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GEYSIR IN ICELAND.

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ABSTRACT. Observations on the geology of Geysir, its behavior, discharge, and temperature distribution, have led to the conclusion that the structure of the Geysir system and the mechanism of its action are more complicated than thought by Bunsen.

In an appendix special consideration is given to Thorkelsson's assumption that a reduction in pressure caused by spring gases and steam as they rise in narrow channels is the real factor in geyser action. A bibliography of Geysir and geyser action is also appended.

INTRODUCTION.

"Here a poet would have an opportunity of painting a picture of whatever Nature has of beautiful and terrible united."
(Uno von Troil, 1773.)

GEYSIR is the most famous spouting hot spring in the world. It was known to science centuries before Waimangu in New Zealand had been heard of, or the performances of Old Faithful had been beheld by white men. Its behavior had attracted tourists as well as learned men, and legion is the number of notes and descriptions of Geysir from the 17th century up to the present day.

"Geysir" is a proper name given by the Icelanders in the 17th century to this particular spring (pronounced "gaiseer"). It is derived from the verb *gjosa* (principal parts: *gys*, *gaus*, *gosi*) meaning gush, spout, erupt; thus the translation of geysir would be gusher or spouter. Some other springs have received the same name; for instance, Geysir at Reykjanes, and Littli-Geysir at Ölfus. As distinct from these, the famous Geysir is sometimes called "Stóri Geysir" (=Great Geysir). However, no such adjective is necessary. Geysir is owned by the Icelandic government, which holds it in high esteem and has

issued strict rules as to how it should be guarded and treated (48); thus, "Geysir" means just one thing in Iceland.

Among many other pioneers of our modern science, Bunsen visited Geysir, now almost a hundred years ago, to study its action and its relation to other volcanic processes. Through his work the word geysir was introduced as a technical term for all hot springs showing intermittent fountain action. For unknown reasons this spelling in English has been modified to "geyser," which is now given by Webster as "correct." In German the spelling is more uncertain. Curiously enough, Bunsen wrote "geisir," but most other German writers have used "geysir" correctly. Von Wolff, however, in his last work, "Der Vulkanismus," must have been influenced by English and writes "geyser."

Geysir is situated in southwestern Iceland about 50 km. from the sea, at approximately 100 m. altitude, close to the church Haukadalur (Hawkdale). The area belongs to the southwestern plain region built up of palagonite (a heterogeneous formation consisting of tuffs and breccias associated with moraines, boulder-clays, and glacial sediments) alternating with basaltic lava flows. Just northwest of Geysir a small stock-like mass of liparite, forming the so-called Lauga(r)fjall, protrudes 60 to 70 m. above the plain. An extensive area of silica sinter, that according to v. Waltershausen (101) covers about 1,000,000 m²., has formed at Haukadalur. To the north and west it is bounded by Laugafjall, to the east and south by the small river Beiná. This area is studded with hot springs, many of them geysers. In addition steam percolates to the surface and oozes out from the siliceous gravel all over the area. (One can place a blanket on the ground, and a thermometer under the blanket after awhile will register 30 to 50° C.) In the northern part of this sinter area Geysir is situated.

Geysir and its congeners in this particular hot-spring region of Iceland all belong to the family of alkaline springs. The Geysir water shows pH = 8.0, and the amount of dissolved materials is about 0.1 per cent (analyses by Bunsen and others, 12, 19, 20, 81). The spring gases are the ones commonly met with in alkaline waters (14), (72), mostly N₂, and in addition CO₂, O₂, a fair amount of H₂, A + He, and even traces of H₂S.

GEYSIR'S DOME.

Geysir is surrounded by a regular dome-shaped eminence of silica sinter, on the top of which is a flat basin or crater. In

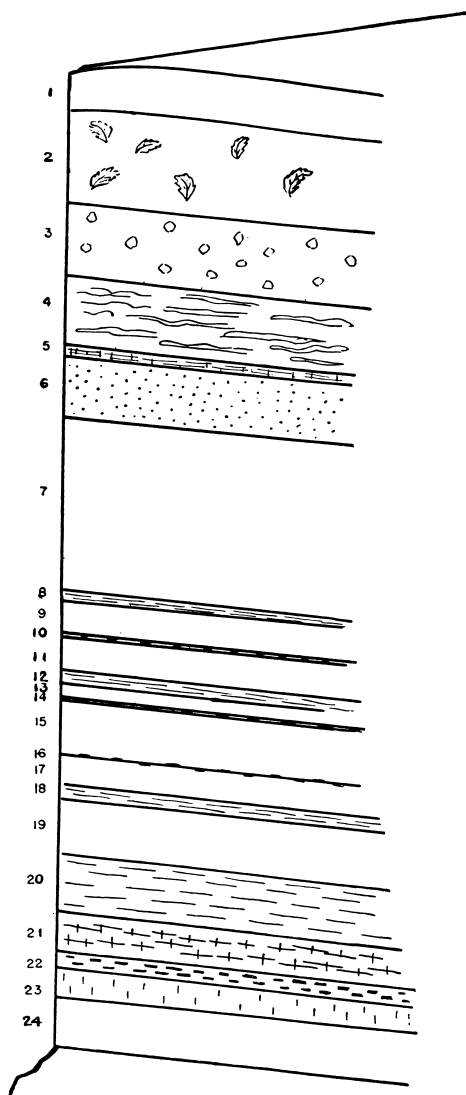


Fig. 1. A vertical section through part of the dome of Geysir. The profile is 3.6 m. high. Layers Nos. 1, 2, 4, 6, 7, 9, 11, 13, 15, 17, 19, and 24 consist of silica sinter; No. 2 is full of fossil leaves of birch (*Betula odorata*), No. 4 is sheared and rolled out to thin flakes, No. 6 is cherty, the others are ordinary silica sinter. Layers Nos. 8, 12, 18, and 20 consist of a mixture of sinter and clay. Nos. 5 and 21 consist of yellowish-brown clay. Nos. 10, 14, and 16 consist of soft, white, jelly-like clay. Nos. 22 and 23 consist of blue and red clay respectively. Layer No. 3, which is 27 cm. thick, consists of light brownish volcanic ash and lava pebbles. All layers dip inward about 5°.

the center of this dome a vent extends about 23 m. downward, and through it columns of water are shot as high as 60 m. into the air during an eruption.

Clearly the dome around Geysir has been built up by precipitation of silica from the hot-spring water as it flowed out of the basin. It is stratified, and a profile through the various layers can be studied at a cut made in the north flank of the dome. Figure 1 gives the result of this study. The various layers of clayey material, as shown in Fig. 1, are interesting, for this clay is identical with the decomposition product that is formed by the action of *acid* hot-spring water on basaltic rock at other places in Iceland; and it appears that only acid waters can produce this kind of clay. On the other hand, only alkaline waters deposit silica sinter. This profile indicates, therefore, that several times during its history Geysir may have changed from an alkaline to an acid spring, and vice versa. Recorded descriptions make it appear highly improbable that any such change took place after 1630, which again implies that the age of Geysir is thousands of years.

Layer No. 3, containing a bed 27 cm. thick, made up of volcanic ash and pebbles, is also interesting in this connection. After 1630 Geysir was a powerful geyser and must have been quite able to wash away such loose material from the rim of its crater. The fact that this thick bed could accumulate makes it probable that Geysir at that time was a quiet spring, therefore the deposition of this bed must have occurred before 1630. This is indicated also by the fact that the bed of volcanic ash is roofed with a sinter layer abounding in fossil leaves of birch (*Betula odorata*). This is the only fossiliferous layer in the whole profile. Underbrush of birch covered Iceland when the first settlers came in the 9th century, but was soon destroyed. It is reasonable to assume that no such vegetation has existed around Geysir's crater for the last 500 years. The thick bed of volcanic ash may have formed in 1294 when Hekla, which is situated 35 km. to the southeast, had a great eruption accompanied by heavy ash-fall; or it may be still older.

The evidence thus far gathered would seem to justify the conclusion that Geysir is several thousand years old, but this does not imply, of course, that it always showed geyser action. It probably was a quiet spring during most of its life.

So far as recorded measurements go, they do not indicate any increase in the height of Geysir's dome during the last 300

years [see, e.g. Table, p. 18, in a paper by Tuxen (96)], which suggests that deposition of new silica either is very slow, or is counterbalanced by the loose ground on which the dome is built yielding under the superincumbent load; for it is a simple matter of observation that new silica is constantly being deposited. By experiments Forbes (32) found that the rate of deposition on Geysir's dome was $1/500$ inch per 24 hours; this would correspond to about $5\frac{1}{2}$ m. in 300 years, or almost twice as much as the present height of the dome.



Fig. 2. A cross-section through Geysir from NNW to SSE. The cut on the left side corresponds to the profile of Fig. 1.

The shape of the crater is interesting. The central vent is circular and about 3 m. wide at the top; farther down, about 2.7 m. At the very top it widens out like the mouth of a bugle, forming a smooth, beautiful basin of perfect radial symmetry 14 m. wide. Ordinarily it is filled with hot water, but immediately after a major eruption it is dry. A cross-section of it is given in Fig. 3. Whenever one sees such perfect shapes in Nature one stops and wonders how they were created. In this

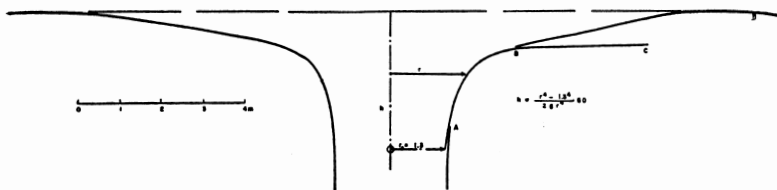


Fig. 3. The shape of Geysir's crater. The left side of the drawing gives the shape as actually measured; on the right side the curve ABD represents the actual shape of the crater, whereas ABC is the curve computed from the equation $h = \frac{r^4 - 1.3^4}{2gr^4} \cdot 50$. The two curves coincide over the distance AB.

case, however, there are so many factors involved that an exact evaluation of the formative processes is impossible. The following calculations, which take into consideration only a few of the possible factors, are of necessity only approximate; but the fact that they happen to be in very good agreement with the observed shape indicates that the principle underlying these calculations may embrace the most important of the factors.

Up through the vent shoots a mass of water m , with initial velocity v_0 . At a certain height h , the velocity has become v (see Fig. 3) and since the energy must remain constant, we obtain the following equation:

$$\frac{1}{2}mv^2 + mgh = \frac{1}{2}mv_0^2$$

hence

$$v^2 + 2gh = v_0^2 \quad (1)$$

In a given time unit an equal amount of water must flow through the same cross-section. If the radius of the vent be r_0 , and the radius of the basin at height h be r , then

$$r_0^2 v_0 = r^2 v \quad (2)$$

By substituting for v in equation (1), we obtain:

$$\frac{r_0^4}{r^4} v_0^2 + 2gh = v_0^2$$

hence

$$h = \frac{r_0^4 - r^4}{2gr^4} \cdot v_0^2 \quad (3)$$

In addition to the gravity constant, equation (3) contains the constant radius of the vent, $r_0 = 1.3$ m., and the initial velocity v_0 . Calculations show that the equation fits the observed shape of the Geysir-basin if v_0 is taken as 7 m./sec. This is shown graphically in Fig. 3.

BEHAVIOR OF GEYSIR.

Contrary to common belief, most geysers do not have eruptions with regular periods, nor are they constant in the intensities of their eruptions or in the heights attained by the water jets emitted. Geysir is typically an irregular geyser and has always been so. Table I gives the versions of various writers regarding the rhythms of the geyser activity.

Observations by Uno von Troil (1772) on both duration of the quiet intervals and heights of the erupted jets are shown graphically in Fig. 4.

All observers have noticed that there is a wide range in the heights attained by the jets; one year the maximum height may be 60 meters, another year, 20 meters. Abortive eruptions or "floods," as they are called in Iceland, were also characteristic

of Geysir. They were accompanied by subterranean detonations and a sudden development of vapor and gas bubbles that dashed toward the surface and caused the water in the center of the basin to swell and rise in the shape of a conelike mound the altitude of which would attain 2 meters.

TABLE I.
Duration of Quiet Intervals Between Eruptions of Geysir.

Authorities	Date of Observation	Interval in hours
Sveinsson (Bishop of Skálholt) ...	17th century	24
Sigurdsson (Governor)	18th century	6-8
Olafsen and Povelsen	18th century	6-8
Uno von Troil	1772	irregular
Ohlsen	1804	6
Hooker	1809	30
McKenzie	1810	
Henderson	1816	
Krug von Nidda	1833	24-30
Descloizeaux	1846	11-30
Winkler	1860	80-100
Paijkull	1865	irregular
Burton	1872	6
Keilhack	1883	irregular, up to three weeks
Thoroddsen	1895	
Thoroddsen	1896-1897	1-12
Thoroddsen	1898-1907	often several weeks
	1915-1935	dormant

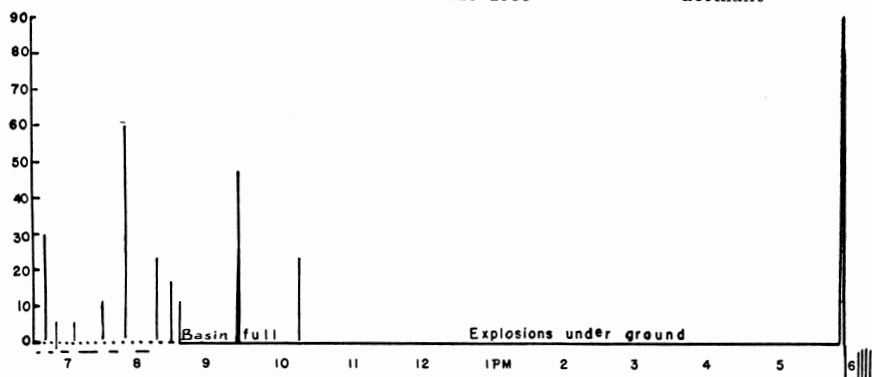


Fig. 4. Graphical representation of the action of Geysir from six-thirty a. m. to seven p. m. on September 21, 1772, according to observations by Uno von Troil (95). Abscissa is the time scale; ordinate gives the heights of the various jets in feet.

What has been said so far indicates that at no time in its history did Geysir display any regularity in its performances.

The following remarks summarize the history of Great Geysir.

The age of Geysir is unknown, but the building-up of the large area of silica sinter between Beiná and Laugafjall must have taken thousands of years. This does not mean, however, that Geysir itself necessarily was active all this time, although the study of a profile in the Geysir cone indicates a considerable age (see p. 384).

The existence of hot springs in this area was first mentioned in 1294. In this year the volcano Hekla had a great eruption as a result of which "new hot springs were formed at Haukadalur, and some old ones disappeared." (Íslenzkir Annálar, 1888.) Also in 1630 pronounced alterations of the springs of this area are said to have been caused by an earthquake.

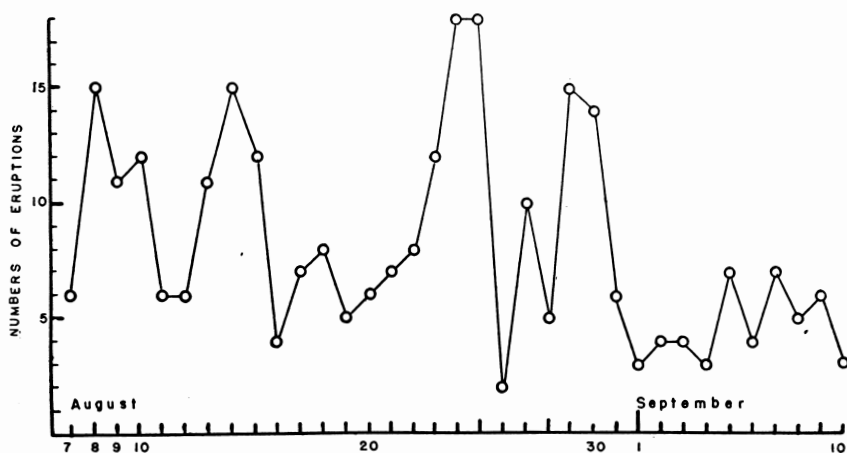


Fig. 5. Graphical presentation of the frequency of Geysir's eruptions during part of August and September 1935. Abscissa is the time scale, ordinate gives the number of eruptions per day (24 hours). Data published by Einarsson (27).

The name Geysir was first applied in 1647 [by Bishop Sveinson (see Table I)]. Towards the end of the last century Geysir became less active, but the earthquake of 1896 revived it temporarily. However, it soon became slow again, passing gradually into a dormant stage. The last eruption worth mentioning took place in 1907 during an official visit of the Danish King, but large quantities of soap were required to persuade it to pay this tribute to its royal visitor.

So Geysir slept for many years until three Icelanders (27) in 1935 suddenly awakened it by a surgical operation that

resulted in a complete rejuvenation of the old geyser. A gap was made in the lip of the basin, forcing the water level down about one meter, and, presto, it started to spout as willingly as before.

The frequency of the eruptions as recorded by Einarsson shortly after the reawakening can be seen from the graph, Fig. 5. The heights of the jets were said to be 40 to 50 m. (maximum 60 m.). But subsequently the Icelandic government, which is the owner of Geysir, possibly in an endeavor to preserve the subterranean energy, locked the gap, and thus made the water of the basin resume its old level, in order that it should perform only when worthy visitors arrived. But this time Geysir was not willing to respond to treatment. In spite of the fact that the old conditions were thus restored, it refused to go to sleep. Today it plays, although infrequently, even when the water level is at its highest. However, it can also be made to erupt to order; viz. by baiting it with soap and lowering the water.

The eruptions of Geysir after its reawakening have been described by Einarsson (27). Apparently they are not very different from those described during the 19th century. A brief account follows of two eruptions witnessed by me, at which time temperature measurements were made. They will be discussed later.

The first eruption occurred unexpectedly at 3 a. m., August 22, 1937. The basin was then full of water. Unfortunately, I did not see the prelude to this eruption; the tent had been pitched about 300 m. from Geysir, and at three o'clock in the morning I was awakened by rumbling and detonations underground, and by slight tremblings of the earth. When I got up, Geysir was in full activity, the fountain playing about 50 m. high. After this violent outburst the eruptive activity continued paroxysmally. The water had subsided about 6 m. It was boiling violently, and every two to five minutes jets were thrown about 10 m. into the air. Between five and six o'clock the eruptions became fainter and eventually died away. These after-eruptions had then lasted for about two and a half hours. Subsequently the water level rose to the top of the basin. It overflowed at twelve noon. About half an hour later, soap was applied and Geysir again erupted.

This second eruption was evoked in honor of the foreign ministers of the Scandinavian countries who were brought to

the spot from a meeting at Reykjavik. An official guard removed the shutter from the gap in the lip, thus letting down the water level about one meter, and a case of laundry soap was dropped into the basin. About half an hour later the first warnings of the forthcoming eruption were noticed.

12:55 p. m. A series of explosions underground, with slight trembling of the earth, but these events had no visible influence on Geysir, which remained quiet as before.

1 p. m. Water in basin began boiling. Soon it boiled vigorously and small jets were thrown up into the air.

1:12 p. m. Great eruption commenced: All of a sudden the boiling water of the basin was sucked down the pipe and remained underground for about 40 seconds. Then it shot out, forming a solid column 50 m. high; gradually it developed into a steam column; finally only steam escaped. And then, rather abruptly at 1:19 it stopped dead.

No after-eruptions occurred corresponding to the falling stage of the eruption phase such as we had seen the same morning. According to Einarsson these two types of eruptions as here described are typical for Geysir at the present time, and the eruption ending with a steam column characteristically occurs when soap has been applied.

At 1:30 p. m. the water level was 7 m. down and the temperature measurements showed the spring to be very cool with only 87.2° C. at the bottom. In spite of this, a thick fog of steam quietly ascended from the spring, and the water level continued to drop.

At 6 p. m. the water was 16 m. down. Geysir steamed copiously but was absolutely quiet all afternoon. Next morning the basin was full.

In terms proposed by Fix (31) the second eruption may be summarized as follows:

1. Premonitory phase, 5 minutes.
2. Preliminary phase, 12 minutes.
3. Eruption phase, 5 minutes; this phase consisted of several successive maxima separated by discharge of lesser height. It cannot be subdivided into a rising stage or a falling stage.
4. Steam phase:
 - (a) Violent steam stage, 2 minutes; separation from the eruption phase is difficult, however.
 - (b) Passive steam stage, about 8 hours.

DISCHARGE OF GEYSIR.

When Geysir is quiet the discharge is now about 2.5 liters per second. This figure would seem to be fairly reliable; it was the estimate I put down in my notebook in August 1937, and an identical figure was given by Einarsson in a publication in November 1937 (28). It corresponds to 9 m.³ (=9 metric tons) per hour.

During an eruption and shortly after an eruption, however, the discharge is different. The amount of water ejected during a great eruption cannot be accurately estimated, but it is considerable. The basin overflows in all directions, some of the water spreads out over a large surface, some of it forms steaming brooks that radiate from Geysir. Toward north and east one can follow these steaming brooks over a distance of half a mile.

No accuracy can be attached to the following calculations, but they do support the notion that the discharge is appreciable.

As already explained, the main phase of a major eruption is started by a fountain of water being thrust straight up from the vent, to a height of *ca.* 50 meters. The velocity v of this water jet at the base can be calculated from the height h attained: $v = \sqrt{2gh} = \text{ca. } 30 \text{ m./sec.}$ The cross-section of the jet is approximately 5 m.², therefore it must pass 150 m.³ water and steam per second through the mouth of the vent. During the eruption seen by me this impressive fountain was kept up continuously for seven minutes, but gradually more steam appeared, and finally pure steam stood straight up from the orifice. If we assume, in agreement with certain calculations by Thorkelsson, to which we shall return later, that one-fourth of the initial column consisted of liquid water, the rest being steam and gases, then the water discharge would amount to *ca.* 40 m.³ per second, or 2400 m.³ per minute.¹ One minute thus corresponds to 11 days of normal discharge.

The immediate conclusion is that the Geysir vent itself is entirely inadequate to supply such quantities of water; the contributions must be sought, therefore, in large subterranean reservoirs that are emptied during the eruptions.

After a great eruption the basin is dry, and the water level may, according to Einarsson (27), be as low as 22 meters.

¹ A strong wind blew the water column eastward; only a small fraction of the water fell back into the basin.

After the second eruption witnessed by me the water subsided 16 meters.

According to several series of measurements by Einarsson the water then rises rather regularly at a rate of 2.0 to 2.5 meters per hour. Since the circular cross-section of the vent is from 5.0 to 5.5 m.² this corresponds to an inflow of about 12 m.³ per hour, which is close enough to the figure taken as the normal discharge (=9 m.³/hour).

However, this is not the whole story. It will be recalled that the water did not start to rise immediately after the second eruption seen by me. On the contrary, for five hours immediately following the eruption the water dropped 9 meters. This means that the vent drained backwards at practically the same rate as that with which it was filled up during the observations of Einarsson. After this backward draining had taken place for at least five hours, the direction of the flow reversed itself, and during the next night the vent filled up at what would seem to be the normal rate.

After the first eruption witnessed by me the behavior was again different. The basin was dry and the water stood 6 m. down the pipe (see p. 389). Then it immediately began to rise, and in six hours the vent plus the basin, which has a capacity of more than 100 m.³, was filled up. This time the inflow rate was extraordinarily high, about 23 m.³ per hour as against normally 9.

To sum up: The normal discharge of Geysir is about 2.5 liters per second; the various subterranean channels that empty into the Geysir vent thus normally supply this amount of water. But during an eruption these channels evidently supply much more water. After an eruption the supply may be either abnormally high, or abnormally low; indeed it may even be negative, i.e. water runs from the vent backwards into the channels.

TEMPERATURE MEASUREMENTS.

The temperature conditions of Geysir as we found them with a remote-reading resistance thermometer are given in Tables II and III and shown graphically in Fig. 6.² Three series of

² The measurements were carried out with the coöperation of Mr. Odd Dahl, physicist at the Michelsen Institute at Bergen, Norway, who designed and built the thermometer, which is of the electrical resistance type, with

our measurements are given: they are marked "before eruption," "intermediate stage," and "after eruption."

Let us first consider the measurements "before eruption" conducted during the afternoon of August 21, 1937. At this time Geysir had had no eruption for about a week. But, as said before, it came to eruption ten hours after these measurements were taken, at three o'clock the next morning. With the help of a pulley the thermometer coil was moved up and down the full length of Geysir's vent, and the change in temperature was registered continuously. At certain points the thermometer was also left stationary for some time. It could thus be shown that at these points the temperature did not remain quite constant, but showed irregular variations. However, the amplitudes of these variations were only about one degree. By repeating the measurements the temperature curve as given in Fig. 6 could be reproduced. We think, therefore, that this curve corresponds fairly accurately to the actual temperature distribution in the vent at this time.

The thin, dash line to the right in the graph gives the boiling temperature at various depths of the water column. The thin, broken line EE has been inserted to instance the type of temperature distribution that can be inferred from measurements by Einarsson in 1935 (27). His measurements, which were made shortly after the reawakening of Geysir, are in many ways similar to the measurements of Descloizeaux and Bunsen conducted in 1842.

The earlier observers did not find a temperature maximum at about 15 m. depth, and have assumed, therefore, that the temperature steadily increases with depth. In the present measurements there is a characteristic decrease with depth below the 15 m. level.

a coil of nickel wire with high temperature coefficient exposed to the temperature to be measured. The resulting resistance was compared through a Wheatstone bridge circuit with a known resistance of negligible temperature coefficient, and the variation in resistance calibrated in terms of temperature.

The thermometer coil is protected by a shellac-soaked insulating layer and pushed into a tight-fitting brass tube with bottom closed. It is connected to the bridge circuit through 35 meters of a three-conductor rubber-insulated cable the outer diameter of which is about 8 mm.

As to the accuracy of the apparatus, laboratory tests proved that temperatures could be determined to 0.1°C. , and the bridge would permit the same accuracy up to about 200°C.

TABLE II.

Temperature Distribution in Geysir, August 21 and 22, 1937.

Depth in meters	Temperature, ° C.	
	Before eruption	After eruption
1	75*	**
5	75*	**
8	85*	94.0
12½	112.5	94.0
15½	116.5	93.2
19	113.2	90.5
22½	111.3	87.2

* Temperature not constant, varies $\pm 2^\circ$.

** Water surface at a depth of 7 m.

TABLE III.

Temperature Distribution in Geysir during the Falling Stage of the
Eruption from 4 A. M. to 6 A. M., August 22, 1937.
(Marked "Intermediate Stage" on the graph.)

Temperature, ° C.		
At 8 meters depth†	At 15½ meters depth	At 22½ meters depth
*101.2, eruption	*104.5	*104.0, eruption
96.0	106.0, eruption	Thermometer thrown out
98.8	101.2	100.1, eruption
101.2, eruption		96.5
98.2	*107.6, eruption	100.0
100.0	99.1	104.1, eruption
101.2	100.7	93.7
103.8, eruption	104.0	100.2
98.7	107.0	
	109.5, eruption	
	101.2	
	103.9	
	105.1	
	106.5	
	107.6, eruption	
	103.8	
	107.6	

* Each column of figures corresponds to a series of measurements with approximately one-half minute interval between the individual readings. First the series of three readings at 15½ meters depth was taken, then the series at 22½ meters, then the second series at 15½ meters, and finally the series at 8 meters.

† This level is 2 to 3 meters below the water surface, which is in constant oscillation.

Bunsen thought that the temperature at a given point in the vent increases steadily from one eruption to another. Einarsson seems to be of the opinion that his new series of measurements support this view. But a critical examination of the data indicates a series of irregular fluctuations rather than anything

else [see also the criticism by Thorkelsson (82) and Tuxen (96)]. Undoubtedly there is, generally speaking, a certain increase of the temperature from one eruption to another, but it is important to note that, so far as observations go, the eruptions do not necessarily begin when the temperature is at a maximum, and boiling temperatures are never reached anywhere in the water column before a new eruption starts.³

The temperatures measured by us with the remote-reading thermometer are, as a rule, decidedly lower than the temperatures given by either Bunsen or Einarsson. In the first place, this may mean that Geysir is cooler now than it used to be a hundred years ago; for Einarsson's measurements are also lower than those of Bunsen. Secondly, a systematic error may encumber the earlier measurements, for the temperatures demonstrated by our second and third series of measurements (marked in the graph "intermediate stage" and "after eruption") are much lower than anything found by earlier investigators. The explanation probably is that it is unsafe to use a maximum thermometer. As seen from the graph, the temperature in these cases decreases with depth, and such a condition is hard to discover with maximum thermometers. In addition to this, there undoubtedly are cracks and openings in the wall of the Geysir pipe through which very hot water or steam enters the vent. If a maximum thermometer is directly hit by such a hot water jet it will register a temperature far above that of the main body of water. Indications of such small jets or bubbles were spotted with our remote-reading thermometer, but as it takes about two minutes before equilibrium is established between our instrument and its environment, these phenomena could not be further explored.

From such considerations we may conclude that measurements with the maximum thermometer are likely to give a distorted picture of the temperature distribution, as well as an erroneous notion of the absolute amount of heat possessed by the water column.

It should be emphasized, therefore, that just after an eruption deep in the tube, Geysir is relatively very cool, with the hottest water on top.

Apparently Geysir heats up before the next eruption com-

³ Hallock's experimental work on the Giantess in the Yellowstone Park shows, according to Allen and Day (2), that after an eruption the temperature *first* rises, then remains constant until the next eruption. Boiling does not occur in the tube.

mences, but the theory of a *regular* increase in the temperature from one eruption to another must be modified.

Consider again the first series of measurements marked "before eruption." When they were taken, about 95 per cent of the time interval between the foregoing and the next eruption had elapsed. This means that the next eruption either occurred when the temperature everywhere in the water column still was far below the boiling point, or that a sudden increase of the

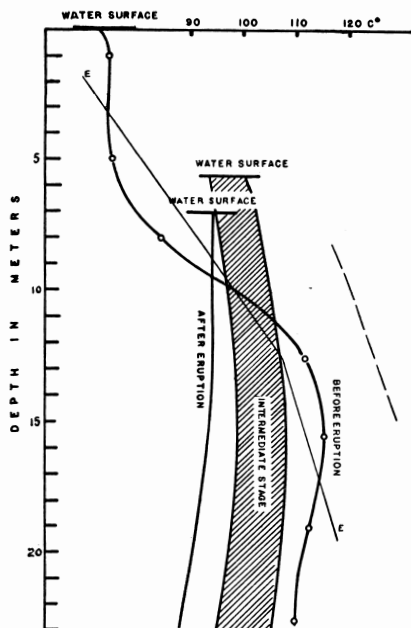


Fig. 6. Temperature distribution in the Geysir well. The curve marked "before eruption" was measured August 21, 1937, ten hours before an eruption. The area marked "intermediate stage" refers to measurements made between four and six a. m., August 22, 1937. This was shortly after a major outburst. The water level had subsided 6 meters, the water boiled violently and every three to five minutes jets were thrown about 10 m. high into the air. The thermometer was in the well all the time. It was fastened to a stone (four lb.) to make it sink rapidly. Repeatedly the stone with the thermometer was flung up in the air with the water jets, but fortunately the thermometer was never damaged. The curve marked "after eruption" was measured at 1:30 a. m., August 22, 1937, ten minutes after a major eruption provoked by soap. The spring was then very quiet. The curve marked EE corresponds to the temperature distribution as inferred from measurements by Einarsson (27). The dash curve to the right gives the boiling point of the water under normal atmospheric pressure and a hydrostatic head corresponding to a water-filled basin.

temperature took place during the last hours of the time interval.

This long quiet interval of about one week should be contrasted with the subsequent short quiet interval. It will be recalled that at 6 a. m. on August 22, 1937, one eruption had finished. The spring was then very cool, the actual temperature distribution corresponding approximately to the curve limiting the left side of the hatched area marked "intermediate stage" (Fig. 6). But before one o'clock the same day Geysir, provoked by soap, had again staged a magnificent eruption.

If it is true that a certain temperature must be reached at which Geysir goes off, then it must be assumed that in the one instance it took a week to feed Geysir with the same amount of heat that in the other instance took only seven hours.

SUMMARY OF FACTS ON GEYSIR.

In southwestern Iceland, near the church of Haukadalur, Geysir and about fifty other hot springs occur within a large area of silica gravel.

Around Geysir a large cone of silica sinter with a wide central basin at the top has formed. Geysir has been known as a spouting geyser for 300 years, but is possibly older. Its crater is probably several thousand years old.

Geysir has never shown any regularity either in the height of its eruptions or in the duration of the quiet intervals between eruptions. Between 1915 and 1935 it was absolutely inactive, but was then reawakened through an operation by which a gap was made in the lip of the basin, placing the water surface one meter below its former level. Immediately Geysir became active, throwing jets of water 60 meters high. Subsequently the gap was locked and the water resumed its old high-mark, but in spite of this, Geysir continued to spout at irregular intervals.

The normal water discharge of Geysir is about 2.5 liters per second. During an eruption it is much higher. In certain stages of the eruption the discharge per minute corresponds to 11 days' discharge under normal conditions. Just after an eruption the basin is dry and the vent is almost empty. Copious steaming occurs, but there is, of course, no water discharge. However, the rate of inflow into the basin may either be abnormally high or abnormally low, even negative, i.e. the water in the vent drains backward into subterranean chambers. Temperature measurements taken after 1935 indicate that Geysir

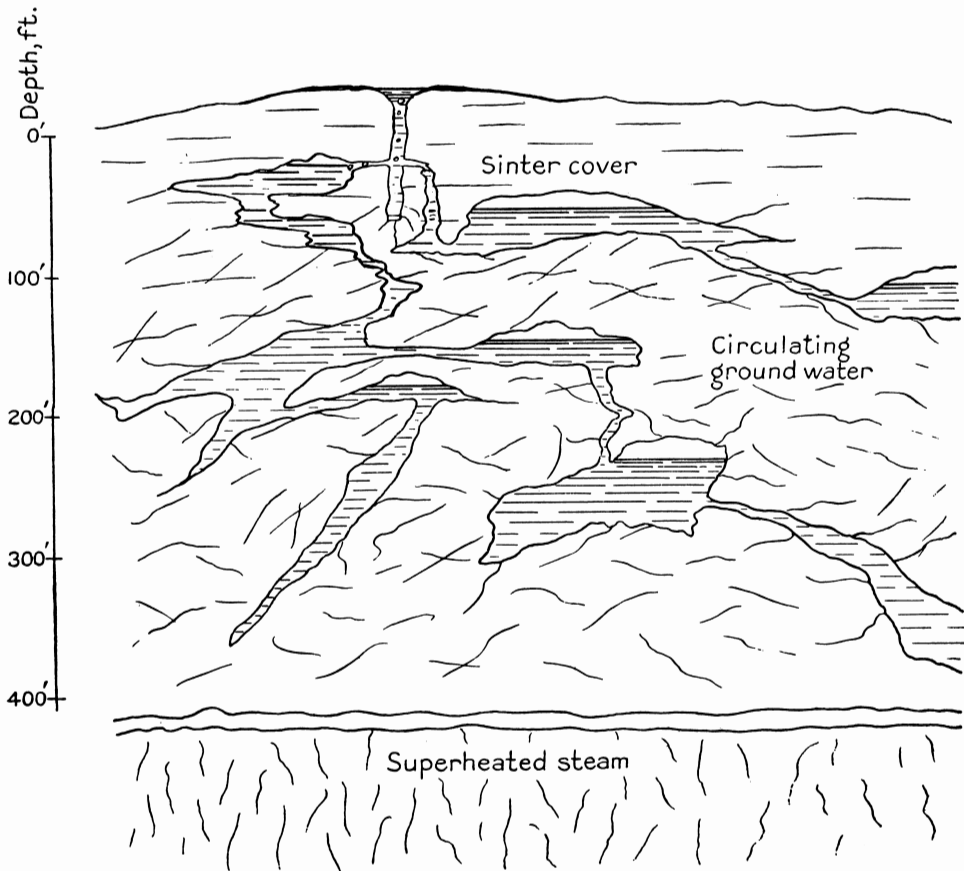


Fig. 7. Schematic diagram of Geysir.

This diagram is substantially a copy of a drawing by Allen and Day (2) as showing the essential parts of a geyser. But in order to make it apply specifically to Great Geysir it has been altered so as to show the closed bottom of the Geysir pipe with the hot-water inlets at the 15-meter level. The great existence of the subterranean reservoirs and channels in Geysir is inferred from observation, but their number and actual shape are subject to conjecture, so in this respect the drawing is schematical. The actual temperature distribution in Geysir shows that an essential part of the hot-water supply enters into the vent at a depth of approximately 15 m. Below this level the water is cooler and relatively more stagnant, and does not take so active a part in an eruption as the overlying water.

is somewhat cooler now than a hundred years ago. When the spring is quiet the temperature distribution is as follows (see Fig. 6): The temperature increases with depth and reaches a maximum (*ca.* 117°) at a depth of about 15 meters. From then on to the bottom it decreases. Immediately after an eruption the lower part of the well is much cooler; the water column now stands low in the pipe with the hottest water (less than 100°) at the top and still cooler water below. Then the pipe and the basin fill up and during the quiet period of the geyser the regular temperature distribution is re-established. Irregular temperature fluctuations occur, but there are no indications that the boiling point is reached anywhere in the water column before a new eruption starts.

The Geysir basin communicates with a great many subterranean reservoirs, passages, and channels that empty into the vent. The capacity of the vent itself is inadequate to supply the necessary water for an eruption, and a cross-section through Geysir is therefore much more complicated than that pictured by Bunsen, and corresponds more nearly to a diagram given by Allen and Day (2) to explain the essential parts of a geyser. Figure 7 gives this diagram slightly modified so as to correspond to the actual dimensions of Geysir. During an eruption, not only the Geysir vent but also some of the large hot-water reservoirs underground are more or less completely emptied.

It is not true that an eruption starts if and when the water in the Geysir pipe is heated to a certain temperature. Rather it seems that the initiation of an eruption is independent of the temperature conditions in the pipe—naturally within certain limits. Clearly the eruption starts outside the vent, but what actually starts it is a matter of speculation that will be considered in the next section.

APPENDIX.

1. *Geyser Action.*

There are many geysers in the world and it is a reasonable assumption that they work according to a common principle, but no satisfactory geyser theory is generally known. A systematic survey of the literature has therefore been made in an endeavor to extract a theory applicable to all geysers. Practically all the manifold theories to explain the working mechanism of geysers rest on observations on Icelandic geysers, chiefly on Great Geysir itself.

Bunsen's theory (12), (13), (104) is best known, and is the one usually considered in text-books and hand-books of geology. Bunsen assumed a temperature distribution of the type given by the curve EE of Fig. 6, page 396. He further assumed that there was a regular increase of the temperature from one eruption to another, effected by hot steam entering the well. Thus eventually boiling temperatures would be closely approached in the well at a depth of 10 to 15 meters. If the water column now could be rapidly raised one meter or so, then the almost boiling water would find itself under a smaller hydrostatic head and at once start boiling; the vapor thus produced would reduce the hydrostatic pressure in the whole well and an eruption would follow. In the air bubbles that periodically are given off, Bunsen saw the agent that first was able to lift part of the water column to a higher level and thus initiate the eruption.

One reason for the general acceptance of Bunsen's theory is probably that various geyser models can be made to work on his principle. However, most of those who have given special thought to the subject have come to the conclusion that this theory may not be applicable to all cases of geyser activity. In the annexed bibliography, references will be found to papers pertaining to geyser action, geyser theories, and to criticism of Bunsen's theory. A résumé of all these papers would expand the present discussion beyond bounds. Suffice it here to state that several critics have shown that, even when limited in its application to Great Geysir, Bunsen's theory involves an unworkable mechanism.

Allen and Day have thoroughly considered this point in their monograph on Hot Springs of the Yellowstone National Park, pp. 208-231. Nothing can be added to their trenchant analysis, and it is unnecessary, therefore, to repeat the arguments here. If the reader remembers the facts on Geysir as given in the present paper, and studies the above-mentioned pages of Allen and Day's monograph, he will realize the shortcomings of any modification of Bunsen's theory to explain the mechanism of Great Geysir. To me it seems necessary to adopt, in the case of Great Geysir, a more complicated structure, such as required by Allen and Day to explain the essential parts of a geyser system (see Fig. 7). The important features of the structure thus inferred have already been summarized (p. 399). It remains to discuss in more detail how an eruption may now be explained.

Thorkelsson's theory on geyser action (50), (82), (84), (85) has so far received little attention, probably because his publications have appeared in Danish or Icelandic journals having a limited distribution. He assumes the existence of spring gases, as well as steam, in underground chambers, and finds in the displacement of water by these gases, as they rise in narrow channels, the reduction in pressure that is the real factor in geyser action. His ideas are supported by calculations that are given in detail in a paper of the Icelandic Academy of Sciences, 1928. The result is briefly as follows:

The gas bubbles, which are assumed always to be saturated with water vapor at the temperature of the spring water, steadily expand on their way up the channel. If the water discharge of the spring is a cm.³ per second, and the discharge of the gases and vapor is b cm.³ per second at 0° C. and normal pressure, then Thorkelsson shows that if there are no convection currents and no cooling at the surface due to a spreading out of the water, we have:

$$\frac{b}{a} = \frac{10.33}{273 \, p r \rho} \cdot (t' - t)$$

where r is the latent heat of evaporation, ρ the density of the vapor at 0° C. and normal pressure, p denotes the tension of the water vapor at temperature t , and t' is the temperature of the spring at a depth where the volume of the gas bubbles becomes vanishingly small.

If the temperature distribution in a spring is known, this formula thus permits a computation of the ratio between the volume of spring gases including water vapor and that of liquid water passing through any given cross-section of the well.⁴

If the Geysir structure is pictured as given in Fig. 7, the vent and the adjacent chambers will be partly empty after an eruption. By the normal inflow of hot water they will gradually be refilled, and spring gases and vapor will accumulate

⁴ Such computations as well as a study of the spring gases present make it probable that in the spouting springs of Iceland the volume of gases and steam given off is much larger than that of water.

At about 20 m. above sea level at Reykjanes there used to be a geyser that spouted sea-water; Thorkelsson (85) thinks the only explanation for this phenomenon is that spring gases and vapor so effectively reduced the hydrostatic head that sea-water could ascend to this height. Thorkelsson (90) also mentions a geyser at Reykir in Mosfellssveit (a few meters above sea level) spouting 8 m. high, although the maximum temperature was 98° C.

at various places under the ceiling of the cavities. The gradual rise of the water in the vent will increase the hydrostatic pressure and thus compress the gases, until a constant pressure is reached by overflowing of the water in the basin.

The capacity of the cavities to store gases is limited, and after a while the compressed gases are forced, therefore, into the Geysir vent, where they rapidly ascend to the surface, expanding as they rise.

In certain geysers having a fixed period the gases thus expelled after all cavities have been filled to their storing capacity are able to fill the upper part of the vent so effectively as to reduce materially the hydrostatic pressure. This in turn liberates a new swarm of the trapped gases, boiling in the lower part of the vent usually follows, and an eruption has started.

In Geysir, however, the gases and steam now given off are not quite sufficient to cause the necessary reduction of the hydrostatic pressure without any extra help. Geysir is always on the verge of eruption but requires a slight irritant to make it go off. This trigger action can be effected artificially with soap (which enormously lowers the surface tension), or by lowering the water surface. When it goes off by itself, which happens once in a while, this may possibly be ascribed to a sudden change in the air pressure or an accidentally increased supply of spring gases or heat. The gas content of the Geysir water depends upon many factors and cannot possibly always remain constant.

The gradual decline and twenty-year sleep of Geysir are best explained by assuming that the trapped gases of the subterranean reservoirs gradually leaked out and percolated to the surface by other routes than through the Geysir pipe. The release of the hydrostatic head by cutting the gap in the crater lip then made a sudden escape possible through the Geysir pipe. Thus the passage was cleared, and subsequently the confined gases could find egress by this route even after the re-establishment of the old water head.

It should be added that, according to Thorkelsson's theory it is not necessary that a geyser boil during an eruption; the spring gases, if abundant, can do the trick without help from boiling water. Therefore this theory furnishes an explanation for the behavior of cold geysers, such as the one near Kane, Pennsylvania (22), the gas geyser at Herlany (11), (65),

(108), and others.⁵ Thus all geyser phenomena are explained by fundamentally the same mechanism.

It would be of great interest to organize systematic studies of Great Geysir, with particular emphasis on a statistical study of the eruptions, continuous temperature measurements, and collection of gases during eruptions. From the results of such studies the details of geyser action could undoubtedly be worked out. Great Geysir in Iceland is the father of all geysers and has thus far furnished data for a hundred years of geyser theories.

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