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AN EVALUATION OF GEOTHERMAL ENERGY IN JAPAN

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SUMMARY

An attempt is made to evaluate the geothermal energy in Japan, on the following assumptions:

(1) There are about 200 volcanoes of the Quarternary in Japan.

(2) Magma chambers were identical in shape and size and formed regularly at constant intervals of 500 years.

(3) The shape of the chamber is cylindrical, 10 km in depth, 5 km in radius and 5 km in thickness.

(4) When molten magma is solidified, it discharges 5 weight percent of steam. The temperature of magma chamber drops linearly from 1200°C to 900°C, and the rate of discharge of steam is uniform. Total energy stored in magma chambers is obtained as $E = 2.367 \times 10^{18}$cal. If the total steam energy is converted into electric power at the heat efficiency of 12%, the resulting power will be about 12,000 MW.

INTRODUCTION

A few attempts have been made to evaluate geothermal energy by means of calculations on the stored heat of hydrothermal areas or the heat of hot rocks (see References). The present author has attempted to evaluate geothermal energy by a new method. In the consideration of steam energy, unknown factors are involved, and the following assumptions must be made:

(1) It is known that there are about 200 volcanoes in Japan. Let us assume that there is one latent magma chamber in each volcanic area and that magma chambers were formed at regular intervals. If we estimate the formation period of 200 magma chambers as $1 \cdot 10^5$ years, magma chambers will have been formed at an interval of 500 years.

(2) It is assumed that the initial temperature of a magma chamber is 1,200°C, and the temperature drops linearly until it becomes 900°C, discharging steam at a uniform rate. In fact, steam will be generated even at temperatures below 900°C, if the ground water is supplied to the chamber, but the problem lies outside our present consideration. When molten magma is solidified with the drop in temperature, it discharges 5% of its weight in steam.

(3) It is assumed that magma chambers are identical in size and shape,

being cylinders of vertical axis, with a radius of 5 km, a height of 5 km, and being 10 km below the ground surface.

According to Fukutomi's (1964) calculation of heat conduction, the magma chamber with the above mentioned depth and size would require $7 \cdot 10^4$ years in order to cool from 1,200°C to 900°C. We have therefore to consider that the magma chambers formed before $7 \cdot 10^4$ years ago should be excluded from the object of evaluation. This consideration leaves 141 magma chambers out of 200.

In short, this evaluation has been made by treating the steam energy in magma chambers as a progression in accordance with the period of their formation and by calculating the amount of energy as the sum total.

NUMBER OF MAGMA CHAMBERS NECESSARY FOR EVALUATION

When a magma chamber is cooled by heat conduction only, the one formed $7 \cdot 10^4$ years ago is expected to have become 900°C at present. As a matter of fact, however, the temperature of the magma chamber formed $7 \cdot 10^4$ years ago has dropped to a temperature below 900°C, since there is energy discharge due to heat flow from the geothermal areas or volcanic activities in the past. Hence the magma chamber that maintains the temperature of 900°C at present is necessarily the one formed x years after $7 \cdot 10^4$ years ago. Taking this view into consideration, we get the following relation:

$$Q_c x = Q_h\,(7 \cdot 10^4 - x) + Q_e \tag{1}$$

where: Q_c = heat energy discharged from the magma chamber in one year by conduction; Q_h = amount of heat flow from the geothermal areas in one year; and Q_e = energy of volcanic activities.

Estimation of Q_c

The total energy discharged when the temperature of a magma chamber drops from 1,200°C to 900°C will be:

$$\rho C V\,(1{,}200 - 900) = 159 \cdot 10^{15} \quad \text{(kcal.)}$$

where: ρ = density of molten magma = 2.6 g/cm^3; C = effective specific heat of molten magma = 0.518 cal./g°C; and V = volume of magma chamber = $3.925 \cdot 10^{17}$ cm^3.

The energy discharge will be different in accordance with the solidification stage of the magma chamber, but for simplicity we shall assume that it takes place at a uniform rate, then:

$$Q_c = 159 \cdot 10^{15}\ \text{kcal.}/7 \cdot 10^4\ \text{year} = 227 \cdot 10^{10}\ \text{kcal./year}$$

Estimation of Q_h

The amount of heat flow from geothermal areas in Japan is comparatively small and the measured value reported so far is about $10 \cdot 10^3$ kcal./sec.

The annual amount of heat flow Q_h is, therefore:

$$Q_h = 10 \cdot 10^3 \text{ kcal./sec} \times 315 \times 10^5$$
$$= 315 \cdot 10^9 \text{ kcal./year}$$

Estimation of Q_e

Nakamura (1965) has proposed the following equation as the energy of volcanic activities:

$$Q_e = 1.6 \pm 0.4 \cdot 10^{10} \times M \text{ ergs}$$

M is the weight (g) of erupted rocks.
If we assume now that there is a cone shaped volcano 500 m in height, 30° in slope angle and that there is underground distribution of lava 2 km long, 2 km wide and 1 km thick, the result will be $M = 1.1 \cdot 10^{16}$ g.

$$\therefore Q_e = 525.6 \cdot 10^{13} \text{ kcal.}$$

Substituting the values of Q_c, Q_h and Q_e into eq. 1 we get $x =$ 10,500 years. Since the formation interval of magma chambers is 500 years, twenty-one magma chambers were formed during this period. That is, the number of magma chambers relevant to the present calculation becomes 120.

ESTIMATION OF STEAM PRESSURE AND SPECIFIC HEAT OF STEAM IN MAGMA CHAMBER

It is necessary for evaluating the steam energy discharged from a magma chamber to know the specific heat of steam, for which we have to estimate the steam pressure in the magma chamber. It seems that a magma chamber is not connected to the surface when it is formed, but that after activity is begun, the chamber may be open to the surface through the channels of the erupted lavas.

The mechanism of the opening of magma chambers is not well known at present, because we have no knowledge of the elastic strength of high temperature rock bodies surrounding the magma chamber. Here the author will assume that the magma chamber is connected with the surface through the hot water reservoir. That is, it was assumed that the magma chamber is subjected to the hydrostatic pressure of water in cracks or the pore water pressure of the stratum.

While the underground temperature gradient is controlled by the thermal conductivity of the stratum, an assumption is made here that the stratum is uniform and that the temperature between the surface and magma chamber is distributed linearly.

Now let us assume for simplicity that the specific volume of water to the depth of 2 km is constant and then evaluate the hydrostatic pressure at the depth of 3 km.

If we assume that the hydrostatic pressure at the depth of 2 km is 200 atm. and that the temperature is 240°C, the specific volume of water obtained from the steam table will be 0.0012 m^3/kg. Letting hydrostatic pressure at the depth of 3 km be 200 atm. as the first approximation and temperature be 360°C, the specific volume obtained from the table will be 0.0019 m^3/kg. As a result, the mean value of the specific volume and the hydrostatic pressure in the first approximation will become as follows:

$$\tfrac{1}{2}\,(0.0012 + 0.0019) = 0.0016\ \mathrm{m^3/kg}$$

$$P_1 \fallingdotseq 200 + \frac{1{,}000}{0.0016} \times 10^4 \fallingdotseq 260\ \mathrm{atm.}$$

In the second approximation, hydrostatic pressure at the depth of 3 km is put as 260 atm., which was obtained from the first approximation with temperature at 360°C. Then we can get 0.0017 m^3/kg from the table as specific volume, and the mean specific volume and hydrostatic pressure will become as follows:

$$\tfrac{1}{2}\,(0.0012 + 0.0017) = 0.0015\ (\mathrm{m^3/kg})$$

$$P_2 \fallingdotseq 200 + \frac{1{,}000}{0.0015} \times 10^4 \fallingdotseq 270\ (\mathrm{atm.})$$

Thus 270 atm. is obtained as the hydrostatic pressure at the depth of 3 km.

In the same way we can get 290 atm. as the hydrostatic pressure at the depth of 4 km. In this case, the value of the first approximation is almost equivalent to that of the second approximation.

The steam pressure of the magma chamber can be estimated by assuming that the law of Boyle - Charles holds between the depth of 4 km and 10 km:

$$Pv = RT \tag{2}$$

$$p(H) = \int \frac{1}{v(H)}\, \mathrm{d}H \tag{3}$$

Here P is the pressure in atm., v is specific volume m^3/kg, T is absolute temperature °K and H is height m of the fluid.

From eq. 2:

$$R = \left(\frac{Pv}{T}\right)_{4\ \mathrm{km}} = \frac{290 \times 0.00864 \times 10^4}{480 + 273} \fallingdotseq 33.2$$

From eq. 3:

$$P(H) = \int_{4\ \mathrm{km}}^{10\ \mathrm{km}} \frac{1}{v(H)}\ \mathrm{d}H$$

$$\frac{\mathrm{d}P}{P} = \frac{1}{R}\,\frac{\mathrm{d}H}{T} = \frac{1}{R}\,\frac{H}{T}\,\frac{\mathrm{d}H}{H}$$

$$\left[\ln P\right]_{4\ \mathrm{km}}^{10\ \mathrm{km}} = \frac{1}{R}\,\frac{H\ 10\ \mathrm{km}}{T\ 10\ \mathrm{km}}\left[\ln H\right]_{4\ \mathrm{km}}^{10\ \mathrm{km}}$$

$$\therefore \ln \frac{P\ 10\ \mathrm{km}}{P\ 4\ \mathrm{km}} = \frac{1}{R}\,\frac{H\ 10\ \mathrm{km}}{T\ 10\ \mathrm{km}}\ \ln \frac{10}{4}$$

$$= \frac{1}{33.2} \times \frac{10{,}000}{1{,}200 + 273}\ \ln 2.5$$

$$= \ln 2.5^{0.24}$$

$P_{10\ \mathrm{km}}$ = 1.25

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$$P_{10\text{ km}} = 1.25 \times P_{4\text{ km}} \fallingdotseq 360 \text{ (atm.)}$$

The specific heat of steam at 900–1,200°C and 360 atm. is estimated to be approximately 0.7 kcal./kg°C from the steam diagram.

SUM TOTAL OF STEAM ENERGY HELD IN MAGMA CHAMBERS

The amount of steam generated when magma is solidified will be $512 \cdot 10^{11}$ kg since it has been assumed to be 5% of the weight of magma. Discharge of the steam is assumed to be maintained uniformly at the temperature between 1,200°C and 900°C. The temperature and the steam energy of the newest magma chamber are the greatest, and the steam energy held in a magma chamber of each period may be expressed as follows.

Steam energy of magma chamber	period of formation
$E_o = C_p \times 1{,}200 \times S$	present
$E_1 = C_p\,(1{,}200 - d_t)(S - d_g)$	500 years ago
$E_2 = C_p\,(1{,}200 - 2d_t)(S - 2\,d_g)$	1,000 years ago
$E_{m-2} = C_p\,\{1{,}200 - (m-2)d_t\}\{S - (m-2)d_g\}$	59,000 years ago
$E_{m-1} = C_p\,\{1{,}200 - (m-1)d_t\}\{S - (m-1)d_g\}$	59,500 years ago

$$E = E_o + E_1 + E_2 + \ldots + E_{m-2} = E_o + C_p\,(m-1)\left\{1{,}200\,S - \frac{(m-2)}{2}\,(d_t \cdot S + 1{,}200\;d_g)\right\} + \frac{(m-2)(2m-3)}{6}\,d_t \cdot d_g \tag{4}$$

Where: C = specific heat of steam at constant pressure = 0.7 kcal./kg · °C
m = number of magma chamber = 120
S = maximum steam amount of magma chamber = $512 \cdot 10^{11}$ kg
d_t = common difference of temperature = 300°C/119
d_g = common difference of steam amount = $512 \cdot 10^{11}$ kg/119

Substituting these numberical values into eq. 4 we get:

$$E \fallingdotseq 24 \cdot 10^{17} \text{ kcal.}$$

CONCLUSION

With a view to making a rough estimation of the geothermal energy in Japan, the total sum of steam energy in magma chambers was calculated. This evaluation has been made by treating the steam energy in magma chambers as a progression in accordance with the period of formation and calculating the amount of energy as the sum total. The figure obtained as the result was $24 \cdot 10^{17}$ kcal. Since various assumptions were made in the calculation, the numerical value is expected to vary under different conditions. It is, however, conceivable that the above-mentioned figure can be regarded as an approximate standard.

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