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ART. XLI.—*Some Conditions affecting Geyser Eruption*;
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1. *Introduction: the influence of hydrostatic pressure.*

BOTH field observation and experiment have contributed to our present knowledge of the physical causes of geyser eruption. The natural history of geyser regions has been summarized by Weed,* and the experimental work by Andreae.† Weed concludes that geysers occur only in acid volcanic rocks, and along natural drainage lines where meteoric waters accumulate for discharge. The source of heat is conceived to be escaping hot vapors from slowly cooling lavas, the only known geysers occurring in regions of recent volcanic activity. New geysers originate by the opening of new waterways along fissure planes in the rock, and such new orifices of overflow are continually forming to compensate the diminution in activity of older vents. The cause of the intermittent spouting which distinguishes the typical geyser was originally stated by Bunsen‡; the boiling point of water rises with increased pressure, hence decreases from the lower end of a water-filled tube upward. If water of a lower stratum, nearly, but not quite, at the boiling point, be lifted by the entrance of steam from below to a level of less pressure and lower boiling point, "the heat which it possesses is in excess of that necessary to make it boil. This excess of heat is instantly applied to the generation of steam: the column is lifted higher and the water below is further relieved. More steam is generated, and from the middle downwards the mass suddenly bursts into ebullition. The water above, mixed with steam-clouds, is projected into the atmosphere. . . ."§

* School of Mines Quarterly, New York, 1890, vol. xi, No. 4, p. 289.

† Neues Jahrbuch für Min. Geol. und Pal., 1893. Bd. ii, p. 1.

‡ Tyndall: Heat as a Mode of Motion; Appleton, 1888, p. 168.

§ Tyndall, l. c., pp. 169-170.

The accuracy of Bunsen's theory was early confirmed by experiment and the only mechanism necessary to produce geyser eruption is a tube filled with water, open above and heated below. Many further experiments have been made, however, with a view to explaining the variations observed in the period and interval of geyser eruptions, the relative amount of steam and water, and the effect of artificial stimulants in hastening eruption. Andrea's experiments were directed toward the imitation of Peale's* types, a classification based on the form of the basins and the relation of the periods of steam and water in the eruption. It is noteworthy that in most of these experiments, the apparatus recommended has an open basin above, which retains the water thrown out and permits it to *flow back* into the geyser tube.

In Peale's classification no mention is made of the nature of the geyser-spring during the interval of quiescence; in some cases there is continuous overflow or discharge, in others there is no overflow except during eruption. As it may be shown that this fact of the presence or absence of hydrostatic pressure at the geyser vent has an important bearing on the conditions of eruption, the writer would suggest a classification based on this very simple distinction; it is a singular fact that in the published descriptions of geysers this point has been frequently overlooked. If geyser waters represent meteoric drainage, they are affected by the laws of hydrostatic equilibrium. In such case a tube continuously overflowing is in a distinctly different class from one which throws off its waters to join the superficial drainage to the sea only during the period of its occasional or intermittent discharge. The first case is represented by such a geyser-spring as "Excelsior," in the Yellowstone Park, a violently boiling cauldron in the hill slope, continually discharging vast volumes of water into the pond below, which in turn drains into the Firehole River; the Great Geyser of Iceland and the Rotomahana Geyser† of New Zealand are other types of the continually overflowing class. "Old Faithful" is the type of the second class: its waters may be seen in violent ebullition a few feet below the orifice of the vent, but overflow takes place only during eruption.

Any apparatus designed to imitate accurately either of these must be provided with a supply reservoir having subterranean connection with the geyser tube, by which water may siphon in to replace that discharged. Obviously this replacement takes place in nature: if the water, as asserted, is meteoric, and governed by the same laws that determine the loci of springs, the natural method of such replacement is by the action of gravity. In the case of Excelsior, this subterranean compensa-

* U. S. Geological Survey of the Territories, 1884, vol. xii, pt. 2.

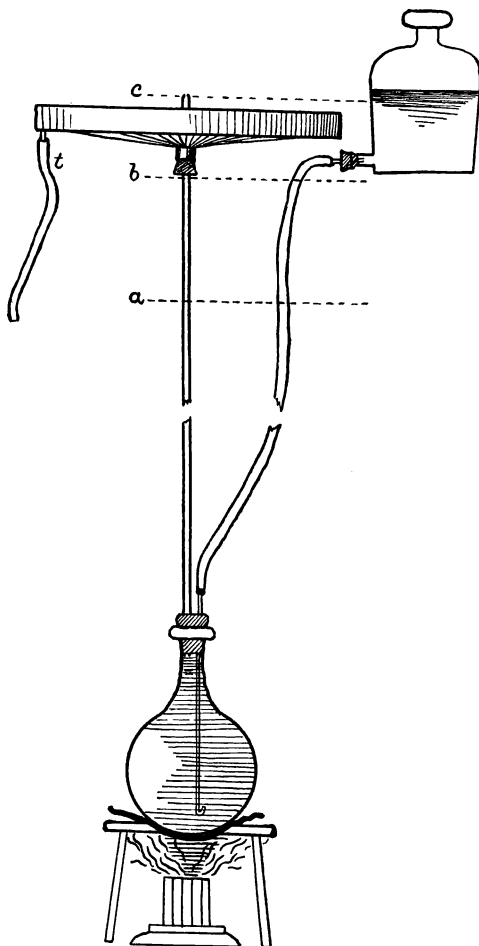
† Destroyed by the Tarawera eruption in 1886.

tion is continuous; the effective head of water at the orifice of exit is fairly constant: in the case of Old Faithful the water-column is in equilibrium, and replacement occurs only after each eruption, when this equilibrium has been disturbed by the ejection of the column.

2. *Experimental Demonstration.*

A simple device to illustrate this process was described by G. Wiedemann* and mentioned by Andree†. Wiedemann made no geological comparisons, the apparatus having been constructed for class-room illustration in physics; and most of the geological experimenters have used back-flow apparatus, without supply reservoirs. The essential parts of Wiedemann's apparatus are a water-column heated below, and a supply-tube entering this column and connecting it with a reservoir of cooler, superficial waters. When the excess of steam generated has thrown out the main column, cooler water filters in through the supply tube, and fills the geyser tube to the level of the reservoir. For effective and regularly repeated geyser eruptions, the reservoir level must be maintained a little below the height of the mouth of the geyser tube.

The accompanying figure illustrates Wiedemann's apparatus, as it has been used by the writer. The dimensions are



* Wiedemann's *Annalen*, xv, 1882, p. 173.

† l. c., p. 4.

as follows: capacity of each flask, one quart; length of main geyser tube 4 feet, diameter (outside) $\frac{5}{16}$ inches: diameter of basin 2 feet; the bottom flares funnel-wise from the center slightly, and is provided with a $\frac{1}{4}$ inch outlet tube *t*. The lower flask rests on a sheet of wire-netting over the flame of a four- or six-tube Bunsen burner, and the basin and reservoir bottle are supported above on a wooden frame. The basin is of zinc and may be raised or lowered so that the mouth of the geyser tube is flush with the bottom of the basin or raised above it as shown. The supply tube is recurved slightly at the bottom of the flask, so that the cold jets which siphon in from the reservoir will not be directed against the glass wall of the flask and break it. The reservoir bottle is connected by rubber tubing with the supply tube, so that the bottle may be freely raised or lowered to various levels indicated by the dotted lines *a*, *b* and *c*.

Experiment 1. "Old Faithful" Type.

When heat is applied below, the reservoir level being at *a*, after about 14 minutes an eruption takes place, characterized by violent ebullition in the flask below, ejection of the water-column to a height of about 4 feet and of a mixture of steam and water for a few seconds longer: then the water-level in the reservoir is seen to fall suddenly, a stream is seen to be flowing into the lower flask from the curved tip of the supply-tube, the cooling of the base of the column is accompanied by condensation of steam and downward suction, the water rises to level *a* again and a period of repose follows. It should be noted that if the level of the cooler water in the reservoir is at *a*, the expanded warmer water in the geyser tube is somewhat above *a*. The process described is repeated at regular intervals of about $1\frac{1}{2}$ minutes, the duration of each eruption being about 20 seconds. If the water in the reservoir be not renewed it gradually becomes warmer and the intervals are of shorter duration. In this case, or with the reservoir level somewhat higher, as at *b*, and the geyser mouth raised above the basin as shown in the figure, we have in miniature the conditions of "Old Faithful."

Experiment 2. "Excelsior" Type.

The conditions are altered if we raise the reservoir level to the point shown in the figure, namely, just above the height of the geyser mouth (*c*). In such case there is continuous overflow of the hot water, and if the outlet tube *t* be left open, this will continually flow off: this overflow must be constantly compensated at the supply tube by cooler water from the reser-

voir, so that the water in the flask never reaches the boiling point. If the water-level of the reservoir be maintained constant, this circulation will continue indefinitely, and in such case there will be a dome-shaped mass of hot water continually boiling up and overflowing at the geyser's mouth, as in the case of the Excelsior geyser. Now at this stage, if the water-level in the reservoir be allowed to sink under the drain upon it, it may fall to a level *six inches* below *c*, without interrupting the continuous overflow; in other words, it may fall back to the *b* level, and yet the geyser will continue to act as a boiling spring, without entering into an eruptive phase. The cause of this is to be found in the differential expansion of the water noted above, and a convectional upflow which acts as a driving power even against a reversed head, after overflow has once been established.* The overflow tube *t* may at this stage be led into the reservoir at the *b* level; this establishes a permanent circulation, the only loss being by evaporation. With the diminution in pressure if the level of the reservoir sinks, there is tendency toward diminished inflow of cooler water at the supply-tube: this implies rise in temperature of the water at the base of the geyser-column, which tends to augment both volumetric expansion and convectional velocity. Hence there is here a critical point where the hydrothermal and hydrostatic forces are in very delicate equilibrium; if the reservoir is lowered an inch, the overflow decreases, ebullition takes place below, and an eruption of extraordinary violence takes place. The same effect is at once produced by placing the glass stopper in the reservoir bottle, and so checking the atmospheric pressure. When the mouth of the geyser-tube is flush with the bottom of the basin, an eruption may be induced by stopping the overflow tube *t* and permitting the water-level to rise in the basin, thus augmenting the pressure on the geyser column. Eruptions once started will continue intermittently, if the hydrostatic conditions are maintained constant: if, however, the water-level of the reservoir again rises to a point where continuous overflow is possible at the geyser's mouth, the eruptions will cease and a hot-spring phase will follow.

3. Field application of the results of experiment.

The two simple experiments described, when compared with the facts of nature, account for the most essential variations observed in the phenomena of geyser eruption. Both are methods of draining the reservoir: the one continuous, the other spasmodic. In the same way the geyser-springs drain

* Such convection currents gain no momentum without overflow, hence at the *a* level convection played no essential part in the phenomena observed.

off the superficial waters that accumulate from the abundant rainfall of the Yellowstone Plateau. The "Excelsior" cauldron is stated by Hague* to discharge constantly into the Firehole River 4400 gallons of boiling water per minute, "and there is no evidence that this amount has varied within the last two or three years (1887)." Weed† has estimated, on the moderate assumption that one-third of the eruption-column of Old Faithful is water, that 3000 barrels are thrown off at each eruption. Here we have examples of continuous and spasmodic drainage methods, both sending their waters eventually to the Madison River, and resupplied from a local source.

The geyser basins are topographic hollows, which supply vents for the meteoric waters accumulated in fissures of the decomposed rhyolite. These waters are heated by vapors escaping from the only partially cooled deeper lavas, and are escaping in the form of springs and geysers. In the springs the overflow is occasioned by hydrostatic pressure: in the geysers it is permitted by occasional violent discharge. The transition from one phase to the other may readily be induced, as shown in Experiment 2, by very slight changes in the hydrostatic pressure, i. e. variations in the mean level of ground-water (*Grundwasserspiegel*), or in the local head for any specific case. The head may be modified at either the source (supply-reservoir) or the orifice of exit; head is diminished by lowering the reservoir through formation of new outlets or through decreased supply, or by building up a cone around the geyser tube. Conversely head may be increased by excessive supply (rainfall) at the reservoir, by clogging of outlets, or by the water finding a new vent at a lower level.

Bunsen stated that the transition from a geyser to a tranquil "Lang" like those frequently found in Iceland, would be occasioned by building up the geyser's bowl so as to raise the water-level, and thus "the water in the depths below, owing to the increased pressure, cannot attain its boiling point, and the eruptions of necessity cease."‡ While this may be true in special cases, we are inclined to believe that the efficient cause of cessation of eruption is generally to be found in an increase in the amount of continuous overflow, due either to new outlets (which may in many cases be subterranean), or increase in the local head. Probably many of the geysers whose eruption intervals are irregular, are in a condition of equilibrium near the critical point described in Experiment 2, so that very slight changes in the local pressure bring about eruption or cessation.

* Arnold Hague: *Geol. History of the Yellowstone Nat'l Park*, Trans. Am. Inst. of Min. Eng., vol. xvi, 1888.

† l. c.

‡ Tyndall, l. c.

It should be noted that exactly the reverse of Bunsen's prediction takes place in our apparatus; an overflowing spring, when confined by building up a basin about it (see page 327), finally ceases to overflow: convectional currents are thus checked, the boiling point is reached below and eruption begins.

On this hypothesis it will be seen that the source of heat is conceived to be fairly constant in the geyser region for like depths, while the variations in the springs are dependent wholly on delicately-balanced hydrostatic conditions; this seems consistent with the facts. A glance at the published atlas sheets (U. S. Geological Survey) of the Yellowstone Park will show that the three principal geyser basins are on drainage lines, and represent the sources of the Gibbon and Firehole Rivers, which unite to form the Madison. These basins are slight depressions in the rhyolite plateau, in a region of maximal rainfall "quite unlike that found in the adjacent country, as is shown by the meteorological records."* On the opposite side of the Continental Divide to the south, and of the Central Plateau on the east, the headwaters of the Snake and Yellowstone Rivers are represented by large lakes. No such lakes exist on the Madison side, the fissured rhyolite there holding its waters in hundreds of subterranean conduits, like a huge hot sponge, and this water overflows in the depressed areas in the form of sinter-building springs and geysers. The Norris and Upper Geyser Basins are about 7400 feet, the Lower Basin about 7200 feet above mean sea level; while the higher points on the divide rise to 8500 feet, affording drainage into these basins of 1100 feet fall. It is further significant that the highest of the geyser-basins is more than three hundred feet below the level of that enormous water-surface, the Yellowstone Lake, where hot springs still abound, and only a few miles of uninterrupted rhyolite sheets stretch between the geyser-basins and the lake.

With a fairly constant source of heat, and springs variously overflowing or confined according to the height of their orifices relative to the local source in each case, it would follow from the experiments that continuously overflowing geysers should exhibit greater irregularity in their eruptive periods and intervals than those so confined within their tubes that no discharge is possible except by incessant eruption. This is borne out in the types mentioned: Excelsior, the Great Geyser of Iceland, and Rotomahana are all known to have been quite irregular: while Old Faithful, the Constant, the Minute-man and the little Model, in the Yellowstone district, are all of the confined type and erupt with great regularity. Excelsior, now recognized as the greatest geyser in the world, was formerly called

* Hague, l. c.

the "Cliff cauldron" and was not known to be a geyser until 1878, when it was first seen in action: it continued to play at irregular intervals for four years and then ceased, resuming its eruptions in 1888. These were continued for only a short season, and since that time the vent has continuously discharged vast volumes of hot water, without explosive eruptions. There is evidently a delicate balance of adjustments between the hydrostatic and thermal forces which govern the actions of this torrent in the depths; it is possible that the level of the source is affected by exceptional variations in the mean annual rainfall. We should thus expect a period of eruption to follow within a year of a season of exceptional dryness, and consequent diminution of head.* In the case of Old Faithful regular eruptions have taken place about once an hour ever since its discovery in 1870: it is a very old vent, as indicated by the seventy feet of sinter which have been built into the walls of its conduit. It is probable that the water-column became confined by reason of the gradual erection of this enclosing shaft; where there may have been formerly continuous overflow, the column is now in equilibrium with its source, and is ejected only under accumulated steam pressure with rhythmic regularity. The tube fills to within a few feet of the orifice soon after each eruption; this implies percolation into the tube of cooler waters through lateral ducts: as it takes practically a uniform period, some sixty-five minutes, to heat this new column to a state of ebullition at the base, and has done so for twenty-eight years of human record, it is fair to conclude that the heat supply is constant.

While this coincidence of overflow with irregularity of eruption, and confinement with regularity, is in general accord with the facts of observation, it is not essential to the theory that every irregular geyser should visibly overflow at the surface or that every regular one should be enclosed. A non-eruptive spring may have subterranean outlets, and an overflowing one may play at quite regular intervals; in such a case ebullition in the depths will depend on the ratio of the amount of inflowing cooler water to the amount of heat supplied: in some cases, too, the overflow may be from a separate superficial source. Complications in the conduit system, such as steam-filled chambers, curved ducts and connections with other geysers, will readily account for the composite eruptions observed at some of the vents: a long steam period following the first eruption may be induced in our apparatus by partially reducing the

* It is noteworthy, though hardly relevant to this case, that in Virginia City, Montana, northwest of the Yellowstone Park, the mean annual rainfall for 1877, the year preceding the first observed eruptions of Excelsior, was much less than the average of the mean annual records for the next four years.

atmospheric pressure at the reservoir-bottle with the stopper: the same effect is produced by clamping the rubber supply tube and thus checking the inflow of cooler water. When a powerful geyser-spring passes from an eruptive phase to quiescence, or the reverse, there is probably a reflex effect on the level of the source, for the total volumetric discharge is probably usually less for the same period under thermal action alone, than when hydrostatic pressure is combined with convection. In other words, geyser eruption is probably not so effective a method of drainage as continuous overflow in certain cases; thus the eruptive phases of Excelsior may have induced a rise of level in the source, an increase of head, and a consequent return to a condition of violent overflow without eruption.

4. Soaping Geysers.

It has long been known that by artificially confining the steam in small-mouthed geysers of high surface temperature, eruption may be brought about prematurely. In Iceland the Strokr is thus stimulated by dumping into the neck of the funnel large pieces of turf. In the Yellowstone district, it has been found that a small amount of soap or lye added to the geyser water will frequently hasten eruption. This is explained by Hague* as due to the increased viscosity of the liquid. "Viscosity must tend to the retention of steam within the basin and . . . explosive liberation must follow . . . Viscosity in these hot springs must also tend to the formation of bubbles and foam when the steam rises to the surface, and this in turn aids to bring about the explosive action, followed by a relief of pressure, and thus to hasten the final and more powerful display." Graham,† as a result of experiments with an artificial geyser, agrees that viscosity has much to do with the confinement of the steam, but questions the influence of bubbles and foam.

Experiment 3. The effect of soap.

The apparatus was arranged to give regular eruptions as in Experiment 1, with the geyser-tube flush with the bottom of the basin and the water maintained about an inch deep in the basin without overflow. A small quantity of fine shavings of Ivory soap was thrown into the basin: these gradually dissolved and the milky solution was, after several eruptions, sucked into the flask below. The occasional steam-bubbles, which, in pure water, rise rapidly through the geyser-tube and

* Arnold Hague: Soaping Geysers, Trans. Amer. Inst. Min. Eng., vol. xvii, 1889, p. 546.

† This Journal, January, 1893, p. 54.

escape at the surface during the intervals between eruptions, were less numerous, very small, and slower in their upward movement through the soapy solution; after five or six eruptions it became evident that the intervals were somewhat shorter (averaging 1 min. 20–30 seconds instead of 1 min. 30–40 seconds) and the periods very noticeably longer (40–45 seconds instead of 20 seconds). The ebullition in the flask was more violent than in the case of pure water, and columns of fine bubbles accumulated in the geyser-tube, only to be ejected with a violent sputter and give place to a new accumulation. It was evident that these accumulated myriads of tiny steam bubbles, confined within the tube and adhering to the walls of the tube, formed a cushion opposing considerable resistance to pressure from below.

After the diffusion of the soapy solution had become general, the reservoir (and consequently the geyser-column) was lowered to the level *a*; the intervals were at once shortened to an average of about one minute, in consequence of the rapid accumulation at the surface of the column and *within the tube* of the cushion of steam bubbles. So resistant is this cushion, that as it grows by the addition of new bubbles rising from below, the water column is actually depressed, down to the neck of the flask; here a point is reached where the frictional resistance of the froth cushion and the hydrostatic pressure are balanced. A further accumulation of steam forces up the column of foam, release of pressure permits the water to burst into violent ebullition and an eruption takes place. From this it would appear that in those geysers where the tube is small, the growth of a cushion of steam soap-bubbles may play a very important part in accelerating the development of eruptive conditions.

Summary.

1. Geysers and boiling springs are subject to the laws of hydrostatic pressure, in common with other springs.

2. In a geyser-spring, overflow once established may be maintained by convection even against a reversed head; this leads to a critical point in the spring's mode of discharge.

3. In this condition, with a constant source of heat, very slight changes in the local head are sufficient to induce a change in the nature of a geyser-spring's mode of action. Such change in the head may be caused by variation in rainfall, by building up a sinter cone, by forcing new outlets at lower levels, or by clogging of old conduits.

4. Geyser basins afford drainage channels for meteoric waters. The drainage takes place by either continuous over-

flow (hot springs) or spasmodic eruption (geysers). Both types, as well as transitional forms, are represented in the Yellowstone Park.

5. In general, those geysers which are irregular in their eruptions have continuously overflowing vents; and the most regular geysers have confined waters, which overflow only during eruption. This is explained by the fact that the overflowing vents are under hydrostatic pressure, cooler water from lateral ducts is continually replacing that which flows off, and the ebullition necessary to produce eruption is thus prevented; eruption can only take place in the seasons of minimal inflow of cooler water, when the heat is in excess. Where the water is confined, on the other hand, and the supply of heat constant, cooler water rushes in only after each eruption, and a definite interval is required to bring it to the boiling point at the base of the column. Overflowing and confined springs should be distinguished in any description or classification of geysers.

6. For the artificial stimulus of geyser eruption, an important effect of the bubble-forming alkalies, in small tubes, is the initial depression of the water-column by the growth of a confined cushion of minute steam bubbles. The release of pressure induced by the final ejection of the froth column causes eruption.