PUBLICATIONS OF THE EARTHQUAKE INVESTIGATION
COMMITTEE, SECTION B, ART. IV.

On the Geyser in Atami.

BY

K. HONDA and T. TERADA.
Lecturers of Physics, Tōkyō Imperial University.

With Plates I–XII

I. INTRODUCTION.

The remarkable feature of the periodic eruptions of geysers has attracted the attention of many observers. Mackenzie,[1] who travelled in Iceland in 1811 and observed the Great Geyser, first tried to explain the phenomenon; but his theory proved unsatisfactory. Bunsen,[2] travelling on the same island in 1847, made observations on the Great Geyser, and explained the phenomenon by his well-known theory of the vertical pipe. According to him, the origin of the eruption lies in the lower part of the vertical pipe which does not exceed 20m in the case of this geyser. Müller[3] constructed a model after Bunsen and showed that it works periodically, if two portions of the vertical pipe be heated. His theory, however, is not free from objections. Contrary to the Bunsen's view, O. Lang[4] considered the seat of the eruption to lie at a great depth in a canal connected with the vertical one, the water in which acts as a valve for the enclosed vapour. Models given by Julius Ziegler[5] and by G. Wiedemann[6] explain the

1) Mackenzie, Travels in Iceland, 1811.

2) Bunsen, "Physikalische Beobachtungen über die hauptsächlichsten Geysir, Islands," Gehlers Physikalisches Wörterbuch (2te 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, S. 225.

5) 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 Phys. u. Chem. (2), 12.

phenomenon of the geyser from similar points of view. The models consist of a vertical pipe and a large cavity containing hot water and connected to a water tank placed at a suitable height. The constant heating of the cavity produces periodic eruptions of water and steam. Models constructed by J. Petersen, A. Andreae and others[1] do not differ much in principle from those just referred to. The experimental investigations by Andreae[2] and E. Ebert[3] shew that by proper modification of different parts of the models, the several types of eruptions observed in natural geysers can easily be imitated; but the latter remarks that it seems difficult to explain by such a simple theory all the diversities of the manner of eruptions observed in numerous geysers in Iceland, North America and New Zealand.

In Japan, we have two geysers, one at Atami and another at Onikōbe, the force of eruption of the latter being very weak. Twenty years ago, we had another one in Noboribetsu in Hokkaidō, the eruption of which is said to have recurred a few times per hour, projecting hot water a few meters above the ground. At present, it has completely lost its periodical character.

The geyser of Atami is situated on the eastern slope of the coast mountain range of Izu. Its orifice is about 1 km distant from the sea shore and about 22 m above the sea level. Differing from other geysers, the geyser of Atami is characterized by the regularity of its eruption, which consists of alternate projections of hot water and steam, usually five times in succession. The orifice, which originally opened vertically upward, has been covered by a heap of stones to prevent the dangers caused by the eruption, and directed horizontally, so that

1) J. Petersen, "Darstellung der Geysir Erscheinungen," Neues Jahrbuch für Mineralogie, Geologie u. Palaeontologie, 1879, 2.

A. Andreae, "Ueber einen künstliche Nachbildung der Geysir-phänomene," ibid, 1893, 2.

K. Antolik, Zeitschrift f. d. phys. u. chem. Unterricht, 1890–91.

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

2) A. Andreae, loc. cit.

3) H. Ebert, "Versuch mit dem G. Wiedemannschen Geysir-Apparat," Ann. d Phys. u. Chem. (2), LXIII.

the water projected does not return to the mouth, as it does in many other geysers. At present, three orifices (A, a, a′, Pl. I) are exposed, among which the one (A) is to be distinguished as the principal opening. There is besides, another mouth, hidden underground. The water projected by these orifices is distributed to numerous bath-houses by a system of conduits.

According to the result of the analysis by Dr. Martin in 1874 and by Dr. Tawara in 1883, the mineral constituents of the water of the spring in 1 litre are as follows;—

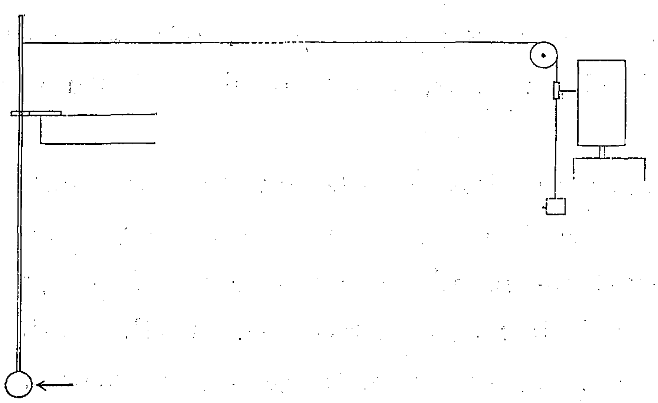
Mineral constituents	Martin	Tawara
Solid residuals	10.0104 gr.	9.235 gr.
Sodium chloride	3.79	5.409
Potassium chloride	1.81	0 354
Calcium chloride	1.767	2.893
Magnesium chloride	2.333	0.0145
Calcium sulphate	0.193	0.1313
Ferrous bicarbonate	0.0031	0.002
Calcium bicarbonate	0.0042	trace
Silica	0.110	0.5249
Manganese chloride	trace	trace
Sodium bromide	,,	,,
Potassium bromide	,,	,,

The water is of a strong saline taste, containing about ½ percent of sodium chloride, that is, about one fifth of that contained in sea water.

The ordinary 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. Boiling water appears just inside the mouth. It soon retires and again appears. This state is continued 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 great velocity by the steam, which gradually increases with the diminishing water. When the roaring sound of the steam reaches its maximum, the water almost disappears. The steam now diminishes and is soon followed by a second gush of water. When these discharges of the water and steam have been repeated five or six times, activity ends with the last discharge of steam, which gradually subsides into an amount as inconsiderable as 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 the steam come out incessantly for above twelve hours, after which as a rule a long repose follows. In years most noticeable for this anomaly, it has occurred almost monthly, whereas in the last few years only two or three times.

II. ARRANGEMENTS FOR OBSERVATIONS.

To make detailed observations of the general manner of eruptions, the following arrangements were used.



A pendulum was made of a brass rod, at the lower end of which a lead ball was fixed (3 cm in diameter), and vertically suspended by a short horizontal axis fixed to the rod and pivoted to a catch at the end of a large wooden beam laid horizontally over the principal orifice. The pendulum hung nearly vertically, the lead ball facing closely to the mouth. To the upper end of the rod was attached a string, which passed horizontally to a pulley of the recording instrument. The string after passing over the pulley was attached to a suitable weight. The whole system was so adjusted that the pendulum hung vertically under the balancing action of its own weight and the tension of the string going to the recorder. When the eruption begins, the pendulum is deflected by the pressure of the water and steam. The vertical part of the string below the pulley conveys a pen, which is guided as in the limnimeter[1] used by one of us for recording the level change of artesian wells. The motion of the pen is recorded on a cylinder rotating about a vertical axis. From the records obtained, we can easily distinguish the water and steam-pressure from each other. The part of the record representing the water pressure is much disturbed by zigzags.

Since it was, however, desirable to record the water and the steam separately, the pendulum was transferred to a place in front of the orifice, where all the water ejected flows through a narrow canal to a tank. The whole system was shielded off from the impulsive action of the splash and the steam by a screen of wooden planks. The records thus obtained were completely free from steam pressure.

To record the pressure of the steam only, was a matter of considerable difficulty. Just before the orifice, the steam pressure was tolerably strong; but, there, it was impossible to separate the steam pressure from that of the water. Where the ball of the pendulum did not receive any pressure from the splash of the water, the steam pressure was not strong enough to cause any sensible deflection of the pendulum, so that the arrangement failed to give any

1) K. Honda, Publications of the Imp. Earthq. Inv. Comm., No. 18, p. 73.

satisfactory result. The aspiration method was also tried, but it failed to produce sensible diminution of the pressure in our recording apparatus. We, at last, adopted the following arrangement, which was essentially nothing more than an air-thermograph. A hollow cylinder or a bulb of iron sheet (radius = 2 cm, length = 9 cm) was introduced into a side orifice (a), where the water flows out slowly, and where it was possible to find a position such that the bulb was exposed to the heating actions of the steam only. To avoid too rapid expansion and contraction of the enclosed air, the bulb was covered with two layers of cloth. Since this orifice is a small branch of the principal orifice, and the manner of the eruption quite similar for both mouths, the side orifice may be considered as representing the mode of eruption in the principal one on a reduced scale. The bulb was connected by a fine copper capillary tube (diameter = 2 mm.) to one of the arms of an U-tube containing mercury. In another arm of the tube, a float carrying a light vertical pen-holder was introduced. The motion of the float caused by the expansion and contraction of the air inside the bulb, was recorded on a vertical drum by the pen, guided as in the case of the limnimeter.

For the statistical investigations, a simple apparatus which might continuously record the exact time of eruption and also, if possible, the general manner of each eruption was desirable. For this purpose, a mercury tide gauge constructed after Mr. S. Nakamura's design[1] erved very well. The lead pipe of the instrument was inserted in the neck of the geyser. At the beginning of activity, the instrument records the periodic level-change of the head of water inside the orifice. When the velocity of the water increases, it records the kinetic pressure of the ejected water. The steam pressure does not display itself on the records. The instrument has been working satisfactorily since the end of March, 1904.

For the determination of the temperature, a maximum thermometer which was graduated up to 150°C, was used.

1) S. Nakamura, Proc. of Tōkyō Math.-Phys. Soc., Vol. I, p. 123.

III. RESULTS OF OBSERVATIONS.

1. Ordinary Eruption.

a) *Flow of water and steam. Fig. 1.*

To record the initial stage of eruption, the lead ball of the pendulum was lowered as near as possible to the bed of the canal just outside the mouth, and the small initial quantity of water was compelled to flow entirely through a narrow aperture cut in the edge of a wooden board fixed to the bed close to the mouth. The ball hung just outside the aperture.

Referring to Fig. 1, we see that there exist three distinct series of intermittences. The first series which appears as an introduction to the display, consists of a small quantity of water with an average period of $1^m 40^s$. 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 interval of 6 minutes. The water increases in quantity and force, till at last the third or principal series sets in. On the first outburst of the third series, we see always the superposition of the last one of the second series. The third series is to be distinguished from the previous series by both its violence and the quantity of the water and steam put out. Besides, the roaring sound of the steam is a remarkable characteristic of this series. The sequence of the water and steam occurs with a mean period of about 11 minutes, and is repeated usually five or six times, not rarely four or seven times.

The pendulum was actuated by the impulsive force of the water and steam; the diagram shows a greatest excursion somewhat later than the actual maximum of the water. In this stage, the velocity of the steam is gradually increasing. When the water decreases to an inconsiderable spray and the steam predominates, the pendulum draws back. The disappearance of zigzags in the curve shows the prevalence of the steam.

b) *Flow of water only. Figs. 2 and 3.*

The records are generally similar to those given in Fig. 1, except that in this case, the impulsive pressure of the steam and splash is almost entirely eliminated. In these diagrams, we also see the superposition of the second series at the beginning of the third one. It will be observed that the last one of the third series is often distinguished by the small quantity and the weak force of the water.

c) *Flow of steam only. Figs. 4 and 5.*

In these diagrams, the zero line falls abruptly as soon as the cloth of the bulb is wetted by the condensed steam; this is due to the cooling caused by the evaporation. The ordinate of the curve may be considered as indicating in some measure the velocity of the steam at any instant and hence the area enclosed by this curve and the zero line is a rough measure of the quantity of the steam expelled. In subsequent experiments, it was found better to take the envelope off the bulb, whereby the falling of the zero line is avoided.

When two corresponding diagrams, Figs 2 and 4, or 3 and 5 are placed one upon another so as to bring their abscissae into coincidence, the recurrence of the alternate ejections of the water and steam can clearly be seen.

d) *Level-change during the time of repose. Figs. 6 and 7.*

The end of the lead pipe of the tide-gauge was inserted in the neck of the geyser as deep as possible. It was estimated that the end was only a half meter below the mouth. Since the neck is crooked in a very irregular manner, further attempt to insert the tube deeper than this failed. The record was continuously taken from the end of one eruption to the beginning of the next one.

The diagram obtained reveals to us a remarkable fact that within about 40 to 50 minutes after the end of an eruption, the head of hot water appears within a half meter below the mouth. The head seems to oscillate about its position of equilibrium for about one and a half to two hours, till the next activity begins. This interval may be considered as the time of preparation for the next eruption.

e) *Time of occurrence. Figs. 8, 9 and 10.*

The end of the lead pipe was drawn up to just inside the mouth. The clockwork gives one revolution every 24 hours. The records have been taken continuously from April, 1904. up to the present. From the statistical investigation of these records, we may infer the following facts:—

i) From April, 1904, to March, 1905, the mean period of the eruption was very nearly 24/5 hours. In May, 1905, there occurred an abnormal decrease of the activity of the geyser and since August of the same year, the activity has decreased to about four times per day.

ii) If the times of occurrences be plotted on a diagram, the successive days as abscissae and the hours of the day as ordinates, we obtain a set of five points per day. Connecting corresponding points, five broken lines are formed. These lines show a striking parallelism with the inverted curve representing the variation of the mean atmospheric pressure for successive days. The high pressure corresponds almost without exception to the short period and the low pressure to the long period.

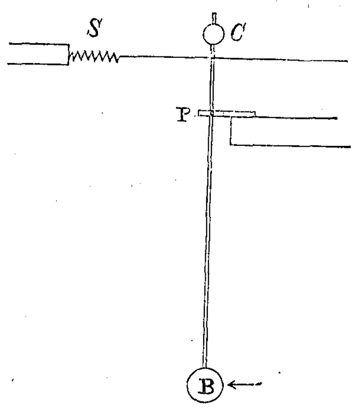
iii) The sum of the daily intermittence of water and steam given out, taken for the five daily eruptions, is generally abundant on the days in which low pressure prevails. The eruptions in which the alternations of water and steam occur more than eight times, fall in usually with approaching low pressure.

f) *Temperature of the hot water during eruptions.*

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

g) *Velocities of the water and the steam.*

To determine the velocities of the water and the steam, the pendulum arrangement was modified in the following way. The pendulum bob was replaced by a larger brass one B, and the center of mass of the pendulum was brought to the axis of rotation P by using a counterweight C, as shown in the annexed figure. From the upper part of the pendulum rod, two strings were stretched in opposite directions, one of which passed to the recording apparatus, while another one was stretched by a spring s fixed to a rigid support. The weight of the recording apparatus was so adjusted that the rod hung vertically, when it was acted upon by no pressure. When the pendulum was set to work in a proper stage of an eruption, the pressure due to the water and the steam could separately be observed. After the record has been taken in the usual manner, a series of known weights—30, 50, 80, 100, 200, and 300 grams—were successively applied to the pan hanging under the recording pen, and the corresponding deflections of the rod were recorded on the cylinder. From these observations, we could calculate the amount of the pressure exerted by the water and the steam upon the brass ball.



The total pressure exerted by a fluid stream upon a sphere is known to be approximately equal to one half of that upon a circular disc of the same diameter. Hence

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

where p is the pressure, r the radius of the ball, ρ the density and v the velocity of the water or the steam.

For the water, the maximum velocity was calculated to vary from 1.5 to 2.0 m per sec.

For the steam, the velocity was found to vary from 18 to 24 m per sec., as given in the following table:

No. of Intermittence	Velocity
1	24 m/sec
2	25—24
3	22—18
4	24—23
5	22—18
6	22—18

In the above calculation, we took for the value of ρ, the density of saturated vapour under atmospheric pressure.

h) *Quantities of water and steam.*

Since the quantity of the water and the steam in each eruption differs considerably for different eruptions, it was sufficient to get a rough estimation of the amount. Again, to make an exact measurement of the total quantity of the water or the steam is almost hopeless, in the present condition of the orifice, as it is branched into several mouths; some of these are hidden underground, whence the hot water is distributed by a number of separate conduits.

The direct method for the quantity of the water was to measure the quantity supplied to a number of tanks and to estimate the total from the section of the conduits. The tanks chosen for this purpose were those of Kyūkikwan and of Sagamiya. The results are:

Kyūkikwan	11^h	p.m,	April 1, '04.	3.38 m^3
Sagamiya	11^h	a.m,	,, 2, ,,	1.28.

Since the numbers of the conduits for the exposed orifices A, a, a′ are 21, 2, 3 respectively, the total quantity of the water will approximately be 1.28×26 $m^3 = 33.2$ m^3 or 184 *koku*. It was also estimated that the total quantity of the water which flows out from the hidden orifice, is $3 \times 3.38 = 10.1$ m^3 or 56.3 *koku*. Hence the whole discharge of one eruption will approximately be 45m^3 or 250 *koku*. This number is a little greater than that obtained by Dr. Tawara, and nearly coincides with that given by J. Tsuyuki, a resident in Atami.

The rough estimation of the steam was carried out in the following way. Let the quantity of the steam be denoted by Q, we have

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

where Sv is the flux of the steam. If V be the ordinate of the steam diagram, we may put

$$v=kV,$$

$$\therefore \qquad Q=S\rho k\int Vdt.$$

In our case, k was found to be 500 and S was estimated to be 300 cm². Hence

$$Q=121\int Vdt.$$

For an eruption, we found $\int Vdt=6500$, and therefore

$$Q=800 \text{ kg.} =213 \textit{ kwan}$$

These numbers for the water and the steam must be considered as giving the orders of magnitudes of these quantities.

2. *Abnormal Eruption, the Nagawaki.*

Figs. 11 and 12.

The record of *nagawaki*, kept at Kyūkikwan is given below:

1894: Jan. 6; Feb. 22, 7^h p.m.—23, 11^h a.m.; March 30, 4^h p.m. —31, 6^h30^m a.m.; April 30, 6^h a.m.—2^h p.m.; June 7, 5^h a.m. —5^h p.m.; Aug. 20, 4^h p.m.—21, 6^h a.m.; Sept. 27; Nov. 17, 4^h a.m.—4^h p.m.; Dec. 28, 8^h a.m.—8^h p.m.

1895: Feb. 18, 4^h p.m.—19, 5^h a.m.; April 9, 8^h a.m.—5^h p.m.: June 12, 4^h p.m.—13, 6^h 30 a.m.; Aug. 14.

After this date, the record is missing till 1903.

1903: Sept. 8^h p.m.; Dec. 29, 3^h p.m.

1904: None.

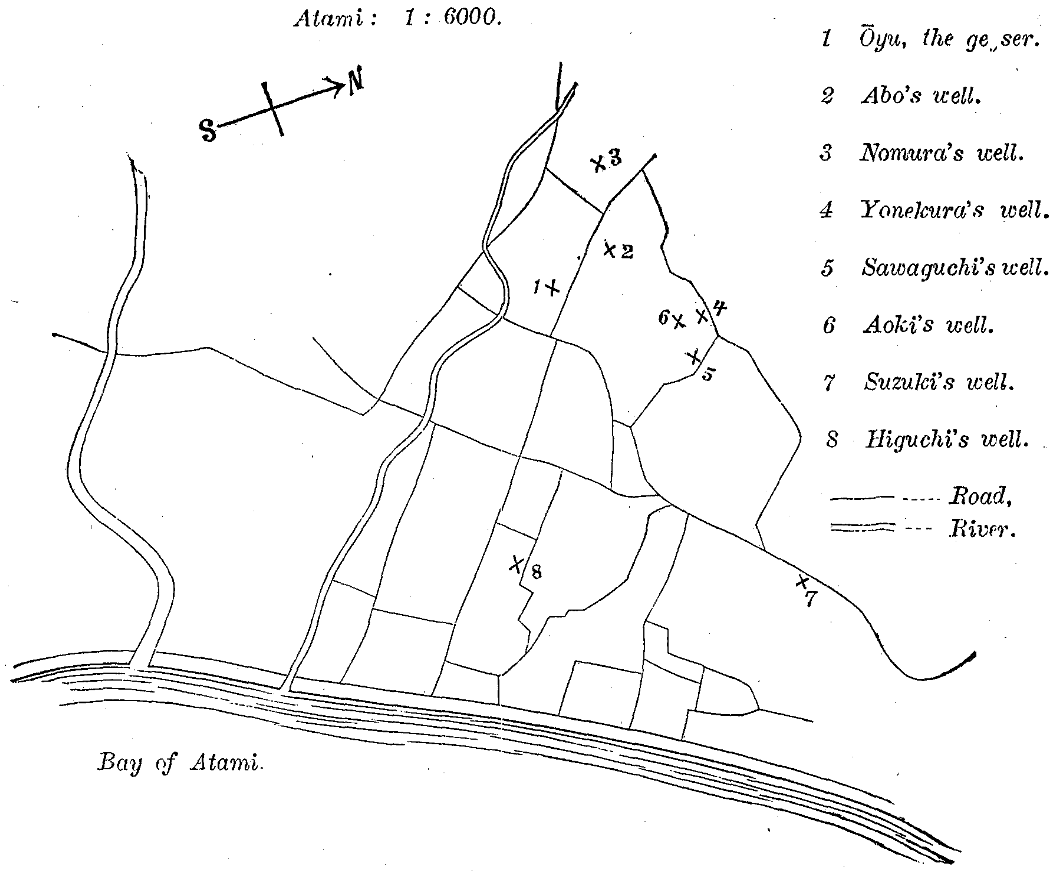
The first *nagawaki* recorded by our arrangement began at 4^h30^m a.m. on Jan. 14, 1905, from the third series of the ordinary eruption. During two or three days before the *nagawaki*, the period of the successive eruptions seems to have been slightly diminished, but in such a degree that may be found 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. As given in Fig. 11, the flow of the water continued without interruption, gradually decreasing in quantity and mixed up with the steam. At 7^h40^m p.m., it came to a sudden repose; at 2^h40^m a.m. on 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 eruption at last set in, but with the period remarkably shortened and the general activity strikingly reduced. The number of eruptions per day was ten, a remarkable contrast to the ordinary frequency of five per day. The frequency decreased afterward very slowly with the time (Fig. 12), and recovered its original value after the lapse of about a month.

The second *nagawaki*, which occurred on May 27, 4^h 30^m a.m.—28, 6^h 20^m a.m., '05, was quite similar to the previous one in its general aspects, though it took place in conjunction with an extraordinary decrease of the general activity. The third *nagawaki* occurred on Dec. 13, 6^h p.m.—14, 9^h 40^m a.m., '05, and the fourth on March 6, 6^h 40^m a.m.—7, 2^h a.m., '06. They are quite similar in the general aspects to the one above referred to. It is an interesting coincidence that these *nagawakis* began at the same phase of the ordinary eruption, and that a center of low atmospheric pressure was approaching from the Pacific in each case.

3. *Extraordinary Decrease of Activity.*

Figs. 13 and 14.

During the course of the last few years, several wells have been bored in this district. Many of them give a moderate quantity of hot water only by pumping. In 1905, the number of the wells has been greatly increased, amounting to about twenty in all. Sawaguchi's well bored on March 27, '05, burst out with great force, continuously



throwing up a column of steam and hot water about 8 m high. On May 22, another, Yonekura's, of a much greater activity was opened within a few hundred meters from the geyser, giving out hot water at a rate of about 310 cubic meters per day. Two days afterwards, still another, Higuchi's, 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 times per day, though the force of each eruption presented no appreciable change. After the boring of the other two, the frequency of the geyser remarkably decreased; it was 3.6 on May 26. Moreover, the first and the second series of each eruption became considerably longer than usual and the principal series was lessened in force. After the *naga-waki* which occurred on May 27, the number of eruptions per day was temporarily increased to 6, though the quantity of the hot water was rather decreased. On June 5, the frequency again fell to 3.6 and on June 11 to only 3.2; the first and the second series were prolonged to three and a half hours, while the principal series was reduced to only three weak eruptions. The consequent decrease in the quantity of hot water caused trouble to several bath-houses supplied by the geyser, and the above three wells which must have been the probable cause of the decrease, were all stopped—Yonekura's on June 12, Sawaguchi's on the next day and Higuchi's on July 12. Immediately after the stoppage of the first two wells, the frequency of the geyser increased to 4 and moreover the preliminary series of each eruption was shortened and the principal eruption gradually tended to regain its original force. After stopping Higuchi's, the frequency gradually increased and attained 4.5 in August, which was still a little short of the original value. Since then, the frequency has gradually decreased to 4 and remained nearly constant up to the present, though it was temporarily disturbed by two *nagawakis*. As to the mode of each eruption, it has quite recovered its original force. It is to be remarked that still new wells remain open, Aoki's, which are near the geyser and give a moderate quantity of hot water.

The stoppage of wells was a matter of no small difficulty. The sight witnessed by us during the stopping of Yonekura's well may be worth recording. The well was about 25m deep and threw up a column of hot water mixed with steam about 8 m high, from an iron pipe of 4 inches diameter. Cylinders of sheet iron filled with sand and pebbles which were intended to stop the well, were violently thrown up in the air when put in the orifice. An iron rod of about 10 kg weight thrown into the mouth was held by the water near the mouth, neither falling nor rising. Next, an iron pipe of 2 inches diameter and of about 6 m length, was filled with sand and forced into the orifice. Though the quantity of the water and steam was considerably lessened by this pipe, the upward pressure still overcame the weight of the pipe and when the pipe was released, it was thrown up into the air about one meter high. Next a similar pipe filled with iron bolts and sand was applied. This pipe fell freely down the well. Immediately, the quantity of water was greatly reduced and a number of pieces of tuff imbedded with small crystals of iron-pyrites, was pelted out with the jet of steam and scattered within several meters from the spot. Then another iron pipe was thrown into the hole and cold water was poured down, which completely stopped the activity.

From the fact that the iron bar above described was held in equilibrium by the pressure of the water jet, we may roughly estimate the velocity and the mean density of the splash at the orifice. If w be the weight and S the sectional area of the rod, and if ρ be the mean density and v the velocity of the jet, we have

$$w = S\rho v^2$$

Again, if R be the radius of the orifice and Q the quantity of water given out per second,

$$\pi R^2 v\rho = Q$$

By our previous measurement, $Q=0.0036$ cubic meter per sec. The result of our evaluation is thus

$$v=12 \text{ m/sec}; \quad \rho=0.73,$$

i.e., the jet of water fills up about 7/10 of the area of the orifice. The power of the jet calculated from these data is about 3.5 H.P.

4. *Level Change and Temperature of Artesian Wells.* Figs. 15 and 16.

Level-changes 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 25 m above the sea level, shows a regular up and down motion of about 10 cm, five times per day (Fig. 15) corresponding to the eruption and repose of the neighbouring geyser. When the geyser is at the height of its activity, the level of the well is at its maximum. The slow rising of the mean level is partly due to rain. Effects of the tidal and the atmospheric pressure are also recognizable, but not very remarkable. The temperature of the water in this well is 50°-60°C.

In Suzuki's well, situated more remote from the geyser than the

Nomura's and nearer to the sea, the effect of the geyser is not observed, but the level rises and falls with the tide (Fig. 16). The record shows peculiar zigzags indicating that the surface of the water is continuously disturbed by the boiling. If the water be pumped out a little at first, it continues to flow eruptively for a while, till a definite quantity is reached and then follows repose. If the pump be actuated again after a few hours, a nearly equal quantity of boiling water flows out in a similar way. But, if pumped earlier, a small quantity may be drawn out only after hard pumping. The level of this well is about 11 m below the ground and 22 m above the sea level. On one occasion, the temperature of the water in the well at different depths was measured with a maximum thermometer and found to be remarkably high. The results are given in the following table :—

17.6 m	6.6 m	103°C.	115°C.
26.6	15.6	123°	128°
32.1	21.1	139°	135°
35.7	24.7	140°	138°
44.9	33.9	140°	147°
54.0	43.0	142°	152°

The first and the second column denote the depths measured from the surfaces of the earth and the water respectively ; the third column is the actual temperature corresponding to each depth ; and the last is the corresponding boiling point of water under pressure, calculated from the Regnault's results. From the above table, we see that the temperature of the water rapidly increases almost proportionally with the depth up to about 20 m from the surface of the water ; then the rate of the increase becomes abruptly small. This shows that at about 20 m below the surface of the water, there is a layer or a space between layers in which highly heated water is continuously flowing. At these depths, the actual temperature is a few degrees higher than the corresponding boiling points under pressure, so that the boiling is continuously going on, as shown by the limnimeter set up in the well.

Here it is to be noticed that the rise of the boiling point due to the dissolved substances is at most one degree.

Abo's well which is situated midway between the geyser and Yonekura's well, is about 33 m deep and gives out hot water by pumping. The results of the temperature measurement at different depths, made by a maximum thermometer, are as follows:

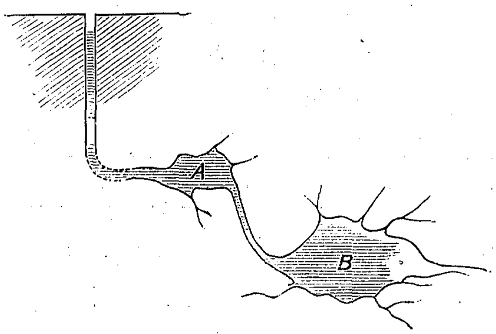
At the water surface	62.0 C.
23.0 m below,	95.5
28.5 ,,	98.3
29.7 ,,	104.3
31.0 ,,	118.2

From the results in these two wells, it is evident that in the district of Atami, there exist layers with very high temperature near the surface.

IV. EXPLANATION OF THE PHENOMENA.

Existing theories are not sufficient to explain the exact manner of the eruption of the geyser of Atami. Wiedemann's model though plausible in many respects, fails when applied to this geyser, in which water and steam are alternately projected several times in succession. We sought, therefore, for other alternatives and constructed several models for experiments.

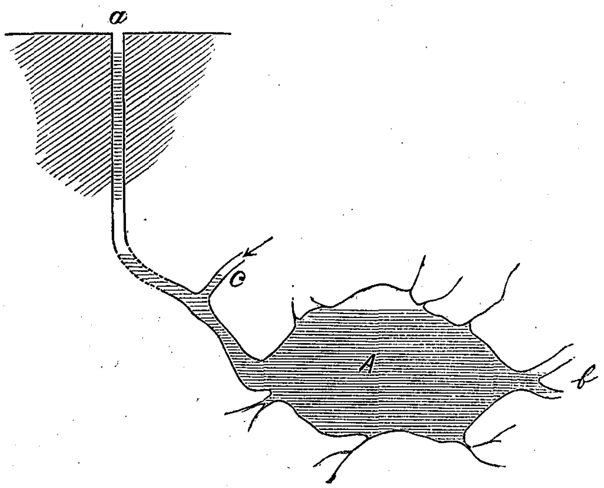
First, we conceived two subterranean cavities (*A* and *B*) connected in series, as shown in the annexed figure and supposed *B* to begin the eruption earlier than *A*, by the underground heat. The model constructed according to this supposition worked almost satisfactorily, except that the mode of intermittence in the principal series of the eruption was not quite similar to the actual geyser; for, in this model, the steam predomi-



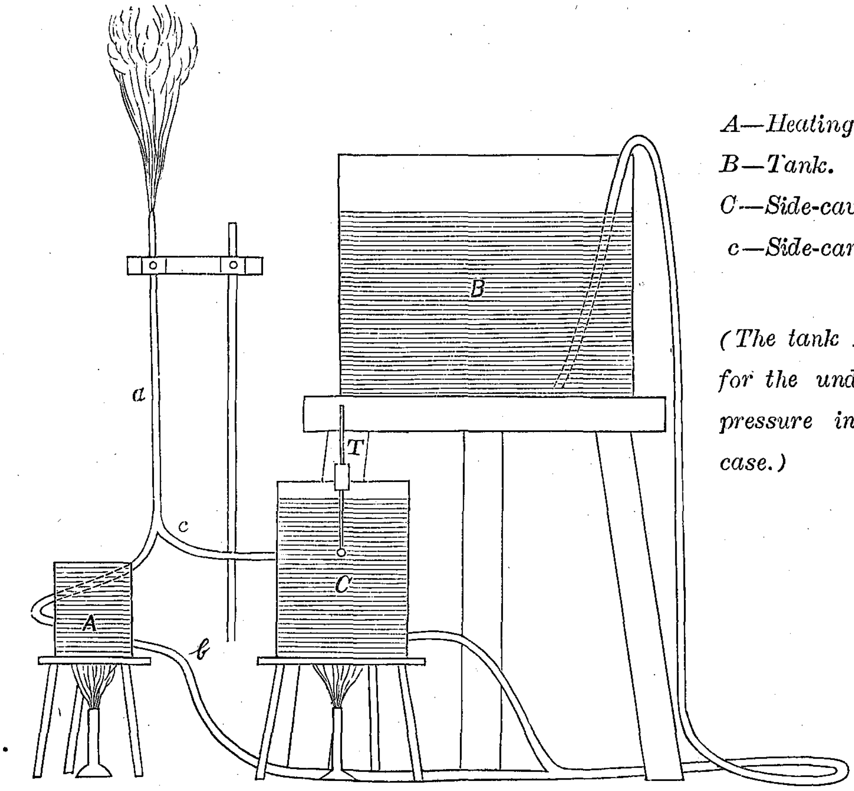
nated toward the end of each eruption, instead of showing a regular alternative intermittence of steam and water as in the actual case.

After a sequence of modifications and experiments under various conditions, we arrived at last at the following theory which seems for the present to be sufficient to explain the phenomena of the geyser in question :—

Referring to the figure, *A* is a cavity lying at 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 that depth. The source of the heat is probably to be attributed to the hot water and steam running through numerous veins and canals extending beneath the district. When the tension of the vapour in the cavity attains its critical value, the water is ejected and then the steam follows. When a certain amount of the 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 the vapour and the second gush follows. These eruptions are repeated several times, till the vapour pressure is so reduced as to admit the comparatively cold water from the feed-canal *b* and also from *c*. Thus the activity is quenched for a while till the next eruption begins.



A—*Heating cavity.*
B—*Tank.*
C—*Side-cavity.*
c—*Side-canal.*

(The tank B stands for the underground pressure in actual case.)

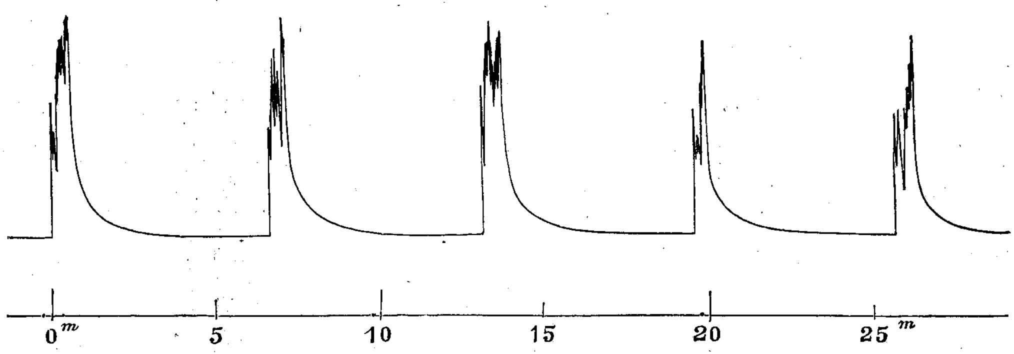
A model constructed according to this view worked satisfactorily. Referring to the figure, A is the working cavity, c the side-canal fed by the second cavity C larger than A. B is the large tank supplying A and C; a is a glass tube representing the vertical pipe of the geyser. These are all connected by cauchouc tubings as shown in the figure. Both A and C are made of brass, thickly covered with asbestos to prevent cooling, and moreover, are provided with glass gauges showing the water levels inside. The cavities filled with water are heated by proper Bunsen burners, care being taken to keep the temperature of the water in C somewhat below the boiling point—the temperature being read by the inserted thermometer T. We give below the dimensions of the principal parts of our model:—

Capacity of A: Height$=$13.0 cm; Diameter$=$9 cm.
„ „ C: „ $=$18.5 cm; „ $=$15 cm.
Height of the orifice above the bottom of $A=1$ m.

Internal diameter of the vertical pipe = 5 mm.
Diameter of the orifice = 2.5 mm.
,, ,, ,, tube b = 7 mm.
,, ,, ,, ,, c = 5 mm.

The period of the eruption depends on the heating of the cavity A, increased heating shortening it. The number of the intermittences increases with the temperature of the water in C. In our experiments, the mean period of the eruption was 6.5 minutes and when the temperature in C was 95°C, the number of intermittences in each eruption was 3 to 4.

In this way, the manner of the eruption was imitated even in its details. The figure here given is one of the records of the eruption



of our model, obtained by the air-thermograph already mentioned. The preliminary series of the eruption was not recorded by this arrangement, in which the air-bulb was placed somewhat high above the orifice.

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 value. 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 the 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 the eruptions immediately after *nagawaki*, is nearly doubled, may partly be explained, if we consider that the temperature of the heating cavity is raised during the course of the *nagawaki* by the incessant flowing of superheated water. 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 the eruption increases remarkably at first and then gradually decreases with the gradual expulsion of the air by the successive eruptions; even the weakness of the activity in the actual case is imitated with great faithfulness. During a few hours after *nagawaki*, the cavity 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 cavity and cause the increased frequency of the eruption.

It is a fact of common observation that the temperature of some ordinary hot springs rises with the low atmospheric pressure. This is undoubtedly due to the increase of the flow caused by the enhanced circulation due to the reduction of the pressure. If in the supposed heating cavity of the geyser, the interchange of the water due to the slow circulation through numerous veins and fissures be accelerated by some cause, the time required for the sufficient heating for the eruption must necessarily be prolonged. This consideration seems to explain the influence of the atmospheric pressure on the period of the eruption above mentioned. Again, the probable influence of the well-boring on the geyser, may be explained on the same basis. The wells may increase the circulation of the underground water in the 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 would find its easier vent through a new passage opened with less resistance, at the expense of the quantity originally ejected by the old one alone. The prolongation of the first and second series of the eruption, suggests the slowness with which the pressure in the heating cavity approaches the critical value. Careful investigation of the change in the wells, leads us to the strong belief that the striking coincidence of the well-boring and the extraordinary decrease of the change in the geyser, is a necessary and not an accidental one. If the frequency of the 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 disturbance.

It should be noticed that almost simultaneously with the beginning of the abnormal decrease of the activity, severe shocks of earthquake were felt in the Island of Ōsima, an active volcano situated in front of Sagami Bay, about 27.5 miles from Atami. On this account, it was generally believed that the decrease was the consequence of some change of the subterranean activity associated with the earthquake. The belief seems to have its origin in the tradition that the occurrence of *nagawaki* has some relation to the activity of Ōsima. But, judging from the manner of the change of the geyser accompanying the boring and stopping of the wells, we are inclined to believe that the principal cause of the disturbance is to be attributed to the well-boring.

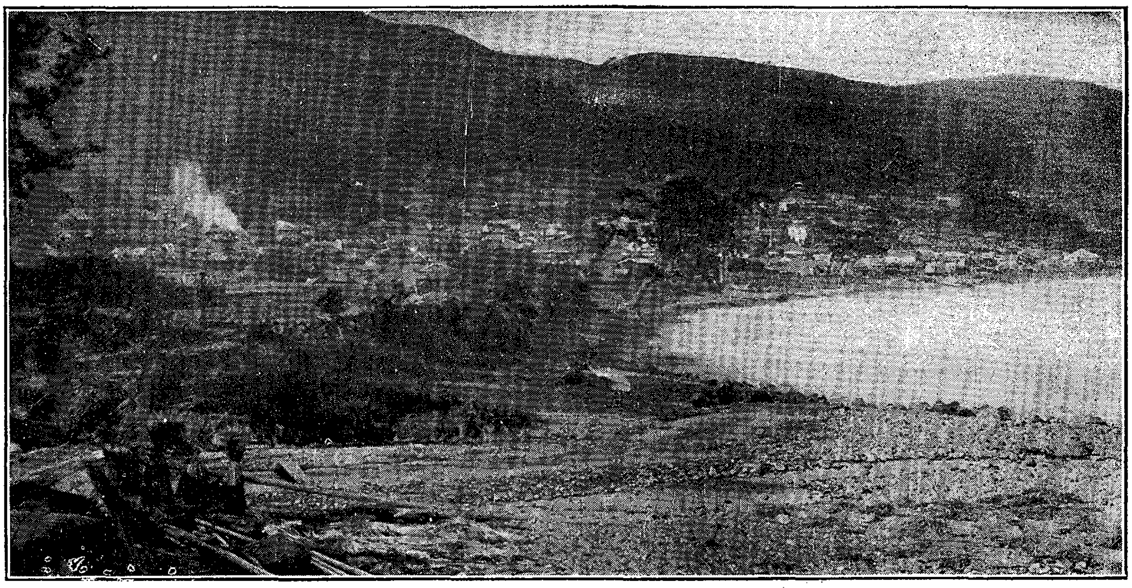
The question naturally arises as to the actual source of the immense quantity of the hot water poured out daily by this geyser. It seems, according to the accepted view of the modern geologists, that the water condensed from the superheated steam coming from the very depth of the earth's crust forms a considerable part of the mineral water of such a hot spring. Accepting this as a partial explanation, we feel inclined to trace the greater part of the hot water ejected by this geyser to the underground water circulating at a comparatively small depth heated by the extraordinary heat under the district. The presence of the sea-water constituents in the water of the geyser is probably due to the sea-water penetrating through several fissures in the neighbouring bay, which bears strong geological evidence to having once been the crater of an volcano.

In conclusion, we wish to express our best thanks to Mr. S. Kusumi, the apotheker to Kyūkikwan, to whom we are very much indebted for his zealous assistance during the course of our observations.

Pl. I.

General View of Atami.

Rising steam of the geyser to the left of the scenery.

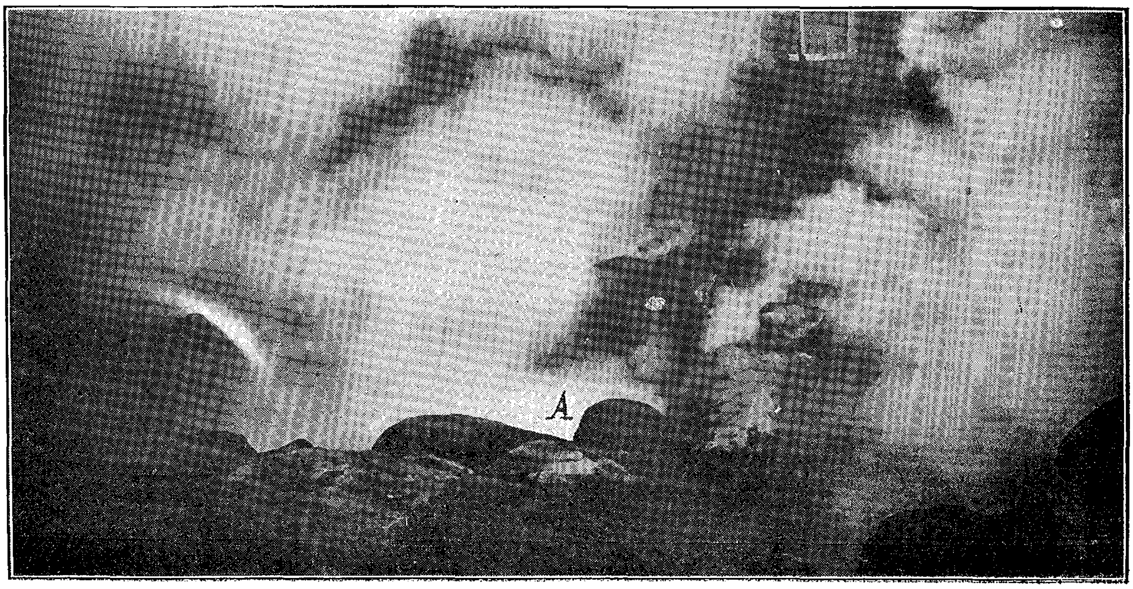


Geyser in Repose.

A: principal orifice; *a*, *a'*: minor orifices. Lead tube to the mouth.

Geyser in Full Activity.

White sprays colliding with rocks to the left.



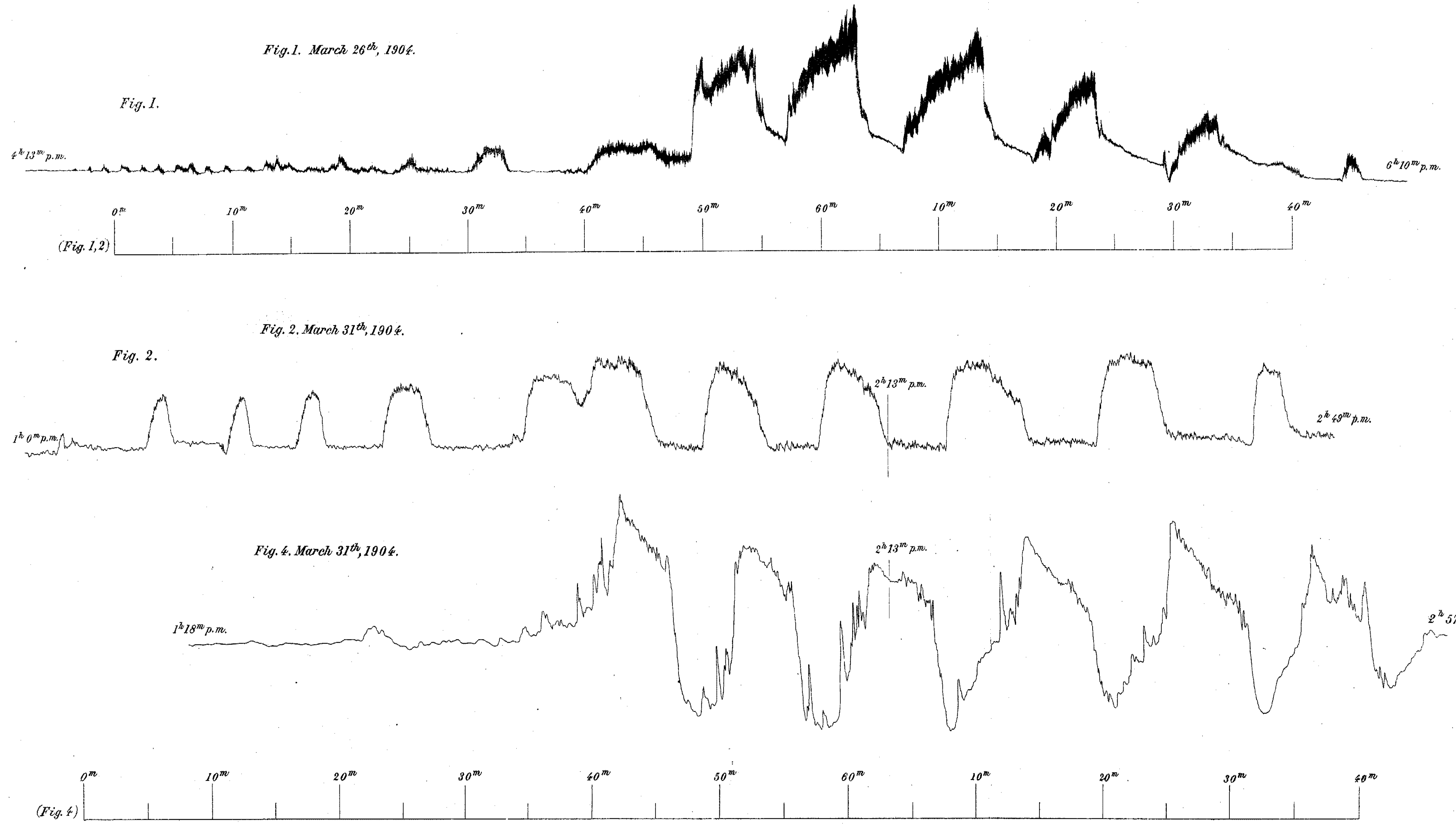


Fig. 1. March 26th, 1904.
Fig. 1.
4h 13m p.m.
6h 10m p.m.
0m 10m 20m 30m 40m 50m 60m 10m 20m 30m 40m
(Fig. 1, 2)
Fig. 2. March 31th, 1904.
Fig. 2.
1h 0m p.m.
2h 13m p.m.
2h 49m p.m.
Fig. 4. March 31th, 1904.
1h 18m p.m.
2h 13m p.m.
2h 57m p.m.
0m 10m 20m 30m 40m 50m 60m 10m 20m 30m 40m
(Fig. 4)

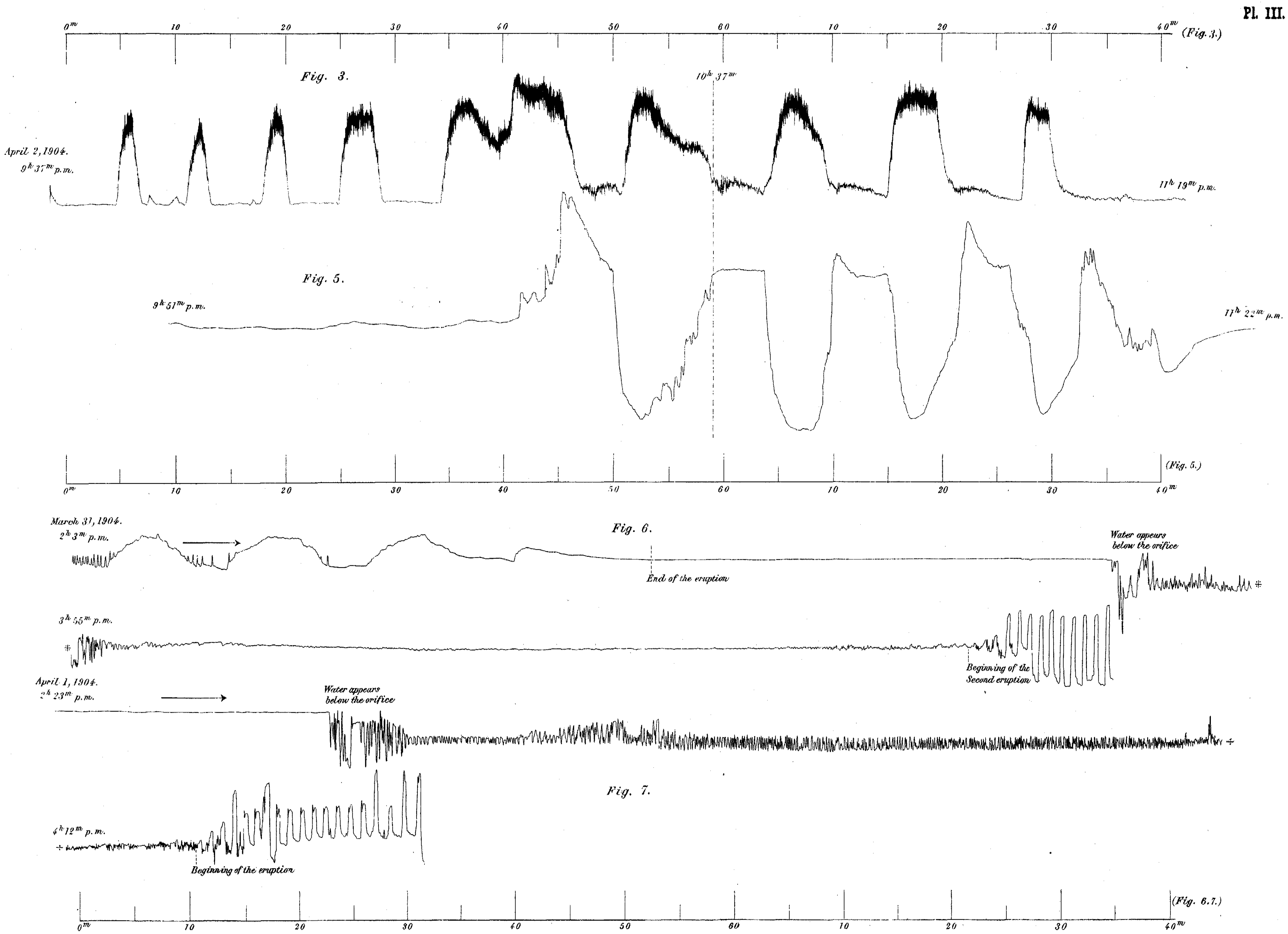

0m 10 20 30 40 50 60 10 20 30 40m (Fig. 3.)
Fig. 3.
10h 37m
April 2, 1904.
9h 37m p.m.
11h 19m p.m.
Fig. 5.
9h 51m p.m.
11h 22m p.m.
0m 10 20 30 40 50 60 10 20 30 40m (Fig. 5.)
March 31, 1904.
2h 3m p.m.
Fig. 6.
End of the eruption
Water appears below the orifice
3h 55m p.m.
Beginning of the Second eruption
April 1, 1904.
2h 23m p.m.
Water appears below the orifice
Fig. 7.
4h 12m p.m.
Beginning of the eruption
0m 10 20 30 40 50 60 10 20 30 40m (Fig. 6.7.)

Fig. 8. April 15–20, 1904.

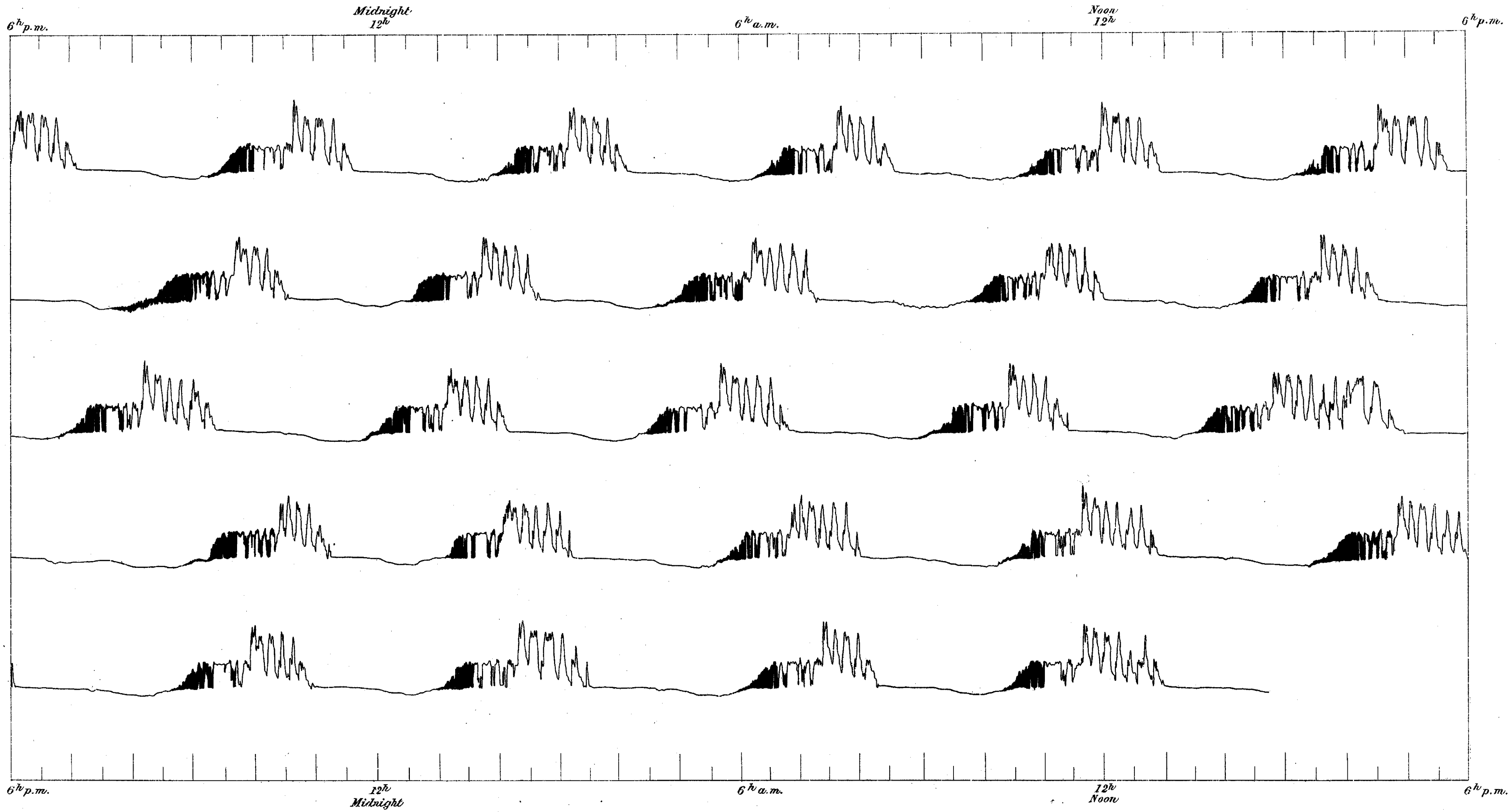


Fig. 9. August, 1905.

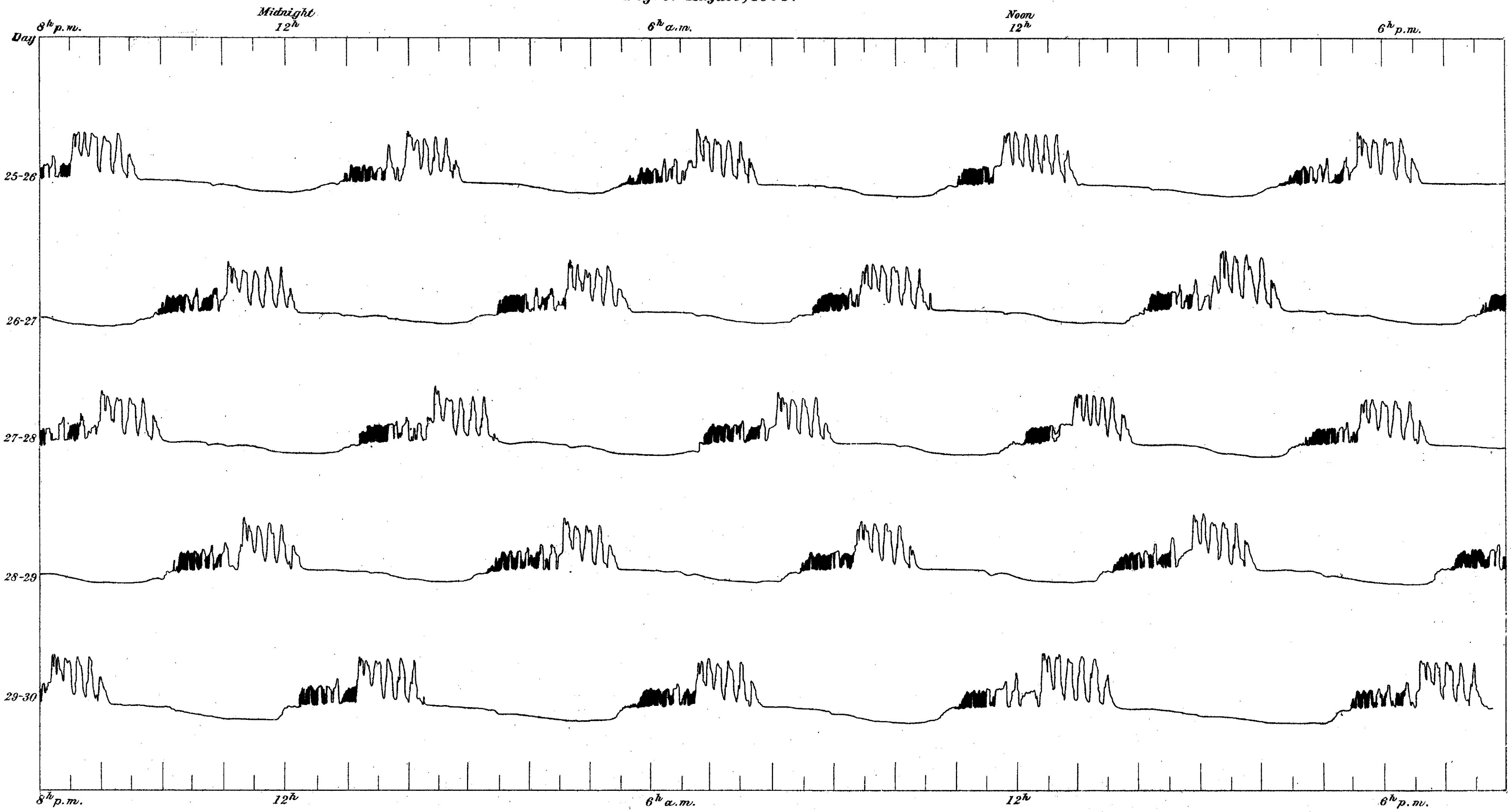


Fig. 10 April 10 – September 17, 1904.

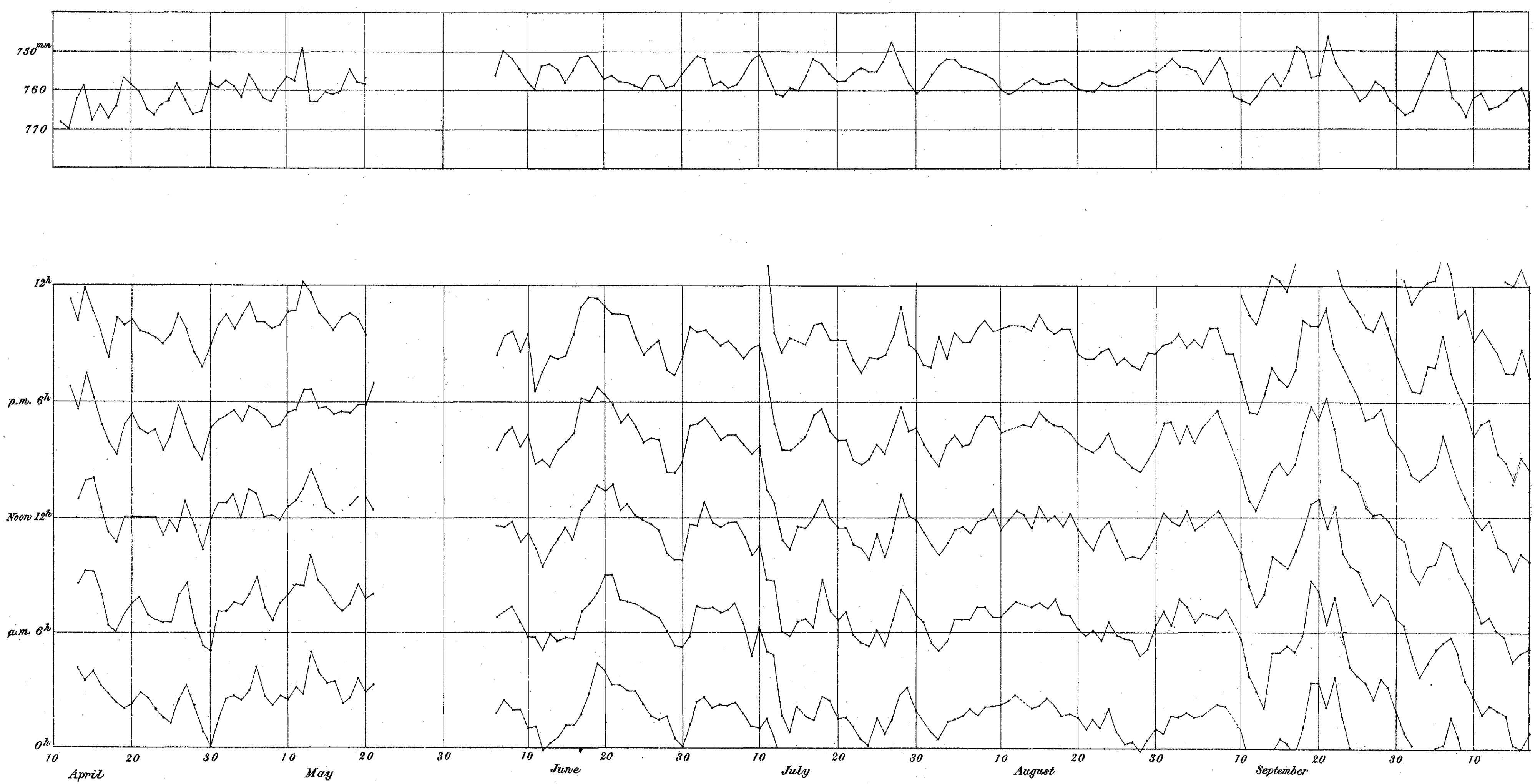


Fig. 11. January, 1905.

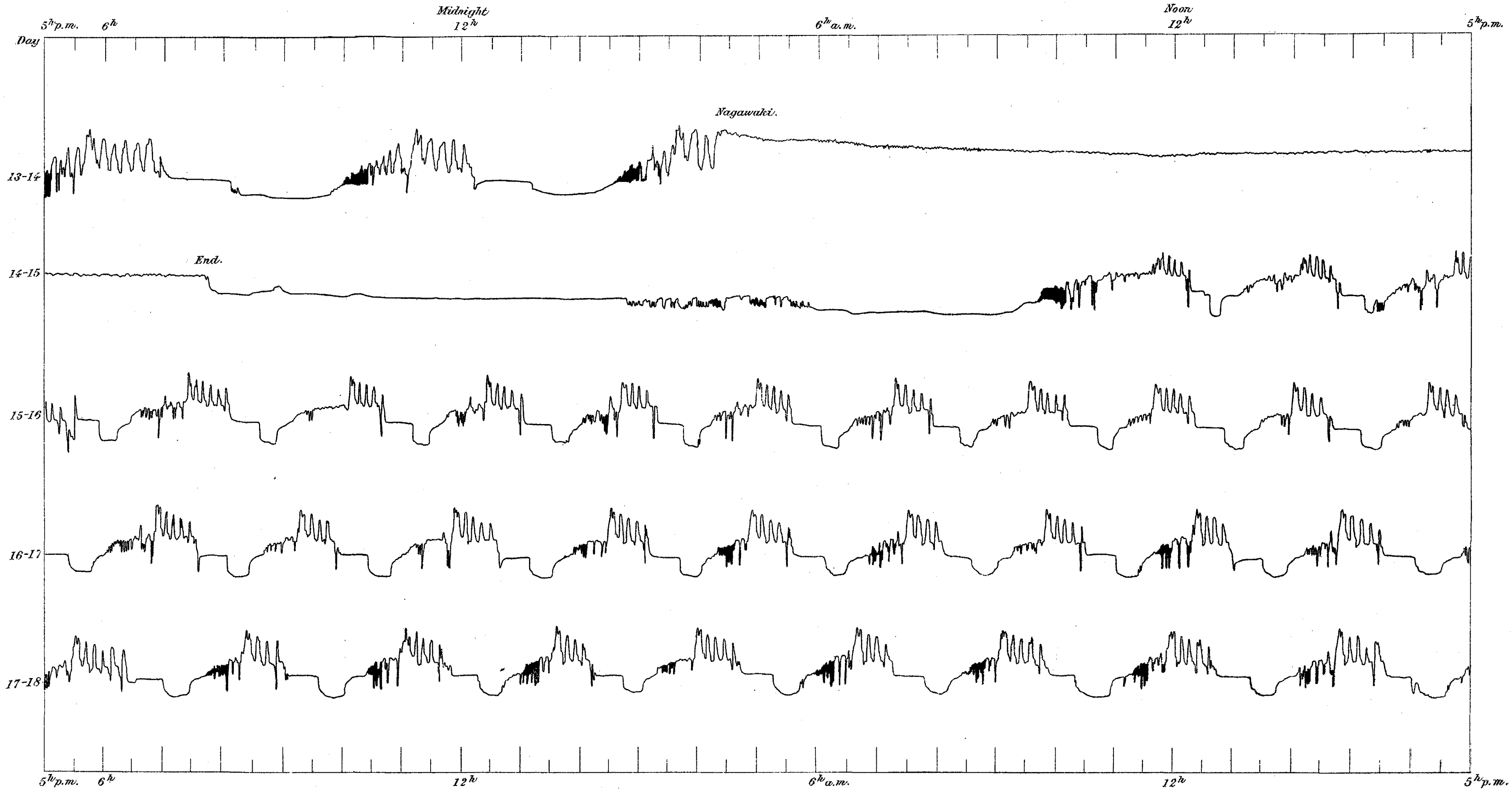


Fig. 12. January to February, 1905.

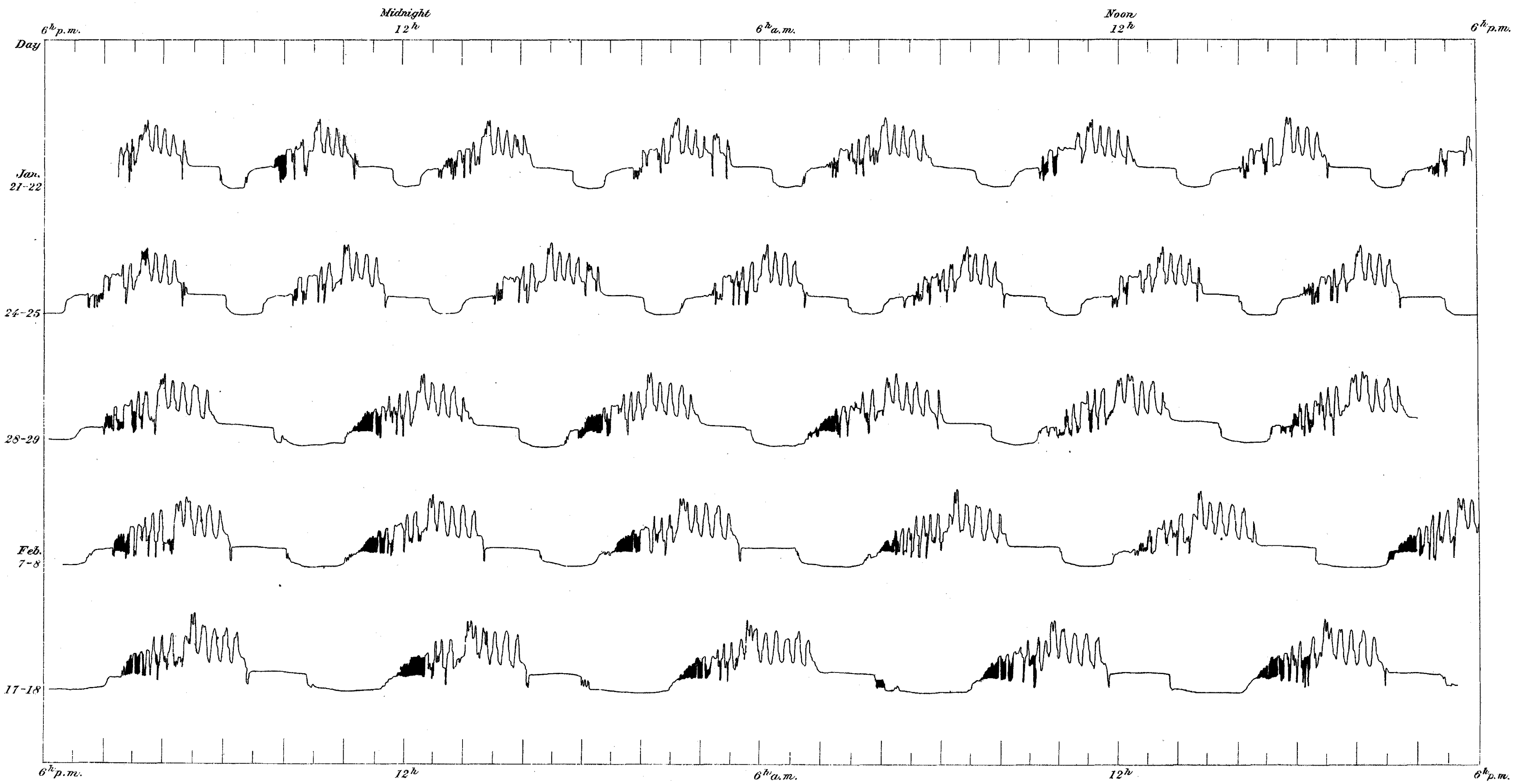


Fig. 13. June, 1905.

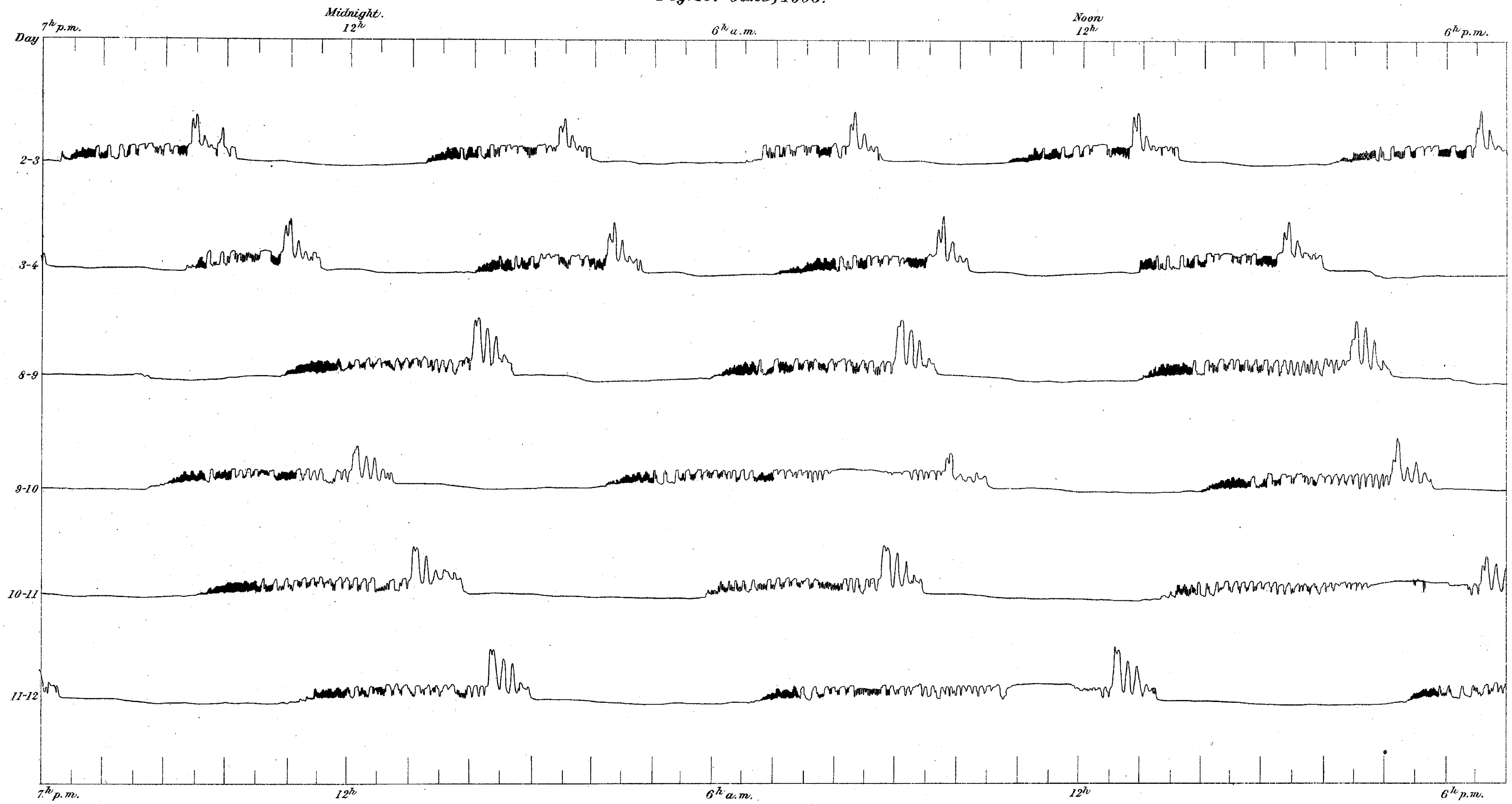
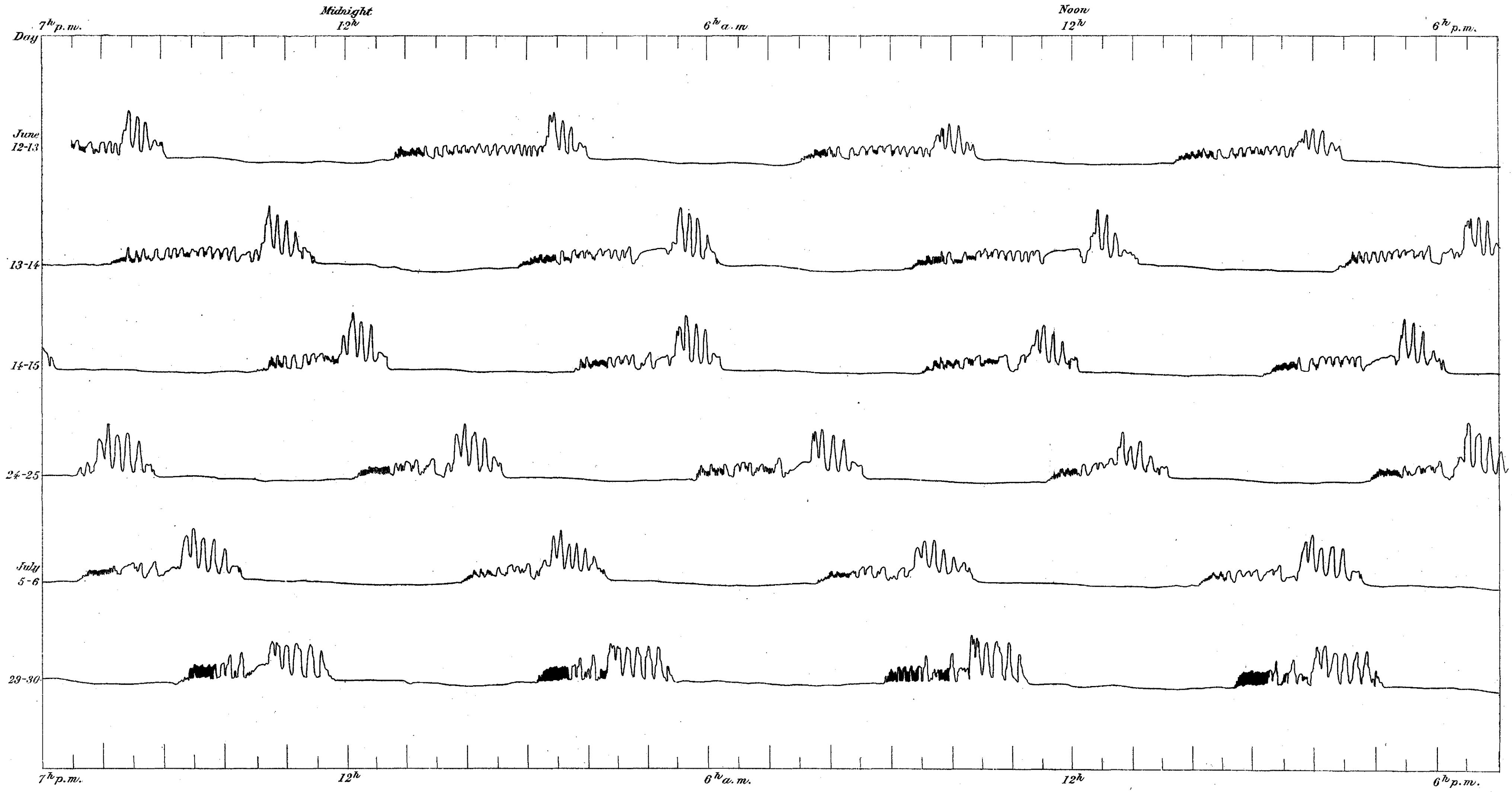


Fig. 14. June to July, 1905.



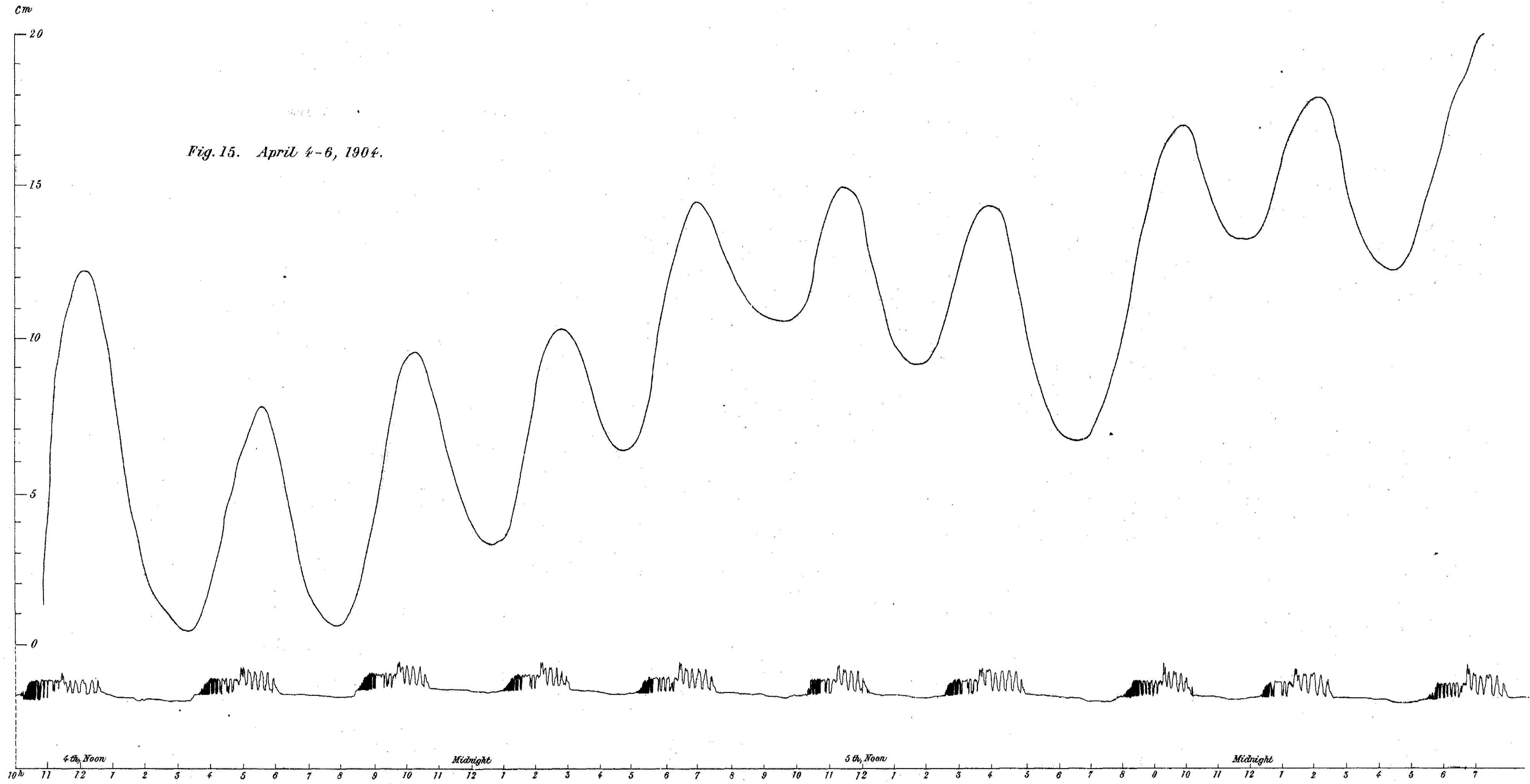


Fig. 15. April 4-6, 1904.

Fig. 16. June, 1904.
Natural Size.