STEAM WELLS AND OTHER THERMAL ACTIVITY AT "THE GEYSERS" CALIFORNIA

By

E. T. ALLEN AND ARTHUR L. DAY

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FIG. 1—CONTOUR MAP OF A PORTION OF "THE GEYSERS" IN SONOMA COUNTY, CALIFORNIA.

Surveyed and drawn by
Geo L Calderwood

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INTRODUCTORY

The St. Helena or Mayacmas Range is one of the Coast Ranges of California. Rising near Sonoma 35 miles north of San Francisco it extends northwesterly, parallel to the shore line at a distance of about 30 miles and forms a part of the boundary line between Sonoma County on the west and Napa and Lake Counties on the east. The principal chain is close to 50 miles in length and its highest peaks reach an altitude of 4,500 feet. A tributary ridge branching off at Mount St. Helena runs in a direction somewhat more easterly, almost as far south as the main range.

The slopes of these mountains are covered with sediments and metamorphics—sandstones and shales, cherts, schists and serpentines which are assigned to the Franciscan formation. The backbone of the range, however, is doubtless volcanic, for lavas, chiefly andesite, are exposed on the summits of Mount Cobb, Mount St. Helena and other high peaks, and there are limited areas of lavas, tuffs and obsidian in other places.[2]

Hot springs are numerous on both sides of the range, but the western side, both on account of its higher temperatures and greater chemical activity as well as its relation to recent industrial development, is scientifically the more interesting, and to it, therefore, this investigation has been exclusively devoted.

An important relation between the hot springs and many quicksilver mines of the western side of the range and one which seems to have been entirely unnoticed by others, has been pointed out to the authors by H. W. Gould, metallurgist and quicksilver producer of San Francisco, whose activities have brought to him an intimate knowledge of the geological features of this district. Mr. Gould shows, by the map,[3] the almost rectilinear alignment of: The Aetna, Corona, Oathill, Mirabel, Great Western, Helen and Socrates Quicksilver Mines, all of which are associated—generally closely associated—with warm, hot or sulphur springs; the Little Geysers and The Geysers, hot-spring groups about 5 miles apart with at least three lesser hot-spring areas lying between them; hot springs at intervals

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[1] Near Cloverdale, Sonoma County.

[2] Map of the State of California, Geology by James Perrin Smith. State Mining Bureau, 1916. Quicksilver resources of California, Bull. 78 of the California State Mining Bureau 1913, by Walter W. Bradley (map opposite page 32).

[3] W. W. Bradley referred to above. Not all the localities mentioned in the text are shown on any map.

Fig. 2—Sulphur Creek Canyon looking east.

for a mile west of The Geysers; the Sulphur Banks, an active fumarole area and, finally, the Cloverdale Quicksilver Mine which is associated with declining fumarolic activity. The line connecting all these points is about 25 miles in length, virtually straight throughout and roughly parallel with the mountain range with which the original volcanic activity is associated. A similar relation between hot springs, fumaroles and volcanoes has been repeatedly observed in other places where fault lines have been traced, and it is not improbable that careful observation may adduce further evidence of a fault in this locality. All geologists agree that these faults must be vitally connected with the cause of hot springs; their real significance deserves close attention and will be discussed later on.

"THE GEYSERS"

From The Little Geysers westward the hypothetical fault line just referred to practically follows Sulphur Creek, the bed of which is a narrow canyon forming the southern boundary of the St. Helena Range. The most active point on this line is "The Geysers," an old health resort 18 miles east of Cloverdale and 25 miles north of Healdsburg, with both of which it is connected by stage road. The resort consists of an old hotel, the earliest wing of which is said to date from 1852, a group of cottages and a modern bath-house. The buildings are located on the south[1] bank of Sulphur Creek. The hot ground is on the other side (fig. 2). Beginning in the bed of the creek, where several hot springs occur, it extends east and west for an extreme distance of 400 yards and stretches up the steep slope of the mountain to distances varying from 200 to 500 yards. The ground is dotted at intervals with small hot springs and fumaroles and marked with thin salt patches in dry weather. The name "Geysers" is a misnomer, as no geysers occur here.

The bounds of the hot ground are pretty sharply defined; on the south by Sulphur Creek, on the north and east by woods, while the western limit is marked by a steep ridge forming the western bank of a little tributary of Sulphur Creek known as Geyser Creek (figs. 3 and 4), up the almost percipitous bank of which activity continues for 50 or 100 feet in the upper half of the canyon. The total area is thus about 35 acres. It is divided into two unequal parts by a ravine which, beginning near the northern border at a point about 500 feet east of Geyser Creek canyon, drops rapidly to a depth of about 40 feet and runs southwesterly for a few hundred yards, where it opens into Geyser Creek canyon. Along the sides and to the south of the ravine close to Sulphur Creek, as well as along the lower reaches of Geyser Creek canyon, there is a growth of live-oak, pepperwood and

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[1] The trend of the range for several miles in this vicinity is more nearly east and west than is the *general* trend.

manzanita; elsewhere the ground is bare or sparsely covered with grass or weeds. Seen at a little distance in warm, dry weather when no steam is visible, this rather diminutive area appears not unlike any other of the numerous open spaces which constantly recur among the dark-green oaks on these steep declivities and which, covered with a carpet of short, dry grass, golden in the summer sun, are so characteristic of the Coast Mountains.

Fig. 3—Looking up Geyser Creek in early morning when huge steam clouds obscure upper slopes.

Like most of the St. Helena Range this area is covered with sediments and metamorphic rocks. Along the eastern border sandstones outcrop all the way to the top of the mountain ridge, and drilling has proved that sandstones and in some places shales and cherts underlie the hot ground at depths sometimes less than 100 feet. The same rocks are also plentifully exposed along the banks of Sulphur Creek not far down stream and along the highways of the vicinity. Chert is exposed on the banks of Sulphur Creek and at one point on Geyser Creek (fig. 5). High above the hot area and within half a mile of it, stands a great ledge of mica schist, while serpentine and serpentine conglomerates, so common in the Coast Range, occur in several places. The conglomerates form low cliffs along the two creeks where they are in process of decomposition, and a prominent outcrop of the fresh serpentine is found in about the center of the area along the trail to Steamboat Fumarole. No igneous rock has been found at the surface, but that an intrusion reaches up to a level not far below it is one of

Fig. 4—Looking north in Geyser Creek canyon at noon when free from steam.

the interesting facts which has been disclosed by drilling. A core taken from Well No. 5 at a depth of about 230 feet was submitted to F. E. Wright for examination and found to be gabbro.

Fig. 5—Chert exposure (left) on west bank of Geyser Creek.

SPRINGS AND FUMAROLES

Well-marked fumaroles are found at The Geysers in only a few places. The Smokestack (fig. 6; see map, fig. 1), which opens at a point 40 feet up on the western bank of Geyser Creek near the Devil's Pulpit, pours out the greatest volume of steam. It issues from a little flat on the otherwise precipitous slope and on account of the slippery mud is accessible only from above. A climb to it in July 1924 revealed a little basin, the dried mud of which indicated the presence of water in wet weather. Much, if not most of the rain on this steep slope doubtless runs off, but the ground to the west rises several hundred feet higher and there is, therefore, no reason to believe that a hot spring can not exist there in the wet season.

About 125 feet down stream on the opposite bank of Geyser Creek and perhaps 30 feet above it, the Safety Valve (fig. 7) emits several jets of steam from the muddy bank; but the most distinctive fumarole in the district and the one best known to tourists is the Steamboat (fig. 8), the strong vertical and constantly puffing steam jet of which gives to it its name. Short iron pipes 1.5 inches in diameter have been forced down into the ground for 3 or 4 feet at the Steamboat and Safety Valve, and from these most of the steam now escapes. These are the only very active fumaroles at The Geysers, and even these are quite feeble compared to those in many other localities.

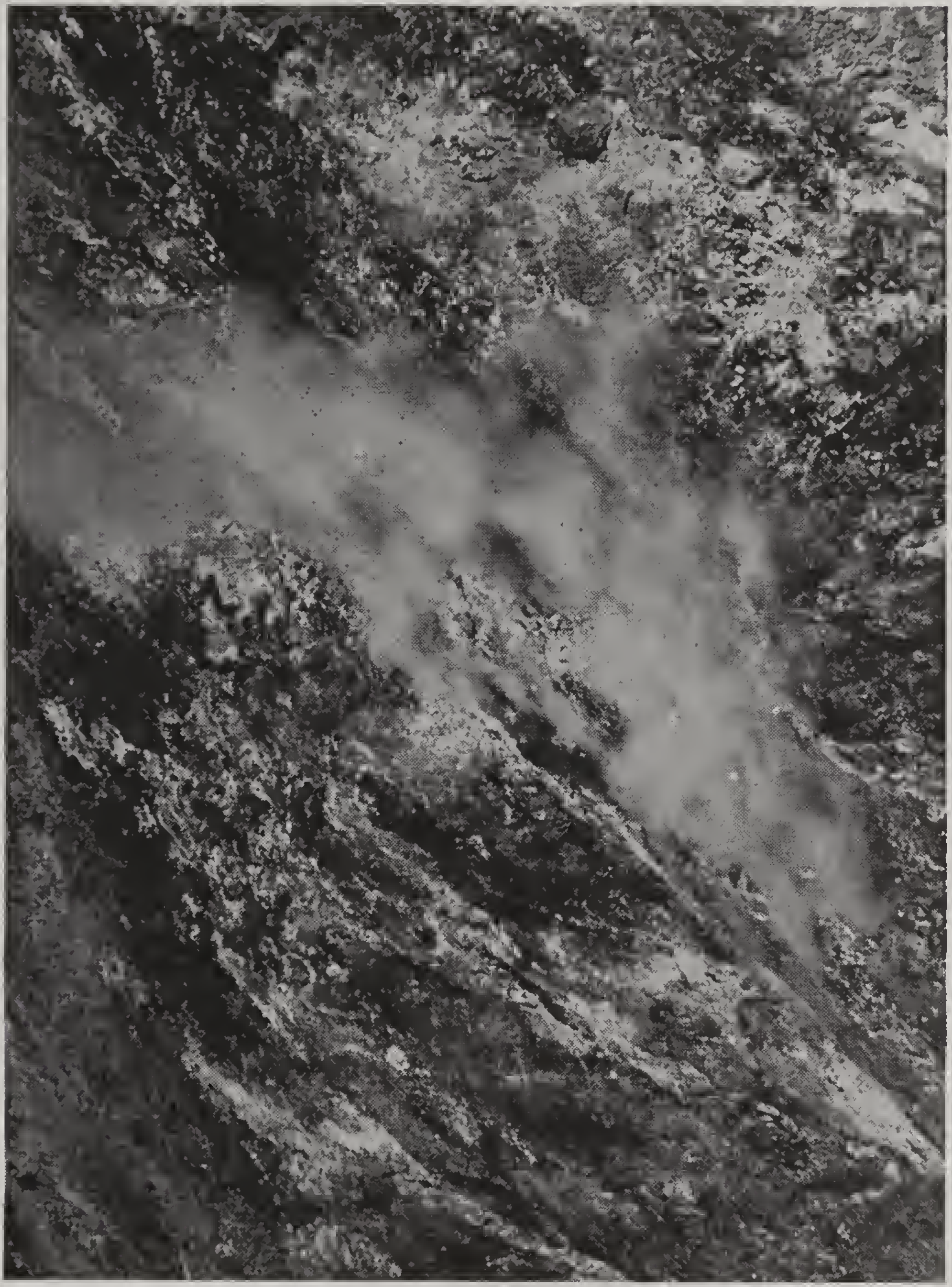

FIG. 6—The Smokestack at noon when least steam is visible.

Seventy-five yards or more east of Geyser Creek and twice that distance south of Steam Well No. 2 (see map, fig. 1) there is a group of small vents lined with sulphur needles, from which steam is noiselessly escaping. But while well-defined fumaroles at The Geysers are few, steam and gases are constantly seeping through the ground, especially in the western half of that area, and on cool, damp days, particularly at morning (fig. 3) and evening, large clouds of condensed steam may be seen where in hot, dry summer weather it is almost entirely absorbed by the atmosphere.

Fig. 7—The Safety Valve seen at midday.

The *hot springs* are all small and shallow, in fact insignificant in size; the largest being no more than 3 feet in diameter. In temperature they are comparatively high, as few springs are below 60° C. and the hottest are at boiling temperature; yet nowhere do we find

Fig. 8—The Steamboat Fumarole in morning hours.

signs of excessive heat like violent spouting and geyser action. Springs like the Witches' Cauldrons (fig. 9) and some others spout at times, but rather feebly, exhibiting on the whole a mild thermal activity not unlike the fumaroles. Physically these springs vary little in type; there is comparatively little clear water; most of it is turbid or muddy, though mud pots and mud volcanoes are never found here. The sediments are always loose but never plastic, and no sinters[1] of any kind are in process of deposition.

As many hot-spring districts owe their distinctive appearance in great measure to the nature of the sinter deposited by their waters, the problem of deposition—to what extent it is a matter of physical and chemical forces and how far it depends on the life processes of certain organisms like algae—well deserves further attention. At The Geysers few springs contain a vegetable growth—such at least as is apparent to ordinary scrutiny; a very few, of comparatively low temperature, are choked by green algae which, however, seem to be exercising no influence on mineral deposition.

As in so many other hot-spring districts, the odor of hydrogen sulphide is quite generally prevalent, and occasionally the odor of what seems to be ammonium sulphide is detected. About the acid springs in the Geyser Creek canyon and at the Steamboat group there is a characteristic and disagreeable odor which has been noticed in other similar localities and which so far has not been traced to any known substance. Possibly it is caused by some organism.

Most of the springs are grouped in a few small areas, all of which are probably determined by the drainage. The majority occur in Geyser Creek canyon, one tiny group is found close to the Steamboat Fumarole,[2] while a third group rises near the base of the slope to the south of the Steamboat and discharges directly into Sulphur Creek.

In the hottest part of Geyser Creek canyon nearly opposite Steamwells 1 and 2, two active springs rise in the western edge of the little creek (fig. 9). The Witches' Cauldrons, as they are called, are characterized by a strong emission of gas and by high temperature and spouting when they are not chilled by excess of invading stream water, but their most remarkable feature is the fine black sediment (fig. 10), which by a chemical process is constantly forming in them and which, discharging into the little stream, transforms it to an inky fluid whose jet-black current flows on for some little time before sedimentation restores the water to its natural appearance—a phenomenon never observed by the authors in any other place.

Boiling springs containing a similar sediment are found at several other points in the neighborhood—some within the area and some outside.

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[1] It is just possible that the "Arsenic" spring, which is quite unimportant, is depositing sinter; nothing but its water was examined.

[2] The largest spring is marked Teakettle on the map.

Fig. 9—At right and left in foreground are two bubbling springs known as the Witches' Cauldrons. Photo taken when inundated by creek.

Fig. 10—Looking down on Witches' Cauldrons from above. Note effect of inky precipitate.

Fig. 11—Acid springs in overhanging east bank of Geyser Creek.

The most numerous group of springs at "The Geysers" occurs on the east bank of Geyser Creek, a little less than halfway down the canyon. Here the receding bank, which is pretty thoroughly decomposed by the chemical action of the waters, has formed a bench 6 or 8 feet above the stream level, 15 or 20 feet in breadth and perhaps 125 feet in length, along which are ranged in a row a dozen or more small springs. Most of the springs are set into the bank (figs. 11, 12, 13) which overhangs some of them. The waters are all acid and their tiny effluents in the early summer of 1925 kept the bench wet with hot acid water so ruinous to shoe leather. Under favoring conditions this bench is incrusted with salts. At the Devil's Pulpit there is a small spring sometimes known as the Punch Bowl, but more appropriately marked on the old map as the Devil's Teakettle, for it throws out, with a pulsating action, a little shower of water like a sprinkler, to a distance of 5 or 6 feet. The springs of the Steamboat group, only half a dozen in all, carry exceptionally little water even for this semi-arid region, and some of them dry up in hot weather.

Fig. 12—"Washtub," Geyser Canyon.

On the lower slope of the eastern half of The Geysers area, not far above Sulphur Creek, there are half a dozen warm seepages (temperature 50° to 60°) occupying as many shallow gullies, which discharge in the aggregate considerable water. The largest supplies the bath house. The Magnesia Spring, long held in repute for its medicinal qualities, emerges on the hillside not far to the west and at about the same level. A short distance upstream from the bath house several distinct springs of much higher temperature rise in the bed of Sulphur Creek. They are submerged at high water, but when summer is well advanced the creek recedes and the springs can be tested without difficulty. These and the other springs of this group, so far as tests have been made, are alkaline.

Fig. 13—One of chain of springs along Geyser Creek.

TEMPERATURES AT THE GEYSERS

In the summer of 1924 a comparatively large number of ground temperatures were taken at The Geysers and its environs. Small holes were dug to depths varying from 15 inches to 4 feet and the temperatures in them were measured with an armored maximum thermometer. Variations of course were found, but a majority of the observations lay between 98° and 99° C., certainly a little higher than the hottest springs and fully as high as the temperature of boiling water for the prevailing pressure. The reader should not gain the impression that such temperatures were found close to the surface over the *whole* area covered by the map; places showing the effects of volcanic gases were generally chosen for the tests. Since then, however, highly abnormal temperatures have been discovered at greater depths in spots which at the time of our surface exploration showed no signs of subterranean heat.

The great majority of the natural vents are not of sufficient size to admit a thermometer: indeed, they are better described as gas seepages rather than vents. The fumaroles grouped on the slope east of Geyser Creek (see map) are better defined, but no temperatures in any of them surpassed that of boiling water. The same is true of the Smokestack, though at the time its temperature was taken it was hardly possible to make a satisfactory observation on account of the difficulty of getting close to it. Slightly higher temperatures were found at the Steamboat and Safety Valve, where depths of about 3 feet could be reached. The temperature at the Steamboat was 102° C. The readings of three maximum thermometers and a calibrated thermocouple were compared in this vent and found to be almost identical. At the Safety Valve many observations were made, but only one of them showed a temperature as high as 102°. This was the very highest temperature outside the steam-wells that was found in the whole district. It should be remarked that the steam flow in both these fumaroles is much stronger than it is in any other natural vent at The Geysers, with the possible exception of the inaccessible Smokestack. On June 27, 1925, the temperature at the Steamboat was 101.5°, while the highest temperature that could be obtained at the Safety Valve was only 98.5°. This was possibly due to failure to reach the same depth as before, or to find the exact path of the principal steam jet, or, possibly, to the influence of a larger body of ground water,—in any case the difference is not important.

In the springs three or four series of temperature measurements were made. Unfortunately those of 1924 were lost and only a few of them can now be recalled. Two series were made in 1925—the first on May 22, almost immediately following a period of rainfall which for ten days prior to May 20 had been heavy enough to fill the streams, wash the roads and leave rain pools in favorable situations. This was at the end of an unusually wet season. The second series was made on June 27 in the midst of a very hot, rainless period which had lasted continuously since the previous date.

Inspection of table 1 shows that the temperatures in this locality, as remarked before, are comparatively high—a fact which is readily understood when the high ground-temperatures are remembered in connection with the semi-arid character of the country. Out of the total number of well-defined springs, about 30 in all, nearly two-thirds reach a temperature of 80° C. or more, and about half surpass 90° C., while the hottest springs are within 1° of the temperature of boiling water for this locality. Some forty or fifty barometric observations were made here from May to July 1925, when pressures were found to vary from 709 to 720 mm., under which conditions water boils between 98.1° and 98.5° C. During the same time the hottest springs reached 97.5° C. Those who are familiar with hot springs are aware of the fact that they often boil vigorously at temperatures a number of degrees below the true boiling point, owing to the fact that the atmospheric pressure is partly counterbalanced by the gases other than steam which are escaping at the surface of the water.

TABLE 1.—*Temperatures of hot springs and fumaroles, The Geysers, Sonoma County, California.*

Place	Date	Temperature ° C.	Date	Temperature ° C.
	1925		1925	
Geyser Creek, above No. 13	May 22	17.5	June 27	42.0
Do. below No. 3		21.0		....
Geyser Creek, near outlet [in shade]		....		38.0
Spring No. 3, "Boracic Acid" Spring		51.5		55.3
4		93.0		89.0
5, Devil's Kitchen		91.5		85.3
8, 35 ft. above the last		63.0		....
9, 15 ft. above No. 8		72.0		88.5
10, Liver Spring 5 ft. above No. 9		89.0		88.5
11, Washtub 15 ft. above No. 10		95.5		96.0
12, Tiny spring under rock, just west of No. 11		97.5		97.0
Witches' Cauldron–Lower pool		40.0		96.5
Witches' Cauldron–Upper pool		28.5		94.0
Devil's Teakettle		95.2		97.5
Spring No. 29, New spring east of Steam Well No. 2		79.0		53.5
30, New spring close to No. 29 (black sediment)		97.5		95.0
Group 31, Teakettle	May 23	95.0		88.0
Do. Spring just below Teakettle		70.0		68.0
Do. Spring just above Teakettle		96.0		96.8
Do. Tiny spring—just above the last—(black sediment)		95.0		....
Do. Small sulphur spring 2 ft. south of the last		84.0		....
Spring No. 32, South of Well 5 and below road (black sediment)		89.0		....
Bathhouse Spring east side of tank		50.0		52.0
Hot rivulet running into tank, east side		54.0		....
Seepage in gulley just west of Bathhouse Spring		....		40.0
Fumarole near the last		....		95.0
Spring No. 33, Spring in bed of Sulphur Creek above bathhouse, north side of creek		....		84.5
Spring No. 34, Spring in bed of Sulphur Creek (black sediment)		....		88.0
Magnesia Spring		60.5		60.5
Lemonade Spring		....		86.0
Mud Spring above Lemonade Spring	May 27	....		64.0
Ink Spring	May 22	....		79.0
Steamboat Fumarole	May 27	101.5		....
Safety Valve Fumarole		98.5		....

Referring again to the table, it will be seen that during this time a few springs were practically constant in temperature; that most of them showed variation, but smaller than might be expected when the wide seasonal difference between the two dates at which the observations were made is kept in mind; and furthermore that the change is not always in the same direction. The large temperature rise in the Witches' Cauldrons is easily explained by the fact that they are found in the edge of a creek bed in which the water subsided markedly in the course of a month. The small temperature changes shown by most of the springs are quite at variance with changes in the springs of the Lassen National Park which respond so generally to seasonal differences that we were led to the conclusion that the hot springs there must be largely supplied by ground water.[1] Without conceding that ground water does not constitute a large part of that in The Geysers springs also, it must be admitted that the recorded temperatures form no solid ground for the affirmative conclusion, though it is by no means certain that a comparison of the above observations with winter temperatures would not show much greater differences.

SURFACE DRAINAGE AND ITS EFFECT ON THE SPRINGS

The majority of the hot springs of The Geysers come to the surface at low points where drainage water would be expected to emerge; all of them indeed are so situated that if they were cold springs one would find nothing illogical in their relation to the topography. Most of them occur in the Geyser Canyon, the bed of Sulphur Creek, or in the gullies draining into these from the mountain-side; in the unusual cases where springs issue on high points like the Devil's Pulpit or the Smokestack there is always still higher ground above them and they are either very small or dry up entirely in the hotter weather. Steam vents on the other hand, while they sometimes follow the creek beds, occur also in situations where no logical relation to topography is apparent.

With the question in mind as to what extent the water of these springs may be of surface origin, the observer on the ground can not but suspect that the small size of the springs and their meager discharge is connected with the *total amount* of the drainage. For half the year the region is practically rainless and though considerable precipitation takes place in the fall and winter months, the run-off on these very steep slopes is doubtless high, and in the dry season the parched surface of the ground and the dwindled volume of the streams are convincing evidence of a limited body of ground water. Indeed, when the small hot springs of the Coast Mountains are contrasted with those of a region like the Lassen National Park or more strikingly with the great geyser basins of the world, all of which are closely

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[1] Volcanic activity and hot springs of Lassen Peak, A. L. Day and E. T. Allen, Carnegie Inst. Wash. Pub. No. 360, p. 154, 1925.

associated with large supplies of ground water, their character appears but the natural result of their topographic and climatic surroundings.

Fortunately The Geysers region came under the observation of the authors in two successive years of quite unequal precipitation. The pronounced drought, beginning in the autumn of 1923 and continuing throughout the year, was followed in the autumn of 1924 and the winter months of 1924-5 by a season of exceptionally high rainfall. In May 1925, as we have already recounted, the swollen condition of the streams, the general occurrence of rain-pools, of occasional landslides on the mountain slopes and the flourishing condition of vegetation were all in striking contrast to the aspects of the country in the previous year, but a change of corresponding magnitude was certainly not perceptible in the springs. Those in Geyser Creek canyon appeared to be of about the same level as they were a year earlier. Their tiny outlets seemed to be discharging a somewhat larger volume of water but there was no conspicuous difference. The group next the Steamboat Fumarole seemed to contain an appreciably larger volume of water, and the seepages on the southern slope of the area above the bath-house were unquestionably carrying more water than they did a year earlier. Confirming the last conclusion the temperature of the bath-house supply was found to be about 10° lower (50° instead of 62° C.) than in 1924. On the whole, however, the visible differences in the discharge of the water were less than expected, and taken by themselves can not be said to constitute a strong argument for the predominance of surface water in the springs.

At the time these observations were made, a number of other facts bearing on the same problem came to notice. *New springs* appeared at points where none had existed in the dry weather of the previous year. At the foot of a steep bank near the trail between Wells 2 and 4 (see map) two springs were found, about 10 feet apart, each about 18 inches in diameter. The eastern one was spouting to the height of an inch or two at a temperature of 97.5°, contained a sediment of black mud and was in every way similar to more permanent springs. The other spring had a temperature of 79°. A depression close by contained at that time a rain-pool perhaps 30 by 30 feet. At a later date a new hot spring was discovered near the bath-house, in the bed of Sulphur Creek. The volume of this spring was considerable and the temperature was 84.5° C. Warm seepages hitherto unnoticed were also found at other points. Nearly all these newly found springs occurred in bare or open ground, either close to the trail or close to places which had been frequently visited and, as they represent precisely the phenomena sought for, it is inconceivable that they should have existed in 1924; or if they existed at all they must have been discharging so little water as to have attracted no attention. It is this *variation* in flow that is really important whether it ceases altogether or not. In the barren ground on the narrow summit of the Devil's Pulpit (fig. 14) immediately to the north of Geyser Canyon was found a small basin 2 or 3 feet in diameter lined with the black

Fig. 14—Geyser Creek canyon looking north at midday. Devil's Pulpit slightly to left of center.

mud characteristic of many hot springs in this locality. There was no water in the basin at that date (May 22), but the ground was still steaming. A similar find on the summit of the Smokestack in 1924 has been mentioned in another connection. At a point 35 yards north of Well No. 4 on the trail from Well No. 2 to the Steamboat, a fumarole, less active now than in former years, was observed repeatedly in 1924. In the early part of our second visit (1925) its depression was occupied by a shallow hot spring which later dried up and gave place to a steam jet. Other phenomena of the same kind and of a more striking character have been observed by us in other hot-spring regions. They constitute one of the most convincing lines of evidence for the close relationship of hot springs to ground water.

DISCHARGE OF THE HOT SPRINGS ON GEYSER CREEK

It is hardly a practical task to gage the individual springs at The Geysers. They are often unfortunately located for measurement, and taken separately practically all are of insignificant volume. It is possible, however, to measure the aggregate discharge of the springs on Geyser Creek, which is estimated to be fully half of the total outflow of hot water at The Geysers and perhaps considerably more. Preliminary experiments were made about the middle of June 1924. At that time the water in Geyser Creek was so low that the discharge could be measured directly. Dams with outlet pipes carrying the total volume of water were built across the creek and the water was caught and measured in vessels of known capacity while the time was taken. In this way it was learned that at that time the discharge of Geyser Creek near its mouth was only about 17 gallons per minute, or 26,000 gallons per day. At a point nearly opposite the Devil's Arm Chair the flow was practically the same, while just below the Witches' Cauldrons it was only about 12,000 gallons per day. A dam built near the head of the canyon at the top of a small fall indicated that the discharge here was less than half what it was at the mouth, but this figure was not trusted on account of leakage in the dam which could not be stopped. In 1925 the measurements were continued. The stream was then so high that the method thus far used was deemed impractical and small weirs were adopted. In 1924 temperature measurements of the water taken all the way up the creek at intervals of 25 feet had indicated no significant influx of either warmer or colder water below the second dam opposite the Devil's Arm Chair. In 1925 there was a point a short way above the confluence of the canyon with the ravine mentioned on p. 11, where some influx of steam or hot water occurred, but it must have been a very small fraction of the total hot water flowing into the creek. It may also be noted that the above-mentioned ravine was dry in 1924 though not in 1925.

Taking these facts together, the most advantageous positions for the weirs were seen to be: for the lower, a point a little below Spring 3 (see map), and for the upper weir a point opposite the Devil's Pulpit

Table 2.—*Aggregate discharge of hot springs along Geyser Creek in summer of 1925, The Geysers, Sonoma County, California.*

Date	Lower Weir			Upper Weir			Hot-Spring discharge		
	H* in inches	Q in cu. in. per second	Q in gals. per day	H′* in inches	Q′ in cu. in. per second	Q′ in gals. per day	Q–Q′ in cu. in. per second	Q–Q′ in cu. ft. per day	Q–Q′ in gals. per day
May 26	5.38	758	283500	3.75	580	216900	178	8900	66580
May 27	5.06	692	258800	3.56	537	200800	155	7750	57970
May 28	4.75	629	235300	3.30	479	179200	150	7500	56100
June 27	2.13	189	70690	.88	65	24310	124	6200	46370
July 4	2.00	172	64330	.81	58	21690	114	5700	42640

* The measurements were made in eighths of an inch and converted into decimals for convenience.

about 30 yards above the Punch Bowl (Devil's Teakettle on the map). Between these two points Geyser Creek gets practically all its influx of warm water and in the dry season there are no tributaries. There may have been a very slight accession of cold water from the gulley between the Pulpit and the Smokestack on the earliest dates given in the table below; at least our records mention a little rivulet seen there May 22, but it was very slight and rapidly dried up. Table 2 gives the discharge of the creek at the two points mentioned for five different dates. The formula of Francis:[1] $Q = 3.33\ LH^{\frac{3}{2}}$ is used in the computation, where Q is the *discharge,* L is the *length* of the weir and H the *head.* $L = 18.25$ inches and $L' = 24$ inches. The accented symbols refer to the *upper* weir. $Q - Q'$ is therefore the influx of hot water between the two weirs. The results may be slightly affected by evaporation, but inasmuch as the distance between the weirs is only 250 yards while the current is tolerably rapid and the temperature most of the way was moderate in 1925, the error is believed to be slight. The results show that the total discharge of the springs is quite limited and that there is an unmistakable decline in the discharge as the dry season advances, though the variation is by no means as great as that in the stream. Small as the discharge is, at the lowest, 42,640 gallons July 4, 1925, it is much higher than it was in June 1924 when the *total discharge of the creek* was only 26,000 gallons. It is also obvious that a variation so small and gradual would be likely to be missed unless actual measurements were resorted to. It is not claimed that the measurements apply exclusively to the actual overflow from the springs; observation indicates that water is probably oozing from them even when they show no visible overflow, and it is not improbable also that the above figures $(Q - Q')$ include some water not belonging to any well-defined spring. But the measurements do show clearly that a body of ground water varying in volume with the season is constantly reaching the surface along this creek, water none of which is from tributary streams and most of which is derived directly from hot springs. A part of the water of these springs is therefore of surface origin.

THE SPRING WATERS

Inasmuch as "The Geysers" is one of the oldest health resorts in California, the composition of the spring waters attracted early attention. A considerable number of them were analyzed in the eighties by Dr. Thomas Price and Dr. Winslow Anderson,[2] whose results have been translated into modern form by Gertrude E. Goodman and published by Waring in his *Springs of California.*[3] They have been

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[1] See Horton, U. S. Geol. Surv., Water Supply Paper No. 150, p. 25.

[2] Mineral springs and health resorts of California, by Winslow Anderson, San Francisco, 1892.

[3] U. S. Geol. Surv., Water Supply Paper No. 338, pp. 86–87, 1915.

TABLE 3

	1		2		3		4		5		6		7		8		9		10		11		12	
Temperature	22° C. (72°F.)		21° C. (70° F.)		58° C. (137° F.)		42°C. (108° F.)		59° C. (138° F.)		100° C. (212° F.)		100° C. (212° F.)		37°C. (98° F.)		59° C. (139° F.)		58° C. (136° F.)		58° C. (136° F.)		39° C. (103° F.)	
Properties of reaction:																								
Primary salinity	Trace.		0		11		8		12		16		35		6		2		2		2		16	
Secondary salinity	98		98		10		0		6		14		27		26		34		30		29		22	
Tertiary salinity	2		0		0		0		0		70		38		68		64		68		69		62	
Primary alkalinity	0		0		0		5		0		0		0		0		0		0		0		0	
Secondary alkalinity	0		2		79		87		82		0		0		0		0		0		0		0	
Tertiary alkalinity	136		35		182		28		242		8		15		30		37		27		13		18	
Constituents.	By weight	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.	By weight.	Reacting values.
Sodium (Na)	Tr.	Tr.	....	....	22	0.96	29	1.26	18	0.78	322	14.00	130	5.67	40	1.74	19	0.81	17	0.73	32	1.37	177	7.69
Potassium (K)	Tr.	Tr.	....	....	Tr.	Tr.	1.6	.04	....	....	....	....	2.1	.05	Tr.	Tr.	Tr.	Tr.	....	....	5.5	.14	37	.95
Barium (Ba)	Tr.	Tr.	....	....	....	....	....	....	....	....	....	....	....	....	Tr.	Tr.	....	....	....	....	....	....	....	....
Calcium (Ca)	20	1.00	17	0.85	42	2.11	50	2.49	45	2.24	22	1.10	35	1.76	12	.61	....	....	19	.96	22	1.12	....	....
Magnesium (Mg)	9.5	.78	8.7	.72	69	5.70	76	6.25	40	3.29	135	11.11	33	2.74	82	6.76	125	10.28	119	9.81	316	25.98	141	11.58
Iron (Fe)	1.2	.04	1.0	.04	1.3	.07	.6	.02	.7	.03	....	....	....	....	39	1.41	45	1.60	35	1.22	80	2.87	59	2.11
Aluminum (Al)	2.1	.23	1.5	.18	5.1	.56	1.6	.18	.5	.06	84	9.34	7.9	.88	156	17.28	170	18.85	173	19.15	56	6.19	87	9.60
Manganese (Mn)	....	....	....	....	Tr.	Tr.	....	....	....	....	....	....	....	....	Tr.	Tr.	....	....	....	....	....	....	....	....
Hydrogen (H)	....	....	....	....	....	....	....	....	....	....	53	52.52	5.5	5.46	.86	.85	3.2	3.15	3.7	3.65	57	56.81	22	21.33
Sulphate (SO_4)	88	1.83	75	1.56	88	1.83	40	.83	55	1.15	4,230	88.07	795	16.56	1,376	28.65	1,665	34.69	1,706	35.52	4,540	94.48	2,570	52.70
Chloride (Cl)	....	....	....	....	....	....	....	....	....	....	....	....	....	....	Tr.	Tr.	.00	.00	....	....	....	....	20	.56
Carbonate (CO_3)	....	....	1.0	.03	....	....	279	9.30	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Metaborate (BO_2)	....	....	....	....	330	7.68	....	....	....	....	....	....	....	....	[a]20	.47	Tr.	Tr.	....	....	Tr.	Tr.	....	....
Siliea (SiO_2)	25	.83	17	.56	137	4.51	81	2.69	614	20.37	220	7.26	75	2.47	161	5.32	281	9.30	295	9.76	361	11.94	282	9.34
	145.8	....	121.2	....	694.4	....	558.8	....	773.2	....	5,066	....	1,083.5	....	1,886.86	....	2,308.2	....	2,367.7	....	5,469.5	....	3,395	....
Carbon dioxide (CO_2)	Tr.	Tr.	....	....	....	....	....	....	....	....	....	....	....	....	5.1	.23	....	....	....	....	....	....	....	....
Hydrogen sulphide (H_2S)	28.1	1.65	....	....	183	10.73	(b)	....	(b)	....	(b)	....	(b)	....	41.9	2.46	62	3.63	(b)	....	(b)	....	(b)	....

[a] Reported as "borates"; recalculated from HBO_2 by comparison with other analyses. [b] Excess.

1. Iron Spring. Analyst and authority, Winslow Anderson (1888).
2. Iron Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.
3. Bather water spring. Analyst and authority, Winslow Anderson.
4. Indian Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.
5. Eye Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.
6. Devil's Tea Kettle Spring. Analyst, Thomas Price, Authority, Winslow Anderson.
7. Witches Cauldron Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.
8. Alum Spring. Analyst and authority, Winslow Anderson (1888).
9. Hot Alum Spring. Analyst and authority, Winslow Anderson (1888).
10. Hot Alum Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.
11. Hot Acid Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.
12. Lemonade Spring. Analyst, Thomas Price (1888). Authority, Winslow Anderson.

Composition of hot-spring waters, St. Helena Range, California. The Geysers and Little Geysers. Collected in 1924.

Name and location of springs	H	NH_4	Na	K	Mg	Ca	Mn	Ni	Fe''	Fe'''	Cr	Al	SO_4	S_2O_3	S	HCO_3	CO_3	SiC_2	B_2O_3	Cl
The Geysers:																				
Boracic Acid Spring	12.5	1355	10	6	574	42	.....	.....	102	none	.....	32	.....	none	.....	none	none	221	none	none
Devil's Kitchen Spring	9.5	1396	12	5	281	47	1.4	tr	63	none	2	14	5714	none	.....	none	none	225	10	.....
Bubbling Spring	25.9	732	7	4	419	42	2.2	4.3	96	none	4.9	65	5659	none	.....	none	none	379	none	tr
Liver Spring	6.6	627	3	6	288	33	1.5	2.6	103	21	2.5	15	3530	none	.....	none	none	312	none	tr
Poison Spring	9.8	510	4	4	173	21	0.9	tr	55	none	tr	22	2762	none	.....	none	none	334	10	tr
Spring below Teakettle (near Steamboat)	11.3	1270	3	1	174	10	0.7	tr?	44	none	2.3	11	4783	none	.....	none	none	305	none	none
Arsenic Spring	1.5	173	9	3	201	46	1.5	tr	none	28	none	5	1487	none	.....	none	none	230	36	1.8
Lemonade Spring	17.2	267	10	4	32	21	0.16	0.8	none	43	none	36	2020	none	.....	none	none	280	none	1.0
Witches' Cauldron (lower)	none	111	18	6	108	58	0.55	none	tr	none	none	none	763	2.7	none	176	none	66	48[1]	1.5
Spring in bed of Sulphur Creek	none	100	6	6	55	33	0.35	none	2	none	none	none	497	1.6	none	99	5	82	none	0.5
Bath-house Spring	none	37	2	1	76	42	.....	none	none	none	none	none	280	none	none	275	10	110	none	1.8
Magnesia Spring	none	23	4	1	87	53	0.35	none	none	1	none	none	236	none	none	341	16	99	none	1.5
Ink Spring	none	738	17	5	52	90	0.40	none	2	none	none	none	2232	2.3	tr	167	none	37	none	1.2
Indian Mud Spring	none	163	70	4	43	33	0.40	none	2	none	none	none	389	55.5	none	435	59	84	13[1]	0.7
Little Geysers:																				
Pool south of cabin	0.3	85	none	none	6	4	tr	none	none	3	none	none	265	none	.....	none	none	49	none	none
Largest pool in central area	1.2	192	3	1	4	3	tr	tr	105	15	none	5	868	none	.....	none	none	65	none	none
Smaller spring in central area	0.5	152	3	1	3	1	none	none	83	none	none	3	614	none	.....	none	none	42	none	none
Very small spring southern edge of central area.	none	31	none	none	36	6	0.3	none	none	3	none	none	229	none	.....	none	none	51	none	none

[1] Calculating the boron as the radical BO_2 in the alkaline springs we should have 59 and 16 instead of 48 and 13 respectively.

reproduced here for comparison with our own, which are tabulated in table 3. In several particulars these waters are unusual and possess considerable interest for chemists and geologists. In the dominance of sulphates and the almost complete absence of chlorides they recall the waters of the Lassen National Park. Chlorides are present in undoubted traces, but much ordinary distilled water probably contains as much. Like the hot springs of the Lassen National Park the majority of the waters are acid, but here the resemblance ceases. The divergences are to be attributed to wide differences in the character of the rocks in the two districts. As serpentine is commonly exposed at The Geysers it is not surprising to find the magnesium content of the spring waters much higher than the calcium. The derivation of the magnesium is in fact fully confirmed by an examination of the serpentine, which in most places is found to be in process of decomposition, often honeycombed with cavities sometimes as large as a man's arm, which are commonly lined with salt, of which sulphate of magnesium is the most important constituent. The cavities are probably due largely to the falling out of constituent parts of the conglomerate which have been loosened by chemical action. An analysis of the serpentine in this area shows that except for calcium it contains nearly all the constituents found in the spring waters, even to the secondary constituents, manganese, nickel and chromium.

Analysis of Serpentine.

SiO_2	42.24
TiO_2	none
Al_2O_3	1.33
Cr_2O_3	0.60
Fe_2O_3	8.55
FeO	1.40
NiO	0.07
MnO	0.08
MgO	34.14
CaO	none
BaO	none
Na_2O	none
K_2O	none
$-H_2O$	0.47
$+H_2O$	11.10
S	0.13
CO_2	none
P_2O_5	undet.
	100.11
Less O_2	0.05
	100.06

Green Metamorphic from The Geysers area.

SiO_2	48.22
TiO_2	1.34
Al_2O_3	14.40
Cr_2O_3	0.06
Fe_2O_3	2.68
FeO	7.74
NiO	0.02
MnO	0.16
MgO	5.99
CaO	10.52
BaO	0.02
Na_2O	5.40
K_2O	0.20
$-H_2O$	0.31
$+H_2O$	2.76
S	0.02
CO_2	none
P_2O_5	undet.
	99.84

Manganese in small quantities is no doubt present in many spring waters where it has not been looked for, but chromium and nickel in appreciable amounts are probably rare outside the Coast Range. Very unusual is it to find spring waters so low in the alkalis; many of the springs contain hardly more than the reagents used in the separation, as several blanks have shown. The absence of the alkalis is further evidence of the relation of the waters to serpentine. At first sight it may appear strange that the *acid* waters are so high in silica, in this locality higher in fact than the alkaline waters—which seems like a chemical anomaly. It is not unusual, however, and it may be added that silica is always carried into solution when silicates are decomposed by acids, the amount depending on the nature of the silicate, the concentration of the acid and other conditions. All the waters carry appreciable amounts of calcium and the acid waters carry aluminum also in similar amount. The calcium must originate from some other source than serpentine, and while *some* aluminum is found in the serpentine, it averages in the acid springs nearly one-tenth as much as the magnesium, a fact which indicates that some of it probably has another source. Calcite occurs in the sandstone in small amounts, but there is no proof that the waters reach it. At least one lime-bearing metamorphic, a fine-grained green stone, an analysis of which is appended, is found in the area. The rock contains considerable sodium, however, and this, as we have seen, is found in the waters in very small quantity.

Except for calcium, aluminum and ammonium, all the bases are probably derived from serpentine. As ammonium is the chief basic constituent of all the waters, it is rather remarkable that it was entirely overlooked by the older analysts. Its origin can be traced directly to the gases and will be discussed in that connection (p. 74).

All the waters were very carefully tested for boric acid by a most reliable method, but in most cases the amount found was inappreciable.

The *alkaline springs,* few in number in this locality, possess no distinctive characteristic, such as size, temperature range, peculiar thermal action or deposits of special nature, which enable the observer to distinguish them from the acid springs. The sediments of some, to be sure, are colored black by a peculiar sulphide of iron which has never been noticed in any of the acid springs, but the occurrence is not general; the sediments of some alkaline springs are white. By simple chemical tests, however (sensitive litmus paper and phenolphthalein solution), the field observer may classify all the waters except those close to neutrality.

Reference to the chemical analyses (table 3) shows that the alkaline waters are more complex in composition than the acid waters, so far as the number of the acid radicals is concerned; simpler, however, in the number of bases. The first point is a consequence of the chemical processes involved in the development of the alkaline waters; the second is a mere matter of solubility. The distinctive acid radicals are carbonate, bicarbonate, thiosulphate and sometimes sulphide[1] in

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[1] Presumably bisulphides also occur, but of these salts little is known.

small amounts, and the alkalinity is due chiefly to bicarbonate of ammonium, magnesium and calcium. Owing to the peculiar character of the rocks from which the mineral matter is derived the alkalinity is only slightly dependent on the *alkali metals,* while owing to the composition of the gases it is dependent in considerable measure on *ammonium.* An inspection of the equivalents in table 4 makes these facts clear.

There are two points connected with the composition of the alkaline spring waters to which attention should be especially directed. First the acid radical SO_4, which is practically the only one in the acid waters, is found in all the alkaline springs without exception, and reference to table 4 shows that the equivalent value of this radical is generally as high or higher than the sum of the radicals which are the source of the alkalinity. Secondly, not only the concentration of this radical, but the *total concentration* of the alkaline waters is so much lower than that of the acid waters as to constitute a different order of magnitude.[1] Both these points are important, holding as they do the key to the origin and development of the alkaline springs.

A minor problem of some interest to the chemist, on account of its bearing on natural processes, is the relation which the distinctive radicals in the alkaline waters hold to one another. Since bicarbonates lose more or less readily a portion of their carbon dioxide and pass into carbonates, and since soluble sulphides under the influence of air may, under some conditions, be oxidized to thiosulphate, it is a question whether the carbonates and thiosulphates found in the earlier analyses (1924) were original constituents of the water or the result of chemical changes occurring in transit to Washington.

The idea occurred to us that the amount of volcanic gases in springs of this character might invariably or generally be of such a magnitude as practically to exclude air and prevent the formation of thiosulphate; and of such a magnitude also as to supply sufficient carbon dioxide to prevent the formation of carbonate.

Assuming this to be true, the conditions of shipment are such as to make it quite possible that the secondary constituents in question were formed in transit. In sealing water samples in glass bottles it is practically necessary to leave some air around the stopper to insure a tight seal and this air might possibly be accountable for the small amount of thiosulphate found. Furthermore the samples had been sealed while the water was hot, and the contraction of the water in cooling had resulted in a reduction of pressure inside the bottle which would of course increase the tendency of carbon dioxide to escape into the vapor space and leave carbonate in the water. Several additional samples of water were therefore collected in 1925 under conditions

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[1] To this rule the Ink Spring, found outside the restricted area of The Geysers, is the single exception, but only two of the acid waters possses a lower concentration.

TABLE 4.—*Chief constituents of alkaline springs in terms of their chemical equivalents. The Geysers canyon, Sonoma County, California.*

	NH_4	Na	K	Mg	Ca	SO_4	S_2O_3	HCO_3	CO_3	BO_2	$\frac{SO_4}{HCO_3+CO_3+BO_2}$
Witches' Cauldron	6.15	0.78	0.15	8.88	2.89	15.88	0.05	2.89	none	1.37	3.7
Spring in Sulphur Creek	5.54	0.26	0.15	4.52	1.65	10.35	0.03	1.62	0.17	none	5.8
Bath-house Spring	2.05	0.09	0.02	6.25	2.10	5.83	none	4.51	0.33	none	1.2
Magnesia Spring	1.27	0.17	0.02	7.15	2.64	4.91	none	5.59	0.53	none	0.8
Ink Spring	40.92	0.74	0.13	4.28	4.49	46.48	0.04	2.74	none	none	17.0
Indian Mud Spring	9.04	3.04	0.10	3.54	1.65	8.10	0.99	7.13	1.97	0.37	0.9

best adapted to preserve its original character, and the analyses were made in the field as soon after collection as possible. The bottle was first filled with the water of the spring. Then by a simple device the bottle was allowed to suck in through a glass tube more spring water as fast as it cooled. The cooling was hastened by a pail of cooler water. Finally just enough water was removed to keep the stopper dry as it was sealed in.

The tabulated results of analyses made in the field laboratory include no carbonate, while two of the samples collected previously without special precaution contained small amounts, so that unless conditions in the springs had changed, carbonate was not an original constituent of the waters. Since that time, however, a large number of field tests made in California, Nevada and the Yellowstone Park have shown that carbonate is a common constituent of hot springs though many contain bicarbonate only. The tabulated results show that thiosulphate is an original constituent of two springs in The Geysers district; one of them outside the area proper.

	Date	HCO_3	CO_3	S	S_2O_3
Magnesia Spring	1924	341	16	none	none
	1925	377	none	none	none
Bath-house Spring	1924	275	10	none	none
	1925	282	none	none	none
Ink Spring	1924	167	none	trace	2.3
	1925	336	none	present	5.6
New Spring	1925	53	none	none	58

It appears therefore from the results that there is no uniformity in the amount of volcanic gases in individual hot springs—even those of the same district—and that the amount of gas is frequently insufficient to prevent the chemical changes just considered. The *source* of the alkaline springs will be discussed further on pp. 78-82.

SALTS

In dry weather the ground at The Geysers and other hot areas in the neighborhood is more or less incrusted with thin patches of salt (fig. 15) many samples of which were collected in the search for evidence on sources or genetic conditions, especially such as might throw light on the ultimate problems in hand. In some places appearances indicate that the salts are derived from hot-spring seepages which evaporate under the influence of the warm ground and dry air. This is judged to be the source of the salts which gather on the bench by the little chain of springs in Geyser Creek canyon (see p. 22); in general, however, the salts occur on comparatively high ground or on steep slopes where there are no springs but where the odor of hydrogen sulphide, the presence of steam, or the high temperature of the ground indicate that they are the direct product of fumarole activity or, to be more specific, a decomposition product of the surface rocks, the active agent in which process is sulphuric acid originating from the oxidation of hydrogen sulphide in the volcanic gases. A unique occurrence of salts was found beneath an overhanging bank opposite the Devil's Pulpit in Geyser Creek canyon, where in May 1925 dripping solutions had resulted in the formation of stalactites—one of which had reached 9 inches in length. They consisted principally of epsom salt. Speaking generally, the salts are mixtures chemically similar to those found by analysis in the spring waters; that is to say, they are characterized by a preponderance of ammonium and magnesium sulphates with similar secondary constituents, and by almost complete absence of alkalis. Aluminum and iron, usually in the ferric state, occur in comparatively small amounts. Chromium has not been noticed and calcium has been found only in traces among the salts.

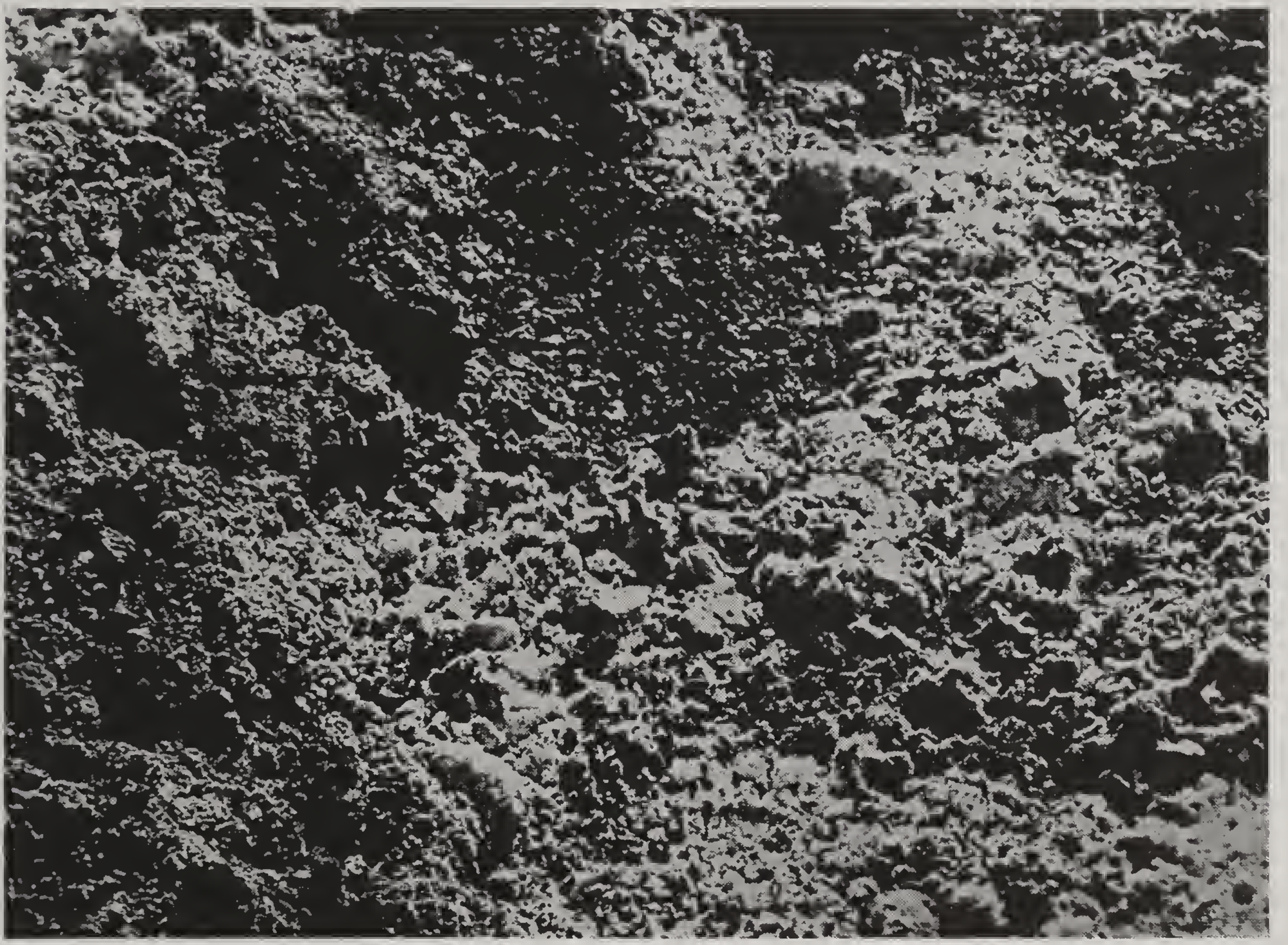

Fig. 15—Salt incrustations beside Steamboat Fumarole.

Optically the salts often consist of complex aggregates of interlacing crystals, many constituents of which have not been recognized, but several occurrences for one reason or another have been more carefully studied and, for indispensable aid in this work, we are indebted to F. E. Wright and H. E. Merwin.

Many visitors at The Geysers have probably noticed in the field small spots of a vivid green color in certain of the salt patches. They are quite conspicuous and characteristic of the locality. The color seems to be due to sulphate of nickel, which metal in amounts of some tenths of a per cent has been found in many of the salt samples, particularly in one which showed in the field a bright green color and, though most of it on more careful examination proved to be white, Wright observed a segregation of a green constituent which was found to be high in nickel. The color certainly is not due to chromium which in this specimen was absent, and if it is due chiefly to ferrous iron, practically all of that constituent had changed to ferric iron before the sample was examined, and this without any of the signs of oxidation which are generally visible in such cases.

FIG. 16—Magnesium sulphate occurring in cavities of serpentine.

Voltaite, a relatively stable sulphate of dark-green color which is probably due to the combination of ferrous and ferric iron which it contains, occurs at The Geysers in comparatively thick loose masses of rather large crystals intermixed with a small amount of other material. It was identified by Merwin in a sample collected close to the Teakettle (near the Steamboat Fumarole) and several other spots are now recalled, the peculiar appearance of which was probably due to this salt.

More important than any of these occurrences are the relatively copious deposits of sulphate of magnesium which may be seen in half a dozen places in The Geysers area. Its significance lies in the fact that it forms the connecting link between the springs and the serpen-

FIG. 17—Salts encrusting wall rock of Devil's Kitchen where acid ammonium sulphates were found.

tine rock which supplies to the waters a large part of the mineral matter they contain. The salt often occurs in cavities in the serpentine (fig. 16) which, under the disintegrating influence of the fumarole gases, is gradually changing into it. It consists of white lathlike crystals, dull, lusterless, often mealy in appearance. The following is an analysis of the purest of several samples examined. It was picked out by Merwin with the aid of the binocular microscope.

	Found	Cal. for $MgSO_4.5H_2O$
H_2O	42.97	42.80
Mg	10.80	11.55
Ni	0.09	....
Fe	0.18	....
Mn	0.11	....
Ca	0.09	....
SO_4 (diff.)	45.76	45.65

The crooked form of the fibrous crystals in certain samples, resembling as they do the ice spicules which grow up from the capillary pores of loose frosty ground in winter time, strongly suggests similar conditions of growth. Optical study reveals a pseudomorphic structure, that is, each large crystal is made up of numerous smaller kernels variously oriented; rarely a single small crystal has changed bodily to one of different properties. The salt is probably derived by loss of water from the higher hydrate, epsom salt ($MgSO_4.7H_2O$). Hygrometric measurements of the atmosphere at The Geysers are wanting, but the rather low dissociation pressures[1] of epsom salt make it probable that the warmth of the ground as well as the dryness of the atmosphere is instrumental in the formation of the pentahydrate above described. There is no mystery about the occurrence of the higher hydrate at one particular spot, for there, as has been stated, an excess of cool water was present.

Two other salts, always intimately associated in hard white or light-brown formless lumps, occur at several points in this fumerole field, and though inconspicuous they are of considerable interest because of the light they throw on the chemical conditions to be found in such localities. These salts incrusted the wall rock of the spring known as the Devil's Kitchen on Geyser Creek (fig. 17; see map); the ground above the Devil's Arm Chair (fig. 18) and the bank close to the Teakettle where it was observed in 1922 and also in 1924. Chemical analyses were made of the purest portions of several samples. Like all other salts which were analyzed they were dissolved, filtered from silica, etc., and the solution was made up to a known volume.

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[1] Frowein, Zeit., phys. Chem. 1, 13, 1887; Cohen, Arch. Neerland (2) 5, 295, C. B., 1901 vol. 1, 772.

Fig. 18—Slope above Devil's Arm Chair. One of localities for acid ammonium sulphates.

aliquot parts of which were used in analysis. In the present instance the results were corrected on the assumption that the small quantities of magnesium and ferric iron found were in combination with ammonium as double sulphates, but the corrections are unimportant; the ratios are little changed (see table 5). All the samples are clearly ammonium acid sulphates in which the acidity is less than that of NH_4HSO_4 and more than that of $(NH_4)_2SO_4.NH_4HSO_4$. At first the latter salt was the only one detected by the microscope, but careful observation showed that on dry days another salt in long hairlike crystals grew out of the moist surfaces of the lumps, and these crystals, as Merwin found, possessed the refractive indices of the simpler salt NH_4HSO_4. In more humid weather the hygroscopic nature of the substance reduced it to a syrupy solution. The material collected is not therefore a definite compound as the constancy of the analyses at

TABLE 5.—*Analysis of ammonium acid sulphates, The Geysers, Sonoma County, California.*

	Sample No. 8_1		8_2		10	
	Weights	Equiv.	Weights	Equiv.	Weights	Equiv.
H	0.0046	0.0046	0.0029	0.00290	0.00495	0.00495
NH_4	.2145	.01190	.1580	.00876	.2350	.01303
Mg	.0013	.00011	.0090	.00074	.0010	.00008
Ni	none	....	....	....	....	....
Fe'''	.0040	.00021	.0035	.00019	.0040	.00021
Sum		.0168		.0128		.01827
SO_4	.8115	.0169	.6160	.0126	.8795	.01831

Corrected results.

	Sample No. 8_1		8_2		10	
	Weights	Equiv.	Weights	Equiv.	Weights	Equiv.
H	0.0046	0.0046	0.0029	0.0029	0.00495	0.00495
NH_4	.2113	.0117	.1435	.00795	.2322	.01287
SO_4	.7875	.0164	.5329	.01109	.8578	.01786

	Ratios found	Ratios in the pure salts	
	H : NH_4 : SO_4	H : NH_4 : SO_4	
Sample 8_1	1 : 2.54 : 1.78	1 : 1 : 1	NH_4HSO_4
Sample 8_2	1 : 2.74 : 1.91	1 : 3 : 2	$NH_4HSO_4.(NH_4)_2SO_4$
Sample 10	1 : 2.60 : 1.80		

first led us to believe, but a mixture of the two acid ammonium sulphates.

These salts are derived from the volcanic gases reacting with the oxygen of the air (see p. 78). The interesting point about their genesis in this connection is the high acidity necessary for their formation; the less acid salt crystallizes according to Dorp[1] only from solutions which contain as much as 16 per cent sulphuric acid, while the simpler salt (NH_4HSO_4) crystallizes from solutions containing not less than 33 per cent acid. We have confirmed the latter result, approaching the boundary curve between the two salts from opposite directions, that is, the salt NH_4HSO_4 was crystallized from mixtures where it preceded or followed the double salt. The limiting concentration of sulphuric acid was found to be 33.86 per cent and 33.72 at 22°, while Dorp found 33.84 per cent at 30°. It is therefore certain that surprisingly high concentrations of sulphuric acid may occur in nature where the climate is sufficiently arid. Rock decomposition would doubtless be greatly accelerated under such conditions and would probably be relatively rapid with much lower concentrations of acid. At Lassen Peak the authors[2] found evidence of two stages or types of rock decomposition which were conditioned by the acid concentration; the one yielding kaolin and salts free from aluminum sulphate, the other conditioned by more concentrated acid yielding not kaolin but silica, with salts in which aluminum was the predominant metal.

A complete list of the minerals which have been identified in salt mixtures collected at The Geysers is given below. Some of them, now interesting chiefly to the mineralogist, may perhaps in the future supply useful information in the analysis of problems of a character similar to those here discussed.

$(NH_4)_2SO_4 . MgSO_4 . 6H_2O$—Boussingaultite or Cerbolite
$(NH_4)_2SO_4 . Al_2(SO_4)_3 . 24H_2O$—Tschermigite
$MgSO_4 . Al_2(SO_4)_3 . 22H_2O$—Pickeringite
$MgSO_4 . 5H_2O$*
$NH_4HSO_4 . (NH_4)_2SO_4$*
NH_4HSO_4*
Formula uncertain—Voltaite
$Al_2(SO_4)_3 . 16H_2O$—Alunogen

* These three minerals seem not to have been found in nature before.

SEDIMENTS

Hot-spring sediments are the "insoluble" products of rock decomposition, precipitates formed either in the springs themselves or, in some cases perhaps, in the spring waters before they reach their outlets. Loosely embedded fragments of partially altered rock or rock minerals often occur with them. The sediments in this locality

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[1] Zeit. Phys. Chem. 73, 284, 1910.

[2] Day and Allen, op. cit., p. 140.

Table 6.—*Partial analyses of hot-spring sediments at The Geysers, Little Geysers, etc., Sonoma County, California.*

	The Geysers and environs							Little Geysers		
	Ink Spring	Witches' Cauldron	Teakettle (near Steamboat)	Spring above Devil's Teakettle	Lemonade Spring	Indian Mud Spring	Slope of Smokestack	Central area largest pool	South of cabin	Southern border of central area (edge of little rivulet)
Volatile matter including H_2O, S, etc.	13.72	12.62	16.46	7.68	9.40	7.46	9.32	22.30	17.83	17.60
SiO_2	61.10	52.57	78.36	81.44	71.82	73.90	74.78	35.84	62.34	37.86
Al_2O_3	16.04	21.85	2.12	4.83	11.71	10.14	12.23	40.31	17.67	26.96
Fe_2O_3	6.80	6.51	0.87	1.40	2.02	4.28	0.84	....	....	10.58
TiO_2	0.78	2.14	2.23	1.15	1.83	0.68	1.45	....	....	....
CaO	....	1.47	0.30	1.06	0.40	0.56	0.38	....	0.50	....
MgO	0.38	0.68	0.42	1.46	1.14	1.44	0.74	....	0.20	6.66
	99.82	97.84	100.76	99.02	98.32	98.46	99.74	98.45	98.44	99.66

are generally loose, fine-grained, non-plastic, sometimes gelatinous, muds, usually white or whitish but colored at times by sulphur, oxide of iron or black sulphide of iron; the compact deposits properly termed "sinter" are never found. The character of the sediments is evidently the result of local conditions, for true sinters occur in a number of places on the same side of the St. Helena Range. Less than half a mile to the west of The Geysers near the border of hot ground is a small area of calcareous sinter, embedded in which straws, acorns, etc., prove it to have been formed at the surface. Twenty-five miles to the southeast, a small deposit of siliceous sinter occurs at Calistoga,[1] and thirty miles northwest of The Geysers, the Vichy Springs, near Ukiah, are depositing calcareous sinter at the present time. The conditions which determine the presence or absence of sinter in hot-spring deposits is a problem of considerable interest, but a fuller knowledge of the subject will be necessary before it can be solved.

Chemical analyses of the spring sediments at The Geysers (see table 6) show that silica, alumina and volatile matter, including water and sometimes more or less sulphur, are the chief constituents. Microscopic analysis proves that the major constituent of all the sediments is opal, but as the material is isotropic and not visibly crystalline, and as the only measurable optical property is the refractive index, no further information of value could be obtained by this method. It was not therefore deemed worth while to complete the analyses.

In some localities there is a striking difference between the sediments of the acid and alkaline springs even when the two classes occur side by side, but at The Geysers there seems to be no distinctive difference except that in the alkaline springs a black sulphide often occurs in addition to the substances common to both. In the analyses of such sediments, the sulphide was first removed by dilute nitric acid and is not included in the table. This sulphide is rather remarkable both physically and chemically. It is black, lusterless, so fine-grained that it often settles very slowly, reveals no crystallinity under the microscope, and is insoluble in hydrochloric acid. In the test of several samples, iron always proved to be the principal metallic constituent and this was invariably accompanied by a small amount of nickel. No other metal was found.[2] The ratio of nickel to iron was determined in several instances. In the sulphide of the Devil's Punch Bowl, the results were $\frac{\mathrm{Ni}}{\mathrm{Fe}}=\frac{0.0021}{0.0838}=0.025$; while in the black mud collected from the slopes of the steaming Smokestack, which is of

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[1] In a meadow near Pacheteau's Baths. In the course of the last few years the hot springs which deposited this sinter have ceased to flow—a result of drilling of nearby wells. (Private communication from Mr. A. Rocca.)

[2] No mercury has yet been detected in any of the sediments, though this area lies within the limits of the quicksilver belt, and cinnabar in small amounts has been found at two points. It occurs in steaming cracks coating opal.

essentially the same nature as the hot-spring sediments, the nickel-iron ratio proved to be only 0.011. Both the iron and the nickel are probably derived chiefly from the serpentine, and the precipitation of both by soluble sulphide in the waters is doubtless in progress at the present time. It is impossible to say precisely to what mineral species this insoluble sulphide is to be referred. Its chemical behavior indicates it to be a cryptocrystalline pyrite or marcasite. Coating smooth pebbles on the bottom of the Witches' Cauldron, where the greatest amount of this sulphide occurs, was found a thin crust of a mineral having the color and luster of pyrite. It may be added that a similar product was found coating numerous lumps of clay in one of the alkaline springs of the Lassen National Park, while in all the acid springs of the neighborhood the sulphide was plainly crystallized pyrite. Evidently pyrite does not crystallize well from waters of this character. It is a plausible conclusion from the data before us that the loose black sulphide and the denser bronze crust are both cryptocrystalline pyrite, the differences in properties being due to difference in the state of division.

A remarkable fact concerning the sediments under discussion is the absence in them of any constituent showing plasticity, birefringence, or a refractive index characteristic of kaolinite or any other of the clay minerals. Kaolin is the preponderant constituent of the sediments in the hot springs of the Lassen National Park and preliminary exploration has revealed its presence in at least a number of places in the Yellowstone Park. It should be noticed at the same time that mud pots occur in both these localities, though they are not found at The Geysers. At first the absence of kaolin at The Geysers was attributed to the nature of the rock; feldspars have not been found here in the zone of decomposition, while in the Lassen Springs the feldspars and volcanic glasses were the only minerals to which the formation of kaolin could be traced. But this conclusion has been nullified by the subsequent discovery of small deposits of clay in the active area at The Geysers though not in the springs themselves. The first of these was collected at a point about 50 yards northwest of the Silver Polish bank. It was a very plastic mud, having nearly the physical and chemical properties of kaolinite. The color is blue, much paler when dry, and the average refractive index (Wright) is a trifle higher than ordinary kaolinite. The analysis, made on a sample, from which the soluble matter had been removed by water, simply dried on the steam bath, indicates a kaolinite in which the alumina has been partly replaced by chromic oxide.

Similar substances with varying percentages of chromium have been described by other observers.[1]

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[1] See Wherry and Brown, Am. Mineral, 1, 63, 1916, for some analyses and references. See also Journ. für Prak. Chem. 34, 202, 1845.

Analysis of chrome-kaolinite (miloschite).

SiO_2	46.06
Al_2O_3	35.28
Cr_2O_3	2.42
Fe_2O_3	1.42
TiO_2	0.05
NiO	trace
MnO	undet.
MgO	0.08
Na_2O	undet.
K_2O	undet.
H_2O	14.85
	100.21

Another occurrence of an emerald-green clay, very plastic when wet and possessing similar optical properties, was found about 200 yards from the first deposit. A partial analysis gave $Fe_2O_3 = 2.11$ per cent, $Cr_2O_3 = 6.37$ per cent. As these deposits are doubtless of secondary origin, the area should contain some mineral from which they were derived, unless, indeed, it can be shown that the clay was transported from a distance, which appears unlikely. A more plausible hypothesis in explanation of the absence of kaolin from the springs at The Geysers—at least from the acid springs—is that its formation is prevented by the relatively high acid-concentration which is found here. In the Lassen Springs where kaolin is the chief constituent of the sediments the acidity is generally much lower and the waters usually contain only traces of alumina, but in the warm ground, as previously remarked, in many places where silica without kaolin is associated with salts high in alumina a higher concentration of acid is indicated. Furthermore, at The Little Geysers, 5 miles from The Geysers on the same hypothetical fault line, where the rocks, serpentine, mica schists and other metamorphics appear to be sufficiently similar to those at The Geysers, but where the acidity of the spring waters is very low, the sediments are high in alumina (see table 6), quite plastic and possess optical characteristics—birefringence and refractive index—like those of kaolinite (Wright).

Analysis of "Silver Polish"

SiO_2	87.12
Al_2O_3	2.20
Fe_2O_3	0.54
TiO_2	6.00
CaO	0.10
MgO	none
H_2O	4.58
	100.54

Though not a hot-spring sediment, the nonplastic clay from the Silver Polish bank occurring on the trail between Wells 2 and 4 is doubtless the product of similar agencies and may properly be mentioned here. It is nonplastic, contains little alumina, and the presence in it of free sulphuric acid is significant of its origin. Most of the material had the refractive index of opal, but certain larger brownish grains possessed a distinctly higher index and these disappeared when the material was fused with potassium acid sulphate, leaving nearly pure silica. The brown patches were probably titanium oxide which the analysis shows to be present in unusually large amount.

Fig. 19—Drilling first well. The Geysers, 1922.

THE STEAM-WELLS

In the summer of 1921 J. D. Grant, of Healdsburg, California, began drilling on the hillside to the east of Geyser Creek (fig. 19) with the hope of utilizing the steam for power. At that time he was unaware of the fact that a similar project had already been successfully attempted at Larderello in Tuscany, but he had become impressed with the constant escape of steam at The Geysers and its relatively high temperature at the surface and believed that both would increase with depth. The results confirmed his conclusion, though the first shallow bore-hole, when closed, blew out the casing and was abandoned. In the following summer the well now designated No. 1 was drilled on the east bank of Geyser Creek and reached its present depth (203 feet) in September 1922. For the first 80 feet, only soft material was encountered but the steam-flow increased rapidly with depth (fig. 20). The soft surface layer consisted of thoroughly decomposed rock and was probably similar to the surface mud well exemplified at the Smokestack fumarole just opposite on the other side of Geyser Creek (see p. 14). At a depth of 80 feet the sandstone cap was struck and the drilling was continued through it, after which an 8-inch steel casing was lowered and "anchored" in the rock by pouring around the pipe several hundred pounds of

Fig. 20—A plank across mouth of casing, weighted with drill rod weighing about a ton, fails to "hold down" steam, 1922.

molten zinc which congealed and furnished a firm and tight joint. Boring continued to a total depth of 203 feet as an open hole, after which the well was closed by a heavy gate valve attached to the top of the casing. The drilling was done with a churn drill (fig. 20) without special equipment, the steam in the drill-hole being controlled by admitting a stream of cold water to condense it. At the end of each half hour or so the well was allowed to "blow." Considering that the workmen had had no previous experience of the kind, it speaks well for their skill, initiative and perhaps their good fortune, that the work was completed without serious accident. A steam gage attached to the outlet pipe registered a pressure of 62 pounds to the square inch when the well was closed.

Fig. 21—Drilling second well with steam power from first. Photo obtained from J. D. Grant.

Encouraged by the success of the first venture to continue the undertaking, on October 18, 1922, the promoter began a second well within 50 feet of the first, carried it down to a depth of 318 feet and closed it by the same methods. Steam from the first well was used without filtering or other treatment to furnish power for drilling the second which was completed July 20, 1923 (fig. 21). The gage pressure in this well when closed showed 61 pounds. Notwithstanding that the wells were so close together, the pressure of neither seemed to be affected by the discharge of the other (fig. 22). Also, when either well was allowed to discharge continuously for months and then closed again the pressure soon attained the same value as before.

FIG. 22—Wells No. 1 and No. 2 discharging into atmosphere, 1924. Excellent view of Smokestack Fumarole right.

Beginning in the summer of 1924, a third well was sunk on the extreme border of the hot ground, but the boring was discontinued at a depth of 154 feet.

During the first two years a local stock company, "The Geysers Development Company," was organized to carry on the work and Kingsley G. Dunn of San Francisco was the engineer in charge. After some vicissitudes, this pioneer group gave way to a new organization with stronger financial backing, and in January 1925 drilling was resumed by the Diamond Drill Contracting Company, of Los Angeles, under the direction of J. D. Galloway, engineer, of San Francisco. This Company, using a rotary equipment, has already drilled five holes, numbered successively from No. 4 to No. 8, of which Mr. Galloway recently presented to the Engineering Societies of New York the following account:

"During the first seven months of 1925 four wells, No. 4, No. 5, No. 6 and No. 7 were drilled. These four wells are of the same size and type and are distributed over an area about 550 feet long. An open hole is first drilled through the overburden and into rock as far as possible. Into this hole a 10-inch wrought steel casing is set and the space between casing and the walls of the hole filled with Portland cement grout. After the cement is set, the hole is then drilled deeper into the rock until the flow of steam is good and then an inside 8-inch wrought steel casing inserted and the space between the two casings is filled with cement grout which is allowed to set. After this the well is drilled as an open hole, deeper into the ground. Data on the four wells, No. 4, No 5, No. 6, and No. 7, are given in the following table with some for No. 8 now drilling.

	Wells				
	No. 4	No. 5	No. 6	No. 7	No. 8
Depth of 10″ casing	153′	91′	83′	103′	68′ (15″)
Depth of 8″ casing	256′	203′	208′	176′	160′ (12″)
Depth to bottom of well	451′	416′	487′	483′	——*

* In June, 1926, this hole had reached a depth of 640 feet. Both pressure and temperature were still somewhat lower than in the other wells and drilling was still in progress though the rock encountered at this depth was a hard chert.—The authors.

"In drilling the wells, the incoming steam is condensed by the stream of cold water pumped down to the bottom of the well through the interior hole of the drill stem. The water is sent down under pressures up to 250 pounds per square inch, and under the pressure rises to the top of the well outside the drill stem and flows off through a side vent. A point is reached when the cold water sent down comes back heated to near the boiling point and this indicates about the depth required. All openings on the well are then closed and the drill removed. When all is clear, a valve at the top is opened and the hot water is blown from the well by the geyser effect. Rocks and dust are also blown out and it takes a week or so before the well clears the passages.

"In drilling through the rock, the hardness varies greatly. The drill often encounters fissures or fumaroles in its passage downward and these underground fumaroles indicate the presence of steam."

The opening of a well after the tools are removed presents an imposing spectacle. As the valve is opened steam and hot water rush violently out with a great roar, rising in successive leaps like a geyser and carrying a shower of sand and loose rocks which bombard the steel frame of the derrick with a rattle like a fire of musketry. The column quickly reaches its maximum height of 200 to 300 feet and in a few moments much of the excess water and loose debris are cleared out, leaving a huge jet of intensely hot, roaring steam rushing from the well at high velocity, the noise of which can be heard for several miles and which at close range is absolutely deafening.

Fig. 23—Wells open. No. 1 and No. 2 left, No. 4 center, No. 5 right and No. 6 partially closed down between No. 4 and No. 5. 1925.

PRESSURE, TEMPERATURE, AND OUTPUT OF THE STEAM-WELLS

While the method employed in drilling the later wells is obviously unsuited to the determination of the nature of the rock below ground and the rise in temperature with depth, the log of the earlier wells yields considerable information of value, but its consideration belongs more properly in another section of this paper (see pp. 82 and 88). In depth the wells vary from about 200 feet to nearly 650 feet. The pressure is greater in the deeper wells but it is not proportional to depth; it does not even follow the same order. When closed and capped the pressure in different wells varies from 60 pounds to 275 pounds to the square inch. Mr. Galloway's paper, already referred to, contains interesting information upon this point also. With his permission we quote once more:

> "*Characteristics of the Steam*—The steam pressure, wells closed, varies and the same is true of the quantity of steam discharged under different pressures. In the case of Wells No. 6 and No. 7, the wells have not been closed long enough to indicate the maximum pressure but it is believed that it will reach 300 pounds to the square inch. Since

Well No. 6 was brought in with an initial closed pressure of about 250 pounds, the static pressure in other wells has become greater. The following table indicates this.

	Wells					
	No. 1	No. 2	No. 4	No. 5	No. 6	No. 7
Initial Static Pressure............	64 lbs.	67 lbs.	82 lbs.	143 lbs.	240 lbs.	198 lbs.
Static Pressure, Sept., 1925.......	67.5	67.5	107	211	276	....

"*Tests*—Numerous tests of the quantity of steam flowing from the wells have been made. Steel discs 1/16″ thick with circular openings of different diameters are clamped between flanges and the steam allowed to escape until such time as the pressure becomes constant for each disc. The edge of the opening in the disc is rounded to a knife edge from which the diameter is measured. Pressures are read by calibrated test gages on a pipe tapped into the well casing a few feet below the orifice and the quantity of steam flowing determined by Napier's formula.

Fig. 24—Wells Nos. 4, 5, 6 and 7 discharging. 1925. Photo by Kidd.

"A considerable difference in quantity and pressure of steam is found in the different wells. No. 1 and No. 2, which are some distance from the others and not so deep, stand at 62 pounds, gage-pressure when closed. These wells are close together and undoubtedly connected. Wells No. 4, 5, 6, 7 (fig. 24) driven under the supervision of the writer in this year (1925) show wide differences. No. 4, 6 and 5 lie in a straight line in the order named, the distance between No. 4 and No. 6 being 275 feet and between No. 5 and No. 6 the same; No. 6, being midway between No. 4 and No. 5. The maximum static pressure for No. 4 is 111 pounds, of No. 6, 276 pounds and of No. 5, 210 pounds. It is probable that if No. 4 were drilled deeper it would deliver greater quantities of steam and register greater pressures. Well No. 7, 160 feet distant from No. 6 at right angles to the line of the other wells, is somewhat larger than No. 6 and it is thought the static pressure of this well will reach 300 pounds. The highest yet reached is 276 pounds in No. 6. After the wells have been open for a time, and are then closed, the pressure rises rapidly. No. 6, opened for several weeks and discharging at about 150 pounds, rose to 270 pounds pressure in 50 minutes. However, after a well has been open, it takes several days to build up the highest pressure recorded.

Fig. 25—Well No. 6. Steamboat Fumarole in foreground.

"In practice, since the wells must deliver steam into a common header, the quantity of steam from each well will vary. If 75 pounds header pressure be assumed, then the four wells described will deliver the following quantities of steam per hour:

Well No. 4	7,500 lbs.
Well No. 5	52,000
Well No. 6	38,000
Well No. 7	40,000
	137,500

"With a water rate of 27.5 pounds per kilowatt-hour, condensing, these four wells represent a switchboard delivery of 4,500 kilowatts, after allowing 10 per cent losses in steam in transmission. Each well on the average will thus deliver about 1,000 kilowatts." (figs. 25, 26.)

Fig. 26—Well No. 6 just completed and shut off. 1925.

Up to the present time the opening of the wells has had no visible effect on the natural fumaroles; apparently they keep on steaming at the same rate as ever (fig. 27). Neither has the discharge of any of the wells had the effect of diminishing the pressure in any other, although two of the wells are within 50 feet of each other.. On the contrary, Mr. Galloway's record reveals the fact that after the opening of No. 6 the pressure in the neighboring wells No. 4 and No. 5 increased somewhat, but the individual pressures are still far apart

Up to the present time the maximum pressure of none of the wells is appreciably affected by long-continued discharge; when closed again the pressure gradually regains its former value.

In the summer of 1925 with the kind cooperation of Mr. Galloway, a series of temperature measurements with corresponding pressures was made in the wells. An 8-inch outlet pipe (horizontal) which was screwed into each valve body was tapped to admit a threaded $\frac{3}{8}$-inch pipe closed at the inner end while the outer end also could be closed by a removable plug. The small chamber thus formed admitted a maximum mercurial thermometer about 6 inches in length, graduated in single degrees from 100° to 200°. When a test was to be made, the thermometer was carefully slipped into the small pipe, which was then closed by a screw-cap. Valves were so arranged that the thermometer pipe could be surrounded by steam under full pressure or steam discharging at any lower pressure down to that of the atmosphere. Three thermometers, made by the Taylor Instrument Companies of Rochester, were used in the measurements and, as the table shows, there was no systematic difference in their reading. One of them, No. 1, was afterward carefully calibrated, and the errors in reading were found not to be greater than ±0.1°. In making a measurement the thermometer was left in the pipe usually for 15 minutes, then withdrawn and read as quickly as possible with a reading glass.


Fig. 27—Safety Valve in 1925 after boring Wells No. 4, No. 5 and No. 6.

The accidental temperature errors from all sources may be judged by comparing the measurements made in the same well *on the same date,* as the latter represent duplicate determinations made within an hour. That the differences are not entirely due to errors of measurement is obvious from the results in Well No. 1 which remain unaccounted for, but they are probably due chiefly to delays in withdrawing the thermometer and a consequent shortening of the mercury column to which a 200°-maximum thermometer is prone. Except the duplicates in Well No. 1, the differences are: 0.2°, 0.2°, 2.0°, 0.7°, 0°, 0.6°, 1.0°, 0.5°—average about 0.7° C.

Table 7.—*Measured temperatures and pressures in the Steam Wells at The Geysers, Sonoma County, California. Pressure and temperature taken at the top. Wells closed.*

Place	Date	Time of test min.	No. of thermometer	Temp. in C°.	Pressure in lbs. per sq. in.	p+1 at (13.8 lbs.) = p′	p″ *	p′–p″
	1925							
Well 1	June 20	15	2	122.0	62	75.8	30.7	45.1
		"	1	143.8	62	75.8	58.3	17.5
	21	"	2	148.7	62	75.8	66.6	9.2
	26	"	1	154.0	62	75.8	76.7	0.9–
	27	"	3	154.2	65	78.8	77.1	1.7
Well 2	June 20	15	3	153.0	60	73.8	74.7	0.9–
		"	3	153.2	60	73.8	75.1	1.3–
	21	"	1	153.0	60	73.8	74.7	0.9–
	26	"	3	154.0	60	73.8	76.7	2.9–
	27	"	2	153.1	63	76.8	74.9	1.9
Well 4	June 17	15	1	98–99	0	13.8	13.8	0
	18	"	110 max.	98.5 & 99	0	13.8	13.8	0
	19	"	1	166.0	62.5	76.3	104.1	27.8–
		"	2	166.2	62.5	76.3	104.6	28.3–
	20	20	2	164.0	62	75.8	99.1	23.3–
		"	1	162.0	62	75.8	94.3	18.5–
	21	25	3	164.8	87.5	101.3	101.1	0.2
	26	15	2	167.5	95.5	109.3	108.0	1.3
	27	"	1	167.2	95.5	109.3	107.2	2.1
Well 5	June 11	....	....	169.0	50	63.8	112	48.2–
	15	....	1	181.3	138	151.8	149.7	2.1
	16	15	2	184.0	145	158.8	159.2	0.4–
	17	"	2	185.0	152	165.8	162.8	3.0
	18	"	1	186.0	159	172.8	166.5	6.3
		"	2	186.7	159	172.8	169.1	3.7
	19	"	2	188.0	167.5	180.5	174.0	6.5
		"	3	188.6	167.5	180.5	176.3	4.2
		"	1	188.0	167.5	180.5	174.0	6.5
	20	20	3	189.2	169	182.8	178.7	4.1
	21	15	1	190.0	169	182.8	181.8	1.0
	26	"	1	172.0	102	115.8	120.4	4.6–
	27	"	2	189.0	180+	193.8	177.9	15.9
Well 6	June 15	....	....	178.5	116	129.8	140.4	10.6–
	16	15	1	181.0	116	129.8	148.7	18.9–
	17	"	2	181.0	116	129.8	148.7	18.9–
	18	"	2	181.0	116	129.8	148.7	18.9–
		"	1	180.0	116	129.8	145.3	15.5–
	19	"	3	181.0	116	129.8	148.7	18.9–
		"	1	180.5	116	129.8	147.0	17.2–
	26	"	3	181.0	126	139.8	148.7	8.9–
	26	"	2	180.5	126	139.8	147.0	7.2–
	27	"	1	180.0	123	136.8	145.3	8.5–

* p″ = the pressure of saturated steam in lbs. per sq. in. at the temperature read.

Pressures were measured with a Bourdon gage, which from time to time was compared with a standard. The gages were temporarily screwed on to a 3/8-inch pipe attached to the large valve body and controlled by a small needle-valve. The gage was never left attached to the pipe and was connected to it only after cold water had been poured in. The pressures in all the closed wells were taken each morning by R. B. Kidd, usually about the same time the temperatures were read, but occasionally 12 hours earlier if the pressure had been found to be virtually constant for some time.

The first fact of interest which arrests the attention when table 7 is inspected is that in all but one of the wells, No. 6, the *pressures and temperatures eventually approximate to those of saturated steam.* Since the pressure of saturated steam within the temperature range of these wells (154° to 190° C.) varies from 2 to 4 pounds per square inch for every degree Centigrade, the final agreement appears satisfactory. Well No. 6 developed a pressure of 240 pounds not long after it was first closed. Fearing that steam under pressures of this magnitude would force its way outside the casing and ruin the well, the engineer gave orders to keep it open, and during the several weeks of our stay at The Geysers it was discharging almost constantly through a 4-inch outlet pipe. Probably it is this circumstance that is responsible for the wider variations between p′ (the total pressure in the well) and p″ (the pressure of saturated steam at the temperature read) throughout the time of the tests than we find in the other wells.

When the figures in table 7 are examined in detail, it will be found that in Well 2 pressures and temperatures corresponded pretty closely from the first with those of saturated steam, the average deviation in pressure amounting to 1.6 per cent of the latter. All but one of the differences—the last—are negative.

In Well 1 the pressure remained nearly constant while the temperature slowly rose, finally reaching a point where the pressure approximated to that of saturated steam within 1.7 per cent.

After Well 4 was closed the pressure lagged for several days, but during the last three the pressure deviated from that of saturated steam by an average difference of 1.2 per cent only.

Similar to Well 4 was the behavior of Well 5; there was a high negative difference in pressure at first, falling after one day to an average of 3.8 per cent for a period of ten days and reaching on June 21 a limit of 0.6 per cent. On the following recorded date, June 26, the well being partially open, both temperature and pressure had fallen markedly. Most of the differences here are positive.

The history of No. 6 differs from that of all the other wells in that it was discharging throughout the time of the tests, and here the pressure was below that of saturated steam in every test, much lower during the first seven days and on the average 5.5 per cent lower during the last three. All the differences are negative. As the negative differences signify that the pressure read was lower than that of saturated steam for the recorded temperature, the steam must be *superheated* wherever such differences are found. Immediately after the wells are closed, the deviations are always in this direction. Wells 1 and 2 were generally kept closed during the summer of 1925 and they probably had not been recently opened. This seems to mean that the steam as it rises from the depths is superheated and becomes saturated only after it has stood under pressure in the wells—probably because of the condensation of a portion of the steam. Other observations confirm the truth of this hypothesis. In the record of a day's visit to The Geysers in 1922 when the first well (No. 1) had reached a depth of 150 feet, we find that the temperature 3 feet down was 109° C.; the true temperature was probably higher, for the thermometer, graduated to only 110° C., was left in but a moment. This was not a sporadic instance; a similar observation was made in 1924 at the top of Well 3 (p. 83), then 100 feet in depth, when the temperature 9 inches below the top of the casing read 111° C.[1] When the evidence is taken in its entirety the steam of Well 1, like all the rest, appears also to be originally superheated.

The final differences in pressure in the closed wells, as previously remarked, are invariably positive. Though too small to be stressed, they are reasonably accounted for both by the fact that the temperature readings are probably all a trifle low (p. 60) and by the fact that the steam is accompanied by small amounts of gas which would naturally raise the pressure above that of saturated steam.

Some details of the tests are still puzzling; the behavior of Well 4 when discharging at atmospheric pressure and the behavior of Well 1 in the beginning are anomalous. A system of piping with less metal exposed at the surface, less horizontal pipe especially, would no doubt have been an advantage, and more tests in more wells and under a wider range of conditions would certainly have been helpful. Still, the facts as they stand show clearly that if the wells are kept closed the steam finally reaches a pressure which corresponds to that of saturated steam at the temperature read at the top of the well, and what is of greater interest to the geologist, they show that the steam is originally superheated. Mr. Galloway says (personal letter of March 6, 1926) of some later temperature measurements of his own:

> "The temperatures, which I took of the steam-wells at The Geysers, were taken when the wells were discharging. At that time the temperatures seemed to correspond closely to that of saturated steam. Some later tests made this year indicate from 15° to 25° of superheat."

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[1] Later temperature measurements at the top of the *deeper* wells, when the valves were wide open, gave much higher readings (pp. 83 and 84).

CHARACTERISTICS OF SUBTERRANEAN STEAM IN OTHER LOCALITIES

But this is not the full extent of our knowledge concerning subterranean steam; many observations and measurements of its temperature and pressure in other places are also on record. De Stefani[1] states that the pressure of the steam in the older and shallower Tuscan wells, as measured by a manometer, ranges from 1.5 to 1.75 atmospheres as a rule, but at a maximum reaches as high as 9 atmospheres. Nasini,[2] commenting on these measurements, says that the pressures in the stronger wells, being difficult to measure, were merely estimated from the temperature on the assumption that the steam was saturated. When later on the pressures came to be actually measured, wide discrepancies were revealed, as may be seen from the following data:

Fumarole	t	p (found)	p cal. from t
Foro di piazzi anna	162°	3.0 at. absol.	6.4 at.
Foro forte	162	2.5	6.4
Foro della Venella	150	4.0	4.7

The figures show that the steam is superheated as Nasini pointed out. The steam from these older wells was utilized for the concentration of solutions in the preparation of boric acid and other chemicals. Since then the new Tuscan power wells have been developed and measurements of the temperature and pressure in them, according to recent statements of Ginori Conti,[3] confirm the earlier assertions of Nasini. Most of the pressure measurements at Larderello appear to have been made when the steam was discharging; whether any of them are comparable to those made at The Geysers where observations were made on wells which had been kept closed for a week or more, the statements are not sufficiently detailed to make clear.

These are the only places in the world where the pressures of natural steam are known to have been actually measured, but observations have been made elsewhere which, though less direct, are almost equally convincing. Many fumaroles in the Katmai region, Alaska, must emit superheated steam, for in 1919 lead and even zinc melted in the hottest ones[4] within a few feet of the surface and less frequently within a few inches, yet the steam was often escaping

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[1] I soffioni boraciferi della Tuscana. Memorie della Società Geografica Italiana, VI, pt. 2, p. 410, 1897.

[2] I soffioni boraciferi, e la industria dell' acido borico in Tuscana, Rome, 1907.

[3] The natural steam power plant of Larderello, page 8, Firenze, 1924.

[4] The maximum temperature was 645° C., while 13 other temperatures were above the critical temperature of water where the term "saturated steam" ceases to have any meaning. (Allen and Zies.)

rather quietly, sometimes under considerable pressure but never with the manifestations of potential pressure (noise and velocity) characteristic of much cooler fumaroles in that locality.

Fumaroles have been found by the authors in the Lassen National Park and other places emitting steam at temperatures ranging from 5° C. to 50° C. above the boiling point of water for the locality. While the noise of escaping steam was always indicative of excess pressure inside the vent, the temperatures were taken so close to the surface (usually within a foot or two, sometimes much less) that it is incredible that the steam was not superheated, at least in the hottest fumaroles. True, many fumaroles at Katmai and elsewhere emit steam at about the temperature of boiling water for the atmospheric pressure, a phenomenon readily explained on the assumption that they are affected by ground water, but the facts so far as they go indicate that the steam is originally superheated.

NON-CONDENSABLE GASES IN THE STEAM

Certain gases accompany the natural steam from the wells of California, as one discovers when the steam is condensed under proper conditions. To get a sample of the gases, the outlet pipe of the well to be tested was tapped with a drill, generally close to the casing, and a ⅜-inch pipe carrying a small needle-valve was then fitted into the drill-hole so that a sample of steam could be drawn off while the steam flow was under control. A piece of quarter-inch (inside diameter) glazed Berlin porcelain tubing, several feet in length, was then attached to the outlet of the needle-valve with a heavy-walled flexible rubber connection tightly wired on, and to the open end of the tube was attached a short right-angle of glass with the free end turned upward. The latter was then held down in a bucket of water and the steam turned on. When the water was boiling-hot or nearly so a gas-collecting tube was filled with it and the gas was collected by displacement in the usual way.[1]

To determine the amount of the other gases which accompany the steam, a suitable amount of the latter is condensed and its volume determined while the gases which it contains are caught and measured. For the exigencies of field work it will be obvious that advantage lies with apparatus of maximum simplicity consistent with reasonable accuracy. The apparatus used in the present case (fig. 28) consisted of an air-cooled tube, water condenser and metal aspirator joined in series. The first was made up of several 3-foot lengths of quarter-inch glazed Berlin porcelain tubes all tightly connected together with heavy-walled flexible rubber tubing, the whole joining the outlet of the needle valve to the condenser. The condenser was an ordinary

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[1] Day and Allen, op. cit., p. 123.

Fig. 28—Field equipment for determining gases accompanying steam at Well No. 2. 1925.

pyrex flask of 700 c.c. capacity, with stopper, inlet and outlet tubes like a wash bottle. Then followed a pyrex cylinder of 125 c.c. capacity, fitted in the same way and joined to the condenser as guard. The flask and cylinder were mounted on a suitable stand with wooden base so that either the cylinder or both cylinder and flask could be cooled by a dish of water. By a small rubber tube several feet in length the cylinder was connected to the top of the aspirator (capacity 12 liters) through a one-hole stopper. To prevent any air leaking up into the outlet tube of the aspirator a quarter-inch copper tube about 2 feet in length was connected to the outlet in vertical position. All the connections and the stopper of the condenser were tightly wired (fig. 29).

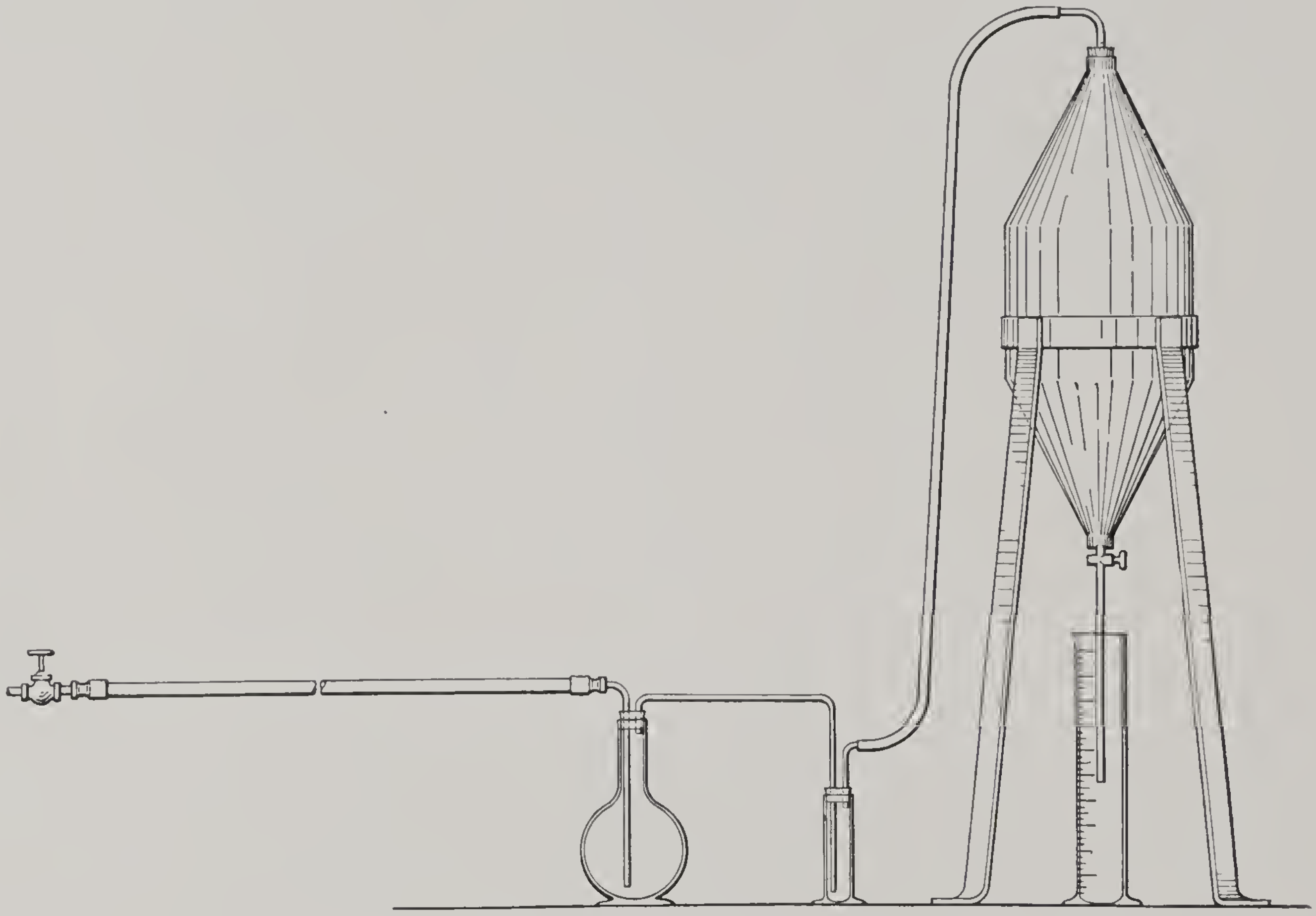

Fig. 29—Sketch of apparatus for determining ratio of gases to steam.

In carrying out a determination the aspirator and its outlet were filled with water, and to insure condensation of the steam at the start a small amount of water, about 35 c.c. in all, was poured into condenser and guard cylinder. A one-liter glass graduate (protected by a special rubber casing) was then set under the outlet of the aspirator, the stop-cock of the latter was opened and steam cautiously let in by the needle-valve. The steam condenses in flask and cylinder; the uncondensed gas together with the air in the apparatus passes on and is caught in the aspirator, while the water displaced in the latter flows into the graduate. As the graduate fills, the flow is stopped for a moment while the volume of water is read and recorded, after which the water is thrown out and the operation continued. To drive out the *soluble* gases as far as possible from the condensed steam, the

Table 8.—*Volume percentage of non-condensable gases which accompany steam at The Geysers, Sonoma County, California, including data.*

Place	Date	t in C°.	p in mm. of Hg	p′ = p corrected	t′ b.p. of water at barom. pressure	Vol. gas in liters at p′ and t	Vol. gas at t′ and p	Vol. water condensed in c.c.	Temp. condensed water C°.	Weight condensed water in grams	Vol. steam at p and t′ in liters	Percentage by volume of gas
Safety Valve..	1925 May 28	21	720	688	98.5	6.72	8.12	499	45	494	867.96	0.93
		21.5	720	688	98.5	6.87	8.29	505	45	500	884.50	0.93
		21.5	719	688	98.5	7.22	8.72	551	50	545	957.56	0.90
Well 2........	May 29	18.5	715	690	98.3	9.12	11.20	505	45	500	884.50	1.25
	June 1	13.5	715	694	98.3	9.04	11.38	518	45	513	907.50	1.24
Well 1........		24	712	681	98.2	9.10	10.87	331	55	326	578.65	1.84
		23	713	683	98.2	9.22	11.08	319	60	314	557.35	1.95
Steamboat....	June 3	19.5	714	681	98.3	5.60	6.78	513	55	505	893.35	0.75
		20.5	712	679	98.2	5.86	7.07	545	55	537	953.18	0.74
Well 4........	June 4	20.5	712	687	98.2	9.93	12.12	407	50	402	713.55	1.67
		18.0	711	690	98.2	9.94	12.28	426	55	420	745.50	1.62
Well 6........	June 13	30	709	665	98.1	6.82	7.84	472	65	463	824.60	0.95
	15	24	715	680	98.3	6.86	8.15	444	60	437	773.05	1.04
		27.5	715	675	98.3	6.87	8.01	463	70	453	801.32	0.99
Well 5........	16	25	715	678	98.3	7.10	8.39	448	70	438	774.82	1.07
		25	716	679	98.3	7.11	8.40	437	50	432	764.20	1.09

temperature of the water in the condenser is permitted to reach about 70° C., while the cylinder is kept cool to condense the vapor. These precautions apply chiefly to the carbon dioxide; the hydrogen sulphide and ammonia form only a small percentage of the total gases and both are determined later in separate tests. As to the carbon dioxide, the amount of it dissolved in the water of the guard cylinder is unimportant since the volume of the water is only 50 c.c. or less, while that of the gas reaches 5 to 10 liters. Furthermore the solution of carbon dioxide in the water of the aspirator need not be feared as the gas does not bubble through it and remains in contact with it but a half hour. Even if 10 per cent of the carbon dioxide were thus dissolved, the total error in the percentage of the uncondensed gases would, in the most extreme case, amount to less than 0.15 per cent of the total steam and gas mixture.

The volume of condensed water, amounting to several hundred cubic centimeters was also quite sufficient to insure a satisfactory determination of the steam. During a test, the aspirator was shielded from sun and wind by a large canvas sail, and a sensitive thermometer resting against the aspirator was read several times in the course of each test to determine the approximate temperature of the gas, while the water was kept as nearly as possible at the temperature of the air. Proper corrections of course were made for air displaced by water in the condenser and for reduced pressure in the aspirator. The condensed water was measured as accurately as feasible under field conditions with the 100 c.c. graduate.

The last column in table 8 gives the percentage by volume of the uncondensed gases (CO_2, N_2, CH_4, etc.) in the mixture of gas and steam. The results for different wells vary from 0.75 per cent to 1.95 per cent by volume, or from 1.33 to 3.35 per cent by weight. The amount is of some importance industrially since steam turbines will be used in the generation of power, and with them of course the more complete the condensation of steam, the greater the power developed. In this respect the steam at The Geysers has the advantage over that in Tuscany, for the latter, according to Nasini, contains from 3 to 5 per cent by weight of non-condensable gases.

ANALYSIS OF THE NON-CONDENSABLE GASES

Gases from steam-wells, springs and fumaroles were collected and analyzed so that the results might be correlated with other data. A method for the collection of gases from hot springs has already been described by the authors.[1] Fumarole gases can be collected free from air only when the flow of gas is strong. The method adopted here was air displacement combined with steam condensation. The apparatus

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[1] Day and Allen, p. 123.

used was the same which served in the determination of steam (p. 66); the gas tube open at both ends was simply connected into the train between the condenser guard and the aspirator. Measurements were of course dispensed with. The only fumarole gas analyzed contains less nitrogen than any other gas sample (see table 9) showing clearly that air was completely eliminated in its collection.

TABLE 9.—*Gases from wells, springs, and fumaroles at The Geysers, and Little Geysers, Sonoma County, California.*

Locality	CO_2	O_2	CO	H_2	CH_4	N_2+A	H_2S	Sum
Well No. 1	64.40	none	none	14.90	15.50	3.60	1.60	100.00
No. 2	61.30	none	......	17.05	16.45	3.80	1.40	100.00
No. 4	62.45	none	......	16.65	15.90	3.45	1.60	100.05
No. 5	65.10	none	none	14.60	15.25	3.20	1.90	100.05
No. 6	65.20	none	none	14.65	15.40	3.45	1.35	100.05
Steamboat Fumarole	67.45	none	none	12.75	14.30	2.85	2.70	100.05
Tea-kettle	65.35	none	none	14.00	15.65	3.95	1.20	100.15
Spring in Sulphur Creek	63.45	none	......	14.50	17.10	4.00	1.00	100.05
Spring 4 Geyser Creek	53.35	none	none	18.00	23.25	5.45	0.15	100.20
Witches' Cauldron Upper Pool	65.25	none	none	13.05	16.65	4.10	1.00	100.05
Ink Spring	62.00	none	none	14.60	18.55	3.75	1.25	100.15
Spring 3 Little Geysers[1]	77.30	0.05	none	2.20	14.15	6.35	none	100.05
Spring 4 Little Geysers	73.60	0.10	none	1.85	16.55	7.90	none	100.00
Spring 5 Little Geysers	75.50	0.20	none	1.75	12.70	$\begin{cases}9.80\\0.10\end{cases}$[2]	none	100.05

[1] Spring 3 is the largest pool on the small central plateau, the most active portion of the area (t = 87.3°). Springs 4 and 5 are at a somewhat lower level, a little southwest of the cabin and about 10 feet apart. No. 5 was filled with thin gray mud (t = 95.9°) and No. 4 was a shallow spring of the "frying-pan" type (t = 71.0°). The temperatures were taken at the time the gases were collected, June 24, 1926.

[2] Nitrogen and argon separately determined.

The analytical methods[3] applied to these gases were the same as those used on the gases from the Lassen National Park, with certain modifications adapted to their peculiar composition. The lead peroxide method for hydrogen sulphide was compared with the iodometric method, which is doubtless the most accurate, though a separate sample is necessary where it is used. For reasons which have been discussed, it is still necessary to use the lead peroxide in the analysis of the other sample. Assuming the iodometric method to give exact results, the determinations by the use of the lead peroxide pellet are in error by 0.03 per cent to 0.28 per cent, averaging 0.12 per cent—practically all positive.

When the high percentage of combustible constituents in the gases from The Geysers was discovered, the procedure was modified by the introduction of another pipette holding an alkaline solution of colloïdal palladium into the train of the apparatus, a solution used for the absorption of hydrogen. This excellent method of Paal and Hart-

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[3] Day and Allen, op. cit. p. 124.

mann[1] deserves high praise. Duplicate determinations in our experience generally agree exactly, and never vary more than 0.05 per cent. It greatly simplifies the problem of the determination of the hydrocarbons; its only drawback seemingly is that it works slowly. An hour was allowed in the absorption of these comparatively high percentages.

Ethane has been reported in the gases from the steam-wells, but the close agreement, when the hydrogen is first removed, between the combustion data on the one hand and the amount of gas after the removal of hydrogen, less the nitrogen, on the other, proves beyond question that there is in none of these gases any appreciable amount of any hydrocarbon besides methane. For the complete combustion of methane the following details were found useful. The residue which contains the hydrocarbons having first been driven into the potash pipette, pure electrolytic oxygen in amounts varying from 35 c.c. to 50 c.c. is drawn into the burette and measured, then driven over into the combustion pipette. When the wire in the latter has been heated to incandescence, the combustible gas is passed slowly in and afterward drawn back and forth several times. The contraction is then measured and the carbon dioxide absorbed. Further combustion may then be effected with the residue. When the contraction has again been measured and the carbon dioxide absorbed as before, about half the residue is left in the combustion pipette while the remaining portion is measured. The latter is then entirely deprived of its oxygen and the nitrogenous residue is used to displace all the methane in the capillaries, which finally is brought to combustion with the remaining oxygen.

At last the oxygen is entirely removed, and from the nitrogen left is subtracted any nitrogen which the original oxygen may have contained.

COMPOSITION OF THE GASES

These gases are sharply distinguished from those of Lassen National Park by their lower percentage of carbon dioxide (though this gas is still present in large excess) and by their unusually high percentages of hydrogen and marsh gas (table 9). Many springs elsewhere are characterized by very large amounts of methane in their gases (almost certainly of secondary origin) and there are some hot-spring gases, notably many from Iceland, which are high in hydrogen, but rarely do both constituents occur together in large amounts.[2]

Considering together the gases from the steam-wells and from the Steamboat Fumarole as least modified by surface influences, we find (table 9) that the carbon dioxide varies from 61.3 per cent to 67.4 per cent, averaging 64.3 per cent. Hydrogen varies from 12.75 per

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[1] Ber. Chem. Gesel., 43, 243, 1910.

[2] Jour. Franklin Inst., 193, p. 68, 1922.

cent to 17.05, with a mean of 15.1 per cent. Methane varies from 14.30 per cent to 16.45 per cent, with a mean of 15.6 per cent, and nitrogen varies from 2.85 to 3.80 per cent, averaging 3.4 per cent. Oxygen and carbon monoxide within the limits of error are absent.

The smaller amounts of hydrogen sulphide as compared to those determined by absorption in the field and recorded in the next section of this paper are to be attributed to the method of collection which, though sound in principle, proved faulty in practice. The water over which they were collected turned dark in the process and presumably contained iron which retained a part of the sulphur.[1] The results obtained by absorption of this gas with caustic soda are considerably higher and doubtless more accurate (p. 73). On the other hand the amounts of the hydrogen sulphide found in the spring gases presumably represent the proportions which actually escape from the springs. Abundant evidence points to the oxidation of much of the sulphur by air and a part of the residual nitrogen from this air is doubtless found with the gases, as the quantity of nitrogen in the spring gases is almost always higher than it is in the steam-wells. In the gases of The Little Geysers the relatively high percentages of nitrogen are quite in accord with the absence of hydrogen sulphide. For the very much lower percentages of hydrogen in The Little Geysers we have as yet no explanation.

Since certain constituents, notably water and carbon dioxide, are invariably present, we infer that they are magmatic, though even these may be augmented by further additions from secondary sources. Gases from fumaroles, hot springs and craters are liable to contain extraneous matter derived from the terranes they traverse just as igneous rocks may contain secondary material with which the original substance has been melted and incorporated. On the other hand the gases directly derived from igneous rocks are probably only a fraction of the original quantity and do not necessarily represent the original proportions, indeed, some constituents may have vanished entirely.

It would be very interesting if we could trace the gases, magmatic or otherwise, to their original sources. It is not inconceivable that we may eventually be able to predict from the composition of the volcanic gases which arise in a given locality the nature of the inaccessible magma which lies beneath. In any event we need to know the quantities of the chemically active gases carbon dioxide, the sulphur gases, and the halogens, when present, whether they are magmatic or not, since they play such an important part in the modification of the superficial strata through which they pass, in the formation of mineral waters and in the determination of salient features of the landscape.

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[1] The significance of this behavior was not realized at the time; the water taken was thought to be pure enough for the purpose.

SOLUBLE GASES

In the determination of the "soluble" gases which accompany the natural steam the apparatus described in the preceding section was employed.

HYDROGEN SULPHIDE

Hydrogen sulphide in many hot-spring and fumarole regions is the most active agent in rock decomposition, yet the amounts of it have been carefully determined in only a few localities. This gas will also have to be taken into account in the construction of a power plant, owing to its corrosive action on metals—whether accompanied by oxygen or not. It may be noted here that the determination of "non-condensable" gas doubtless includes *some* hydrogen sulphide, but since the *total amount* of the latter is only 0.03 per cent of all the gases including steam, the error is negligible. In the determination of hydrogen sulphide we measure the amount absorbed when a measured amount of steam is condensed. About 50 c.c. of solution containing 10 grams pure caustic soda is used for absorption, most of it being poured into the condenser, but a little reserved for the guard cylinder. Distilled water is required for the solution and it is needed also to wash out the entire apparatus at the beginning of each test. The flow of gas is carefully controlled by the needle-valve so that hydrogen sulphide will all be absorbed by the soda and only a negligible amount of water vapor will escape. Here as before, the guard cylinder especially should be kept cool. At the end of the experiment the total volume of the solution is measured and the temperature taken so that the weight of condensed steam can be found. The solution is poured into a clean bottle and to it are added the washings from condenser, cylinder and finally the cooling tube which is detached for the purpose. Before shipment the solution is boiled thoroughly with an excess of "dioxogen" to oxidize all the sulphur to sulphate, after which it is cooled, acidulated with hydrochloric acid to keep the stopper from sticking, and finally washed back into the bottle and sealed. On our return to the laboratory in Washington the whole solution was diluted to 1 liter and determinations made of the sulphur in aliquot parts. To avoid the serious error involved in precipitating barium sulphate from a solution relatively high in sodium chloride, each portion was evaporated to dryness on the water-bath, a little water added and the sodium chloride precipitated with an excess of concentrated hydrochloric acid solution. Finally the precipitated salt was filtered through a Gooch crucible and washed with successive small portions of concentrated hydrochloric acid. Several of the salt residues were dissolved separately and tested for sulphate. Less than a milligram of barium sulphate as a rule was obtained. The average amount is used in correction. After the hydrochloric acid was evapo-

TABLE 10.—*Volume percentages of hydrogen sulphide accompanying steam in steam-wells and fumaroles at The Geysers, Sonoma County California.*

Place	Date	t in C°	p in mm. Hg	Water condensed in c.c.	Temp. of water in C°	Weight of water in grams	$BaSO_4$ found in grams	H_2S in grams equiv. to $BaSO_4$	Grams of H_2S per kilo of steam	H_2S at p and t in liters	Vol. of 1 kilo of steam at p and t in liters	Vol. percentage of H_2S
Safety Valve..	1925 June 3	98.2	713	290	50	286.5	1.359	0.1985	0.693	0.659	1775	0.037
Steamboat....	4	98.3	714	330	50	326	1.197	0.1748	0.536	0.510	1770	0.029
Well 1.......	2	98.2	713	385	50	380.5	1.597	0.2492	0.655	0.623	1775	0.034
Well 2.......	2	98.2	713	305	....	301.5	1.204	0.2390	0.792	0.754	1775	0.042
Well 4.......	5	98.2	713	329	45	325.7	1.347	0.2042	0.627	0.597	1775	0.033
Well 5.......	16	98.3	715	295	45	292	1.334	0.1947	0.667	0.633	1770	0.035
Well 6.......	19	98.4	718	323	45	319.8	1.512	0.2208	0.690	0.653	1763	0.037

TABLE 11.—*Volume percentages of ammonia accompanying steam in steam-wells and fumaroles at The Geysers, Sonoma County, California.*

Place	Date	t in C°	p in mm. Hg	Water condensed in c.c.	Temp. of condensed water C°	Weight of water in grams	NH_3 found in grams	Grams of NH_3 per kilo of steam	Vol. of NH_3 in liters at p and t	Vol. in liters of 1 kilo of steam at p and t	Vol. percentage of NH_3
Safety Valve....	1925 June 3	98.2	713	230	30	229	0.0435	0.190	0.362	1775	0.020
Steamboat......	4	98.3	714	180	40	178.5	0.0325	0.182	0.346	1770	0.019
Well 1..........	2	98.3	714	276	30	274.9	0.0649	0.236	0.449	1770	0.025
Well 2..........	2	98.2	713	264	60	259.5	0.0570	0.220	0.419	1775	0.023
Well 5..........	16	98.3	715	234	50	231.2	0.0395	0.171	0.325	1770	0.018
Well 6..........	13	98.1	709	177	45	175.2	0.0298	0.170	0.325	1781	0.018

rated from the main solution the sulphate was determined as usual. In table 10 are recorded the essential field and laboratory data, and the hydrogen sulphide is computed in grams per kilo of steam and also in volume percentage, that is, the volume of gas at the temperature and pressure of boiling water at the time and place, divided by the total volume of both gas and steam under the same conditions.[1] The natural fumaroles will be seen to contain similar amounts of hydrogen sulphide as the steam-wells.

AMMONIA

Inasmuch as ammonium is more abundant in the springs than are any of the metals, it was considered worth while to determine it in the emanation from the wells and fumaroles. The same apparatus was employed as that used for hydrogen sulphide. Instead of the caustic soda a measured volume of dilute sulphuric acid was used as the absorbent and to it a little methyl orange was added to indicate whether the amount of acid was sufficient for the safe retention of the ammonia. The data required of course were the amount of steam condensed and the amount of ammonia absorbed at the same time. Thus we obtain the weight of ammonia associated with a kilogram of steam. In computing the volume percentage[2] it will be found that the neglect of the "insoluble" or uncondensed gases affects the result not more than one unit in the third decimal place (0.001 per cent). To determine the ammonia the contents of the condenser and guard cylinder and the washings from the whole apparatus were poured into a bottle, sealed and shipped home. The solution was eventually diluted to one liter and aliquot parts were distilled with soda, the ammonia caught in a measured amount of standard acid and titrated with standard alkali. Table 11 shows that the results are reasonably uniform over the area and of the same order of magnitude in the natural fumaroles as in the steam wells.

The question of combination in wells and fumaroles of the gases, ammonia and hydrogen sulphide, can be answered from the experiments of Isambert,[3] who proved years ago that a mixture of the two gases obeys the gas laws at temperatures between 35° and 40° C. and pressures varying from 720 mm. to 1030 mm. $\left(\frac{P_oV_o}{P\,V} = 1.007 \text{ to } 1.008\right)$, just as a mechanical mixture of the gases ought to do, whereas if combination occurred a contraction out of proportion to pressure would have resulted. He also found that when the gases were brought into contact at various pressures and temperatures between 27° and 132° C.

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[1] The expansion of both steam and gas from the boiling point of water to the temperature of well or fumarole was of course assumed to be the same.

[2] The computation assumes that ammonia gas and steam when mixed at high temperatures undergo no contraction. This may not be strictly correct.

[3] Comp. rend., 95, p. 1355, 1882.

TABLE 12.—*Amounts of gases in steam from steam-wells at The Geysers, Sonoma County, California.*

Place	Non-condensable gases			Soluble gases					
	Date	Percentage by volume	Percentage by weight	Date	Hydrogen sulphide		Ammonia		$\frac{\text{Vol. } H_2S}{\text{Vol. } NH_3}$
					Grams per kilo of steam	Percentage by volume	Grams per kilo of steam	Percentage by volume	
	1925			1925					
Well 1	June 1	1.84	3.16						
		1.95	3.35	June 2	0.655	0.034	0.236	0.025	1.36
Well 2	May 29	1.25	2.08						
	June 1	1.24	2.05	June 2	.792	.042	.220	.023	1.83
Well 4	June 4	1.62	2.73						
		1.67	2.81	June 5	.627	.033	....	....	....
Well 5	June 16	1.07	1.87						
		1.09	1.90	June 16	.667	.035	.171	.018	1.95
Well 6	June 13	0.95	1.64	June 19					
	15	1.00	1.73	and					
	15	1.04	1.82	June 13	.690	.037	.170	.018	2.06
Safety Valve Fumarole	May 28	0.90	....						
		0.93	....						
		0.93	....	June 3	.693	.037	.190	.020	1.85
Steamboat Fumarole	June 3	0.74	1.33						
		0.75	1.36	June 4	.536	.029	.182	.019	1.53

there was no heat evolved unless there was condensation, in which case the heat effect was the same as the heat of formation of the salt from its gaseous components. The dissociation of the salt is therefore practically complete under conditions far less favorable than those of the steam wells and fumaroles where the temperatures are much higher and the partial pressures of the components, ammonia and hydrogen sulphide, insignificant.

The components of ammonium acid carbonate (NH_4HCO_3) are also found in the steam. The dissociation of this salt has not, apparently, been worked out, but like other ammonium salts it is known to be greatly affected by water vapor, and despite the more favorable partial pressures than in the case just considered, it is doubtful whether any of the compound exists at these relatively high temperatures.

BORIC ACID

The steam from two of the wells and from two natural fumaroles was tested for boric acid by the method used for hydrogen sulphide; a measured amount of steam was condensed while the boric acid associated with it was absorbed by caustic soda. The solution was sealed and shipped to Washington where subsequently the boric acid in an aliquot part was determined. All four samples were thus examined but unfortunately the notebook containing the amount of steam condensed in each case was lost. It is therefore impossible to give exact figures, but it is certain that the amount of boric acid in these samples could not have been more than 20 to 40 parts per million by weight.

SUMMARY OF GAS ANALYSES

For convenience in comparison, the percentages of non-condensable gases as well as the percentages of the highly soluble constituents in the various natural mixtures of steam and gas are summarized in table 12. By combining these data with those of table 9 we get the complete analyses of all but one[1] of the gases from wells and fumaroles. The results are expressed in table 13.

TABLE 13.—*Complete analyses of several volcanic gases from The Geysers, California. Computed*[2] *from the data in tables 9 and 12.*

Place	H_2O	CO_2	H_2	CH_4	N_2+A	H_2S	NH_3	Sum
Well 1.	98.045	1.242	0.287	0.299	0.069	0.033	0.025	100.000
2.	98.686	.777	.216	.208	.048	.042	.023	100.000
5.	98.869	.716	.160	.167	.035	.035	.018	100.000
6.	98.946	.661	.148	.156	.034	.037	.018	100.000
Steamboat Fumarole.	99.202	.520	.098	.110	.022	.029	.019	100.000

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[1] The sulphur determination in the gas from Well 4 was vitiated by some coarse error.

[2] These figures are given to thousandths of a per cent regardless of experimental error in the principal constituents, the better to express the relationship to the lower constituents.

COMPARISON OF AMOUNTS OF SULPHUR AND AMMONIA IN GASES AND SPRINGS

If we admit that there is no other source of sulphur and ammonia in the spring waters than the volcanic gases, a fact which seems well established, a comparison of the composition of gases and waters may lead to some interesting inferences. In table 14 the amounts of ammonium and the sulphate radical in the spring waters are copied from table 3, and from them the equivalent amounts of ammonia and hydrogen sulphide in terms of volume and weight per kilo (approximately) of water are computed. Among the acid springs are two, the "Arsenic" and the "Lemonade" springs, which carry amounts of ammonia and sulphur similar to those in the gases. All the rest of the acid springs contain much more. Among the alkaline springs, the Ink Spring[1] is exceptional in containing as much sulphur per unit weight of water as the original gases and still more ammonia, but all the other alkaline springs show a marked diminution in both constituents. Despite the rather limited number of figures at our disposal, the increase of sulphur and ammonia in the acid springs and the decrease in the alkaline springs is a fact too striking and too consistent to be without significance. It seems to denote *concentration* on the one hand and *dilution* on the other.[2]

PROCESSES OF SPRING FORMATION

When we attempt, on the basis of evidence, to picture to ourselves the changes physical and chemical, which the ground water and the gases pass through from the time the latter reach the upper strata of the ground till both find an outlet in the basin of some spring, we see first the condensation of a part of the steam and a retention of a portion of the gases in the zone of ground water which extends over the area as a mantle of uneven thickness, but on the whole quite thin, reaching in some places nearer the surface than others but probably vanishing at comparatively shallow depths. The relative amounts of steam and ground water at any particular point, the rate at which the water percolates and the rate at which the steam rises will condition the temperature of the resulting hot water and the amount of gases retained by it. The rate of oxidation also will have a controlling influence, for the more sulphur is oxidized the less hydrogen sulphide will escape and the more ammonia will be held. The higher solubility of ammonia in water, especially where acid is present, no doubt accounts for the tendency in the ratio $\frac{H_2S}{NH_3}$ to decrease with time, as

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[1] This spring occurs on the other side of a high, narrow ridge about half a mile to the west of The Geysers, where local conditions underground may be somewhat different.

[2] A more recent survey of a large number of springs in the Norris Basin, Yellowstone Park, shows that there also with few exceptions the concentration of the SO_4 radical is *much* lower in the alkaline than it is in the acid springs.

Table 14.—*Ratio of hydrogen sulphide to ammonia in the volcanic gases as changed by losses and chemical action.*

Place	Wt. of NH_4 grams	Vol. of NH_3 at 0°C. and 760 mm. c.c.	Wt. of SO_4 grams	Vol. of H_2S at 0°C. and 760 mm. c.c.	$\frac{H_2S^1}{NH_3}$	Grams H_2S per kilo of steam	Grams NH_3 per kilo of steam
Devil's Kitchen	1.396	1732	5.714	1331	0.77	2.03	1.32
Bubbling Spring	.732	908	5.659	1318	1.45	2.00	.69
Liver Spring	.627	778	3.530	823	1.06	1.25	.59
Poison Spring	.510	633	2.762	644	1.02	.98	.48
Spring below Devil's Kitchen	1.270	1575	4.783	1114	.71	1.70	1.20
Arsenic Spring	.173	215	1.487	347	1.61	.53	.16
Lemonade Spring	.267	331	2.020	471	1.42	.72	.25
Witches' Cauldron (Lower)	.111	139	.763	178	1.28	.27	.10
Spring in Sulphur Creek	.100	124	.497	116	.94	.18	.09
Bath-house	.037	46	.280	65	1.41	.10	.03
Magnesia	.023	29	.236	55	1.90	.08	.02
Ink	.738	916	2.232	520	.57	.79	.70
Indian Mud	.163	202	.389	91	.45	.14	.15

[1] Same ratio in gases of wells (Table 12) varies from 1.36 to 2.06, averaging 1.8.

the results show it does (see table 14). Portions of all the gases will escape to the drier ground nearer the surface where the capillaries bring them into contact with atmospheric oxygen. Here oxidation should be most rapid, here more ammonia should be fixed, and where undecomposed rock still remains magnesium and other sulphates will be added to the mixture. The solution becomes more concentrated and portions of it, rising to the surface, crystallize in summer, but when the autumn rains come again the salts are dissolved and carried down into the underground circulation and eventually reach the springs.

In therapeutic character and impliedly in composition the various springs are supposed to exemplify great diversity—a belief reflected in their names. Variations in concentration there are, of course, and to some extent in the proportions of the elements, but the only significant distinction to be drawn is the one which divides the acid from the alkaline springs. It is true, however, in this particular locality, that differences in chemical character are intimately related to concentration, so that it will be well to follow the latter relation a little farther.

If the hypothesis just presented is a true one, springs which draw their supply from ground where no gases rise would be cold, or when a limited amount of gas and steam rises the springs would be warm and of low concentration. The presence or absence of abnormal temperatures and the differences in the growth of vegetation here and there in The Geysers area are matters dependent on the degree of permeability of the ground to volcanic gases, including steam. In spots where formerly there was little or no fumarole activity, boring has developed an ample flow of steam and other gases. The difference between such areas and the more active ones is due either to the absence of superficial cracks in the rock or to more or less obstruction of the cracks by rock detritus. The high concentrations of salts which are found in the acid springs are doubtless derived from ground readily permeable to volcanic gases and to air, and it is significant that all the acid springs except the two of lowest concentration are immediately contiguous to such ground. The process of concentration by evaporation may continue underground to some extent but it must be much less important there. In unusually hot weather, evaporation in the spring basins seems to reach a high figure, for at such times the water level drops suddenly in a very striking way, only to return again during the night or in a cooler interval following, although no rain falls, but this must obviously affect very nearly alike all springs exposed to the sun, whether acid or alkaline, and can have no bearing on the difference between them.

We have noticed that the alkaline springs are usually very low in mineral matter as compared with the acid springs—a fact which would indicate either dilution with surface water in the former or a source in ground where oxidation was limited (table 3). As a matter of fact four of the seven alkaline springs analyzed[1] occur in the edge of stream beds where they are obviously diluted by surface water when the stream is high, and perhaps in lesser degree at other times. Five of the springs have their temperatures maintained by steam jets rising in their very basins, and the presence of black sulphide in them is probably a direct consequence of precipitation by the hydrogen sulphide on the spot. A spring which is not too highly diluted by surface water may in this way be maintained at the boiling point. The other two alkaline springs, the Magnesia and the Bath-house springs, are of relatively low temperature (50° to 60° C.) and their occurrence at the foot of slopes, more or less covered with grass, weeds and bushes where there is but little indication of fumarole activity and where there can be little oxidation, seems to be connected in a perfectly logical way with the low concentration of the fumarole products we find in them.

The relation between concentration and the chemical character of the waters has been discussed before in a treatise on the hot springs of the Lassen National Park,[2] but it is of course highly desirable that observations of phenomena which are the result of complicated conditions, especially where the conditions are not subject to control, should not be confined to a single locality. At The Geysers it has been possible to pursue the subject somewhat farther, but the investigation has led to identical conclusions, namely, that the alkaline springs here result from the chemical action of waters which are acid nearer their source; that the acid water percolating through the ground gradually decomposes the rocks it encounters, and *if the process continues long enough* the acid will be converted into neutral sulphates, and that subsequent to this the chemical character of the process changes; the action of carbonic acid and hydrogen sulphide also, if any of the latter remains (or if any is later absorbed by the water without oxidation), now becomes dominant, with the result that bicarbonates and carbonates, sulphides and probably hydrosulphides are carried into solution, giving to the water an alkaline character. This much can be safely stated from a knowledge of the chemical reactions between certain minerals and glasses on the one hand, and hot water containing the two mentioned gases on the other. But further knowledge of the process in its later stages is needed—what becomes of the iron, and especially the alumina in the rock, whether they form sericite, kaolin, or other minerals, and where they are deposited, are questions which remain undetermined.

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[1] A few other alkaline springs were discovered, most of them seepages issuing near the Bath-house spring whose waters in all probability are of the same character.

[2] Day and Allen, op. cit., p. 164.

There are other rational ways in which alkaline spring waters may originate. If the volcanic gases contain no sulphur or if the sulphur undergoes no oxidation, the waters will be alkaline from the first. Neither of these conditions, however, is fulfilled at The Geysers; the gases always contain sulphur, and the presence of sulphate in all the alkaline waters shows that oxidation must have occurred somewhere in the course of their underground movement.

That the sulphate may arise from the oxidation of sulphide or thiosulphate is a view not entirely shut out. There appears to be no convincing evidence that either of these reactions has ever been observed in alkaline solutions through the agency of air alone. Oxidation of thiosulphates to sulphates by fungi[1] under certain conditions and also by bacteria[2] are on record, but whether such reactions may occur under conditions prevailing in hot springs is another question. The concession that it does occur, however, has no important bearing on the question whether these alkaline springs are or are not of deep-seated origin; they have not the concentration that should belong to waters formed at any considerable depth, and the field evidence is all against that view. Neither is there any reason to believe that the acid waters were ever alkaline.

Low concentration, therefore, so far as it applies to the *sulphate* in alkaline springs, is satisfactorily accounted for in the foregoing, either by direct dilution of a water originally more highly mineralized or by the contribution of little mineral matter to the water in the first place. The low concentration of other constituents also, like silica, carbonate and bicarbonate, agrees well with the slower rate of action which would be predicted for a weak acid like carbonic acid as compared to the action of sulphuric acid on rocks.

While the alkaline springs of Iceland and the Yellowstone Park have been regarded by some able investigators as a subsequent phase in the development of springs which were formerly acid, the alkaline springs at The Geysers, like those in the Lassen National Park, are to be regarded as *contemporaneous* with the acid springs which occur in the same area. The facts indicate a change during the progress of the waters underground rather than a distinct period of development; in the vents where the waters emerge from the ground there is no reason to suppose that they were ever of a different character.

TEMPERATURE GRADIENT

No question is more vitally related to the genesis of hot springs than the rate at which the temperature of the ground rises from the surface downward. It is certainly much greater, at least in some localities, than geologists are aware of. In this respect drilling opera-

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[1] T. Matsumoto, Ann. Missouri Bot. Garden 8, 1-62, 1921.

[2] W. T. Lockett, Proc. Roy. Soc. London (B) 87, 441, 1914.

tions at The Geysers have been of great scientific importance. In 1924 work on Well 3, located near the extreme eastern border of the area, was in progress. A short 10-inch iron casing extended down but a few feet below the surface, leaving the remainder uncased. The well was open and discharging gases and steam. Twice we were able to measure temperatures here. They were taken with an armored maximum thermometer, reading in single degrees from 50° to 150° C. Temperature at the top (the bulb 9 inches below the top of the casing) was 111° C. increasing gradually to 126° at the bottom, which was then about 100 feet down. Boring operations were continued in the well until a depth of 154 feet had been reached, when a drop in temperature occurred which was attributed to an underground stream of water. In any event the temperature gradient was disturbed to such an extent that later measurements were inconsistent with the former ones. This well was drilled by the old churn-drill system. In May 1925 the well was still emitting steam and a thin spray of water which occasionally reached a height of 10 feet (fig. 30). The temperatures in Well 3, measured on May 26, 1925, were as follows:

Well 3.

Depth	Temperature
9 in.	99°C.
10 ft.	99
33	99
82	100
98	101
105	102
115	104
131	110.2
154	112.5

Well 6.

Date	Depth	Temperature
Mar. 24	30 ft.	164°C.
	250	173.5
25	50	159
	234	168
	320	170
	360	170
	422	170
	482 bottom	170

Well 8.

Date	Depth	Temperature
Mar. 25	top	150°C.
	610 ft.	162

Depths were measured from the top of the casing which projected about 3 feet above ground.

That the temperature gradient in Well 3 is not exceptional, may be seen from the measurements of Wells 6 and 8, made at our request in March 1926 by J. D. Grant and Delano Grant.

Another series of temperature measurements in *open* wells was made in June 1926 by one of the authors (Day). Nearly all the wells were then open as they had been left for several months for the purpose of determining in a rigorous fashion whether any diminution in steam supply would result. With the aid of the driller, Mr. Cooper, and his assistant, a temporary fall was rigged at Wells 2, 4 and 5.

Fig. 30—Well No. 3 as it appeared in 1925. Casing is coated with opal formed by evaporation of small amount of water constantly thrown out with steam.

At No. 8 the regular drill rigging was used. To the fall was attached a steel drill rod sharpened at the lower end, to which the armored thermometer was securely fastened so that it could be raised or lowered in the well. Measurements in Wells 2, 4 and 8 were entirely successful, but the rod was blown out of Well 5 by the steam and the thermometer broken. The measurements recorded below were made at the top of the wells mentioned, at the bottom of the casing and at the bottom of the well.

Well temperatures with steam flowing freely.

	Depth	Temperature
Well 2:		
Bottom of well	320 ft.	168.6°C.
Bottom of casing	130	167.5
Top of well	....	165.6
Well 4:		
Bottom of well	451	172.6
Bottom of casing	256	169
Top of well	....	163.4
Well 8:		
Bottom of well	636	157.2
Bottom of well (2d meas.)	636	156.6
Bottom of casing	160	153.9
Top of well	....	150

We have, therefore, three independent series of temperature measurements in open steam wells made by three different observers, all of which show a temperature gradient.

An effort was also made to measure the gradient in two of the closed wells. For actual tests we are indebted to Mr. Galloway, the engineer, and his aides, especially to Mr. Butler, who was in immediate charge of operations on the ground at the time. The tests were made on Well 5 with test-metals melting respectively at 600° F. (315° C.), 500° F. (270° C.) and 450° F. (232° C.). The test-metals in small chips were inclosed in very short lengths of 3/8-inch pipe capped at both ends. To make it possible to lower these metals into the well, the vertical steel outlet pipe (8 inches in diameter) was threaded at the top to fit a heavy conical cap, through the apex of which a small hole (1/16 to 1/8 inch) was drilled. A reel of steel wire 500 feet in length and about 1 mm. in diameter was unwound for a few yards and the free end pushed through the top of the cap after which the test-metals and their receptacles were attached. The cap was then screwed down and the valve of the well opened. The steam which escaped from the small bore-hole in the cap was hardly visible and offered no obstruction to the lowering of the metals. They were therefore dropped to a depth of 250 feet and held 15 minutes. When they were drawn up and the receptacles had been removed and opened, only one metal, that melting at 232°, was completely melted down—the other chips were intact. A test in the side pipe at the same time with the maximum thermometer showed a temperature of 185.5° C. at the top of the well (closed). Inside of 250 feet the temperatures therefore rose at least 46° C., but less than 85° C. In a second test the metals were lowered to the bottom, where they were kept 15 minutes. When removed it was found that neither of the other two metals had been affected. The temperature between 250 feet and 416 feet could not therefore have risen as much as 38°, and possibly not at all. Another trial at Well 4, in which a maximum thermometer was lowered in a similar way, was unfortunate; the pipe which inclosed it got caught—probably under a projecting rock in the wall of the well—and was lost. The operation as described appears easy, but the actual risk of getting burned which the workmen incurred was so great that we did not care to urge another attempt.

The tests at Well 5 show that no very high temperature is to be found at the bottom as the workmen had been inclined to believe; the drawing of the temper in the drill, which they observed, must have been due to local heating by friction.[1]

Wherever temperatures have been measured in deep holes of the earth's crust a gradient[2] has been found, whether the hole is filled with air or water. Even wells filled with rapidly escaping steam, as now appears, are no exception[3] to the rule. If a gradient is found where the steam is escaping it should not be surprising to find it more strongly marked when the well is closed. The condition of saturation which was discovered in the steam after the wells had been closed for some time is evidently confined to the top of the well where practically all the heat loss takes place and where, if anywhere, condensation of steam would be looked for. The water perhaps accumulates in the horizontal pipe attached to the casing; it can hardly drip down to any considerable depth without vaporizing, or the gage would show a higher pressure than it does, whereas if steam without water exists in the depths of the well superheating would be necessary in order to balance the pressure of the saturated steam at the top.

In its geological bearing, one of the most important facts that drilling operations at The Geysers has disclosed is that within a depth of 500 feet from the surface a rise of 130° to 165° C. is encountered.[4] This rise in temperature, to be sure, is not comparable to an ordinary earth gradient; it is due no doubt to ascending currents of steam and varies with the rate of the steam flow—an agency particularly effective in heating water. Whatever its ultimate source, we have here—even under natural conditions—a supply of heat abundantly adequate both in temperature and amount to account for all the hot springs in the vicinity, and there is obviously not the least necessity to assume

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[1] See N. L. Bowen and M. Aurousseau, Fusion of sedimentary rocks in drill holes, Bull. Geol. Soc. Amer., 34, 431, 1923.

[2] C. E. Van Orstrand, personal communication.

[3] The uniformity in temperature from top to bottom in the shallow wells of Hawaii may now be ascribed to the *saturated condition* of the steam.

[4] Reckoning from the variable surface temperature in the hot area itself.

that the springs consist of surface water which has been heated by descending to great depths, even if we accept the theory as otherwise satisfactory—a concession which is not warranted in the case before us.

CAUSE OF THE HEAT

Many causes for the heat of hot springs have been advanced by geologists. Waring, who has had wide opportunities for observation, mentions, in his well-known *Springs of California,* to the text of which the reader is referred, eleven cases where the water may derive its heat from hot rocks by *descending to great depths;* two cases where *chemical action* may be the cause of the heat, and seven instances where the heat may have originated in *earth movements* responsible for the alteration of sediments in which the springs occur. In more than fifty groups of hot springs, Waring mentions the *proximity of lavas or intrusives,* implying the possibility that they may still retain residual heat, while in a similar number of places he draws attention to the *association of hot springs with faults.* The last point is regarded by the writer as especially important, as a summary paragraph on temperature (op. cit. p. 24) makes clear. Waring there says:

> "Observations of the temperature in deep mines and deep borings indicate that in regions of comparatively uniform and undisturbed rock below the first 50 feet (in which the underground temperature is affected by seasonal variation in temperature of the air) the temperature increases at the rate of 1°F. for about each 50 or 60 feet of increase in depth. In favorable localities this increment may be safely assumed in estimating the depth from which the heated water rises. In the greater number of places where thermal springs issue, however, this increment is valueless as a basis for estimating the depth from which the water rises. The high temperatures of the water of most hot springs can usually be assigned to faults or displacements in the rock formations, to volcanic activity, or to chemical action rather than to normal increase of temperature with depth. The rocks along fault lines are probably heated considerably above a normal temperature by the great pressure and friction that have been produced. Water from deep sources moves upward along these zones and is additionally heated by contact with the heated rocks. In some areas of volcanic rocks there are probably masses below the surface that have not yet cooled to a normal temperature, and they heat water which comes near them. Chemical reactions—notably the oxidation of pyrite—liberate heat and may increase the temperature of underground water."

Other geologists have regarded radioactivity as a probable source of the heat, and finally economic geologists, or some of them, have inclined to the view that the water of hot springs may be very largely magmatic, bringing up its heat from the magma itself. The derivation of the heat supply of hot springs from radioactivity has been touched upon by the authors in a former treatment of this subject.[1] It was pointed out in that place that a high degree of radioactivity in mineral deposits bore no relation to local high temperatures, and two investigations of importance bearing directly on the point at issue

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[1] Day and Allen, op. cit., p. 150.

were instanced; an investigation by Schlundt and Moore in the Yellowstone Park and an investigation by Thorkelsson in Iceland, in both of which it had been concluded that radioactivity had no connection with the abnormal temperatures in those well-known hot-spring localities.

The notion that the high temperatures of springs and fumaroles is a consequence of the oxidation of pyrite may have arisen from the observation of the spontaneous combustion of coal in mines where the veins frequently carry considerable pyrite. However it may be in other places, at The Geysers there is positive evidence against the assumption; drilling has shown that the rock underlying the decomposed material at the surface contains only a small amount of pyrite —and that quite unoxidized. Samples of the rock from Well 2 taken from depths between 150 and 200 feet were examined by Wright and by Merwin. All were sandstone carrying a very little pyrite. An analysis of a sample from a depth of 150 feet is appended:

Sandstone from Well 2.

SiO_2	67.46
TiO_2	.44
Al_2O_3	15.34
Fe_2O_3	1.16
FeO	2.35
CaO	1.02
MgO	1.42
Na_2O	3.03
K_2O	2.65
H_2O (total)	3.26
P_2O_5	.11
FeS_2	1.93
	100.17

The pyrite in this sample amounted to 1.93 per cent and it was very bright. A microscopic analysis by Merwin disclosed in addition to pyrite only quartz and sericite. A sample of the rock blown out of Well 6 consisted of shaly sandstone also carrying a little pyrite (bright) and a veinlet of calcite. A sample from Well 4 was of similar character. A core taken from Well 5 at a depth of 230 feet was examined in thin section and found to be gabbro also containing a little pyrite. In a sample of chert from Well 8, pyrite was found in somewhat greater amount than usual and it was also dense and bright. These latter examinations were all made by Wright. In Well 3, J. D. Grant reported that no pyrite was found. While this work is not a systematic survey of the different wells from top to bottom, no observations have shown any considerable amount of pyrite anywhere and if a mass of it had been struck in any place it is inconceivable that a mineral of such distinctive properties should not have revealed itself either by its hardness or by its color, luster and density in the drillings as they were washed out.

In the Lassen Park where evidence from drilling was not available, the possibility of heat from chemical action was considered at some length and the conclusion was reached that neither the oxidation of pyrite nor the decomposition of lavas could be rapid enough to raise the temperature in any considerable degree.[1]

Waring, as we have seen, decides against the view that hot-spring waters generally derive their heat from hot rock by descending to great depth, though this theory is probably commonly held.[2] That the average earth gradient has no application in most hot-spring areas, as Waring believes, is confirmed so far as The Geysers is concerned by the facts discovered in drilling.

Against the general acceptance of the theory that the water of hot springs has been heated by descending to great depths is also the escape of volcanic gases in all the hot-spring districts yet observed by the authors, including some twenty-five groups altogether, and further study of the literature permits the conclusion that the presence of volcanic gases is the rule if not universal. When considered in its general aspects this occurrence of volcanic gases is of profound significance; it is the one thread logically connecting all phases of igneous activity, the cause alike of the volcanic explosions with their imposing steam clouds, the rise of lava in craters, the intense surface temperatures in some volcanic eruptions, the formation of fumaroles with their various characteristics, and finally of the heat of hot-spring waters and of the distinctive features in hot-spring areas. According to this theory the function of faults is to permit the escape of volcanic gases with their associated heat from the magma or batholith. What, otherwise, should be the significance of the association of *volcanoes,* as well as fumaroles and hot springs, with faults?

It is a known fact that all igneous rocks, even when quite unaltered, give off large volumes of gases, the chief of which is steam, when they are heated to high temperatures,[3] and it was Gautier[4] who first pointed out that these gases were of similar composition to the volcanic gases. Indeed it is a chemical necessity that the gases should escape if the rock is sufficiently hot, and a mode of escape is offered, as it should be, by the association with faults of sufficient depth.

The consequences of this view have been discussed in the earlier paper so often referred to, where it was shown that the condensation of steam by ground water furnished the most probable means for the transmission of heat from the depths; that the variable temperatures of many springs at different times of the year, the spouting of springs,

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[1] Day and Allen, op. cit., pp. 151–153.

[2] See C. E. Van Orstrand, Jour. Geol., 32, 194, 1924.

[3] R. T. Chamberlin, Gases in Rocks, Carnegie Inst., Wash. Pub. No. 106, 1908; Arthur L. Day and E. S. Shepherd, Water and Volcanic Activity, Bull. Geol. Soc. Am. 24, 573-606, 1913; E. S. Shepherd, The Analysis of Gases obtained from Volcanoes and from Rocks, J. Geol., 33, 289, 1925.

[4] Compt. rend., 132, 61, 189, and 932, 1901; 136, 16, 1903.

their transformation into fumaroles and vice versa, and finally the disappearance of springs and new outbreaks of thermal activity are all readily accounted for on the basis of this fundamental assumption.

ORIGIN OF STEAM AT THE GEYSERS

The hypothesis that hot springs are fed by ground water heated and augmented by magmatic steam which is condensed in the heating process was deduced in large measure from general considerations—the composition of rocks and their behavior on heating; rock decomposition with chemical reagents; and general physical relations of hot springs and fumaroles. A detailed field application of the idea had been possible only in the Lassen National Park where *superheated* steam had been actually found in only one place. When, therefore, the hot springs at The Geysers were found to be associated with a supply of hot steam generally distributed not far below ground, the discovery was naturally hailed as a confirmation of previous views. But of course it is realized that the magmatic origin of this steam can not command the assent of geologists until the new knowledge that has come to light in the development of the wells, and the tests made on them, has been carefully considered from this viewpoint.

Any satisfactory theory of its origin must take full account of the huge volume of the steam, its high temperature and pressure, and its superheated condition. When the mild character of the original surface activity at The Geysers is compared with the immense steam-flow of today the contrast is truly amazing—doubly so it must be to one who holds that the steam is derived entirely from ground water. Whatever previous views one may have had concerning hydrothermal activity, the facts brought to light in this field should convince him that the immediate origin of the steam lies at a very considerable depth. The steam-wells of California have been carried down to depths of nearly 650 feet, those of Tuscany to about the same depth, and while it can not be said that temperature is proportional to depth, the deeper a well is drilled in either locality the greater the steam-flow and the hotter the steam.

As to the situation in California, the more one ponders the question the more difficult it is to conceive that a body of ground water of any great magnitude can penetrate even to such depths as a few hundred feet. Where cracks or seams exist, water will doubtless penetrate if the steam pressure it encounters is not prohibitive, but the water must be much more copious than it is here to penetrate far in such seams without being again vaporized. It is conceded that the ground temperature at any point and level is not so great before drilling as afterwards, but it must be well above boiling at depths say of 100 feet, except in places where no perceptible amount of steam is rising; where steam can not find its way up, surely water can not find its way down! It is conceivable that ground water under sufficient head might penetrate to a considerable depth about the periphery of a body of hot rock and that a vaporized portion of it might be fed into the cracks of the rock, under pressure, but admitting that possibility the facts point to a surface configuration in no way adapted to such water storage and a body of ground water wholly inadequate to supply continuously such volumes of steam.

SUPERHEATED CONDITION OF THE STEAM

The matter of reconciling the superheated condition of the steam with the conception that it is continuously supplied by a store of ground water is fraught with some difficulty, which had perhaps best be left to the proponents of the theory. On the other hand, if the steam is derived from a magma it would necessarily be superheated at its source.

For readers unfamiliar with geology it may be said that the magma is the moulten fluid from which, in cooling, the igneous rocks are formed, and that it is supposed to differ from *flowing lava* only in its higher percentage of volatile matter. Even after it has become cold and solid, considerable quantities of the volcanic gases, the chief of which is steam, may still be driven out of it by heating again. The pitchstones—lava which has solidified as glass, and is therefore more like the original magma than are the crystalline igneous rocks—contain sometimes as much as 10 per cent by weight of water,[1] and we infer that the magma contained more, as it is hardly credible that some water was not lost while the magma was in the heated condition. Rocks which are formed from a magma by *slow cooling,* as they must be when formed at considerable depth in the crust of the earth, are entirely crystalline and these crystalline rocks contain little water, 0.5 per cent on the average; so that large bodies of magma buried at considerable depth in the earth's crust may be expected to give off large volumes of steam for a long period of time. The capacity of molten silicates to absorb steam, its release during the crystallization of the silicates and the pressures which may develop thereby are questions which have been experimentally studied by Morey,[2] by whose work our conceptions of the magma have been confirmed and extended. The magma is thus a solution, one important constituent of which is water, and the pressure of the steam it emits must be lowered by the mineral matter associated with it, as always happens when steam escapes from a solution. In short the steam must be superheated. But though superheated at the source, it may of course become saturated by a sufficient reduction of temperature or by a

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

[2] G. W. Morey, J. Wash. Acad. Sci., 12, 219, 1922; J. Geol., 32, 291–295, 1924.

sufficient reduction of both temperature and pressure in unequal degree. That a large reduction in temperature has occurred by the time the steam reaches the surface, assuming its magmatic origin, seems certain from what we know of the temperature at which steam is driven out of the igneous rocks and from the copious steam-flow developed by drilling. It is by no means improbable that a large reduction in pressure has also occurred. For the moment, however, we would fix attention on the fact that if the source of steam at The Geysers is magmatic, its large volume and its unsaturated condition are readily explained.

TRANSMISSION OF STEAM FROM ITS SOURCE TO THE SURFACE

The principal facts about the steam flow, that it may be developed by boring anywhere within the hot area, that it increases with depth but not regularly, that boring gives rise to steam wells which when closed stand at widely different pressures, and that each well after a period of discharge returns when closed again to its former pressure—all have been stated in the foregoing. Determinations of maximum pressure indicate that it is constant or nearly so in the same well. A long record for the oldest wells and the investigations described on pp. 59-63 support this statement. The facts show clearly that the rock is not equally pervious to steam in all directions, indeed they indicate that it is not permeable in any direction to an appreciable degree, for there is nothing in the overlying sediments except stratification which could transmit steam in one direction more readily than another, and while it is conceivable that stratified rocks suitably tilted might transmit steam vertically with special facility, they must inevitably transmit it more readily in one horizontal direction, which is not the case here. The ordinary view that the steam reaches the surface through cracks explains the facts in a measure. That the cracks can not be open to any appreciable width at least throughout their whole depth must be obvious. The fault if it exists, as we assume, instead of being an unimpeded passage to the depths is probably a zone or band of rock shattered by an irregular system of seams long enough and narrow enough to interpose a high resistance to the passage of gases. Such an hypothesis would explain the difference in activity which is found in different fumarole regions. Thus the greater steam flow and much higher temperatures in the natural fumaroles of Tuscany than in those at The Geysers should be due to the slighter impediment which the steam in the former locality encounters in its ascent to the surface. It may possibly be affected also by a higher steam pressure at the source, but a variation in this factor alone could not explain the facts, since drilling at The Geysers makes apparently a far greater difference than it does in Tuscany. The irregularities in thermal activity in different parts of the same area may be accounted for in the same way.

On the other hand while the hypothesis serves well in explaining the *increase of steam flow* with depth it does not satisfactorily explain the *increase of pressure,* for the figures (pp. 56-57) prove that wells which emit the greatest quantities of steam do not necessarily possess the highest pressure.

The increase of pressure everywhere with depth shows clearly that at the source, whatever and wherever that may be, the pressure must be much higher than it is in any of the wells. Within the realm of laboratory experience, to be sure, two gas reservoirs connected by even the finest capillaries can not remain for any length of time at very different pressures, but where gases are forced to traverse fine tortuous seams for perhaps thousands of feet the conditions obviously transcend any with which we are familiar.

DURATION OF THE WELLS

Very interesting scientifically and obviously important from the industrial viewpoint is the question how long these wells will continue to flow, and whether they will maintain their pressure unabated for any considerable time. The data on this point are confessedly inadequate to constitute a safe basis for prophecy. Ginori Conti says of the Tuscan fumaroles that "as far as it has been possible to trace, they appear to have been known since the thirteenth century." The great geyser regions are doubtless losing a prodigious amount of heat. Iceland is the only one of these which has been long known to the white man. Records of the Iceland geysers are said to extend back about seven hundred years,[1] but naturally they are not of such a character as to prove or disprove a decline. The Yellowstone Park has been the most studied. Hague[2] says of it that "new springs are constantly breaking out and old ones are disappearing," but in his opinion there is nothing to indicate that any *general* decline has occurred within the forty years during which the Park had then been under observation. Frank J. Haynes and his son J. E. Haynes who have observed the geysers constantly during the summer season from 1881 to the present time confirm this view.

On the other hand the Katmai fumaroles have undergone a very perceptible decline in temperature inside of five years. The first temperature measurements were made there in 1918 by Sayre and Hagelbarger.[3] Another series of temperatures taken the following year[4] indicated a decline. In 1923 Fenner[5] made a second survey of

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[1] See C. S. Forbes, Iceland; its Volcanoes, Geysers and Glaciers, p. 241, London, 1860.

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

[3] Ohio Jour. Sci., 19, 249, 1919.

[4] Allen and Zies, op. cit., p. 108.

[5] J. Geol. 33, 195 and 212, 1925; also personal communication.

the region and, being provided with a map locating the hottest fumaroles found by his predecessors, tested the temperatures of the same fumaroles with small disks of lead, tin and zinc. *All* these hot fumaroles had declined in temperature, while the general aspect of the region, which Fenner had seen in 1919, as well as the appearance of numerous hot springs since the earlier date, constituted unquestionable proof of a general fall in temperature. The Katmai temperatures, however, were measured only a few years after the original eruption of igneous matter in which they are found, and being exceptionally high may very well decline at a diminishing rate as time goes on, and the store of heat there may still be very large. On the other hand it may be that effective steam flow there will be of short duration because the source of heat seems to be unusually near the surface.

In any attempt to forecast the future of the steam output at The Geysers one factor obviously must not be lost sight of; whatever the supply of heat and steam and whatever the source of it, the output of the steam-wells as compared to the natural fumaroles is enormous and it is not therefore to be expected that the life of the wells could be comparable to that of the natural fumaroles. On the other hand, the great industrial drafts upon the steam supply at Larderello which extend back apparently to 1906 and the five years of observation at The Geysers both attest a very great store of energy. It is also a fact worthy of some emphasis that the extremely dry winter and spring of 1923-4, which was responsible for the cutting down of the output of the water-power development of California from 25 to 50 per cent during the summer of 1924, exercised no measurable influence upon the steam flow at The Geysers.

THERMAL ACTIVITY AT OTHER POINTS ALIGNED WITH THE GEYSERS

Thermal activity similar in character to that manifested at The Geysers is found at intervals along Sulphur Creek for a distance of about six miles. It is confined entirely to a narrow belt on the north side, less than a quarter of a mile in width. In the vicinity of The Geysers there are a few slight indications of former activity on the south side, but there is none today[1] and none elsewhere on that side so far as our observations extend.

At many points within this belt ground temperatures a few feet below the surface reach nearly to the boiling point of water for the elevation, but in most of these places the *amount* of heat escaping from springs and steam vents is obviously slight compared to that lost by the undisturbed ground at The Geysers. One of the most

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[1] With the exception of a single cold vent near the hotel from which hydrogen sulphide is escaping.

active of these areas lies just over the high ridge to the west of The Geysers—a comparatively short distance from Geyser Creek. There are a number of acres of barren steaming ground where boiling temperatures are met with in many spots. On the southern border the soft treacherous earth is dotted with sluggish solfataras lined with sulphur needles, and in summer time it is more or less incrusted with salts. The Lemonade Spring, an analysis of which is given in table 3, and a few other acid springs are fed in part by the drainage from this area. A quarter of a mile to the west in a deep narrow gulley is the Ink Spring, the water of which is alkaline (table 3).

SULPHUR BANKS

A mile down stream from The Geysers is another fumarole field, similar in character to that just described and of much greater extent, known as the Sulphur Banks. Its barren surface steaming slightly in summer and marked here and there with white patches of salt never fails to attract attention and forms a conspicuous landmark for those who approach The Geysers from the south and west. Ground temperatures here in the summer of 1924 reached 98° C. not far from the surface in a number of places. Furthermore, the aggregate *amount* of heat escaping from the whole surface may be considerable. The ground is soft and frequently more or less muddy, but there are no springs within the area proper. In the gulley which bounds it on the east there are a few hot springs of which the Indian Mud Spring (table 3) is the only one worthy of notice. A small deposit of sulphur was formerly mined at the Sulphur Banks.

Two and a half miles from The Geysers, up Sulphur Creek at the foot of a ledge of schist opposite Foss's cabin, a little hot water issues at the edge of the creek. Three-quarters of a mile north from this point on Little Sulphur Creek there is a bit of meadow where two springs of moderate discharge emerge. The hotter spring had a temperature of 78° C. in June 1925. A very little hot water issues also at other points along the creek. Opposite the Fairchild cabin three miles above The Geysers Hotel a few hot springs are found along another little run. The highest temperature there was 71°. Slight bleaching of the ground along the slope indicates former fumarole activity, but very little gas is now escaping, and doubtless in consequence of this the ground about the springs is covered with vegetation. Both localities are thermally insignificant.

A half mile upstream from the last, the explorer finds another tributary of Sulphur Creek somewhat larger in size. Following this little stream for a short distance he comes suddenly out of the dense bush into barren ground where considerably higher temperatures are found. On the west side a sloping area 30 by 100 yards in extent is dotted with insignificant muddy springs where temperatures from

83° to 95° C. were observed. On the opposite side of the creek is a short line of diminutive fumaroles, several of which reached 97° in temperature. The altitude here, as indicated by the aneroid, is about 1,800 feet. Patches of bleached ground here and there in the thicket beyond show that fumarole activity was at one time more extended than it is today.

LITTLE GEYSERS

Five miles up from The Geysers and not far below the Socrates Quicksilver Mine, a branch from the northeast, not very much smaller than the main stream, flows into Sulphur Creek. Following this branch for half a mile one enters an amphitheater known as The Little Geysers. It is about a mile in diameter surrounded by steep rocky walls, several hundred feet in height, on the northeast, north and west, but falling away on the south and, especially on the southwest. The stream crosses the basin from north to south. There is hardly any timber to be seen, but the whole area except a few acres in the central portion is covered with a dense growth of stiff thorny underbrush which hinders exploration considerably. No igneous rocks have been found here; like The Geysers area, the surface is covered with serpentines, sandstones, more or less altered, schists and other metamorphics. North of a small unoccupied stone cabin about the center of the basin, a narrow outcrop of mica schist runs north and south for some hundreds of yards.

Drainage at The Little Geysers is scant in the summer time. The discharge of the stream at a point 250 yards south of the cabin was estimated from rough measurements in June 1925 at 300,000 gallons (about 1,000,000 kg.) per day, and in June 1924 it was certainly much less than that. Neither here nor elsewhere in this basin is there any indication of much ground water at any time.

Thermal activity is now practically confined to a few acres in the central portion of the area, but elsewhere, especially to the southwest, the observer will notice at intervals small, bare, gleaming white areas like oases in the dense bush, which on examination prove to be the seat of old fumarole action. The rocks are in various stages of alteration, often entirely changed to opal which is occasionally associated with sulphur, and at one or two points with steam and hydrogen sulphide.

All the hot springs are grouped within a few hundred yards to the east and south of the cabin. Directly east at the end of a swale about 150 yards in length steam is rising among the rocks, and in June 1925 there were four hot muddy springs, two of which reached a temperature of 96° C. A larger but shallow mud-spring, much nearer the cabin which has been used as a vapor bath, had a temperature of 92°, and there were several pools, somewhat cooler, close by it. Seasonal differences were most noticeable in this swale where in June 1924 hardly any water was visible.

Fifty yards south to southwest of the cabin is a little group of hot pools containing more water which seems to be chiefly supplied by the scant drainage from the above-mentioned swale. In June 1925 the hottest of these showed a temperature of 81° C. More gas was observed escaping from these pools than anywhere else at The Little Geysers (fig. 31). In late June 1926 when gases were collected at The Little Geysers the hottest spring in the area southwest of the cabin had a temperature of 95.9° (No. 5). The temperature in Spring 4, 10 feet from the last, was 71°.

Fig. 31—Spring at The Little Geysers, southwest of cabin. (Gas sample No. 4, table 9, was collected from this spring.)

On a small barren flat just south of the pools, and at a little higher level, there is another group of very small hot muddy springs and one or two mud pots where the maximum temperature in 1925 was 95.5° C. (fig. 32). In the drier season of 1924 temperatures as high as 97° C. were observed. The altitude here is estimated by the aneroid at 2,300 feet at which the boiling point of water varies around 97.5° C.

Except for insignificant amounts of serpentine on the south side of the flat (very possibly boulders) the rocks are completely decomposed to silica and oxide of iron. Chemical activity now in progress here is evidently very slight. The waters analyzed (table 3) show very little acid; they are on the verge of neutrality and the small amount of sulphate they contain indicates that they have never possessed much acid at any stage of their history. This accounts for the precipitation of oxide of iron, a process that is no doubt cumulative. None of the black sulphide of iron often noticed at The Geysers has been found in any of these springs. The supply of sulphur is evidently very limited, for the total amount of gas escaping is small and the percentage of hydrogen sulphide it contains is very slight; in fact the gases collected here in 1926 showed not a trace of it (table 9).

Fig. 32—One of small hot springs at The Little Geysers, Central Plateau. (Gas sample No. 3 was collected from this spring.)

Most of the springs described have little or no overflow. What there is either evaporates or finds its way into the stream by subsurface channels. But in estimating the total discharge of hot water from the basin it must not be overlooked that there is a certain amount of seepage along the creek, though only one distinct spring vent was discovered. The Chicken Soup Spring, on the eastern side of the stream several hundred yards south of the cabin, discharges more water than any other spring at The Little Geysers. Its temperature in June 1925 was only 71° C. From most of the area under discussion the heat loss also must be very slight. The heat carried away by the stream, however, is not entirely negligible and may be indicative of a considerable supply of subterranean steam. In June 1924 the water where the stream narrows below the Chicken Soup Spring had a temperature of about 50° C. At that time circumstances prevented an estimate of the stream discharge. In June 1925 the temperature in the same place and for some distance below was 26° C., which is 10° higher than it was above the hot area. Estimating the discharge at 1,000,000 kilograms a day the total subterranean heat carried away every 24 hours by this little brook would amount to 10,000,000 kilogram calories.

In brief The Little Geysers may be characterized as a basin of limited drainage where the hot springs are correspondingly small, a relation confirming the view already expressed concerning the rôle of ground water in hot springs.

CALISTOGA

The town of Calistoga lies at the head of the Napa Valley not far from the base of Mount St. Helena. Its altitude is much lower than that of the other localities described and the manifestation of its thermal energy is different, but because it is aligned with these other localities, and because thermal localities so related seem to be vitally connected through the agency of faults, a brief account of the thermal activity at Calistoga may properly find a place here.

Until recent years there was a small group of hot springs near a knoll of tuff at the eastern edge of the town. Waring,[1] who gives a description of the springs and their environs, says that in 1910 the principal spring discharged about a gallon of water per minute and had a temperature of 173° F. (about 78° C.). The analysis of the waters which he cites shows that they are alkaline waters of low concentration, the chief acid radicals being CO_3, Cl and SO_4, while sodium is the most important metal. Small mounds of characteristic siliceous sinter, doubtless deposited by the waters, were found here in 1924 by one of the authors. It has already been incidentally stated that the flow of these springs ceased when, a few years ago, a number of wells were drilled in the vicinity for the purpose of developing a water supply. The result of the undertaking was as remarkable as it was unexpected. Instead of the cold water they sought the promoters found it boiling hot and associated with steam of such pressure that the water gushed out in the form of geysers (fig. 33). That these geysers are true periodic springs there can be no question. In June 1924 two of them were seen in action by one of the authors. The first, near Pacheteau's baths, threw out a jet of water quite regularly, about once a minute, the eruption lasting for a fraction of a minute and then subsiding completely. The water column, which was about the size of the jet from a large hose, rose to the height of 75 or 100 feet and resembled a true geyser in all the details of its behavior. The other, a geyser of about the same magnitude, was also seen in action. It was said to erupt about once in 35 minutes. According to A. Rocca of Calistoga, who kindly supplied us with the information,

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[1] Op. cit., p. 108.

thirteen geyser wells have been drilled at Calistoga and Myrtledale, all but three of which are now capped so that the hot water can be utilized.

It is not proposed on the basis of a few superficial observations to attempt a detailed explanation of this remarkable phenomenon, but there are certain relations to the subject as a whole which ought to be pointed out. The waters are typical geyser waters in their composition and, like the other alkaline waters of the St. Helena Range, contain a certain amount of *sulphate*. Whether this sulphate is related to their chemical history in the same way as it is in the alkaline waters we have investigated, and whether the chloride which is comparatively high in the Calistoga waters is of magmatic origin or is directly derived from marine sediments, are questions which we raise without answering.

Fig. 33—Artificial geysers at Calistoga, California, developed unexpectedly by drilling. Photo by J. D. Grant.

On the other hand, the fault which according to Waring has been traced in this part of the valley, may very well be directly related to The Geysers canyon, which appears to be a fault valley, and though the chemical processes in progress here may or may not closely resemble those at The Geysers, such processes, as we have pointed out, are probably of a rather superficial character depending on the nature of the surface rock and certain other conditions which vary locally; the vital cause of the phenomena which have been disclosed by drilling seems to be identical in both cases, namely a supply of subterranean steam. The differences in behavior shown by the wells of Calistoga seem to be a natural result of the larger water supply in this broader and better-watered valley, and perhaps also the result of a steam supply of smaller volume and pressure.

COMPARISON OF THE GEYSERS CANYON, CALIFORNIA, WITH THE FUMAROLE FIELDS OF TUSCANY

To those who are interested in ultimate causes as well as to those whose interest centers in a novel industrial project which may eventually reach great importance, a brief comparison of the main features of the thermal activity in Tuscany with those in The Geysers canyon may be welcome.[1]

Thermal activity in Tuscany is confined to that portion of the Catena Metallifera, a mountain range running parallel to the west coast of Italy, which is hemmed in between the higher valleys of the Cecina and Cornia Rivers [Ginori Conti (*a*), p. 4]. Both hot springs and fumaroles, "lagoni" and "soffioni," are numerous over an area of approximately 100 square miles, but the latter on account of their spectacular nature as well as their economic significance have practically monopolized the attention of most observers. Industrial development, which has been in progress here for the last three-quarters of a century, has considerably altered the natural surface of the country and has given rise to artificial pools and steam-wells, but whether artificial or natural the terms "lagoni" and "soffioni" are applied indiscriminately, with a result somewhat confusing to the reader. Nevertheless it seems clear from the accounts of early observers and the evident impression left on their minds that the natural thermal activity in the Tuscan fumarole fields[2] is far more intense than that manifested in The Geysers canyon which we have been considering. According to De Stefani, in Tuscany the fumaroles issue from sediments—sandstones, flints, limestones and marls of eocene and miocene age associated with serpentine, schists and gabbro. That the hot springs and fumaroles follow "lines of fracture" (faults) was clearly brought out 75 years ago by Murchison[3] and later con-

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[1] The data on the Tuscan locality are derived mainly from the following publications:
De Stefani, I soffioni boraciferi della Toscana. Memorie della Società geografica Italiana VI, 2, 410, 1897.
Nasini, I soffioni boraciferi e la industria dell' acido borico in Toscana, Roma, 1907. (This work includes a bibliography.)
Ginori Conti, (*a*) The natural steam power-plant of Larderello, Firenze, 1924; (*b*) Sur l'utilization industrielle des manifestations thermiques terrestres, Chimie et Industrie Paris.

[2] Hamilton, Quarterly Journal of Geology, 1, 273, 1845.

[3] Quar. Jour. Geol., 6, 367, 1850.

firmed in detail by De Stefani. Many facts indicate that the store of ground water is considerable; the hot-spring pools are comparatively large, water is often encountered in drilling and true geysers are mentioned by De Stefani as occurring at Serazzano and Monterotondo.[1] The statement of Ginori Conti that the springs and fumaroles occur in "absolutely barren ground" would indicate acid decomposition of the rocks and this has been made clear by the extensive observations which De Stefani has recorded. The alteration products are silica and various sulphates, including large amounts of calcium sulphate and several borates which are apparently much smaller in amount.

STEAM-WELLS

Temperatures in the Tuscan fields are reported to vary from 100° to 190° C. [Nasini, op. cit., pp. 91–92]. The more recent statements of Ginori Conti have not extended the range.

How far these temperatures apply to *natural* fumaroles is not clear, but the highest temperatures appear to have been obtained in the wells. The boring of small and shallow wells has long been resorted to in the preparation of boric acid, the steam being used in the evaporation of the solutions. The drilling of larger and deeper wells for steam power has been in progress only about 20 years. The depth of these modern wells varies from 60 to 200 meters [Ginori Conti (*a*), p. 11].

Pressure in different wells varies greatly with locality and with depth, though no simple relation to the latter has been discovered. In the older and smaller wells pressures may be as low as 1.5 or 1.75 atmospheres [Nasini, op. cit., p. 93] and in the earlier borings of the present period it never reached above 5 atmospheres, but in a recent well at Serazzano of 90 meters depth a pressure of 7 atmospheres was attained with the valve still partially open [Ginori Conti (*a*), p. 16]. In a deep well, still more recently developed, the pressure though not directly measured has been estimated from quantitative data at 14 atmospheres (about 200 pounds per square inch) [Ginori Conti (*b*), p. 6]. As a matter of prudence the most powerful wells in Tuscany are apparently never completely closed. The temperature and pressure measurements of Nasini on the soffioni have already been recounted (p. 63) and it will be recalled that they proved the important fact that the steam here is *superheated*. The measurements seem to have been made not in the *natural* fumaroles but in the older shallow wells. Nasini's statement has since been confirmed by Ginori Conti on the basis of further data from the deeper wells.

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[1] Ginori Conti informs us that these have now disappeared as a result of drilling.

STEAM OUTPUT

Till recent years the greatest output of steam was from a rather small, shallow well at Larderello, known as "Forte" which yields 4,000 kilograms (8,800 pounds) of steam per hour at a pressure of about one atmosphere effective [Ginori Conti (*a*), p. 9]. The powerful well at Serazzano, just referred to, delivers 24,000 kilograms (52,800 pounds) per hour at a pressure of one atmosphere effective and 13,000 kilograms (28,600 pounds) per hour 5 atmospheres effective. It is an interesting fact that with increasing pressure the output of the more powerful wells is much less affected than that of the weaker ones. A very powerful well at Castelnuovo has yielded 60,000 kilograms (132,000 pounds) of steam per hour at a pressure of one atmosphere effective and over 15,000 kilograms (33,000 pounds) at two atmospheres effective [Ginori Conti (*a*), p. 16].

About 1923, 12 wells at Larderello yielded 120,000 kilograms of steam per hour at two atmospheres absolute pressure or 10,000 kilograms (22,000 pounds) per well on the average [Ginori Conti (*a*), p. 13] as compared to an average of about 34,000 pounds at a pressure of about five atmospheres effective from four wells at The Geysers. The present output at Larderello alone is given as 190,000 kilograms of steam per hour [Ginori Conti (*b*), p. 9], while an interesting calculation based on the total production of boric acid and the known relation of it to the amount of steam brings the total amount of steam now available in all the fumarole areas up to several million kilograms per day [Ginori Conti (*b*), p. 11].

The origin of this steam is regarded by De Stefani as deep-seated. His conclusion has a special interest because the evidence on which it rests is of quite a different character from that advanced by the authors of this paper for the origin of the steam in The Geysers canyon. De Stefani's most convincing argument is that the boric acid which invariably accompanies the steam is never found (except as an alteration product) in the superficial strata; a source of it has not been discovered above the horizon of the most ancient granites. The high temperature of the steam and the constant percentage of gases are also regarded by him as evidence of the deep-seated origin of the steam.

GASES

Here as elsewhere in fumarole regions volcanic gases are prevalent. Their composition has been the subject of many chemical investigations. Nasini (op. cit., p. 93), whose work appears to be the most reliable, gives the following analyses of gases from two different fumaroles at Larderello.

Nasini states that the natural gas in the vapor amounts to 2 per cent to 3 per cent *by volume* (3 per cent to 5 per cent by weight).

Ginori Conti (*b*, p. 11) finds little connection between the thermal phenomena and the superficial strata in which the fumaroles issue; only in the percentage of the non-condensable gases does there appear to be any relation. The gases vary from 2 per cent to over 6 per cent *by weight* and the amount is said to be constant along the same fault line (*b*, p. 11).

In 100 parts of natural gas	Gas in soffione Casotto	Gas in soffione Tini
H_2S	2.070	2.000
CO_2	92.800	92.000
CH_4	1.400	1.900
H_2	2.600	2.400
O_2	.050	.200
N_2	1.048	1.455
A	.021	.029
He	.010	.014

For further details on geology, power installation, etc., the student of the subject should consult the original papers.

From this brief comparison of the two areas in Italy and California many points of similarity in geologic conditions are seen, though the Tuscan area is much more extensive and the intensity of thermal activity in undisturbed ground appears to be much greater. The principal chemical changes in progress near the surface of the ground seem to be of the same general character, the differences being due more to the nature of the superficial rock than to differences in the composition of the gases. The total amount of the alteration in Tuscany also appears to be much greater, probably on account of the greater quantity of vapors constantly escaping there and to the peculiarly susceptible nature of limestone.

The total amount of non-condensable gas is somewhat greater in Tuscany than in California, and so far as there is such a difference the steam from the latter has the advantage in the generation of power by the ordinary steam turbine. It should be remembered, however, that the difference is exaggerated when percentages are stated by weight for the Tuscan gas is denser and it is volume which really counts.

In composition the gases in the two localities differ considerably from one another. Carbon dioxide is the predominant constituent of each, but the percentage of it is much higher in Tuscany. Hydrogen sulphide, chemically the most active of the gases, is somewhat greater in amount in the California wells though still of the same order of magnitude. The California gases are much higher also in hydrogen and methane but the significance of the fact is not yet apparent.

When we come to a comparison of the steam-wells in the two localities, one of the most important facts to be stressed is the superheated character of the original steam in both. It must be borne in mind that only a few wells in California have yet been developed, but the maximum temperature is as high as it is in Tuscany, and half the wells are superior both in pressure and in steam output to any yet reported from Italy.

SUMMARY

The region studied in this paper includes small areas of the Coast Range in California, specifically in the St. Helena Range. The slopes of this range are generally covered with sediments and metamorphics but exposures of andesite on the high peaks, the occurrence of small areas of lava, tuff and obsidian at certain other points and the discovery by drilling of gabbro at a depth of 230 feet at The Geysers, all proclaim this a volcanic region. Another fact of considerable importance in support of the conclusions reached concerning the thermal activity in this region is that there is evidence of a fault extending along the west side of the range for a distance of about 25 miles.

Observations on the hot springs of this locality not only confirm the conclusions reached in the course of investigations in the Lassen National Park in nearly every particular, but materially extend our knowledge in several directions.

(1) Of first importance are the observations and tests that concern the great store of hot steam, increasing with depth, which drilling proves may be tapped at The Geysers not far below ground in the hot area anywhere, even in spots where formerly there was no indication of abnormal temperature. That similar supplies of subterranean volcanic steam of industrial importance may be developed in many other fumarole districts, as Prince Ginori Conti believes, is highly probable, and that they are the secret of the immense stores of heat and its ready transmission in the great geyser basins seems beyond doubt. The fact that the steam at The Geysers rises in a region where all signs point to a meager supply of ground water, that it is accompanied by volcanic gases, and, almost equally significant, that the steam is superheated like the steam at Larderello and like that in many fumaroles at Katmai and probably elsewhere, points to a magmatic origin. The eventual saturation of the steam in the wells at the Geysers is shown by tests to be a subsequent development which requires appreciable time and probably occurs in the wells themselves.

(2) While the volcanic gases, hydrogen sulphide, or to be more accurate its oxidation product sulphuric acid, and to a lesser degree carbonic acid, are the active agents in rock decomposition, the actual process appears to be confined to a zone near the surface. This is

shown by the direct relation between the composition of the spring waters and the superficial rocks, the most important of which is serpentine; by the seasonal variation in the discharge of a large number of the springs which is measurable; by the mutual relation between springs and fumaroles expressed in the appearance of hot springs at new points in wet weather and the drying up of certain hot springs with advancing summer, and also by the evidence revealed in drilling.

(3) Much additional information has been collected on the causes of acid and alkaline springs and on their relation to each other. A marked difference in concentration between the two classes which was forecast from incomplete evidence in the Lassen National Park is here fully borne out—the concentration of the acid springs being so much higher as a rule as to constitute a different order of magnitude. It has been possible to trace many springs pretty definitely to the ground where they rise and to connect the acid springs with places where oxidation is active, and the alkaline springs with places where oxidation is feeble. There is nothing to show that the acid waters were formerly alkaline, as some suppose, and while the evidence indicating that the alkaline springs were acid in their beginning may not be completely convincing to all, it is quite in accord with the facts so far as they are known.

FIG. 34—The Geysers, early morning. 1925.

(4) A comparison of the thermal activity in the St. Helena range with that of Tuscany, so far as the latter can be determined from the literature, has been made.

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