MEMOIRS OF THE COLLEGE OF SCIENCE, University of Kyoto, Series A,
Vol. XXVIII, No. 1, Article 3, 1956

ON SOME RELATIONS BETWEEN THE HOT SPRING AND RADIOACTIVITY

BY

Sigeru OKABE

(*Received April 27, 1956*)

ABSTRACT

Some studies were made on the relation between the hot spring and radioactivity. The rapid variation of radon-content with time in the thermal water of hot springs was observed at several places, and a newly devised method for measuring such phenomena is mentioned along with a proposed model hot spring to fit the phenomena. A theoretical treatment is also given on the relation between the hot spring, radioactivity and ground temperature to explain the anomalous distribution of intense ground radioactivity around the site of a hot spring. And, moreover, some considerations are made on the source depth of the radioactive matter contained in the thermal water of hot springs; a conclusion is reached supporting the theory of its shallow origin.

1. Introduction

Since the discovery of radium many studies have been made on the radioactivity of hot springs throughout the world, mainly in relation to chemical constituents. In Japan, a place famous for its most abundant and utilized hot springs, numerous observations have been made mainly on the radon-content in the thermal water of hot springs in various districts. The accurate measurements of the radon-content in hot springs made by Y. Iimori (**1**) with the I. M. Fontactoscope, I. Iwasaki (**2**), K. Kuroda (**3**), and other researchers should be highly appreciated. K. Kimura (**4**) was the first to introduce the G–M counter into the measurement of radioactive deposits in hot springs, and W. Kolb (**5**) recently published a paper on a method of measuring the radioactive properties of hot springs. S. Iwasaki (**6**) has recently examined the connection between hot springs and ground radiation. The writer has been investigating some geophysical phenomena in relation to ground radioactivity since 1949 (**9**, **10**, **11**, **12**, **13**), and in the present article are reported some studies on the relation between hot springs and radioactivity.

2. Variation of radon-content with time in the thermal water of hot springs

The radioactivity of hot springs has been precisely measured by several researchers, reaching a numerical accuracy of expression in the thousandths. And the difference between the measured values of the radon-content of a particular hot spring in different periods from one to several years' duration has also been examined. But recently I. Iwasaki (7) discussed the great fluctuation in the measured value of radon-content which he had observed occurring once in three hours at a particular hot spring. On the other hand, the writer has been also investigating the same phenomena from a different point of view, and its result will be reported in some detail below.

(*a*) *Method of measurement*

The quantity of radium content in liquid has hitherto been usually measured with the I. M. Fontactoscope or the Lauritsen electrometer specially devised by K. Kimura and K. Kuroda (8). But these methods are not considered to be unconditionally suitable for a repeated measurement of short duration, because of the radioactive contamination by radon and thoron which is inevitably induced in such sort of measurements. To avoid this inconvenience the writer devised a special method for measureing rapidly and accurately the radon-content of hot spring thermal water (**10**) and tried to detect the minute fluctuation of hot spring radon-content in the short duration of several minutes.

The procedure of measurement is briefly summarized as follows.

1) To fill the glass bottle with the hot spring thermal water at the spout and seal it hermetically, excluding bubbles.

2) To leave the sampled bottle alone for three hours.

In these three hours the radon in the sampled thermal water reaches a state of equilibrium with its decay products (see Fig. 1). And the above-mentioned three hours is the minimum duration for sufficient saturation.

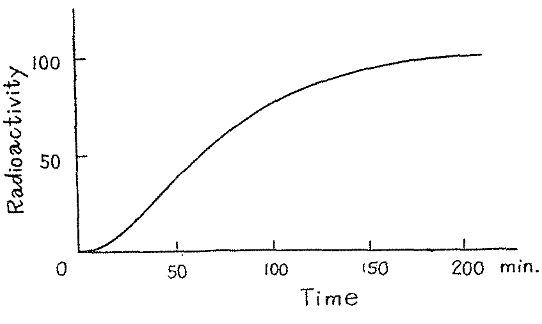

Fig. 1. Saturation curve of radon's decay products measured with β-rays and γ-rays.

It ought to be remarked that the errors resulting from the difference of time of arrival from the subterranean radioactive source are negligibly small because of the long half-life of radon.

An air gap is formed in the upper part of the sampled bottle caused by the difference in thermal expansion coefficient between the water and glass in temperature drop during the three hours' storage, but the radon-content in this air gap was ascertained by the writer (**10**) to be less than 0.1% of the radon-content in the sampled water.

3) To take the water sample after the three hours' storage, and add to it a

certain amount of sulphuric acid and then a certain amount of barium nitrate solution. In this case the 9.5 mg barium nitrate is sufficient for the sample water of 25 cc. Then to filtrate the solution with the combined precipitate of decay products with barium sulphite. The process of this stage needs nearly five minutes and its induced errors are estimated to be less than 5%.

4) To wrap quickly the filtrating paper deposited with the decay products of radon into the stencil paper of copy print in thickness of 1.5 mg/cm^2. This method is considered to be very convenient and efficient for avoiding the injurious effect of radioactive contamination (**11**).

5) To count the radiation number derived from the deposits of radon decay products by quickly winding the stencil paper containing deposits around the G-M counter of the tube type or sticking it to the window of the counter of the end window type.

6) It is to be remarked that sampled water containing thoron, radium, thorium and other elements should be differently handled from the above process, but practically speaking, the existence of these elements does not injure the accuracy of the present method of measuring the short time fluctuation of radon-content in hot spring thermal water, because radium, thorium and decay products of thoron have long half-life compared with that of decay products of radon.

By the above-mentioned method the radon-contents in the thermal water of the hot spring could be accurately and regularly measured once in five minutes. Although there is another method of continuous observation by using the dipping counter, it was proved (**12**) to be inappropriate for the present investigation for detecting short period fluctuations in radon-content because the radon decay products in spring water sticking to the counter tube greatly injure the measured value, and moreover the obtained count by the dipping counter is small compared with the natural count. The count obtained by the present method may rightly be transferred to the intensity of radon-content by using the table previously compiled from the comparison experiment between the count and the mache-number of the solution of a known radon-content by the aid of the I. M. Fontactoscope. The G-M counter used in the present investigation will be described in some detail in § 3. The I-M Fontactoscope used for comparison is the apparatus made by the Scientific Research Institute in Tokyo.

(*b*) *Variation of radon-content with time*

The short time radon-content variations in hot spring thermal water were observed at three hot springs, namely, Misasa and Hamamura (both in Tottori Prefecture), and Ikeda (a mineral spring in Shimane Prefecture) by the above-described method. And their observed results are shown in Figs. 2, 3, and 4, whose ordinates and abscissae represent the radon-content in mache and time in hours respectively. It is to be remarked that the quantity of gushing water differs greatly, those being about 1 litre per minute at Misasa, about 2 litres per minute at Ikeda, and about 10 litres per minute at Hamamura respectively. And, both Misasa and Ikeda are situated at the gorge of a mountain of igneous rock, and on the other hand, Hamamura on an alluvial plain. As clearly seen in the figures, the radon-content in the thermal water of the hot springs or the cold water of the mineral spring varies greatly within the con-

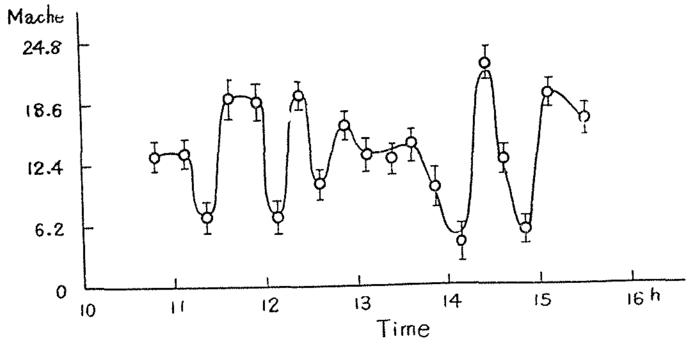

Fig. 2. Variation of radon-content with time at the Misasa hot spring.

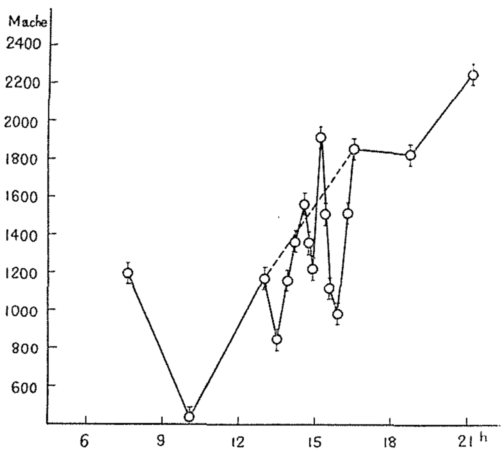

Fig. 3. Variation of radon-content with time at the Ikeda mineral spring.

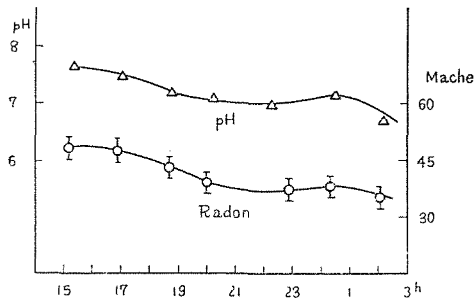

Fig. 4. Variation of radon-content with time at the Hamamura hot spring.

siderably short time of fifteen minutes. It may safely be said that a shorter time variation should certainly exist and could be detected by the above-described method, as the time required in the measuring process is within only five minutes and the successive observation per five minutes or less is possible in the case of a sufficient number of observers. Consequently, the hitherto discussed problems on the radon variation, as deduced from the observed data of every several hours or every several days should carefully be examined in consideration of the violent short time changes revealed by the present observation.

(*c*) *An explanation for the observed short period time variation of radon-content.*

It is well known that the total intensity of radioactivity in a liquid containing fresh radon gradually increases as the radon decays with time, producing radium A, radium B, etc. to reach the saturation state in nearly three hours after the initial radon-absorption in the liquid as shown in Fig. 1. And the radon itself decays with its half-life of 3.8 days. In the present investigation the comparative measurement of radioactive intensity in the thermal water at the instant of gushing out with that after the time of saturation was tentatively applied for the purpose of explaining the nature and mechanism of time variation of radon-content of the thermal water in a short period. Namely, the age of radon was calculated from the ratio of the radioactive intensity at the gushing instant to that after saturation by applying the saturation curve of radon in Fig. 1. The value of $\frac{2}{3}$, of the ratio, for instance, obtained by comparison of radioactive intensity in the initial and final states would be interpreted to tell that the radon in question is 80 minutes old. It should be remarked here that the hot water in question will certainly contain radons of various ages, and correspondingly the value of age obtained by the above method is considered to show vaguely the mean age of accumulated radons of various origins and birth times. But in consideration of the fact obtained in the practical measurement that the ages of radon thus determined were all within 100 minutes, it is safely and rightly

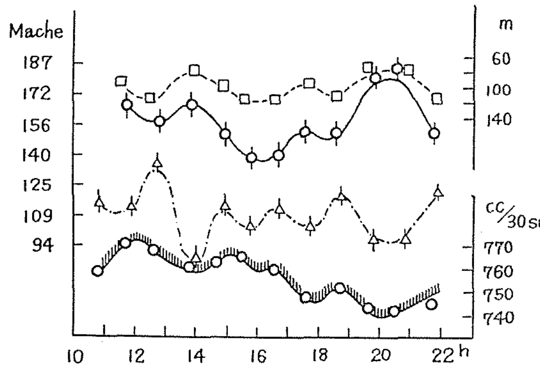

Fig. 5. Misasa hot spring (Spring of the Inn Yasui) July 25, 1951.

- - - - - Age of radon
———— Total radon-content
—·—·— Radioactivity of the thermal water measured as soon as it gushed out
|||||||||||| Quantity of the thermal water

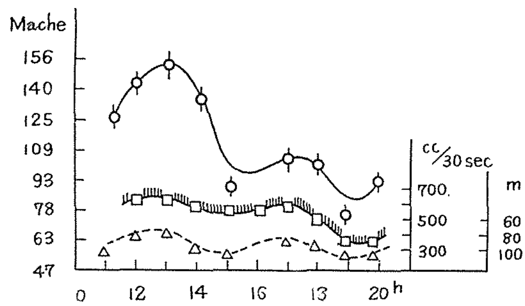

Fig. 6. Misasa hot spring (Spring of the Inn Yasui) July 15, 1951.

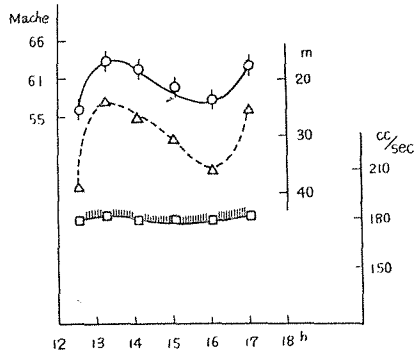

Fig. 7. Hamamura hot spring (Asinoyu of the Inn Tasumoto) July 13, 1951.

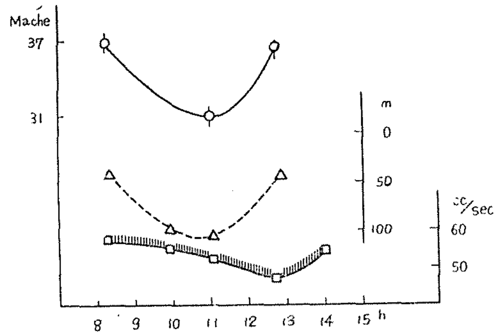

Fig. 8. Sekigane hot spring (Spring of the Hotel Onseiro) July 26, 1951.

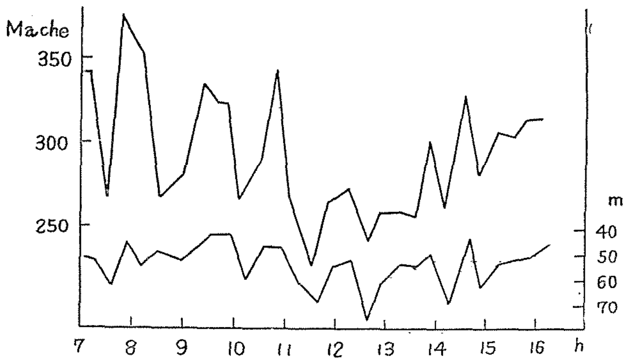

Fig. 9. Ikeda mineral spring. Aug. 15, 1955.

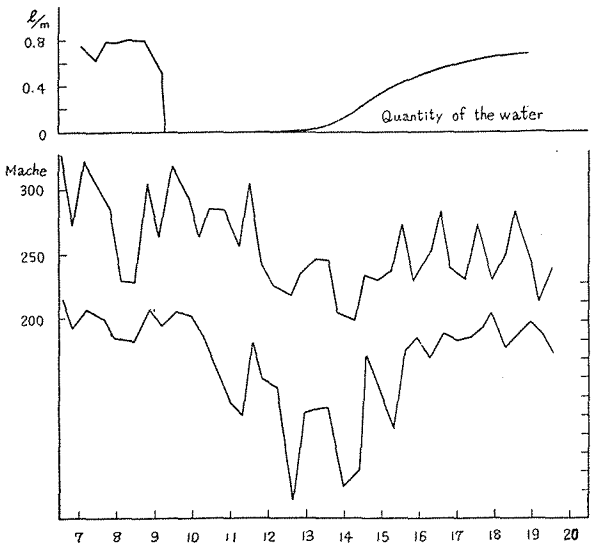

Fig. 10. Ikeda mineral spring. Aug. 16, 1955.

assumed that the radon or the group of radons treated in the present measurement are mainly concerned with those of comparatively younger or fresh radon. In Figs. 5, 6, 7, 8, 9, and 10, are plotted the observed date at Misasa, Hamamura, and Sekigane hot springs (in Tottori Prefecture), and Ikeda mineral spring (in Shimane Prefecture) with regard to the quantity of thermal water at the spout, the radon-content of the thermal water, and the age determined by the above-described procedure. In Fig. 5 the intensity of radio-activity measured soon after the gushing out is also plotted as an example, and in Fig. 10, the observed data at the same spring shown in Fig. 9 are given in the case of an artificial stoppage of gushing mineral water for several hours.

From all the above figures, the following relationships between the gushing thermal water, the radon-content, the age of radon in the above described sense and amplitude of time variation of radon content are clearly observed.

(i). The younger the radon is, the stronger its radioactivity is, at the one and same spring.

(ii). The smaller the quantity of gushing thermal water, the more severe the variation of radon-content with time in case of comparing the two springs in the different districts.

(iii). The time variation of radon-content is intimately related to the quantity of gushing thermal water at some springs, while there is no connection at other springs.

As above stated, the radon concerned in the present measurement, especially for the problem of its time variation, is reasonably considered to be comparatively young or fresh, and consequently the time variation of age of radon is interpreted as mainly relating to the difference of path through the underground vein of the thermal water containing fresh radon. Roughly speaking, we may explain these phenomena by saying that the shallower the underground radon source, the stronger radon intensity in the hot spring thermal water measured at the ground surface. Speaking in more detail, however, there may be many small cavities in the underground and, in the case of a radioactive spring, a considerable amount of radium and other radioactive elements is considered to be precipitated in these cavities. Under these circumstances the intensity of radon-content in the thermal water of a radioactive spring will be greatly influenced by the position or simply the depth of the concerned small cavity containing the strong radioactive liquid which largely contributed the fresh radon to the neutral thermal water. It is generally considered that the thermal water activated by the radioactive liquid in the shallow cavity is less disturbed and weakened by the mingling of the underground water and other disturbances compared with those in case

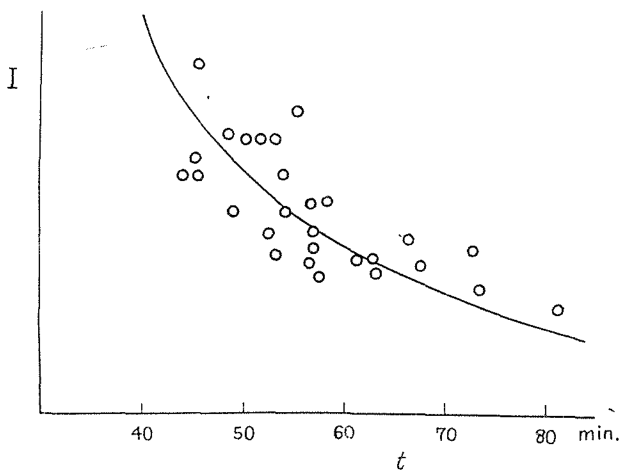

Fig. 11. Relation between the radon-content and their ages.

of deep cavities. Under these assumptions the above-obtained relation between the radon-content in the thermal water and the age or freshness of radon as mentioned in (i), will reasonably be explained. From Fig. 11, which represents graphically the relation observed between the radon-contents and their age of the data plotted in Fig. 9, the following empirical formula is obtained, denoting the radon-content in the thermal water and the age of radon as I and t respectively:

$$I=\frac{a}{t^2}+b\,,$$

where a and b are numerical constants proper to each spring. Namely, the above formula expresses that the intensity of radon measured in the thermal water of any one spring is inversely proportional to the square of its age. After the assumed model or way of radioactivation of the originally neutral thermal water by the strong radioactive liquid in the small underground cavities, the mode of rapid variation of radon-content in the thermal water will also approximately be explained. The phenomenon of rapid radon-content variation is probably caused by difference of contributed or enriched amounts of fresh radon to the neutral thermal water by the underground small cavities at various depths and having strong radioactive liquids of variable intensity. As the underground radioactive cavities in question are considered to correspond to the micro-pores and micro-fissures in case of hot springs with rocky foundations, and the capacity for containing a strongly radioactive liquid in the cavity is estimated to be very small, the radon-content in the thermal water measured at the ground surface will correspondingly show a rapid and violent fluctuation, especially in case of hot spring with small quantity of gushing water, according to the rapid consumption of strong radioactive liquid in the small cavity, and the rapid alternation of the cavity as the furnisher of fresh radon to the neutral thermal water. Of the hot spring with a sand or clay foundation the time variation of radon-content observed is comparatively small and this is reasonably explained by the circumstances that there are probably no distinct underground cavities to show rapid consumption and alternation in furnishing the fresh radon to the neutral water, and moreover, the effect of enrichment of fresh radon to the neutral water, if any exist, may greatly be weakened by the diluting effect of the great quantity of underground water abundant in the sandy layer. In concluding this section, the rapid and violent fluctuation of radon-content in hot spring thermal water was observed at the same hot springs by the improved method of rapid measurement of the thermal water radon-content. And a model radioactive hot spring was tentatively propcsed as an explanation of this phenomenon of radon-content time variation. The existence and effect of small underground cavities containing strong radioactive liquid (cf. **33**) are considered as an approximate explanation of some of the relations obtained in the observation of rapid fluctuation of radon-content in the thermal water.

3. Relation between ground radioactivity and hot springs

It is generally known that the quantity of radon-content in the ground surface or in the superficial layer of the ground is largely influenced by the existence of the fault or underground vein, and the problems have been fully discussed by Z. Hatsuda (**14**), T. Ochiai (**15**), S. Sano (**16**), and other researchers. On the other hand, a correlation between the hot spring and the quantity of radon-content at the ground surface can probably be postulated, in consideration of the circumstances that a large number of hot spring are assumed to originate from underground fissures and veins. But the problem should not be so simply treated, because there are actually various types of hot spring. For example, in the mode of thermal water gushing, there are many types of natural gushing and pumping up, surface origin and by deep boring. And in radioactive intensity, there are strongly radioactive springs and non-radioactive springs. Accordingly, for the purpose of obtaining any relation between ground radiation and hot springs, the precise measurement of ground radioactivity should be applied to as many and various types of hot springs as possible. In our country S. Iwasaki (**6**) has recently reported on this problem for one example of hot spring. In the present investigation, the relations between ground radioactivity and hot spring origin were studied by the precise observation of the ground radiation of nearly twenty hot springs of various types and under different circumstances. It is here to be remarked that the anomalous distribution of ground radioactivity measured and discussed in the present investigation is considered to be mainly concerned with the decay products of radon, because the thoron and its decay products, if existing, cannot become the object of observation for detecting the anomaly of ground radiation in somewhat deep underground layer. We shall refer to this point in some detail in a later section.

(a) Method of measurement

Z. Hatsuda (**14**) made various applications of the "radon-in-soil-air method", "ground-hole-ionization chamber method", "photo-plate method", and "G–M counter method" in his study on radioactivity of the ground near the faults and other places. And T. Ochiai (**15**) and S. Sano (**17**) used the method with the G–M counter in the research of ground radioactivity. In the present investigation of ground activity near the hot springs the observation was made by the G–M counter method and the soil-air method with the Lauritsen electrometer as described in the following:

The method with the G–M counter—In the previous observation a G–M counter tube made by the writer containing alcohol and air was used with a wall-thickness of 0.2 mm of duralumin, a diameter of 35 mm, and a length of 80 mm, as shown in Fig. 12, the natural count being in the range of 50 to 60 c. p. m. Afterwards the

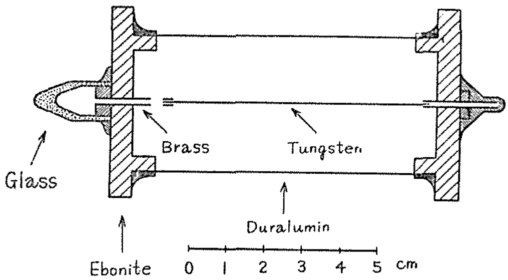

Fig. 12. The structure of the used G–M counter.

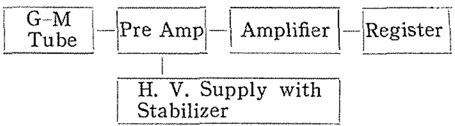

Fig. 13. Circuit of the G–M counter.

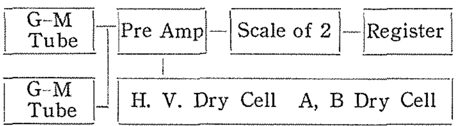

Fig. 14. Circuit of the G–M counter (2s–pl).

G–M counter of end-window type made by the Scientific Research Institute in Tokyo was mainly used in the research observation. This apparatus has a mica-window of 3 mg/cm^2 and shows 30 to 40 c. p. m. as the natural count, and in practice two sets of these counter tubes were used in parallel connection.

In Fig. 13 the connection diagram of the portable counter made by the writer above described is represented. In this case the observation was unprofitably restricted with regard to the place of measurement because of the necessity of applying the source of alternating electric current to the apparatus. In Fig. 14 the connection diagram of the recorder of the end-window counters made by the Scientific Research Institute in Tokyo above described and named (2s–pl), which was somewhat reconstructed for the present investigation, is represented, in which case the dry cells are conveniently used and the parallel sets of two couters brings good results in such a measurement of small counts as in our present observation. The maximum number of accurate counting was estimated to be within 280 c. p. m. in case of the apparatus in Fig. 13, and 800 c. p. m. in case of Fig. 14, but as the present measurement requires a count range of from 60 to 160 c. p. m., both apparatuses would be highly reliable in the point of counting. The duration of counting at one point was in the range of 5 to 10 minutes which was suitably adopted according to the number of counting at the place. And in these cases the errors caused by the statistical fluctuation in a finite duration of counting were estimated to be nearly within 3% of the counts. And the counter tube was efficiently placed, in the practical measurement, at the height of 15 cm above the surface of ground, because measurement at a position lower than 15 cm is considered to be too much sensibly disturbed by the very small and local irregularity of the ground, and the measurement at a higher position than 15 cm is also inconvenient for the measurement of weak β–rays and greatly disturbed in the point of accuracy by γ–rays radiating from the other ground. This was ascertained by some trial measurements by the counter at different heights, and an example is represented in Fig. 15. In the practical measurement, the facts were observed that the counts measured at the position on a road higher than the surroundings or on the heapy ground are apparently of small value owing to the escape of radon from the lateral side of the road on the ground. On the contrary, the counts measured at the lateral side of heapy ground or the hill, and on the fissure of a dry rice-field, were in 10 to 20% of the ordinary value largely observed. Next, in the following Figs. 17~31, the values of counts at the respective points in the same area of hot spring are represented in the figure of ratio of the very counts to the minimum counts observed in that area. This method of representation was suitably adopted for the elimination of errors caused by the secular change in instrumental ability of the counter, the local character of ground radioactivity of a respective small area, and other inevitable disturbances.

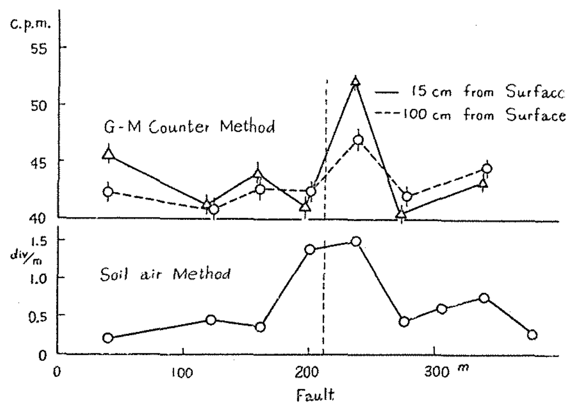

Fig. 15. Survey at the Fault Yoshioka.

The soil-air method with the Lauritsen electrometer—This method is an indirect one in the measurement of soil-air, but convenient in the point of operation. To dig a hole of 10 cm-diameter and 100 cm- or 50 cm-depth in the ground, and, after 3 hours' covering on the hole, suspend a metal plate of $4 \times 6.5\,cm^2$ in the hole, and give the plate a negative charge of 500 volts during 30 minutes. And, next, insert this metal plate into the sample-shelf of the Lauritsen electrometer, and measure the radioactivity of decay products of radon stuck on the metal plate through the aluminum foil window of the electrometer. The Lauritsen electrometer used in the measurement was one made by the Scientific Research Institute in Tokyo and its voltage-sensitivity was estimated as 1.48 div./volt, or 2.30 div./min. for the γ-ray radiated from a radium source of 1 mc at a distance of 1 m from the electrometer. In Fig. 15 an example of concurrent measurement made in the autumn of 1953 is shown with the G-M counter and the soil-air method, the observation side being near the active fault 1 km northward from the Yoshioka hot spring in Tottori Prefecture. But, generally speaking, the soil-air method with the electrometer was not so frequently used as the G-M counter method, because of large errors caused by the local irregularity of the dug hole, and of the heavy labour and time spent in digging the hole and in the processes of measurement.

(b) Daily variation of ground radioactivity

For the purpose of treating the local character of ground activity of any place by the method of radioactive measurement at many points as possible in the area concerned, the effect on the time variation of ground activity by meteorological changes or other like disturbances should fully be examined at each place before the commencement of observation. An example of measurements disturbed by rainfall at the same points, and an example of measurements with daily variations at same points in the area of the Ikeda mineral spring in Shimane Prefecture, are shown in Figs. 16-(a) and 16-(b), which inform us of the large influence of rainfall upon the measured value of ground radioactivity and also, on calm days, the ground-activity remains nearly constant from 9 am to 8 pm. From these observed facts and other experiments, the measurement for the present investigation should preferably be made

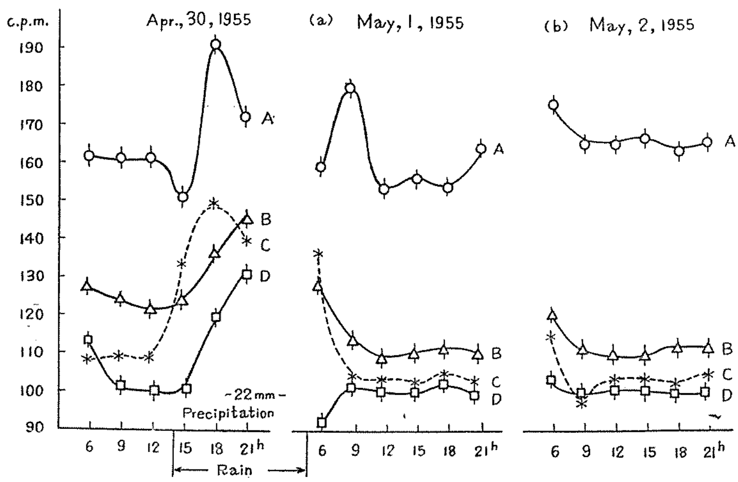

Fig. 16. Daily variation measured at the places of A, B, C, and D near the Ikeda mineral spring.

during the day time between 9 am and 8 pm on calm days, avoiding the rainy days and their following days. And, in case of measurements extending over several days, measurements should repeatedly be made at some reference points during the several days, in consideration of disturbances due to changes in barometric pressure and other causes. As seen in Fig. 16-(b) the ground activity in the early morning shows a large value compared with that in the daytime, and this is resonably explained by the process of release of radon contained in the dew which absorbed radon during the night and evaporated during the early morning, and furthermore by the increase of radon decay products due to the blocking of the capillary openings of the ground surface by the dew.

The increase of ground radioactivity in the case of rainfall will similarly be explained as in the above-described process. The decrease of ground radioactivity at 21h in Fig. 16-(a) which was once largely increased by rainfall of 14h-commencement is explained by the effect of blocking the capillary openings in the deeper layer of the soil by the penetrating water of the rain. From these and as seen in Fig. 16-(a), it is to be strongly remarked that a part of ground radioactivity measured by G-M counter on the ground surface is interpreted as caused by decay products of radon which ascended through the capillary openings in the soil to the ground surface from its original source in somewhat deep underground.

(*c*) *Radioactive measurement at some places with no hot springs*

The radioactive measurements at some ordinary places with no hot springs or active faults have been made for comparison in studying the anomalous distribution of ground radioactivity at places near hot springs. Among ten places of ordinary nature recently measured the following two examples will be mentioned as representative: An example shown in Fig. 17 is the spatial distribution of the numerical data of ground radioactivity measured with the G-M counter at the ground surface at Tottori University on an alluvial plain where no fault or other geological irregularity is found. As shown in the figure, it is easily understood that the maximum value of count ratio does not exceed 1.1 at such a place as there is no geological irregularity or anomalous distribution of radioactive substances. In Fig. 18, another example is shown of the measurement at Yudokoro-cho in Tottori City. The

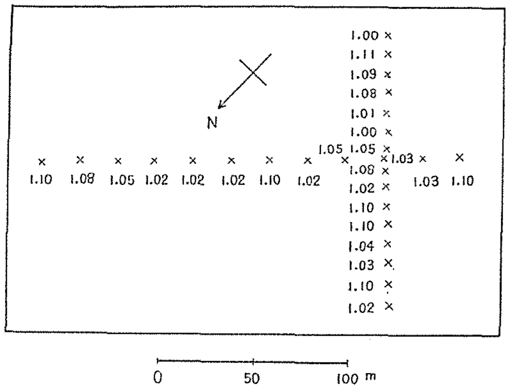

Fig. 17. Survey at the play-ground in the Tottori University.

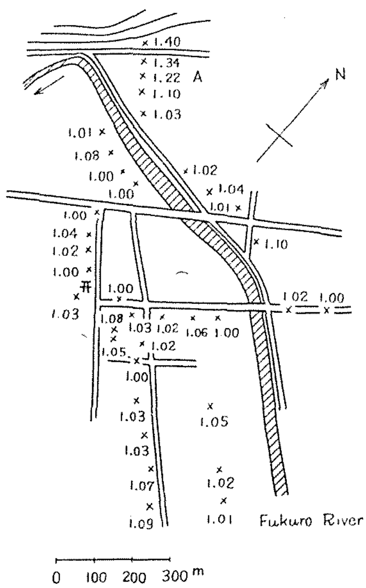

Fig. 18. Survey at Yudokoro-cho in Tottori City.

ground is the alluvial plain of 50 m-thickness, and there is the rock mountain at the north area point A. The count-ratio is specially large in the area A owing to the effect of mountain, but the other major area shows no particularly large values in ground radioactivity. All measurements were made by the G–M counter of the end-window type with two tubes in parallel connection and worked by portable dry electric cells. It is to be remarked that the count-ratio measured at the eight other ordinary places having no geological irregularity show no abnormal value and their differences are all within the statistical fluctuation of counting.

(*d*) *Radioactive measurement at places near hot springs*

The radioactive measurements have been made at many places near hot springs of various kinds for investigating the relationship between hot springs and ground radioactivity. In practical observation, the measuring points were impartially adopted as the circumstances permitted in the area concerned, but carefully selected to avoid the disturbances caused by the influences of hot spring drainage-ditches or the neighbouring houses, structures, pavements, etc. The measurements described in the following comprise thirteen readings which were made at the hot spring areas of Misasa, Hamamura, Togo, Asozu, Kaike, Yosioka, Iwai, Yutani (all in Tottori Prefecture), Kinosaki, Yumura (in Hyogo Prefecture), Akune (in Kagoshima Prefecture), Yunoura (in Kumamamoto Prefecture) and Beppu (in Oita Prefecture). In the following the materials of observation at each place will be represented in some detail.

1. *Misasa hot spring*

The numerical results are shown in Fig. 19. The bed rock of this area is porphyritic granite and it is intruded in spots by the fine grained granite from where

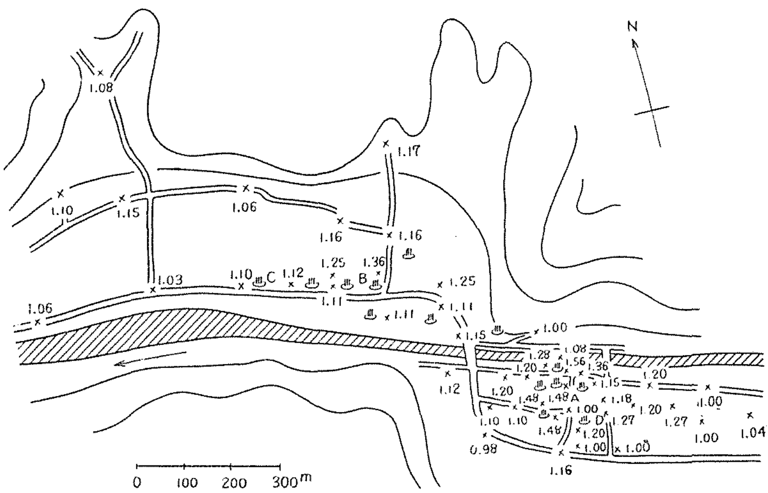

Fig. 19. Survey at the Misasa hot spring.

the hot water springs out. The hot water gushes out naturally at the small area surrounding the two points A and B in the figure, and it needs nearly 30 meters' boring at the area surrounding two points of C and D, there being no hot spring excepting these four points and their surrounding small area. On the radioactivity in the thermal water of hot springs in this area, the contents are all radon except one point in the B-area which contains thoron, and their values are about 100~200 mache in the B- and C- area, and less than 100 mache in the A- and D- area. The temperature of the thermal water is measured as in the range of 40°~80°C in this area.

2. *Togo hot spring*

The numerical results are shown in Fig. 20. This hot spring is situated close to the southern part of the small lake of Togo, and its bed rock is granite which is covered by a clay bed and gravels. The thermal water gushes out by itself through

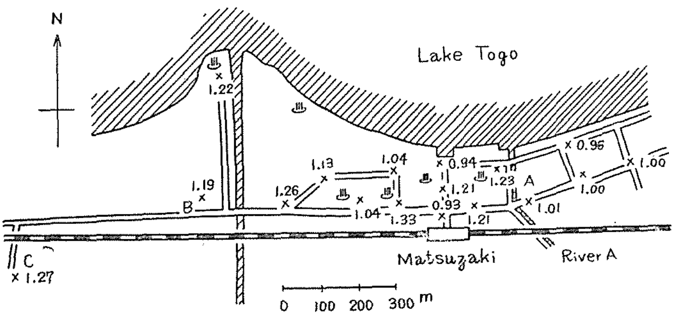

Fig. 20. Survey at the Togo hot sprng.

a boring-tube of about 30 meters. The east side of River A is said to have no hot spring source which fact is well concordant with the small value of the radioactive counts in this area. The large values of counts at the place near two points of B and C may probably be interpreted by the existence of either unexposed faults or a latent hot spring, but its truth should be assertained by future investigation. The value of the radon-content in the thermal water of this area is about 2~18 mache and its temperature is in the range of 42°~54°C.

3. *Asozu hot spring*

The numerical results are shown in Fig. 21. The hot spring is also situated close to the northern part of Lake Togo, and the ground condition is considered to be the same as that of Togo hot spring. The thermal water gushes out by itself through the

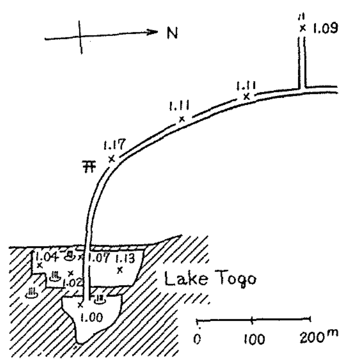

Fig. 21. Survey at the Asozu hot spring.

boring tube. In this case the radioactive counts measured do not show any large values at the point of the hot spring, and this example is the only exceptional case in the present series of observations which does not show any large value in the hot spring area.

4. *Hamamura hot spring and Kachimi hot spring*

The numerical results are shown in Fig. 22. The northern part of the area in the figure is named Hamamura and the southern part is Kachimi, both being considered to be parts of the same hot spring system. In the figure the A-hill is formed by strongly radioactive granite and this rock formation is presumed to extend to the underground in the area of B. The ground surface is an alluvium area with the alternating strata of clay beds and gravels. The temperature of the thermal water at Kachimi is generally higher than that at Hamamura, and the depths of boring are about 10 m and 30 m near the point C in the area of Kachimi and Hamamura respectively. The values of radon-content are measured as 40～60 mache in the small area of D, but in the other area nearly 3～10 mache. The temperature of thermal water is in the range of 40°～70°C, but in the small area of E it is particularly less than 30°C.

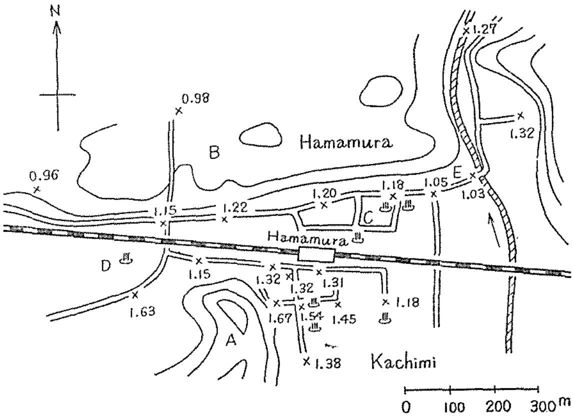

Fig. 22. Survey at the Hamamura and Kachimi hot springs.

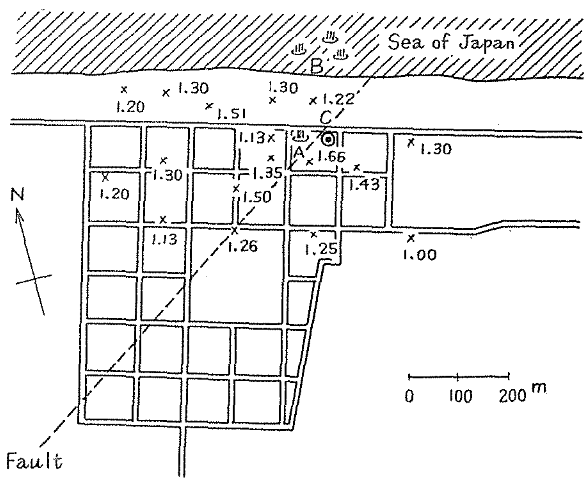

Fig. 23. Survey at the Kaike hot spring.

5. *Kaike hot spring*

The numerical results are shown in Fig. 23. The Kaike hot spring is situated close to the shore of the Japan Sea, and some old hot springs were, as seen in the figure, submerged in the sea water by the severe beach erosion, and only the hot springs at the two points of A and B are available at present. The depth of boring is about 100 m, and the temperature of the thermal water is in the range of 80° ~ 90°C, the radon-contents being very small in 0 ~ 0.5 mache. The bed rock is andesite, being covered by an alternating strata of gravels, sand stone and clay bed with a total thickness of nearly 100 m. In this area the hot water obtained at the spring sources is delivered to each hotel, and, after use, is released without control onto the neighbourihg sandy ground and allowed to be absorbed by the ground, owing to the incomplete sewerage equipment in hotels. It is to be mentioned here that the point C in the figure was recently bored shortly after our measurement and succeeded in obtaining a new hot spring originating from the vein at a depth of 180 m under the ground surface. This point had already been estimated as a promising site for a hot spring both by the analysis of an unexpected fault by the measurement of ground radioactivity with the soil-air method and by the large value of radioactive counts with a G-M counter.

6. *Yoshioka hot spring*

The numerical results are shown in Fig. 24. The rock formation is the mixture of coarse- and fine-grained biotite granite with andesite in spots, covered by the thin layer of surface soil. The hot springs in the present use in this area are all naturally gushing out over the ground surface, and their temperatures and radon-contents run between 40° ~ 50°C and 1 ~ 3 mache respectively. As seen in the figure, there are many points having no hot spring at the present time, in spite of the comparatively large value of ground radioactivity measured. The problem is now in question as to whether these large values of ground radioactivity are caused either by some crack and fissure in the bed rock, or by the latent source of hot spring, and is awaiting future investigation. Recently, the boring work of 30 m at the point A has failed to obtain a new hot spring, and this point coincides unfortunately with the area of small value of ground radioactivity.

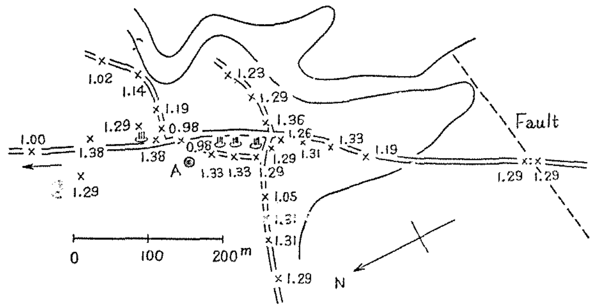

Fig. 24. Survey at the Yoshioka hot spring.

7. *Iwai hot spring*

The numerical results are shown in Fig. 25. The geological formation at Iwai hot spring is a complex of tertiary tuff, shale and sandstone with some liparite in the western area. The temperature and radon-content in the thermal water is in the range of 35° ~ 50°C and about 1 mache respectively. In the area north of the Gamo

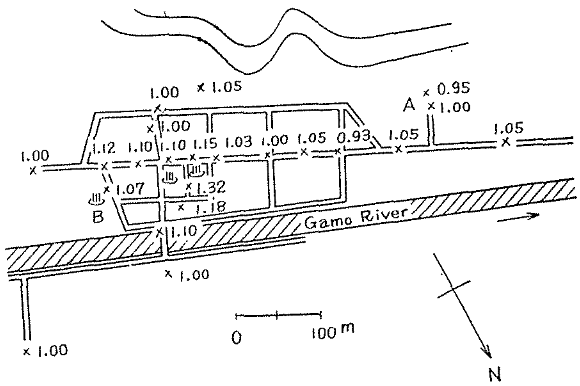

Fig. 25. Survey at the Iwai hot spring.

River and around the point A it was ascertained by boring that there was no hot spring source which finding well corresponds with the small value of ground radioactivity observed in these areas. A hot spring was obtained at the point B at a depth of 30 m.

8. *Yudani hot spring*

The numerical results are shown in Fig. 26. The Yudani hot spring is in an area of tertiary tuff, there being a natural gushing and a temperature of about 30°C. The thermal water contains NaCl and its radon-contents are 4～7 mache. The area

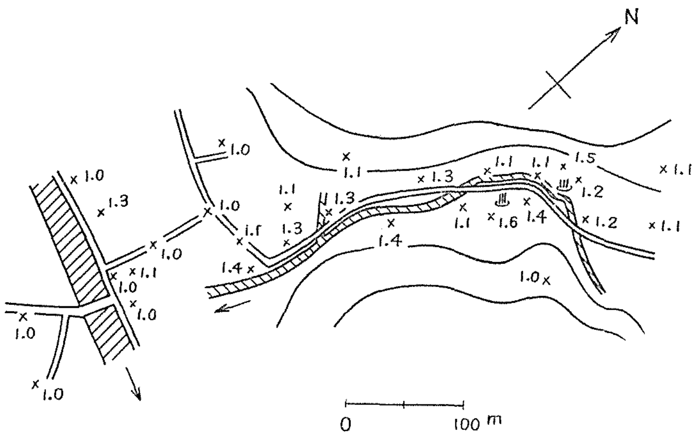

Fig. 26. Survey at the Yudani hot spring.

around the hot springs shows a large value of ground radioactivity which may presumably be explained either by an unexpected fault or by the influence of high underground temperature, but this supposition is being questioned at the present time.

9. *Kinosaki hot spring*

The numerical results are shown in Fig. 27. The geological formation in the area of Kinosaki hot spring is layered by a granitic bed, an intermediate layer of tertiary tuff with liparite-dike, and a surface alluvium layer. The temperature and radon-content in the thermal water are in the range of 50°~59°C and 1~4 mache respectively.

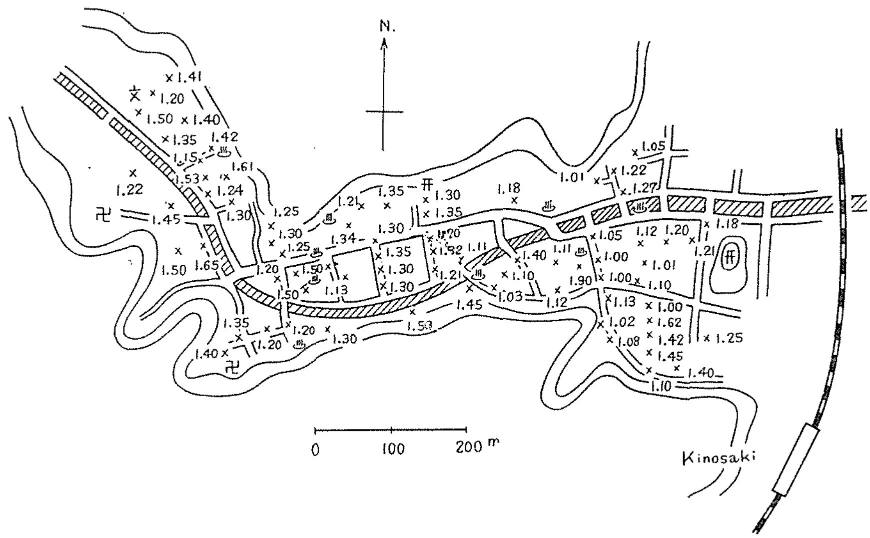

Fig. 27. Survay at the Kinosaki hot spring.

10. *Yumura hot spring*

The numerical results are shown in Fig. 28. The Yumura hot spring is situated on a layer of tertiary tuff, and in the area of the river-side. The hot water of 94°~97°C gushes out naturally, but the radon-content in the thermal water in the area of Yumura is generally small, being less than 0.5 mache.

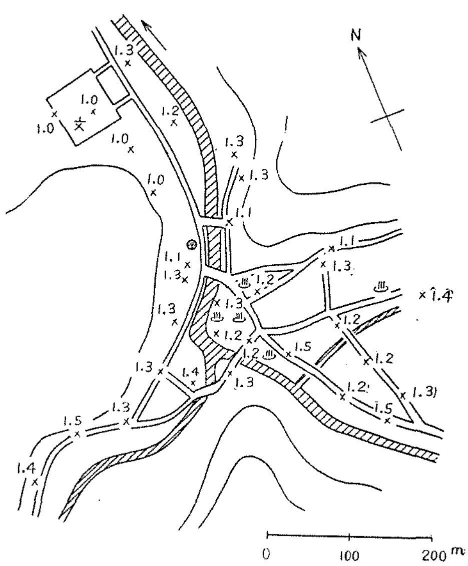

Fig. 28. Survey at the Yumura hot spring.

11. *Akune hot spring*

The numerical results are shown in Fig. 29. The Akune hot spring is situated close to the sea shore on an alluvium plain, and the spring contains salts, the neighbouring salt-farm being

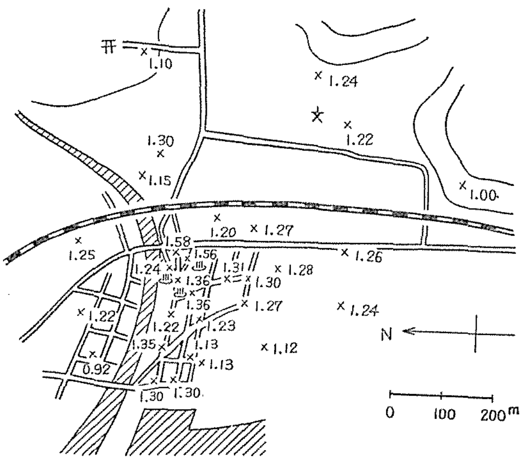

Fig. 29. Survey at the Akune hot spring.

managed by collecting the saline constituent in the underground water. The springs are all made by the 25～30 m's boring, the temperature and radon contents of their thermal water being about 43°C and 5～12 mache (**18**) respectively.

12. *Yunoura hot spring*

The numerical results are shown Fig. 30. In this area the hot water is considered to be gushing out through vein of andesite. In the period of measurement the point A was in the operation of boring, but it is said that the operation of boring was recently suspended for the reason that the temperature of water obtained by the 50-m's boring was less than 25°C. And this fact is fairly concordant with the small value of ground radioactivity, at this very point. On the other hand, the hot springs at a distance of 20 m west from the point A are

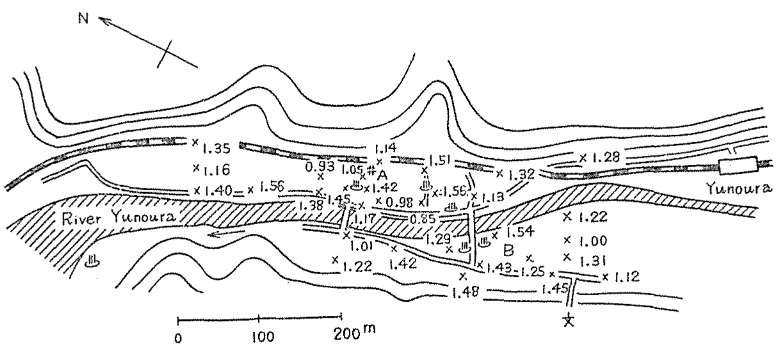

Fig. 30. Survey at the Yunoura hot spring.

gushing out thermal water of 43°C originating from a source 30 m below the ground surface, and the ground radioactivity at this point shows, as seen in the figure, a very large value compared with its surrounding area. And also with regard to the point B the above-described relation is fairly assertained.

13. *Beppu hot spring*

The numerical results are shown in Fig. 31. In the area of the Beppu spring various investigations on the nature of hot spring have been made by the research members of the Beppu Balneological Laboratory attached to Kyoto University. In the figure the distribution of hot spring temperatures measured by T. Nomitsu and K. Yamashita (**19**), and K. Yamashita (**20**) is represented for comparison with the distribution of ground radioactivity measurements with the G–M counter, and the existence of an intimate correlation between them was also ascertained in this case. In the figure all the roads and hot springs in Beppu City are not represented to avoid complication, but generaly speaking, there are found many hot springs in the area of high ground temperature. Namely, the small area between Beppu Port and the west from the Beppu Railroad Station is the area most crowded with hot springs,

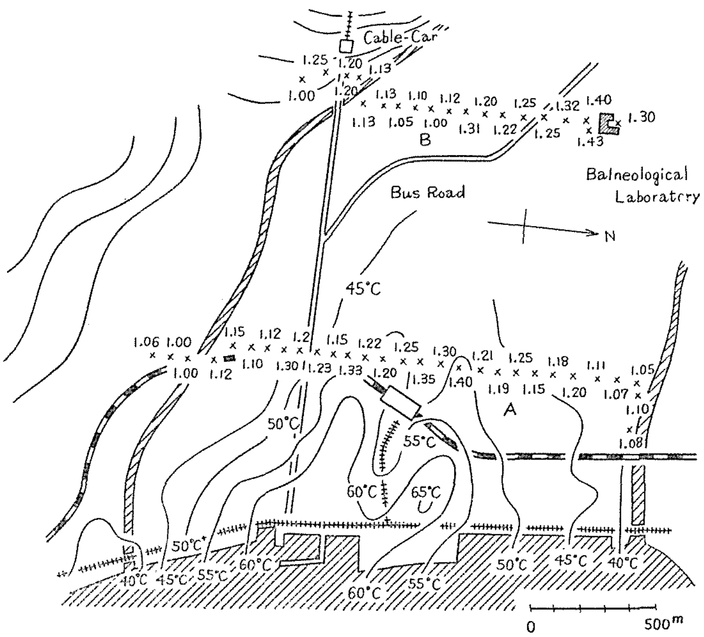

Fig. 31. Survey at the Beppu hot spring.

and, in addition, there are areas of hot springs at the far distant part south from the Port, at the small part around the cable-car station in the west end of the City. It is to be remarked that the small area around the Balneological Laboratory shows a large value of ground radioactivity, and it is said that the hot spring is not yet obtained because of low level of ground water inspite of the existence of hot spring source underneath the ground around the Laboratory. In the area of Beppu the hot spring thermal water contains few radon of 0∼1 mache, and the bed rock under the area is basalt.

(*e*) *Concluding remarks on the results of measurement*

The above-described measurements of ground radioactivity in some areas of hot spring were carefully made during the daytime between 9 am and 5 pm avoiding the rainy day and its following day. In a general review of the present measurements the following characteristics will be noticed:

1. In a hot spring area the ground radioactivity at the very site of the spring is much larger compared with that at a remote place.
2. The above-described relation between hot spring and ground radioactivity holds well in all cases of either radioactive or non-radioactive hot springs.
3. The hot water of non-radioactive springs is considered to be generally derived from the underground layer of bed rock, and really an area far remote from the spring site shows sometimes a comparatively large value of ground radioactivity in such cases as where the hot water concerned is supposed to flow along the common underground bed rock of two sites of the spring and the remote ordinary place. From these facts it is reasonably concluded that the ground radioactivity is greatly influenced by the underground temperature in addition to the existence of faults and veins or fissures.
4. Along the supposed stream of underground water, the ground radioactivity in the area of a hot spring on the upper course of the underground water-stream is generally stronger than that in the area on the lower course.
5. In the course of or after the measurement of ground activity in the areas of hot springs, there were reported the four examples (Kaike, Katsutani, Kinosaki, Misasa) of success in obtaining new hot springs bored at the areas of strong ground radioactivity, and other four examples (Yoshioka, Misasa, Yunoura, Tottori) of failure in obtaining new spring bored at the areas of weak ground radioactivity.

4. Theoretical consideration on the results of measurement

(*a*) *On the density of soil-radon*

In the preceding section the fact was found that the ground radioactivity of the area near a hot spring is much stronger compared with that of a more remote area, and this relation holds for any radioactive or non-radioactive hot spring. For the purpose of explaining this phenomenon, the underground distribution of radon-density, taking the underground temperature into consideration, will theoretically be treated below.

It was formerly ascertained by E. Buckingham (**21**), J. Koenigsberger (**22**), and Z. Hatsuda (**14**) that the motion of gas molecules in the underground layer may be treated in approximately the same manner as those in the free air under the circumstance that the air gaps between the soil particles are larger than the mean free path of gas molecule. And, moreover, it was proved by E. McDermott (**23**) that the underground gas even in shale can reach the ground surface through a small underground fissure, and G. Aeckerlein (**24**) formerly reported that the radon does the main upward diffusion in the underground. From these results of study the density of soil-radon will theoretically be treated as follows.

It is assumed that the underground soil or rock contains uniform amounts of radium, and that radon is derived from these radioactive sources. The amount of radon contained in a unit volume of any underground point is the sum of the newly derived radon at the very point and the diffused radon from the underlying layer, and its certain amount is dissolved in the underground water, its amount being determined according to the partition influenced by the temperature at that point. The dissolved radon decays at that point and does not ascend because of its small diffusion coefficient, and consequently the amount of radon decayed is supplied from the radon source in gas. And it is also assumed that the porosity of the underground layer and the water-content among the sand particles are everywhere uniform. Denoting the amount of radon radiated from a unit volume of soil and contained in the underground gap, the water-content in the underground gap, the density of radon in the underground gap, and the density of radon in the underground water, by Q, k, ρ, and ρ' respectively, the ratio of ρ' to ρ becomes

$$\frac{\rho'}{\rho}=f(T),$$

where $f(T)$ is a certain function of partition rate with the underground temperature T as a parameter. And the above relation will be represented graphically as in Fig. 32. In a first approximation the relation between ρ'/ρ and underground temperature is roughly formulated in the range of temperature of 20°∼50°C as

$$f(T)\cong g-lx\,,$$

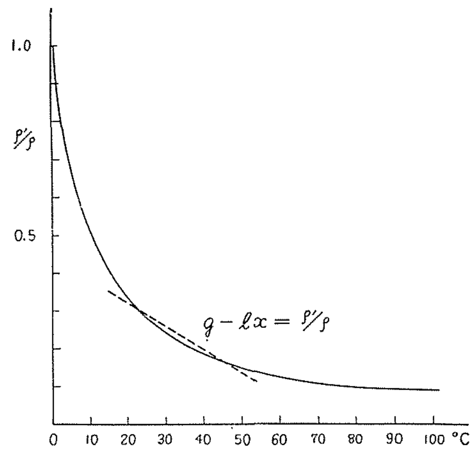

Fig. 32. Relation between ρ'/ρ and the ground temperature.

where g, l are some constants proper to the area concerned, and x is the depth of the point in question from the ground surface, the temperature being assumed to be linearly proportional to x in this case. We thus have

$$\rho'=(g-lx)\,\rho\,,$$

and consequently the radon-content dissolved in the underground water is calculated as

$$k(g-lx)\,\rho\,. \qquad (1)$$

In case when the underground porosity (n) is taken into consideration, the above radon-content in the water becomes

$$nk(g-lx)\,\rho\,. \tag{2}$$

Under the circumstances that the amount of decay in the radon-content expressed by (2) is supplied from the Q in the gap and moreover the radon-content dissolved in the water makes little contribution to the radon of upward diffusion according to its small diffusion coefficient, the amount of radon radiated in the gap will be calculated as

$$Q-\lambda nk\rho(g-lx)\,, \tag{3}$$

where λ ($=2.1\times10^{-6}$ sec^{-1}) is the decay constant of radon. Considering these relations and denoting the diffusion coefficient by D, the general equation of diffusion of underground radon becomes

$$n\frac{\partial\rho}{\partial t}=nD\frac{\partial^2\rho}{\partial x^2}-n\lambda\rho(1-k)+Q-\lambda nk(g-lx)\,\rho\,.$$

In the present treatment on the stationary state of underground radon, $\partial\rho/\partial t$ can be put equal to zero and consequently the differential equation for the density distribution of underground radon may be expressed as follows:

$$\frac{\partial^2\rho}{\partial x^2}-\frac{\lambda\rho}{D}(1-k+kg-klx)=-\frac{Q}{Dn}\,. \tag{4}$$

From the kinetic theory of gas, D is expressed by the formula, $D=T^{\frac{1}{2}}/\gamma\times$const. And the ratio of the diffusion coefficient at 50°C unit with that at 20°C is expressed as $D_{50^\circ}/D_{20^\circ}=\sqrt{323}\,\gamma_{20^\circ}/\sqrt{293}\,\gamma_{50^\circ}=1.05\times\gamma_{20^\circ}/\gamma_{50^\circ}$. In a first approximation, by putting $\gamma_{20^\circ}\cong\gamma_{50^\circ}$, $D_{50^\circ}/D_{20^\circ}\cong1$, and consequently, in a rough calculation, D is treated as a constant in any state of temperature. From the table in G. V. Heavesy and F. A. Paneth's Manual (**25**), D is estimated nearly as 0.07 cm^2 sec^{-1} at the condition of 760 mm Hg at room temperature, and in this case the eddy diffusion may reasonably be neglected. Then, denoting the quantities in Eq. (4) abridgedly as $kl=a$, $\lambda(kg+1-k)/D=m^2$, $Q/Dn=\sigma$, Eq. (4) becomes

$$\frac{\partial^2\rho}{\partial x^2}-\left(m^2-\frac{\lambda a}{D}x\right)\rho=-\sigma\,. \tag{5}$$

In a practical case, taking k as 0.3 and calculating l_{50° by dividing the difference of ρ'/ρ between the value at the underground temperature of 50°C at 40 m–depth and the surface ground temperature of 18°C, with x ($=40$ m), in Fig. 32, we get

$$l_{50^\circ}=0.2/4000=5\times10^{-5}\,.$$

Similarly, by calculating l_{20° in the case of an underground temperature of 20°C at 40 m–depth and a surface ground temperature of 18°C, we get

$$l_{20^\circ}=0.03/4000=7\times10^{-6}\,.$$

From the above calculation, as $kl_{50^\circ}=a_{50^\circ}=1.5\times10^{-5}$, $\lambda a_{50^\circ}/D=4.5\times10^{-10}\ll1$ and the quantity of $\lambda a/D$ with regard to 50°C and 20°C is estimated as more and more smaller values, the term of $\left(\frac{\lambda a}{D}x\right)$ is small compared with the term of m^2 in Eq. (5). Consequently, Eq. (5) is approximately treated as in the following expression in the method of solution by perturbation:

$$\frac{\partial^2\rho}{\partial x^2}-m^2\rho=-\sigma. \tag{6}$$

The general solution of (6) is

$$\begin{aligned}\rho_0&=\left(A-\frac{\sigma}{2m^2}\right)e^{mx}+\left(B-\frac{\sigma}{2m^2}\right)e^{-mx}+\frac{\sigma}{m^2}\\&=A'e^{mx}+B'e^{-mx}+C,\end{aligned}$$

where A and B are the integration constants respectively. Then assuming the solution of (5) in the form:

$$\rho=\rho_0+\varepsilon(x),$$

and taking the relation of $\rho_0-m^2\rho_0+\rho=0$ and $\lambda ax\varepsilon/D=4.5\times10^{-10}\times x\varepsilon\ll1$ into consideration, the following relation will be obtained:

$$\frac{d^2\varepsilon}{dx^2}-m^2\varepsilon=-\frac{\lambda\rho_0 a}{D}x. \tag{7}$$

The general solution of (7) is

$$\begin{aligned}\varepsilon=&\left(A''+\frac{\lambda a}{2m}\left[\frac{A'}{2m}x-\frac{A'}{4m^2}-\frac{C}{m^2}-\frac{B'}{4m^2}-\frac{A'x^2}{2}\right]\right)e^{mx}\\&+\left(B''+\frac{\lambda a}{2m}\left[\frac{B'}{2m}x+\frac{B'}{4m^2}+\frac{C}{m^2}+\frac{A'}{4m^2}+\frac{B'x^2}{2}\right]\right)e^{-mx}\\&+\frac{\lambda a\sigma}{m^4}x,\end{aligned}\tag{8}$$

where A'' and B'' are the integration constants respectively.

In the present estimation the following relations are tentatively adopted as the boundary condition:

$$\rho_0=\varepsilon=0 \qquad \text{at} \qquad x=0, \tag{9}$$

$$\rho_0'=\varepsilon'=0 \qquad \text{at} \qquad x=h. \tag{10}$$

Namely, the relation of (9) is the boundary condition at the ground surface, and it holds in approximation as the account in the free air is in the ratio of $1:10^4\sim10^5$ with that in the underground. And the relation of (10) rightly holds in case of the existence of impervious rock layer for any gases at the depth of h from the ground surface. In practical cases the relation of (10) contains some difficulties, but in the present rough estimation of radon-density in the underground it is tentatively used as a convenience for calculation. It is to be remarked that relation of (10) is approximately fitting for cases where the underground layer at the h depth is saturated with underground water. By applying the boundary conditions of (9) and (10) to the value of ρ_0 and ε, and calculating in numerical values with some omissions,

$$\rho_0 \cong \frac{\sigma}{m^2}(1-e^{-mx}), \tag{11}$$

$$\varepsilon \cong \frac{1}{D}\left(\frac{\lambda a\sigma}{m^4}x - \frac{\lambda a\sigma}{4m^3}x^2 e^{-mx}\right). \tag{12}$$

From the complete expression of $\rho=\rho_0+\varepsilon$, we have

$$\begin{aligned}\rho &= \frac{\sigma}{m^2}(1-e^{-mx}) + \frac{\lambda a\sigma}{Dm^4}x - \frac{\lambda a\sigma}{4Dm^3}x^2 e^{-mx}\\ &= \frac{Q}{Dnm^2}\left[(1-e^{-mx}) + \frac{\lambda a}{Dm^2}x - \frac{\lambda a}{4Dm}x^2 e^{-mx}\right].\end{aligned} \tag{13}$$

Applying the numerical values to the quantities in (13), and putting the numerical values of m as nearly 5×10^{-3},

$$\rho = \frac{Q}{Dnm^2}\left[(1-e^{-mx}) + 1.8\times10^{-5}x - 2\times10^{-7}x^2 e^{-mx}\right]. \tag{14}$$

For the purpose of examining the correctness of expression (13), the values of ρ at the depth of 0.5 m, 1.0 m, and 2.0 m below the ground surface are calculated in case of the underground temperatures of 20°C and 50°C at a place of 40 m depth, by applying the numerical values of practical use to the quantities in the expression (14). Namely, in this case, the density of the soil and the mass of radium in the soil of 1 cc. are assumed to be 2.0 and 5×10^{-12} g. cc^{-1} respectively. The amount of radon radiated from the radium in 1cc-soil is estimated to be nearly 6.9×10^{-23} g. cc^{-1} sec^{-1}. And from the calculation by I. Iwasaki (**28**), the amount of radon derived from a radium deposit exposed to air or to the coexistence of air and water is reduced to the amount in 8% of the total value of radon radiated. Taking the porosity as ($n=$) 0.4, the value of Q above defined is calculated as $Q=9.2\times10^{-19}$ c cc^{-1} sec^{-1}.

From these, we have, when the underground temperature is 20°C at a 40m-depth,

$$\rho_{50\,\mathrm{cm}} = 0.28\times10^{-12}\ \mathrm{c\ cc^{-1}}, \qquad \rho_{100\,\mathrm{cm}} = 0.52\times10^{-12}\ \mathrm{c\ cc^{-1}},$$
$$\rho_{200\,\mathrm{cm}} = 0.82\times10^{-12}\ \mathrm{c\ cc^{-1}};$$

and when the underground temperature is 50°C at a 40m-depth,

$$\rho_{50\,\mathrm{cm}} = 0.28\times10^{-12}\ \mathrm{c\ cc^{-1}}, \qquad \rho_{100\,\mathrm{cm}} = 0.52\times10^{-12}\ \mathrm{c\ cc^{-1}},$$
$$\rho_{200\,\mathrm{cm}} = 0.82\times10^{-12}\ \mathrm{c\ cc^{-1}},$$

where $\rho_{50\,\mathrm{cm}}$, $\rho_{100\,\mathrm{cm}}$ and $\rho_{200\,\mathrm{cm}}$ are the underground radon-densities calculated at the depth of 50 cm, 100 cm, and 200 cm respectively below the ground surface. These values are in good agreement, in the general aspect. with those observed by Z. Hatsuda (**26**) at the depth of 0.6 m, 1.0 m and 2.0 m below the ground surface in the yard of the Kyoto Sectional Meteorological Observatory, and those observed by E. M. Kovach (**27**) at the depth of 0.25 m, 0.75 m, and 2.0 m in the yard of Fordham University in New York. The value measured by Hatsuda at the depth of 2.0 m is practically 1.8×10^{-12} c cc^{-1} sec^{-1}., but the difference between the observed and calculated values in such an order of magnitude is easily eliminated by a little adjustment of the numerical values above used in calculation. In such a manner the underground radon-density at various depths are represented in Fig. 33 by a comparison of the calculated values with the observed values, and from the good agreement of both the calculated and observed values in a general aspect of underground radon distribution the correctness of expression (13) is considered to be proved to a certain degree.

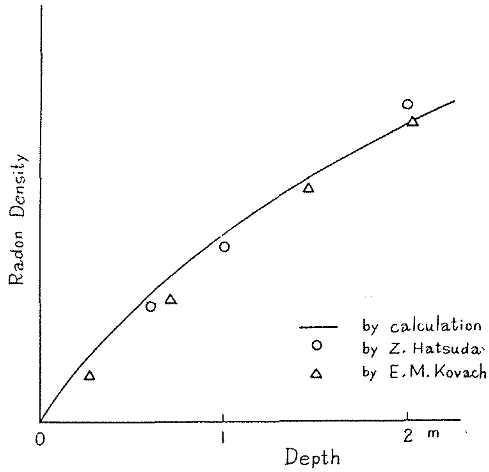

Fig. 33. Relation between the radon-density and the depth.

Concerning the components contributing to the ground radioactivity measured, are presumed the contributions by cosmic rays, the radiation from the radioactive substances in the atmosphere, radium, thorium and other elements in the soil, and the decay products of radon and thoron in the soil. But, in the present case in treatment on the problem of difference of ground radioactivity possibly by the difference of ground temperature, only the decay products of radon may effectively be disscussed, the others being reasonably excluded from the reason of their long life-time and other factors.

On the other hand, the value expressed in (13) is the radon-density in the gap of the soil, but the decay products in the underground water also contribute to the ground radioactivity and this should be calculated for a discussion on the difference of ground radioactivity due to the difference of underground temperature. Denoting the partition rate of radon to the underground water by S, S being assumed to be a function of x, the total ground radioactivity (I) originated from the underground radon is expressed as

$$I=\int_0^\infty \rho(1+S)\, Z e^{-\mu x} dx\,, \tag{15}$$

where μ is the absorption coefficient of radioactive rays, which shows practically different values with respect to the kind of rays, but in this case it is simply assumed as a constant, and Z is the rate of radioactive intensity being measured on the ground surface and originating from the β- and γ-rays radiated by the decay products of underground radon. But, since the radioactivity originated from the decay products of radon which is more deeply seated than 50 cm, cannot reach to the counter on the ground surface, it becomes

$$\int_0^\infty \rho Z\, e^{-\mu x} dx \cong \int_0^{50} \rho Z\, e^{-\mu x} dx\,.$$

Now, S can be assumed to be a constant, as far as the above-mentioned case concerns, from the reason that the temperature on the ground surface (about 50 cm depth) is everywhere the same, and consequently

$$I=\int_0^\infty \rho(1+S)\, Z\, e^{-\mu x} dx \cong \int_0^{50} \rho(1+S)\, Z\, e^{-\mu x} dx\,.$$

Introducing the expression (13) into the above expression, we get

$$I \cong Z(1+S)\,\frac{Q}{Dnm}\left[\frac{1}{\mu^2}+\frac{\lambda a}{Dm^3}\left(\frac{1}{\mu^2}\right)-\frac{\lambda a}{4Dm^2}\left(\frac{2}{(m+\mu)^3}\right)\right]. \tag{16}$$

In this case, assuming the value of μ roughly as 1.0, μ being measured as in the range value in 0.12～2.30 for the γ-rays of RaB～RaD in aluminum-absorption, and calculating I on the ground surface under the condition of ground temperatures of 50°C and 20°C at the 40m-depth respectively, we have

$$I_{50^\circ}=Z(1+S)\,\frac{Q}{Dnm}\,(1+3.6\times10^{-3}-4\times10^{-6})\,, \tag{17}$$

$$I_{20^\circ}=Z(1+S)\,\frac{Q}{Dnm}\,(1+5\times10^{-4}-5\times10^{-7})\,. \tag{18}$$

The values of I derived from both the expressions of (17) and (18) are considered to be nearly the same, and moreover the ground radioactivity measured at the ground surface contains various other kinds of radioactive rays besides the above calculated I. From these reasons, it is provisionally concluded that the observed fact that the relation exists between the strong ground radioactivity and the high underground temperature is not explained by a difference of ground radioactive intensity influenced only by the difference of underground temperature under such a process of reasoning as above treated. But the above calculated values are obtained from the omission and rough estimation of many quantities in the equations concerned, and, in case of the estimation of other values for D, for example, the difference between I_{50° and I_{20° may become a fairly large value deserving of discussion. Taking the small value of 0.00007 cm^2 sec^{-1} as the D of diffusion coefficient of underground radon (the diffusion coefficient of radon in water at 18°C is 0.00001 cm^2 sec^{-1}) the values of I become

$$I_{50^\circ}=Z(1+S)\,\frac{Q}{Dnm}\,(1+3.6-4\times10^{-3})\ ,$$

$$I_{20^\circ}=Z(1+S)\,\frac{Q}{Dnm}\,(1+0.5-6\times10^{-4})\ ,$$

and these values of I seem to be in good agreement with the above considerations. From these reasonings the above-described explanation of strong ground radioactivity by the influence of high underground temperature or the application of the expression (16) to the problem will reasonably be reserved for a future development in the study of ground radioactivity in hot spring areas.

(*b*) *On other causes*

As other causes of the phenomena of strong ground radioactivity at places of high ground temperatures in hot spring areas, the following three are considered to be worth mentioning.

(i) Radon emanating from mobile underground water at places of high underground temperatures

In considering the systems of mobile underground water in hot spring areas, the ground radioactivity in hot spring sites in the upper course of a stream of mobile underground water is generally larger than that in the lower course. This tendency was observed in the hot spring areas at Misasa, Hamamura, Kinosaki, Akune, Yunoura and others as shown in the respective figures. This is interpreted as being a process where the quantity of radon dissolved in the underground water at a place of low underground temperature is nearly 30% of the total radon-content at that point, and that at higt temperature zone this is reduced to nearly 10% of the total radon-content according to the change of partition rate, as 20% of the total radon-content emanates from the underground water in the movement of underground water containing radon from the low to the high temperature zones of underground layer. And the value of ground radioactivity is again reduced to the normal value in the movement of the underground water from the upper course of high underground temperature to the lower course of low underground temperature by the consumption of radon to supply the lack of dissolved radon in the underground water. As these emanations of radon contained in the underground water in the high temperature zone gradually take place in the course of underground water movement, they are only considered to contribute partly to the large ground radioactivity in the hot spring area, and we do not presume them to be the most influential causes. It is to be remarked that the ground radioactivity measured at the ground surface may, under favourable circumstances, become an object of research in the observation of mobile underground water and the distribution of underground temperatures along the stream.

(ii) The difference of emanation rate of radon from the rock or soil according to the difference of temperature

The fact was reported by I. Iwasaki (28) that the higher the temperature, the stronger the radon emanation from the rock or soil containing radium. And, in the preceding section, the place at $x=h$ was layered by impervious bed rock, but, instead of bed rock, a place filled with underground water could also be assumed. In such a case, the radon in the hot underground water rises easily up to the ground surface in the form of bubbles compared with that in the cold underground water. Consequently, the combined effects of the increase of radon emanation from the rock or soil at the place of high underground temperature and the increase of mobility of radon ascending through the underground layer up to the ground surface, also influenced by the high underground temperature, are provisionally expected to explain the relation between the strong ground radioactivity at a hot spring site.

(iii) Precipitation of radium along the stream of thermal water of hot springs

As hot water dissolves a larger amount of radium compared with cold water, the hot water dissolves the large amount of radium contained in the rock in the deep and hot underground layer along its stream course, and precipitates the dissolved radium at the ground surface of comparative low temperature, mixed by the cold underground water. By this reasoning, the strong ground radioactivity at the hot spring site is partly explained.

In concluding this section, an explanation of the relation between the strong ground radioactivity and the hot spring site, compared with other points in the same area was considered. The intimate correlation between the strong ground radioactivity and the point of high underground temperature found in the present observation seems especially to offer a solution to this problem. On this point the intensity of ground radioactivity to be observed on the ground surface was theoretically calculated from the solution of the diffusion equation of radon in the underground layer in both cases of high and low underground temperatures. The numerical results thus obtained were not successful in explaining the above-described relation, but its conclusion may properly be postponed for future investigation, when the quantities roughly estimated in the present treatment are more accurately measured and rightly applied to the calculation. Three other probable causes of the relation between hot spring sites and strong ground radioactivity were also discussed. Of these, the most promising assumption was supposed to be the strong emanation of radon from the rock or soil containing radium under high temperature conditions, having the increased effect of easy upward liberation of radon through the underground layer to the ground surfaces. Concerning these problems, model experiments using radioactive isotopes will eagerly be recommended and urgently be commenced in a succeeding research.

5. On the depth of the radon supply-source

The problems on the process of absorption of radon by the thermal water of hot springs and on the depth of the radon supply-source have been studied by many researchers such as K. Kuroda (**29**), I. Yokoyama (**30**) and recently by K. Kikkawa (**31**). In the present investigation a model on the process of radon-absorption by the hot underground water was tentatively proposed to fit the observed facts, as in (c) of § 2. Judging from the observed data, that the age of radon measured in the thermal water on the ground surface is estimated to be 20~170 minutes after the absorption by the thermal water ass hown in Figs. 5~8, the supply-source of radon, which is measured in the thermal water on the ground surface and problematically treated in the present investigation, was reasonably presumed to lie in a comparatively shallow underground layer.

The assumed shallow origin of radon-supply is ascertained by the other observed results, that the values of the ratio of ground radioactivity at the hot spring site to that of a place remote from the hot spring in the same area are nearly equal to each other in any case of radioactive or non-radioactive hot springs, as shown in Table 1. In the area of Misasa hot spring, for example, the absolute values of ground radioactivity are generally larger compared with those in other hot spring areas as shown in Table 2, but the said values in Misasa are nearly the same as those in other areas of non-radioactive springs. These observed data tell us that the supply-source of radioactivity lie in comparatively shallow layers and do not coincide with the deep original source of the hot spring. Should the deep origin of radioactivity coincide with the origin of hot water, the ratio between the ground radioactivity at the radioactive hot spring site and that at a remote point should show a larger value than those obtained in the practical measurements. The reason for the strong radioactivity of the thermal water in the Misasa hot spring area is believed to be that it happens to lie and gush out the hot water in an area of strong ground radioactivity, and moreover there are many holes in the underground of this area which contain enriched radium deposited by the underground water. These are ascertained by the observed data on the radon measurement of underground water in the area of Misasa by K. Sugihara (**32**) that the radon-content in the underground water shows a large value which is nearly the same as that of hot spring thermal water. From these it is reasonably concluded that the source of radon-supply generally lies in a shallow underground layer in the area of the hot spring and has no connection with the original source of the hot spring thermal water.

Table 1. The ratio of intensity of the ground radioactivity at the places near hot spring to that at the remote places from hot springs.

Name	Radon-content (mache)	Mean value at places near hot springs. (A) Figures in brackets show the number of examples.	Mean value at places remote from hot springs. (B) Figures in brackets show the number of examples.	The value of (A/B)
Misasa (north)	30–200	1.17 (9)	1.09 (9)	1.07
Misasa (south)	10–100	1.39 (8)	1.21 (16)	1.15
Togo	2–8	1.18 (9)	1.05 (7)	1.12
Asozu	1–3	1.05 (5)	1.09 (4)	0.96
Hamamura, Kachimi	3–10 (50)	1.37 (9)	1.19 (11)	1.15
Kaike	0–0.5	1.48 (2)	1.27 (14)	1.17
Yoshioka	1–3	1.32 (9)	1.19 (18)	1.11
Iwai	0–2	1.18 (8)	1.03 (15)	1.14
Yudani	4–7	1.36 (5)	1.14 (22)	1.19
Kinosaki	5–12	1.41 (13)	1.23 (19)	1.14
Yumura	0–2	1.31 (9)	1.23 (18)	1.07
Akune	5–12	1.34 (9)	1.21 (23)	1.11
Yunoura	—	1.43 (9)	1.28 (20)	1.11

Table 2. Relation between radon content and number of counts. (measured with the same counter tube)

Name	Radon-content (mache)	Number of counts near the springs. (c.p.m.)	Name	Radon-content (mache)	Number of counts near the springs. (c.p.m.)
Misasa	180	106±3	Asozu	2	70±2
	120	90±3		2	73±2
	20	88±3	Kachimi	10	72±2
	22	87±3		3	85±3
	4	88±3		48	90±3
	80	99±3	Hamamura	2	65±2
Togo	4	83±3		3	60±2
	7	71±2			
	3	64±2			

Acknowledgment

The writer is greatly indebted to the kind guidance and pertinent advice given by Prof. E. Nishimura, Prof. K. Kimura, Dr. K. Seno, Dr. M. Harada, and Mr. N.

Takeda throughout the present investigation. The cost for the study was partly covered by a grant-in-aid for Scientific Research of the Ministry of Education.

REFERENCES

1. IIMORI, Y., Sci. Pap. I. C. R., **10** (1931), 1105.
2. IWASAKI, I., J. Chem. Soc. Japan, **59** (1938), 1019.
3. KURODA, K., Bull. Chem. Soc. Japan, **19** (1944), 33.
4. KIMURA, K., Memoirs Coll. Sci. Kyoto, A, **23** (1940-41), 7.
5. KOLB, W., Diss. E. T. H. Zürich, No. 1875 (1951).
6. IWASAKI, S., Bull. Geol. Sur. Japan, **3** (1952), 59.
7. IWASAKI, I., J. Chem. Soc. Japan, **64** (1943), 662.
8. KIMURA, K., KURODA. K. and YOKOYAMA, I., J. Chem. Soc. Japan, **69** (1948), 33.
9. OKABE, S., YONEZAWA, H. and NISHIO, J., Libe. Arts J. Tottori Japan, **2** (1951), 11.
10. OKABE, S. and NISHIO, J., J. Chem. Scc. Japan, **74** (1953), 923.
11. OKABE, S., J. Appl. Phys. Japan, **22** (1954), 224.
12. OKABE, S. and NISHIO, J., Libe.Arts J. Tottori Japan, **3** (1952), 7.
13. ——————, ——————, **2** (1951), 13.
14. HATSUDA, Z., Memoirs Coll. Sci. Kyoto, B, **21** (1954), 231.
15. OCHIAI, T., Geophys. Exploration, **4** (1951), 78. (Japan)
16. SANO, S., Geophys. Exploration, **6** (1953), 21. (Japan)
17. ——————, ——————, **7** (1954), 82.
18. KAMADA, S., Sci. R. Kagoshima, **2** (1953), 101.
19. NOMITSU, T. and YAMASHITA, K., Geophysics, **2**, 233. (Kyoto Univ.)
20. YAMASHITA, K., Geophysics, **9**, 29. (Kyoto Univ.)
21. BUCKINGHAM, E., U. S. Burs. Soils. Bull., **25** (1930).
22. KOENIGSBERGER, J., Zeits. f. Geophys. **4** (1928), 76.
23. McDERMOTT, E., Bull. Am. Ass. Petrol. Geol., **24** (1940), 859.
24. AECKERLEIN, G., Phys. Zeits., **38** (1937), 362.
25. HEAVESY, G. V. and PANETH, F. A., *A Manual of Radioactivity* (1938, London), 227.
26. HATSUDA, H., Memoirs Coll. Sci. Kyoto, B, **20** (1953), 304.
27. KOVACH, E. M., Trans. Am. Geophys. Union, **26** (1945), 241.
28. IWASAKI, I., Chemical Researches, 8 (1950), 14.
29. KURODA, K., Bull. Chem. Soc. Japan, **19** (1944), 33.
30. YOKOYAMA, I., J. Chem. Soc. Japan, **70** (1949), 3999.
31. KIKKawa, K., Geophysics, **9** (I954), 117. (Kyoto Univ.)
32. SUGIHARA, K., R. Baien. Lab. Okayama, Japan, **9** (1935), 37.
33. GEOLOGICAL SURVEY, Bull. Geological Survey of Japan, **6** (1955), 10.