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# Radioactive Method for Geological Exploration

By

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**Abstract**

In this paper are described and discussed the methods and principles of radioactive prospecting the author developed including a new method devised by him and some examples of tests and practical applications in the field as well. To solve a problem of diffusion of radon, a new method of electrical analogy is also presented, which will be useful in general for locating a hidden fault.

## Introduction

Since radioactivity was discovered by Henri Becquerel in 1896, every substance has been tested for this property by many. R. J. Strutt[1] (1906) was the first to determine the radium content of various igneous and sedimentary rocks. By his investigations as well as those followed by others, it was made clear that radium is widely disseminated, though very minute in quantity, over all kinds of rocks, being richer, as a rule, in igneous rocks than in sedimentary ones, and in acid rocks than in basic ones. These differences of radium content among various rocks and minerals offer the means of radioactive method for exploring subsurface geologic structures. Some minerals have a radium content amounting to as high as a hundred thousand times that of rocks. Besides these differences, travelling of radioactive elements by transportation by other gases as well as their own diffusion also affords a means of subsurface exploration.

The origin of a radioactive method of prospecting can be dated back to as early as the beginning of this century when von dem Borne[2] (1905) tested it in a uranium mine. He came to show a very conspicuous influence of seams bearing uranium ore upon drifts which they crossed. Since then, similar investigations in bore-holes, tunnels, galleries and so on were carried out by several authors who measured radioactivity of rock samples from these places.

In 1918, Ambronn[3] found a notable increase of radioactivity of soil samples when crossing the buried faults in the vicinity of Blankenburg.

Again he perceived the same in traversing a mineral vein. These results led him to the idea that the radioactive method might be applicable in locating faults, mineral veins and boundaries of different rock types. Developments after Ambronn are as follows: In 1926, Link and Schober[4] made clear the positions and directions of tectonic lines at Eyachtal in Schwerzwald. In 1927, F. Müller[5] obtained similar results at Leuchtenburggraben in Thüringen. He also made tests at Honnef by the Sieg River on a fault and a mineral vein, having found markedly high values in radioactivity on passing these.

In his geological and geophysical surveys near the western margin of Leinetalgraben in Göttingen, V. Patriciu,[6] in 1930, got radioactive profiles along more than ten lines of measurement which strongly suggested the existence and directions of geologically plausible faults overlain by loam of two to ten meters in thickness.

Since about 1930, reports on radioactive prospecting became less in number. In fact, this method of prospecting was overwhelmed by others such as the seismic, magnetic, electric and gravimetric then progressing remarkably.

In Japan a revival of interest in the radioactive method has recently taken place. The author set about this line of study in as early as 1942 from the standpoint that the radioactive method is a very helpful means for geological explorations.

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## Theoretical considerations

Radioactive prospecting is based upon the fact that radium content is characteristic to rock type and that concentration of radioactive elements occurs controlled by geological conditions. For example, if the radium content of one rock is different from that of the adjoining one, concentration of radon contained in the air in the soil overlying the rocks differs accordingly.

From the results of measurements by F. Müller[5] on an ore-vein of lead, zinc and copper in Honnef and those by Ambronn[3] on an iron ore-vein at Ilfield in Harz, we cannot help seeing that there are some relations between radioactivity and mineral veins. This may result only from mechanical conditions such as prevailing in faults, but the present author supposes that occasionally radioactive elements are intimately connected with ore deposits which are usually considered as non-radioactive. In fact, specularite from Wang-chien-tsung-ling, Liao-yang Prefecture, Moukden Province in Manchuria was reported to be radioactive[7], and it is well known that radioactive elements are apt to associate with rare-earth elements, Kalium, Barium, Iron, Mangan and sometimes even Gold, Silver, Copper, Bismuth, Lead, Tin, etc., besides Oxygen, Hydrogen and Silicon.

From a theoretical point of view, Koenigsberger[8] reported a possibility of using radioactive investigation in potash mines for detecting the approach of drifts or borings to tectonic disturbances.

(1) Theory of radioactive method for locating faults.

Now, the reason why radioactivity becomes high near a fault has not yet been well explained. Gockel[9] pointed out that in the vicinity of faults there takes place an increase of permeability of soil due to disturbances. Ambronn[10] also stated the easier circulation of solutions and gases on geologic disturbed surfaces, whereby radioactive materials could be transported and accumulated at their outcrops. With regard to this, the experiment made by G. Aeckerlein[11] (1937) during well-boring at Annaberg in Erz Gebirge in Germany is of great interest. He measured the radon content of water and also the radium content of crushed rocks taken from the well bottom, and found that the maxima of radon always occurred at depths one or two meters shallower than points where the maxima of radium appeared at the places where the well was crossed by fissures or veins. This would imply that radon is persistently ascending through rocks towards the surface of the earth. If it proves to be the case, the crushed zone of a fault should become an easier ascending path for radon.

According to E. McDermott's experiment[12] (1940) on boring cores of shale, the permeation of hydrocarbon gas was obviously through microscopic fissures instead of through intergranular space as usually expected in sands. Through such fissures not only hydrocarbons but carbon dioxide, carbon monoxide, hydrogen, nitrogen, hydrogen sulphide and water vapour etc. escape and find their way to the earth's surface. Also radon gas will associate with them in a very dilute state. According to G. V. Hevesy,[13] the diffusion coefficient of radon for air is less than $0.07\,\mathrm{cm^2\,sec^{-1}}$ at room temperature and pressure of 760 mm Hg, which is exceedingly low as compared with diffusion coefficients of other gases for air. (cf. $H_2$-air : 0.611, $O_2$-air : 0.178, $CO_2$-air : 0.138 at 0°C, 760 mm Hg)

As the interdiffusion is inversely proportional to the pressure of the mixed gas, the diffusion of radon is slower at a great depth than near the surface of the earth, while the increasing temperature acts in a reverse sense, that is, to increase diffusion.

On the other hand, the diffusion coefficient of radon in water at 18°C is $0.99\,\mathrm{cm^2\,day^{-1}}$ (E. Rona), $0.918\,\mathrm{cm^2\,day^{-1}}$ (E. Ramstedt), and at 14°C, $0.82\,\mathrm{cm^2\,day^{-1}}$ (E. Ramstedt) which figures are about ten thousandth the order of magnitude of the diffusion coefficient in air.

The mechanism of the passage of gases through layers of a great thickness of sedimentary rocks has not yet been explained. The law govering the passage of gases through the pores as found in a sedimentary rock layer was investigated by Graham[14] (1834), who found that the volume of a gas (estimated at the standard pressure and temperature) passing through a layer of porous medium was directly proportional to the difference of the pressure of the gas on the two sides of the layer, and inversely proportional to the square root of the density and consequently the molecular weight of the gas. The atomic weight of radon (mono-atomic gas), 222, is greater than the molecular or atomic weight of the other gases usually found in the earth, hence the diffusion of radon coexisting with other gases will be so exceedingly slow that much of it will be left behind. The like phenomenon was also observed by Graham[15] (1863) in the case of effusion.

Consequently, we come to the conclusion that diffusion of radon through compact rock is practically negligible but only possible through cracks or fissures. The short life of this element would seem further to emphasize this conclusion. This is one of the reasons why radon concentrates in the neibourhood of a fault, as along it cracks and fissures prevail.

Besides gases, aqueous solutions can also ascend through the disturbed zone of a fault and will deposit mineral substances along the cracks and fissures and especially in the surface soil overlying the fault. It is very likely that uranium- or radium-salts are associated with these deposits. In consequence, concentration of radon becomes greater near faults than in other places. This reasoning will be supported by the experiments of Ambronn[16] which confirmed that radioactivity of soil taken from about 10 cm below the surface of the earth increased as a buried fault was approached.

(2) Diffusion of gases in soil.

Buckingham,[17] one of the first to apply the kinetic theory of gases to soil aeration, applied the term "diffusion constant" to designate the rate of flow of gases through the soil pore space as a result of kinetic movements. His experiments made on different soil types with varying moisture content and with a different degree of compactness, have revealed that the diffusion constant $D$ increases as proportional to the square of the porosity $S$, that is,

$$D = AS^2$$

where $A$ is a constant whose weighted mean he obtained as $2.16 \times 10^{-4}$ cgs for air and $CO_2$-gas. The value of $A$ varies proportionally with the square of the absolute temperature and inversely with the total pressure. In the above equation, if $S$ is taken to be 1, that is, the porosity be put at 100 per cent, we have $D = 2.16 \times 10^{-4}$ cgs. This value approximates a diffusion constant of $2.20 \times 10^{-4}$ cgs experimentally found by Loschmidt[18] and that of $2.13 \times 10^{-4}$ cgs determined by Obermayer[19] for the free diffusion of $CO_2$ and air. The above extrapolation seems dangerous, but the agreement would suggest that the diffusion process in soil is similar in nature to free diffusion. By this reason the diffusion of radon in soil may be treated in the same manner as in free air as described below.

By the above relations we may assume that the only factor controlling the rate of diffusion in soil is the free pore space, since the nature, texture, granulation and moisture content do not materially affect diffusion, as long as the free space remains constant. This will imply that considerable aeration may take place even in heavy clay soils if the pore spaces in them are not too minute as compared with the mean free paths of gasses.

According to Buckingham's experiment, a considerable amount of $CO_2$-gas leaves the soil by diffusion when its concentration in soil air is of the order of magnitude actually met with. Analogously, we may expect a large quantity of radon is leaving the soil into the atmosphere.

(3) Stationary state of radon content in soil air.

Suppose an elementary volume in the ground, then the timely change of amount of radon in it takes place in the following three ways: 1) Change by diffusion, $\kappa\nabla^2\rho$, where $\kappa$ is the coefficient of diffusion, $\rho$ concentration and $\nabla^2 \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$, 2) rate of increase by production of radon from radium in soil or rock, say $\alpha$, and 3) decrease by disintegration, $\lambda\rho$, $\lambda$ being the disintegration constant of radon. Therefore, the net increase of radon per unit time and in unit volume is,

$$\frac{\partial\rho}{\partial t} = \kappa\nabla^2\rho + \alpha - \lambda\rho \quad\dots\dots\dots\dots\dots(1)$$

In the stationary state we get,

$$\kappa\nabla^2\rho = \lambda\rho - \alpha \quad\dots\dots\dots\dots\dots\dots\dots(2)$$

This is the fundamental formula of the stationary distribution of the concentration of radon in soil.

The movement of radon may take place by processes other than diffusion, such as by the movement of other gases that carry radon, and also by renewal of surface soil air brought about by the change of meteorological factors. But, from what Baver[20] has pointed out for $CO_2$, the diffusion is the predominating process for the movement of radon towards the earth's surface.

(4) Linear radon source lying in underground.

Suppose an outcrop of a fault or a mineral vein which forms a linear radon source extending infinitely in a horizontal direction at the bottom of a soil layer of uniform thickness of which the bed rock is impermeable to radon gas (Fig. 1). When we know the distribution of radon concentration in soil along a line at a constant depth and perpendicular to the linear radon source, the thickness of the surface layer may be determined after the method of Koenigsberger[21] by disregarding, for simplicity's sake, the disintegration of radon. He applied the method of electric image to the solution of the stationary diffusion problem. But he seems to have committed a mistake in his deduction as will be shown later, and the present author has followed his method of image and reached a result which is different from Koenigsberger's result when higher terms are taken into consideration.

Denoting the thickness of the surface layer by h and the depth from which soil air is taken by d, the concentration of radon C at a point P may be given by the expression,

$$C = C' \ln \frac{\rho_2 \rho_3 \rho_6 \cdots}{\rho_1 \rho_4 \rho_5 \cdots} \tag{1}$$

where $C'$ is concentration of radon at the radon source A, and $\rho_1, \rho_2, \rho_3, \cdots\cdots$ are the distances of P respectively from A and its images $A'(c=-c', z=-h)$, $A''(c=-c', z=+3h)$, $A'''(c=+c', z=-3h)$, $A''''(c=+c', z=+5h)$, $A'''''(c=-c', z=-5h)$, etc.

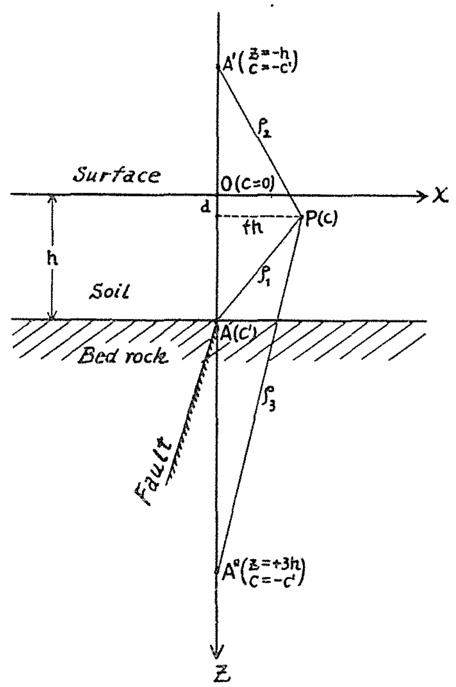


Fig. 1

Since $\rho^2_i = x^2 + (z_i - d)^2$, in which we put $x = fh$,

$$\rho^2_{2n} = f^2h^2 + \{(2n-1)h + d\}^{2*} = \{f^2 + (2n-1)^2\}h^2 + 2(2n-1)hd + d^2$$
$$= h^2\left\{f^2 + (2n-1)^2\right\}\left\{1 + \frac{2(2n-1)}{f^2+(2n-1)^2} \circ \frac{d}{h} + \frac{1}{f^2+(2n-1)^2}\left(\frac{d}{h}\right)^2\right\}.$$

Similarly,

$$\rho^2_{2n-1} = f^2h^2 + \left\{(2n-1)h - d\right\}^{2*} = \left\{f^2 + (2n-1)^2\right\}h^2 - 2(2n-1)hd + d^2$$
$$= h^2\left\{f^2 + (2n-1)^2\right\}\left\{1 - \frac{2(2n-1)}{f^2+(2n-1)^2}\cdot\frac{d}{h} - \frac{1}{f^2+(2n-1)^2}\left(\frac{d}{h}\right)^2\right\},$$

where f is any number and n a positive integer.

And hence,

$$\ln\frac{\rho^2_{2n}}{\rho^2_{2n-1}} = \ln\left\{1 + \frac{2(2n-1)}{f^2+(2n-1)^2}\cdot\frac{d}{h} + \frac{1}{f^2+(2n-1)^2}\left(\frac{d}{h}\right)^2\right\}$$
$$-\ln\left\{1 - \frac{2(2n-1)}{f^2+(2n-1)^2}\cdot\frac{d}{h} + \frac{1}{f^2+(2n-1)^2}\left(\frac{d}{h}\right)^2\right\},$$

on the right side of which the first term will be put equal to

$$\ln(1 - X) = X - \frac{X^2}{2} + \frac{X^3}{3} - \frac{X^4}{4} + \cdots\cdots,$$ and the second to

$$\ln(1 - Y) = -Y - \frac{Y^2}{2} - \frac{Y^3}{3} - \frac{Y^4}{4} - \cdots\cdots.$$

Then we have

$$\ln\frac{\rho^2_{2n}}{\rho^2_{2n-1}} = (X + Y) - \frac{1}{2}(X^2 - Y^2) + \frac{1}{3}(X^3 + Y^3) - \frac{1}{4}(X^4 - Y^4) + \cdots\cdots$$
$$= \frac{4(2n-1)}{F}\cdot\frac{d}{h} - \frac{4(2n-1)}{F^2}\left(\frac{d}{h}\right)^3 + \frac{16}{3}\cdot\frac{(2n-1)^3}{F^3}\cdot\left(\frac{d}{h}\right)^3$$
$$+ \left\{\frac{4(2n-1)}{F^3} - \frac{16(2n-1)^3}{F^4}\right\}\left(\frac{d}{h}\right)^5 - \frac{4(2n-1)}{F^4}\left(\frac{d}{h}\right)^7 + \cdots\cdots, \qquad (2)$$

where $F = f^2 + (2n-1)^2$.

Putting $n = 1, 2, 3, \cdots\cdots$, we get

$$\ln\frac{\rho^2_2\,\rho^2_3\,\rho^2_6\cdots}{\rho^2_1\,\rho^2_4\,\rho^2_5\cdots} = \frac{4d}{h}\left[\left[\left\{\frac{1}{f^2+1} - \frac{3}{f^2+3^2} + \frac{5}{f^2+5^2} - \cdots\cdots\right\} - \left(\frac{d}{h}\right)^2\left\{\frac{1}{(f^2+1)^2}\right.\right.\right.$$
$$\left. - \frac{3}{(f^2+3^2)^2} + \frac{5}{(f^2+5^2)^2} - \cdots\cdots\right\} + \frac{4}{3}\left(\frac{d}{h}\right)^2\left\{\frac{1}{(f^2+1)^3}\right.$$
$$\left. - \frac{3^3}{(f^2+3^2)^3} + \frac{5^3}{(f^2+5^2)^3} - \cdots\cdots\right\} + \left(\frac{d}{h}\right)^4\left[\left\{\frac{1}{(f^2+1)^3}\right.\right.$$
$$\left. - \frac{3}{(f^2+3^2)^3} + \frac{5}{(f^2+5^2)^3} - \cdots\cdots\right\} - 4\left\{\frac{1}{(f^2+1)^4} - \frac{3^3}{(f^2+3^2)^4}\right.$$
$$\left.\left.\left. + \frac{5^3}{(f^2+5^2)^4} - \cdots\cdots\right\}\right] + \cdots\cdots\right]\right],$$

from which follows

$$\ln\frac{\rho_2\,\rho_3\,\rho_6\cdots}{\rho_1\,\rho_4\,\rho_5\cdots} = \frac{2d}{h}\left\{S_1 - \left(\frac{d}{h}\right)^2 S_2 + \frac{4}{3}\left(\frac{d}{h}\right)^2 S_3 + \left(\frac{d}{h}\right)^4 (S_4 - 4S_5) + \cdots\cdots\right\} \qquad (3)$$

* Koenigsberger put $\rho_{2n+1} = f^2h^2 + [(2n+1)h - d]^2$ and $\rho_{2n} = f^2h^2 + [(2n+1)h + d]^2$, but the dimension is obviously unequal on both sides of these equations, and his later reductions are based upon these equations.

where

$$S_1 = \frac{1}{f^2+1} - \frac{3}{f^2+3^2} + \frac{5}{f^2+5^2} - \cdots\cdots$$

$$S_2 = \frac{1}{(f^2+1)^2} - \frac{3}{(f^2+3^2)^2} + \frac{5}{(f^2+5^2)^2} - \cdots\cdots$$

$$S_3 = \frac{1}{(f^2+1)^3} - \frac{3^3}{(f^2+3^2)^3} + \frac{5^3}{(f^2+5^2)^3} - \cdots\cdots$$

$$S_4 = \frac{1}{(f^2+1)^3} - \frac{3}{(f^2+3^2)^3} + \frac{5}{(f^2+5^2)^3} - \cdots\cdots$$

$$S_5 = \frac{1}{(f^2+1)^4} - \frac{3^3}{(f^2+3^2)^4} + \frac{5^3}{(f^2+5^2)^4} - \cdots\cdots.$$

Consequently the equation (1) becomes,

$$C = C' \frac{2d}{h}\left\{S_1 - \left(\frac{d}{h}\right)^2 S_2 + \frac{4}{3}\left(\frac{d}{h}\right)^2 S_3 + \left(\frac{d}{h}\right)^4 (S_4 - 4S_4) + \cdots\cdots\right\} \qquad (4)$$

Calculating the series given by (3) for $f=0$, 0.5, 1.0, 2.0 and 3.0, we have the figures given in Table 1.

Table 1

| S \ f | 0 | 0.5 | 1.0 | 2.0 | 3.0 |
|---|---|---|---|---|---|
| $S_1$ | 0.7854 | 0.5934 | 0.3131 | 0.0676 | 0.0144 |
| $S_2$ | 0.9690 | 0.6107 | 0.2254 | 0.0263 | 0.0037 |
| $S_3$ | 0.9689 | 0.4837 | 0.1029 | -0.0009 | 0.0017 |
| $S_4$ | 0.9962 | 0.5085 | 0.1222 | 0.0068 | 0.0006 |
| $S_5$ | 0.9962 | 0.4062 | 0.0600 | 0.0003 | -0.0001 |

If d is of the order of magnitude of 0.1h, we can see from Table 1 that the series on the right side of the equation (3) converges fairly rapidly. When the value of C for $f=0$, that is $x=0$, is taken as a standard, $C_f/C_0$ for $f=0.5$, 1.0, 2.0 and 3.0 are represented in Table 2.

Table 2 Relative values of $R_f \equiv C_f/C_0$

| d/h \ f | 0 | 0.5 | 1.0 | 2.0 | 3.0 |
|---|---|---|---|---|---|
| 1/10 | 1 | 0.753 | 0.396 | 0.085 | 0.018 |
| 2/10 | 1 | 0.747 | 0.390 | 0.084 | 0.018 |
| 3/10 | 1 | 0.743 | 0.326 | 0.079 | 0.018 |

If h is very large as compared with d, the terms containing $(d/h)^2$ and higher powers may be neglected, then we get

$$C = C' \frac{2d}{h}\left(\frac{1}{f^2+1} - \frac{3}{f^2+3^2} + \frac{5}{f^2+5^2} - \cdots\cdots\right) \tag{5}$$

Just above the source, that is at $x=0$, or $f=0$, C takes the maximum value,

$$C_0 = C'\frac{2d}{h}\left(1 - \frac{1}{3} + \frac{1}{5} - \cdots\cdots\right) = C' \frac{2d}{h} \cdot \frac{\pi}{4} \tag{6}$$

Now, taking $C_0$ as a standard, the relative concentration at $x=0.5h$, 1h, 2h, 3h is respectively 0.756, 0.399, 0.086 and 0.018. In Fig. 2 is shown such relative concentration as related to the distance x, when the thickness of the overburden soil is assumed 5 m, 10 m, 15 m and 20 m.

Comparing these theoretical curves with those obtained by actual observations, the thickness of overlying soil can be estimated approximately. Making use of this method in the measurements made at Obu, Hyôgo Prefecture, the author has obtained an estimate of 5 to 7 meters as the thickness of the covering soil there.[22] In order to get a rather accurate estimate, the following process may be recommended.[23]

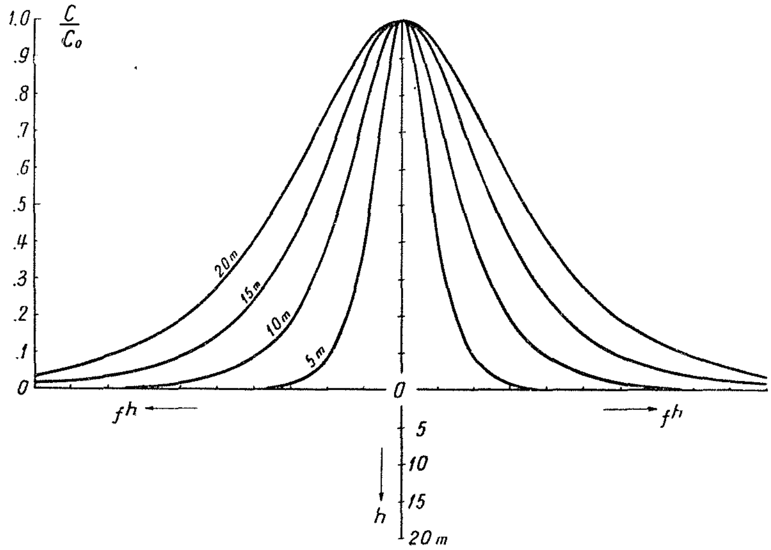


Fig. 2

Writing the parenthesized series in equation (5) by R, we get from equation (5) and (6),

$$R = \frac{\pi}{4} \cdot \frac{c}{c_0} \tag{7}$$

In Table 3 are shown the values of R expressed as a function of f and the relative values $C/C_0$ calculated by the equation (7). In Fig. 3 the function R is graphically represented.

Table 3

| f=x/h | R | C/C₀ | f=x/h | R | C/C₀ |
|---|---|---|---|---|---|
| 0.0 | 0.7354 | 1.0000 | 1.0 | 0.3130 | 0.3985 |
| 0.1 | .7758 | .9878 | 1.25 | .2163 | .2753 |
| 0.2 | .7482 | .9526 | 1.5 | .1476 | .1879 |
| 0.3 | .7057 | .8985 | 1.75 | .1001 | .1275 |
| 0.4 | .6524 | .8306 | 2.0 | .0678 | .0863 |
| 0.5 | .5930 | .7549 | 2.5 | .0310 | .0394 |
| 0.6 | .5314 | .6766 | 3.0 | .0141 | .0180 |
| 0.7 | .4708 | .5994 | 4.0 | .0029 | .0036 |
| 0.8 | .4136 | .5266 | 5.0 | .0006 | .0008 |

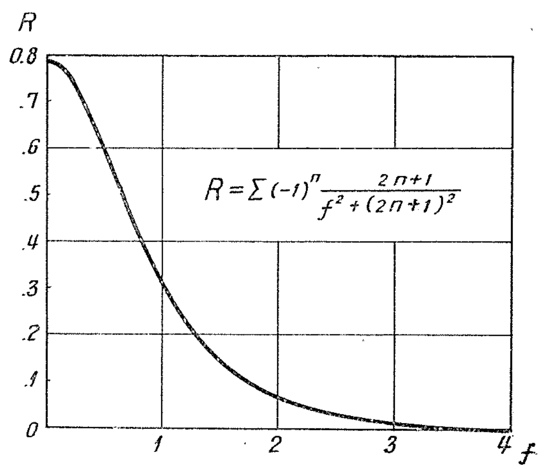


Fig. 3

Now for all stations we have the observed values of $C/C_0$, from which the values of R can be found by the aid of equation (7), and the corresponding values of f can at once be obtained by the interpolation of Table 3. As the values of x are known, we are given a set of equations $x_i=f_ih$ $(i=1, 2, 3,\cdots)$. And the value of h may be found by the method of least spuares. Thus for the actual observation in Obu, we obtained

$$h = 6.59 \pm 0.67 \text{ meters},$$

annexed error being a probable error. The observation equations for deriving this result are shown in Table 4-A.

Table 4

| A: $f_i h = x_i$ | B: $(R_i/4.4)C' = C_i$ |
|---|---|
| 1.73 h =18.2 | 0.00455 C′ = 0.47 |
| 1.53 h =13.0 | 0.01636 C′ = 0.66 |
| 1.07 h = 7.0 | 0.06477 C′ = 1.33 |
| 0.55 h = 5.0 | 0.09886 C′ = 2.69 |
| 0.00 h = 0.0 | 0.16023 C′ = 3.99 |
| 1.42 h = 3.5 | 0.13068 C′ = 0.77 |
| 1.82 h = 5.0 | 0.09886 C′ = 0.41 |
| 1.54 h =10.0 | 0.03273 C′ = 0.65 |
| 1.94 h =15.0 | 0.01000 C′ = 0.34 |

Now, let us proceed to obtain the concentration $C'$ at the source. As the mean depth of sampling is 0.75 m, we get

$$C = C' \frac{2d}{h} R = C' \frac{R}{4.4} \tag{8}$$

As the values of C and R in the above are already known, the unknown $C'$ can be found by the method of least squares. The observation equations in this case are shown in Table 4–B, and the adjusted value of $C'$ is,

$$C' = 17.2 \pm 2.4 \text{ Emans}.$$

In the following is given another method of approach for the estimation of the depth h. From equation (5) by the definition of R and $x = fh$, we obtain

$$\frac{\partial^2 C}{\partial x^2} = K \frac{\partial^2 R}{\partial f^2} \cdot \frac{1}{h^2} \tag{9}$$

where $k = C' \frac{2d}{h}$ and

$$\frac{\partial^2 R}{\partial f^2} = \sum (-1)^{n+1} \frac{6(2n-1)f^2 - 2(2n-1)^3}{[f^2 + (2n-1)^2]^3}, \quad (n = 1,2,3 \cdots) \tag{10}$$

The value of f that makes $\partial^2 R/\partial f^2$ equal to zero makes $\partial^2 C/\partial x^2$ vanish. Such value of f has been found to be 0.561 by a graphical solution shown in Fig. 4. If, on the observed curve of the distribution of C, we could find the value of x, say $\chi$, at which the curve has its inflection point, we get $\chi = 0.561$ h. Therefore the depth h can be put

$$h = \chi/0.561 = 1.78\,\chi \tag{11}$$

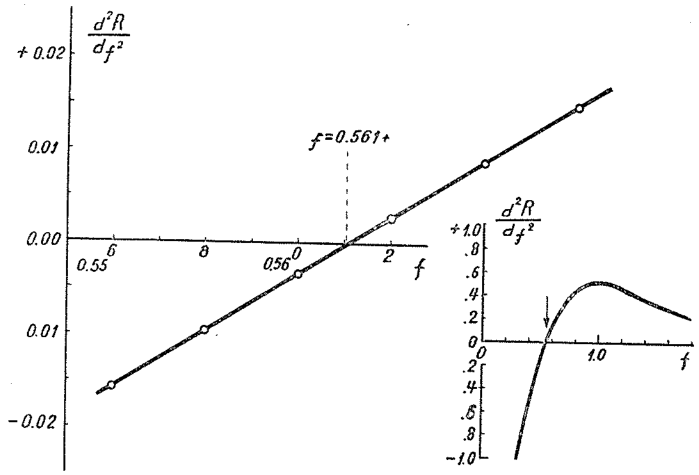


Fig. 4

## Experimental part

(1) Methods of Measurement.

The radioactive methods of exploration practised by the author are

(A) Radon-in-soil-air method,
(B) Ground-hole-ionization-chamber method,
(C) Photo-plate method, and
(D) Geiger-counter method.

In each method, radioactivity is measured at points usually arranged in a line, and the observed values are plotted against the distances along this line to obtain the "radioactive profile". By the principle described in the last chapter, the line joining the corresponding peaks in the radioactive profiles thus obtained of several traverses will nearly give the projection of the buried fault on the surface of the earth.

(A) Radon-in-soil-air method.

This method deals with the radon in soil air extracted from the ground. As the concentration of radon in soil air, especially near the surface, will be affected by the meteorological factors, it is desirable to take the soil air from a considerable depth. In practice, however, difficulties in boring will progressively increase with depth and, moreover, those in obtaining soil air will also do so owing to the increasing moisture. This method essentially consists of 1) collection of soil gas, 2) introduction of it into an ionization chamber, and 3) measurement of ionization.

(i) Collection of soil gas: For this purpose a collecting tube and collcting bottle are used. Their arrangement is shown in Fig. 5 (*A*). The collecting tube suitable for use in sandy soil is made of steel tube 120 cm in length and 22 cm in outer diameter, the lower end being closed and sharpened, provided with many holes in a slightly thinned part between 10 and 30 cm from the lower end. At the top the tube is fitted with a rubber plug through which a glass tube with stopcock is passed (Fig. 5 (*B*)). In case of clayey soil this tube is replaced with a simple one obtained from the former by cutting off the lower part of 40 cm (Fig. 5(*C*)). This tube is inserted in a hole previously made with a boring stick to a 1 meter depth from the surface. The collecting bottle made of brass and of spindle shape is about 900 cc in volume. With the arrangements shown in the figure, the soil air is sucked up into the collecting bottle through the upper cock by the negative pressure produced in it as the water in the bottle flows out from the lower nozzle. After the collection is over, the bottle is brought to the station, preferably chosen inside a house or a tent. If precise measurement is not required, the measurement may be done on the spot in the open field. Prior to the collection of soil air, a volume of air (ca. 200 cc) occupying the interior space of the collecting tube is drawn out and rejected by means of an auxiliary bottle (Fig. 5 (*D*)).

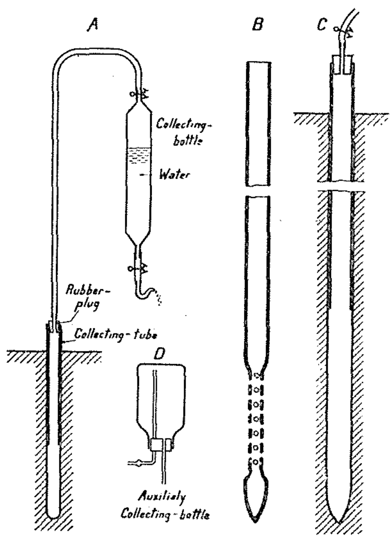


Fig. 5

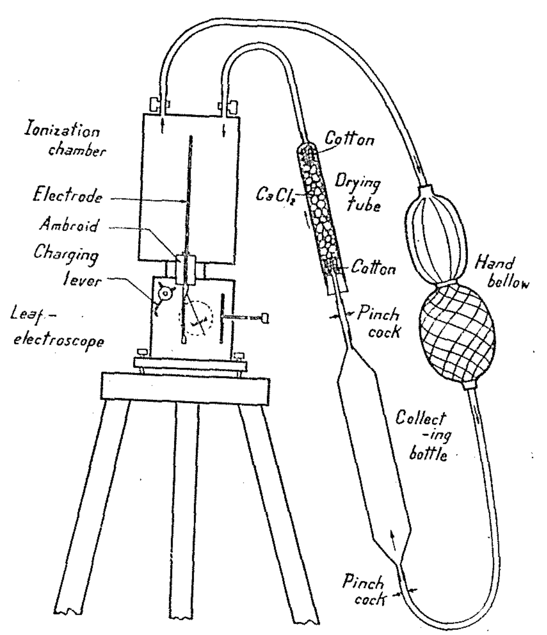


Fig. 6

(ii) Introduction of radon into the ionization chamber: One end of the collecting bottle filled with soil air is connected to one of the two cocks of the ionization chamber through a drying tube filled with drying agent $CaCl_2$, and the other end to another cock of the ionization chamber through a rubber hand-bellow (Fig. 6). Then operating the hand-bellow for two minutes with all cocks open, the soil air is circulated through the connected system. By this operation, radon initially in the collecting bottle will eventually be uniformly distributed among ionization chamber, hand-bellow, collecting bottle and drying tube.

(iii) Measurement of ionization: For this purpose, a fontactoscope of Schmidt-type improved * in several respects by the author was used. As soon as radon enters the ionization chamber, it begins to disintegrate following the sequence Rn⟶RaA⟶RaB⟶RaC⟶etc. The air in the ionization chamber is ionized by radioactive rays (mainly alpha-rays) which are emitted during disintegration. The ionization is measured with an electroscope attached to the ionization chamber as a rate of fall of metal leaf across the scale in the reading microscope. Fifteen minutes after the introduction of radon into the fontactoscope, readings are taken every minute for fifteen minutes.

(iv) Calculation: As the ionization due to radon with its disintegration products increases with time, the observed activity should be reduced to the initial activity, that is, the activity due to the introduced radon alone. The activity may be expressed in terms of scale divisions per minute. From the activity thus determined must be subtracted the natural leak found just before the determination. For the reduction to the initial activity, the conversion factor given by S. Iimori[24] is used. If $f_\theta$ be the conversion factor, $I_0$ the initial activity and $I_\theta$ the observed at $t = \theta$ minus the natural leak, then

$$I_0 = f_\theta I_\theta.$$

Usually fifteen values of $I_0$ are calculated from the observed $I_\theta$ and they are averaged. The amount of radon disintegrated during transportation is taken into consideration by the relation,

$$Q_t = Q_0 e^{-\lambda t}$$

where $Q_0$ = initial quantity of radon collected, $Q_t$ = quantity of radon surviving when the circulation is commenced, $\lambda$ = disintegration constant of radon, and t = time elapsed from collection to circulation.

The fontactoscope used may be calibrated with a standard radium solution.

* Main points of improvement are as follows:

1) The electroscope is equipped with cork cover 1 cm thick in order to avoid irregular motion of the leaf caused by rapid change in temperature.

2) Surface of the insulator holding the central electrode is protected from moisture which might still exist in the ionization chamber by a protector carrying desicating agent.

3) The ionization chamber is doubled, and the inner one is replaced by a new one after each measurement. By this replacement measurements can be repeated speedily without wasting time waiting for the extinction of the effect otherwise due to possible contamination of daughter elements of radon.

However, such calibration is not always necessary when one and the same fontactoscope is used, but intercalibration is always necessary when two or more fontactoscopes are used. In the calibration by the standard solution, the activity is usually expressed as the concentration of radon at the time of sampling in terms of Eman (1 Eman = $10^{-10}$ curies per litre), and in the case of the intercalibration it is expressed as a falling rate in divisions per minute of metal leaf of the fontactoscope.

The initial concentration of radon $C_0$ in soil air is calculated by

$$C_0 = K\bar{I}_0 \frac{V_{ic}+V_c+V_b+V_d+V_t}{V_{ic}} \cdot \frac{1000}{V_c} \cdot \frac{1}{e^{-\lambda t}}$$

where K = constant of fontactoscope, i. e. quantity of radon in Curie at the instant of introduction into the ionization chamber which produces the falling rate of one division per minute, $\bar{I}_0$ = average of activity during the circulation, $V_{ic}$ = volume of ionization chamber in cc, $V_c$ = volume of collecting bottle in cc, $V_b$ = volume of hand-bellow in cc, $V_d$ = volume of pore space in drying tube in cc, and $V_t$ = volume of tubings in cc.

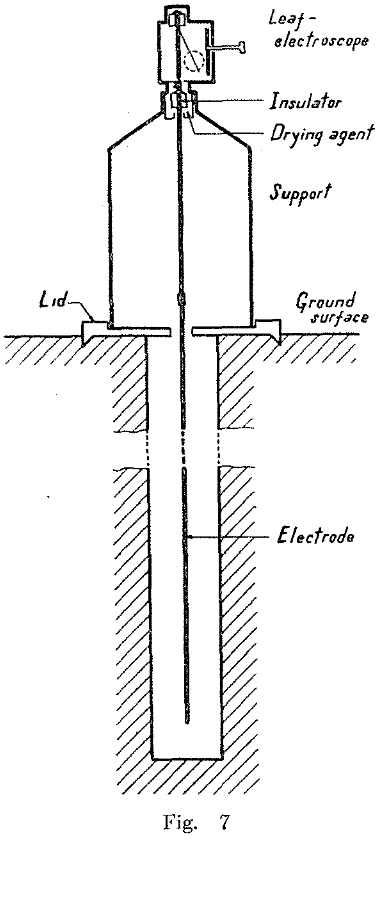


Fig. 7

(B) Ground-hole-ionization-chamber method.

This method involves the measurement of ionization in a hole bored in the ground (Fig. 7). The center electrode of an electroscope is extended into the hole bored previously in the ground, which is utilized as an ionization chamber. The hole is 10 cm in diameter and 100 cm in depth. The electroscope is rested on a bell-like support. The ionization chamber of Engler-type fontactoscope with its base plate removed is suitably used as this support.

In practical measurement, a hole of the size mentioned above is dug in the ground. The wall of the hole should be as vertical as possible. Then it is covered with a wooden lid lined with metal plate, having at the centre a hole 3 cm in diameter provided with a plug which will be removed when in use to give a passage for the extended electrode. After two or three hours, according to the conditions, when the air in the hole would come to an equilibrium with regard to the concentration of radon, ionization in the hole is measured with an electroscope (the top of the IM fontactoscope). The readings are taken every minute as soon as the electrode is charged, lest the active deposits produced from radon should affect the ionization. From the falling rate of the leaf thus obtained, the background or natural leak is subtracted. For measuring the natural leak the lower part of the centre electrode extending into the ground hole is removed at a joint inside the bell-like support and to the bottom of the support is then attached its base plate previously removed. In this arrangement the observed leak is due to the leakage through the insulator, and to the background ionization within the support and the chamber of the electroscope. The electric capacity of the measuring system in this arrangement differs from that in the actual measurement of radioactivity in the ground. But the effect of the difference in capacity may be neglected as the amount of the natural leak is usually only a mere fraction of the leak due to the radioactivity in the ground.

(C) Photo-plate method.

Instead of measuring ionization in the ground hole as stated above, it would be possible to determine the concentration of radon with nuclear emulsions. This is a new idea of the author and proved successful in practical application.[25] For this purpose ET-2E photo-plate (22 mm × 40 mm half of the standard size) is suitable; it is specially manufactured for recording tracks of alpha particles by the Research Laboratory of Fuji Photo Film Co., Ltd.

Insertion of the photo-plate into the ground hole is made by means of a dark slide attached to the lower end of a long handle which penetrates upward through the lid of the ground hole. The handle is made of bamboo with knots broken off and through the inner space of which runs a wire serving as a device for opening and shutting the lid of the dark slide from the outside. The photo-plate in the ground hole is located at a height of 20 cm from the bottom, the back of the dark slide being attached close to the wall of the hole. The effective range in air of alpha particles from radon series is 5.21 cm[26], and this produces the condition that none of alpha particles leaving the wall can have its effect on the photo-plate set as mentioned above. The exposure of the photo-plate should be nearly equal for each measuring point; ten to fifteen hours exposure gives adequate density of alpha tracks for counting under a microscope with magnification 150×. The number of tracks observed in unit area of photo-plate per unit time would give the relative concentration of radon in each ground hole.*

(D) Geiger-counter method.

A Geiger counter affords us another method of radioactive prospecting. As early as 1938, the author put the Geiger counter in use, (then generally used for the detection of cosmic rays) for the determination of thorium in granite by aid of a separate radium determination[27], and proved its applicability for measuring weak radioactivity of rocks.[28] Recently, the author constructed portable Geiger counter equipment (ca. 5 kgr. in total) for use in field work. The construction is shown in Fig. 8. A high tension supply for the Geiger counter has been assembled

* For full details, the author's paper[24] should be referred to.

after the design of R. D. Huntoon[29] with a slight modification resulting in the elimination of bulky, heavy and expensive batteries. The counting rate-meter is to be used only when radioactivity is very strong. In usual cases pulses are counted by a telephone receiver as well as by kicks of the needle of the rate-meter with no resistance in the tank circuit, or by flashes of the neon lamp.

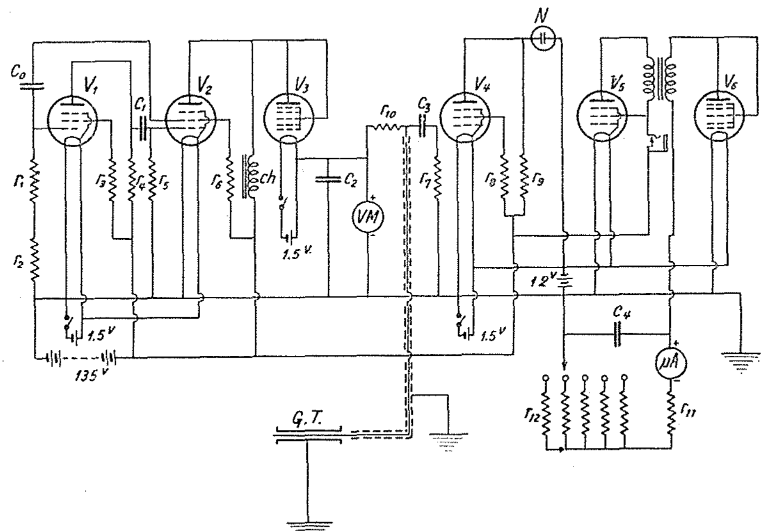

Fig. 8

In carrying out an exploration practically, the counter is inserted in a hole drilled in soil to a depth of 50 cm and with a diameter of 5 cm. At each station, counting is made at least for twenty minutes for soils of moderate radioactivity so as to make the statistical error small. A counter with larger size than the present one (the effective length 20 cm, dia. 25 mm) is preferable for reducing the time of observation.

(2) Discussion of the methods.

Every method described above has its own merit and defect. As the radon-in-soil-air method treats the radon in soil air, of which the greater parts come upwards from depth in the ground, the distribution of radon in soil air will well reflect the underground structure. On the other hand, the method of Geiger counter treats the gamma ray emitted from radioactive elements existing only in the neibourhood of the hole in the ground, and will be inferior to the former method in the exploration of deeper parts. In the ground-hole-ionization-chamber method, the ionization by the rays emitted from the radioactive elements in the wall materials of the hole and by those from the radon in it is measured. If the ionization due to the former is predominant, that due to the latter will become indistinct and the subsurface structure would hardly reflect the radioactive profile. Fortunately, however, the ionizations of both kinds usually change parallel to each other. This will well be explained by the reasonable conditions that a disturbed zone near faults is more permeable for both soil gas and water and the latter would bring radioactive substances from the depths and fix them near the earth surface. As may be anticipated, this method is more sensitive to the variation of atmospheric pressure, to the wind and sun-shine etc. than the radon-in-soil-air method, and outdoor measurement by this method is less accurate than the latter.

The photo-plate method has the same defect as the ground-hole-ionization-chamder method in regard to the external disturbances, but has a superiority that the record of alpha tracks, a direct evidence of radioactivity, is obtained and the method requires no special apparatus except a microscope which will be available in any geological laboratory.

In the Geiger-counter method, owing to the defect stated already, sometimes it might occur that when crossing over a hidden fault no peak in radioactive profile would appear but a difference in radioactivity on both sides of the projection of the fault on the ground surface. In this case the fault might be misinterpretated as a boundary of two rocks having different radioactivity. It appears that this method could be used in the case where the soil is so damp or clayey that other methods are not applicable. It is known that the maximum thickness of soil through which gamma rays can give their effect on the Geiger counter is only one meter or less. Therefore, the use of it is limited to only the cases in which the surface covering is less than one meter in thickness or of autochthonous soil, or is contaminated with radioactive substances carried by water from an underground outcrop of a fault.

(3) Examples of the tests of the methods.

Example I. (The radon-in-soil-air method)

The first test[30] was made in March 1942 at Minotani, Yamada Village in Hyôgo Prefecture. There a reverse fault, described as the Rokkô Thrust by T. Ueji[31] is found running nearly from east to west separating the hornblende-biotite granite on one side and shale of Tertiary formation on the other. Stations were chosen along a line transversal to the strike of the reverse fault in a rice field area on a hillside. The surface soils was autochthonous. As it was early spring, there were no crops in the area, and the surface of the ground had moderate dampness which favoured the sampling of soil air by keeping off the atmospheric air. But the level of underground water was rather high so that at some places the sampling was unsuccessful, especially near the thrust where a stream was running.

The result of measurement is shown in Table 5 and Fig. 9. As seen in the figure, the increase of radon is quite conspicuous on getting near the fault, suggesting the maximum concentration just above it which would be attained if we could set a station there. This was, however, impossible owing to dampness of the ground. It is worth noticing that, though the number of stations is rather few, the average radioactivity in the granite area seems somewhat higher than that in the sedimentary at the distances of some tens of meters from the fault. The soil samples from the two areas were tested in the laboratory for their radioactivities with the Geiger gamma-ray counter specially designed by the author.[28] The measurements were made over 140 minutes on each sample, giving the

Table 5

| Station | Interval of stations | Radioactivity of underground air | Reference |
|---|---|---|---|
| No. 1 | | 1.81 Eman | Granite soil, pretty dry |
| | 23 m | | |
| No. 2 | | 1.39 | Ditto |
| | 16 | | |
| No. 3 | | 6.07 | Ditto |
| | 17 | | |
| No. 4 | | 12.11 | Ditto |
| | 66 | | |
| No. 5 | | 7.84 | Clayey soil with pebbles, damp |
| | 18 | | |
| No. 6 | | 1.20 | Ditto |
| | 38 | | |
| No. 7 | | 0.11 | Clayey soil with pebbles. very damp |
| | 32 | | |
| No. 8 | | 0.31 | Ditto |

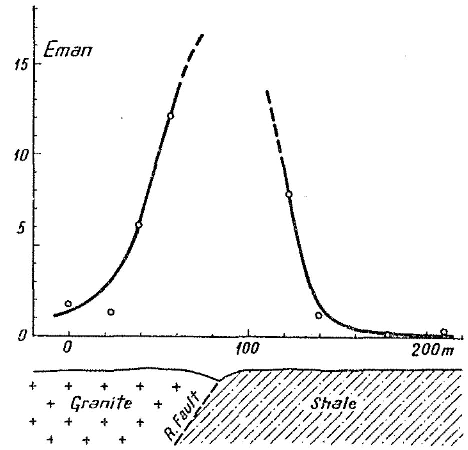


Fig. 9

following ratio of numbers of counting, the background having been subtracted.

Granite soil : Shaly soil = 1123 : 459 ≒ 2.4 : 1

These numerals include the radioactivity of thorium series and the negligibly feeble radioactivity due to potassium, but as the proportion of radium and thorium in ordinary rocks is usually constant, it is inferred that the above ratio approximates that of the radium content in the two kinds of soil. It will be plausible that the above ratio is of the same order of magnitude as the average radon concentration observed in the two areas.

Example II. (The radon-in-soil-air method)

The second test[22] was carried out in March, 1943 at Obu in Yamada Village, Hyôgo Prefecture about 600 m south-west of Suzurandai Station along the Shin-yû Railway. The Rokkô Thrust passed here also. The area surveyed was also a rice field which was then vacant and dry, as the season was early spring, and covered with alluvial deposits instead of weathered rocks *in situ* in the previous example. The topography and geology nearby is shown in Fig. 10, in which AB denotes the line along which measurements were carried out. The results are given in Table 6 and Fig. 11.

A conspicuous peak near the middle of the radioactive profile would correspond to the Rokkô Thrust and a minor one near the right end to the Kikusuiyama Fault. These agreements are fairly good and we can actually see the boundary

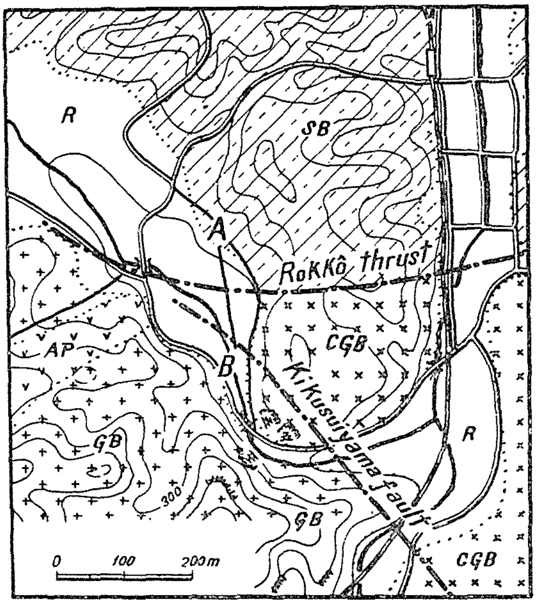


Fig. 10

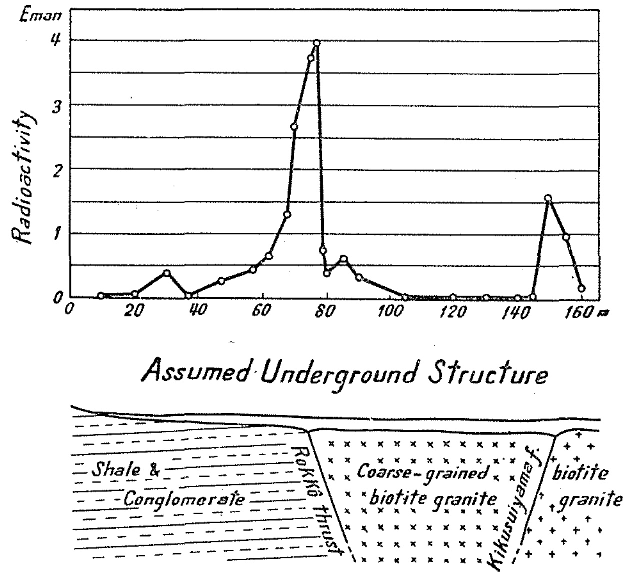


Fig. 11

Table 6

| Station | Distance from a datum point | Radioactivity of soil air |
|---|---|---|
| No. 1 | 10 m | 0.04 Eman |
| No. 2 | 20 | 0.09 |
| No. 3 | 30 | 0.43 |
| No. 4 | 36.5 | 0.06 |
| No. 5 | 47 | 0.30 |
| No. 6 | 57 | 0.47 |
| No. 7 | 62 | 0.66 |
| No. 8 | 68 | 1.33 |
| No. 9 | 70 | 2.69 |
| No. 10 | 75 | 3.77 |
| No. 11 | 77 | 3.99 |
| No. 12 | 78.5 | 0.77 |
| No. 13 | 80 | 0.41 |
| No. 14 | 85 | 0.65 |
| No. 15 | 90 | 0.34 |
| No. 16 | 105 | 0.04 |
| No. 17 | 120 | 0.04 |
| No. 18 | 130 | 0.05 |
| No. 19 | 140 | 0.03 |
| No. 20 | 145 | 0.01 |
| No. 21 | 150 | 1 60 |
| No. 22 | 155 | 0.99 |
| No. 23 | 160 | 0.14 |

of shale and granite, probably the outcrop of the Rokkô Thrust, on the hillside scores of meters east of the position of the peak. As to the position of the Kikusuiyama Fault, the author's observation should be mentioned here. Scores of meters south-east of the position of the minor peak, is located the entrance of a tiny valley, where we can see the boundary across which the grain size of the granite changes clearly. Therefore, it is highly probable that this boundary corresponds to the Kikusuiyama Fault. The thickness of the alluvial deposits near the point of intersection of the traverse line and the thrust is ca. 7 m as has been theoretically estimated previously.

Example III. (Radon-in-soil-air method)

The third test was made in December, 1946, near Takiyashinden in Nishiyama Oil-field, Niigata Prefecture. The principal aim of this test was to find whether this method is applicable in a field entirely composed of sedimentary rocks. In the previous two examples, the fields were related to granite which is

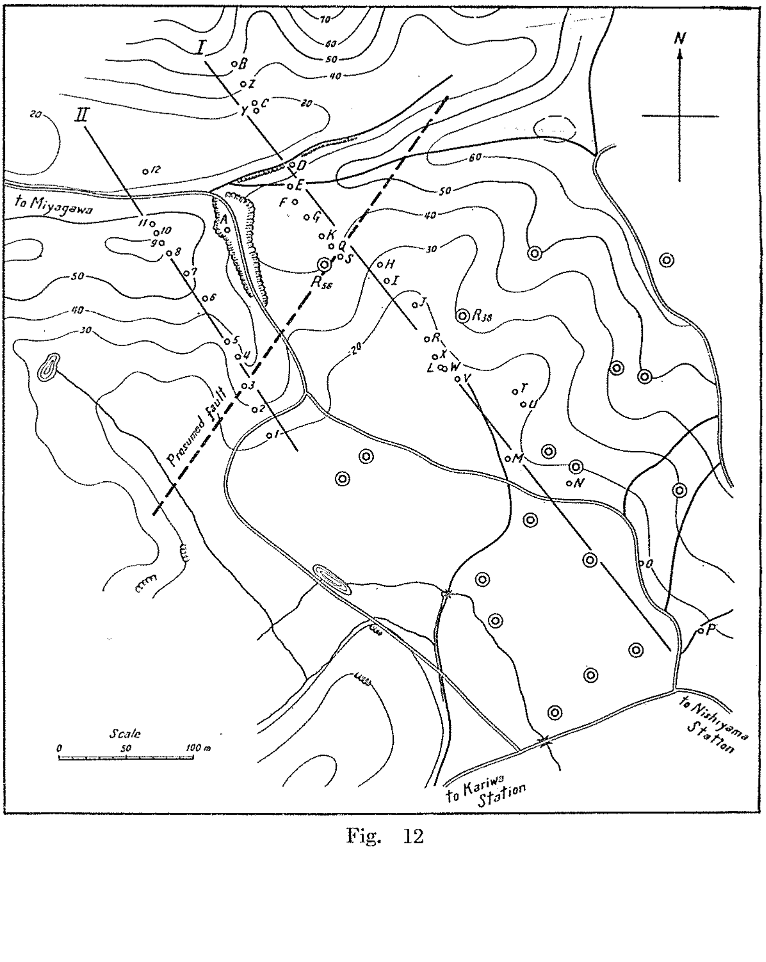


Fig. 12

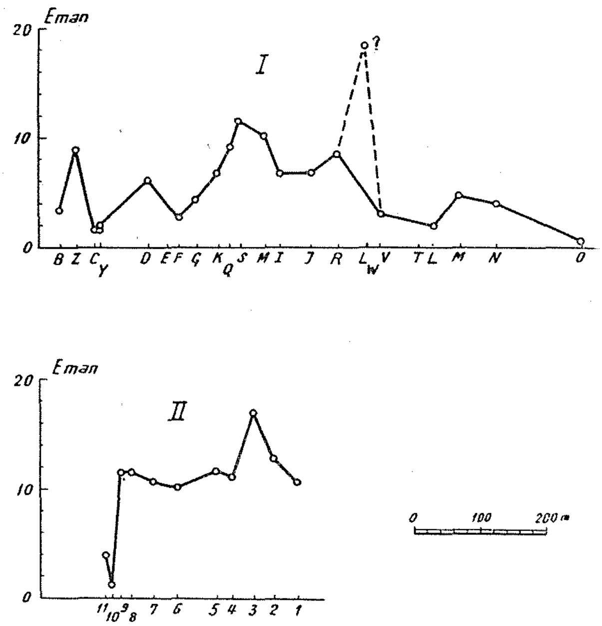


Fig. 13

said to be in general more radioactive than sedimentary rocks. As seen on the map and curves of radioactivity (Fig. 12 and Fig. 13), the result is not so definite as those in the previous examples owing to disturbances due to the topographic complexity and bad weather during the test and so on.

Of the two peaks revealed in the radioactive profile along the line of survey I, one at station L is unreliable, as the place was formerly occupied by a hut for a gas-burner and the leakage of natural gas carrying radon from the neibouring well ($R_{38}$ in the figure) is suspected as taking place in this site. The line joining the other peak at station S and that at the station No. 3 in the profile along the line of survey II coincides with the general trend of the Madonosaka Fault which was determined by a surface geological survey and the oil-well data as well. It may, therefore, be concluded that the said fault would be passing in the underground along this line.

Example IV. (A comparison of four different methods*)

Comparative study has been made of the different methods mentioned above at Syûgakuin in Sakyô Ward, north-eastern part of Kyoto City, in the spring of 1951. A traverse line for radioactive measurements was selected in a barley-field running nearly in the east — west direction normal to a fault presumed by

* A brief description was also made in the previous paper. Refer to the reference 25) p.92.

us from a radioactive survey performed in the previous year. At each station a vertical hole 1 m deep and 10 cm in diameter was dug in the ground. These holes were used as an ionization chamber in the use of the ground-hole-ionization-chamber method described above. The same holes were later used for applying the photo-plate method and the Geiger counter method too. For carrying out the latter, the mouth of the hole was left open, letting the radon in the hole freely escape into the atmosphere. And from this condition, the gamma rays attacking the Geiger counter would be almost only those emitted from the wall of this hole. For the period of counting, twenty minutes was found sufficient.

Determination of concentration of radon in soil air by means of fontactoscope was carried out about two weeks there-after. The traverse line was the same as before, but the position of each station at which the soil air was collected, was set about 2 meters from the holes already used so as to avoid a probable influence of the atmospheric air through the wall of the hole.

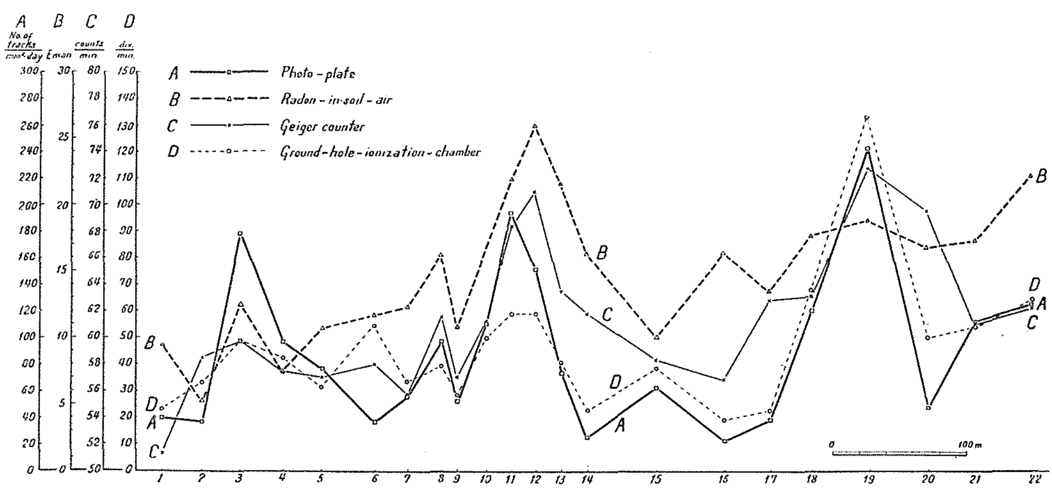


Fig. 14

As shown in Fig. 14, the results obtained by the four different methods give a fair concord. Above all, the photo-plate method is in good agreement with the ground-hole-ionization-chamber method. Thus the applicability of nuclear emulsions to radioactive exploration has been proved by this experiment, leaving room for improvement in details for the future.

From the results attained, it will also be conjectured that radioactivity increases not only in soil gas but also in soil itself as the fault is approached. If this were caused solely by diffusing radon from the depths, the counter method would have failed in showing such a peak as is seen in the radioactive profile, because a mere fraction of the number of impulses counted by Geiger counter is due to radon and the rest to other radioactive elements and to cosmic rays.

Table 7

| No. of station | Interval of station m | Method | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| | | No. of tracks / $mm^2$. day | Eman | No. of Counts / min. | Scale div. / min. |
| 1 | | 40.0 | 9.5 | 51.4 ± 1.5 | 23.2 |
| | 30.2 | | | | |
| 2 | | 37.0 | 5.3 | 58.5 ± 1.6 | 30.6 |
| | 28.5 | | | | |
| 3 | | 179.0 | 12.5 | 59.7 ± 1.6 | 45.8 |
| | 32.2 | | | | |
| 4 | | 97.0 | 7.5 | 57.5 ± 1.6 | 40.4 |
| | 28.2 | | | | |
| 5 | | 77.0 | 10.7 | 57.0 ± 1.6 | 31.4 |
| | 40.0 | | | | |
| 6 | | 36.8 | 11.7 | 58.0 ± 1.6 | 54.3 |
| | 23.6 | | | | |
| 7 | | 56.4 | 12.3 | 55.7 ± 1.6 | 33.3 |
| | 25.5 | | | | |
| 8 | | 96.7 | 16.3 | 61.6 ± 1.7 | 39.3 |
| | 11.6 | | | | |
| 9 | | 52.5 | 10.8 | 57.0 ± 1.6 | 28.3 |
| | 21.6 | | | | |
| 10 | | 110.5 | — | 61.2 ± 1.7 | 49.7 |
| | 18.7 | | | | |
| 11 | | 193.9 | 22.9 | 68.4 ± 1.8 | 58.8 |
| | 17.6 | | | | |
| 12 | | 150.9 | 26.0 | 71.0 ± 1.8 | 58.7 |
| | 19.5 | | | | |
| 13 | | 73.2 | 21 6 | 63.5 ± 1.7 | 40.5 |
| | 19.5 | | | | |
| 14 | | 25.0 | 16.3 | 61.8 ± 1.7 | 22.5 |
| | 52.0 | | | | |
| 15 | | 62.0 | 10.0 | 58.3 ± 1.6 | 33.0 |
| | 50 0 | | | | |
| 16 | | 22.1 | 16.4 | 56.9 ± 1.6 | 19.1 |
| | 34.0 | | | | |
| 17 | | 38.5 | 13.5 | 62.8 ± 1.7 | 22.5 |
| | 31.3 | | | | |
| 18 | | 119.6 | 17.7 | 63.1 ± 1.7 | 67.9 |
| | 43.2 | | | | |
| 19 | | 242.0 | 18.8 | 72.7 ± 1.8 | 132.8 |
| | 40.4 | | | | |
| 20 | | 47.5 | 16.3 | 69.6 ± 1.8 | 50.0 |
| | 35.5 | | | | |
| 21 | | 111.9 | 17.3 | 61.0 ± 1.7 | 54.0 |
| | 42.7 | | | | |
| 22 | | 125.2 | 22.2 | 62.2 ± 1.7 | 64.4 |

## Solution of the problem of stationary diffusion of radon in soil by means of an electric analogy

Two-dimensional distribution of radon within a soil of uniform thickness due to a line source of radon such as a subsurface outcrop of a fault in a bedrock has been treated by J. Koenigsberger.[21] With different geometrical conditions, e. g. with a finite width of the source instead of a line or inequality in levels of bedrock on both sides of a fault and so on, the mathematical treatment would be difficult. So the author has tried to get experimentally a general aspect of distribution of radon in such cases.

By the analogy between diffusion and electrical conduction, i. e.,

$g = -D \operatorname{grad} C$ ............. (1) where $g$ is quantity of gas passing through unit cross-sectional area per unit time, $D$ diffusion constant and $C$ concentration,

$i = -K \operatorname{grad} V$ ............. (2) where $i$ is current density, $K$ specific electrical conductance and $V$ potential,

usually an electrical method is used in solving the problem of diffusion.

Buckingham's elaborate experiments[7] on diffusion proved that diffusion in a porous medium in which movement of material occurs through pore space along sinuous paths, may be treated in the same manner as in a free medium except that the free pore space is taken into consideration (cf. the preceding paragraph "Diffusion of gases in soil"). Garrels, R. M. *et al.*[32] also showed experimentally that the rate of transport by diffusion along sinuous paths is independent of the permeability but depends on what he calls the "effective directional porosity". In rocks or soils composed of non-conductive minerals, diffusion and electrical conduction will occur only in the pore space and along sinuous paths. Hence, in such a case, the effective diffusion constant $D_r$ and the electrical conductivity $K_r$ will be given by

$$\left.\begin{aligned} D_r &= \frac{D_l f}{L} \\ K_r &= \frac{K_l f}{L} \end{aligned}\right\} \qquad (3)$$

where $D_l$ and $K_l$ are respectively the diffusion constant and electrical conductivity in free medium, $f$ the porosity and $L$ the lithologic factor depending upon sinuosity of the paths. The geometrical factor $f/L$ is the effective directional porosity and the same for both electrical conduction and diffusion.

In his recent paper, Klinkenberg[33] reported his experimental results confirming the above deduction. Using a synthetically consolidated core sample, the rate of diffusion of water vapour was measured. This lithologic factor found in this way was 1.9, while that found from the electrical conductivity determined for the same sample saturated with a NaCl solution was 1.7, giving a slight discrepancy which may be considered to be within the limits of experimental error. Also he calculated the lithologic factor for various sands and clays of which porosities and diffusion constants $D_r$ of $CO_2$ had formerly been determined by Buckingham, using a value of 0.168 cm$^2$/sec. for $D_l$ (the diffusion constant of $CO_2$ in air at 27°C at which the experiments were carried out). Then he found that the thus obtained values for the lithologic factor are of the same order of magnitude as those for unconsolidated materials obtained by measurements of the diffusion of water vapour through sands made by F. Zunker.[34]

In conclusion, we can safely utilize the analogy between diffusion and electrical conduction in porous media and an electrical treatment will be far simpler than a diffusion experiment.

As given at the beginning, when a linear source of radon such as a sub-surface outcrop of a fault in bedrocks extends sufficiently long, the diffusion can be treated as a two-dimensional problem in the plane perpendicular to it. Such conditions may be electrically made as follows:

As illustrated in Fig. 15, a current is sent from a point-electrode A to a bar-electrode B through a moderately conductive medium and the electrical potentials at points $r_f$'s are measured with a potentiometer with respect to B. The potential thus observed will correspond to a concentration of diffusing radon in a stationary state. In practice, to avoid the probable polarization of the

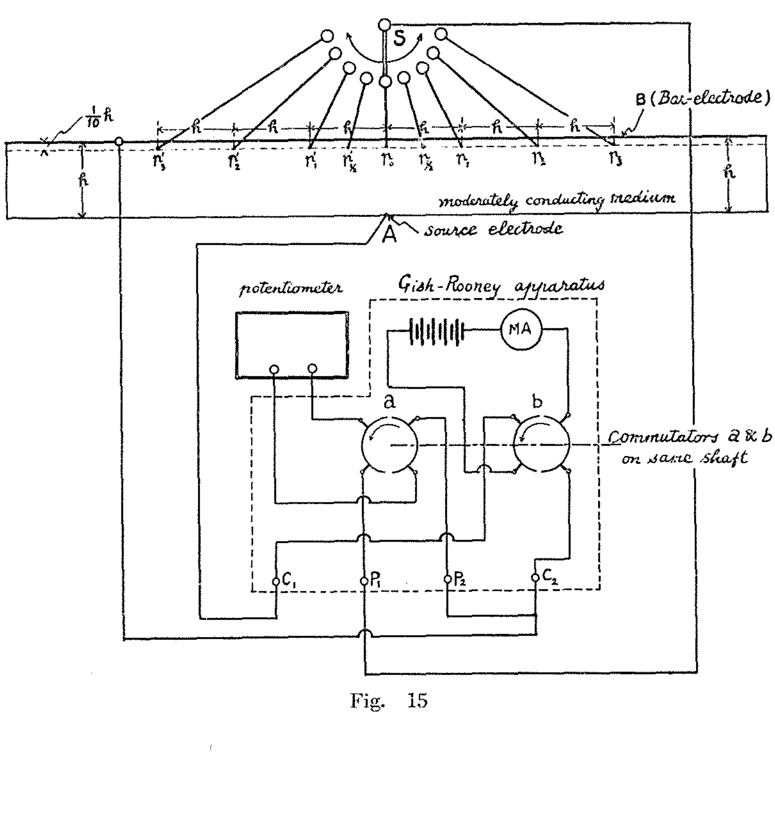


Fig. 15

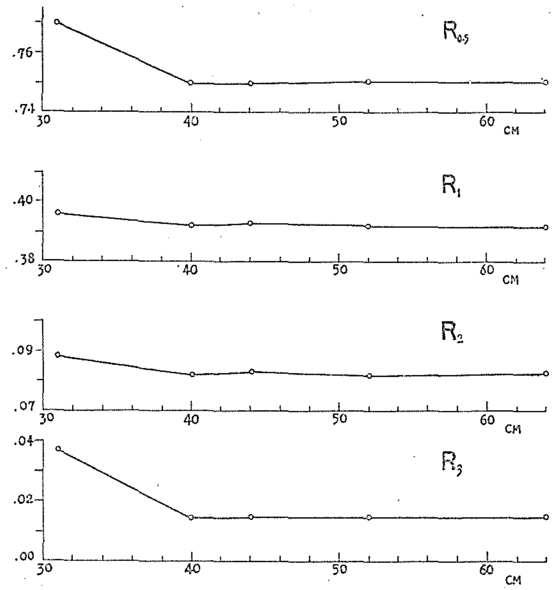


Fig. 16 Showing the end-effect experimentally obtained. The ordinate represents the relative potential $R_f$ with respect to the potential at $x=0$, the abscissa a half length of the blotting paper.

medium due to direct current, Gish-Rooney's apparatus designed for determination of resistivity of the ground was used. The arrangement was that the current terminal $C_1$ was connected to the source electrode A, and the potential and current terminals $P_2$ and $C_2$ to the bar-electrode B, and the potential terminal $P_1$ to the potential electrode at $\mathfrak{r}'_f$s through a rotary switch S.

In the present experiments, a sheet of blotting paper moistened with tap water containing 50–70 % of glycerine by volume and spread over an ebonite plate was used as the medium. It was 10 cm wide and 90 cm long. With this size the end-effect is negligible because of the fact that, as seen in Fig. 16, it appears only when the blotting paper is cut with a half length of less than 40 cm : With that of 30.5 cm when the potential electrode $\mathfrak{r}_3$ is situated so near the end edge that the end-effect is most remarkable for this electrode as shown. A brass bar-electrode was pressed against the blotting paper along one of its longer edge and a point electrode at the center of the opposite edge. Evaporation of water during experiment was prevented by the presence of glycerine and further by a cover of a nylon cloth which was provided with small openings at the points $\mathfrak{r}_o$, $\mathfrak{r}_1$,······ for the setting of the potential electrodes.

In the experiment there arise some difficulties which are of the same nature as those met with in electrical prospecting in the field, i. e., contact potential and the so-called contact resistance of the electrode and polarization of the medium.

To overcome these difficulties is requisite for making use of the electric analogy and this was done as described in the following.

Let $e'_f$ be the potentials actually measured at points $\mathfrak{r}_f$ which are at the depth of one-tenth of the width $h$ from the bar-electrode and at lateral distances $x = fh$ ($f$ being 0, 0.5, 1, 2, 3 etc.) from the point $\mathfrak{r}_0$ above the source, then the theoretically expected potential, i. e. the potential free from the aforesaid difficulties, $E_f$ will be written as

$$E_f = e'_f - (c_f + d_f) \cdots\cdots\cdots\cdots\cdots (4)$$

where $c_f$ is a disturbing potential depending upon current density and $d_f$ another disturbing potential independent of current density. Disturbing potentials other than these two can hardly be conceivable. Now then, as a first approximation, $c_f$ may be expressed as $e'_f K$ ($K$ : a constant if resistance of the medium remains unchanged).

Then, the relative potential $R_f$ with respect to the potential at $\mathfrak{r}_0$ is

$$R_f = \frac{E_f}{E_o} = \frac{e'_f\,(1-K) - d_f}{e'_o\,(1-K) - d_f} = \frac{e'_f/e'_o - d_f/e'_o\,(1-K)}{1 - d_f/e'_o\,(1-K)} = \frac{R'_f - A_f}{1 - A_f} \cdots\cdots (5)$$

where

$$A_f = \frac{d_f}{e'_o\,(1-K)} \quad \text{and} \quad R'_f = e'_f/e'_o, \text{ and hence}$$

$$A_f = \frac{R'_f - R_f}{1 - R_f} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

The values of $R_f$ have already been calculated as $R_{0.5} = 0.753$, $R_1 = 0.396$,

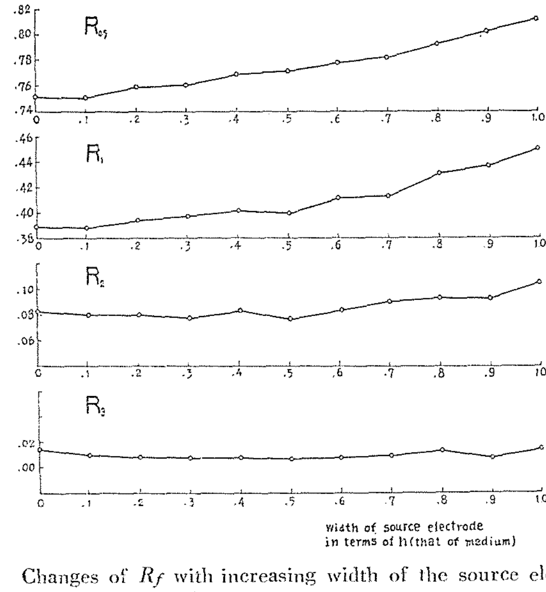


Fig. 17 Changes of $R_f$ with increasing width of the source electrode.

$R_2 = 0.085$ and $R_3 = 0.018$ (cf. Table 2. p. 238). Hence, by measuring $e'_o$ and $e'_f$, the value of $A_f$ will be found by the equation (6). If a current is so adjusted that $e'_0$ is kept always constant, $A_f$ will be constant for the same medium and independent of the shape of the source electrode or the path of the current within the assumption employed.

Following the above-mentioned reasoning, the author has tried to find the values of $R_f$ by experiments in the cases where the widths of the source electrode are 1, 2, 3, ......., 10 cm against h = 10 cm instead of a point. In nature this case corresponds to the case where a fault is assumed to be broad, forming the so-called "fault zone". The result is shown in Fig. 17, from which it can be seen that the effect of the width of the source electrode is appreciable only in the vicinity of the center station $\mathfrak{r}_0$ and at the station $\mathfrak{r}_{0.5}$ nearest to $\mathfrak{r}_0$; the effect of the width of a value 0.5 h is to increase $R_f$ from 0.752 to 0.772 or only by 2.7 %, an unexpectedly small effect.

The second experiment corresponds to the case in which one side of a vertical

Table 8

| Distance / t cm | | Left side | | | | Right side | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 h | 1 h | 2 h | 3 h | 0.5 h | 1h | 2 h | 3 h |
| 0 | $R'_f$ | .707 | .430 | .125 | .051 | .717 | .428 | .140 | .058 |
| | $R_f$ | .753 | .396 | .085 | .018 | .753 | .396 | .085 | .018 |
| $a = R'_f - R_f$ | | −.047 | +.034 | +.040 | +.033 | −.036 | +.032 | +.055 | +.040 |
| $b = 1 - R_f$ | | .247 | .604 | .915 | .982 | .247 | .604 | .915 | .982 |
| $A_f = a/b$ | | −.190 | +.056 | +.044 | +.034 | −.146 | +.053 | +.060 | +.041 |
| $1 - A_f$ | | 1.190 | .944 | .956 | .966 | 1.146 | .947 | .940 | .959 |
| 1 | $R'_f$ | .755 | .471 | .137 | .059 | .675 | .380 | .127 | .052 |
| | $R_f$ | .794 | .440 | .097 | .026 | .716 | .345 | .071 | .011 |
| 2 | $R'_f$ | .821 | .507 | .144 | .065 | .626 | .330 | .120 | .053 |
| | $R_f$ | .850 | .478 | .105 | .032 | .674 | .293 | .064 | .013 |
| 3 | $R'_f$ | .901 | .552 | .159 | .074 | .573 | .290 | .112 | .056 |
| | $R_f$ | .917 | .525 | .120 | .041 | .627 | .250 | .055 | .016 |
| 4 | $R'_f$ | .995 | .593 | .168 | .083 | .510 | .240 | .107 | .057 |
| | $R_f$ | .996 | .569 | .130 | .051 | .572 | .197 | .050 | .017 |
| 5 | $R'_f$ | 1.022 | .595 | .170 | .084 | .458 | .202 | .100 | .055 |
| | $F_f$ | 1.018 | .571 | .132 | .052 | .527 | .157 | .043 | .015 |

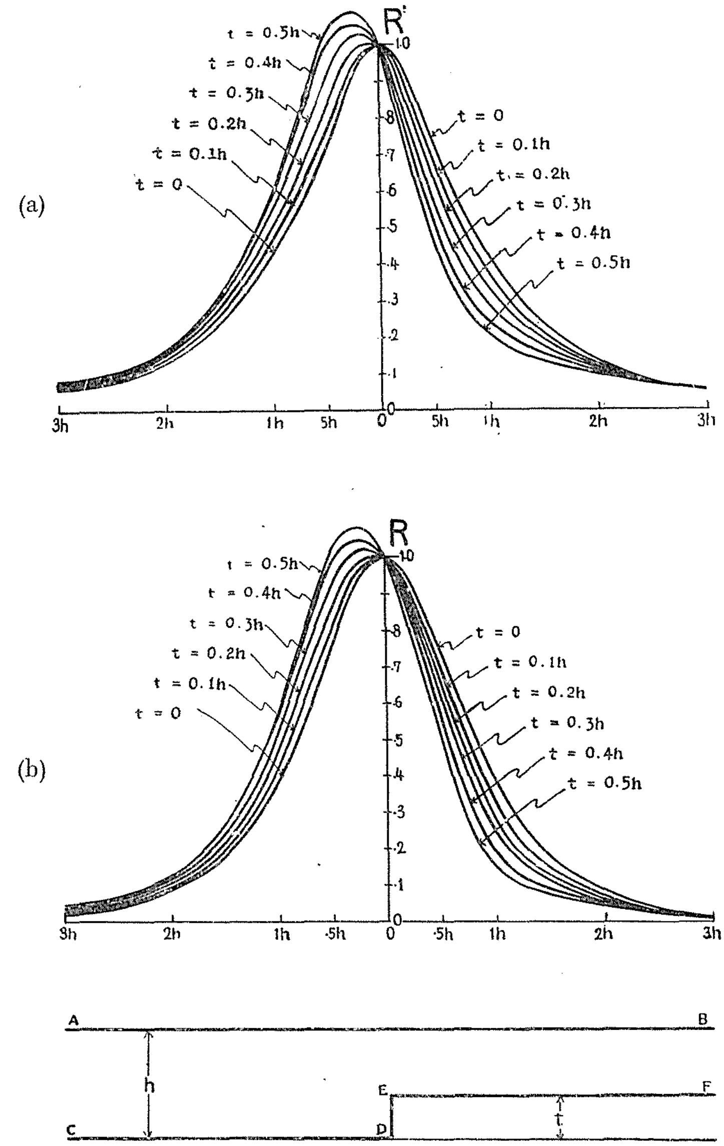


Fig. 18

fault in bedrock is higher than the other. In this experiment, the blotting paper was cut off in the form ABFEDC as shown in Fig. 18, in which t denotes the throw of the fault. The measurement of potentials at $r_f$ is the same as before. In Fig. 18 (a) were plotted the observed values, while in Fig. 18 (b) the values corrected by following the aforesaid reasoning. In Table 8 are shown the observed values ($R'_f$), the values of $A_f$ and the corrected values ($R_f$).

It is worth noticing that as the throw of the fault increases, the maximum of the curve shifts towards the thrown side of the fault and the forms of the curves deviate from being symmetrical on both sides of the maximum, the slope of the curve on the thrown side being less steep than that on the opposite, but by no means so pronounced. This result gives a warning to the customary way of assuming a fault as just below the peak in radioactive profile.

## Practical applications

(1) Research in Narahashi Oil-field, Yamagata Prefecture.

During the period of the research (10–30th August, 1947) there were three wells in this region and there now are five ones. The position and number of these wells are shown in the map in Fig. 19. A fault was assumed geologically between wells No. 1 ($R_1$) and No. 2 ($R_2$) on the ground surface. The former

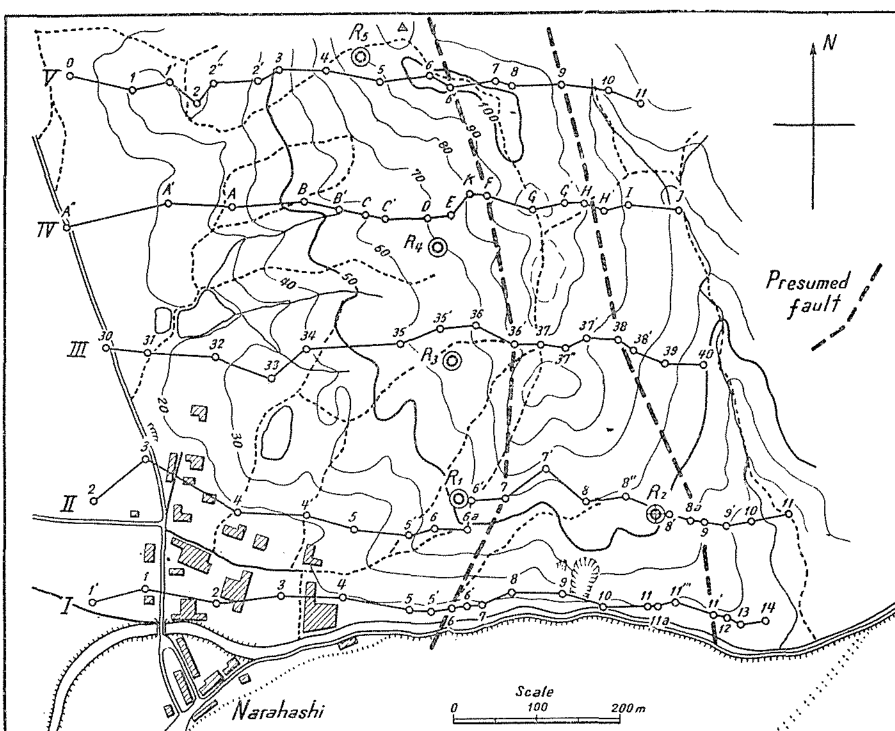


Fig. 19

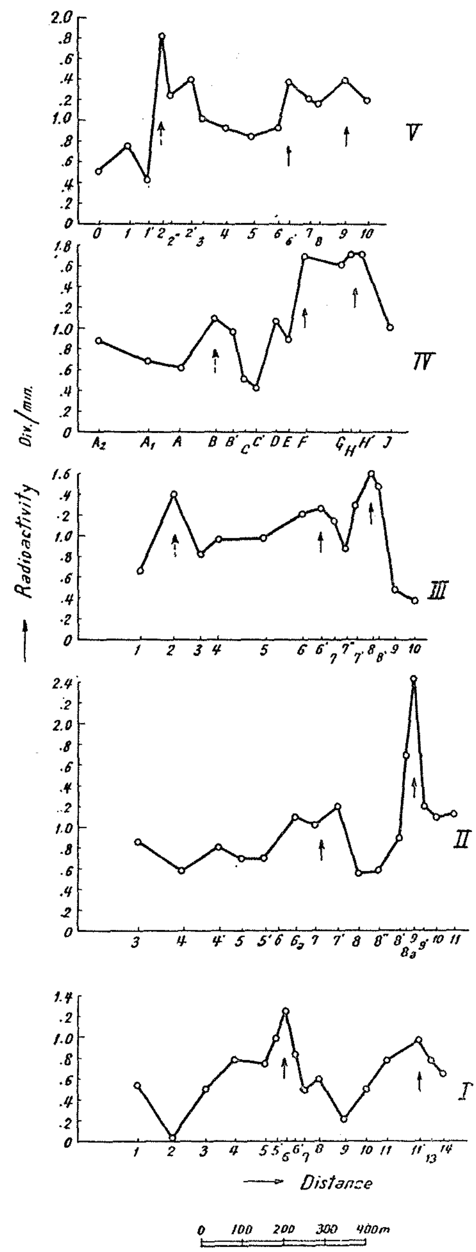


Fig. 20

cut an oil-containing layer at a depth 166.6 m below sea level, while the latter revealed no sign of oil. Well No. 3 ($R_3$) situated 160 m north of No. 1 also produced oil at a depth of 148.4 m below sea level. These data and the others showed that the north part of the region was promissing for oil. On the other hand, the oil reservoir here was of the type "sealed up by fault", so that the exact knowledges about the position and trend of the fault were very important for the future development. By surface survey as well as pit survey it was hopeless to trace this fault in the Shibikawa formation, because the latter was covered with thick layers of agglomerate and volcanic detritus. Accordingly much was expected of success in location of the fault by the radioactive method.

The method adopted was radon-in-soil-air method. The soil air to be tested for its radon content was drawn from a mean depth of 90 cm. With such a depth, radon content would not avoid the influences of rainfall and atmospheric pressure. So a standard station was set where the measurement was repeated every day and the observed values at all the stations were corrected with these data. The position of stations and lines of survey are shown in Fig. 19. Owing to dampness and clayeyness encountered at places, which made it impossible to draw up soil air, the distribution of stations was not fully satisfactory. In Fig. 20 and Table 7 are shown the results. Along line I there appear two peaks in radioactive profile, one at station No. 6 and the other at No. 11′. Between stations No. 9 and No. 10, a spring is found and between No. 11 and No. 11′ the ground is damp. As to the latter, if it were not so, a higher peak of radioactivity would be expected between No. 11 and No. 11′. In line II a hump with considerable width of which the center is station No. 7 and a conspicuous peak at No. 9 are found. These two maxima presumably correspond to those appearing at a shorter interval in line III, and also to those in lines IV and V. Joining these corresponding maximum points respectively, we get two lines running nearly parallel in the direction of north by west in the northern part, and diverging southward in the southern part of the area surveyed. These lines may be supposed to be the projections on the surface of the earth of sub-surface outcrops of two buried faults.

The irregularities appearing in the vicinities of stations No. 2 on line III, B on line IV and No. 2 on line V are also remarkable and presumably would be

TABLE 9

| Line I | | Line II | | Line III | | Line IV | | Line V | |
|---|---|---|---|---|---|---|---|---|---|
| No. of station | Radio-activity div./min. | No. of station | Radio-activity div./min. | No. of station | Radio-activity div./min. | No. of station | Radio-activity div./min. | No. of station | Radio-activity div./min. |
| 1 | 0.56 | 3 | 0.84 | 1 | 0.66 | $A_2$ | 0.37 | 0 | 0.51 |
| 2 | 0.02 | 4 | 0.57 | 2 | 1 42 | $A_1$ | 0.63 | 1 | 0.76 |
| 3 | 0.53 | 4′ | 0 82 | 3 | 0.82 | A | 0.62 | 1′ | 0.41 |
| 4 | 0.79 | 5 | 0.69 | 4 | 0.97 | B | 1.11 | 2 | 1.84 |
| 5 | 0.74 | 5′ | 0.70 | 5 | 0.99 | B′ | 0.97 | 2″ | 1.24 |
| 5′ | 0.98 | 6a | 1.11 | 6 | 1.21 | C | 0.50 | 2′ | 1.42 |
| 6 | 1.25 | 7 | 1.03 | 6′ | 1.28 | C′ | 0.42 | 3 | 1.04 |
| 6′ | 0.80 | 7′ | 1.20 | 7 | 1.17 | D | 1.09 | 4 | 0.93 |
| 7 | 0.48 | 8 | 0.55 | 7″ | 0.86 | E | 0.91 | 5 | 0.85 |
| 8 | 0.60 | 8″ | 0.54 | 7′ | 1.30 | F | 1.71 | 6 | 0.95 |
| 9 | 0.22 | 8′ | 0.88 | 8 | 1.62 | G | 1.61 | 6′ | 1.40 |
| 10 | 0.53 | 8a | 1.67 | 8′ | 1.46 | H | 1.72 | 7 | 1.23 |
| 11 | 0.78 | 9 | 2.46 | 9 | 0.48 | H′ | 1.73 | 8 | 1.17 |
| 11′ | 0.96 | 9′ | 1.21 | 10 | 0.37 | J | 1.03 | 9 | 1.40 |
| 13 | 0.79 | 10 | 1.12 | | | | | 10 | 1.21 |
| 14 | 0.66 | 11 | 1.16 | | | | | | |

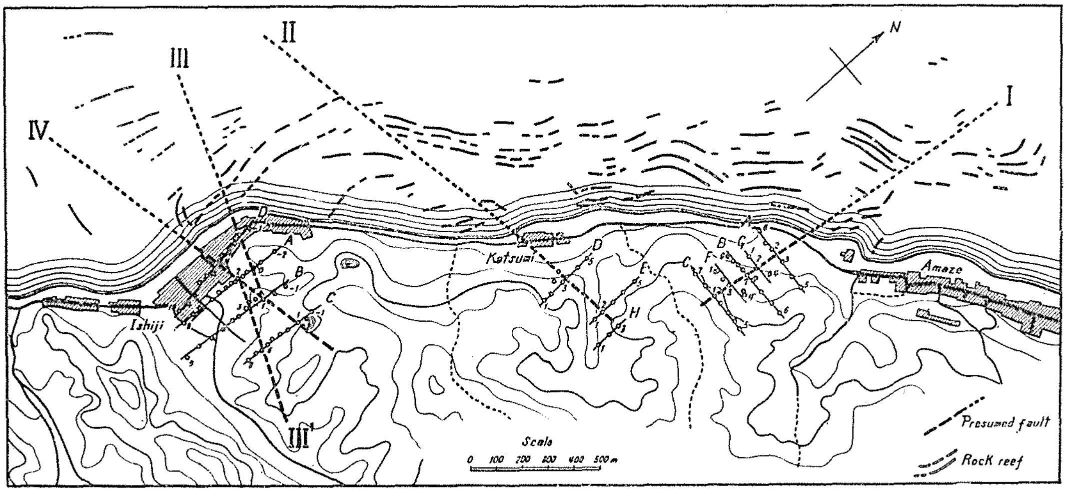


Fig. 21

due to a certain underground structure. Investigation of these irregularities, however, are omitted here.

Of the two faults presumed here radioactively, the west one (Fig. 19) would in all probability be the projection on the surface of the earth of the subterranean outcrop of the fault geologically assumed between the wells No. 1 ($R_1$) and No. 2 ($R_2$) as already mentioned, and the east one is the fault newly inferred by the present radioactive prospecting. The trend of the west fault having been thus confirmed radioactively, the two new wells No. 4 ($R_4$) and No. 5 ($R_5$) were drilled in 1948 and found to be oil-productive.

(2) Research at Amaze Oil-field in Niigata Prefecture. (10–17th, Sept., 1947 and 16–21th, April, 1948).

Along the coast of Amaze (The Sea of Japan) and its neibourhood there have been found a number of reefs lying more or less in order at the sea bottom. Judging from discontinuity in their arrangement, several faults have been assumed. The aim of this research was to check the supposed faults with the radioactivity determinations of their extensions on the land.

In the Amaze area the measurement was first made along three lines, A, B and C, which were transversal to the prolongation on the land area of the supposed fault line I (Fig. 21). A hump was observed in the middle of line A and on line C (Fig. 22), a conspicuous peak was found at station C-1, but in the corresponding place on line B appeared an M-shaped variation of which the minimum occurred at station No. 2. Near this station the ground was swampy, but after several trials we were barely able to find out the points (stations No. 2 and No. 7) where the collection of underground air was possible. Considering the position of the peak on line C, we had to expect a similar peak in the site between stations No. 2 and No. 7 on line B. The depression in the M-shaped variation could be explained by the dampness of the soil there which suppressed the rising of radon from beneath. The results of auxiliary measurements along lines G and F would support this view. In consequence, a fault (I) passing through station C–1, and the midst of B–2 and B–7 (situated near the middle point of M-shaped variation) and of A–2 and A–3 may be inferred.

Similar conditions were met at Katsumi about 1 km southwest of the field mentioned above. The supposed fault II was running east by north through Katsumi hamlet. At first we prepared three lines of survey. Along E-line a definite peak of radioactivity was observed near station No. 2, but along D-line was also found a peak which was not so conspicuous. Stations No. 6 and 7 of D-line considerably deviated from the main trend as they were chosen so as to avoid damp ground. As for H-line, we expected a maximum value near station No. 3, and indeed radon content increased from No. 1 to No. 2, but observation at station No. 3 could not carried out owing, regretably, to the break down of the boring stick, the repair of which was impossible for lack of time. During the observation there, a typhoon passed the Kwantô district and it might have somewhat disturbed the results with low pressure and copious rain.

Near Ishiji Town a similar investigation was made next spring. The geological conditions were the same as in the former cases. Lines A, B and C lay

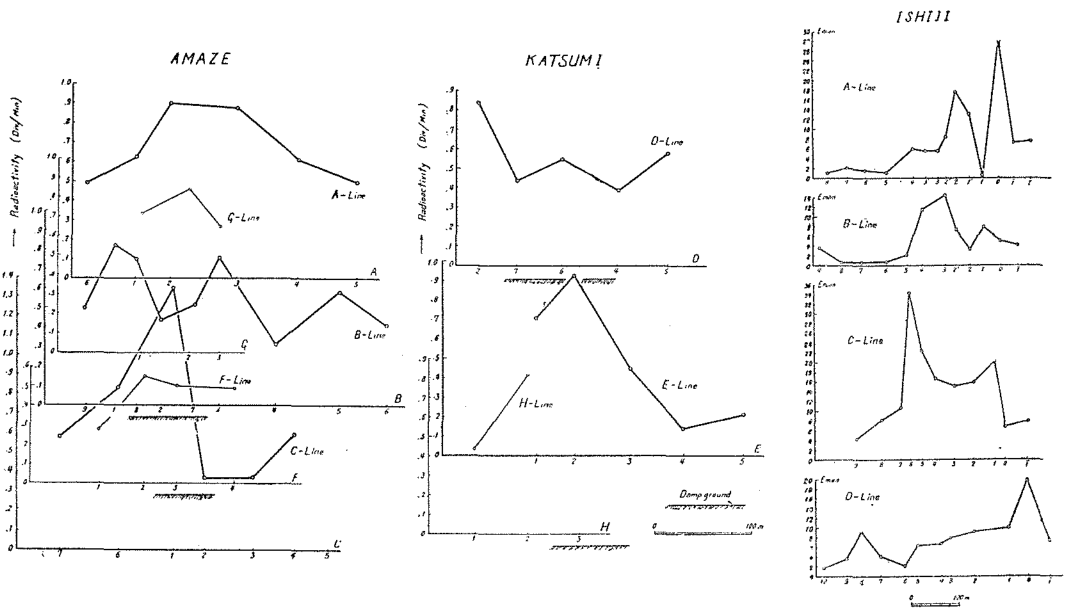


Fig. 22

mostly on the hillsides of a Tertiary formation behind the town and line D on the sandy shore along a main street of the town. The radioactive profiles obtained along these lines are shown in the right hand side of Fig. 22. The interpretation of the results, as shown in Fig. 21, was also possible by the landward prolongations of faults III and IV supposed on the sea bottom.

A presumed fault III running through a gap of rows of rock reefs on the sea bottom was found landing in the south-east direction near station D–0, then passing through station A–0, and reaching staion B–1. Being cut by another fault IV running east and west, this fault started from station A–2 and found its extension through stations B–3 and C–6.

In all, it may be said that not only the existence of the assumed faults conjectured from the arrangement of submarine rock reefs was verified but also the existence of their extensions on the land area were confirmed by the radioactive method.

(3) Research in Shimizu Gas-field (May 3– June 6, 1948).

Natural gas occurrs in the shearing zone of the Tertiary sediments in Shizuoka district. Near Shimizu City, gas reservoir beds are found by well data at three depths 35 m, 55 m and 70 ~ 160 m, with thicknesses of 10 m, 2 m and 14 ~ 17 m respectively. Of these, the shallower two beds are in the alluvium, while the last is located in the breaking zone of Tashiro-tôge Thrust, which is the most important gas-producing layer. Radioactively this thrust was traced for its southwestern extension near Nagasaki in Udo Village for the purpose of finding the proper positon of a gas well to be newly bored.

The area surveyed was, for the most part, rice fields of which some were then already irrigated and the rest left unwatered, so stations were mostly chosen on the dry vegetable field. As it had been found by the preliminary test that the soil about 40 ~ 50 cm from the ground surface was blue clay and dampy in general, the ground-hole-ionization-chamber method was used instead of the radon-in-soil-air method in which extraction of soil air was supposed to be very difficult in these circumstances.

Measurements were made in the usual way except for adoption of a 60 cm depth for the ground hole instead of the usual 1 m, owing to the shallowness of the underground water level. The electroscope used, a top of IM fontactoscope, was damaged after the observation of the first and fifth lines of stations, and the remaining lines were surveyed with an electroscope of Ambronn-type fontactoscope which was lent to us by courtesy of the then Underground Resources Surveys of the Department of Commerce and Industry. Using this electroscope the observations along the first line were repeated, and by the repetition the ratio of constants of the two electroscopes was determined. This ratio was employed to express the values obtained by the IM electroscope in terms of those by the Ambronn-type electroscope.

Observations were carried out along ten traverse lines with station intervals usually of about 40 m; sometimes the distance was reduced to 10 m according to circumstances. Along some traverses observations were repeated on different days. The results showed a fair accord in the general trend, with slight differences in values of radioactivity at individual stations. As the change in barometric pressure, wind and rainfall should have effects upon the radioactivity in the ground hole, observations along one traverse were usually accomplished in a single day.

The observed radioactive profiles along all the traverse are shown in Fig. 23. In Fig. 24 are also shown the traverses of stations and the position of the subsurface outcrop of the fault (thick broken line of wavy form) which can be presumed from the positions of the peaks of the radioactive profiles. In the area surveyed, the dissected Tertiary formation is overlain by alluvial deposits. Hence it is very likely that here the topography of the surface of the bedrock underlying the area is a continuation of that of the hill (Tertiary formation) slightly northwest of the surveyed area. As stated above, if a thrust, presumably the extension of Tashiro-tôge Thrust, passes under this area with a northwest inclination of a relatively low angle, e. g. 20°~ 30° as may be assumed from the well data of Oshikiri producing field situated near this area, the projection of

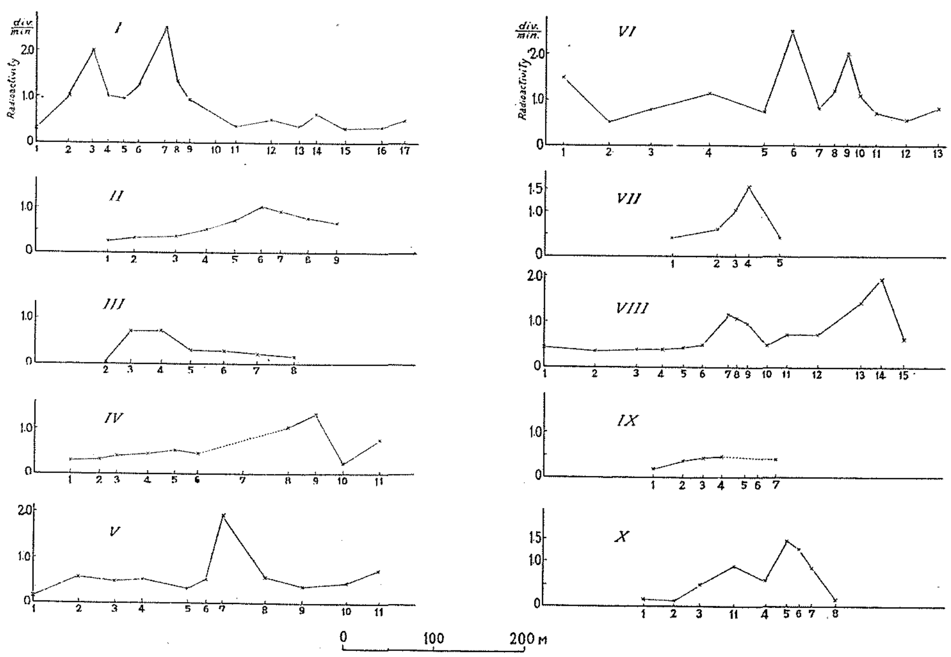


Fig. 23

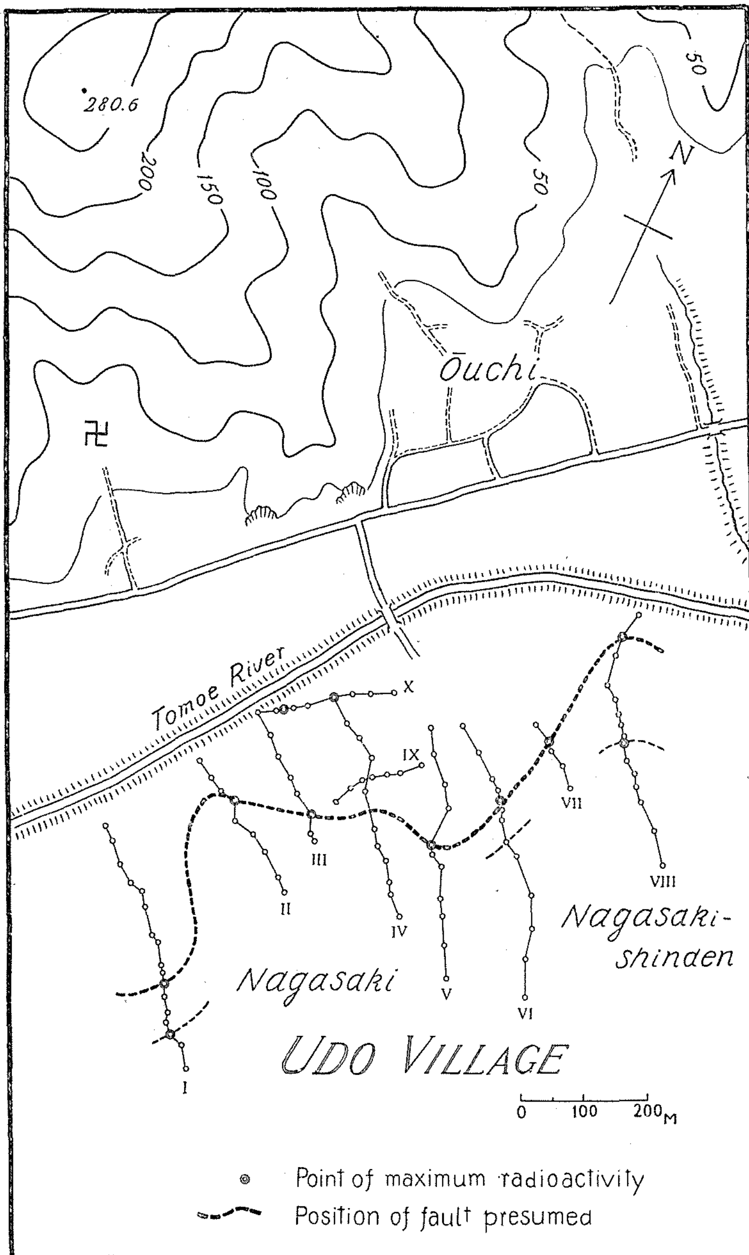
280.6
200
150
100
50
50
N
Ōuchi
Tomoe River
X
IX
VII
III
II
IV
V
VI
VIII
I
Nagasaki
Nagasaki-
Shinden
UDO VILLAGE
0 100 200M
Point of maximum radioactivity
Position of fault presumed

Fig. 24

intersection of the thrust plane with the undulatory surface of the bedrock upon the surface of the ground will be a wavy curve. Comparing the form of the subsurface outcrop of the thrust (Fig. 24) with the contours of the near-by hill, we could come to a conclusion that the former is the projection of intersection of the two surfaces just mentioned. From the peaks at stations I–3, VI–6 and VIIII–7, we can infer the existence of a branch of the main fault situated on its south side. Such a branch is often observed in the surface geological survey along Tashiro-tôge Thrust in the northern part of this area.

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