ON THE GEYSER IN ATAMI, JAPAN.

BY K. HONDA AND T. TERADA.

THE remarkable phenomena of the periodic eruptions of geysers have attracted the attention of many observers. Mackenzie [1] observed the Great Geyser of Iceland in 1811 and tried to explain the phenomenon. But his theory proved unsatisfactory. Bunsen [2] visited the same geyser in 1847 and proposed his well-known theory of the vertical pipe. Müller [3] constructed a model after Bunsen and showed that it worked periodically if two portions of the vertical pipe be heated. This theory, however, is not free from objections. Contrary to Bunsen's view, O. Lang [4] considered the seat of eruption to lie at a great depth below the vertical pipe, the water in which acted as a valve for the enclosed vapor. Models given by J. Ziegler [5] and G. Wiedemann [6] explain the phenomenon of the geyser from a similar point of view. Other models by J. Petersen, A. Andreae and others [7] do not differ much in principle from those just referred to. The experimental investigations of Andreae [8] and H. Ebert [9] show

[1] Mackenzie, Travels in Iceland, 1811.

[2] Bunsen, Physikalische Beobachtungen über die hauptsächlichsten Geysir Island, Gehlers Physikalisches Wörterbuch (2 Auflage), LXXII.; Pogg. Ann., 72, 1847.

[3] Müller, Lehrbuch der Kosmischen Physik, Braunschweig, 1894, S. 619.

[4] O. Lang, "Ueber die Bedingungen der Geysir," Göttinger Gelehrten Nachrichten, 1880, S. 225.

[5] J. Ziegler, Vorträge des phys. Vereins in Frankfurt a. M., 1872, demonstrated by Dr. Nippoldt.

[6] G. Wiedemann, "Ueber einen Apparat zur Darstellung der Erscheinungen der Geysir," Ann. der Physik und Chemie (2), XII.

[7] J. Petersen, "Darstellung der Geysir Erscheinungen," Neues Jahrbuch für Mineralogie, Geologie and Paläontologie, 1879, II.

A. Andreae, "Ueber einen künstliche Nachbildung der Geysirphänomene," Ibid., 1893, II.

K. Antolik, Zeitschrift f. d. Phys. u. Chem. Unterr., 1890–91.

A model given by A. C. Munby, Nature, 65, p. 247, is of a somewhat different principle.

[8] Andreae, loc. cit.

[9] H. Ebert, "Versuch mit dem G. Wiedemannschen Geysirapparate," Annalen d. Phys. u. Chem. (2), LXIII.

that by properly modifying different parts of the models, several types of natural geysers can be imitated. The latter, however, remarks that such a simple theory is not able to explain all the diversities in the manner of eruption observed in numerous geysers in Iceland, North America and New Zealand.

Different from other geysers, the geyser of Atami in the province of Izu is characterised by the regularity of the eruption, which consists in alternate projections of hot water and steam, usually five times in succession. The water projected does not return to the orifice as it does in several other geysers. The orifice, which originally opened vertically upward, has been covered by a heap of stones to prevent the dangers caused by the eruption. At present three orifices are exposed, among which one is distinguished as the principal opening. Besides, there is another mouth hidden underground; the water projected by these orifices is distributed to several bath-houses by conduits. The water is of a strong saline taste, containing about ½ per cent. of sodium chloride, *i. e.*, about one fifth of that contained in the sea water. The mouth of the geyser is not far from the sea coast and about 22 m. above the sea-level.

The eruption occurs usually five times in a day and night. During the time of repose, we see only a small quantity of steam rising from the mouth. As the time of the eruption approaches, a rumbling sound is heard underneath. The boiling water appears just inside the mouth. It soon retires and again appears. This state continues for about three quarters of an hour. Next a small quantity of hot water flows out intermittently. This is followed by an intermittent stream of moderate quantity with a longer period. The activity soon attains its maximum. A torrent of hot water gradually increasing in force is torn into a violent splash and projected with a great velocity by steam which gradually increases with the diminishing water. When the roaring sound of steam reaches the maximum, the water almost disappears. The steam now diminishes and is soon followed by the second gush of water. After these states have been repeated five or six times, the activity ends with the last steam which gradually subsides into an inconsiderable amount as seen at the beginning. It takes above two hours from the beginning to the last stage of the eruption. The time of repose is a little less than three hours on the average. These regular recurrences are often interrupted by an abnormal outburst, called *nagawaki*, at which the water and steam come out incessantly for above twelve hours and after which a long repose follows as a rule. In years rich in this anomaly it occurred almost monthly, whereas in the last few years only once or twice.

Our excursion to Atami was undertaken to make detailed observations as to the manner of eruption and if possible to get an insight into the internal mechanism of the geyser. Arrangements were contrived to keep records of the manner of each successive eruption.

A pendulum consisting of a brass rod and a heavy lead ball was hung before the principal orifice. The water and steam, projected nearly horizontally, deviate the pendulum by the impulsive pressure. The motion of the pendulum was transmitted by a cord and pulley to a recording pen guided by two vertical pillars with grooves, in which roll two friction-wheels attached to the penholder. The vertical displacement of the pen was recorded on a cylinder making one revolution every two hours. The pendulum was afterward removed to a position where the impulsive action of vapor and splash was shielded off and the flow of water only could be recorded.

To record the manner in which the steam is ejected, an arrangement was used which was nothing more than an air-thermograph. A small cylinder of sheet zinc was introduced into a mouth neighboring to the principal orifice, where it was possible to find a position such that the bulb was exposed to the heating of the steam only. This orifice, being a smaller branch of the main one, could be considered as representing the main one on a reduced scale. The bulb was connected by a fine copper capillary tube to one of the arms of a U-tube containing mercury. The motion of the mercury meniscus in another arm was recorded on a cylinder by a pen mounted on a float on the mercury and guided by two vertical pillars with grooves and two friction-wheels attached to the penholder. To determine the temperature of the water and steam a maximum thermometer was used.

To take continuous records of the exact time of eruption, and also the general manner of each eruption, a mercury tide-gauge, constructed after Mr. Nakamura's design,[1] was used. The lead pipe of the instrument was inserted to the neck of the geyser. The pressure of the projected water at the neck during each eruption was recorded on a cylinder revolving once every 24 hours. The automatic records of daily eruptions have been taken during the last two years.

In the following lines, a brief account of our results of observation is given.

I. Ordinary Eruption.

An ordinary eruption consists of three distinct series, termed conventionally the first, the second and the third, differing in period and force and succeeding one another very regularly. Fig. 1 is a reproduction of one of the records obtained by our pendu-

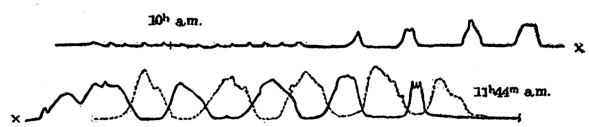

Fig. 1.

lum recorder. The abscissa represents the time, and the ordinate the deflection of the pendulum by the pressure of water. The dotted line shows the velocity of the steam obtained by our air-thermograph. The first series, which begins the outburst, consists of a small quantity of water appearing with an average period of 1 minute and 40

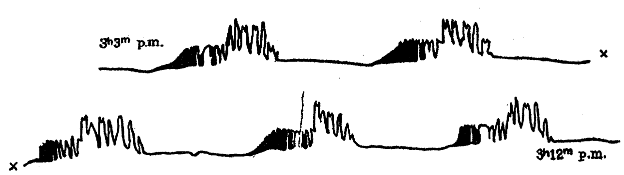

Fig. 2.

seconds. After this intermittence has been repeated a score of times the second series follows. A moderate quantity of water comes out three or four times with a mean period of six minutes. The water increases in quantity and force till at last the third or

[1] S. Nakamura, Proceedings of the Tokyo Physico-Mathematical Society, Vol. I., No. 15, p. 123, 1902.

principal series sets in. On the first outburst of the third series we see very often the superposition of the last one of the second series. The third series is to be distinguished from the previous series by its violence and the quantity of water and steam. The sequence of the water and steam occurs usually five or six times with a mean period of about 11 minutes. Fig. 2 is a record obtained by the mercury tide-gauge, and shows regular periodic sequence of eruptions with a mean period of 24/5 hours.

II. Abnormal Eruption; Nagawaki.

The first *nagawaki* recorded by our arrangement began at 4:30 A. M. on January 14, 1905, from the fourth eruption of the third series. During two or three days before the *nagawaki*, the period of successive eruptions seems to have been slightly diminished; but in such a degree that may be found not seldom in our records without leading to either *nagawaki*, or anything extraordinary. The *nagawaki* began, as it were, almost suddenly in the midst of an ordinary eruption. The flow of hot water continued without interruption, gradually decreasing in quantity and mixed with steam. At 7:40 P. M., it came to a sudden repose; at 2:40 A. M. on the 15th, an intermittent flow of hot water resembling the second series of an ordinary eruption began and continued for about three hours. After a repose of four hours ordinary eruptions at last set in, but with the period remarkably shortened and the activity strikingly reduced. The number of eruptions per day was ten, a remarkable contrast to the ordinary frequency of five. The frequency decreased afterward very slowly with the time, and recovered its original value after the lapse of about a month.

The second *nagawaki*, which occurred on May 26, was quite similar to the previous one in its general aspects, though it took place in conjunction with the extraordinary decrease of the general activity.

It is an interesting coincidence that the two *nagawakis* of January and May began at the same phase of the ordinary eruption at nearly the same hour of day, and that a center of low atmospheric pressure was approaching from the Pacific in each case.

III. Influence of Atmospheric Pressure.

Examining our records of long observation, we found a remarkable fact that low atmospheric pressure *retards* and high atmospheric pressure *accelerates* the eruption of the geyser. This curious fact may be seen from Fig. 3. Times of the successive eruptions are plotted as the ordinates corresponding to each day which is laid off as abscissa; corresponding points for successive days are connected into five broken curves (*b*)–(*f*). Curve (*a*) represents the daily change of the mean atmospheric pressure. The probable cause of the strange concidence would be given later.

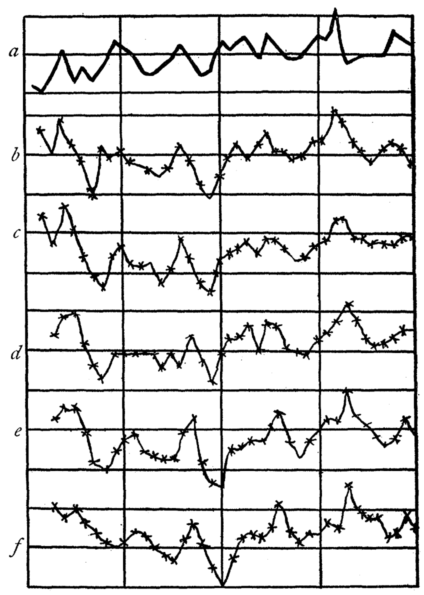

Fig. 3.

IV. Temperature of Hot Water During Eruption.

A maximum thermometer was placed about 1.5 m. inside theorifice and the temperature has been read daily since last April. It was found that the temperature at this depth was almost invariably 103°–104° C. At the orifice, however, it was about 100° C., indicating a rapid cooling of the hot water. Hence it may easily be conjectured how hot the underground water would be at a depth of some ten meters.

V. Velocities of Water and Steam.

The pressures of water and steam upon the bob of a special pendulum arrangement were recorded on the cylinder, and estimated afterward by the substitution of known weights. The total pressure upon a sphere is known to be approximately equal to one half of that upon a circular disk of the same diameter. Hence

$$p = \frac{\pi r^2 \rho v^2}{2}, \quad \text{or} \quad v^2 = \frac{2p}{\pi r^2 \rho},$$

where p is the pressure, r the radius of the bob, ρ the density and v the velocity of water or steam. For the water we obtained, at the mouth,

$$v = 1.5\text{–}2.0 \text{ m. per second,}$$

and for the steam

$$v = 18\text{–}24 \text{ m. per second,}$$

the velocities varying within the limits according to the phase of each eruption. In this calculation, we took for the value of ρ the density of saturated vapor under ordinary atmospheric pressure.

VI. Quantities of Water and Steam.

For the rough estimation of the quantity of water thrown out in an eruption, we measured directly the amount supplied to a number of tanks and calculated the total from the sections of several conduits. The quantity thus estimated amounts to 45 cubic meters.

The rough estimation of the quantity of steam was carried out in the following way:

Let the quantity of steam be denoted by Q. Then

$$Q = \int Sv\rho dt,$$

when S is the area of the orifice. If V be the ordinate in the curve representing the relation of velocity of steam to time, obtained by our special thermograph above referred to, we may put

$$v = kV, \quad \therefore \quad Q = S\rho k \int Vdt.$$

Since v was determined by the pendulum experiment, and the corresponding V from the thermograph curve, k can easily be known; by calculation, it was found to be 500. S was estimated to be 200 cm.^{2}; for an instance, we obtained

$$\int Vdt = 6{,}500, \quad \therefore \quad Q \doteqdot 500\ kg,$$

the number must be considered as giving only the order of magnitude.

VII. Extraordinary Decrease of Activity.

During the course of the last few years, several wells have been bored in this district. Most of them give a moderate quantity of hot water only by pumping. Since the last year, the number of wells was greatly increased, amounting to about twenty in all. Sawaguchi's well, bored on March 27 of this year, burst out with great violence, throwing up a column of hot water about 8 m. high. On May 22, another one, Yonekura's well, of greater activity, has been opened within a few hundred meters of the geyser, giving hot water at a rate of 310 cubic meters per day. Two days afterwards another one, Hignchi's well, of not much less activity, was bored. After the boring of the Sawaguchi's, a slight decrease in the frequency of the geyser was observed; on May 20 it was reduced to 4.4, though the force of each eruption presented no appreciable change. After the boring of the other two the frequency remarkably decreased; it was 3.6 on May 26. Moreover, the first and second series of each eruption became considerably longer and the principal series was considerably lessened in force. After the *nagawaki* of May 27, the frequency was temporarily increased; but on June 11, it fell again to 3.2. As shown in Fig. 4, the first and second series lasted for three and a half hours and

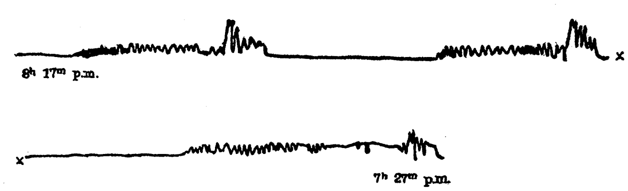

Fig. 4.

the third was reduced to only three weak eruptions. Consequent decrease in the quantity of hot water caused trouble to several bath-houses supplied by the geyser, and therefore the above three wells were all stopped — Yonekura's on June 12, Sawaguchi's on the next day and Higuchi's on July 12. The frequency of eruption has gradually increased since then, and in the middle of August, it attained 4.5 which is yet somewhat short of the original value. As for the mode of each eruption, it has quite recovered in force.

VIII. Level Change and Temperature of Wells.

Level change of two wells near the geyser were recorded by means of Honda's limnimeter. Nomura's well, which is within 200

m. of the geyser and quite high above the sea level, shows a regular up and down motion corresponding to the eruption and repose of the neighboring geyser. Effects of the tidal and atmospheric pressure are also recognizable, but not very remarkably. (Fig. 5.) The

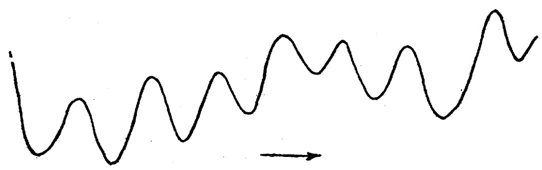

Fig. 5.

temperature of the water of this well is 50°–60° C. In Suzuki's well, which is more remote from the geyser than Nomura's, the effect of the geyser is not observed, but the level rises and falls with the tide. (Fig. 6.) The head of the water is 22 m. above the sea

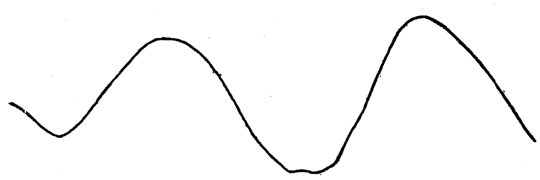

Fig. 6.

level. Temperature measurement with a maximum thermometer was made in Abo's well, which is situated in the midway between the geyser and Yonekura's well. The results are tabulated as follows:

At the surface of water,	62°.0 C.
23 m. below,	95°.5
28.5 m. "	98°.3
29.7 m. "	104°.7
31.0 m. "	118°.2

Thus, a remarkably high temperature was found to exist in the surface layer of the district.

IX. Explanation of the Phenomena.

Existing theories on geysers fail to explain the exact manner of eruption of the geyser of Atami. After a series of experiments with several forms of models, we arrived at a theory which we hope may fairly explain the phenomena of the geyser in question.

Referring to Fig. 7, *A* is a cavity lying in a considerable depth; *a* is the vertical pipe and *b* a canal which supplies the water to *A*. We conceive a side canal *c* intermediate between *A* and *a*, which leads to a second cavity *C*, not shown in the figure. The temperature of the water in *a* and *c* is supposed to be lower than the corresponding boiling point. Water in *A* is heated by the wall of the cavity, the temperature of which is supposed to be decidedly higher than the boiling point at the depth. The source of the heat is probably to be attributed to the hot water and steam running through numerous veins and canals extending in the depth of the district. When the tension of the vapor in the cavity attains a critical value, the water is thrown off and then the steam follows. When a certain amount of steam is given off, the pressure in the neck is reduced to such a degree that the water flows in from the side canal and stops the eruption momentarily. Soon the downward pressure of the water column is overcome by the tension of vapor and the second gush follows. These eruptions are repeated several times, till the vapor pressure is so reduced as to admit the comparatively colder water from the feed canal *b* and also from *c*. Thus the activity is quenched for a while till the next eruption begins. A model (Fig. 8) constructed according to this view, worked very satisfactorily. The manner of eruption was imitated in many details.

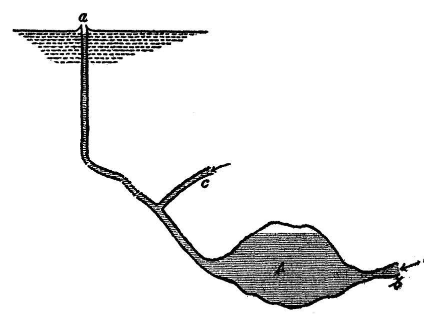

Fig. 7.

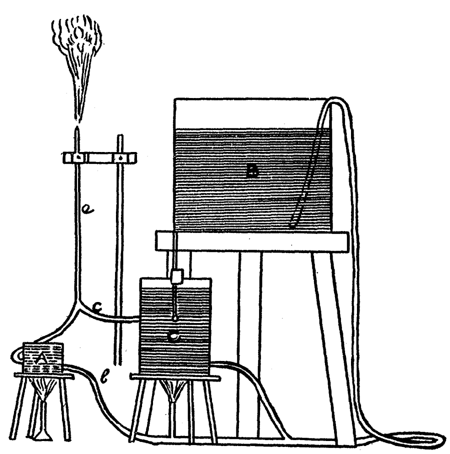

Fig. 8.

The number of intermittences in an eruption increases with the temperature of the water in *c*.

The phenomena of *nagawaki* may be explained partly by the supposition that the underground temperature is raised above its normal value and so the temperature of the cavity *C* becomes higher than the ordinary case. If the temperature of the cavity *C* in our model be raised to a certain value, the eruption corresponding to *nagawaki* begins. It resembles the actual one even in some details. The cause of this occasional change of temperature is probably the change of the subterranean volcanic activity which keeps the underground temperature in this district considerably above the boiling point of water.

The fact that the frequency of eruptions immediately after *nagawaki*, is nearly doubled, may partly be explained, if we consider that the temperature of the heating cavity was raised during the course of the *nagawaki* by the incessant flowing of superheated water from a great depth. It may be added as a very suggestive fact that if in our model, a quantity of air be blown into the heating cavity, the frequency of eruption increases at first remarkably and gradually decreases with the gradual expulsion of air by successive eruptions; even the weakness of activity in the actual case is imitated with great faithfulness. During a few hours after *nagawaki*, the cavities as well as the canals leading to the orifice remain drained out, so that it is possible that air or other gases may enter into the cavities and cause the increased frequency of the eruption.

It is a common fact of observation that the temperature of some ordinary hot springs rises with low atmospheric pressure. This is undoubtedly due to the increase of flow due to the enhanced circulation of water caused by the reduction of the pressure. If in the supposed heating cavity of the geyser, the interchange of water due to the slow circulation through numerous veins and fissures (not shown in the figure), be accelerated by some cause, the time required for the sufficient heating for eruption must necessarily be prolonged. This consideration seems to explain partly the influence of atmospheric pressure on the period of eruption above mentioned. Again, the possible influence of well-boring on the geyser, may be explained on the same basis. Such a well may increase the circulation of underground water in its vicinity and result in the retardation of the eruption of the geyser in a similar manner. Moreover, it is quite natural that the hot water should find its easier vent through a new passage opened with a less resistance, at the expense of the quantity originally given out by the old one alone. The prolongation of the first and second series of an eruption, suggests the slowness with which the pressure in the heating cavity approaches the critical value. The careful investigation of the variation of the frequency in connection with the boring and stopping of the wells, leads us to the strong belief that the striking coincidence of the well-boring and the decrease of the activity of the geyser, is a necessary, and not an accidental one. If the frequency of eruption does not yet quite attain its former value long after the stopping of the wells, we need not wonder at all, since some irreversible change in the subterranean mechanism might have happened during the period of the anomaly.

Physical Laboratory,
Imperial University, Tôkyô,
December 28, 1905.