

WATER CONTENT IN THE CRUST AND THE HYDROTHERMAL REACTION AS A POSSIBLE CAUSE FOR THE SWARM-TYPE EARTHQUAKE

By

Shogo MATSUSHIMA

(Received November 29, 1967)

Abstract

The volume change by the phase transformation has been supposed as an important cause for the earthquakes. The possibility that the hydrothermal reaction will be the cause for the earthquakeswarm is studied. From the estimated curve of maximum water content in the crust, it is concluded that one of the most active region of the earthquakeswarms will be the place of active hot springs along the volcanic belt and at the depth of 3-10 km.

Some estimations were attempted about Matsushiro earthquake as an example. The calculated heat energy of reaction is about 8×10^{22} ergs and the elastic energy by the volume increase is 10^{22} ergs. Enough water supply is expected on the assumptions that the vapor pressure gradient is 10^{-3} - 10^{-2} bar/cm, the clearance of crack is 10^{-1} -1 cm, and the porosity for crack is 10^{-4} - 10^{-5} at and around the seismic sphere.

1. Water content in the earth's interior

One of the most important factors which affect the tectonic phenomena in the earth's crust and the upper mantle is the existence of water there. For the cases of earthquake occurrence, it is widely understood that the intergranular fluids reduce the friction of the sliding surface extremely, as well as decrease the effective pressure which substantially affects the brittleness of material (Handin [1966]). High vapor pressure also reduces the melting temperature of rocks in the upper mantle (*e.g.*, Shimada [1966]). If the local heating occur and some quantity of free water come out by the dehydration reaction at that place, the partial melting will begin to produce the thin layer of the molten magma. Many other tectonic processes will be closely connected with the existence of water in the earth's crust and the upper mantle.

Unfortunately, quite less informations about the existence of water in the earth's interior have been presented. However, in recent years, the stability conditions for many kinds of hydrated minerals have been studied experimental-

ly (Clark [1966]), not only at low pressures but also at sufficiently high pressures which cover the wide region of the upper mantle (Newton and Kennedy [1963], Kitahara *et al.* [1966], Newton [1966], and Matsushima *et al.* [1967]). It seems that there are clear tendency that the minerals containing a great deal of water of crystallization have the low dehydration temperature. The relation of water content and the equilibrium temperature for the various dehydration reactions is shown in Fig. 1. As for the following reaction

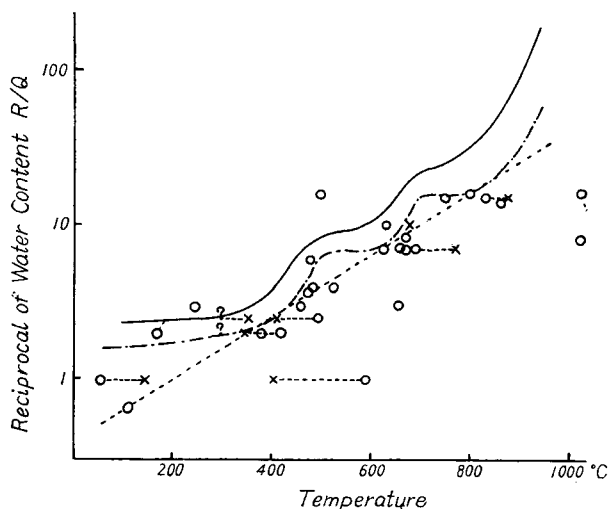
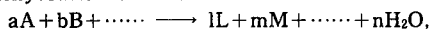
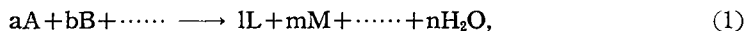


Fig. 1. Relation of the reciprocal of water content of reactants, R/Q , and the equilibrium temperature for the dehydration reaction



where R and Q are the number of cation and water of crystallization in reactants, respectively. The open circles and the 'x' marks are the experimental values and the calculated ones, respectively.



put the number of cation in the reactants R , and the amount of water of crystallization in the same minerals Q . In Fig. 1, the ratio R/Q for the various reactions are plotted to the equilibrium temperature at 1 kb. The ratio R/Q represents the reciprocal of water content and means the ability of water absorption at the temperatures less than the equilibrium one for the material with some chemical composition. The dotted line in Fig. 1 shows the approximate relation of R/Q and T for the various reactions at high pressure above 1 kb. The equilibrium temperature increases rapidly with pressure up to 1 kb, however it will be regarded as constant above 1 kb.

If we give attention to some fixed simple chemical composition, the curve of water content for the material with this composition is not smooth but changes

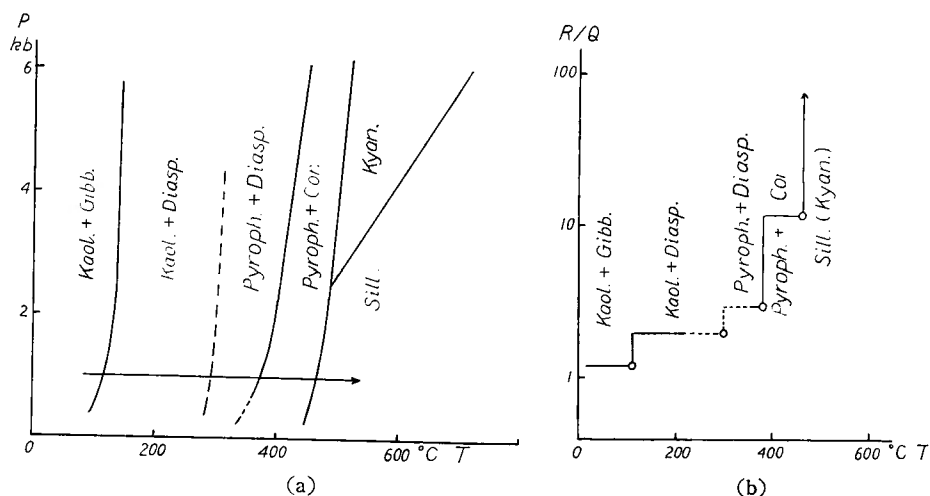
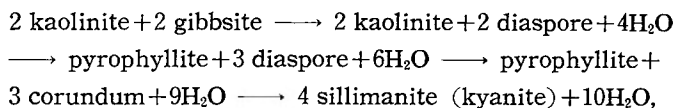


Fig. 2. (a) The equilibrium diagram, and (b) the relation of reciprocal of water content R/Q and the equilibrium temperature T at 1 kb, for the material with the chemical composition Al_2SiO_5 .

stepwise. Fig. 2(a) shows the dehydration diagram of mineral assemblage with the composition Al_2SiO_5 (Matsushima *et al.* [1967]). For the series of the dehydration reaction



the relation of water content is given in Fig. 2(b). It seems, from Fig. 1, that the most of equilibrium boundaries drop in three temperature ranges 400–500°C, 600–700°C and 800–900°C. If the material with any chemical composition has the stable hydrous phases up to enough high temperature, water content in the earth's interior will have the curve shown as the broken line in Fig. 1. However, the kind of the stable hydrous phase decreases rapidly with temperature above 500°C, then the materials with quite limited compositions only make the complete assemblages of the hydrous phases and the one with the arbitrary composition makes only the mixture of hydrous and unhydrous phases. Then the curve of water content in the earth's crust will be very much shifted upward at high temperature side, like as the solid line in Fig. 1.

2. Dehydration temperature

The equations for the calculation of the equilibrium temperature of the dehydration reaction have been given by many authors (*e.g.*, Greenwood [1963]). These formulas are rather complicated for the actual calculation, notwith-

standing some approximations are taken into the formulas. The quite simple formula which relates the heat of reaction at the standard state and the equilibrium temperature at the moderate vapor pressure is given in the following. The free energy of the reaction ΔG^R at P, T is

$$\Delta G^R = \Delta H_o + \int_{T_o}^T \Delta C_p dT - T \Delta S_o - T \int_{T_o}^T \frac{\Delta C_p}{T} dT + P \Delta V_o^c + RT \ln f^w, \quad (2)$$

where subscript o refers to the standard state (1 atm., 25°C), and superscripts c and w refer to the solid phases and water, respectively. Separate ΔG^R into the solid phases and water, the result is

$$\Delta G^R = \Delta H_o^c - T \Delta S_o^c + P \Delta V_o^c + \int_{T_o}^T \Delta C_p^c dT - T \int_{T_o}^T \frac{\Delta C_p^c}{T} dT + G^w, \quad (3)$$

$$G^w = G_T^w + RT \ln f^w,$$

or

$$\Delta G^R - \Delta H_o^R = -T \Delta S_o^c + \left[P \Delta V_o^c + \int_{T_o}^T \Delta C_p^c dT - T \int_{T_o}^T \frac{\Delta C_p^c}{T} dT \right] + (G - H_o)^w. \quad (4)$$

At equilibrium,

$$-T \Delta S_o^c + \Delta H_o^R + (G - H_o)^w + \left[P \Delta V_o^c + \int_{T_o}^T \Delta C_p^c dT - T \int_{T_o}^T \frac{\Delta C_p^c}{T} dT \right] = 0. \quad (5)$$

If the pressure and the temperature is not too high, the terms in the parentheses can be neglected, and the formula becomes,

$$-T \Delta S_o^c + \Delta H_o^R + (G - H_o)^w = 0. \quad (6)$$

As is shown in Fig. 3, the approximate linear relation holds between $(G - H_o)^w$ and temperature, above 200°C. The relation is,

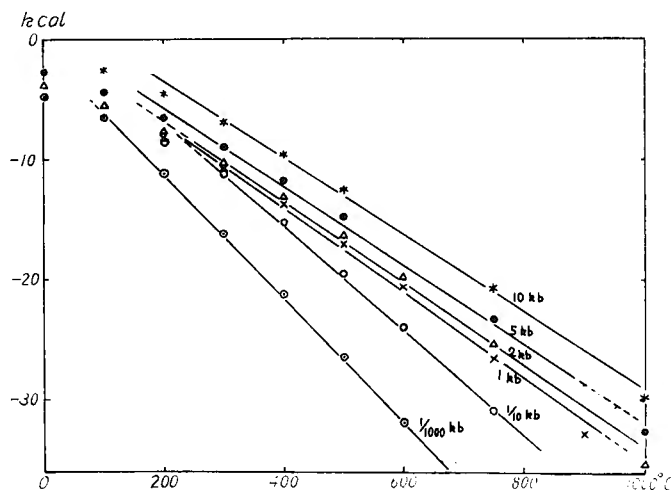


Fig. 3. Temperature variation of free energy of water at high pressures (after Sharp [1960]).

$$(G-H_o)^w = n\{a(T-T_o')-b\}, \quad (7)$$

where n is the quantity of free water in the equation (1), a and b are the functions of pressure only, and T_o' is some fixed temperature (0°C , for the present case). If we put ΔS_o^c and ΔH_o^R as follows, respectively,

$$\Delta S_o^c = n\Delta S_o', \quad \text{and} \quad \Delta H_o^R = n\Delta H_o', \quad (8)$$

equation (6) becomes

$$(T-T_o') + \frac{\Delta S_o' T_o' - b}{\Delta S_o' - a} = \frac{\Delta H_o'}{\Delta S_o' - a} \quad (9)$$

or

$$(T-T_o') + A = \frac{JH_o'}{B}. \quad (10)$$

$\Delta S_o'$ is the entropy change for the solid phases only per one mol of free water in the dehydration reactions at the standard state, which is ranging from 5 to 9 e.u.. Putting $\Delta S_o' = 7$ e.u., and using $a = -34$ cal/deg and $b = -1000$ cal for the water pressure of 1 kb in (7), we have the following equation,

$$(T-T_o') = \frac{\Delta H_o' \text{ (cal)}}{27 \text{ (cal/deg)}} + 70. \quad (11)$$

The calculated temperature for the several dehydration reactions are also shown in Fig. 1. The minerals with high R/Q have the high values of JH_o' based on the standard heat of formation of oxides. This suggests that the equilibrium temperature is higher for the reactions including the minerals with higher R/Q .

3. A possible cause of the earthquakeswarms

In a previous paper (Matsushima [1966]), the classification of earthquake sequences was attempted based on the experimental study of rock fracture in the solid medium. It was concluded that the type of the earthquake sequence largely depends on the focal depth of shocks, and there remains a large quantity of unreleased stress after the fracture in the deep (in relative sense) seismic region. The most of shallow earthquake groups are classified into two types of sequence, that is, the aftershock type and the earthquakeswarm type. The aftershock type means that a major part of stress is released by one main shock, while the earthquakeswarm type suggests that the only quite minor part of stress is released by every shock. The latter type rather resembles the feature of the shocks at the depths of the earth's interior. Therefore, it does not seem to be unreasonable to seek a cause of swarm-type earthquakes which is different from the tectonic origin.

It is well known that the much parts of swarm-type earthquakes have oc-

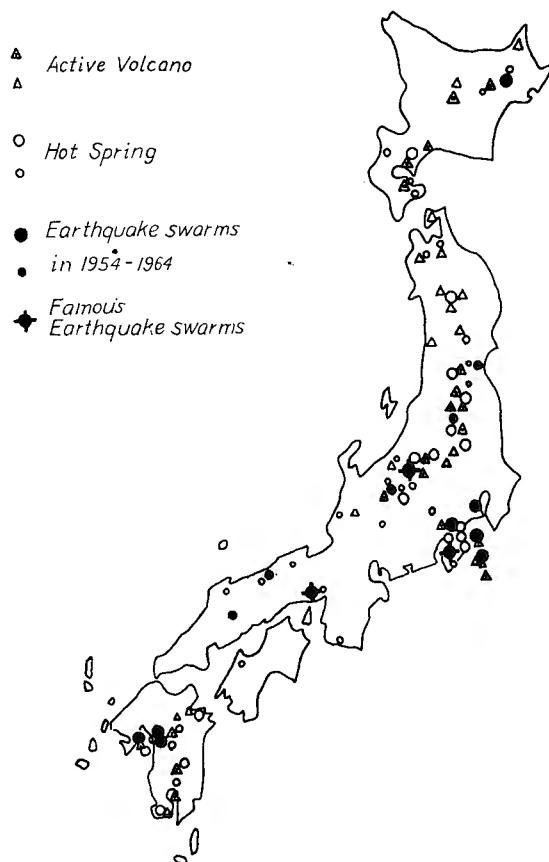


Fig. 4. Distributions of volcanoes, hot springs and earthquakeswarms in 1954-1964, in Japan Islands.

curred along the volcanic belt. In Fig. 4, the earthquakeswarms which occurred in 1954-1964 in Japan Islands are shown as well as the other three famous swarms. These are Arima [1899], Itoh [1930] and Matsushiro [1965-1967] earthquakes.

One of the most obvious cause of the earthquakeswarms is the active behavior of magma under the volcanoes. These are well known as the volcanic earthquakes type A (Minakami [1959]). However, such obvious volcanic earthquakes occur at quite limited districts, that is, at and immediate neighborhood of the active volcanoes. There have been many other shock groups occurred fairly far from the volcanic mountains. It will mean that the major cause of the earthquakeswarms does not always connect with the behavior of the volcanic magma, though it has still some relations with the volcanic phenomena in the crust.

It will be suggested from Fig. 4 that the hot springs will have some rela-

tions with the earthquakeswarms. The principal origin of the hot springs have been thought to be the active volcanoes or the recently frozen magma reservoir at the depths of the crust. The possibility that the hot underground water is the cause of the earthquakeswarms will be discussed in the followings. Many cases are considered for the function of hot underground water as the cause of earthquakes. These are the vapor eruption through the narrow fissures, decrease of solid friction or effective pressure, and the volume expansion of the medium by the hydrothermal reaction. In the present paper, the last case will be discussed in detail.

The hydration reactions which absorb a large amount of water will occur at the temperatures of 300–500°C, shown in Fig. 1. There is another important factor for the intensive hydration. It is enough supply of water into the reactive region. The state of water which is most abundant in the crust is the underground water, which will distribute in the uppermost layer of few km thick and will decrease rapidly with depth for the reason of the decrease of the intergranular porosity. The above stated conditions for the intensive hydration reaction suggest that the earthquake swarms by the hydration reaction will apt to occur under the district of active hot springs at the depth of 3–10 km, because it is expected that the temperature there is high enough, 400–500°C, and the plenty of water can be supplied.

4. An example of the numerical estimation: Matsushiro earthquakes

Matsushiro earthquakeswarm is the quite remarkable example. There is no active volcano near Matsushiro district, but there is an extinct volcano at the center of the district and many famous hot springs surround there. Many precise geophysical explorations have been reported about this earthquakes. Some calculations are tried for an explanation of Matsushiro earthquakeswarm, using the observed data. Let us prepare the necessary constants previously.

Assuming the temperature of the seismic region 400°C, and then the reciprocal of water content $R/Q \sim 4-5$, we have the following approximate values for the hydrothermal reactions at there.

- (1) One mol of water is absorbed in 100 cm³ of the materials of the reaction region.
- (2) The mean volume expansion of solid phase is 10% for this hydration reaction.
- (3) About 10 kcal is libeled as the heat of reaction at 400°C and 1–3 kb.

The radius of the nest sphere of shocks at Matsushiro district is about 4 km, and the center of the sphere is at the depth of 5–6 km (PSOME, ERI [1967]). The considerable crustal uplift was observed by the leveling plane

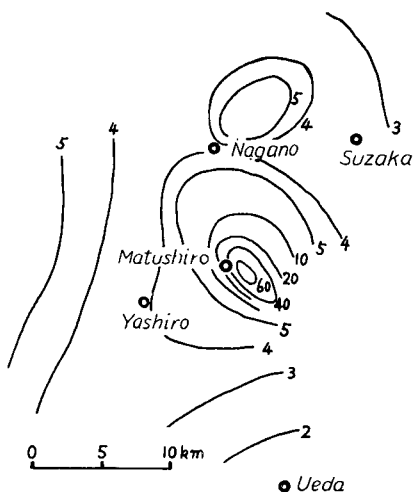


Fig. 5. Contour of the crustal uplift at Matsushiro district during the intensive swarm earthquakes, from April-June 1966 to September-December 1966 (after Geographical Survey Institute, and Earthquake Research Institute, University of Tokyo).

survey carried out before and after the most active period of swarm. The result is shown in Fig. 5. Assuming the uplift of the district 10 cm on the average over the whole area above the seismic sphere, we obtain the following values.

The surface area of this seismic

district is $5 \times 10^{11} \text{ cm}^2$,

the surface of the seismic sphere is

$2 \times 10^{12} \text{ cm}^2$,

the volume of the sphere is

$2.5 \times 10^{17} \text{ cm}^3$,

and the volume increase of the seismic

nest is $5 \times 10^{12} \text{ cm}^3$.

If we suppose that this whole seismic region had been compressed by the stress of 100 b on an average, and the whole stress was released by the shocks, the elastically recovered volume increase is

10^{13} cm^3 , assuming the Young's modulus 10^{12} and Poisson's ratio 0.3. There is the dilatancy effect accompanied by the breaking down of the brittle material. The volume expansion by the dilatancy is same order of magnitude as the maximum volumetric strain, at 1-3 kb (Brace *et al.* [1966]). Another origin for the crustal uplift is, of course, the volume increase by the phase change, the chemical reaction for the present case. The estimation for the last case is quite inconclusive and then the optional value will be used here. Now, if we assume 1/3 of the whole volume increase is attributed to the chemical reaction, the amount of the volume increase reaches to $5/3 \times 10^{12} \text{ cm}^3$. Then the material of $5/3 \times 10^{13} \text{ cm}^3$ is expected to participate in this reaction. It turns out that 2×10^{11} mols or 3.5×10^{12} grams of water are absorbed in this region. This reaction is exothermic, and

$$E_R \sim 8 \times 10^{22} \text{ ergs}$$

is generated as the heat of reaction.

Since the reactions occur here and there at the restricted parts in the seismic region, the volume expansion by this reaction is confined in quite limited part. Accordingly, the local stress or strain will reach at high value before fracturing. Put the maximum strain 10^{-2} , the total volume of the stressed region becomes $5/3 \times 10^{14} \text{ cm}^3$. The total elastic energy produced by the chemical

reaction is

$$E_e = \frac{1}{2} \mu \epsilon^2 \cdot V \sim 10^{22} \text{ ergs.}$$

On the other hand, the potential energy for the crustal uplift is about

$$E_p = Mgh \sim 10^{22} \text{ ergs,}$$

and the seismic energy is about (PSOME, ERI (1967)),

$$E_s \sim 2 \times 10^{21} \text{ ergs.}$$

The reaction rate and the water transfer are the important factors for the possibility of the hydrothermal reaction hypothesis. In the preceding discussion, the reaction rate was assumed to be high enough. It does not seem to be so unreasonable above 400°C, though no definite discussion has been presented about this problem. The transfer of enough water into the reaction region is closely related to the permeability at and around the region. Let us estimate the permeability at the surface of the sphere of this seismic region. The supplied water into this sphere should be $4 \times 10^{12} \text{ cm}^3$ in 10^8 sec. Assuming the pressure gradient of water at the surface of the sphere 10^{-3} – 10^{-2} bar/cm , and the viscosity of water $10^{-1} \text{ centipoise}$, we get the permeability k ,

$$k \sim 10^{-6}$$
– 10^{-7} darcy.

This high permeability will need the existence of a large number of cracks in the medium. Put the number of rectangular cracks with unit length in a unit volume m , the volume of water passing through a unit cross section in unit time is given as

$$Q_m = -m \frac{bd^3}{12\mu} \text{ grad } P,$$

where b is the width of crack and d is the clearance, if all the cracks are orienting to the normal of the cross section. Since the orientation of crack is at random, the component of water flow to the direction of the maximum pressure gradient is 1/3 of Q_m . Accordingly, the permeability for this medium is

$$k = \frac{1}{3} \frac{mbd^3}{12\mu}. \quad (12)$$

Put $b=ld$, the volume of cracks in a unit volume is $mbd=ml d^2$, and permeability is

$$k = \frac{1}{3} \frac{mld^4}{12\mu}.$$

Supposing the porosity for cracks 10^{-4} – 10^{-5} , and $d=10^{-1} \text{ cm}$, we have $ml=10^{-2}$ – 10^{-3} , and then

$$k \sim 10^{-7}$$
– 10^{-8} darcy.

It is concluded that the transfer of water of 2×10^{11} mols into the seismic region in a few years is not necessarily impossible.

However many uncertainties are left unsolved for the application of the present hypothesis to Matsushiro earthquakes. These problems must be solved in future for the study which hypothesis of earthquake origin is most suitable for each earthquake.

References

- Brace W. F., B. W. Paulding, Jr., and C. Scholz, 1966; Dilatancy in the fracture of crystalline rocks, *J. Geophys. Res.*, **71**, 3939-3953.
- Clark S. P., Jr., 1966; High pressure phase equilibria, in *Handbook of Physical Constants*, edited by S. P. Clark, Jr., *Geol. Soc. Amer., Mem.* **97**, 345-370.
- Greenwood H. J., 1963; The synthesis and stability of anthophyllite, *J. Petr.*, **4**, 317-351.
- Handin J., 1966; Strength and ductility, in *Handbook of Physical Constants*, edited by S. P. Clark, Jr., *Geol. Soc. Amer., Mem.* **97**, 223-289.
- Kitahara S., S. Takenouchi, and G. C. Kennedy, 1966; Phase relations in the system $\text{MgO-SiO}_2\text{-H}_2\text{O}$ at high temperatures and pressures, *Amer. J. Sci.*, **264**, 223-233.
- Matsushima S., 1966; Fracture of rocks in solid medium: - A consideration of the occurrence of the earthquake sequences, *Special Contr. Geophys. Inst., Kyoto Univ.*, **6**, 289-301.
- Matsushima S., G. C. Kennedy, A. Jagannadham, and J. Haygarth, 1967; A study of equilibrium relations in the system $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ and $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$, *Amer. J. Sci.*, **265**, 28-44.
- Minakami T., 1959; The study of eruptions and earthquakes originating from volcanoes (Part I and II), *Kazan (Jap. Volc. Soc.), Ser. II*, **4**, 104-114 and 115-130.
- Newton R. C., and G. C. Kennedy, 1963; Some equilibrium reactions in the join $\text{CaAl}_2\text{Si}_2\text{O}_8\text{-H}_2\text{O}$, *J. Geophys. Res.*, **68**, 2967-2983.
- Newton R. C., 1966; Some calc-silicate equilibrium relations, *Amer. J. Sci.*, **264**, 204-222.
- Sharp W. E., 1962; The thermodynamic functions for water in the range -10 to 1000°C and 1 to 250,000 bars, *Univ. Calif. Radiation Lab. Rept.* **7118**.
- Shimada M., 1966; Effect of pressure and water on the melting of basalt, *Special Contr. Geophysical Inst., Kyoto Univ.*, **6**, 303-311.
- The Party for Seismographic Observation of Matsushiro Earthquakes and the Seismometrical Section, Earthquake Research Institute, 1967; Matsushiro earthquakes observed with a temporary seismographic network, Part 3, *Bull. Earthq. Res. Inst., Tokyo Univ.*, **45**, 187-223.