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Hydrothermal System and Seismic Activity of Hakone Volcano

by

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Abstract

The structure of the Hakone hydrothermal system and geochemistry of thermal waters are described. The subsurface temperature map and the zonal distribution of thermal waters strongly suggest that thermal energy of the Hakone system is essentially supplied by dense volcanic steam rich in sodium chloride coming up through the volcanic conduit, from which subsurface streams of sodium chloride waters are derived.
Tne seismic activity of Hakone mostly takes place at relatively shallow depths in the central part of the caldera. The chemical and physical properties of the dense steam are examined assuming that the phase transformation of water to steam is the major cause for volcanic earthquakes. The Cl-SO_4 chemistry permits estimation of sodium chloride content of 0.5 to 1 % in original dense steam responsible for sodium chloride waters. Thanks to the work of Sourirajan and Kennedy(1962) temperature pressure condition of volcanic dense steam at depths of 1 to 2 km below sea-level is estimated to be about 385°C and 230 bars, dissolving 0.5 to 1 % of sodium chloride in steam. Below the depth of 4 km, earthquakes seldom occur, the hydrothermal system is saturated with solid sodium chloride, resulting in lowered vapor pressure. This implies that the permeation of meteoric water to the volcanic steam system mostly takes place at a depth less than 4 km. The analogy of hot eyes(centers of geothermal fields) and cold eyelids(surroundings of low temperature area) is emphasized for better understanding of hydrothermal systems.

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Introduction

Hakone belongs to the Fuji volcanic zone on the northern extension of the Izu-Mariana Island Arc. There are 11 Quaternary volcanoes in the Izu-Hakone district including Fuji,Hakone, and Yugawara volcanoes. About 40 geothermal fields entirely controlled by the "Hot Spring Business" are known in this district, extending 80 km north-south by 30 km east-west. The hydrothermal activity is intense along the east coast of the Izu peninsula. The total energy discharge from the area amounts to 11 x 10^7 cal/sec, of which Hakone has 27 %, discharging 3 x 10^7 cal/sec. Atami is the second largest followed by Ito (Fig.1).

Here is briefly described the structure of the Hakone hydrothermal system and geochemistry of the thermal waters. The main discussion is given to the chemical and physical properties if high temperature and pressure dense steam directly responsible for the seismic and hydrothermal activity of Hakone.

Geologic history

Figure 2 is the geologic map of Hakone by Kuno(1950). The following short comment on the geology of Hakone is given mostly based on the works of Kuno. Hakone is a triple volcano composed of two overlapping calderas and seven post-caldera cones. The volcanic eruptions began about 400,000 years ago (Suzuki, 1970), and built up a huge strato-volcano reaching a height of 2,700 m above sea-level. The first caldera was formed about 200,000 years ago. The caldera was entirely filled with a thick pile of fluidal lava flows and a shield volcano appeared in it. A catastrophic eruption with outpouring of pumice flows took place about 40,000 years ago and just after this event, the second caldera was formed.*

*The western wall of the second caldera is obscure probably because of overlapping of the major fault with that of the first caldera.

The seven post-caldera cones successively appeared along the Kintoki-Makuyama tectonic line. The seventh lava dome, Kami-Futago, appeared 5,000 years ago. A violent steam explosion took place at the northern part of Kamiyama, which collapsed about 4,000 years ago. Extensive solfataric activity is still taking place at Kamiyama and Komagatake.

Distribution of thermal wells

There are more than 300 deep wells for thermal waters. Their average depth is about 500 m, but several reach a depth of 1,000 m. Most of the wells are in the eastern half of the Hakone caldera.

In the period of Edo age, about 200 years ago, natural orifices of thermal waters were known as the seven sites of hot springs of Hakone, which were mostly located along the deep valley Hayakawa. There is an old saying about the occurence of hot springs in this district. "We can't expect hot springs where we can see Mt.Fuji." Kuno proposed a new saying that hot springs are expected where the Yugashima formation, the basement rocks of the Izu-Hakone district, is exposed. We will demonstrate that the two sayings are valid in the light of our work on the hydrothermal system.

Isothermal structure

Figure 3 is an isothermal map of Hakone at sea-level (Ōki and Hirano, 1970 and 1972). Temperature is the highest in the central part of the caldera, decreasing outward with a concentric pattern showing a correlation with the structure of the caldera. The interval between the isothermal lines of the western side are narrower than that of the eastern side. The isothermal lines are expanding toward the east, suggesting a flow mechanism of thermal water from west to east.

Figure 4 is an east-west cross section illustrating the geologic structure and isothermal profile. Basement rocks of the Hakone volcano are the Yugashima formation and the Hayakawa tuff breccias. The Yugashima formation of lower to middle Miocene is mostly composed of submarine pyroclastic sediments hydrothermally altered to dark greenish compact rocks. The Hayakawa tuff breccias, upper Miocene to lower Pliocene, are also hydrothermally altered. Both of the basement formations are at relatively shallow depth. The old and young somma lavas are rather thinned and sometimes are missing in the bottom of the caldera(Kuno et al.,1970). A thick pile of pumice falls and flows is recently recognized under the central cone deposits(Ōki and Odaka, 1972). This fact implies that the engulfment responsible for the appearance of the Hakone caldera was not so large, but that a huge amount of the volcanic edifice was blown away by catastrophic explosions. The pumice layers and the basal part of central cones provide a major reservoir for thermal waters.

Hydrology of thermal waters

The hydrology of the Hakone system is essentially controlled by the water level of Lake Ashi in the west and by that of Hayakawa valley in the east. The water table is gently inclined to the east. An interesting fact is that with increasing depth in drilling operations, the water level of perched water appeared in the drilled hole declines and finally stops when the hole reaches the major reservoir. A comparison of the water levels of deep wells suggests again the presence of subsurface flow from west to east. Temperature in the body of the old somma is relatively low, which means that the body of the strato-volcano is just like a sponge partly filled with cold groundwater.

Zonal mapping of thermal waters

Zonal mapping of thermal waters is mostly based on the relative abundance of major anions such as Cl, SO_4, and HCO_3. Four zones are recognized, as shown in Figure 5(Ōki and Hirano, 1970).

<u>Zone I</u>, characterized by acid-sulfate waters associated with solfataric fields, is found at the highest part of central cones Kamiyama and Komagatake.

<u>Zone II</u>, characterized by bicarbonate-sulfate waters with mode-

rate temperature and pH, is widely distributed in the western half of the caldera. The distribution and mode of the occurence of zone II waters strongly suggest that the major part of HCO_3 is supplied by the decomposition of fossil plants, which are commonly intercalated in the volcanic deposit.

Zone III, characterized by sodium chloride waters with high temperature, occurs as subsurface streams starting from a depth of 300 m beneath an active solfatara, Soun-jigoku, trends to the east, and finally appears as hot springs on steep slopes of Hayakawa valley.

Zone IV, sometimes refered to mixed type waters, is widely distributed in the eastern side of the caldera, which is deeply dissected by the two drainages of Hayakawa and Sukumogawa. Zone IVa is mixed type waters restricted to the basal part of the central cones. Zone IVb is waters restricted to the basement rocks of the Hakone volcano.

Table 1 shows the chemical composition of each type of thermal waters. Water of zone I is low in pH and Cl, but high in SO_4, Ca, Mg, and Al. Water of zone II is also low in Cl, but high in SO_4, HCO_3, Ca, and Mg. Water of zone III is quite high in Cl, Na, and SiO_2, but low in SO_4 and HCO_3. Water of zone IV contains appreciable amounts of the major anions.

Compositional trend of thermal waters

Figure 6 is a triangular diagram of the three major anions illustrating the compositional trend of the Hakone thermal waters. Zone III waters are in the Cl corner and zone I waters are in the SO_4 corner. Groundwater infiltrated through central cones tends to be richer in bicarbonate with increasing depth of burial. Cold groundwater restricted to the bottom of the caldera, having no obvious relation to the geothermal activity, is quite high in bicarbonate(Table 1, Hirano et al.,1971). This may suggest that bicarbonates dissolved in zone II waters are formed by the decomposition of fossil plants in the volcanic edifice. Zone IV waters are well explained by mixing of zone II and zone III waters. The trend of zone IV waters in the diagram is convex toward total CO_2 apex, suggesting the formation of bicarbonate during mixing and flowing of thermal waters. The content of bicarbonate in zone III waters is extremely low. If volcanic gases from the magma reservoir contain considerable amounts of CO_2, the zone III waters should be richer in bicarbonate than observed. However, the bicarbonate content of zone III waters is very low, especially those of high temperature. This supports the conclusion that bicarbonate is formed by decomposition of fossile plant instead of being of volcanic origin.

Genetic model of Hakone hydrothermal system

Figure 7 is a genetic model of the Hakone hydrothermal system(Ōki and Hirano, 1970). Asymmetric patterns of the isothermal structure and zonal distribution of thermal waters as well as the eastward inclination of water table all suggest the following mechanism for the genesis of the Hakone hydrothermal system.

Groundwater which infiltrates through the western side of the caldera is flowing eastward, passing through the basal part of the central cones, and then contacts high temperature volcanic steam coming up through the volcanic conduit. At a depth of a few kilometers below the central cone Kamiyama, temperature and vapor pressure are high enough to dissolve a considerable amount of sodium chloride in steam. By mixing of low temperature groundwater with high temperature dense steam, high temperature streams of sodium chloride water are formed that run through the permeable zone and mix with groundwater percolating down from the surface, and then finally appear as hot springs on the steep slopes of Hayakawa valley.

At the top of the major reservoir being penetrated by the steam vent, the thermal water boils. The confining pressure on the thermal water decreases as it approches the surface. This means that most salts dissolved in the gas phase are left behind in the liquid phase. Condensation of secondary steam derived from depth may take place repeatedly within local layers of thermal waters in the body of central cone above the major reservoir. With repeated processes of vaporization and condensation of thermal water, volatile components such as hydrogen sulfide and carbon dioxide are enriched in the gas phase, which finally appears as volcanic gases in solfatara. We should like to propose a term "volcanic cone effect" for this process. The physical and chemical properties of the high temperature steam will be given in a later section.

Seismic activity of Hakone

Local seismic activity sometimes takes place in the Hakone caldera. Since the earthquake swarms of 1959 to 1960, seismic observations have been made by Minakami,and more recently by Hiraga of our institute(Minakami,1960, Minakami et al.,1969, and Hiraga et al.,1971,1972,1973). Minakami reported that the Hakone earthquakes are of A type occurring in a narrow area bounded by the isothermal line of 100°C at sea-level. Depths of the foci are generally shallower than 4 km, mostly 1 to 2 km below the surface(Fig.8). The generation of Hakone earthquakes may correlate with boiling of thermal water at various depths within the central cones.

Ward et al.(1969), Ward and Bjornsson(1971), Ward(1972) and Hiraga(1972) emphasized the occurrence of micro-earthquakes in the major active geothermal fields, suggesting large output of thermal energy at depths of a few hundred meters.

Sodium chloride waters

White(1957) emphasized the importance of sodium chloride in the origin of volcanic thermal waters. Special attension will be given to the genesis of the Hakone sodium chloride waters and temperature-pressure conditions of dense steam rich in sodium chloride. As shown in chemical analyses, zone III waters are extremely rich in sodium chloride, but poor in SO_4 and HCO_3. The content of SO_4 seems to reflect the degree of dilution with low temperature groundwater. Figure 9 is a Cl-SO_4 diagram of zone III waters. For convenience of description, subscripts a, b, and c, are put to each branch of zone III(Fig.10). Zone III waters of each branch are placed on each individual straight line on this diagram. Precipitation of Cl-bearing minerals is unlikely to occur in thermal waters of Hakone. Neither is precipitation of sulfates such as gypsum and anhydrite expected from thermal waters, because they are unsaturated with calcium sulfate.

By extrapolating the best fitting lines to SO_4 equals zero, a possible content of sodium chloride in the original steam can be derived. Alternately, the extrapolation of Cl to zero yield a possible content of SO_4 in meteoric groundwater. It is seen from the diagram that the Cl content of original steam for zone IIIa is 6.010 g/kg, which is equivalent of 9.907 g/kg of sodium chloride. Similarly, that for zone IIIb is 3.406 g/kg, corresponding to 5.615 g/kg of sodium chloride. Thus, the sodium chloride content of volcanic steam responsible for zone III waters ranges from 0.6 to 1 %, and the contribution of volcanic dense steam can be evaluated at 50 to 30 %.

An alternate check on the sodium chloride content of original volcanic steam can be obtained by a study of the total discharge of thermal energy and sodium chloride. The total discharge of sodium chloride by thermal waters directly related to the hydrothermal activity of Kamiyama is measured to be 0.22 kg/sec. The contribution of zone I and II waters to the discharge of sodium chloride is fairly small, about 0.01 kg/sec, and can be neglected. The most majority of sodium chloride is transferred by means of the zone III and IV waters. Most sodium chloride is therefore supplied by high temperature dense steam coming up through the volcanic conduit.

Yuhara and his colleagues(1966) measured the thermal discharge from the solfataric fields of Kamiyama to be 0.7×10^7 cal/sec, not including thermal waters from deep wells. We measured the energy discharge by thermal waters from deep wells directly related to the hydrothermal activity of Kamiyama(zone III and a part of zone IV) to be 1.5×10^7 cal/sec. The total energy discharge by thermal waters and solfataric activity in Kamiyama thus amounts 2.2×10^7 cal/sec.

If the enthalpy of steam is assumed to be 600 kcal/kg as the first approximation, the steam discharge of 36.5 kg/sec can provide the energy of the Hakone hydrothermal system. One third of thermal discharge is liberated through solfataric fields, and the other two thirds are provided by the hot water system.

The quotient of the total discharge of sodium chloride (0.22 kg/sec) by the calculated steam(36.5 kg/sec) is close to 0.6 % of sodium chloride in steam, which gives good agreement with the sodium chloride content of 0.56-0.91 % estimated by $Cl-SO_4$ chemistry.

Estimation of temperature-pressure condition of dense steam

Thanks to the work of Sourirajan and Kennedy(1962), we can estimate the temperature-pressure conditions of the volcanic dense steam, based on the following assumptions. The phase transformation of liquid to gas is the major cause of Hakone earthquakes. This means that the system has two fluid phases and the thermal brines are unsaturated with sodium chloride. In figure 11, superheated dense steam at around 385°C and 230 bars can dissolve about 0.5 to 1 % of sodium chloride. When temperature decreases down to 374°C, the critical temperature of water, sodium chloride is hardly dissolved in steam, but mostly remains in the liquid phase. With minor variation of temperature and pressure at around 385° to 374°C and 230 to 220 bars, about 1% of sodium chloride can be allowed in the gas phase or alternately in the liquid phase. The variation of depth of earthquake foci may be related to the variation of dissolved salts in thermal brines.

At depths of 1 to 2 km below sea-level, temperature and pressure of the hydrothermal system may be 385°C and 230 bars or slightly larger. Assuming the pressure to be caused by the water column, pressure at a depth of 4 km, the lowest limit of Hakone earthquakes, is 400 to 500 bars. On the diagram(Fig.11), isotherms of the two fluid phases at 400 to 500 bars should range from 450° to 480°C, with several percent of dissolved sodium chloride. Sourirajan and Kennedy(1962) also indicated that the vapor pressure of the system $NaCl-H_2O$ never exceeds 400 bars at any temperature, provided that the system is in the gas-solid-liquid equilibrium, in other words, is saturated with solid sodium chloride. Below depths of more than 4 km, the hydrothermal system must be in the three phase region of gas-liquid-solid sodium chloride, resulting lowering of vapor pressure. This implies that the permeation of meteoric water to the volcanic steam system mostly takes place at depths of less than 4 km.

The origin of thermal waters has long been a major problem. We have suggested that the infiltration of meteoric water is going on at depths of less than 4 km in the central part of the Hakone caldera. Therefore, the original dense steam which we have estimated from the chemistry of zone III waters is not simply juvenile water, but instead is a high temperature and high enthalpy steam containing a mixture of juvenile water and meteoric water. We still cannot explain the ultimate origin of the thermal waters and sodium chloride.

Hot eye and cold eyelid

Figure 12 is an isothermal map of Hakone and the adjacent areas at 400 m below sea-level and Figure 13 is a north-south cross-section of isotherms(Ōki et al.,1974 in preparation). It is seen that Hakone is an extremely large geothermal area of 12 km in diameter. The map suggests that an important tectonic line extends along the east coast of the Izu peninsula, through which a large amount of thermal water is discharged. The center of the geothermal activity is circled with many isotherms, reminding us of hot eyes which discharge thermal waters. The hot eyes are surrounded by low temperature zones which may well be compared to cold eyelids, that cover the hot eyes, where the temperature gradient is very small, sometimes less than 3 deg/100 m(Fig.12). It is also important that many of the hot eyes appear in the bottoms of the dissected calderas as described in the old saying. The cold eyelid actually lies on the caldera rim and high mountains, from which infiltration of groundwater is going on to compensate for the water discharged from the hot eyes. The combination of hot eyes and cold eyelids seems to required for the development of the hydrothermal systems.

The young volcanoes like Fuji and Asama, composed of thick piles of volcanic materials, do not display hydrothermal activity on the surface, because the thick piles perform the role of the eyelid and prevent the activity of the hot eye. A large, deeply dissected caldera will be the best for the developement of hydrothermal systems. When the geothermal activity is very strong, separating the vapor dominated hydrothermal system from the hot water system(White et al.,1971), the hot eye will appear in central cones like Hakone. If thermal waters are discharged faster than the water balance of the system permits their replacement, the hot eye will be closed by the invasion of the cold eyelid as the cold surface water replaces the hot thermal water.

Acknowledgement

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Table 1 Chemical analyses of Hakone thermal waters(ppm)

zone	I	II	III	IV		G.W.
No.	1	2	3	4	5	6
Type	A.S.	S.B.	NaCl	M.	M.	B.
Temp. C	49.7	57.5	91.5	65.5	56.0	13.1
pH	2.9	8.1	7.7	8.4	8.0	7.2
Ev.Res.ppm	1076.	1269.	4940.	1851.	1201.	141.
H	1.18	-	-	-	-	-
Li	0.0	0.068	2.43	0.27	0.042	-
Na	42.7	88.5	1490.	441.	348.	8.23
K	8.90	12.1	154.	39.8	3.40	2.06
Ca	87.4	140.	114.	106.	53.9	19.1
Mg	24.3	84.9	0.0	16.8	0.0	5.59
Fe	0.099	0.56	0.105	0.257	0.00	5.80
Al	22.6	0.22	0.12	0.05	0.03	-
Mn	-	0.0	0.007	0.44	0.00	-
Cl	7.15	19.8	2568.	617.	549.	2.03
HSO_4	52.4	-	-	-	-	-
SO_4	526.	381.	81.5	226.	85.1	13.0
HCO_3	0.	590.	29.7	287.	36.7	108.
CO_3	-	1.72	-	2.11	0.26	-
BO_2	-	0.34	3.58	2.34	0.70	-
$HSiO_3$	-	5.87	4.09	13.9	1.74	-
H_2SiO_3	301.	238.	411.	282.	67.2	54.5
HBO_2	-	5.79	122.	16.1	20.6	-
CO_2	-	14.2	2.19	2.75	-	5.34
Total	1074.	1583.	4983.	2054.	1167.	224.
Li/Na	-	0.00077	0.0016	0.0006	0.00012	-
K/Na	0.21	0.14	0.10	0.09	0.01	-
B/Cl	-	0.076	0.012	0.007	0.01	-
Total CO_2/Cl	-	22.5	0.009	0.35	0.016	-
SO_4/Cl	80.8	19.2	0.032	0.366	0.155	-
Depth of well	H.S.	525m	506m	351m	650m	30m

Analyzed by T.Hirano and Y.Tajima

A.S. acid-sulfate water
S.B. sulfate-bicarbonate water
NaCl sodium chloride water
M. mixed type(sodium chloride-sulfate-bicarbonate water)
G.W. groundwater
B. bicarbonate water
H.S. hot spring

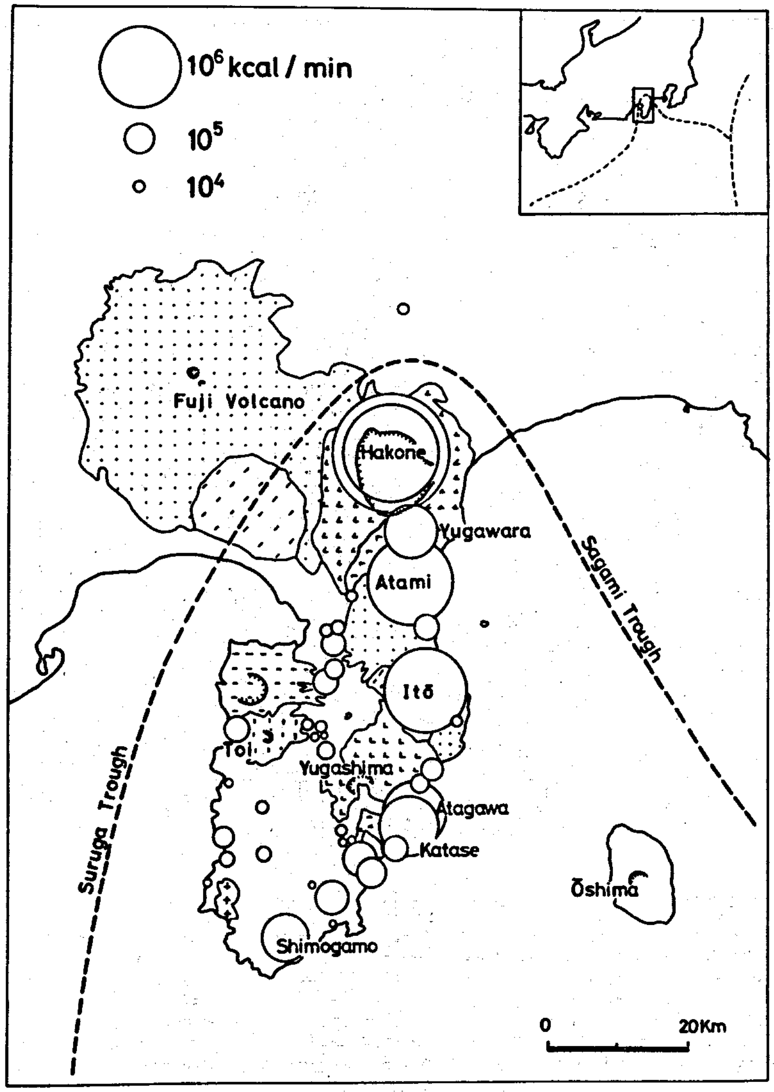


Figure 1. Distribution of Quaternary volcanoes and geothermal discharge by thermal waters and steam. The outer circle of Hakone is thermal discharge by thermal waters and steam. The inner circle is by thermal waters only.

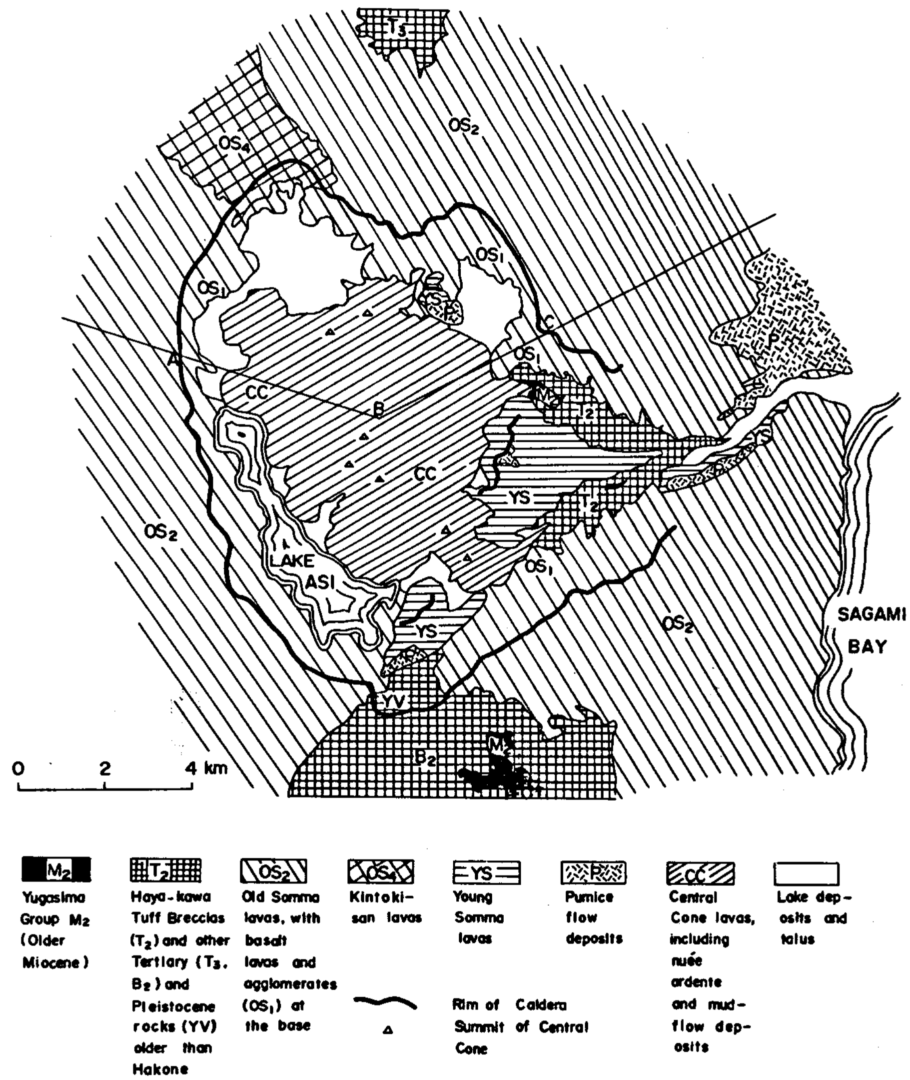


Figure 2. Geologic map of Hakone volcano(Kuno,1950)

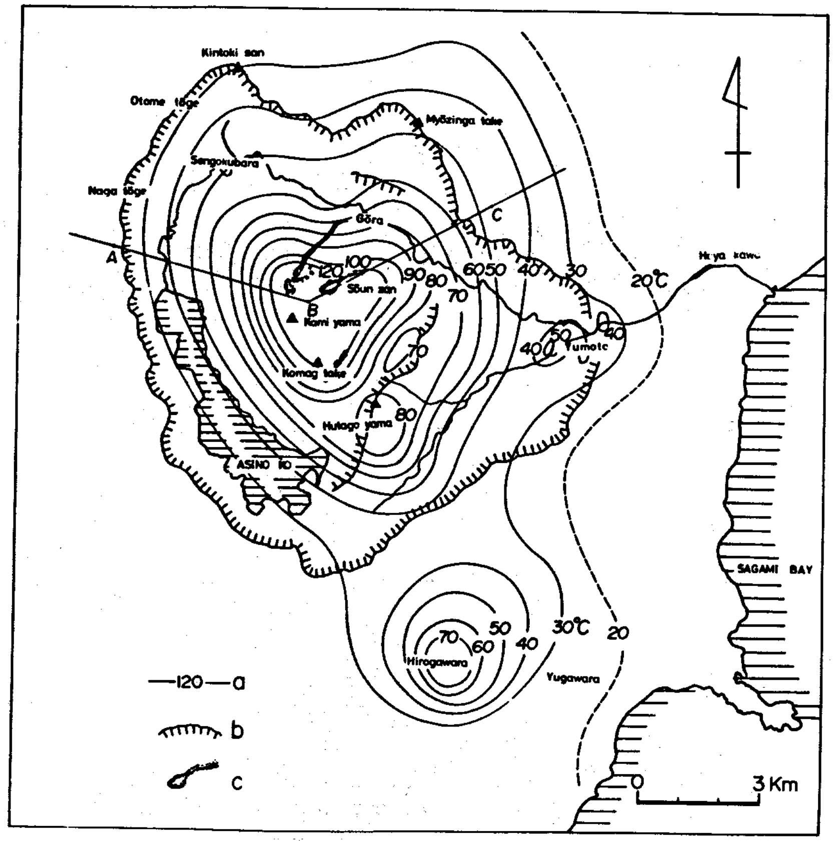


Figure 3. Isothermal map of Hakone and adjacent area at sea-level (Ōki and Hirano, 1970 and 1972).
a: isothermal line , b: caldera rim ,c:solfatara

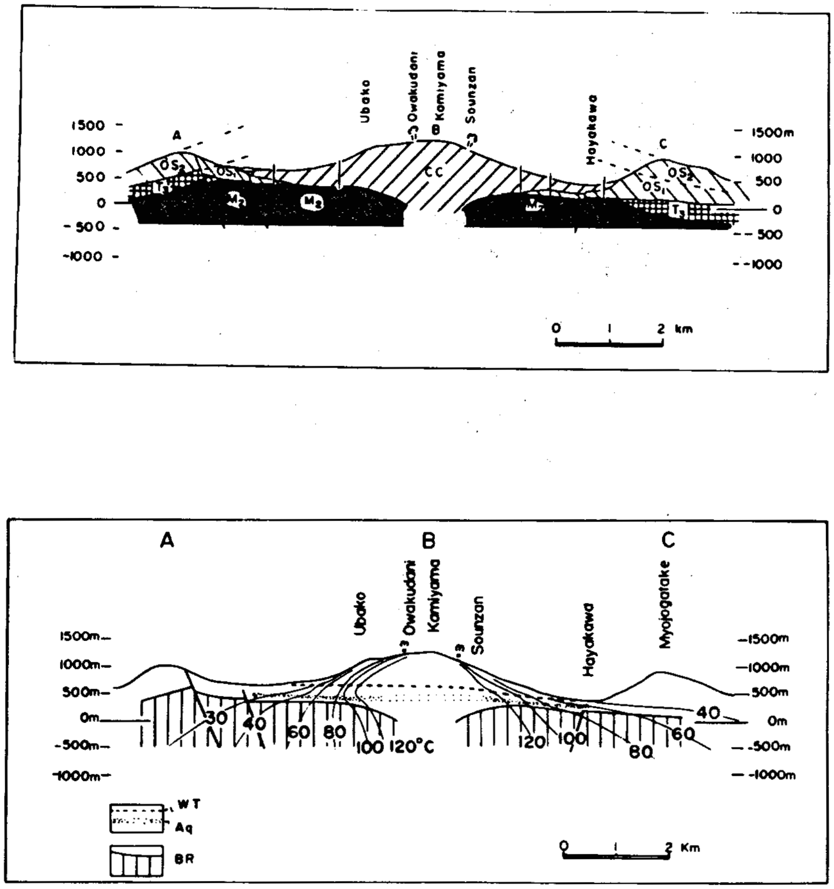


Figure 4. East-west cross section illustrating geologic structure(upper) and isothermal profile(lower). M_2 : Yugashima formation, T_3 : Hayakawa tuff breccias, OS_1 and OS_2 : old somma, CC: central cones, the basal part of CC is mostly pumice falls and flows.
WT: water table of the major reservoir of thermal waters.
Aq: aquifer, BR: basement rocks(Yugashima formation and Hayakawa tuff breccia.(Ōki and Hirano,1970)

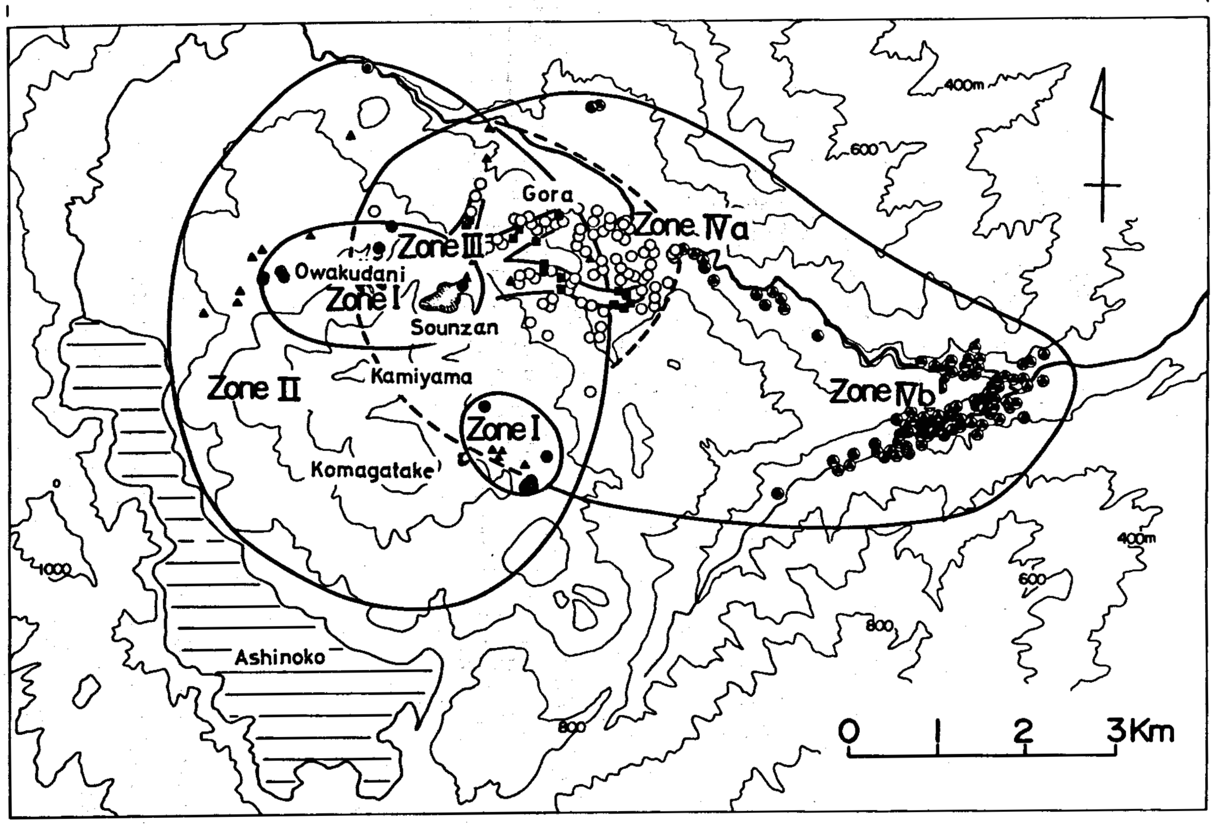
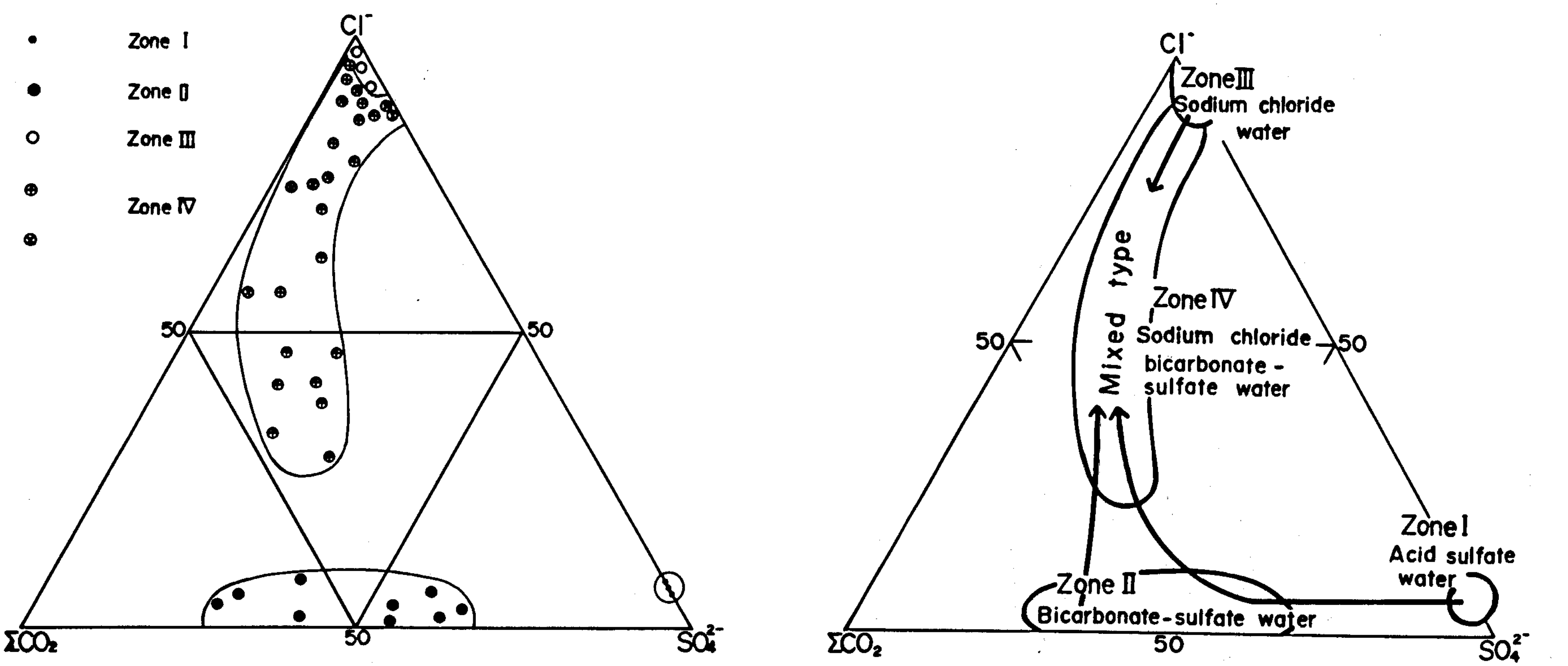


Figure 5. Zonal mapping of thermal waters
Zone I:acid sulfate waters, Zone II:bicarbonate-sulfate waters, Zone III:sodium chloride waters
Zone IV:mixed type.(Ōki and Hirano, 1970)



a

b

Figure 6. a: Cl-total CO_2-SO_4 diagram
b: illustrating compositional trend of Hakone thermal waters

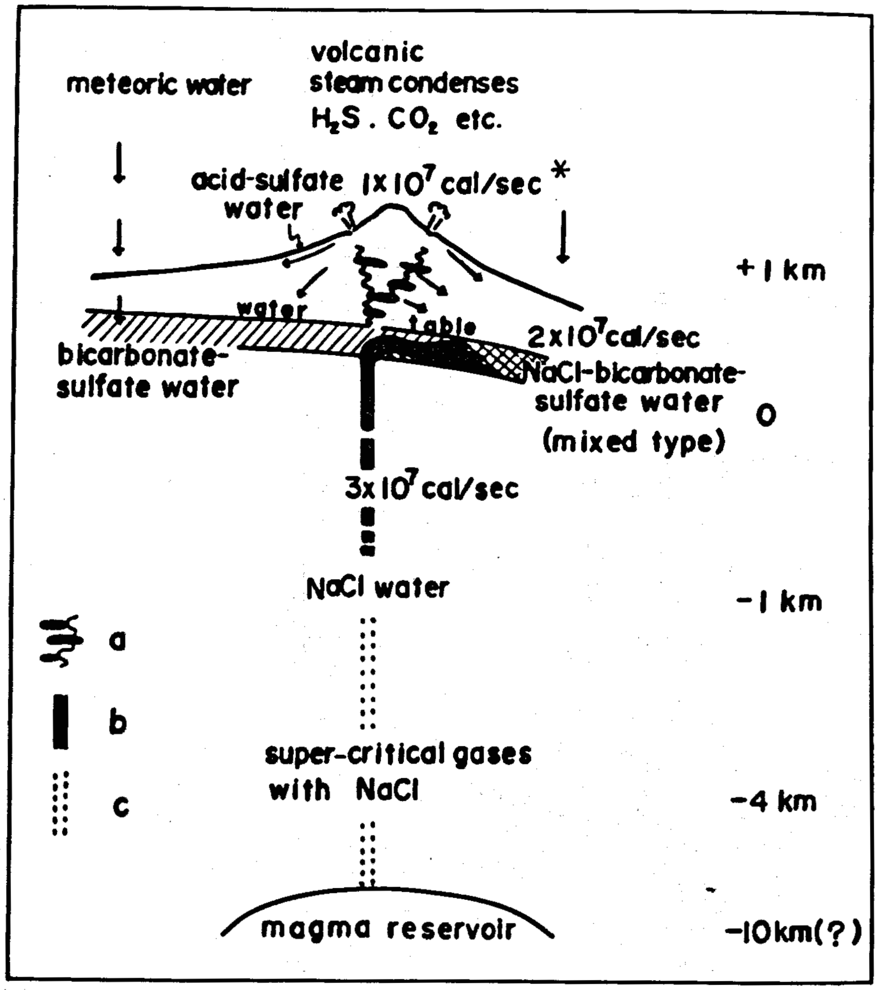


Figure 7. Genetic model of Hakone hydrothermal system. a: repeated processes of vaporization and condensation of volcanic steam resulting in concentration of volatile components such as H_2S and CO_2. b: sodium chloride water(zone 3). c: super critical gases(steam) with NaCl. (Ōki and Hirano,1970)

* 1×10^7 cal/sec(total thermal discharge from solfataras)= 0.7×10^7 cal/sec(from Kamiyama)+0.3×10^7 cal/sec(from Komagatake)

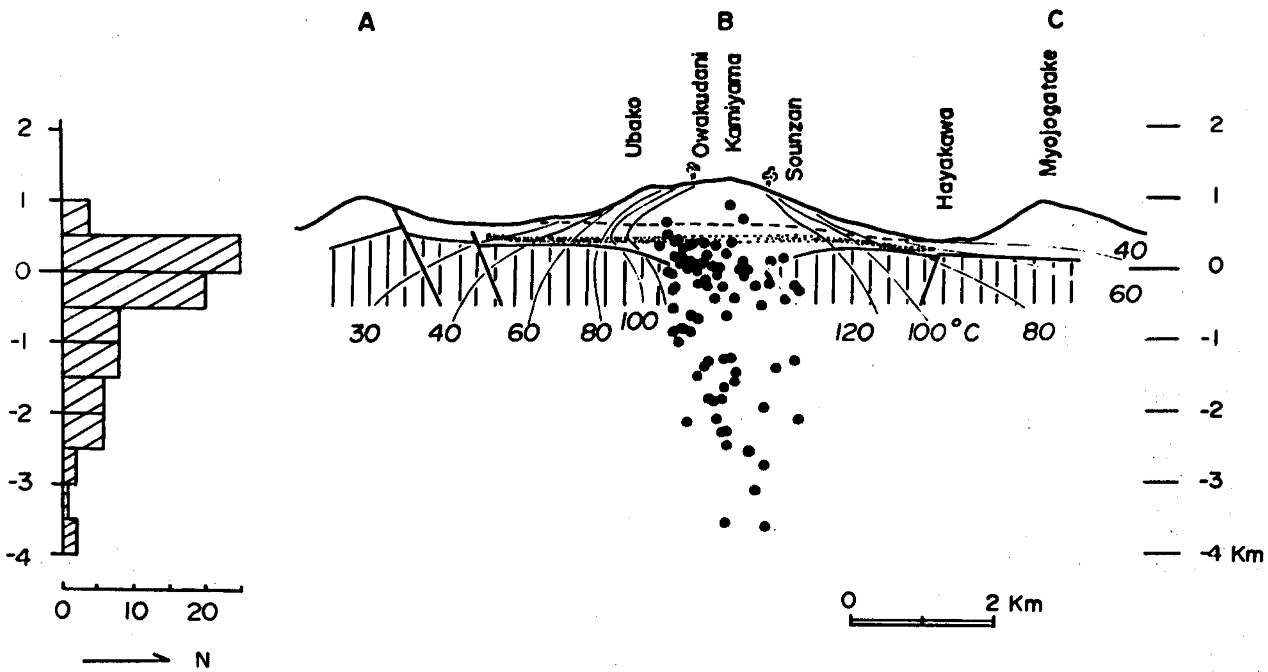


Figure 8. Distribution of epicenters and the depth frequency relation plotted on east-west cross section(Minakami, 1960, Minakami et al.,1969 and Hiraga 1972)

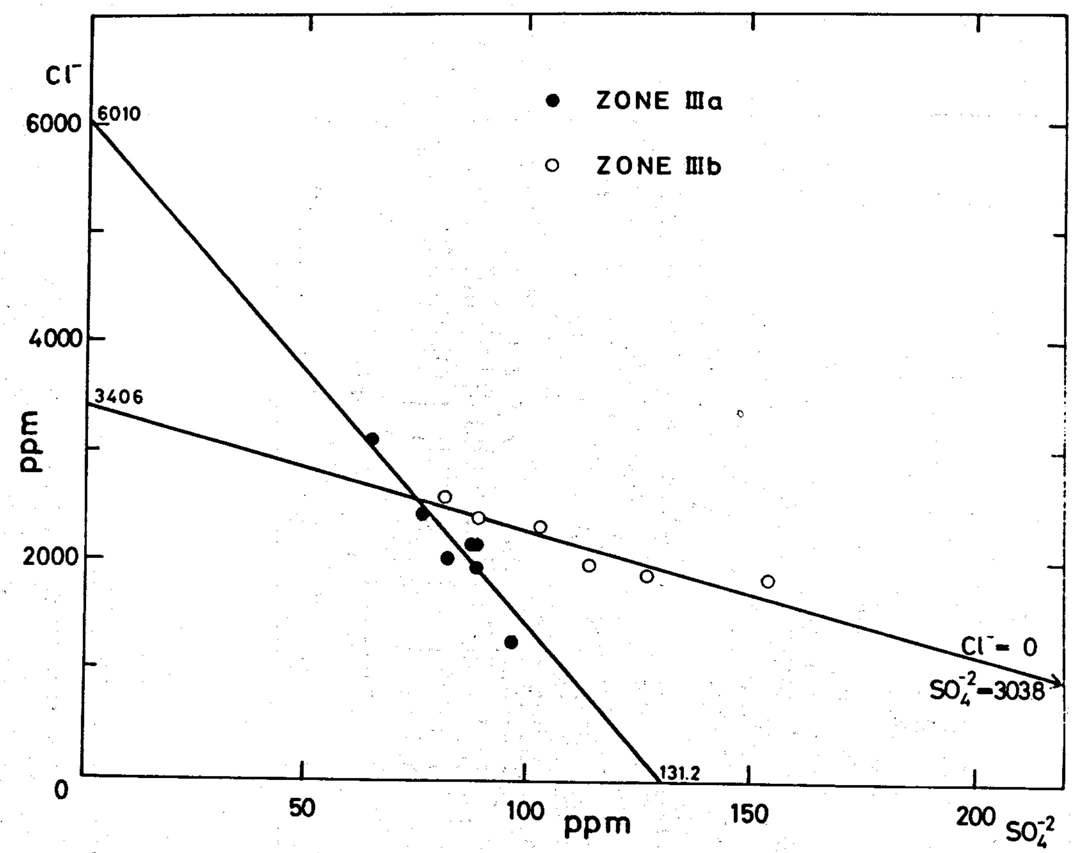


Figure 9. Cl-SO_4 diagram of zone III waters

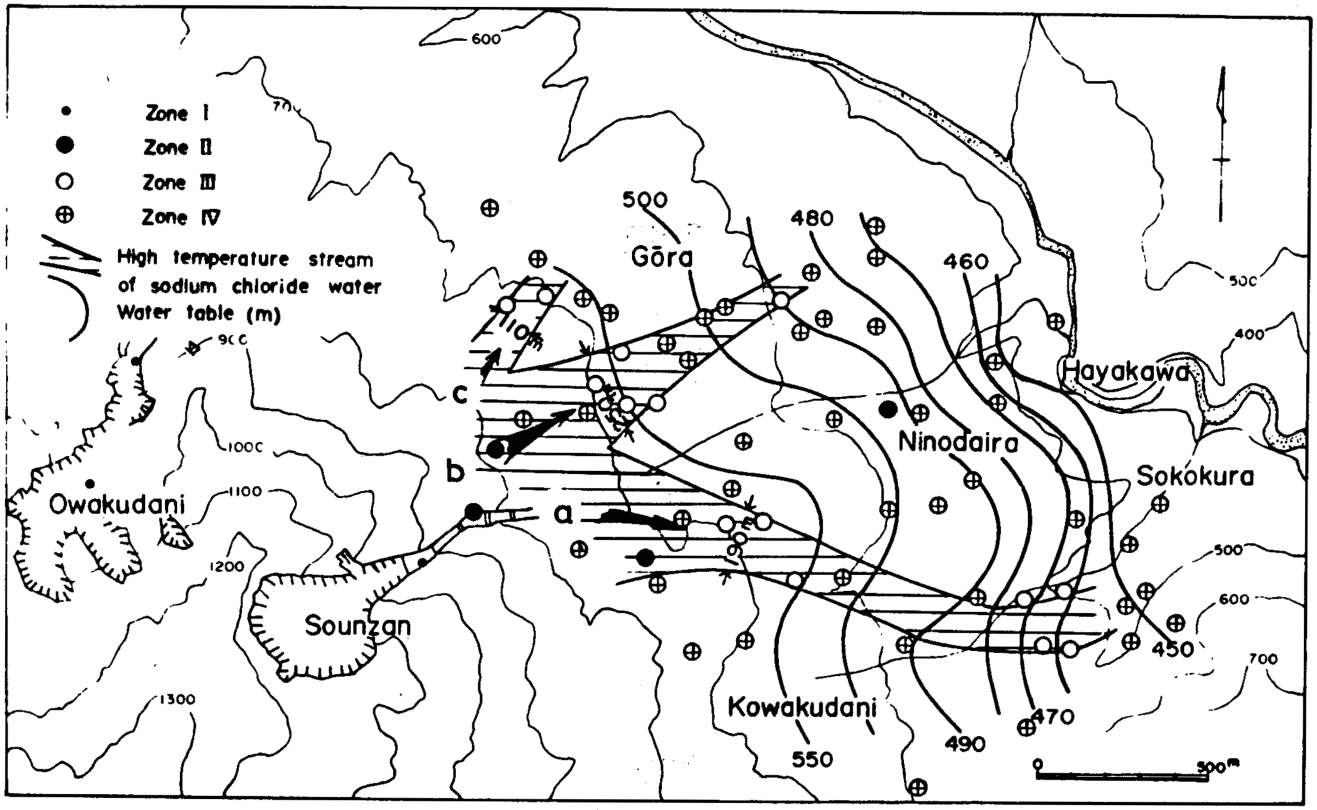


Figure 10. Distribution of zone III.
Numbers attached to the thick contour lines are the heights of water table of the major reservoir in meter.

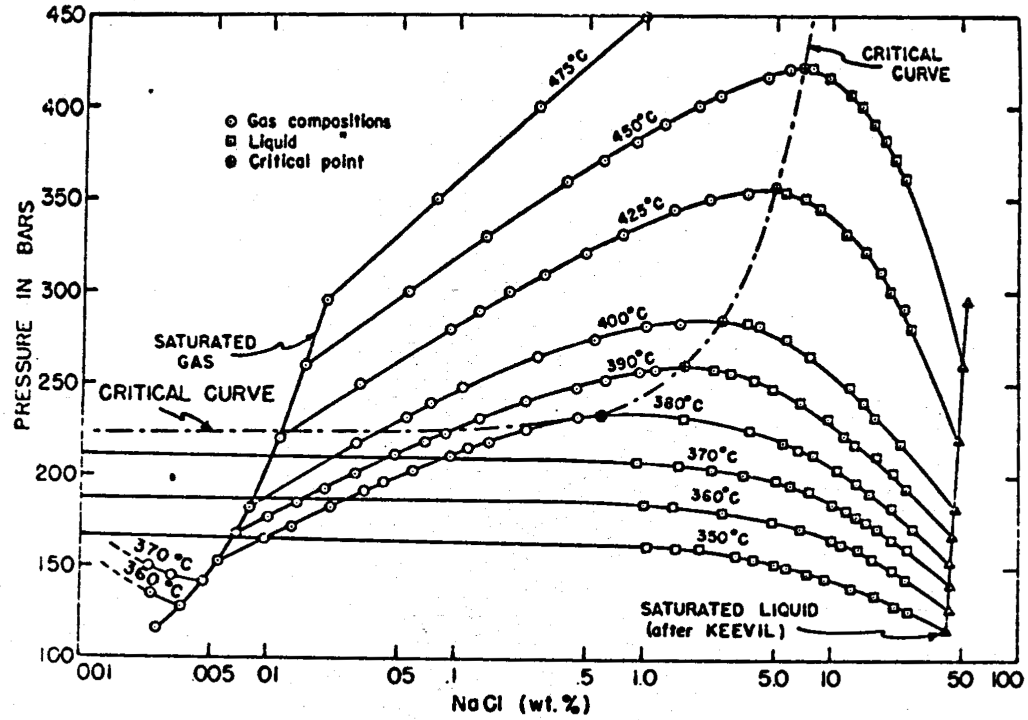


Figure 11. Isotherms, 350°-450°C, showing composition of coexisting gases and liquids, in NaCl-H_2O system (Sourirajan and Kennedy, 1962).

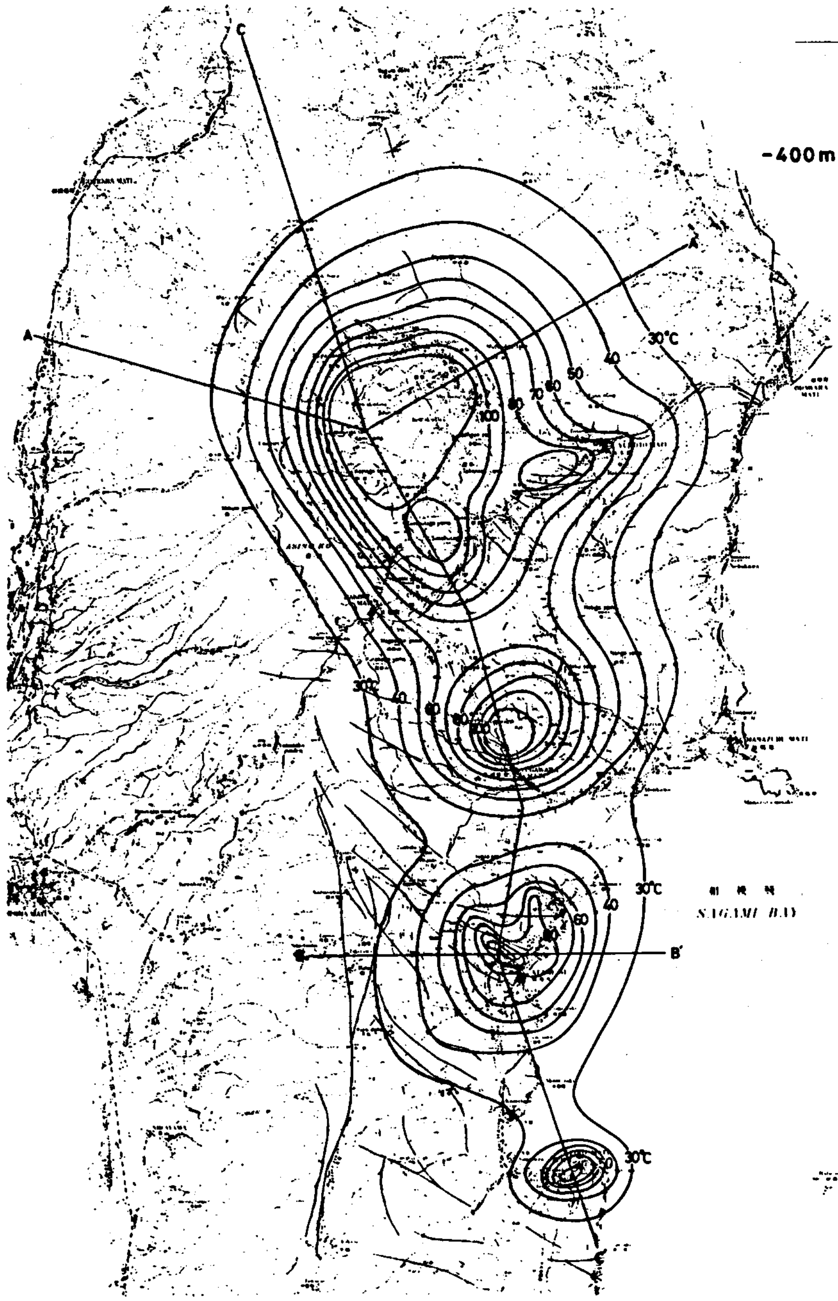


Figure 12. Isothermal map of the Hakone and adjacent area at 400 m below sea-level(Ōki et al., in preparation).

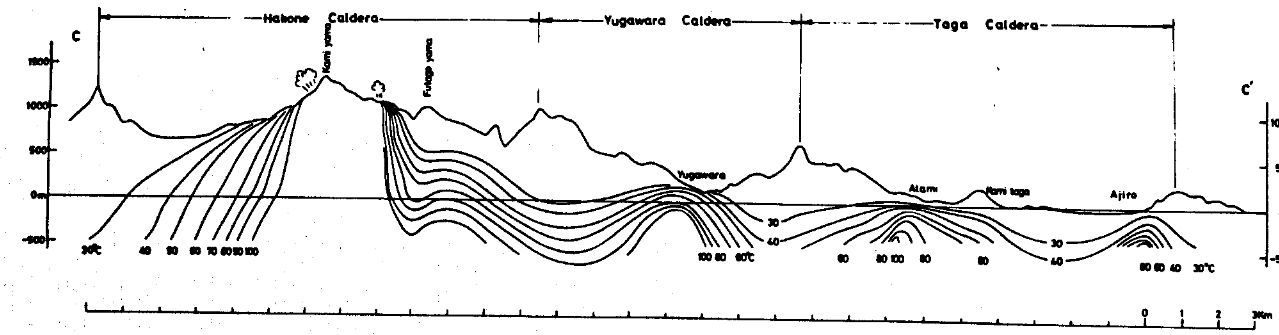


Figure 13. North-south cross section showing the isothermal structure of the Hakone and adjacent area(Ōki et al.,in preparation).