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EFFECTS OF EXPLOITATION IN THE BEPPU HYDROTHERMAL FIELD, JAPAN

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ABSTRACT

Exploitation of the Beppu Hydrothermal System began mainly in the lowland areas as early as the 1880s, and by the 1920s, 1000 wells were extracting about 400 kg/s of geothermal water for domestic uses. This caused (1) intrusion of seawater into the hydrothermal aquifer near the coast, (2) a decline in piezometric head along the coast, and (3) declines in water level and temperature in the shallow aquifer. During the 1960s and 1970s, many wells were drilled over the entire area of Beppu; the number of wells increased to over 2300 and the discharge increased to about 650 kg/s. In particular, high temperature chloride-type waters have been extracted predominantly in the highland areas. This has resulted in: (4) decreased pressure in deep chloride waters, which has caused a reduction in the flow rate of chloride water from highland to lowland areas, and (5) intrusion of steam-heated shallow waters into the chloride waters, which has lowered the chloride concentration and raised the bicarbonate and/or sulfate concentrations.

1. INTRODUCTION

Beppu (Kyushu Island) hosts some of the largest spa resorts in Japan, and its history can be traced back to at least the 8th Century. In ancient times, people used its natural hydrothermal features, ranging from hot springs to superheated fumaroles and steaming ground, for hot spring bathing and cooking. During the modernisation of Japan in the latter half of the 19th Century, drilling of wells was promoted to enhance the discharge of hot water and steam from the Beppu Hydrothermal System. Today, there are over 2,200 active wells in an area of 5 km (E-W) $\times$ 8 km (N-S). The total mass and heat discharge from these wells are about 600 kg/s (50 kt/day) and 350 MW, respectively (Yusa and Oishi, 1988).

A paper describing the history of exploitation at Beppu over the last 100 years and the resulting changes to the hydrothermal system will soon appear in *Geothermics* (Yusa et al., 2000). However, we introduce the content here to the WGC2000 held in Beppu.

2. BEPPU HYDROTHERMAL SYSTEM

The Beppu Hydrothermal System is closely associated with the late Quaternary Yufu-Tsurumi-Garan Volcanic Center, which occupies the eastern end of a volcanic belt along the Beppu-Shimabara Graben that crosses Kyushu Island from east to west (Fig. 1). The geological, hydrological, and geochemical features of the system were previously described by Allis and Yusa (1989), and Sturchio et al. (1996).

Hydrothermal activities at Beppu are developed on the eastern flanks of the volcanic center, with active fumaroles present near the summits of Mt. Tsurumi and Mt. Garan (Fig. 2). There are three principal types of thermal water in the Beppu Hydrothermal System: high-temperature sodium-chloride water, bicarbonate water, and sulfate water. These diverse compositions can be formed from a single parent hydrothermal fluid (beneath the volcanic center), which is inferred to be a sodium-chloride type water of 250-300°C and 1400-1600 mg/kg chloride. The parent fluid flows out eastwards to the coast along two major flow paths (Allis and Yusa, 1989): a southern flow path (the Beppu Thermal Zone) and a northern flow path (the Kamegawa Thermal Zone). Recently, a third flow path towards the Yufuin area to the west has been suggested (Sturchio et. al, 1996).

3. HISTORY OF EXPLOITATION

The inferred locations of the original natural thermal features in the Beppu Hydrothermal Area were first mapped by Suzuki (1937) (Fig. 2). Comparison of the location of these sites with isotherms at 100 m below sea level, drawn using data obtained in the 1960s (Allis and Yusa, 1989) (Fig. 2), shows that the original thermal features were sited only along the subsurface high temperature zones.

Exploitation of the Beppu Hydrothermal System started as early as 1880s, and used a special drilling technique known as "kazusa-bori". This technique was based on man-power and the flexibility of bamboo drilling rods, and it enabled depths of over 100 m to be reached. During the early part of the 20th Century, the number of drilled wells increased rapidly to reach around 1000, but during the economic depression between 1925 and 1945 few wells were drilled. After WW II, and particularly during the 1960s and 1970s, extensive drilling occurred using modern techniques and the number of drilled wells more than doubled. Recently, the number of new wells being drilled has decreased; firstly due to restrictions by the local government for the purpose of preserving the thermal water resource, and secondly due to a reduction in the demand for thermal water. Most wells in Beppu have been drilled for private use.

Changes in the distribution of drilled wells from 1949 to 1985 are shown in Fig. 3. The distribution in 1949 is thought to be almost the same as that in the early part of the 20th Century. Until this time, the wells were restricted to the vicinity of the natural thermal features, but after WW II they were distributed over almost the whole of the Beppu area. The present (1998) distribution is almost the same as that in 1985.

Due to exploitation, both the mass and the heat outputs from the wells increased, especially after the drilling boom in the 1960s and 1970s (Table 1). The mass output did not increase significantly, despite a twofold increase in the number of wells, due to a decrease in the number of flowing wells. However, the heat output increased more than twofold, indicating that the exploitation was specially targeting high-temperature fluids from the highland areas (Yusa, 1984).

4. CHANGES IN THE HYDROTHERMAL SYSTEM

4.1 Changes in Piezometric Head

When drilling started in Beppu around the end of the 19th Century, all wells near the coast were artesian. The first survey of the piezometric head of subsurface thermal water was made in the coastal area of the Beppu Thermal Zone between 1933 and 1938 (Seno, 1938). This survey showed that the piezometric head was over 2 m higher than mean sea level near the coast, and rose inland. As its slope was less than that of the ground surface, the head became lower than the ground surface at about 0.8 - 1 km from coast; here the ground elevation is about 10 m above the sea level. This outlined the artesian area at that time.

A second survey of piezometric head conducted in 1960 over the same area as the first survey (Seno and Kikkawa, 1961) found that the level of the head had declined by between 1 and 2 m along the coast, but the general distribution was almost the same as in 1933-38. Presently, most wells discharging sub-boiling water are pumped (air-lift). However, some wells in the lowland region are still capable of artesian flow, which suggests that the decline of piezometric head in parts of the original hot spring area of the Beppu Thermal Zone may be less than 2 m.

Using water levels measured during the drilling of new wells in the 1960s, Allis and Yusa (1989) determined the distribution of fluid pressures at 100 m below sea level for the entire Beppu Hydrothermal System (Fig. 4). The data show several head minima anomalies that appear to be due to drawdown effects. One of these is in the upstream area of the Kamegawa Thermal Zone, where the head is about 50 m lower than its surroundings. This anomaly occurs in a heavily-exploited area where some wells discharge super-heated steam, which is an indicator of substantial drawdown and dryout at feedzone depths.

4.2 Seawater Intrusion near the Coast

Three anomalies of low piezometric head occur near the coast (Fig. 4), where wells have static water levels below sea level. These anomalies are probably due to drawdown by neighbouring wells and indicate a potential for seawater intrusion into the coastal aquifer. Further evidence of decline in the piezometric head is the disappearance of almost all the natural hot sandbaths along the foreshore, with only a weak manifestation remaining after about 1965.

Seawater intrusion into hot spring water was detected as early as 1926 by the first geochemical survey; this was in the southeast corner of the Beppu Thermal Zone (Yamashita et al., 1937), coinciding with the southernmost anomaly in Fig. 4. Changes in the location and extent of seawater intrusion in and around this area are shown in Fig. 5. In 1926 the seawater intrusion was limited to a narrow area to the south of the Asami River, but by 1950 the intruded region had extended over a wider area northwards beyond the Asami River (Kikkawa, 1951). Data obtained in 1963 (Kikkawa et al., 1964) and 1976 (Kikkawa and Kitaoka, 1977) show that since 1950 the intruded region has extended slightly farther northwards along the coast. These data indicate the development of a drawdown in piezometric level by withdrawal of thermal groundwater. Elsewhere along the coastline, for example in the Kamegawa Thermal Zone (Kitaoka, 1978), seawater has intruded less than 100 m inland.

4.3 Declines of Water Level and Temperature in a Shallow Well

The best record of changes in water level and temperature in the geothermal aquifers of the Beppu Thermal Zone is from a shallow well (8.5 m depth, 70 cm diam.) located in the precincts of a Shinto shrine about 1.1 km inland from the coast (Fig. 4, location A). The temperature when first measured in January 1925 was as high as 43.2 ^{o}C; such a high temperature is thought to result from the uprising of thermal water under high pressure (Kikkawa, 1960).

Daily measurements of temperature and water level were made in this well for 40 years until 1967, when the well became dry. The annual mean values for water level and temperature, together with annual rainfall observed at BGRL are shown in Fig. 6. These data show that the water level fluctuated around a depth of about 7 m below the ground surface in clear response to precipitation until the mid-1950s, after which the water level dropped rapidly to finally disappear (although it rose temporarily in 1961-63). The temperature fluctuated irregularly after rainfall, but remained at 30-40 °C until around 1950 (although it showed a decreasing trend), after which it dropped below 30 °C (although it temporarily rose higher than 30 °C in 1961-63). These phenomena indicate the decline in pressure of the deep thermal water, associated with increasing exploitation (Yusa, 1989).

4.4 Chemical Changes

During the intense exploitation of the 1960s and 1970s, many wells were drilled (especially in the highlands) from which large amounts of high-temperature sodium-chloride type water were discharged, producing steam and water at the wellhead. Since this time, chemical changes such as chloride decline have become evident across the entire Beppu region (Yusa et al., 1989 and 1990).

(i) Beppu Thermal Zone

The decline in chloride concentrations has been most pronounced for boiling waters within the Beppu Thermal Zone; these originally had high concentrations but there have been declines approaching 50% in several wells. In contrast, bicarbonate concentrations have increased. A typical example of the variations with time in well B (Fig. 4) is shown in Fig. 7: this shows a four-fold decrease in chloride concentration and a three-fold increase in bicarbonate concentration since monitoring started in 1968. Since around 1985, little drilling has been done and the variations have been small. However, the data clearly show that the changes of these two components are in the opposite direction.

A trend of chloride decline has also been observed in sub-boiling waters in the lowlands, excluding areas of seawater intrusion, particularly for those waters having relatively high concentrations. There has been no obvious change in bicarbonate concentration.

Allis and Yusa (1989) have shown that the fluids discharged from the Beppu Thermal Zone are mainly mixtures of chloride-rich and bicarbonate-rich end members, although there is also a sulfate-rich water within a narrow region. The chloride waters originate from the parent geothermal water deep within the system. The bicarbonate and sulfate waters are steam-heated waters formed at shallow depths. The changes in chloride and bicarbonate and/or sulfate concentrations indicate that the proportion of chloride water has decreased with time (and bicarbonate/sulfate water increased) due to a reduction in pressure of the deep chloride water.

(ii) Kamegawa Thermal Zone
Within the Kamegawa Thermal Zone, chloride concentrations in boiling water from most wells has decreased with time, and thermal waters from some wells at relatively low elevation have stopped boiling (Yusa et al., 1990). This suggests that the mixing ratio of high-temperature chloride water has decreased as a result of the pressure drop of deep chloride water, similar to that in the Beppu Thermal Zone. This interpretation is supported by an extreme example of anion changes with time (Fig. 8), indicating the increase of mixing with a steam-heated shallow water because of the increase in sulfate concentration. A similar decline of chloride concentration has also been observed for the sub-boiling waters (Fig. 12b).

Chloride concentrations have increased in a few wells located in the heavily-exploited area where there is a piezometric head minimum (Fig. 4). Most of those waters have also decreased in pH. The distribution of the chloride concentration and pH in this area shows that acidic high-chloride waters (pH: 3 - 5, Cl: 1500 - 2500 mg/kg) exist upstream. The chloride increase and the pH decrease may suggest an inflow of acidic high-chloride water into the area of reduced pressure resulting from the intense exploitation.

5. CONCLUSIONS

Exploitation of the Beppu Hydrothermal System by shallow domestic wells since the 1880s has caused: **a decline of piezometric head along the coast, intrusion of seawater near the coast, and declines of water level and temperature in the shallow aquifer.**

In particular, increased discharge of chloride-type waters in the highlands during the 1960s to 1970s has caused a decrease of pressure in deep chloride waters, resulting in a reduction in flow rate of chloride water from highland to lowland areas. It has also resulted in intrusion of steam-heated shallow water into the chloride waters, which has lowered the chloride concentrations and increased the bicarbonate and/or sulfate concentrations.

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Table 1. Mass and heat extracted from wells in the Beppu Hydrothermal System

	Zone	1924	1949	1959-61	1973-75	1985-87
Number of Wells	Beppu	826	674	785	1132	975
	Kamegawa	?	305	535	1250	1269
	Total	?	979	1320	2382	2244
Mass Output (kg/s)	Beppu	189	218	213	266	226
	Kamegawa	?	213	252	390	353
	Total	?	431	465	656	579
Heat Output (MW)	Beppu	43	48	67	119	126
	Kamagawa	?	52	86	231	226
	Total	?	100	153	350	352

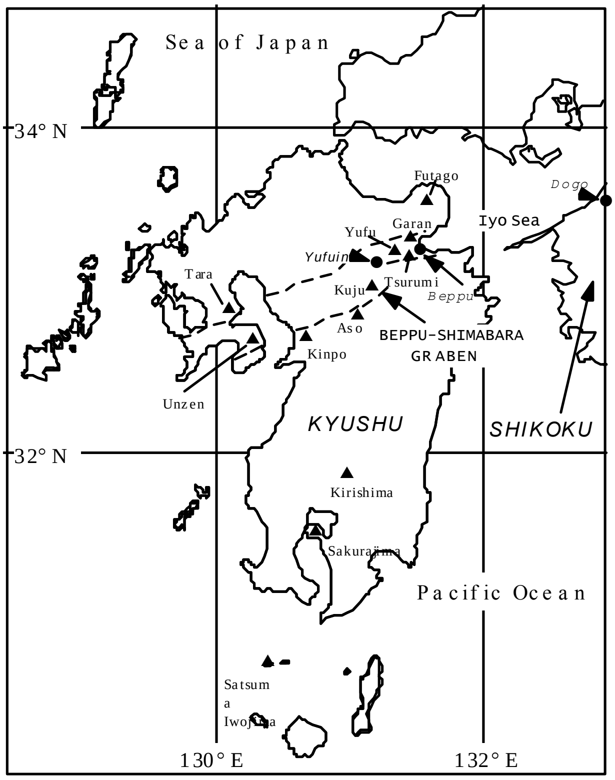

Figure 1. Location map of Kyushu Island, Japan. Solid triangles are locations of Quaternary volcanic centers. Dashed line encloses the Beppu-Shimabara Graben.

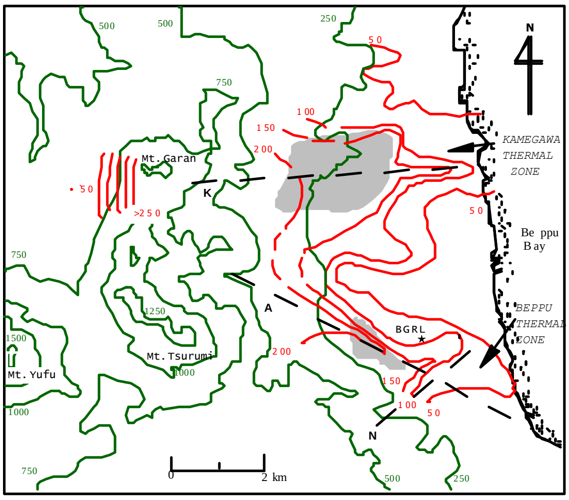

Figure 2. Distribution of original sites of natural thermal features (circles) in Beppu Hydrothermal Field. Thick red curves show isotherms °C at 100 m below sea-level. Shaded areas are two-phase zones inferred from fluid pressure and temperature data. Dashed lines A and K are the Asamigawa and the Kamegawa faults respectively, and dashed line N is an unnamed fault. Elevation contours are in (m) above mean sea level.

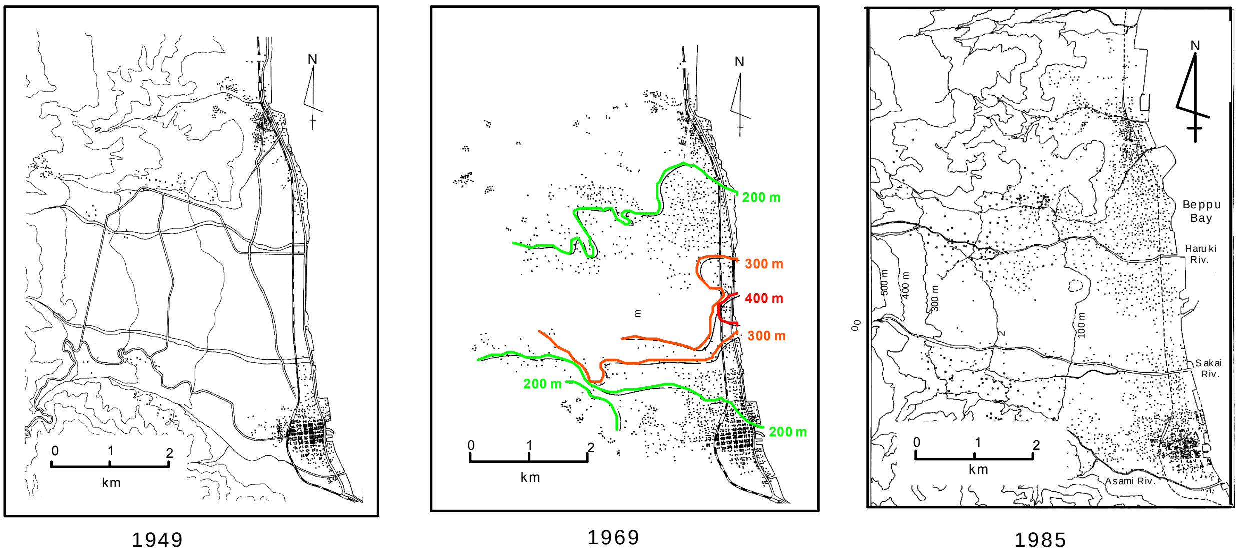

Figure 3. Change in the distribution of drilled wells in the Beppu Hydrothermal Area. The curves with attached numeral in the 1969 distribution show approximate depths of wells in meter; these are generally shallower along the Asamigawa and the Kamegawa faults (Fig. 2), and deeper at the central area apart from the faults.

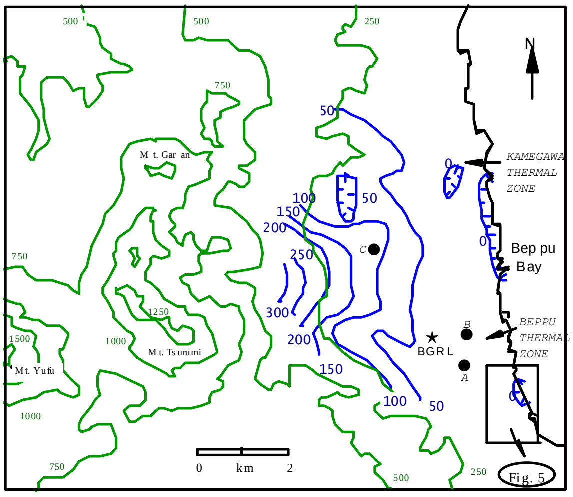

Figure 4. Piezometric heads (thick curves) in meter above mean sea level in the Beppu Hydrothermal System, based on a figure by Allis and Yusa (1989). Napped areas indicate low piezometric head anomalies. A: location of the shallow well of Fig. 6, B: location of the well of Figure 7, C: location of the well of Figures 8, BGRL: site of Beppu Geothermal Research Laboratory.

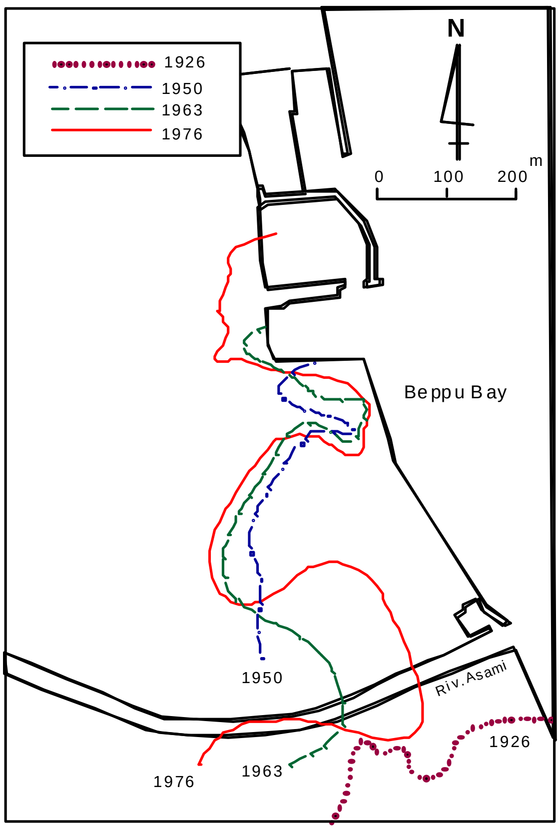

Figure 5. Change in position of the seawater intrusion front. The location is shown in Figure 4.

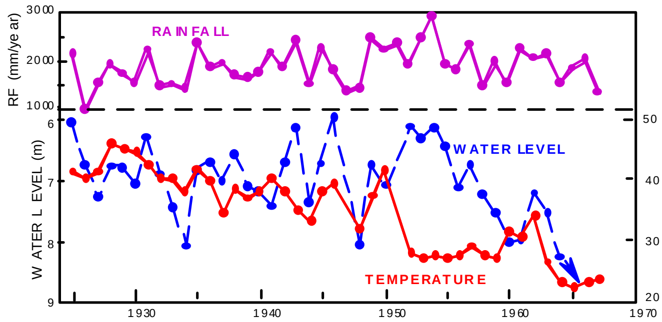

Figure 6. Long-term changes in water level (depth below ground) and temperature in a shallow well, and rainfall in the Beppu Thermal Zone. The well location is shown in Fig.4 as A; rainfall was measured at BGRL (Figure 4).

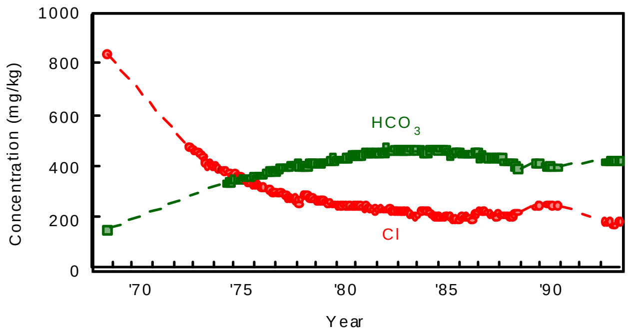

Figure 7. Time variations in chloride (Cl) and bicarbonate (HCO3) concentrations of boiling water discharging from a well in the Beppu Thermal Zone. The location of the well is shown in Figure 4 as B.

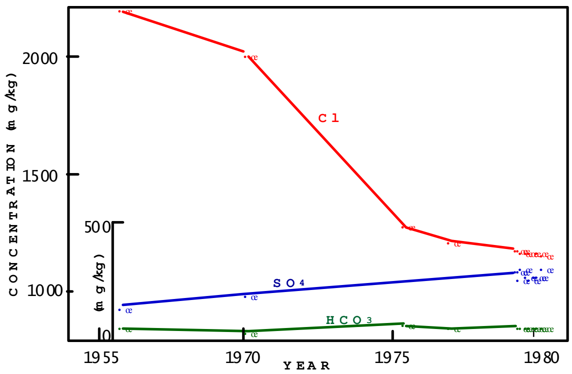

Figure 8. Time variations in major anion concentrations of a boiling water in the Kamegawa Thermal Zone. The location of the well is shown in Figure 4 as C.