

CONTRIBUTION OF GROUND WATER SYSTEM TO THE DISTRIBUTION OF GEOTHERMAL STATE

By

Kyozo KIKKAWA

(Received August 31, 1972)

Abstract

Distribution of underground temperature is obtained in Beppu from observations during well drillings. It involves some regional characteristics. The chemical characteristics of ground water are compared with the thermal states. The correspondency shows that the properties of thermal state are mostly related to the flow of thermal water in deep aquifer. Statical heads of ground water observed after or during the drilling works show relatively complicated distributions owing to their differences with depths of holes. They are simplified as being composed of two kinds of piezometric levels respectively corresponding to the upper ground water and the deeper thermal water. Thermal water is diluted owing to the downwards percolation of ground water. Piezometric level of the thermal water has a more gentle gradient than that of the upper ground water. Both levels become nearly equal in the area of alluvial strata near the coast. Control of exploitation of the thermal water is required in upstream region in order to keep the seawards slope of its piezometric level and preserve the present thermal activity near the coast.

1. Introduction

Beppu Hot Springs in former days were composed of eight swarms of hot springs, each of which was quite isolated from the others. Some of them discharged steam or acid hot water in hilly parts in contrast with others discharging almost neutral hot water in coastal parts. They were all located near the bluffs along the southern and northern boundaries of the topographical fan of Beppu. Both boundaries nearly correspond with geologic faults forming the limits of both sides of a sinking belt which includes Beppu City. Such configurations of hot springs had long been visible in spite of an increase in artificial drill-holes around each swarm of natural springs.

Until about twenty years ago, the phenomena of hot springs was hypothetically expressed as follows. Underground steam of volcanic origin ascends through cracks of rock along faults. A part of it appears from fumaroles or makes acid springs in shallow layer of hilly part and the other gives heat and chemical elements to relatively deep ground water by mixing. Hot ground water thus formed flows in confined aquifer and flows out as springs in the lower place. Studies on hot springs were then divided into two parts. One dealt with geothermal activity chiefly concerning the nature of underground steam in hilly regions and the other dealt with ground water hydrology in the coastal aquifer. The latter has developed considerably in

Beppu by investigating the effects of tide, precipitation, artificial draught and etc., because the utilization of hot springs concentrated in coastal area.

The demands for drill-holes for individual use have increased remarkably over the last twenty years. The city was, in some parts, pitted with holes. Drill-holes have also extended to the mountain area involving steaming ground. Consequently, new knowledge has been obtained as to the thermal origin of hot springs. It originates from the existence of the liquid thermal water below the region occupied by the steam. Underground steam can be realized as only a transformation of the thermal water owing to the lowering of pressure with its flow in the aquifer (Kikkawa [1971]). The main part of the heat of hot ground water is supplied by mixing of gaseous or liquidish state of the thermal water. Then, it must be said that the flow of the deep thermal water takes a fundamental role to form the thermal state in the underground layer and its investigation has primary importance in the understanding of hydrothermal activity.

Thermal water is characterized by its chemical constituent of the sodium chloride type. It has a high chlorine content being about equivalent to its sodium ion and can be distinguished from the effect of the sea water directly intruding into the aquifer (Yamashita [1965]). We can then roughly estimate the mixing quantity of the thermal water by observing the temperature and chlorine content of any sample of ground water in this area. High temperature and chlorine content show the large mixing ratio of the thermal water. On the other hand, high temperature but low chlorine content leads us to suspect the gaseous mixing of the steam.

2. Thermal state in the layer

It is noticed that information on the temperature in this area is still not so sufficient as to characterize the underground conditions affected by the flow of thermal water, though the chemical data have been fairly accumulated in our institute. The temperature of the water discharged from a well is often much lower than that in the aquifer owing to the conduction of heat to the surrounding media during upflow in the pipe. The lowerings of temperature differ not only with hydrological conditions but with the differences of equipment in each well, because withdrawals from most of wells now depend on airlift pumps. More typical lowerings of temperature appear in boiling wells situated in hilly geothermal areas. Temperature in a pipe of such a well is everywhere under the control of relation between boiling temperature and pressure after boiling of thermal water begins in the pipe. Therefore, we cannot easily estimate the temperature in the aquifer from the observed value at the surface where boiling temperature is determined under the atmospheric pressure. The temperature must be the value directly observed in the underground layer in order to designate the character of the ground water. Such observations can be done only during the drilling work of the well. A number of reports on drilling works in Beppu have been collected and arranged so as to give a general aspect on the dist-

tribution of underground temperature. Data are carefully selected because the observations on temperature in drilling works contain much room for error. Only reliable data are used as standards and others play supplemental roles so that a compatible aspect with our experiences can be presented. Nevertheless, the thermal state in a relatively shallow layer, especially in a geothermal area, cannot be accepted as reliable because the effect of artificial inflow of water for the drilling

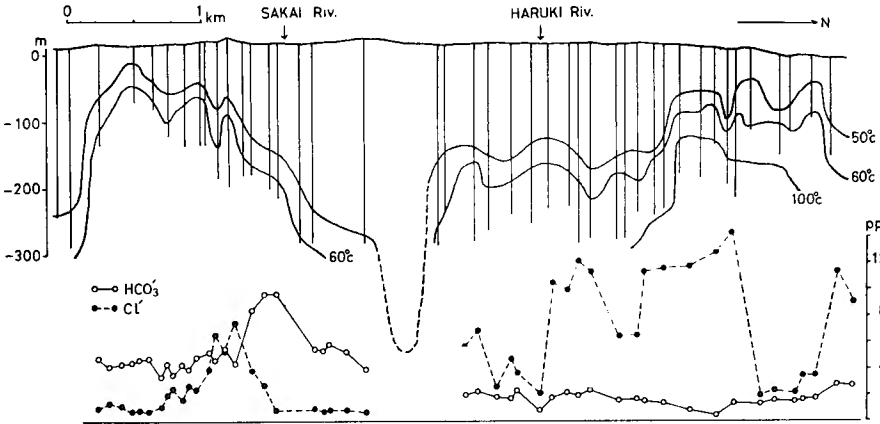


Fig. 1. Thermal and chemical distributions on A-A' cross section

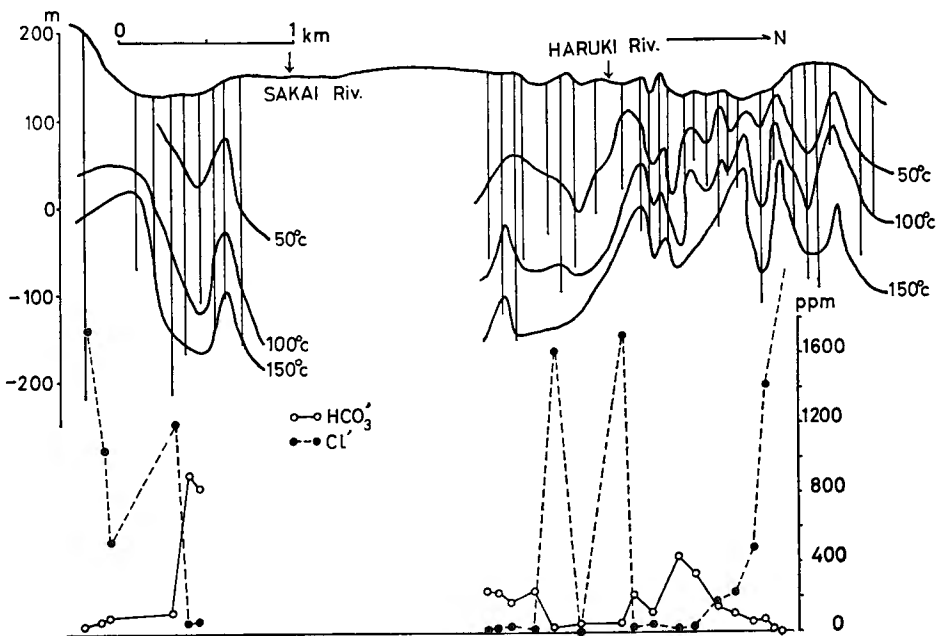


Fig. 2. Thermal and chemical distributions on D-D' cross section

work remains for a long time. Observations in such layers must show considerably lower temperatures than the actual states.

Data at 733 positions of wells are used to gain the thermal state in underground layer. Those positions are distributed around almost the entire area of Beppu Hot Springs except the middle part of the city, where it has been difficult to gain hot springs within the usual depth. We take some cross sections in N-S direction, nearly parallel to the coast, intervals of which are about 300 m. After plotting the observed values of temperature with depths on vertical lines indicating positions of drill-holes, isothermal lines are given on each cross section. Figs. 1 and 2 are examples of them and respectively correspond to A-A' and D-D' lines in Fig. 3. Values of depth in these figures are taken as heights from the mean sea level. They show the general tendencies of the temperature increasing with depth and decreasing towards the coast. It is interesting that Beppu Hot Springs can be divided into three parts from the viewpoint of the thermal state as clearly found in Fig. 1. Southern and northern parts belong to the zones of high temperature relating to the geologic faults already known. The part between them makes a stripe-like area being about 500 m width, where isothermal lines sharply descend on both sides. Distribution of temperature in this part seems to be pressed down by the ground water stream and is found to reach only 50°C below 500 m depth on a cross section more closely approaching the coast than the A-A' line. Horizontal variations of thermal state are more clearly

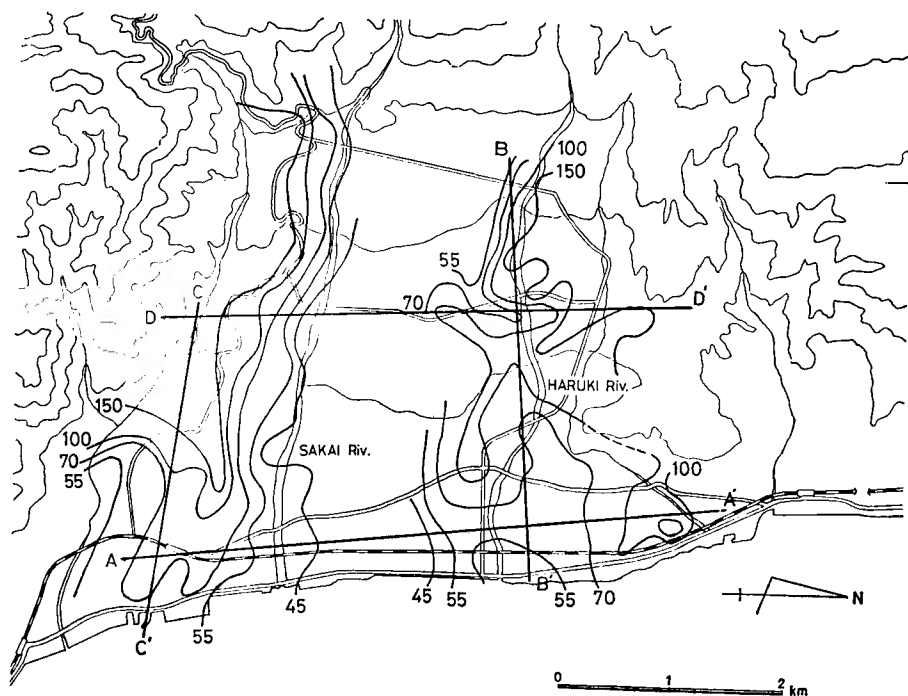


Fig. 3. The distributions of temperature at 200m depth below ground surface

expressed in Fig. 3, where isothermal lines give the distribution of underground temperature at 200 m depth below ground surface. Almost all isothermal lines in it are prolonged in a *W-E* direction. Such a state reflects the direction of the flow of thermal water in the aquifer and provides information on hydro-geologic conditions controlling it.

3. Correlation with chemical state of ground water

The chemical characteristics of ground water are given by the analyses of water samples discharging from drill-holes. It does not follow that the water sample always shows the same character as that of ground water in the aquifer tapped by the hole. It is quite usual in some areas of the geothermal field to make some equipment so that ground water in shallower aquifer is withdrawn after it percolates downwards along a pipe and is heated by geothermal action, because we cannot gain a sufficient amount of water in the deeper thermal aquifer. Let us investigate the correspondencies between thermal state and chemical character of the water in the layer, paying attention to the effect of the above-mentioned artificial equipment.

Contents of chloride and bicarbonate ions are compared with distributions of underground temperature on each cross section as in Figs. 1 and 2 though wells chemically analysed do not always coincide with those thermally observed. It is clear that the chlorine content has a tendency to be rich in the region of higher temperature. This confirms the supposition that the thermal state is essentially controlled by the flow of thermal water in a liquidish state. Some discrepancies are noticed in places of high temperature, where chlorine contents are not so rich as those in other regions of similar temperature. For example, the middle zone of the southern part is a typical one. It contained many natural springs in former days and was considered to be the most active thermal area among the city. High temperature is still found in the shallow aquifer of this zone as in Fig. 1, though chlorine content seems to be similar as that in other areas of lower temperature. It may be owing to the flow of shallow ground water heated by underground steam in the upstream region. Somewhat high content of bicarbonate ion in this zone confirms this supposition. Similar process can be adapted to the high content of bicarbonate ion in the stripe-like zone near the northern edge of the southern part, where isothermal lines sharply descend northwards. Such bicarbonate ions are understood as given owing to the supply of carbon dioxide from steam and reaction with calcite or clay minerals in the strata.

Another origin of chloride ion in ground water is the sea water intruding into the aquifer. The area of sea water intrusion is already known in Beppu and the high contents shown near the northern edge in Fig. 1 belongs to this area.

There are some geothermal areas in the northern part where chemical character is rather well defined by sulfide than by bicarbonate. (Kikkawa and Shiga [1966]). However, distribution of sulfide is excluded from this paper because it is too compli-

cated to gain a general view in comparison with chemical and thermal states in the whole area.

4. Correlation with hydrologic state of ground water

Some aspects were already prepared as to the characteristics in the regional variations of hydrothermal activity by investigating the observed thermal and chemical states as above-mentioned. They are fundamentally due to the hydrologic conditions of three kinds of ground water, steam, thermal and ordinary water. The flow of ground water essentially follows the gradient of hydrologic potentials designated by the heights of static heads in drill-holes. Static heads can be observed soon after the completion of wells and sometimes at various depths during drillings. It is a common case that the static level of water in a hole suddenly descends when drilling progresses to the deeper layer. The rate of such descents seems to be extreme in hilly areas near mountains. Approaching the coast, vertical changes of static heads become not so attractive during a drilling work. Occasionally, somewhat higher levels of heads are observed with depths. Equipotential lines in accordance with observed static head in each well are consequently so much uneven that horizontal distribution of potential is difficult to be expressed in usual manner on a map. Such a difficulty is chiefly owing to the differences of deepnesses of aquifers tapped by drill-holes and suggests the necessity of a hydrologic model involving vertical profiles of potentials in order to find the conditions controlling the stream of ground water.

For example, observed static heads are plotted in Figs. 4 and 5 which represent the underground states on the cross sections taken along the lines of $B-B'$ and $C-C'$ in Fig. 3. Those lines are considered to be in accordance with the main directions of the streams of ground water in the northern and southern parts. First of all, levels of ground surface are drawn in the figures and then observed static level of water in each well is marked as a circle. Crosses designate the positions of heads observed at depths while drilling. Isothermal lines and chemical characters on those cross sections are also shown. It is clear that static heads become deeper with depths of drilling. They exceed 100 m depth from ground surface in upstream regions. Such a state gives the possibility of downward seepage to the deeper aquifer and shows that three dimensional consideration of ground water stream is necessary to understand the present condition of hydrothermal activity. It cannot be expressed by the usual hydrologic model of a confined aquifer but by leaky one, and rather corresponds to the three dimensional flow presented by Tóth [1962], in which the ground water stream is treated as a continuous one through different kinds of strata in a whole basin.

A representative diagram approximately adapted to the ground water system in Beppu was already presented by Kikkawa [1971], in which ground water is simplified by two parts, upper and deeper, their communication being somewhat rest-

stricted owing to the relatively poor permeability of the layer of tuff between them. Thermal water flows in the deeper aquifer, composed of the former volcanic rock,

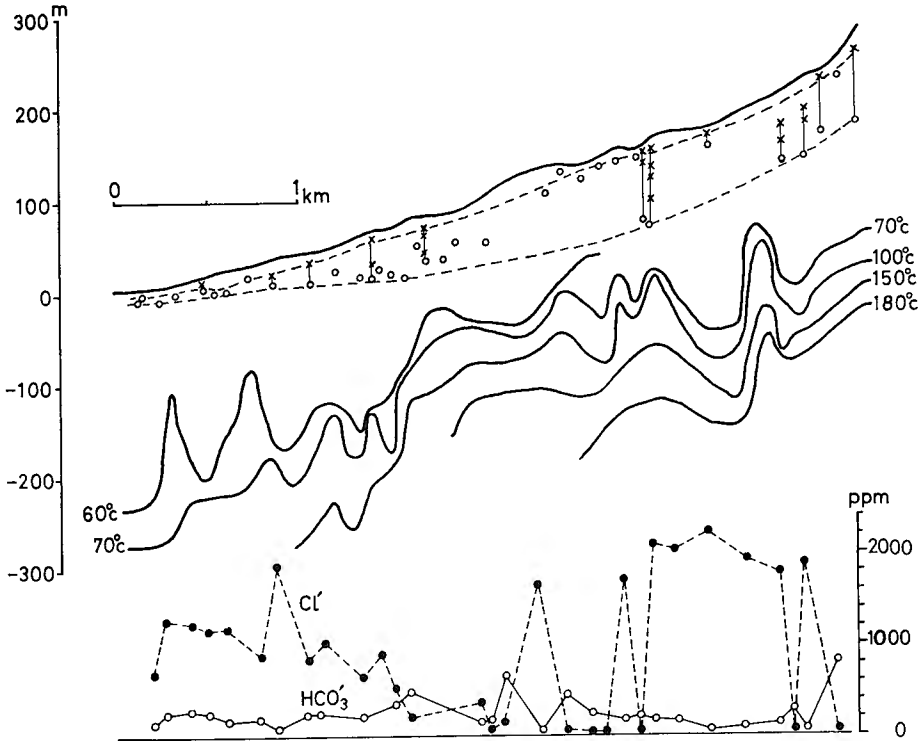


Fig. 4. Distributions of thermal and chemical states and piezometric levels on $B-B'$ cross section

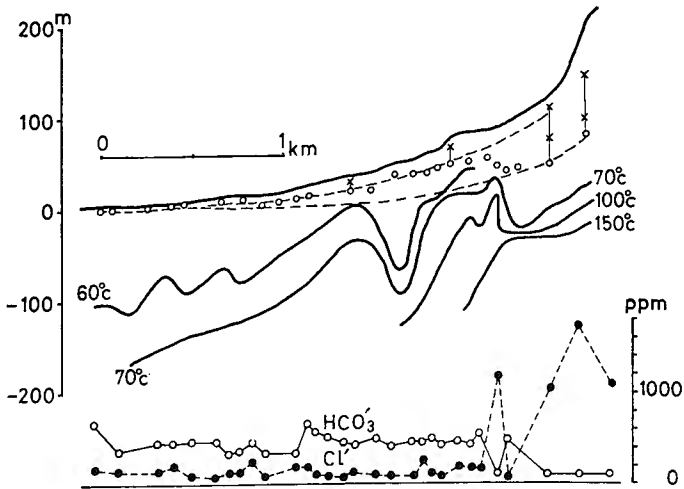


Fig. 5. Distributions of thermal and chemical states and piezometric levels on $C-C'$ cross section

and is diluted by the downward recharge of ground water almost everywhere except the narrow part along the coast. There are however some regions beneath the hilly area, occupied by underground steam and resisting the downward percolation of ground water. Hydrologic conditions expressed in Figs. 4 and 5 nearly correspond to the state in this diagram.

Two dotted lines are introduced respectively in Figs. 4 and 5 in order to gain a general aspect approximating to the three dimensional stream of ground water. They give the upper and lower limits of the observed statical heads and are assumed to act as representative of the piezometric levels in both the aquifers simplified as above described. Ground water stream on each cross section is thus approximated by two kinds of horizontal flow under the condition of vertical recharge or discharge between them. The upper dotted line gives the flow of ground water in the upper aquifer locally heated by underground steam. The lower line contributes to that in the deeper aquifer chiefly occupied by the thermal water. Distributions of chemical characters show that more saline waters of sodium chloride type are obtained in the area where statical heads of wells are mostly located on the lower dotted line. On the contrary, wells having higher statical heads are found to discharge the water chemically characterized as only heated by steam or geotherms. Distributions of isothermal lines in both figures also involve the effects of diluting the thermal water and ascents of steam from it.

Thermal water in deeper aquifer flows towards the coast with deeper but more gentle slope of piezometric level than in the upper aquifer. Both piezometric levels gradually approach and somewhere join with each other though the place of intersection cannot be clearly defined owing to the rough estimation of the statical head in this paper. Area of discharge of thermal water is then formed in the downstream region where natural hot springs were active in former days. It is certain that the inflow of thermal water to the discharge area took an important role on the thermal state near the coast. In the history of exploiting hot springs in such areas, it is typically known that depths of drill-holes have deepened more and more in these years. It suggests the gradual lowerings of distributions of underground isothermal lines in these areas. Such trouble-some phenomena must originate from the decrease in inflow of thermal water according to the successive lowering of its piezometric level in the upstream region. Exploitations of boiling wells in hilly areas are the chief cause of such tendencies, because they act as direct withdrawal of thermal water in upstream region. It is undoubtedly important to preserve the seawards gradient of piezometric level of thermal water in order to guard the present thermal state in the coastal area. An urgent problem is now presented of keeping under control the exploitation of hot springs especially in upstream regions of the thermal area.

5. Conclusion

Ground water system in a basin is usually illustrated as a group of different kinds

of confined or unconfined waters. They were primarily treated as individual flows in hydrologic problems. Hydrology on leaky aquifer introduced the communication between them and Tóth's model expanded such communications so as to treat them as a continuous stream involving refractions of equipotential lines at boundaries of different strata. It is however difficult to find the information to distinguish the hydrological character of each type of ground water in different courses of a stream. Hydrologic communication is usually presumed only from the consideration on the dynamical conditions of ground water.

Thermal water in deep aquifer is characterized by its temperature and chemical constituent among different kinds of ground water in a hydrothermal area and is very useful in finding the process of its flow or interchange between other waters. Hydrologic potentials observed in many drill-holes with different depths show somewhat complex distribution especially in the area of the foot of mountain because they are affected by the vertical flow of ground water. Effects of such vertical flows correspond to some characteristics given in thermal and chemical distributions in underground layer. The result obtained here may be adapted not only to similar hydrothermal areas but to other areas under similar hydro-geologic condition.

References

- Kikkawa, K. and S. Shiga, 1966; Relations between halogen contents of hot spring water, Special Contributions, Geophys. Inst., Kyoto Univ., **6**, 173-186.
- Kikkawa, K., 1971; Some physical properties of the steam discharged from geothermal ground, Contributions, Geophys. Inst., Kyoto Univ., **11**, 91-101.
- Tóth, J., 1962; A theory of groundwater motion in small drainage basins in Central Alberta, Canada, J. Geophys. Res., **67**, 4375-4388.
- Yamashita, K., 1965; The chemical character of the boiling springs in the Beppu hydrothermal field, Special Contributions, Geophys. Inst., Kyoto Univ., **5**, 7-16.