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THERMODYNAMICAL PROPERTIES OF NATURAL STEAMS AND HYDROTHERMAL STRUCTURE OF BEPPU GEOTHERMAL AREA

By

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Abstract

Thermodynamical properties are measured of the natural steams from Beppu Geothermal Area. It becomes clear that the most part of the natural steams are thermodynamically wet saturated ones, even if they are apparently dry. Then, assuming that a large number of the steam wells eject the secondary steam coming from the thermal water which is boiling in the ground, we calculate the boiling temperature, the depth of boiling and the statical head of the thermal water layer. Geographical and vertical distributions of these factors are very complicated. This complexity may suggest the existence of multiple thermal water layers in the narrow hydrothermal region.

1 Natural steams from Beppu Geothermal Area

Many fumaroles and steam wells are found around Beppu Hotspring Resort. They eject mainly natural steam having temperature from 94°C to 133°C. The fluid states of the natural steam are various and we can classify them into six states as follows,

1) super heated steam,
2) real dry saturated steam,
3) apparent dry saturated steam,
4) wet steam in fog state,
5) wet steam in shower state,
6) boiling spring.

Super heated and real dry saturated steams can be identified according to the pure thermodynamical conditions for instance the temperature and the density of the steam at a pressure condition. The third state, called here as "apparent dry" saturated steam, means a vapour state which is wet thermodynamically but dry apparently and we can not catch the liquid water by the usual methods. Then, with the increase of the liquid part the steam becomes apparently wet and the small particles of the liquid water wet the surrounding things, and we can recognize sensuously the wet steam but can not catch the substantial water flow. We name here this state of the steam as "wet steam in fog state". Next, "wet steam in shower state" means such a state of the steam as we can observe not only the vapour flow but also the liquid water flow from the fumarole or the steam well, and follows the boiling spring when the liquid part becomes much more. Above two states of the wet steams do not differ thermodynamically but do experimentally. Fumaroles and steam wells in the Beppu Geothermal Area are distributed as shown in Fig. 1, and classified by some marks according to the above mentioned classification of the steam.

They are geographically in some groups, that are, Otobaru, Kankaiji, Shirayu, Hachiman, Hotta, Ogura, Myoban, Kannawa and Minamikamegawa.

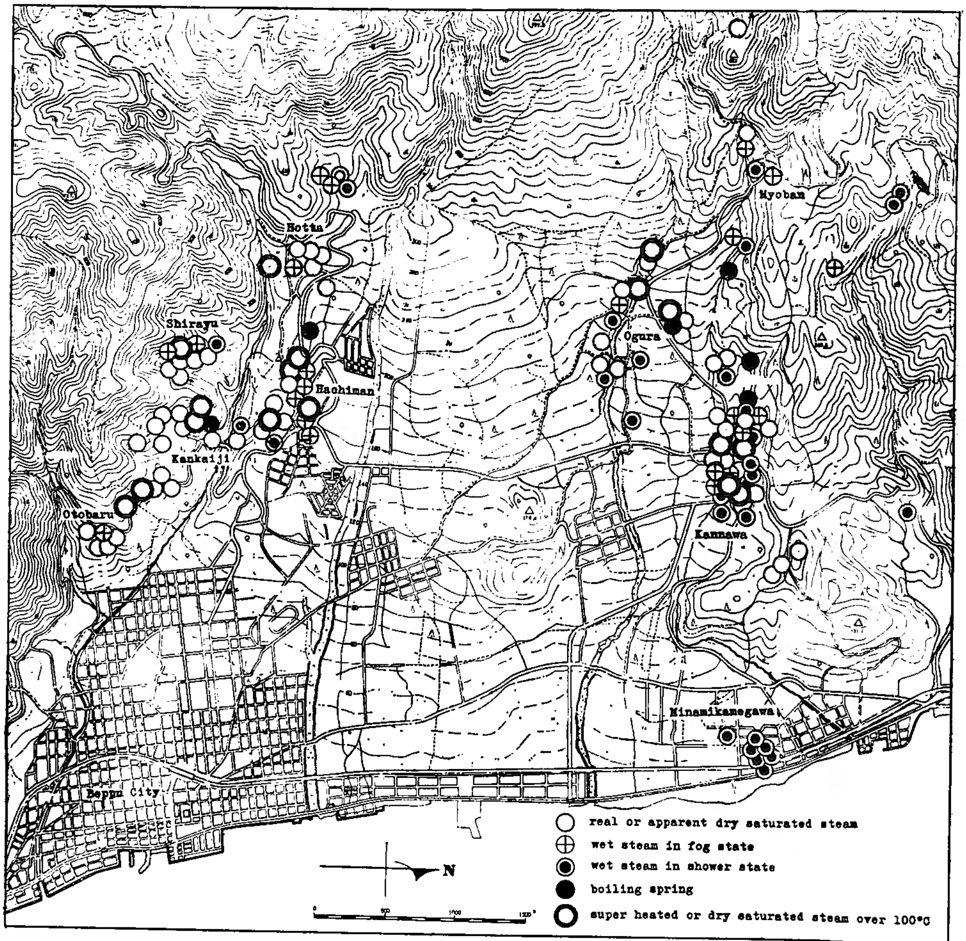

Fig. 1. Fumaroles and steam wells in the Beppu Geothermal Area.

This geographical distribution has been discussed in relation to geological structure of this area by M. Suzuki (1937). On the other hand, as the various states of the steam and the various orifice temperatures are found in each group, it may be reasonable to deduce that this variety of the natural steam may not be affected by the essential geological conditions, but may be results modified by the conditions of the steam vents in comparatively shallow ground.

2 Thermodynamical properties of the natural steams

Temperature, density and projection velocity of the natural steams have been measured in spring, 1961 by K. Yuhara (1964), who has, from these data, calculated mass flows of the vapour and the water, thermal output by natural steams and degree of dryness or wetness, assuming that the natural steam is a mixed fluid of the saturated vapour and the small particles of the liquid water at the observed temperature and pressure. The results are illustrated in Figs. 2, 3 and 4. As shown in Fig. 2, the densities of the natural steam under 100°C range from a point near saturation curve to fairly large density corresponding to nearly unit degree of wetness. On the other hand, the densities upper 100°C are generally smaller than that under 100°C, but larger than the saturation curve. This means, so far as seen in Fig. 2, that the natural steam at higher temperature than 100°C may also be wet saturated steam. The method of density measurement is to weigh a constant volume of the natural steam, and sampling the constant volume of the steam at the orifice condition is so difficult that the measured density includes some errors. Then, consider-

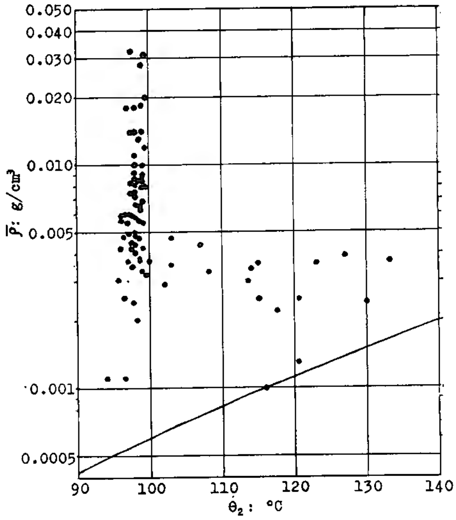

Fig. 2. Density and temperature of the natural steam.

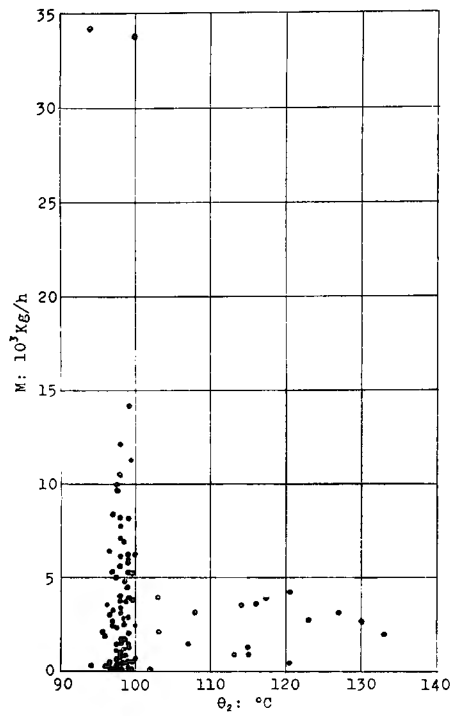

Fig. 3. Mass flow and temperature of the natural steam.

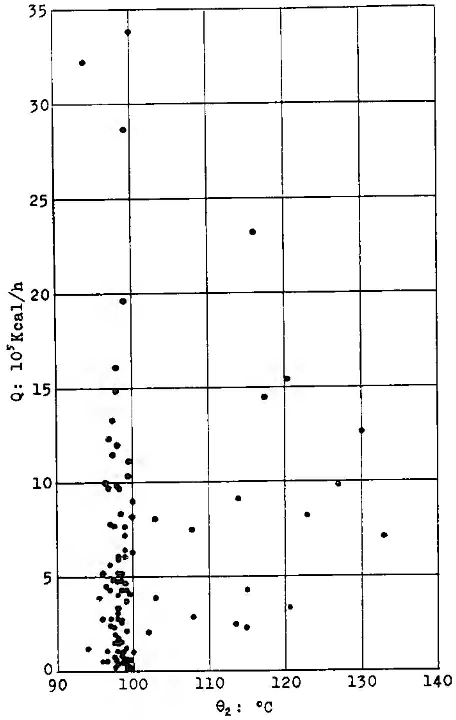

Fig. 4. Thermal output and temperature of the natural steam.

ing the accuracy of the density measurement, we can now not emphasize the existence of the wet saturated steam at heigher temperature than 100°C, but we can also not confirm the undoubted super heated steam. Even if the steam is super heated, this is not necessarily the primary steam from the magma but may be a variety from the saturated steam by the throttle effect through the well pipe or the steam vent. For the example, natural lumps of the scale in the pipe or the vent may act as a series of the throttles, then the steam

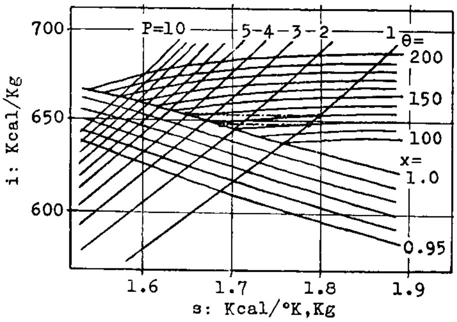

Fig. 5. Mollier's diagram showing the throttle effect.

flowing through there should change the state from the wet to the dry as shown in Mollier's diagram. Fig. 5 shows that the saturated steam of about 128°C at about 2.5 kg/cm^2 changes to the super heated steam of about 120°C at about 1 kg/cm^2, and the saturated one of about 145°C at about 4 kg/cm^2 changes to the super heated of about 130°C at about 1 kg/cm^2. These temperatures and pressures of the saturated steams may be imaginable in the ground of geothermal area.

From such a consideration as above discussed, although the primary magmatic steam is not denied in this geothermal field, we presume that the large number of fumaroles and steam wells eject the secondary steam coming from the thermal water which is boiling in the ground. This phenomenon of the boiling in the ground has experimentally been verified in many geothermal fields such as Isola D'Ischia by F. Penta and B. Conforto (1951) and Wairakei by F. E. Studt (1957).

3 Calculation of the boiling conditions and the statical head of the thermal waters

Now, we try to calculate the boiling conditions in the ground of Beppu Geothermal Area according to the assumption descrived above. T. Fukutomi (1942) has introduced a theory of the boiling which includes some relations between the observable physical factors of the wet steam at the orifice and the boiling conditions such as the depth of boiling, the statical head of thermal water and the boiling temperature in the ground.

We can get, from his theory, some simply modified forms,

$$\theta_1=\frac{\frac{v_2}{V/A}-1+\frac{c}{l}\frac{\rho}{\rho_v}\theta_2+\frac{c_v}{l}\left(\frac{v_2}{V/A}-1\right)\theta_2}{\frac{c}{l}\left(\frac{\rho}{\rho_v}-1+\frac{v_2}{V/A}\right)}, \tag{1}$$

$$v_1=\frac{\left\{1-\frac{c}{l}\left(1-\frac{c_v}{c}\right)\theta_2\right\}V}{\left\{1-\frac{c}{l}\left(\theta_1-\frac{c_v}{c}\theta_2\right)\right\}A}, \tag{2}$$

$$h=D+\frac{P_1-P_0}{\rho g}-\frac{1}{2g}(v_2{}^2-v_1{}^2), \tag{3}$$

$$w=h-\frac{v_1}{k}-\frac{P_1-P_0}{\rho g}, \tag{4}$$

neglecting the heat conduction to the surrounding ground and the friction along the well pipe. Where A=sectional area of a vertical well, V=the volume output of the thermal water per unit time, v_1=flow velocity at the beginning point of the boiling, v_2=projection velocity of the natural steam at the orifice, θ_2=orifice temperature, θ_1=temperature of the thermal water at the beginning point of the boiling, c=specific heat of thermal water, c_v=specific heat of the steam, l=latent heat of evaporation, ρ=density of the thermal water, ρ_v=density of the steam, h=depth of the beginning point of the boiling, P_1=pressure at the beginning point of the boiling, P_0=the atmospheric pressure, g=the gravity accerelation, w=statical head of the thermal water, D= a hypothetical depth of the statical head corresponding to minimum h, k= a constant proportional to the permeability of the thermal water layer which is supposed as the compressed ground water type before boiling, taken as 0.5 sec^{-1}.

The values of D have been calculated for several θ_1 by T. Fukutomi, but we use here such an approximate relation between D (m) and θ_1 (°C) as

$$D=0.61(\theta_1-100)^2 \tag{5}$$

which is reduced from the calculated values in the temperature range from 100°C to 150°C.

From the equations (1), (2), (3) and (4), and the data which have been illustrated in section 2, we can calculate the boiling temperature, the depth of the boiling and the statical head of the thermal water. The results are shown in Table 1 in which the steams with higher temperature than 100°C are excepted because there are no sufficient evidence to confirm the liquid origin, although they may be also from the thermal water as discussed in section 2. It is very important to know the geographical and sectional distributions of the depths and the temperatures of the beginning points of the boiling to understand the underground hydrothermal structure, but the number of data is not sufficient. Therefore, we interpolate the depth for the lower temperature than θ_1, for instance, 110°C or 115°C, with the equation

$$v=\left[1+\frac{\left\{\frac{\rho}{\rho_v}\frac{P_0(d+\theta)}{P(d+\theta_2)}-1\right\}(\theta_1-\theta)}{\frac{l}{c}-\theta\left(1-\frac{c_v}{c}\right)}\right]v_1 \tag{6}$$

Table 1.

Name of group	Number of well	Height m.s.l. (m)	θ_2 (°C)	Degree of wetness	θ_1 (°C)	h (m)	w (m)	h' at 110°C (m)	h' at 115°C (m)
Hotta	1	270	97.5	0.948	102	2	2	—	—
	2	275	96.5	0.888	130	483	465	—	—
	3	270	97.0	0.854	132	619	600	26	102
	5	270	96.5	0.792	155	1852	1808	41	120
	9	255	95.5	0.830	141	1031	1003	49	124

Hachiman	5	180	99.5	0.921	134	750	729	65	147
	6	175	99.5	0.971	109	58	54	—	—
	14	175	99.0	0.942	119	215	206	59	140
	16	175	98.5	0.959	106	24	21	—	—
	17	170	98.0	0.950	112	87	81	58	—
	19	160	97.5	0.927	118	176	167	55	136
	20	150	98.0	0.945	109	33	28	—	—
Kankaiji	1	145	98.0	0.926	112	67	61	39	—
	2	175	97.5	0.904	119	217	208	66	148
	3	145	99.0	0.926	119	210	199	38	120
	4	230	98.0	0.904	125	390	376	41	119
	6	225	98.0	0.887	129	516	500	60	141
	12	245	97.5	0.830	137	867	844	65	147
Otobaru	1	200	99.0	0.915	116	139	130	49	129
	3	200	97.5	0.879	129	556	539	65	147
	4	180	98.5	0.880	122	312	301	66	142
	5	275	97.5	0.869	144	1170	1140	66	148
	7	185	98.0	0.874	129	554	539	65	147
	8	200	98.0	0.571	173	—	—	—	—
	9	200	98.0	0.881	129	555	538	66	148
	10	200	99.0	0.864	167	—	—	—	—
Kannawa	2	120	99.0	0.980	110	49	44	49	—
	3	120	97.0	0.971	110	60	56	60	—
	5	105	98.7	0.880	132	657	640	66	148
	7	120	99.0	0.991	102	3	3	—	—
	8	120	97.5	0.961	130	486	456	—	—
	11	120	99.0	0.957	112	94	89	66	—
	13	115	98.5	0.907	128	502	486	60	137
	14	115	98.5	0.957	108	31	27	—	—
	15	120	99.5	0.667	180	—	—	—	—
	19	110	98.5	0.912	177	—	—	—	—
	20	110	97.0	0.890	107	30	27	—	—
	25	150	98.0	0.873	127	388	373	—	—
	29	165	98.0	0.861	127	455	440	42	114
	30	155	98.3	0.909	122	313	302	60	141
	32	155	98.0	0.935	146	1425	1392	—	—
	33	155	98.2	0.911	112	94	89	66	—
	34	190	99.0	0.896	113	57	50	19	—
	35	150	94.0	0.561	171	—	—	—	—
	36	145	97.7	0.765	133	693	683	66	148
	37	145	96.5	0.537	160	—	—	—	—
	38	165	98.6	0.842	171	—	—	—	—
	39	185	99.5	0.817	126	434	410	—	—
	40	145	99.0	0.959	111	72	67	55	—

Ogura	1	215	97.3	0.886	180	—	—	—	—
	3	250	96.0	0.906	107	32	29	—	—
	5	235	99.0	0.903	148	1324	1288	27	100
	6	225	98.6	0.851	142	1081	1052	41	117
	7	240	98.7	0.933	102	3	2	—	—
	12	190	99.2	0.864	120	258	248	65	141
Myoban	1	320	100.0	0.948	111	83	78	66	—
	2	340	98.3	0.715	120	226	215	38	117
	3	310	96.0	0.870	135	777	756	66	148
	4	260	98.4	0.930	118	197	188	60	138

where v and P are the ascending speed and the pressure of wet steam at a point of temperature θ (here 110°C and 115°C), d is a constant (273.2°C), and the steam is assumed as the perfect gas. Then applying the equations (3) and (6), we can evaluate the interpolated depth, h', corresponding to θ. Table 1 indicates also the values of h'.

4 Hydrothermal structure of Beppu Geothermal Area

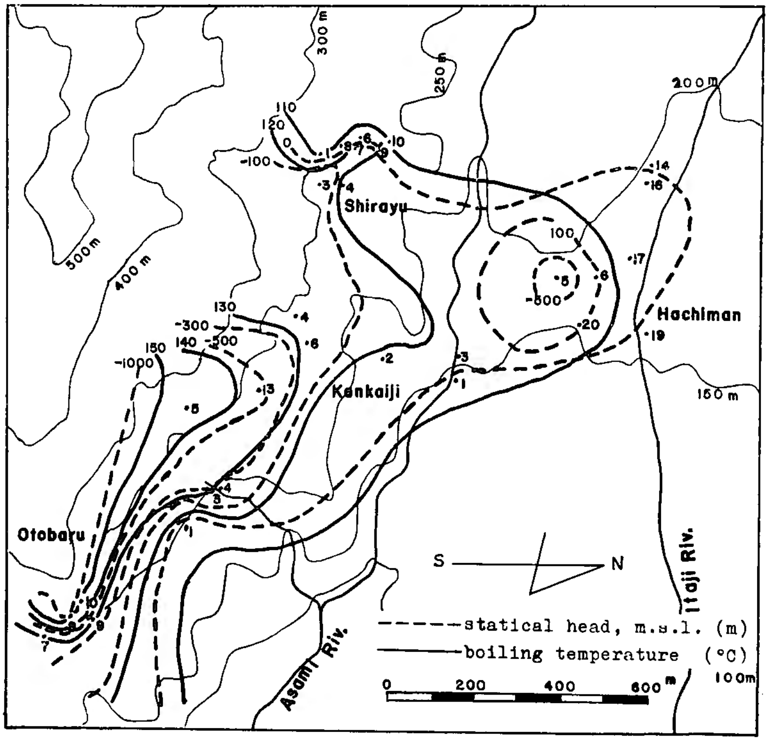

Fig. 6. Distribution of the boiling temperature and the statical head at Shirayu-Kankaiji-Otobaru zone.

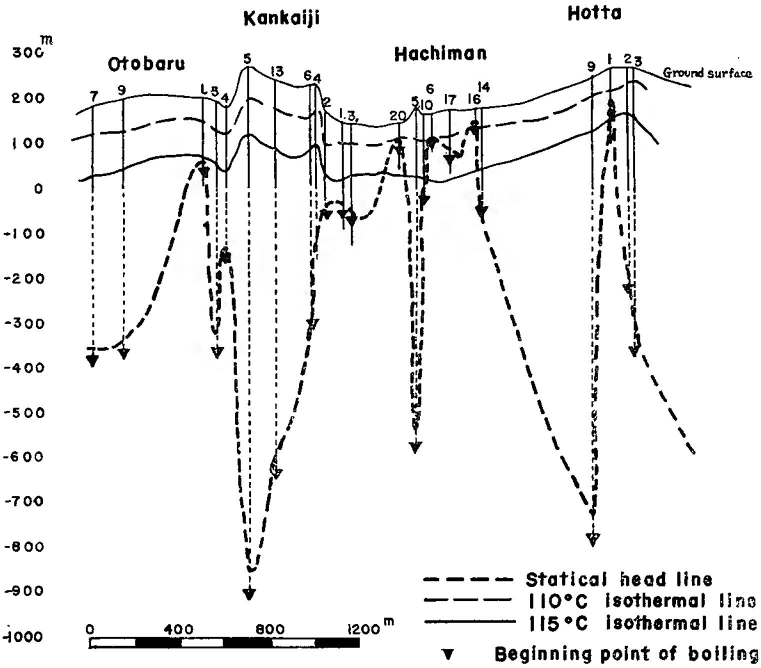

Fig. 7. Vertical section of the statical head and the steam temperature along Otobaru-Hotta line.

The calculated temperatures of the beginning points of boiling range from near 100°C to 180°C and the higher they are the deeper the depths of the beginning points of boiling and the statical heads are. This general relation between h and θ_1 may be a natural result reduced from (3) and (5), and can be expressed by a similar equation to (5).

Fig. 6 indicates the distributions of the boiling temperatures and the statical heads above the mean sea level at Shirayu-Kankaiji-Otobaru zone. The temperatures and the heads are respectively higher and deeper near mountain than near Asami River. A vertical section along the evident fault line is shown in Fig. 7. From these two figures we can know the complicated structure of the hydrothermal system, that is, the statical head curves are winding intensively and the difference of neighbouring two heads exceeds frequently several hundreds meters. This complexity may suggest the existence of numerous thermal water layers in the narrow region, while, if it is seen from a different stand point, it may reduce a conclusion that the initial assumption is unreasonable and the steam from wells of which statical heads are very deep is the primary steam without undergoing a change into the liquid state.

On the contrary, at Kannawa, the distributions of the boiling temperatures

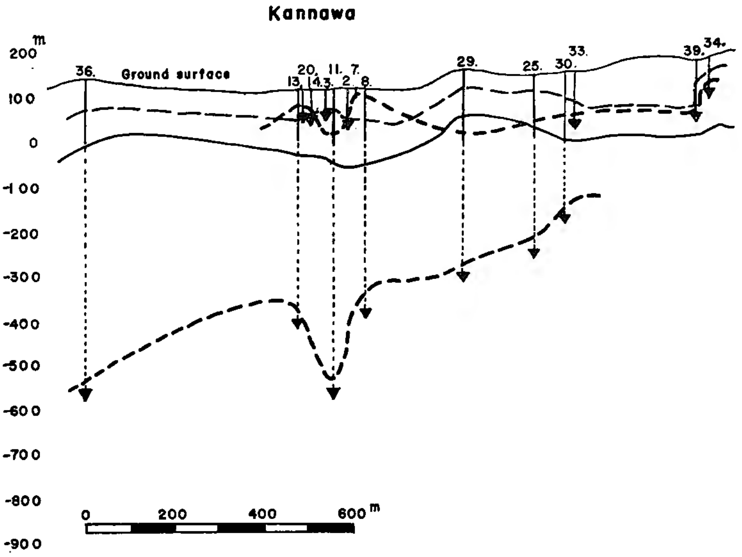

Fig. 8. Vertical section of the statical head and the steam temperature at Kannawa.

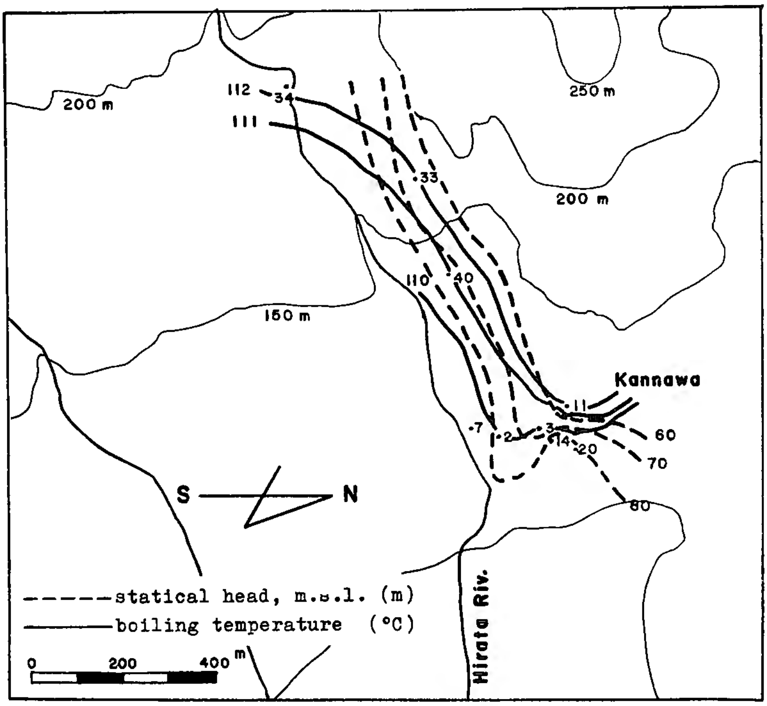

Fig. 9. Distribution of the boiling temperature and the statical head of the shallow group at Kannawa.

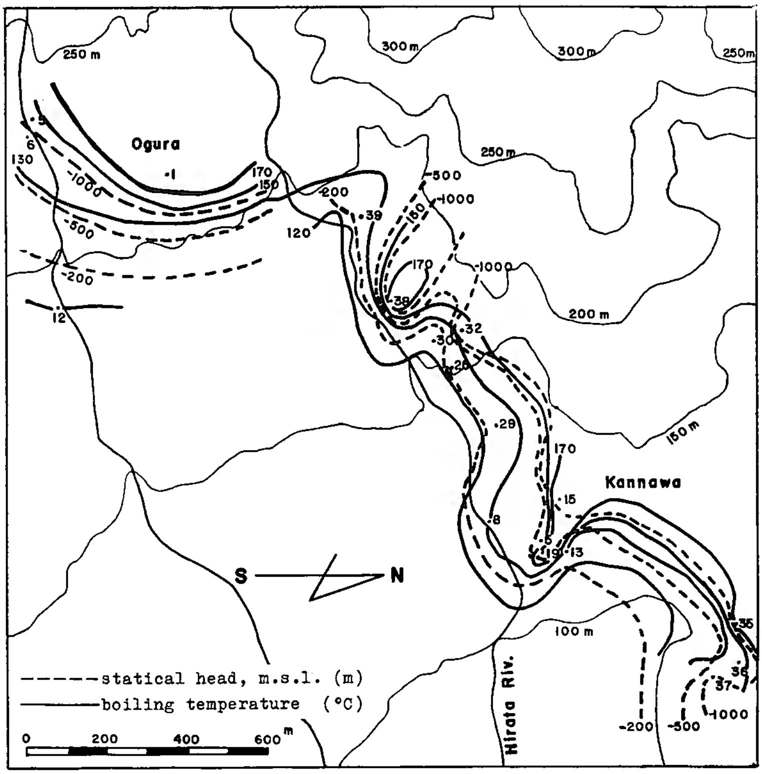

Fig. 10. Distribution of the boiling temperature and the statical head of the deep group at Kannawa.

and the statical heads are comparatively simple and the heads may be classified into two groups as shown in a sectional figure (Fig. 8). One is the shallow group in which the heads are higher than 50 m above the mean sea level and the other is the deep one in which the heads are lower than −150 m. Figs. 9 and 10 show the geographical distributions of the temperatures and the heads for the shallow and deep groups. In the both groups the temperatures and the heads are higher and deeper near mountain. The shallow group tends to eject wet steam and the deep, comparatively dry. It may be sure that the steam of the shallow group originates from the thermal water compressed in an artesian aquifer, while the details of the deep group are yet unknown.

It is most important to consider that the natural steam comes from what sources and through what processes in Beppu Geothermal Area. We will make effort to perfect the procedure of geothermal phenomena and approach to the true geothermal nature.

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