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HYDROLOGICAL STUDY OF ATAMI HOT SPRINGS

BY

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ABSTRACT

In Atami spa, temperatures and heads of many hot springs were measured from 1953 to 1955, and their chemical constituents were also analysed. Geographical distribution of these elements suggests the underground structure of the springs, especially the underground flow of hot water and the intrusion of sea water. From the geochemical consideration for the chemical contents we presume that their origin is partly in the sea water.

Water-level observation in a hot-spring well was continued from 1954 to 1955. Tidal and barometric effects on this well were remarkable and interference effect produced by pumping other wells was also observed. These effects are discussed separately, and the transmissibility, the coefficient of storage and other physical characters are calculated.

PART I. GENERAL SURVEY OF ATAMI HOT SPRINGS

1. Introduction

The Atami spa, one of the most famous spas in Japan, is in the area formed by volcanic action of the Yugawara and Taga volcanoes and has been studied by many scientists geologically, geophysically and geochemically. Ōtuka and Kuno (1) mention that the source of the Atami hot springs is in "Yugashima group" which is thick strata of lavas and pyroclastics of pyroxene-andesites and basalts given by submarine eruptions during the older Miocene period because there are close relations between the spring- and group-distributions. Detailed geological investigation of Atami district was carried out by Ōtuka (2), who made clear that faults lead the hot water from deep underground to shallow formation. Fukutomi (3) classified the Atami hot springs into two series as the result of geochemical study. One of them is a series characterised by high temperature, large amounts of chloride and water rising through fissures from deep to shallow, while the other series differs from the former in their relatively low temperature and some content of sulphate, and the springs belonging to this series are spread extensively. He called the former "the hot springs in the central region" and the latter "the hot springs in the marginal region". It is interesting to know the present condition of the Atami hot springs, because a lapse of about 20 years from Fukutomi's investigation may bring about some changes. It may also be of value to recognize such changes in order to know the nature of the hot springs.

About 100 years ago there were some natural hot springs and a geyser (Ōyu geyser) in Atami, but nowadays we find 250 hot-sprig wells. The flow of the natural springs decreased gradually with the progress of exploitation of other hot springs (**4**, **5**), and the Ōyu geyser stopped gushing in 1926. Most of the springs, at present, are wells, which are pumped except a few flowing spring. This may show that the hot springs communicate with each other in the underground, and the heads of them declined gradually.

On the other hand, it is well known that some hot springs near the sea are contaminated by sea-water intrusion. This intrusion increases the Cl-contents, lowers the temperature and depreciates the economical value of the hot springs. It is therefore important to know the degree of the intrusion in view of the protection of hot springs as underground resources.

The present writer observed, from 1953 to 1955, the head and the orifice temperature of about 80 hot springs in Atami, and analysed also the chemical contents. The results show not only the present situation of the springs, but also some information about the preceding problems, compared with past data.

2. Distributions of orifice temperature and chemical elements

The orifice temperature and some chemical elements of hot springs were measured twice, in August, 1953 as well as in August, 1954. The results are given in Table 1.

The distribution of orifice temperature in August, 1953 is shown in Fig. 1, being similar to that observed in August, 1954. Comparing them with the distribution in 1936 (**3**), we see the same trend that the highest temperature section of Atami is in "the central region", but near and at the south of the mouth of Wada River and on the northern sea-shore the temperature decreased. The distribution of Cl-content in 1953, described in Fig. 2, shows that there is much chlorine area near and at the south of the mouth of Wada River, though this area had less Cl-content in 1936.

Fukutomi (**3**) used a temperature-Cl diagram as an evidence that there are two distinct groups of hot springs in Atami. Plotting in this diagram the data obtained in the present observation, we get Fig. 3, in which the marks "●" represent the hot springs of the central region, and they deviate from the line indicated by Fukutomi, the difference between the central and the marginal regions being, however, not so obvious as found in 1936. On the other hand, it is clear that some springs lie approximately on the line A–B. All of them are near and at the south of the mouth of Wada River, and they are shown in Fig. 3 by the

Table 1

No.	Temperature °C		PH	Cl g/l		SO_4 mg/l	Methyl orange alkalinity mg/l	Remarks
	Aug., 1953	Aug., 1954	Aug., 1954	Aug., 1953	Aug., 1954	Aug., 1954	Aug., 1953	
1	78.0	82.0	7.9	1.54	2.09	564	15	
2	66.0			1.05			15	
3		54.0	7.7	11.70	11.10	1388	43	
4	75.0	69.8	8.2	0.47	0.49	690	30	
5	68.5	66.0	8.0	0.37	0.28	416	23	
6	71.3	75.5	8.2	0.42	0.41	760	30	
7	72.2	68.5	8.2	0.38	0.39	669	38	
8	62.3	59.2	7.9	0.40	0.44	710	26	
9		63.0	8.1	1.16	1.51	759	19	
10	91.2			2.18			21	
11	93.3	94.2	8.3	1.99	2.24	430	19	
12	91.2			1.87			26	
13	94.5	96.0	8.0			358	18	
14	91.5	92.2	8.3	1.23	1.77	484	15	
15	88.0	91.1	8.2	2.18	2.46	356	23	
16	88.5	90.2	7.8	1.88	2.17	382	22	
17	88.0	90.8	8.1		2.47	368	19	
18	94.3	95.7	8.2	3.23	3.26	248	23	
19	69.5	68.0	8.4			244	41	
20	71.6	67.3	7.9			290	47	
21	99.0	98.9	8.5	3.34	3.29	237	21	flowing spring
22	96.0	97.4	8.0	1.84	2.12	394	19	
23	95.0	91.4	8.3	1.49	1.86	435	22	
24	91.0	92.3	8.2	3.03	2.93	303	17	
25	94.0	95.0	8.0			309	21	
26	96.0			3.60			21	
27	79.0	75.0	8.0			303	30	
28	100.0	98.8	8.4	3.60	3.56	222	17	flowing spring
29	76.6	74.5	8.0			196	13	
30	71.3	69.0	8.2	1.36	1.40	91	27	
31	69.2	70.3	7.8	0.14	0.16	860	11	
32	55.0	57.8	8.1	0.13	0.10	190	38	
33	91.4	93.7	7.9	4.05	4.82	130	17	
34	52.0			2.18			23	
35	43.0	45.9	8.3	0.95	1.14	473	17	
36	53.5	53.2	7.9	1.55	1.51	388	14	
37	56.0	55.5	8.0	1.52	1.25	539	13	
38	57.0		7.7	0.25	0.21	830	15	
39	45.0	44.6	8.2	4.18	4.25	252	13	
40	46.0	49.5	8.5	3.67	3.97	917	19	
41	55.2	53.0	7.8	4.78	4.52	1024	21	
42	47.5	49.2	8.8	1.28	1.40	744	12	
43	49.0	51.7	8.5	2.60	2.96	956	13	
44	96.0						19	
45	95.5	97.1	8.2	4.40	4.52	139	21	
46	99.0	98.8	8.4	3.68	3.71	242	22	flowing spring
47	86.0	85.0	8.8	0.45	0.53	638	23	
48	96.0	95.5	8.1	3.61	3.54	214	11	flowing spring
49		70.5	8.0	2.01	2.18	224	16	
50		72.2	8.1	1.20	0.79	282	13	

Table 1 (continued)

No.	Temperature °C		PH	Cl g/l		SO_4 mg/l	Methyl orange alkalinity mg/l	Remarks
	Aug., 1953	Aug., 1954	Aug., 1953	Aug., 1953	Aug., 1954	Aug., 1954	Aug., 1953	
51		72.0	8.6	1.04	1.20	341	33	
52	90.1	88.2	8.0	1.26	1.42	242	19	
53	60.5	60.7	7.9	0.22	0.24	850	16	
54	81.2	83.5	8.4	1.23	1.47	473	21	
55	79.0	79.5	8.4	1.37	1.53	520	15	
56		95.0	8.3	1.24	1.86	584	15	
57	74.0			0.91			32	
58		96.5	8.8	0.59	0.87	445	32	
59	58.8	60.5	7.8	0.22	0.77	902	23	
60	67.5	67.5	8.0	0.24	0.23	909	18	
61	48.3	51.1	7.6	5.51	5.90	1032	21	
62	52.0	50.5	8.0	0.22	0.22	873	21	
63	70.2		8.9	0.22	0.22	720	24	
64	65.2	65.7	8.0	0.28	0.33	753	20	
65	45.1	48.0	8.0	0.21	0.25		24	
66	38.0	36.8	8.0	0.04	0.02	36	44	
67	40.0	42.1	7.8	0.82	0.70	810	32	
68			8.3		4.14	750		
69					2.18			
70		77.0	7.9		0.42	690		
71		75.0	8.1		0.37	680		
72		48.0	7.1		0.50	141		
73		64.6	8.2		0.25	252		
74		81.5	7.9		1.42	529		
75		53.1	8.2		0.45	676		

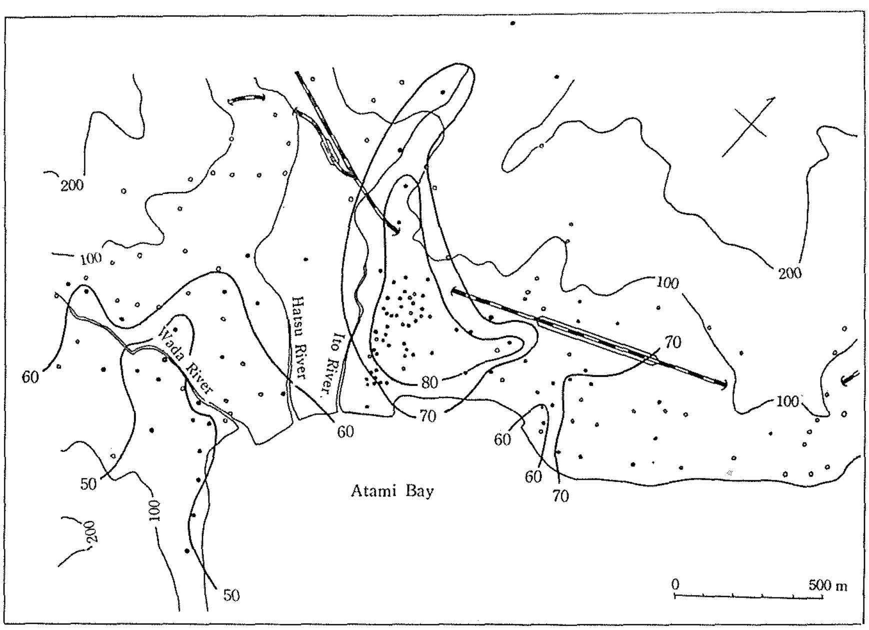


Fig. 1. Distribution of the spring temperature (C°) in 1953. Black points show the observed wells.

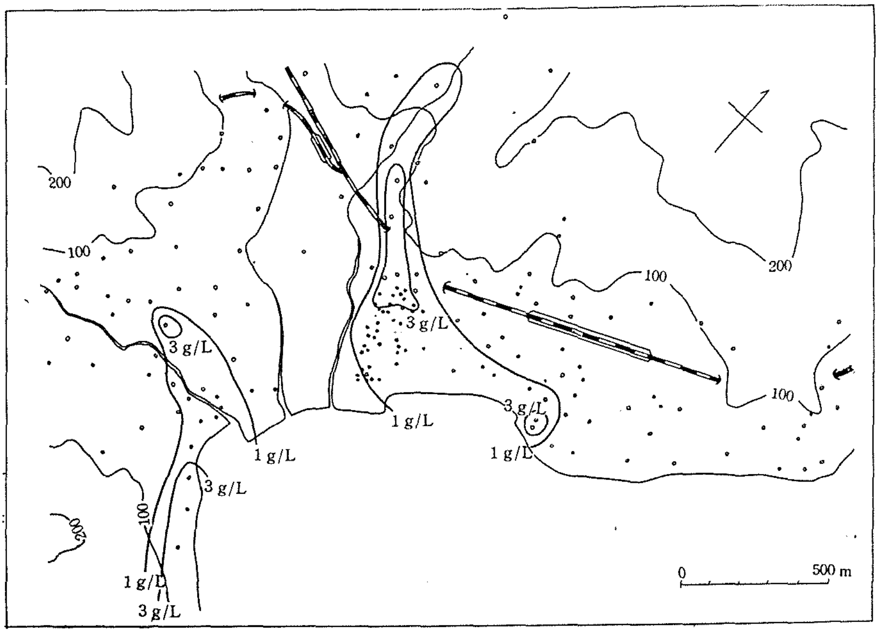


Fig. 2. Distribution of the Cl-content in 1953.

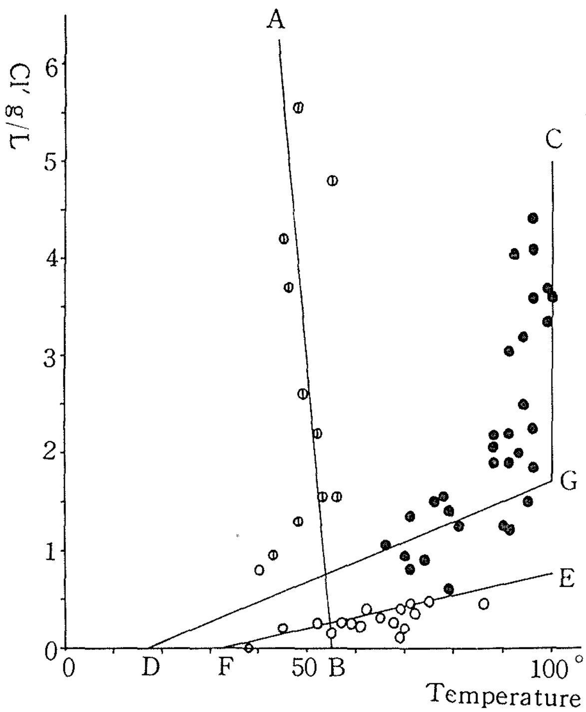


Fig. 3. *Relation between the temperature and the Cl-content*; "●" shows hot springs in the central region, "◐" hot springs near and at the south of the mouth of Wada River and they lie approximately on line A–B, and "○" hot springs in other region. Lines C–G–D and E–F were given by Fukutomi, who asserted that the hot springs in the central region lie along the former and those in the marginal region lie along the latter.

marks "⦶". It may, therefore, be rational that we distinguish the hot springs near and at the south of the mouth of Wada River from other springs. If the line A–B is extended beyond A, it will pass near a point (Cl≒19 g/l, temp.=20°C) which is regarded as sea water. If, moreover, we assume that the sea water intrudes into land without temperature change, the hot springs on the line A–B are considered to be caused by the mixture of pure hot water as symbolized by point B with sea water. A probable cause of this intrusion of sea water is over-pumping hot water from the ground.

The present distribution of SO_4-content is similar to that in 1936, and the springs in the marginal region have more SO_4 than those in the central region. However, the area of less SO_4-content is narrowed in the northern part of the central region. If the hot springs of the central region are characterized by more chloride and less sulphate, as noted by Fukutomi, this feature of geographical distribution may suggest the slight decline of activities of hot springs in the central region.

The distribution of alkalinity is quite complicated. The high alkalinity is an index of HCO_3– and CO_3-contents, but they are affected by the escape of CO_2 from the hot water. It is therefore natural that the distribution of alkalinity is complicated.

3. Hydrostatic pressure of the hot springs in the central region

In order to estimate the underground flow of hot water, we must know the distribution of hydrostatic pressure. Ōtuka (2) showed the distribution of water tables of Atami hot springs along a line nearly parallel to the coastline from the data as obtained on the occasions of repairing the wells. From this distribution we may estimate that one source of Atami hot springs is in the central region, since the maximum water table is in this region. It is, however, inaccurate to estimate the flow from the data along a line, and it is desirable to get in areal range. However, it is very difficult to measure the hydrostatic pressure of all hot springs in Atami, because, in recent years, the water table of Atami hot springs are lowering gradually and air-lift-pumps are installed directly in most wells and also the structure of most private wells in the marginal region is beyond our scope. We therefore attempt to measure the hydrostatic pressure of the hot springs only in the central region.

The greater part of the wells in the central region is controlled by the Atami Municipal Office, so that their structures and pumping mechanisms are known. As soon as a pump starts, the pressure of the air-tank increases rapidly to the maximum, and then decreases asymptotically to a constant value. Since the maximum denotes the hydrostatic pressure at the lower end of the air-tube, if the density of the hot water and the depth of the air-tube are known, we can calculate the height of the hydrostatic head by the air-tank pressure. When the hot water begins to issue from the upper end of the rising main, the head of hot water begins to decrease and then will settle in a steady state which corresponds to the constant value of air-tank pressure. Thus we can calculate the water head during pumping, too. The value of the specific weight of the hot water is different from spring to spring, but we here use the value of $0.99\,g/cm^3$, because the wells No. 17 and No. 45 have about 10 g/l of total chemical contents, and if the temperature of hot water is 70°C the specific weight may be given approximately by the formula: $1+0.01-0.02=0.99$. The total amount of the chemical contents used in this calculation is the highest and the temperature is nearly the lowest in this region. Discrepancy yielded by use of this presumed constant will be examined subsequently. As it is also possible to calculate the hydrostatic pressure of the hot water at the bottom of the well, we can then compare the pressure with that of the sea water at the same depth. In this calculation we also use the density of $0.99\,g/cm^3$ for the hot water and $1.03\,g/cm^3$ for the sea water. Fig. 4 shows the distribution of the pressure differences between the hot water and the sea water during both pumping and stopping. In this figure we find a zone of high head with the shape of a tongue extending to the coast. This feature is also maintained during the course of pumping, but on this occasion, the zone where the pressure difference between the hot water and the sea water is positive is narrowed and consequently many of the hot springs may be in a negative domain.

The total amount of the chemical contents used in the present calculation is the maximum one in the region and also the minimum temperature in the region is used for the temperature, so that the pressure of each hot spring is less than that calculated. After all, the actual zone having positive pressure difference may be smaller than that shown in Fig. 4. Since the pressure measurement of the air-tank during pumping is not of long duration, the water table might not reach a steady state, and longer pumping may bring about more reduction of positive zone.

Since we could not get a core sample in Atami, the detailed underground geological conditions are unknown. From the results of the geological investigation of the ground surface, Ōtuka (2) considered that the hot springs in Atami form a water table as ground water because there are many large and small fissures in the Yugasima group. This consideration gives us an idea that the hot springs in this region may have an aquifer. The aquifer, furthermore, may be artesian, since there are a few flowing springs. If the aquifer is connected

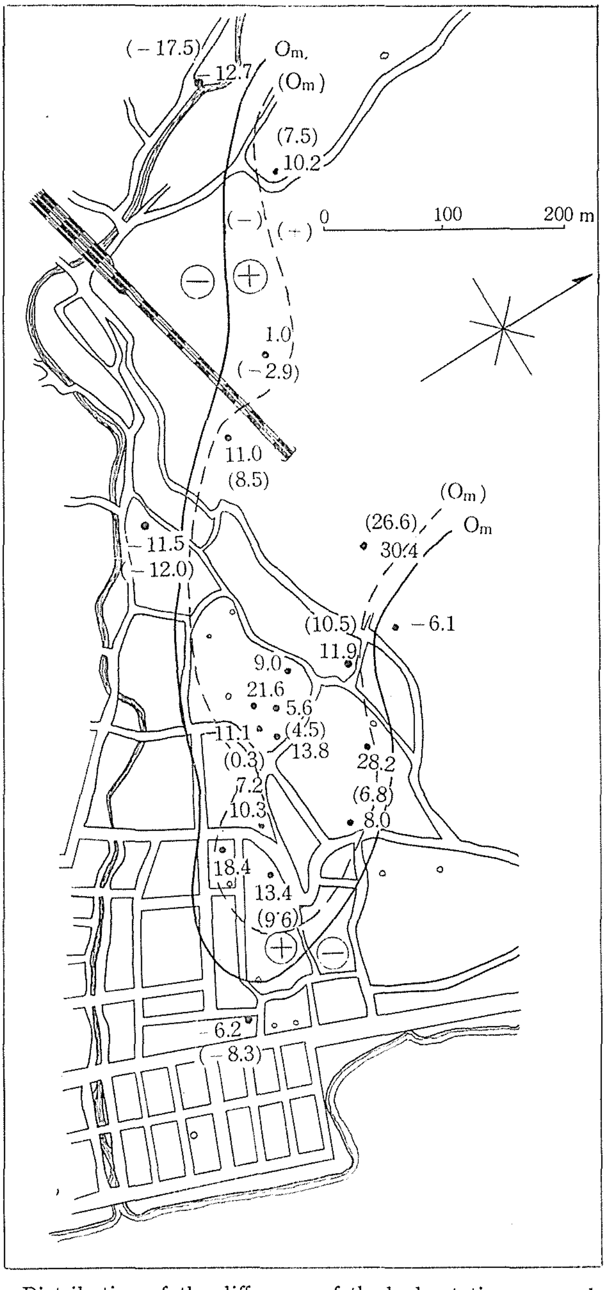


Fig. 4. Distribution of the difference of the hydrostatic pressure between the hot springs and the sea water at the depth of well bottom. It is shown by column length of pure water, and full curve shows statical state and dotted curve and numbers in parenthesis show the pumping state, in August, 1954, and the marks of plus show that the pressure of hot spring in this area is larger than that of sea water.

with the sea, the hot spring having smaller pressure than sea will give rise to the decrease in temperature and the increase in Cl-content. As a matter of fact, Wells No. 19, No. 25, No. 27 and No. 29 have a tendency of decreasing temperature and increasing Cl-content. Therefore, it may be natural to regard this aquifer to be connected with the sea.

4. Some considerations on the origin of the chemical contents

The hot springs near, and at the south of, Wada River are diluted by the sea water as shown in §2, and there also may be a suspicion about sea water intrusion to some part of the central region where the springs have lower pressure than that in the sea water. These hot springs are shown in Fig. 5 with the marks "●", and had, in 1936, Cl-content less than 0.5 g/l and further less other components. When such hot water is mixed with the sea water, it may approach, more or less, to the sea water in chemical composition.

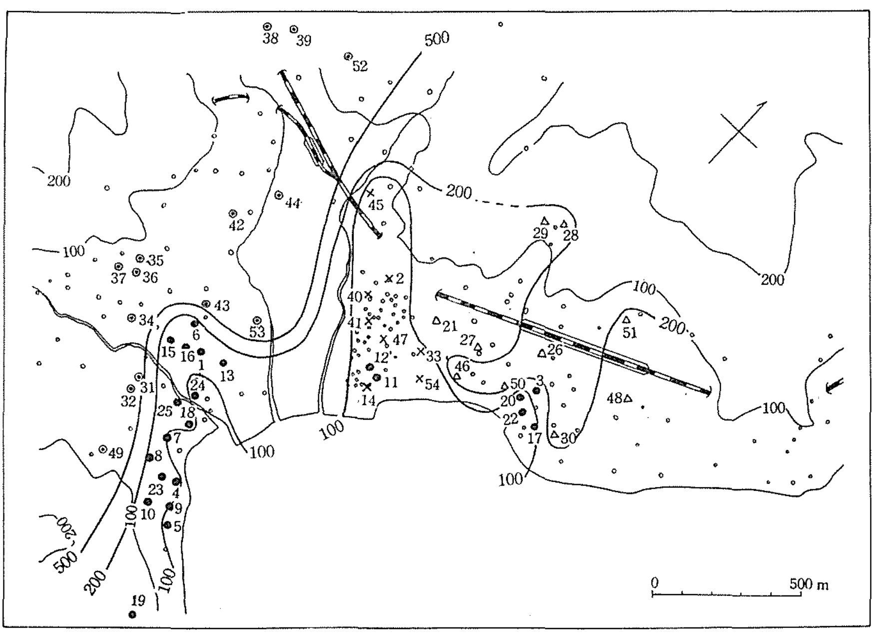


Fig. 5. Distribution of the "deviation". The marks, ●, ⊙, △ and ×, correspond to types, (a), (b), (c) and (d), in Fig. 6; side figures are the analysis number.

Seno (7) used a method of comparing Na, SO_4, Mg, Ca and K with Cl in weight and then illustrated the results in a diagram. He also introduced the total deviation "δ" of the hot water, which is defined as follows:

$$\delta_X = \left\{\frac{X\ (\text{hot water})}{Cl\ (\text{hot water})} - \frac{X\ (\text{sea water})}{Cl\ (\text{sea water})}\right\} \times 100\,,$$

and

$$\delta = |\delta_{Na}| + |\delta_{SO_4}| + |\delta_{Mg}| + |\delta_{Ca}| + |\delta_K|.$$

Then the total deviation δ is an index to show whether the salts of water are originated from the sea water or not. He also suggested that when $\delta \leq 30$, the source of salts must be in the sea water and when $30 < \delta \leq 50$, it may be in the sea water.

Analysis tables of Atami hot springs in recent years are collected in "Nippon Kōsenshi" (8), from which we shall infer the origin of chemical elements of Atami hot springs. When the chemical elements of the hot springs near the mouth of Wada River are illustrated in Seno's diagram, they show a feature unlike that of the sea water, as seen in Fig. 6 (a). The values of δ in this area are about

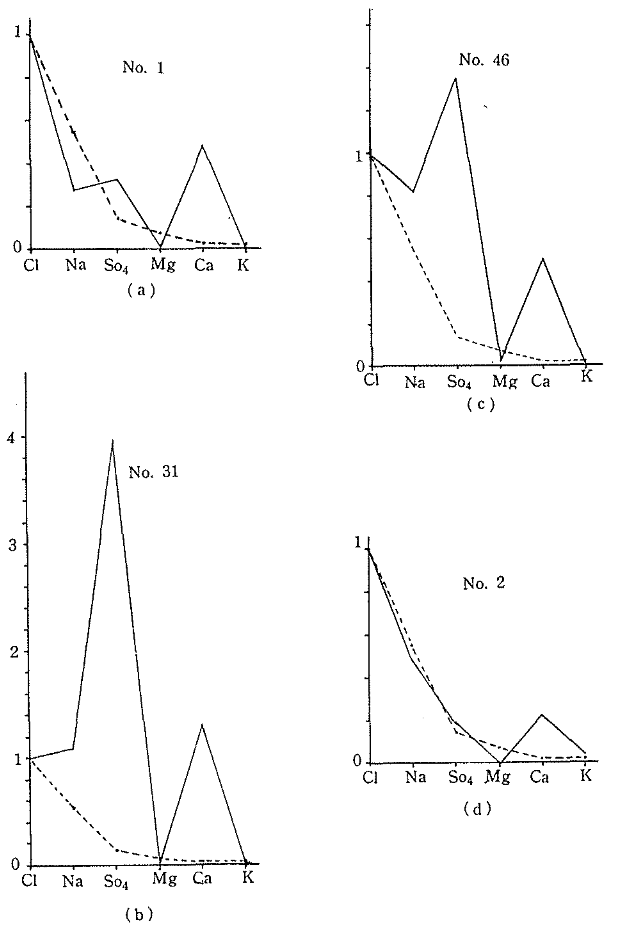


Fig. 6. Examples of Seno's diagram of the hot springs, (a) near and at the south of Wada River, (b) in the south-western part, (c) in the northern high ground, and (d) in the central region of Atami; dotted lines show the sea water.

100 ~200. Though it may not be correct to regard, from this diagram, the chemical elements of these springs as coming from sea water, yet it may be true, judging from the fact described in §2, that most of Cl ions of the hot water come from the sea water. Thus, the chemical contents of these hot springs consist of some matter, of the magmatic- and the marine-origin, and are influenced by the surrounding formation by such chemical actions as solution, sedimentation and ion exchange. If a chemical composition with the same ratio as the sea water is subtracted from the composition of these hot water, the rest expressed in equivalent per million is negative for Na, K, and Mg ions, and the sum of their absolute values and SO_4 value is equal to the Ca value (see Fig. 7). From these results

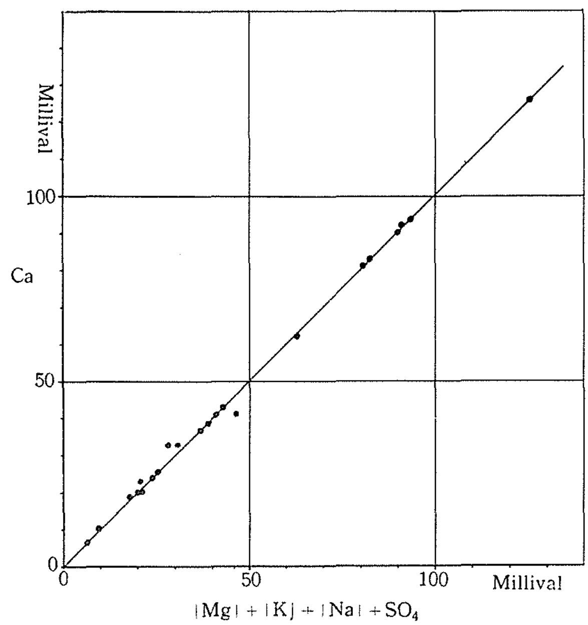


Fig. 7. Relation among Mg, K, Na, SO_4 and Ca residuals, which are introduced by substracting a chemical composition having the same ratio as sea water from the composition of hot water.

we may deduce the conclusion that $CaSO_4$ is dissolved in pure hot water of less chemical contents, and Na, K and Mg ions added to it by the intrusion of sea water are exchanged with Ca ions in the surrounding formations, thus finally the hot water has the present chemical constituents. According to this interpretation, there is little dissolved matter originating in the magma, and $CaSO_4$ is required in the ground. It is confirmed by Kuno (9) that gypsum exists as the secondary mineral in this district. The cation exchange in the hot water may also be possible as in ground-water reported by Love (**10**). After his interpretation, the following discussion may be introduced. "In earlier geologic history the whole area of Atami was submerged beneath the sea and therefore was saturated with sea water. After emergence from the sea, the salty water was gradually flushed out of the formation by the hot water which contains much Ca ions. During this leaching and flushing, the colloids saturated with Na, K and Mg ions were thus brought into contact with water containing Ca as its chief basic constituent. Cation exchange took place leaving the colloids saturated with Ca ion while Na, K and Mg ions were removed from the aquifer by the flushing action. When exchange process is reversed by new intrusion of the sea water, the active colloids give up Ca ion in exchange for Na, K and Mg ions in the sea water. The resulting concentration of cation in the contaminated hot water tends to be higher in Ca and lower in Na, K and Mg than would be expected from simple mixtures of hot water containing $CaSO_4$ and sea water."

The hot springs on the northern beach of Atami have the same character as those near the mouth of Wada River. They are also shown in Fig. 5 by the marks "●", and might be contaminated by the sea water. The hot springs shown in Fig. 5 by the marks "⊙" are distributed in the south-western part of Atami, and have about 2 g/l of the total amount of chemical contents which is less than those of other springs. They also have a type of chemical elements shown in Fig. 6 (b), the "deviation" of which is more than 400. A characteristic of the chemical property of their springs is to have SO_4 ions four times as Cl content. In connection with this characteristic, it is interesting to remember the studies of volcanic ash by Miyake (**11**), Noguchi (**12**), and Iwasaki (**13**), who reported that there are much SO_4 and little Cl in the soluble component of volcanic ashes from Aso, Asama, Kusatsu-Shirane and Izu-Mihara volcanoes.

The hot springs in the high ground of northern Atami, marked with "△" in Fig. 5, have also a little chemical constituent and a large value of the deviation, and the ratio of some chemical components is shown in Fig. 6 (c), which differs somewhat from Fig. 6 (b). Chemical constituents of both hot springs in the south-western part and the northern high ground may be secondary, dissolved from the formation, since these springs have low temperature and less constituents.

Finally, the hot springs in the central region have the type of chemical composition as shown in Fig. 6 (d), and are marked with "×" in Fig. 5. They have the deviation less than 100, and their constitution resembles to that of the sea water, compared wlth other springs in Atami. Yazima (**14**), Honda and Terada (**15**) suggested that the origin of chlorine of these springs may come from the sea water, but, at the present time, it is difficult to prove it.

5. Summary

(1) Hot springs in the central region of Atami have the temperature of about 100°C, and much Cl and few SO_4 ions. These results are similar to those observed in 1936, but the activity of these hot springs becomes slightly weak, since the less sulphate area characterizing the central region becomes narrower.

(2) Hydrostatic pressure of the greater part of hot springs in the central region is larger than that of the sea water, and at present the sea water filtering into these springs should not occur. However, a few springs on the beach of the central region have a tendency of decreasing temperature and increasing Cl content, and their pressure is less than that of the sea water, so they may be contaminated by the water, and it was also proved from their chemical constituent.

(3) It becomes clear that the hot springs near and at the south of the mouth of Wada River are contaminated by the sea water, because their temperature decreases and their Cl content largely increases in comparison with the past state. Chemical constituent of these springs differs from that of the sea water, but the difference is explainable when the dissolving $CaSO_4$ and the cation exchange in underground are considered together with the sea water intrusion. This intrusion may be caused by the over-pumping.

(4) Hot spring in the south-western part and northern high ground of Atami have a little chemical constituent. It seems that their dissolved matter probably comes from the volcanic formation of this area. Some hot springs on the northern beach of Atami may also be contaminated by the sea water, since their Cl ions have been increasing in recent years.

(5) According to the pressure distribution of hot springs in the central region, it seems that the hot water comes through fissures from deep ground and spreads in an aquifer, which may be artesian, because there are some flowing springs in this region.

PART II. WATER LEVEL FLUCTUATION IN A HOT-SPRING WELL

6. Information about an observed well and method of observation

In Atami, most wells are pumped by air-lift-pumps of 2~20 horse-powers, but only one well named "Nagisa" is suitable for water-level observation, which is on the reclaimed ground 4.5 m above sea-level and 60 m from the sea-shore. On account of comparatively low temperature of 43°C, it has not been used. Underground geological condition around this well are unknown, but it appears from the general geology of the surroundings that the well penetrates into the "Yugashima group" and the hot water comes from the strata.

To measure the water level fluctuation in the well, Richard's automatic tide gauge was used, its reduction rate being 1/30. Observation continued from September 1954 to December 1955. Some examples of the record are shown in Figs. 9, 11, 12, 14 and 15. The water level in the well can be expressed by the following relation:

$$W_t = W_0 + aT_{t-\alpha} + bP_t + R + A\,, \qquad (1)$$

where

W_t = water level in the well at time t (cm),

W_0 = mean water level in the well (341 cm above a datum level and 319 cm below the ground surface),

$T_{t-\alpha}$ = deviation of sea level from the mean at time $(t-\alpha)$ (cm),

a = tidal efficiency of the water level in the well,

α = time lag between changes of the water and the sea levels,

P_t = change of atmospheric pressure from the mean at time t (cm of water column),

b = barometric efficiency of the water level in the well,

R = term of precipitational effects,

A = term of interference-effects produced by starting and stopping pumps of neighbouring wells.

The time lag of effect of barometric change is not found on the records, as the apparatus used is not so sensitive as to record a sharp barometric change.

In the following discussion the tidal data at Itō and the barometric and precipitational data at Aziro are used. Though Itō is at a distance of 15 km and Aziro is at a distance of 7 km from Atami, there may be not so large errors in using these records, when the general tidal and barometric effects are considered. As the data of A, driving conditions of air-lift-pumps in city-owned wells are used. On the other hand, there are many private wells and their discharges are generally smaller than those of the city-owned wells. Thus, it is enough to use the data of the city-owned wells in the first stage of discussion of the effect of pumping.

7. Tidal effect on the water level in the well

When there are little changes in the atmospheric pressure as well as in the driving condition of pump and there is no precipitation, then P_t, R and A are zero. Thus we have

$$W_t - W_0 = aT_{t-\alpha}\,. \qquad (2)$$

Periods in which the above conditions were satisfied are June 28～July 2, July 4～6 and July 12~17, 1955. In these periods, comparing $W_t - W_0$ with T, we can estimate the tidal efficiency "a" and the time lag "α". Fig. 8 shows the relation between the tide level and the corresponding water level in the well, at the maximum and the minimum. The tidal efficiencies are calculated by the method of least squares and the mean value is $0.495 \fallingdotseq 0.5$.

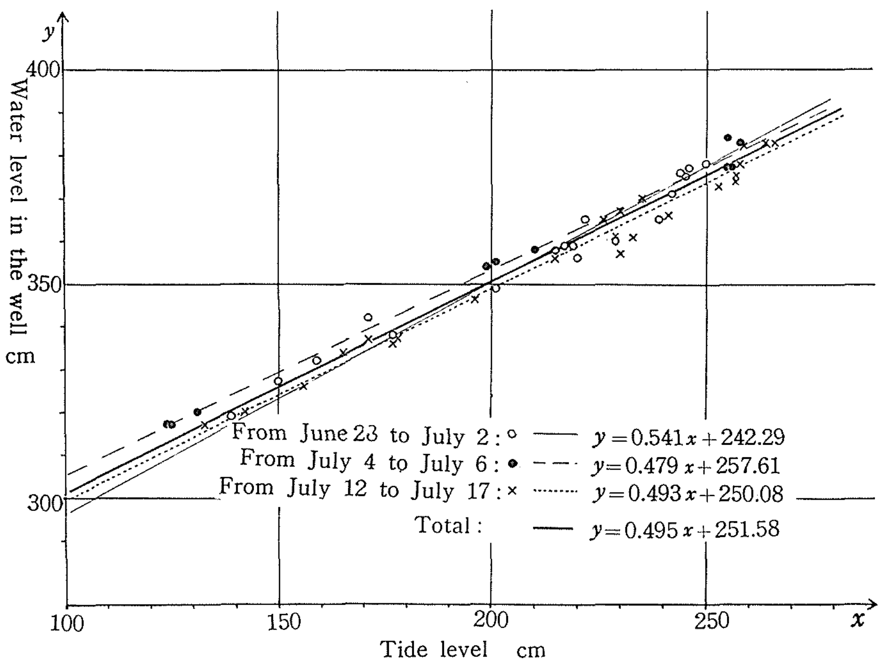


Fig. 8. Relation between the tide level and the water level in the well.

When we consider the time lag, the eight-day clock of the apparatus was replaced by a one-day clock and the time check was marked electrically every hour from August 5 to August 9, 1955. Thus the time errors can be kept to a few minutes. The times of appearance of the maximum and minimum water level are compared with those of the tidal records, as in Table 2. Phase lag ranges from 20 to 95 minutes and the means is about 60 minutes. The variation of phase lag of apparent tidal effect is caused by the tidal wave constitution. When the effects of tide move in an aquifer, each component reduces its own amplitude and delays its own phase, then the resultant wave of these components is observed in a well as a water level record. The harmonic analysis of the tide and the water level was done by Darwin's method in a period from January 1 to January 29, 1955, and the result is shown in Table 3.

Table 2.

Date		Time of appearance: Water level in tbe well	Time of appearance: Tide	Time difference of the appearance
		h m	h m	minutes
Aug. 5	Min.	13 00	11 45	75
	Max.	19 30	18 25	65
Aug. 6	Min.	1 00	0 00	60
	Max.	7 00	5 40	80
	Min.	13 30	12 15	75
	Max.	19 30	18 45	45
Aug. 7	Min.	1 40	0 35	65
	Max.	7 25	6 25	60
	Min.	13 40	12 40	60
	Max.	20 40	19 05	95
Aug. 8	Min.	2 10	1 05	65
	Max.	8 20	7 05	75
	Min.	14 00	13 20	40
	Max.	20 30	19 45	45
Aug. 9	Min.	2 20	2 00	20
	Max.	9 00	7 55	65
	Min.	14 40	13 50	50
			Mean	61

Table 3.

	M_2		S_2		K_1		O_1	
	H_m	κ_m	H_s	κ_s	H'	κ'	H_0	κ_0
	cm	°	cm	°	cm	°	cm	°
Tide	35.4	145.1	17.1	179.4	22.1	176.5	18.3	155.3
Water level in the well	13.7	168.1	7.9	204.3	12.0	195.2	10.1	180.0
(Water level)/(Tide level),	0.39	—	0.46	—	0.54	—	0.55	—
(Water level)-(Tide level), degree	—	23.0°	—	24.9°	—	18.7°	—	24.7°
(Water level)-(Tide level), minute	—	48	—	50	—	75	—	106

8. *Effect of barometric pressure change on the water level*

As cyclones and fronts accompany the rain, it is difficult to pick up the case of pressure change without rainfall from the actual record. Thus, we were obliged to take the data of February 20, 28 and October 11, 1955, when it was raining. An example of the record of the water level is shown in Fig. 9, together with tidal and barometric curves. The records should include the effect of precipitations, but it may be negligible as shown in a subsequent section. When in

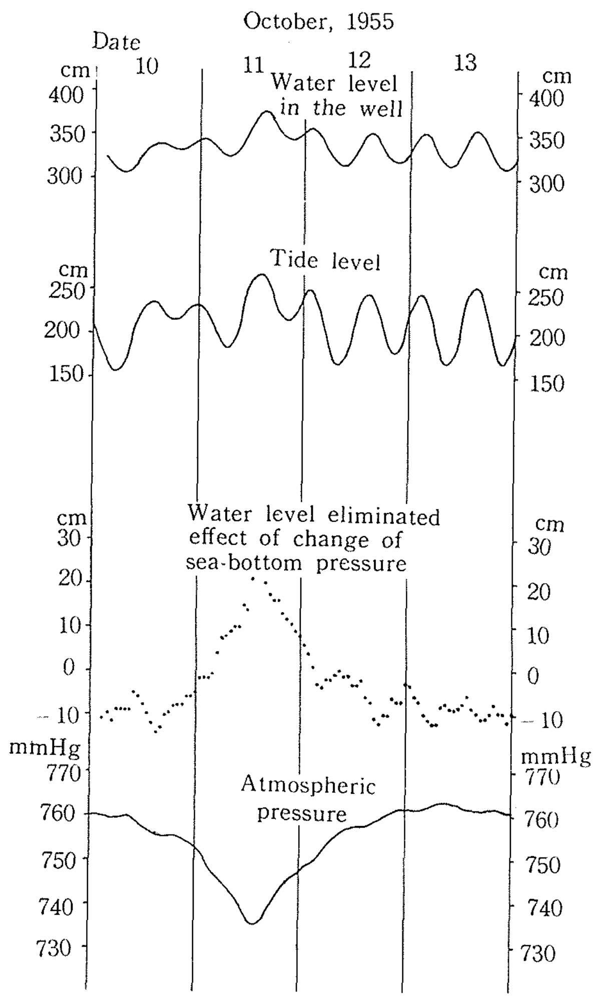
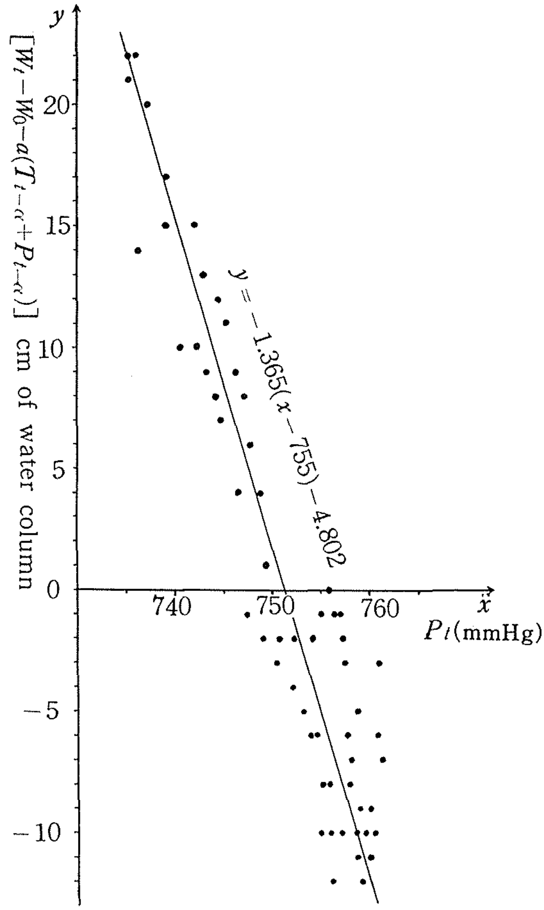


Fig. 9. An example of the effect of the atmospheric pressure change on water level in the well.

Eq. (1) both A and R are nearly zero, we have

$$W_t - W_0 - aT_{t-\alpha} = bP_t. \tag{3}$$

The left-hand side of this equation shows the water level change from which the tidal effect is eliminated, and it may be calculated with the values of a and α of the former section. For the discussion of the effect of barometric pressure change on the water level in a well, we must divide it into three elements which are on the sea-surface, the ground-surface and the water-surface in the well, but the last two elements are usually discussed as one. The increase of atmospheric pressure on the sea-surface causes descent of the sea-level, but this compensation



October 11 and 12, 1955

Fig. 10. An example of the relation between the water level eliminated effect of change of sea-bottom pressure, $W_t - W_0 - a(T_{t-\alpha} + P_{t-\alpha})$, and the atmospheric pressure, P_t.

Table 4.

	b'	
	cm of water column / mm Hg	cm of water column / cm of water column
1955, Feb. 18～20	−1.148	−0.845
Feb. 26～28	−1.574	−1.158
Oct. 10～12	−1.365	−1.003
Mean		−1.002

is usually imperfect and the increase of atmospheric pressure may bring about the increment of sea-bottom pressure, and then the water level in the well may ascend at the flood tide. Thus, the effect of atmospheric pressure change may be written as:

$$bP_t = aP_{t-\alpha} + b'P_t \,. \tag{4}$$

The first term on the right-hand side of Eq. (4) shows the effect on the sea-surface, so that the damping rate a and the phase lag α are nearly equal to those in the tidal effect. The second term shows the effect on the ground-surface and the water-surface. Thus, Eq. (3) is expressible as follows:

$$W_t - W_0 - a(T_{t-\alpha} + P_{t-\alpha}) = b'P_t \,. \tag{5}$$

The values of the left-hand side of Eq. (5) may be calculated with a and α which are given in the former section, and their variations are also plotted in Fig. 9. The value of b' is determined from Fig. 10 by the method of least squares, and is listed in Table 4 together with other examples, the mean value being -1.00. The "barometric efficiency" in other papers corresponds to b used here, and it follows from Eq. (4) $b \fallingdotseq a + b' \fallingdotseq -0.5$. The relation $b' \fallingdotseq -1$ shows that the pressure change on the ground-surface does not affect the water level in the well, and that the aquifer is nearly rigid.

9. Annual variation and effect of precipitation on the water level

If the discharge rate of the hot water from the aquifer is equal to the recharge rate, the pressure of the hot spring should be kept at a constant value. When the discharge exceeds the recharge, the head of the hot ground water falls gradually, and then the head will be settled at a level when the discharge and the recharge are balanced. On the other hand, when the discharge is less than the recharge, the head will rise.

In Atami, with the increase of the discharge from the aquifer, the head of the hot ground water has decreased. Total discharge rate is at present about 9×10^3 m^3/day (**19**), and it is important to know whether this discharge is over or under the recharge, the secular variation of the mean head of the hot ground water being helpful to know. We average the values in 24 hours to compare with the daily data of the atmospheric pressure and the precipitation, and the effect of tide may also be nearly eliminated.

Fig. 11 shows daily means of the water level of the Nagisa well, the sea level and the atmospheric pressure*. The water level from which both tidal and

* It is based on Monthly Report, C. M. O., Japan, and somewhat differs from the data shown in other figures as it is reduced to the mean sea level.

barometric effects with the same coefficients as given before are eliminated is also shown in Fig. 11. They denote the annual variation which is low in winter and high in summer, but neither monotonously decrease nor increase. This suggests that the recharge and discharge of the aquifer are nearly balanced through a year. A main cause of the annual variation is generally the precipitation, but, as shown in Fig. 11, the daily mean of the water level has no reliable correlation, and the effect of precipitation upon this well seems to be not so remarkable. Furthermore, in order to pay attention to the effects of short periods, the hourly water level, from which both tidal and barometric effects are eliminated, is calculated during several days before and after December 19, 1954, as well as during several days before and after February 27, 1955, when there was respectively a solitary rain. The result is shown in Fig. 12, in which we cannot find the

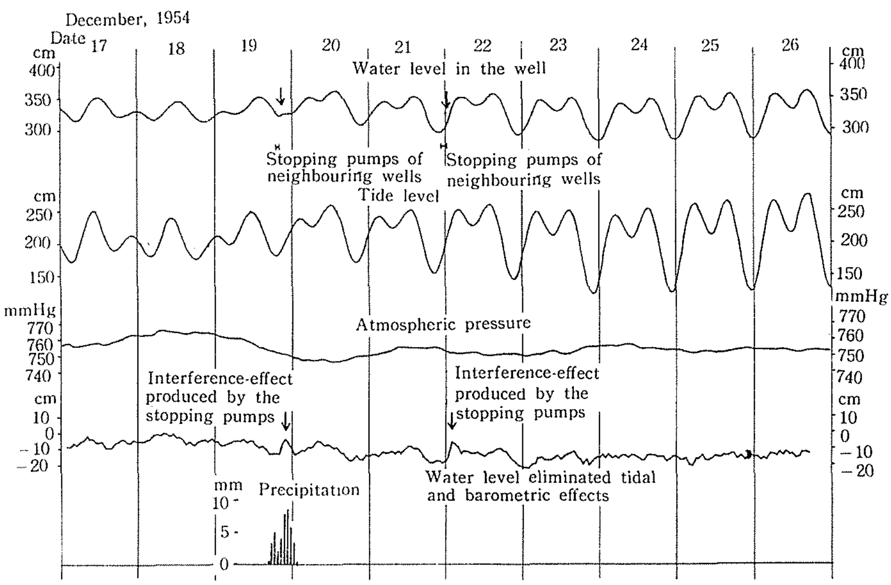


Fig. 12. Water level in the well and other factors during several days before and after Dec. 19, 1954.

ascent of head for the precipitation. Finally, the effect of precipitation upon this well seems to be very small, and it coincides with the result of study in Beppu (**20**) where the hot springs near the sea-shore were scarcely affected by the precipitation. Annual density variation of sea water contributes to annual pressure change at the sea bottom, but, by this effect, sea-bottom pressure is greater in winter and smaller in summer than that calculated from the sea level (**21**). Therefore the annual variation of the well-water level is also inexplicable by this density variation.

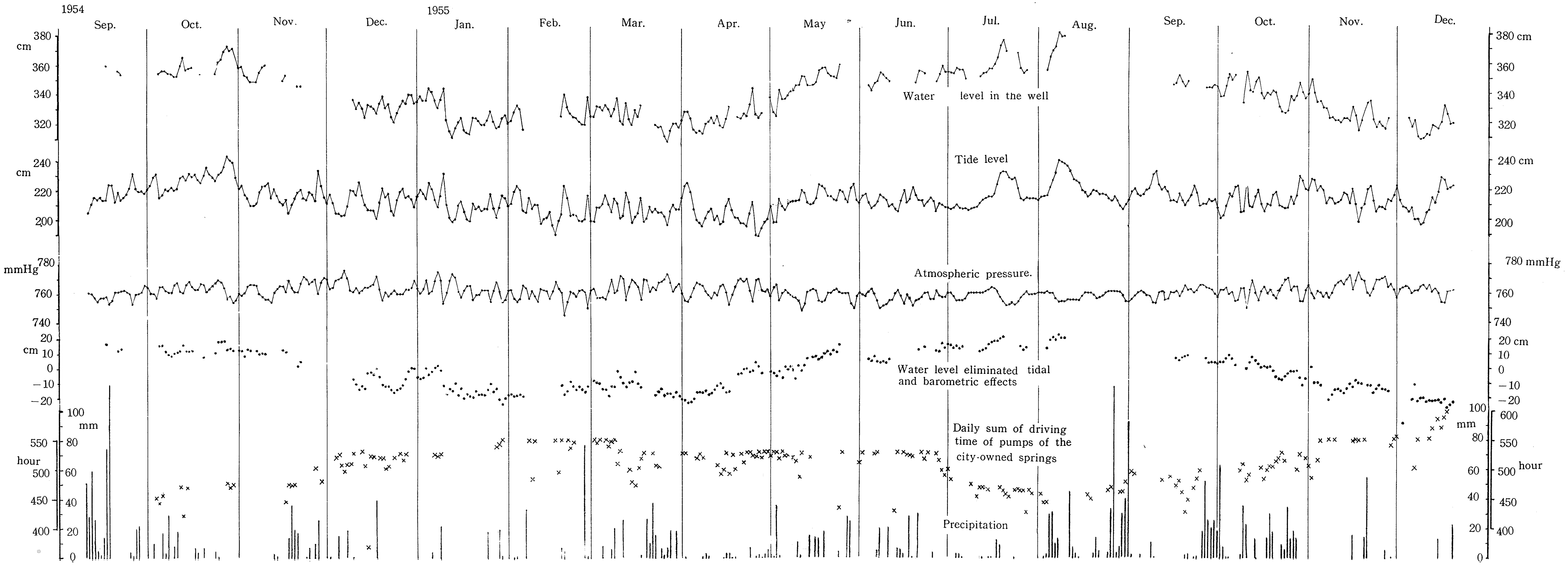


Fig. 11. Daily means of water level in the well and other factors,

Daily sums of driving time of pumps of city-owned springs are registered by Atami Municipal Office and also shown in Fig. 11. They have reciprocal correlation with the annual water-level variation, being approximately an index of annual variation of total discharge from the aquifer. Thus, the annual variation of head shown in Fig. 11 seems to be related to the change in the discharge.

10. Interference-effect produced by starting and stopping pumps of neighbouring wells upon the water level in the observed well

During this observation period, remarkable changes of the water level in the Nagisa well were found and they were inexplicable by the effects of tide, atmospheric pressure and precipitation, but related with starting and stopping pumps of other wells.

There are several hot springs near the Nagisa well as shown in Fig. 13. It is important to know which springs interfere with the Nagisa well. In Beppu (**22**), some springs are affected by adjacent wells and others by rather distant wells, and the extent and the direction of the interference are indeterminate. To search for the well of which discharge affects the head of the observed well, we examined the abnormal changes on the water level record, comparing

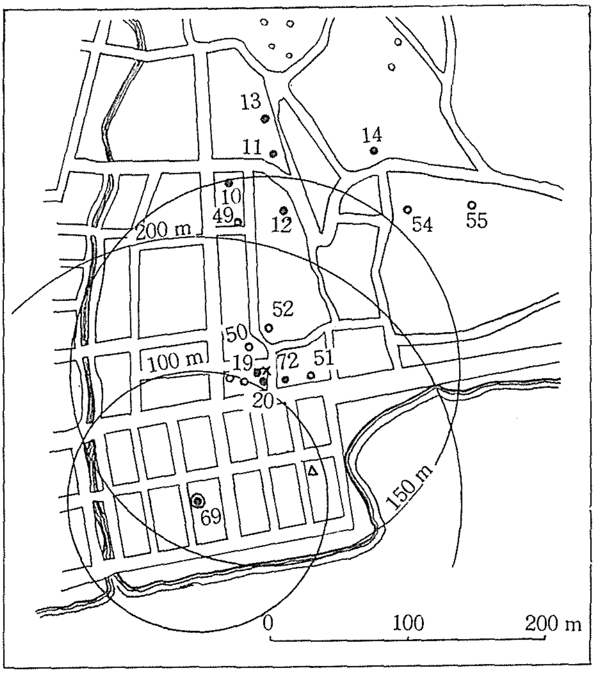


Fig. 13. Distribution of hot springs near "Nagisa well"; ●, municipal well; ○, private well; ⊙, observed well; △, a well under drilling; ×, assumed representative well.

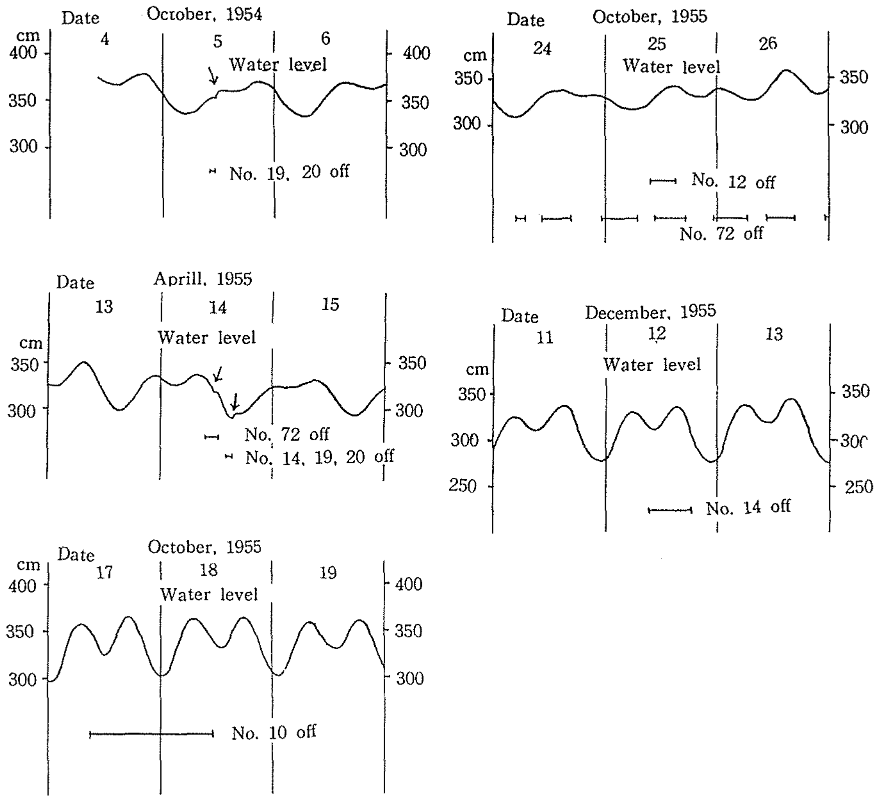


Fig. 14. Relation between water level in the observed well and stopping pumps of neighbouring wells.

with driving condition of pumps installed in neighbouring city-owned wells. Some examples are shown in Fig. 14, from which it appears that No. 19 and No. 20 wells affect greatly the head of the Nagisa well, and No. 10, No. 12 and No. 14 do not affect at all and No. 72 does sometimes. The driving conditions are registered only for the city-owned wells and not for the private wells, but the head of the Nagisa well must be affected by the change in pumping condition of both city-owned and private wells in a limited area where No. 19, No. 20 and No. 72 wells exist.

An example of the observed abnormal change is shown in Fig. 15. The lowest row of this figure gives true interference-effect reduced by eliminating tidal and barometric effects from the record of the water level. Rise and fall of the water level occurred simultaneously with stopping and restarting the pumps of neighbouring wells. The quantitative relation between the rate of discharge and the water-level change may be connected with the property of the aquifer, and will be discussed in the next section.

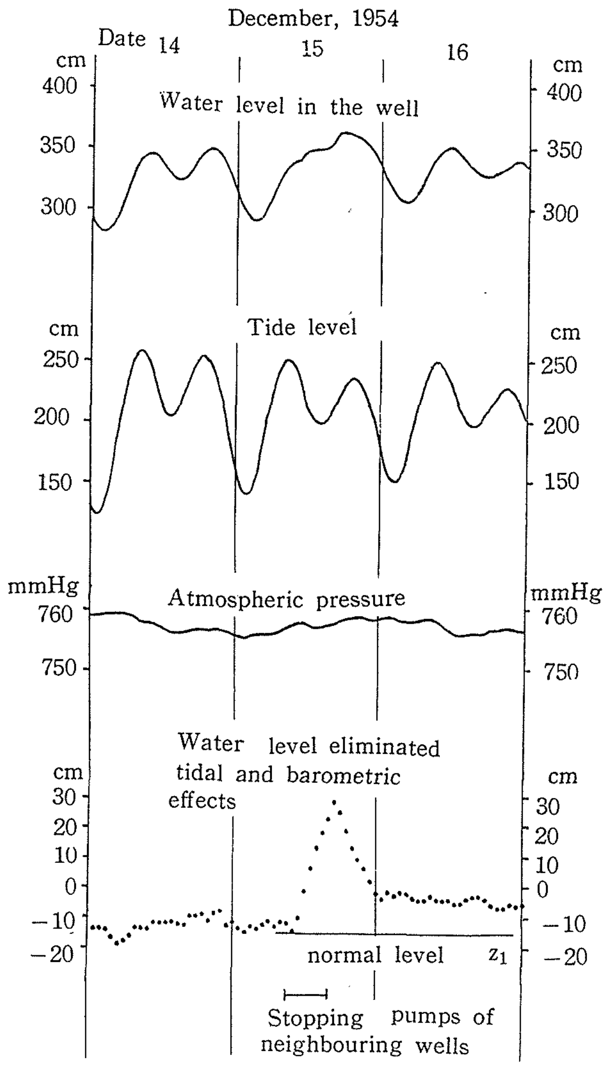


Fig. 15. An example of the interference-effect produced by stopping pumps of neighbouring wells on the water level in the well.

11. Physical properties of the aquifer in the central region of Atami

The region extending from the Nagisa well to the west is called "the central region of Atami" as described above. Hot-spring wells in this region seem to be in the same aquifer, because they closely resemble in chemical and hydrological properties. The aquifer is in "Yugasima-group" described in section 1. This group has no sand stratum but a great many large and small fissures, so its permeability can be assmed to be uniform enough to regard it as a nearly homogeneous aquifer (**2**). It may also be artesian, because there are a few flowing hot springs in this region.

It is of interest to know whether the aquifer is connected with the sea or not, and we can find some informations about this problem: (1) for the hot springs of which pressure is less than that of sea water, the temperature decreased and the Cl content increased; (2) if the aquifer is not connected with the sea, the tidal effect upon the well is produced by the tidal load change on the sea bottom through the impermeable formation to the aquifer, but it is contradictory to the former result that the aquifer is nearly rigid; (3) it is also said that there are springs in the bottom of the Atami Bay (**14, 19**). Thus, the aquifer is regarded to be directly connected with the sea. If some additional conditions are assumed for the aquifer, we can lead its transmissibility and coefficient of storage. These conditions are as follows.

(a) The aquifer is homogeneous, isotropic and horizontal, and its thickness is uniform.

(b) When the interference-effect is considered, the aquifer is regarded as a horizontally infinite layer, while the real range is about 1 km^2.

(c) When pumping of a well is continuous, the head distribution of the neighbourhood is able to reach the nearly steady state, that is, the discharge from the aquifer is compensated by the recharge from the outside. This assumption is necessary only for the discussion of interference-effect, and unsuitable for a long period, because the head of Atami hot springs has fallen gradually in recent years.

Most hot water in Atami is forced out by air-lift-pumps. When pumping is continuous at a constant discharge, the water level in the observed well would be kept in steady state from the assumption (c), and then if the pumping stops, the water level will rise. In this case, the stopping of pumps is equivalent in mathematical treatment to the starting pump of negative discharge, $-Q$, over the continued positive discharge, Q. Thus, applying Theis' theory (**23**), we can express the water level in the observed well with the assumptions (a) and (b), that is,

$$z-z_1 = \frac{Q}{4\pi kD}\int_{\lambda}^{\infty}\frac{e^{-\lambda}}{\lambda}d\lambda\,, \tag{6}$$

where z_1 = water level, from which tidal and barometric effects are eliminated, in observed well before stopping pump,

z = water level, from which tidal and barometric effects are eliminated, in observed well after stopping pump,

Q = rate of discharge,

k = permeability,

D = thickness of the aquifer,

$\lambda = \frac{r^2 S}{4kDt}$,

r=distance from pumped well to observed well,

S=coefficient of storage,

t=time elapsed from the stopping of pump.

When $\lambda \ll 1$, it follows approximately

$$z - z_1 \doteqdot \frac{Q}{4\pi kD}\left(\ln\frac{4kDt}{r^2 S} - 0.577\right), \tag{7}$$

and this approximation holds roughly when $t > 2$-hours as seen in Fig. 16. Eq. (6) or Eq. (7) shows the behaviour of water level in the observed well at a distance r from a pumped well. In practice, there are some pumping wells which affect the water level of the Nagisa well, but it is permissible to imagine a representative well for the actual wells, because they are in a limited area. The relation between t and $z-z_1$ is given from the data as shown in Fig. 15, and illustrated semi-logarithmically in Fig. 16.

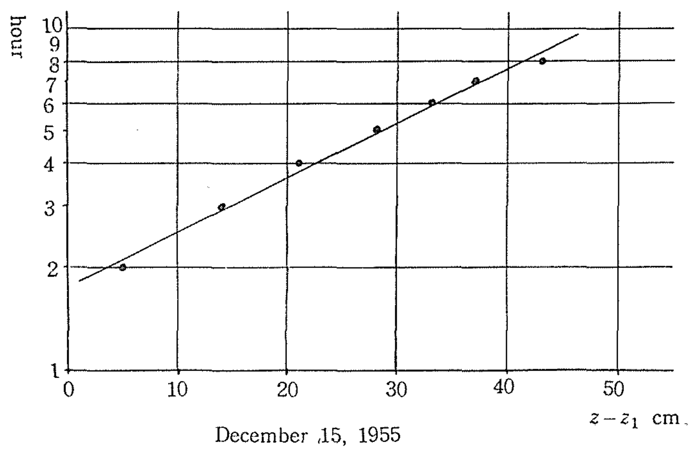


Fig. 16. An example of the relation between t and $z-z_1$.

After the restarting pump with the same rate of discharge Q, putting the period of the stopping as t_1, we get

$$z - z_1 \doteqdot \frac{Q}{4\pi kD}\ln\frac{t}{t-t_1}. \tag{8}$$

The relation between $\frac{t}{t-t_1}$ and $z-z_1$ is shown in Fig. 17.

According to the investigation of the Atami Municipal Office, the sum of actual discharge rates of some wells in the limited area, Q, was 600 l/min in December, 1954 and r is about 200 meters. The values of T and S are calculated

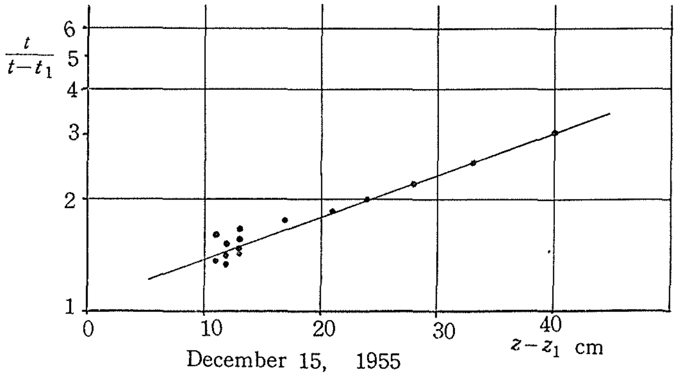


Fig. 17. An example of the relation between $\frac{t}{t-t_1}$ and $z-z_1$.

Table 5.

		$T=kD$ cm²/min	S (1)	S (2)	S (3)
Dec. 15, 1954	Case of stopping pump	1750	1.7×10^{-5}	1.5×10^{-5}	2.6×10^{-5}
	Case of restarting pump	1232	—	—	—
Mar. 10, 1955	Case of stopping pump	2545	2.2×10^{-5}	2.9×10^{-5}	2.3×10^{-5}
	Case of restarting pump	4100	—	—	—
Dec. 7, 1955	Case of stopping pump	3220	1.4×10^{-5}	1.1×10^{-5}	1.1×10^{-5}
	Case of restarting pump	2025	—	—	—
Mean of all values		2600			2.0×10^{-5}

(1) Calculated with "T" for stopping pump.
(2) Calculated with the mean of both"T" for stopping and restarting pump.
(3) Calculated with the mean of all "T".

by the method of least squares, and these results are shown in Table 5. The cause of disagreement of these results may be ascribed to the uncertainty of z and Q, and that the assumptions used may not be completely accurate. Finally, $T=kD=2600\,\text{cm}^2/\text{min}$ and $S=2.0\times10^{-5}$ are given in round numbers.

In §8, we regarded the aquifer as rigid from the result that the pressure change on the ground surface does not affect the water level in the well. On the other hand, the aquifer seems to have elastic characteristics, because the water level variation obeys Theis' equation. This means that the water in the aquifer is compressible and the permeable medium of the aquifer is nearly incompressible. Jacob (**24**) introduced, in his elastic theory, the coefficient of storage as

$$S = \rho g D\left(\frac{\theta}{E_w}+\frac{p}{E_s}+\frac{\theta q}{E_c}\right), \tag{9}$$

where ρ is the density of water, g the acceleration of gravity, θ the porosity of the medium of which the aquifer is composed, p the negative ratio of a given change in compressive stress to the change in hydrostatic pressure producing it, q a dimensionless quantity of clay intercalated in the aquifer, and E_w, E_s and E_c are moduli of elasticity of the water, the solid skeleton and the clay, respectively. When the aquifer is rigid, Eq. (9) may be reduced to

$$S = \rho g D\frac{\theta}{E_w}. \tag{10}$$

Substituting in Eq. (10) $S=2.0\times10^{-5}$, $\rho=1\ \mathrm{g/cm^3}$, $g=980\ \mathrm{cm/sec^2}$ and $\frac{1}{E_w}=48.9\times 10^{-12}\ \mathrm{cm\cdot sec^2/g}$, we get $D\theta=4.2\times10^2$ cm. Since θ is unknown, the value of D is not determined, but the order of D presumed with the probable θ may be from 10^3 to 10^4 cm.

We can also estimate the physical properties of the aquifer from the tidal effect. When the above conditions (a) and (b) are assumed, the problem can be treated as one-dimensional wave propagation. If the amplitude and the phase of tidal wave are given by H_T and κ_T, and those of water-level fluctuation by H_W and κ_W, we can introduce the next relation like Ferris' equation (**25**):

$$H_W \cos(nt-\kappa_W) = H_T e^{-x\sqrt{\frac{nS}{2T}}} \cos\left((nt-\kappa_T-x\sqrt{\frac{nS}{2T}}\right), \tag{11}$$

where n is the velocity of each tidal component, x the distance from a point where the aquifer is in contact with the sea, and S, T and t are the coefficient of storage, transmissibility and time respectively. Thus,

$$\frac{H_W}{H_T} = e^{-x\sqrt{\frac{nS}{2T}}}, \tag{12}$$

and

$$\kappa_W-\kappa_T = x\sqrt{\frac{nS}{2T}}. \tag{13}$$

We can, therefore, calculate the values of $x\sqrt{\frac{S}{T}}$ and x, and the results are shown in Table 6. The distinct discrepancy between the value calculated from Eqs. (12) and (13) may be caused by a simplification of the natural complex situation to a simple model for mathematical treatment. Thus, according to a rough estimation, the aquifer may be in contact with sea at a place on sea bottom from 0.7 to 1.7 km off-shore.

Table 6.

(a) Calculated with the ratio of amplitude.

Tidal component	$\frac{H_W}{H_T}=e^{-x\sqrt{\frac{nS}{2T}}}$	$x\sqrt{\frac{ns}{2T}}$ (radian)	x (cm)
M_2	0.39	0.904	1.65×10^5
S_2	0.46	0.776	1.34
K_1	0.54	0.615	1.50
O_1	0.55	0.597	1.51

(b) Calculated with the phase lag.

Tidal component	$\kappa_W-\kappa_T$	$x\sqrt{\frac{ns}{2T}}$ (radian)	x (cm)
M_2	23.0	0.401	0.71×10^5
S_2	24.9	0.435	0.75
K_1	18.7	0.326	0.80
O_1	24.7	0.431	1.09

12. Summary

(1) Tidal effect on the observed well of hot ground water is obvious, and the tidal efficiency is about 0.5 and the phase lag about one hour.

(2) Water level in the well rises with the barometric pressure decrease and falls with its increase. The barometric efficiency is about 0.5 and the phase lag is very small. The barometric pressure change affects the water level through the sea and the well directly, but not the ground surface, and this means that the permeable medium of the aquifer may be rigid.

(3) The water level is high in winter and low in summer, but the effect of precipitation upon the well is inappreciable. The cause of this annual variation seems to be the seasonal variation of the total pumping rate of Atami hot springs. Therefore, the head of hot ground water in Atami will fall more and more with future exploitation.

(4) The interference-effects produced by starting and stopping pumps of neighbouring wells upon the observed well are very noticeable. The hot springs in the central region of Atami are closely connected with each other, and may be in the same aquifer.

(5) The aquifer may be regarded as a confined one, and its transmissibility is about 2600 cm^2/min, its coefficient of storage about 2.0×10^{-5}, and the order of the thickness of the aquifer may be from 10^3 to 10^4 cm.

(6) The aquifer seems to be in contact with the sea at a certain place on sea bottom from 0.7 km to 1.7 km off-shore.

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