet above the surrounding plain. The general relations of the thermal features and the domes are best described by Kelley and Soske (1936, p. 496–501).

Four groups of hot springs and mud pots occur within a distance of 2½ miles on a northwest line. The rhyolite domes lie on a second line nearly perpendicular to the hot-spring line. The springs, like those of Gerlach and Lake City, are situated in a basin containing fine clastic sediments of Quaternary age.

When the Salton Sea was flooded by the Colorado River from 1905 to 1907 the hot springs were submerged and the domes became islands (Mendenhall, 1909; Waring, 1915, p. 41). By the spring of 1935 the shore line of the sea had receded about 1½ miles from Mullet, the lowest dome (Kelley and Soske, 1936, p. 498). In recent years irrigation and drainage in Imperial Valley have resulted in another rise in lake level. When the area was visited on April 12 and 13, 1948, the Mullet dome was on the lake shore and the northwestern springs were again submerged. The main group of springs and mud volcanoes was covered by rising water shortly after 1948.

Wells were drilled near the rhyolite domes in a search for CO_2 (Kelley and Soske, 1936, p. 502). Abundant gas was found at high pressure and temperature, but associated steam was objectionable. Later wells were drilled east of Mullet Island and north of the line of mud pots, where temperatures were lower and the CO_2 was almost free of water vapor. Most production was from depths of 400–500 feet, and initial gas pressures were between 200 and 300 lbs. per square inch. (*See* Fig. 3.)

Observations, April 1948.—On April 12 and 13, 1948, the thermal features of the area about a mile southeast of the Mullet dome consisted of mud volcanoes, mud pots, muddy bubbling pools, perpetually spouting springs, steam vents, and at least one active geyser. The spouters and steam vents were particularly abundant near the center of the thermal area, which also included the geyser and many muddy pools but few mud volcanoes.

Many mud volcanoes are situated north and northwest of the steam vents and spouters. These mud volcanoes were formed by extrusion of mud flows, one on top of another similar to shield volcanoes, and not by explosive eruption. Although none of these was noticed in 1948, only the part of the area near board walks was examined because of the treacherous nature of much of the soft mud. Veatch (1857, p. 292) describes an eruption in 1857 similar to that of Gerlach, Nevada.

In addition to steam, the gases emitted from the area include CO_2 and some H_2S, as indicated by the presence of some sulfates and a little native sulfur

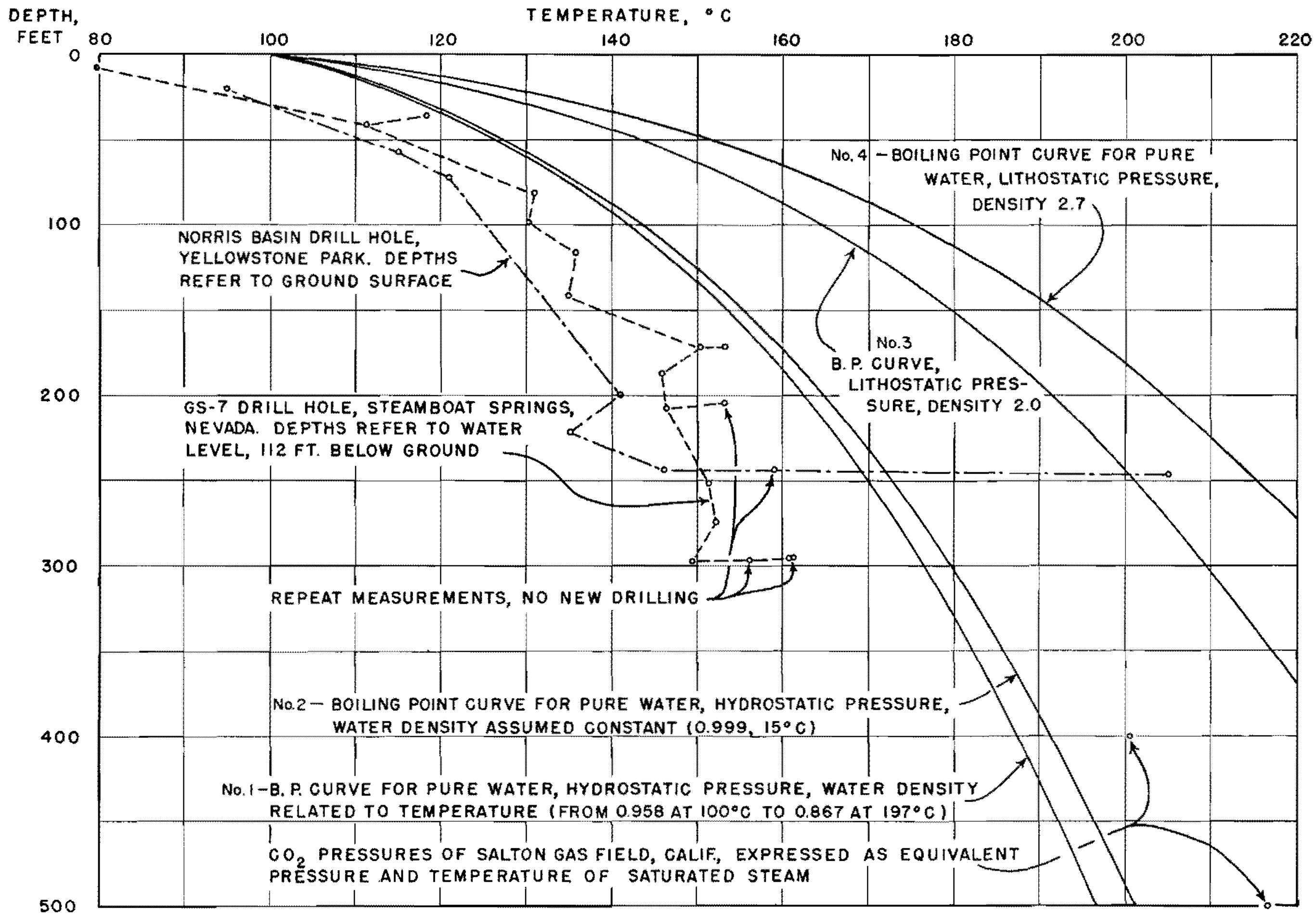

FIGURE 3.—TEMPERATURE-DEPTH RELATIONS OF TWO THERMAL DRILL HOLES, COMPARED TO BOILING-POINT CURVES

All the domes except Obsidian Butte show some recent acid alteration similar to the sulfuric acid alteration of many hot-spring areas. Some warm vapors are still being emitted from the two Pumice Buttes about a mile and a half south-southwest of the mud volcanoes, and Mullet Dome is even more active. A short distance southeast of the crest of this dome, pumiceous rhyolite is still being decomposed by acid attack. A temperature of 55.3° C was obtained at a depth of only 14 inches below the surface.

The old well on Mullet mentioned by Kelley and Soske (1936, p. 502) is on the south slope of the dome. The well was drilled through the dome and into sediments to a depth of 3500 feet, and in recent years the water rose in the well and erupted mildly three or four times a day to a height of several feet. No eruption was seen during the 1948 visit, but evidence of recent overflow was found. The water level in the well was surging between depths of 7.6–8.0 feet below the collar of the well, which was about 19 feet above the then-existing level of the Salton Sea. The temperature at water level was 72.9° C, only slightly less than the 73.3° C measured on the effective bottom, 18.8 feet below the collar.

An odor of H_2S was strong near the well, and a metallic film deposited on the steel tape used to measure temperature may have been native quicksilver.

Volcano Lake, Baja California

Mud volcanoes exist on the west shore of Volcano Lake 60 miles south-southeast of the Salton springs and about 20 miles south of the International Boundary. Mendenhall (1909, p. 14) states that the thermal features are similar to those of the Salton area but are on a larger scale.

The area is in the structural trench containing Coachella Valley, Imperial Valley, and Gulf of California and is presumably underlain by very thick and probably fine clastic sediments. The hot springs lie immediately southeast of Cerro Prieto, a prominent hypersthene andesite or dacite volcano of probable Pleistocene age. Only one small group of mud volcanoes were found during an investigation February 4, 1954, but others may have been disturbed or concealed by extensive levees that have been constructed in the area.

Acid Hot-Spring Areas

Mud volcanoes occur in some of the acid areas of Yellowstone Park (Allen and Day, 1935, p. 102–107), Lassen Park (Day and Allen, 1925, p. 103, 155), Coso hot springs, California, and in a number of localities in New Zealand (Grange, 1937, p. 89–95), Iceland (Barth, 1950, p. 113), and elsewhere.

The mud pots and mud volcanoes are largely restricted to localities where fine-grained clay and silica are abundant products of acid alteration. Sulfuric acid is produced by reaction of H_2S with atmospheric oxygen above and near the water table (Allen, 1934, p. 345–349). Complete disintegration to incoherent clays is therefore restricted to a near-surface zone. Steam and other gases stream up through fractured bedrock into the superficial mud deposits. If the gas-streaming is mild or if the mud is high in water content, the thermal feature is a mud pot, but if gas-streaming is violent and the mud is viscous and relatively low in water content, the thermal feature is a mud volcano. The underlying rocks are too competent to be erupted. Intense gas-streaming may erode and enlarge the channels, but generally the bedrock is not disturbed.

Mud volcanoes are rare in many acid areas because the pH of the environment is commonly too low (Table 1), or the original rocks were too high in silica to form abundant incoherent alteration products. The mud of some acid areas may not be dominantly a product of acid alteration. Deep residual soil at Boiling Lake in Lassen Park, and local clastic sediments in other places have supplied the fine-grained material necessary to mud volcanoes. The soil and sediments in these acid areas are commonly underlain at shallow depth by competent rock, in contrast to the deep fine-grained sediments of the Lake City thermal system.

Thermal activity in acid areas is ever-changing in intensity and in geographic position. Even the most vigorous of hot springs, fumaroles, or mud volcanoes eventually become less active, dormant, or extinct. Other similar fea-

TABLE 2.—ENERGY AVAILABLE IN A THERMAL SYSTEM WITH BOILING-POINT TEMPERATURE RELATIONS AT DEPTH AND CONTROLLED BY HYDROSTATIC PRESSURE (CURVE 1 OF FIG. 3)

One pound of water from the specified depth or temperature assumed to form appropriate proportions of water and steam at 100° C and 1 atm pressure

Depth ft.[1]	Temp. °C.[1]	Enthalpy[2] Btu	Excess Btu[3]	Steam[4] wt.%	Steam[5] cu.ft.	Total vol. cu.ft.[6]	Ratio, expanded to initial volume	Mech. energy ft.lbs.[7]
0	100.0	180.1	0	0	0	0.01672	1	0
4.7	103.5[8]	186.4	6.3	.65	0.174	0.191	11.4	368
25	115.6	208.3	28.2	2.91	0.78	0.80	47	1650
50	126.5	228.3	48.2	4.97	1.33	1.35	79	2810
100	142.8	256.8	76.7	7.91	2.12	2.14	123	4480
134.1	150.0	271.7	91.6	9.44	2.53	2.55	145	5350
200	162.3	294.6	114.5	11.82	3.17	3.18	180	6690
300	176.4	321.2	141.1	14.54	3.90	3.91	217	8230
500	196.6	359.7	179.6	18.5	4.96	4.97	269	10,500
541	200.0	366.3	186.2	19.2	5.14	5.15	278	10,900
	250.0	467	287	29.6	7.93	7.94	395	16,800
	300	578	398	41.1	11.0	11.0	489	23,300
	350	718	538	55.5	14.9	14.9	532	31,500
	374.0	903	723	74.6	20.0	20.0	400	42,300

[1] Most temperatures interpolated from curve 1 of Figure 3. Depths interpolated for temperatures of 103.5°, 150°, and 200° C. Depths not calculated for temperatures above 200° C.

[2] Keenan and Keyes, 1936, p. 31–32.

[3] Calculated from enthalpy of water at 100° C.

[4] From excess Btu relative to 970.3 Btu (heat necessary to convert 1 lb. water to steam at 1 atm pressure).

[5] Volume 1 lb. of saturated steam, 26.8 cu. ft. at 1 atm pressure.

[6] Calculated from initial specific volume of water, sp. vol. at 100° C, and final volume of water and steam.

[7] Mechanical work of expansion of steam in 1 atm pressure. Cubic feet of steam multiplied by 144 sq. in./sq. ft. and 14.7 lbs./sq. in. The mechanical energy is approximately 7½ per cent of total excess energy shown in column 4 (1 Btu = 778.3 ft. lbs.).

[8] Equivalent to maximum superheat recorded in natural thermal water at surface, 3.5° C in Giant Geyser (Allen and Day, 1935, p. 20).

tures come into existence, but the birth of one seldom coincides with the decline or extinction of another. The birth of a new "thermal feature" with many of the characteristics of mud volcanoes has been described from the Norris Basin area of Yellowstone Park (Turner, 1949, p. 526–527).

No evidence is available to indicate that mud volcanoes of acid areas ever erupt with the violence of the Lake City group or even the more vigorous of the Gerlach and Salton mud volcanoes, all of which are of the deep-sediment type. However, the total expenditure of energy from many of the acid mud volcanoes in time is probably much greater, because of continuous activity.

ENERGY OUTPUT OF THE LAKE CITY ERUPTION

Computed Mechanical Energy

Table 2 shows the total excess energy (above 100° C) stored in water under hydrostatic pressure at selected temperatures and depths. The per cent of steam and the available mechanical energy have been computed on the assumption that water of the indicated temperature (and corresponding saturation pressure) is suddenly exposed to a pressure of 1 atmosphere. Water is converted to steam until both phases reach a temperature of 100° C. Temperatures and corresponding depths of columns 1 and 2 are derived from curve 1 of Figure 3. This theoretical boiling-point curve is a very important guide in predicting subsurface temperatures in vigorous thermal areas.

Under the assumed equilibrium conditions, all the mechanical energy is used in expanding the steam against air pressure. In an eruption a small part of the mechanical energy is used in lifting water or mud against gravity.

Relation of Mechanical Energy to Total Energy

In Table 2 the mechanical energy expressed in foot pounds is only about 7½ per cent of the total excess energy available above 100° C. Most of the total excess energy is used to convert water into steam, and most of the mechanical energy is actually utilized in expanding the steam against air pressure. If water is erupted directly from a depth of 100 feet to a height of 100 feet above the ground, 184 foot pounds of energy is required for 0.92 pound of water that remains from an original pound, or 200 foot pounds of energy for the original pound of water, including the part that is evaporated to steam. Friction, turbulence, air resistance, and evaporation below 100° C are neglected. This energy is only about 4½ per cent of the available mechanical energy or about 0.3 per cent of the total energy available above 100° C. The discrepancy is even greater if all energy available above atmospheric temperature is considered.

Table 3 shows the computed mechanical energy available in a thermal system of mud and water. The mud is assumed to consist of 20 per cent of water by weight or about 40 per cent by volume, depending on the mineralogy of the silicates and the temperature. The initial pressure on the mixture is assumed to be lowered abruptly to a pressure of 1 atmosphere. The differences between Tables 2 and 3 result from the low content of water, the difference in heat capacity of silicates relative to water, and the diversion of all excess heat above 100° C into the water fraction to form steam. A pound of mud erupted from a depth of 100 feet to a height of 100 feet above ground requires 200 foot pounds of energy, or about 12 per cent of the available mechanical energy (Table 3), as compared to only 4½ per cent for water. In actual eruptions, mud will probably not be erupted as high as water under similar circumstances.

The calculations demonstrate the abundant mechanical energy that is available in a thermal system with temperatures near boiling at depth.

TABLE 3.—ENERGY AVAILABLE IN A THERMAL SYSTEM OF MUD AND WATER WITH BOILING-POINT TEMPERATURE RELATIONS AT DEPTH AND CONTROLLED BY HYDROSTATIC PRESSURE (CURVE 1 OF FIG. 3)

One pound of material, 80 per cent silicates by weight and 20 per cent water*, assumed to form appropriate proportions of water and steam at 100° C and 1 atm pressure; density of silicate portion assumed 2.67, bulk density 2.0; heat capacity of silicates assumed 0.39 Btu per pound per degree C.

From		Excess Btu		Total steam, lbs.	Total steam, cu. ft.	Mechanical energy, ft. lbs.
Depth ft.	Temp. °C.	From water*	Silicates†			
25	115.6	5.6	4.9	0.0108	0.29	614
50	126.5	9.6	8.3	0.0184	0.49	1,045
100	142.0	15.3	13.1	0.0293	0.78	1,660
200	162.3	22.9	19.4	0.0437	1.17	2,470
300	176.4	28.2	23.8	0.0537	1.44	3,040
500	196.6	35.9	30.1	0.0681	1.82	3,860

* 20 per cent of corresponding values from column 4 of Table 2; 20 per cent by weight is approximately 40 per cent by volume, depending on the temperature.

† Heat available from silicates in cooling from indicated temperatures to 100° C.

Relative Energy of Eruption

Ordinarily data are inadequate to calculate directly the expenditure of energy by a mud volcano or a geyser in eruption. A useful quantity that can be calculated is here called the relative energy, and is defined as the product of the mass of material involved times the height that average water is erupted above ground. Calculations based on geysers and erupting wells at Steamboat Springs, Nevada, suggest that only about 5 per cent of available mechanical energy is actually utilized in erupting water to observed heights. The proportion of energy utilized in mud-volcano eruptions is probably of the same order of magnitude, although energy loss owing to turbulence and friction may differ from geysers. Any error introduced by assuming equality is probably small compared to the errors introduced in determining the mass of material involved and the average height of eruption.

Lake City Eruption

The mass of mud involved in the Lake City eruption is estimated to be about 6 million cubic feet with a present density near 1.8 and a total mass of about 300,000 tons. The average height of eruption is completely unknown, but the morning after the most vigorous activity small amounts of mud were still being thrown to a height of 100 feet. The average height of eruption of all mud involved in the activity may have been 100 feet or more, but a conservative estimate of 20 feet is assumed in the following calculations. The relative energy of eruption is found to be 300,000 tons multiplied by 20 feet, or 1.2×10^{10} ft. lbs.

The actual expenditure of mechanical energy was probably about 20 times the relative energy, or 2.4×10^{11} ft. lbs., and the total excess energy above 100° C may have been 300 times as great, or 3.6×10^{12} ft. lbs. (See footnote 7, Table 2.)

Relative Energy of Geyser Eruptions

The chloride concentration of erupted water is ordinarily enriched significantly over that of water collected from the geyser vent prior to eruption. In the eruption process, some water is vaporized to steam and chloride is concentrated in the remaining water. If the water supply of the geyser prior to eruption is homogeneous in chloride content, the temperature of the water supply immediately prior to eruption can be computed from columns 5 and 2 of Table 2. The sample must be collected by a method that minimizes evaporation in the atmosphere below the boiling point. Actual measurements by the writer in geysers and erupting wells at Steamboat Springs, Nevada, have shown good agreement between computed and measured temperatures and depths. The total energy of the eruption can also be calculated from Table 2. When total discharge and height of eruption are measured or estimated, the relative energy of a geyser eruption can be calculated.

According to calculations based on data from Allen and Day (1935, p. 184, 187), the relative energy of an eruption of Old Faithful in Yellowstone Park is in the order of 8×10^6 foot pounds. (The height of eruption of average water is assumed to be 80 feet and the discharge per eruption, 1600 cu. ft.) Excelsior geyser (Allen and Day, 1935, p. 267–271) is now inactive, but it was by far the most vigorous of all Yellowstone geysers. From descriptions, the height of eruption of average water is assumed to be 100 feet and its discharge an average of 130 second feet for a duration of 10 minutes. With these assumptions, its relative energy of eruption was 5×10^8 foot pounds, or only $\frac{1}{25}$ that of the Lake City eruption.

Waimangu geyser in New Zealand (Grange, 1937, p. 114) erupted to a maximum height of 1000 feet or more from 1900 to 1917. This geyser was the largest that is known in recorded history. Its relative energy cannot be computed because no estimate of its discharge has been recorded. If the height of eruption of average water is assumed to have been 5 times as much, and its discharge 5 times as great as that of Excelsior, its relative energy may have been about equal to that of the Lake City eruptions.

Mechanics of Eruption of Mud Volcanoes

General

The source of energy of mud volcanoes, as well as of other high-temperature hot springs and fumaroles, is believed to be volcanic heat. The volcanic energy is transferred to the surface of the earth in part by conduction, but probably to a greater extent by circulation of water. Although some of the water of a hot-spring system is probably of volcanic origin, most is believed to be surface water heated in the thermal system (Allen and Day, 1935, p. 40–41; White and Brannock, 1950, p. 570–573). The energy of eruption of mud volcanoes is contained in the hydrothermal system near the surface. The principal evidence for this conclusion is the relatively small size and low temperature of mud volcanoes and the complete absence of new volcanic rock.

The mud volcanoes of sedimentary basins are characterized by fine-grained water-saturated clastic sediments, with no near-surface basement of competent rocks. The water table is at or very near the ground surface, gases are not conspicuous, and discharge of water is more abundant than in most acid areas. The sediments are relatively incompetent, and are fine-grained and low in permeability. They probably have the strength to resist stresses of short duration but have little strength to resist long-applied stresses. On the other hand the calcite veins in a matrix of mud found in the eruption debris indicate that fractures do exist and are maintained.

Most of the water normally discharged from the Gerlach and Salton areas, and presumably also from the Lake City area, is clear with little suspended sediment. This is evidence that the sediments of these thermal systems behave as solids and not as dense liquids. The semi-plastic nature of the sediments, however, is effective in producing a pressure gradient in the hydrothermal system that is probably intermediate between the pressure gradients of curves 1 and 3 of Figure 3.

Convection within the water system is probably absent or is greatly inhibited relative to that of well-fractured competent rocks. In a sufficiently vigorous thermal system, the temperature gradient is probably higher than the gradient of curve 1 in Figure 3 but is considerably less than the gradient of curve 3. The energies available for eruption are correspondingly intermediate between the values shown in Table 3 and those of Table 4.

TABLE 4.—ENERGY AVAILABLE IN A THERMAL SYSTEM WITH BOILING-POINT TEMPERATURE RELATIONS AT DEPTH, AND CONTROLLED BY LITHOSTATIC PRESSURE (CURVE 3 OF FIG. 3)

Density of 2.0; other assumptions and calculations are similar to those of Table 2. One pound of water from specified depth assumed to form appropriate proportions of water and steam at 100° C and 1 atm pressure.

From		Enthalpy Btu	Excess Btu	Steam lbs.	Steam cu.ft.	Total vol. cu. ft.	Ratio, expanded to initial volume	Mech. energy ft. lbs.
Depth ft.	Temp. °C.							
0	100.0	180.1	....	....	....	....	....	....
25	127.4	230.1	50.0	0.0516	1.38	1.40	82	2,920
50	143.6	259.7	79.6	0.0821	2.20	2.22	128	4,650
100	164.9	299.4	119.3	0.123	3.30	3.31	187	6,980
200	191.4	349.7	169.6	0.175	4.68	4.69	255	9,900
300	209.6	385.0	204.9	0.211	5.65	5.66	301	12,000

Cause of Eruption

Thermal systems with temperature gradients close to the boiling point curve are highly unstable. If material is suddenly removed at the top of the system, the pressure is lowered throughout. Each point at depth, formerly just at its boiling point, is now above its boiling point. Boiling then starts throughout the column, or if mild boiling had previously existed, the rate of boiling rapidly increases. In competent fractured rock, water is displaced upward and out of the system by expanding gas bubbles, decreasing the hydrostatic pressure on the system and setting off a chain reaction that results in geyser action. The same unstable relations are also of critical importance in understanding mud-volcano eruptions in basin sediments.

Any sudden decrease in the pressure of the system is potentially the trigger for an eruption. The beginning phases of mud-volcano eruptions of the sedimentary-basin type have not been observed or described, so specific causes can only be postulated. These may include an unusual combination of gas bubbles erupting considerable mud from a pool that is ordinarily a mud pot; an unusually rapid lowering of barometric pressure; or some other ordinarily insignificant change. Regardless of the specific cause of the trigger action, not determinable from present evidence, there is no doubt that abundant energy and the potentialities for eruption exist in the unstable temperature-depth relations of the thermal system.

If thermal systems are as unstable as the energy considerations suggest, major eruptions like the Lake City activity should be more common. However, the thermal system usually adjusts itself to minor change without incurring a major eruption. A slight decrease in pressure on the system probably results in a slight increase in boiling, insufficient in amount to exceed some critical value necessary to cause eruption.

The nature of the water solution also aids in the adjustment of a thermal system. In Figure 3 and Tables 2–4 the water of the system is assumed to be pure water. In actuality the water contains some dissolved substances tending to increase the boiling points and dissolved gases tending to decrease the boiling points. A solution of this type has no single boiling point, and its reaction to increasing temperature is best regarded as a boiling range. The temperature-depth curve of Steamboat drill hole GS-7, shown on Figure 3, is typical of the Steamboat drill holes in this respect: Equilibrium temperatures to depths of 200–250 feet below the water table generally lie below but very close to hydrostatic pressure curve 1 of Figure 3 and do not cross the curve. At greater depths the temperatures fall increasingly short of the theoretical boiling-point curve. The system is believed to be a single-phase liquid near the the base of the explored zone, but as the hot water rises and pressure decreases sufficiently, a vapor phase starts to form. The upper part of the temperature curve is determined to a major extent by boiling within the system. Actual temperatures lie below the theoretical curve because of the vapor pressures of gases in solution.

The significance of these relations in inhibiting eruption lies in the fact that the boiling point of the solution is raised as the quantity of dissolved gases decreases, in contrast to a pure-water system in which the boiling point is not affected by the quantity of steam that has formed. Stated in a different way, if a solution of water and gas is exposed to a constant temperature 1° above the temperature where vapor first forms, dissolved gas is selectively lost to the vapor and the solution soon comes to equilibrium at the new temperature because the boiling point has been raised. In contrast, if pure water is exposed to a constant temperature 1° above its boiling point, the water will continue to boil until all is evaporated, without reaching equilibrium.

The proposed explanation for the Lake City eruption assumes the energy for eruption is stored within the thermal system, and no major change in rate of flow or heat has occurred deep in the system. Calculations indicate that the thermal system does contain a very adequate source of energy, but complete answers for some of the vagaries of eruption are not apparent.

An alternative explanation assumes an increase in temperature or in rate of flow, relating the eruption to a surge of very hot water with vapor pressure considerably in excess of the near-surface pressure. This explanation may seem particularly attractive for the Lake City eruption because of its great vigor, unusual magnitude, and the fact that four or five major centers were active contemporaneously. An increase in temperature is believed to be unnecessary, but is not ruled out by present evidence.

Relation to Volcanic Eruptions

Phreatic or Cryptovolcanic Eruptions

Some eruptions or eruption products classed as phreatic or cryptovolcanic are closely related to the Lake City type of activity, if the energy for eruption were contained in water of hydrothermal systems at temperatures approximating the hydrostatic boiling-point curve. Reliable criteria are difficult to establish. The water table must have been at or very near the surface; the eruption products are characterized by local distribution, and probably by abundant fine-grained clay-rich particles; and no new volcanic fragments are involved. A search should be made for hydrothermal minerals known to be associated with shallow-depth hydrothermal systems. These include zeolites, montmorillonite and kaolinite clays, hydromicas, carbonates, opal, and probably chalcedony, chlorite, and pyrite. On the other hand, if the field evidence favors the derivation of the eruption products from competent rocks, volcanic vapor pressures exceeding lithostatic pressures are indicated. New volcanic products such as scoria definitely eliminate hot springs systems as the principal or direct source of the energy that initiated eruption.

A breccia of late Pleistocene age at Steamboat Springs, Nevada, is distributed over an area 1000 feet long and 750 feet wide. The writer believes it is a mud-volcano deposit erupted on a scale at least equal to that of the Lake City eruption. The deposit consists of unsorted material ranging from clay-sized particles to boulders as much as 6 in. in diameter derived from the underlying alluvium and sinter. Many fragments were hydrothermally altered prior to eruption; on the borders of the area this heterogeneous material lies on unaltered alluvium. Similar deposits probably exist elsewhere.

Volcanic Eruptions Intensified by Hydrothermal Energy

The destructive power of true volcanic eruptions may be increased greatly by energy that has been stored in a vigorous hydrothermal system.

Much of the energy of the very destructive Tarawera, New Zealand, eruption of 1886 may have been derived from hydrothermal systems of Lake Rotomahana (Smith, 1886, p. 47–49). Grange (1937, p. 29, 36–37, 55, 78–85) has summarized the events and the eruption products. The activity first started early in the morning of June 10, 1886, on the northeast side of the Tarawera rhyolite domes and advanced rapidly to the southwest, forming a chain of craters 9 miles long. Within about 3 hours the whole chain was in maximum eruption, but after 2 hours the activity had almost ceased.

Basalt scoria and ash were erupted to the north and northeast from the craters on the Tarawera domes and from one of the southwestern craters, but a large volume of erupted material containing appreciable clay, known as Rotomahana mud, was derived from older material of the Lake Rotomahana thermal area in the south-central part of the chain of craters. The volume of Rotomahana mud is estimated to be about a fifth of a cubic mile (Grange, 1937, p. 29; Smith, 1886, p. 56). The mud was distributed to the north for a distance of at least 20 miles from its source, according to Grange's map of volcanic showers.

Prior to the eruption, the world-famous White and Pink Terraces containing hot springs and geysers had existed on the shores of the former Lake Rotomahana. Mud pots, mud volcanoes, and acid springs were abundant (Grange, 1937, p. 91–94). The terraces and all of the hot springs were completely destroyed or modified beyond recognition by the eruption.

Grange (1937, p. 83) states:

> "Besides being much lower than (Tarawera) mountain, the country round the old Rotomahana is formed of weaker rocks, some of them lake deposits, and much of them decomposed and altered to clays by the long-continued thermal activity. Across this low country the "fissure" widens out to a great, irregular crater-basin, three miles long and from half to one mile and a half wide. Here the weak surface rocks were shattered into sand and dust, and scattered over the surrounding country, leaving an excavation some three miles in area and bounded, at most places, by vertical walls from 200 to 300 feet high."

The southern part of the large basin contained numerous funnel-shaped depressions ranging up to 40 feet in diameter. Although not described in detail, they are suggestive of the mud-volcano vents of the Lake City area. The estimated average depth of material erupted from the basin is 300 feet. Fumaroles and other "points of activity" (mud volcanoes?) still existed in the Rotomahana crater 2 months after the eruption, although the craters on Tarawera were completely inactive.

A hydrothermal system with temperature-depth relations similar to those shown on Figure 3 probably cannot initiate a major eruption, but if vapor pressures in underlying magma are sufficiently high to disrupt and fragment the overlying cover, an important supply of stored energy is then made available to augment the direct volcanic energy. Of particular significance is the large volume of hot wall rocks and interstitial water that are involved in the eruption because of their stored thermal energy. In contrast the stable or passive wall rocks of most volcanic vents are involved only to a minimum extent in eruptions. The exceptional vigor of that part of the Tarawera eruption originating near Lake Rotomahana was probably due to energy from the hydrothermal systems of that area.

The energy of all explosive volcanic eruptions may be increased to some extent by energy from water-saturated rocks. The great vigor of some submarine eruptions and eruptions involving crater lakes may be due in considerable part to such stored energy, which becomes available following the initial disruption.

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