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31. The Source Region of the Matsushiro Swarm Earthquakes.

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Abstract

Teleseismic and near-field data of the Matsushiro earthquakes were studied collectively in order to clarify the source mechanisms of the swarm activity. The author first applied Aki's and Brune's techniques to the Love waves recorded at Gifu, 180 km southwest of Matsushiro, and found that the seismic moment of major swarm shocks is about $0.7\sim3.5\times10^{22}$ dyne·cm for the magnitude range of $4.6\sim5.1$. Stress drop for these shocks is then estimated at $0.6\sim7.0$ bars, by assuming several other source parameters properly.

Comparison of the retriangulation data with theoretical fault models proved that horizontal ground movements in the epicentral area are attributed fairly well to a buried strike-slip fault, as formerly suggested by geologists on the basis of surface evidence. Geometrical dimensions of the buried fault were thus estimated at 3 km (deep)$\times$7 km (long), with surface cover of 0.5 km (thick). Land offset across the fault plane for about 2 m was also estimated. As was discussed previously, the fault is believed to have grown rather gradually through the various stages of activity. From this point of view, possible contribution from nearby shocks to the fault development was studied on the basis of a simple dislocation model to explain observations fairly well.

Analysis of leveling data resulted in another notable conclusion. The work done in the gravity field to achieve the observed land upheaval was estimated at approximately 1.7×10^{22} erg, which is almost ten times as large as the total seismic energy released from there. If this sort of energy originates from the strain energy in rocks, therefore, the apparent volume of seismic activity ($30\times15\times5$ km^3) seems too small to accumulate it. The crustal volume on a regional scale should be assumed as the energy source for the present activity. Bulk increase of fractured rocks was pointed out as one of the possible mechanisms of the local land upheavals referring to the remarkable gravity change detected in the same area.

Finally, research on the Matsushiro earthquakes by various groups was reviewed in order to develop a speculative picture of the seismic event which progressed in the Matsushiro area.

Contents

1. Introduction

The Matsushiro Seismological Observatory of J.M.A. recorded several earthquakes with very short S-P times on August 3, 1965. That was the very beginning of the Matsushiro swarm activity, although nobody understood correctly, at that time, what sort of event was starting under the ground. Indeed, the activity has continued for more than two years since then, releasing more than 700,000 large and small earthquakes from a limited volume of the crust. It is doubtlessly the highest swarm activity that is ever known.

The swarm was not so active in the first several weeks, but soon it started to increase more or less steadily until the first climax of activity was observed in November of the same year. The unlimitedly increasing activity and subsequent fear of the local people have attracted the notice of seismologists. Consequently a series of field expeditions has been organized on a national scale, coordinating all the university institutes and the governmental laboratories related to earthquake research.

The principal stages of the swarm appeared in 1966. In this year, we observed the two succeeding climaxes in the March-April and the September-November periods, respectively. After the last climax, which was associated with a large amount of outflow of underground water and disasterous land-slides, the swarm gradually turned to an inactive state, though we have recorded several felt shocks and several tens of unfelt shocks monthly, still now (April, 1970).

The Matsushiro swarm seems to be almost over. Results of the field expeditions, which were long continued by scientists from various organizations, are now being published in many reports on this particular event (cf. R. Morimoto and T. Hagiwara, 1967). Under these conditions, the present paper analyses the seismological and geodetic data of the swarm earthquakes to discuss the source mechanisms. In addition, it selects several of the published articles in order to develop an idea of the physical processes and tectonic background of this extraordinary activity.

2. Seismic source parameters

There have been developed useful techniques which enable us to derive the basic parameters of a seismic source from teleseismic signals. K. Aki (1966) presented a technique to estimate the seismic moment at a source by analysing the Love waves at remote stations. The Matsushiro earthquakes were so small that only domestic stations could record them clearly. For example, the Gifu station of J. M. A. has recorded many of the strong earthquakes at Matsushiro nicely on its Wiechert seismographs (Figs. 1 and 2). As can be seen from Fig. 3, the principal part of the seismogram is predominated by the tangential component, suggesting that it is attributed to the Love waves. The epicentral distance is only 180 km, approximately, but we may apply the teleseismic technique since it is still ten or more times as large as the effective wave-lengths. The station's location is found to be ideal for

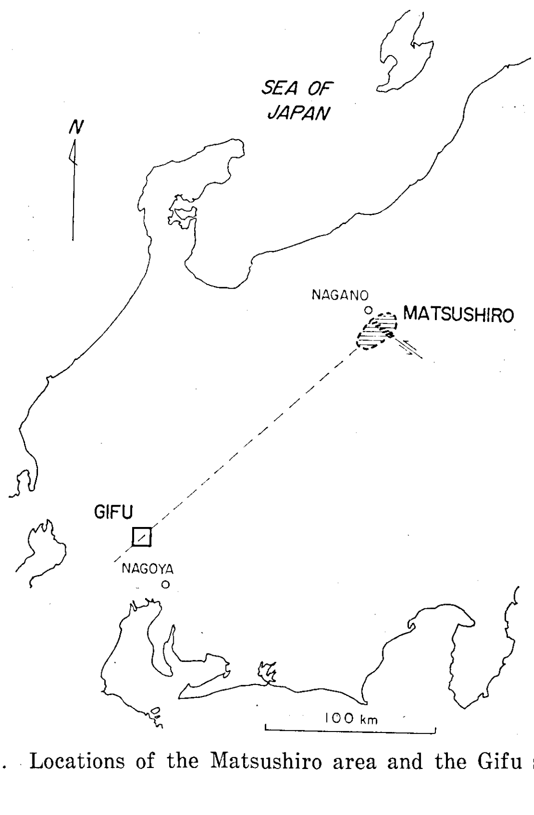

Fig. 1. Locations of the Matsushiro area and the Gifu station.

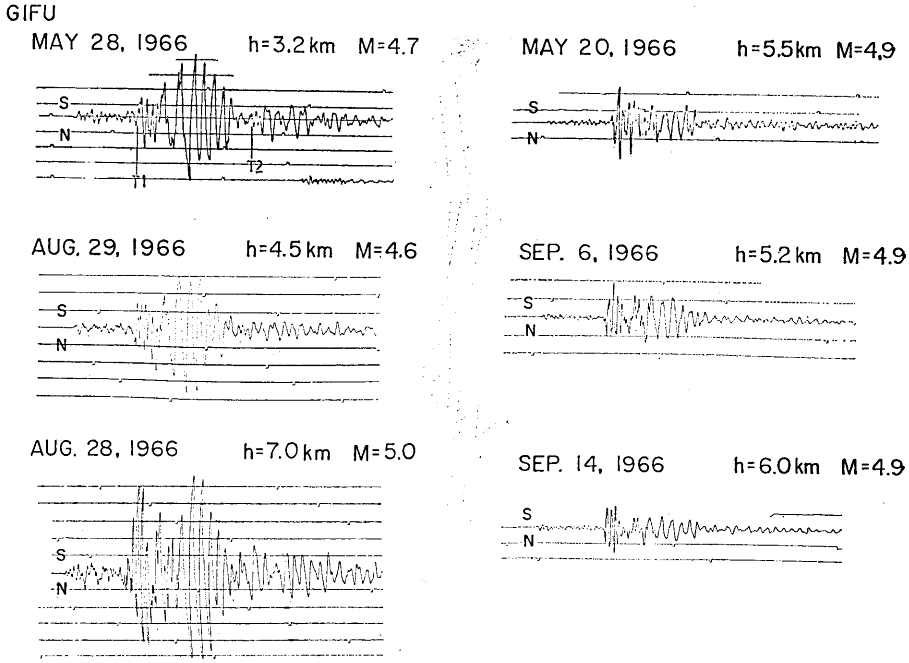

Fig. 2. Examples of the Matsushiro earthquakes recorded at Gifu.

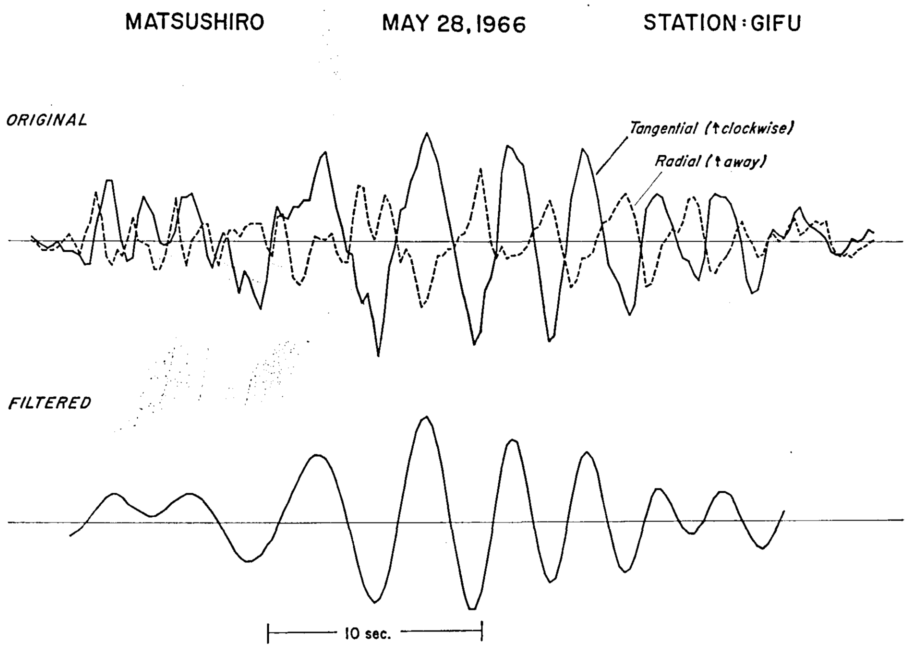

Fig. 3. Radial and tangential components of the principal part of a seismogram.

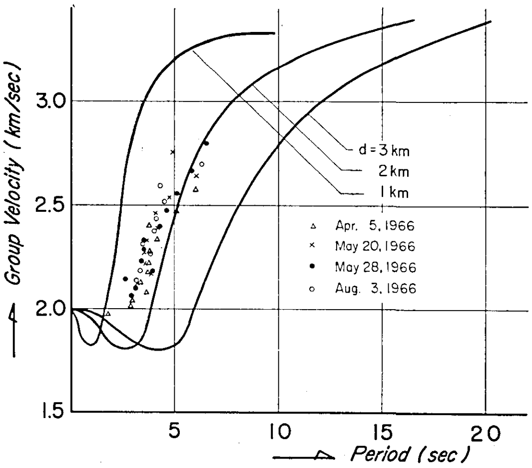

Fig. 4. Dispersion of surface waves.

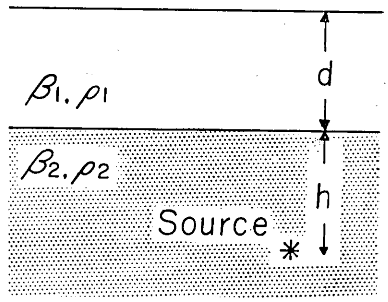

Fig. 5. Love-wave radiation from a buried source.

the present purpose, because it is located southwest of Matsushiro, which is the azimuth almost perpendicular to the extension of the supposed fault (see the next section) and to the trend of one of the nodal lines of the source mechanisms (M. Ichikawa, 1967).

Under these considerations, a dispersion curve was drawn as illustrated in Fig. 4, from which we learn that the observation is explained reasonably by a crustal model of shear wave velocity $(\beta_2)=3.5$ km/sec, with a surface layer of $\beta_1=2.0$ km/sec and $d=2$ km, where, β_1 and d denotes the shear wave velocity and the thickness of the first layer, respectively. Focal depths of the earthquakes in Fig. 2 are estimated at 3~7 km, which are obviously deeper than the bottom of the surface layer. In order to apply Haskell's theory (1964) to the present case, therefore, the writer followed Aki's paper and modified Haskell's equations for the source below the surface layer as follows (Fig. 5):

$$|u_\varphi(0)|=2B' \cos 2\phi, \tag{1}$$

where, $u_\varphi(0)$ is the Love waves amplitude at the surface, and

$$B'(\lambda, r, h)=\frac{\lambda e^{-\lambda r_{\beta_2} h}}{4\beta_2^2 r_{\beta_2} F'(\lambda)}\sqrt{\frac{2}{\pi\lambda r}}e^{-i\lambda r+i\frac{\pi}{4}},$$

$$r_{\beta_1}=\sqrt{\left(\frac{C_L}{\beta_1}\right)^2-1}, \qquad r_{\beta_2}=\sqrt{1-\left(\frac{C_L}{\beta_2}\right)^2},$$

$$\frac{1}{F'(\lambda)}=\left(\frac{C_L}{U_L}-1\right)\frac{\sin(\lambda r_{\beta_1} d)}{r_{\beta_1}\rho_2 d},$$

referring to Haskell's notations.

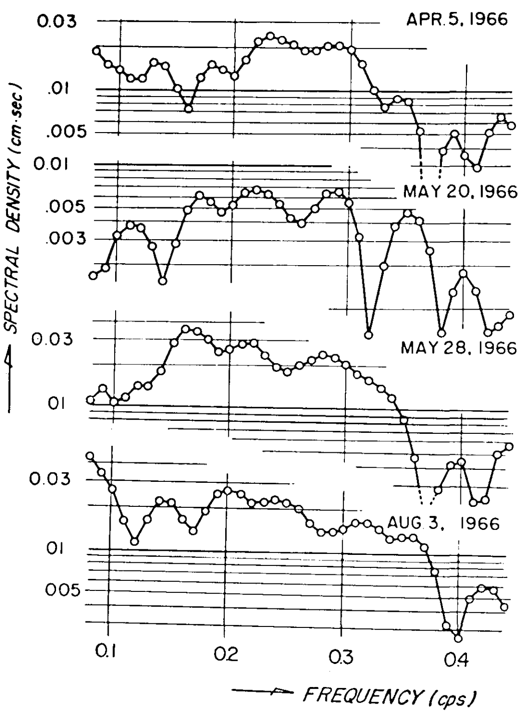

Fig. 6. Spectral density computed for the four representative earthquakes.

Taking ρ_1 and ρ_2 as 2.0 and 2.6 gr/c.c., respectively, we finally obtain from (1) that the amplitude spectral density at Gifu is expected to be 3.6×10^{-24} cm·sec per unit moment, at the frequency range of 0.2 cps. Fig. 6 illustrates four examples of seismic spectra, from which we read the density at the specified frequency and obtain the seismic moment, M_0 by use of the above-stated constants. In Table 1 are listed the moment for nine major earthquakes thus computed, being $0.7 \sim 3.5 \times 10^{22}$ dyne·cm depending on the respective magnitude.

The present technique has been applied conveniently to those major earthquakes with magnitude 5 or so. However, it is not convenient for smaller earthquakes, as their seismograms at Gifu are too small to measure the spectral density accurately. Therefore, an alternative technique was applied to those small earthquakes following the scheme by Brune et al. (1963). That is to say, the area which

Table 1. Source parameters.

Date	h (km)	M	M_O (10^{22}dyne·cm)	A_R (cm^2)	UA^* (cm·km^2)	σ^* (bars)
Apr. 5, 1966	4.3	5.1	1.5	3.6	150	6.7
May 20, 〃	5.5	4.9	0.7	0.7	69	7.0
〃 28, 〃	3.2	4.7	3.5	2.4	351	0.6
Aug. 3, 〃	3.2	5.0	3.5	3.6	351	1.9
〃 28, 〃	7.0	5.0	3.2	3.8	321	2.1
〃 29, 〃	4.5	4.6	2.8	1.9	279	0.6
Sept. 6, 〃	5.2	4.9	2.2	0.75	219	2.3
〃 27, 〃	5.1	5.0	2.7	1.1	270	2.5
Oct. 26, 〃	6.0	5.0	3.0	2.9	300	2.2

* $\mu=10^{10}$ cgs
$c=0.3$

is involved by the envelopes of the surface wave part is measured on the respective seismogram and is plotted against the magnitude (Fig. 7). The least square method is then applied to the present data to obtain the following empirical formula, that is,

$$\log A_R = 1.8\,M - 8.6. \quad (2)$$

This figure involves the nine earthquakes in Table 1, from which is obtained a formula as follows,

$$\log M_0 = \log A_R + 0.10. \quad (3)$$

By (2) and (3), we obtain,

$$\log M_0 = 1.8\,M + 13.5, \quad (4)$$

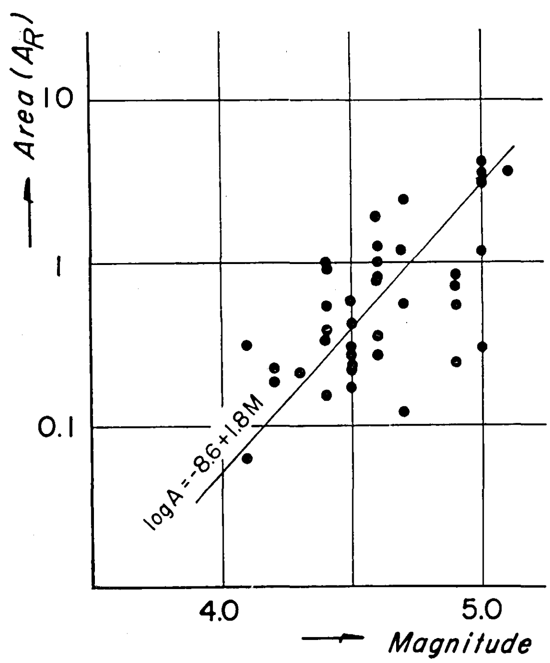

Fig. 7. Seismic moment versus magnitude.

which empirically formulate the relation of M_0 to M for the Matsushiro swarm. It is interesting to compare the present data with Brune's diagram (1968), which seems to indicate a formula,

$$\log M_0 = 1.7\,M + 15.1, \quad (5)$$

for the Californian earthquakes.

Eq. (4) will be used in the next section, in order to simulate the fault's development on the basis of the dislocation theory.

3. Development of a buried fault

There have been conducted various series of geodetic surveys in order to monitor the associated crustal movements on the local and regional scales. In addition to this geodetic work, including levelings, triangulations, geodimeter surveys, and gravity observations, temporary stations have been installed at several sites of interest to operate tiltmeters and strainmeters continuously.

Fig. 8 outlines the history of the Matsushiro swarm from the viewpoint of crustal movement studies, where, extension of the Sorobeku-Minakamiyama base-lines (Kasahara et al., 1968, see also Fig. 9), upheaval of the Minakamiyama area relative to a local fixed station (Tsubo-

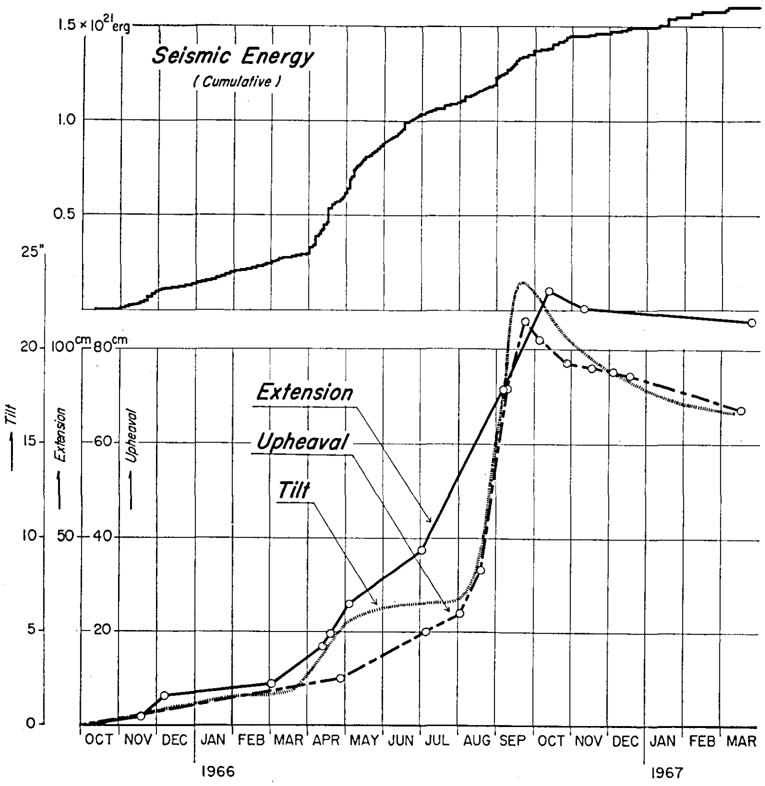

Fig. 8. Development of various sorts of crustal deformations compared with seismic energy release.

kawa et al., 1968), and the ground tilt (N-S component) at the Matsushiro Seismographic Station of J.M.A. (Hagiwara and Yamada, 1966) are illustrated in comparison with various seismic stages as indicated by the seismic energy release curve (Hagiwara and Iwata, 1968).

As clearly indicated in the energy release diagram by an alternative combination of steep slopes and by more or less steady increases of the curve, the Matsushiro swarm has developed through several stages. For example, at least three steep slopes are noticed in the curve, indicating the climax phases in each stage, they are,

1st climax: November, 1965
2nd climax: March-April, 1966, and,
3rd climax: August-September, 1966.

It is interesting to see that this mode of the swarm activity is well reflected at the three earth deformation curves in the lower half of Fig. 8.

We are strongly persuaded by this evidence as well as by the mutual

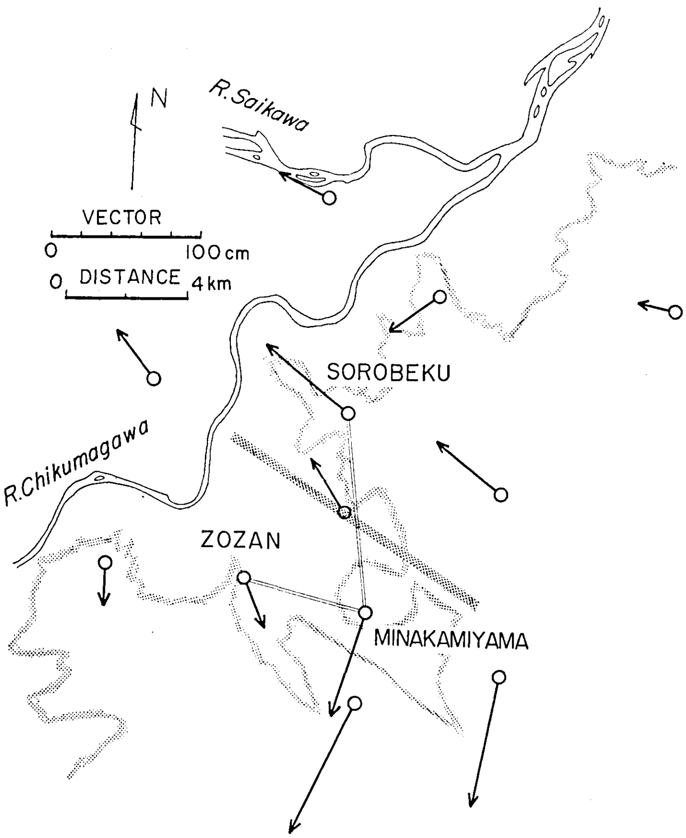

Fig. 9. A buried fault as indicated by the retriangulation data (after G.S.I.).

agreement of the three curves that the observed modes of the deformations have essential bearing to the source mechanism of the present event. In fact, the extraordinary extension of the Sorobeku-Minakamiyama base-line has been attributed to the development of a buried fault as proved by subsequent studies on the surface evidence. For example, a series of ground fractures had become noticeable in Matsushiro since the spring of 1966. Nakamura and Tsuneishi (1967) studied them from the geological point of view and found out that they are probably originated from a strike-slip fault underlying the north of Mt. Minakamiyama as illustrated by a shadowed belt in Fig. 9. Subsequently their speculation was soon supported conclusively by the GSI (Geographical Survey Institute) group who conducted triangulation there. Vectors in Fig. 9 represent horizontal displacement of each station referred to in the 1904 data, where the two stations beyond the Saikawa river (not shown in the figure) are assumed as fixed. The vectors scatter considerably, of course, reflecting the complication of the ground conditions.

But, we still notice that they are basically in a trend of the strain field due to a strike-slip fault. If the writer's speculation is correct, the fault is in the left-lateral sense, extending as represented by the shadowed belt. The station on the fault line seems to have moved less than the adjacent stations as Sorobeku. This suggests the fault to be buried, which is also a reasonable supposition judging from the surface evidence.

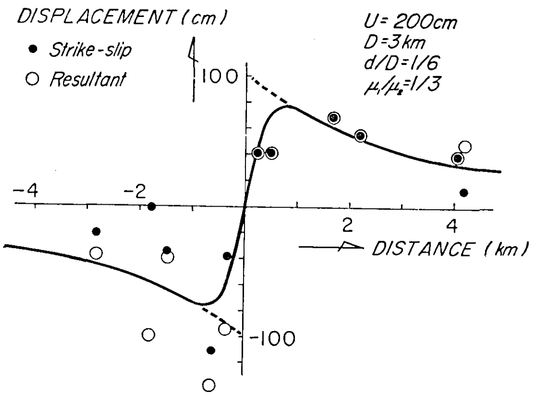

Fig. 10. Amplitude of the displacement vectors decaying as a function of the distance from the fault.

Under these considerations, the triangulation data are compared with a buried fault model (Kasahara, 1964). In Fig. 10 are plotted the station's displacement against their separation from the fault line, empty and solid circles denoting, respectively, the resultant amplitude and the amplitude component parallel to the fault extension. The theoretical curve represents a model of a two-dimensional vertical strike-slip fault buried under the surface layer, where its parameters are taken, tentatively, as follows:

fault offset: $U=200$ cm,

fault width in the vertical direction: $D=3$ km,

thickness of the surface layer: $d=D/6$,

rigidity ratio of the 1st (surface) and the 2nd layers: $\mu_1/\mu_2=1/3$.

The present set of parameters is of course tentative, and must meet with careful examinations before we accept it as final. Taking a large scattering of the data into consideration, however, the writer is rather doubtful of more precise analysis of the present material. He will use the above-stated parameters for the following discussion emphasizing the risk of inaccurate conclusions. The fault's length may be taken as 7 km, approximately, in any case.

Determination of the fault parameters leads us, then, to a further discussion on the source mechanisms by use of the well-known formulae as follows:

$$\bar{U}=\frac{M_0}{\mu A}, \qquad \bar{\sigma}=\frac{\mu c E_s}{M_0}, \tag{6}$$

where, $\bar{U}$, μ, A, $\bar{\sigma}$, c, E_s, denotes, respectively, the mean dislocation, rigidity, fault area, mean stress-drop, efficiency of energy conversion, and energy of seismic waves, referring to Brune's notations. $\bar{U}\cdot A$ and σ in Table 1 are computed in this way, assuming $\mu=10^{10}$ c.g.s. and $c=0.3$. Then the stress-drop is estimated at 0.6~7.0 bars for the listed earthquakes. These are considerably low but not so unusual as the value for very shallow earthquakes.

$\bar{U}\cdot A$ in the same table permits us to estimate the mean dislocation at the respective source. We may calculate it for the individual source, if we could estimate A precisely. However, let us follow Brune's scheme (1968) and simulate development of the buried fault, attributing it to the cumulative sum of dislocation due to the adjacent earthquakes.

Solid circles in the index map of Fig. 11 represent the earthquakes used for this purpose. They are the major earthquakes of magnitude 4.5~5.5, which occurred within a certain range from the fault. Referring to Table 1 or by use of (4), we determine M_0 of the respective earthquake. Then we calculate and sum-up the effective dislocation across the major fault using (6), where A is taken as $7\,\text{km}\times 3\,\text{km}$ after the previous discussion. A series of step lines in the same figure illustrate the simulated fault movements in comparison with the ground extension as observed on the Sorobeku-Minakamiyama baseline. It is

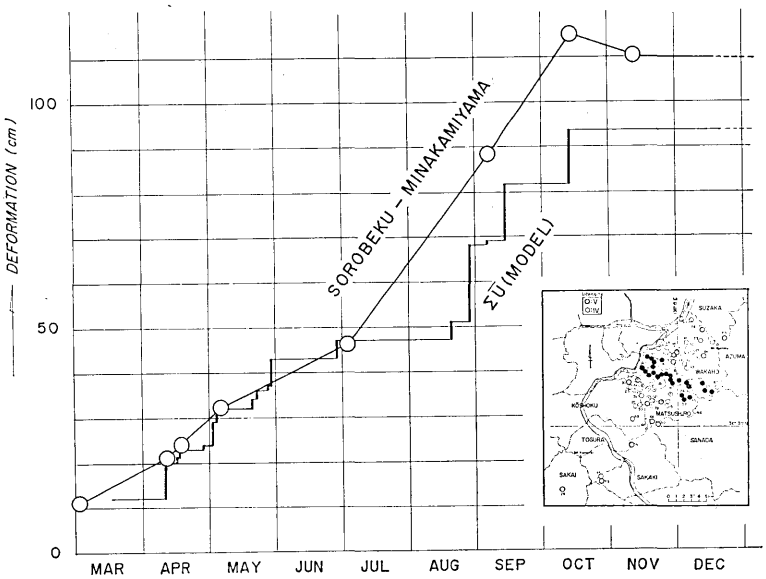

Fig. 11. Observed extension of the Sorobeku-Minakamiyama base-line (open circles) compared with the simulated fault development. Solid circles in the index map (lower right) illustrated the earthquakes used for the present simulation.

very interesting to observe that the two series of lines are in good harmony to each other with respect to their development mode.

4. Land upheavals and outflow of underground water

Precise levelings by the Geographical Survey Institute and by the Earthquake Research Institute have discovered considerable land upheavals occurring over the seismic area. The most outstanding feature of them is perhaps the uplift in the epicentral area with its maximum on the north flank of Mt. Minakamiyama, which amounted to almost one metre during the period October, 1965—September, 1966 (see Fig. 8). As shown in Fig. 12, this extraordinary movement is of local character and is closely related to the faulting which was discussed in the previous

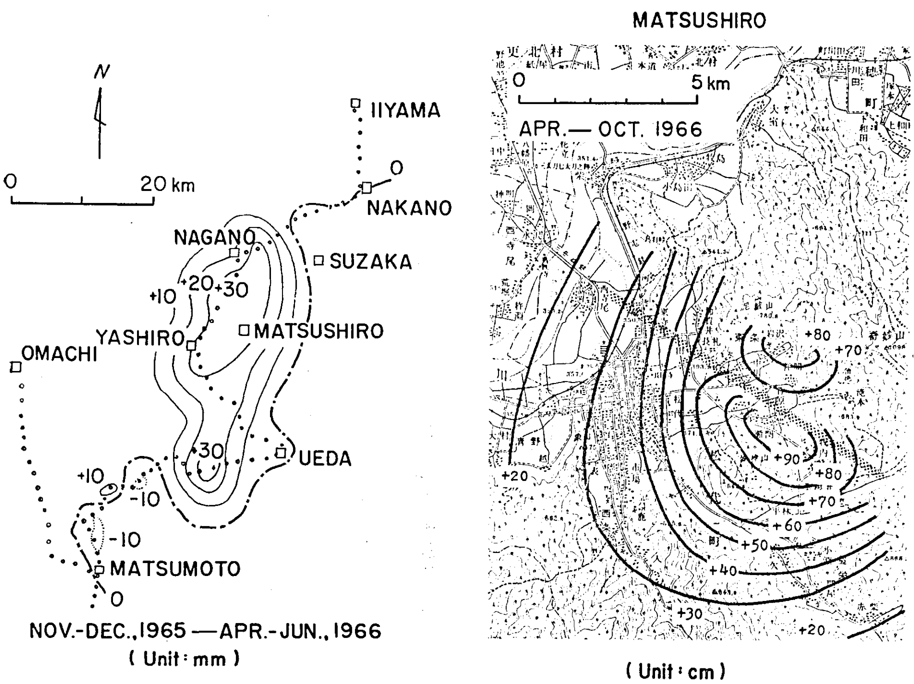

Fig. 12. Vertical land movements as discovered by:
[left] the regional releveling (after G.S.I.) and
[right] the local releveling (after Tsubokawa. et al., 1967).

section. Briefly speaking, the local upheavals (Fig. 12, right) seem to consist of two principal components, i.e. the basic mode of doming up and the differential movement across the fault. The latter, which was discovered in the late second stage, resulted in 20-30 cm uplift of the southwest side of the fault relative to the other side, by the end of September, 1966. Its amplitude and horizontal extension being not so large as those of the first component that it might be a secondary effect of the movements, such as a very local block movement activated by faulting.

The first component, or the doming up of the epicentral area, is considered more essential, on the other hand. This mode of uplift was first noticed as early as the end of 1965. Since then, it started to increase steadily and was accelerated through the second and third climaxes (Fig. 8). As shown in Fig. 12 (right), it extends considerably to cover some $10\times10\,km^2$ of the epicentral area with its maximum on the north flank of Mt. Minakamiyama. It is not necessarily simple to explain the mechanisms of the present event, but the writer would notice three sorts of evidence seemingly useful for this purpose, they are, (a) outflow of underground water, (b) characteristic development of ground fractures, and (c) secular changes in local gravity.

The first two items have been discussed in detail by Nakamura and Tsuneishi (1967) (see also Tsuneishi and Nakamura, 1970), in relation to the swarm processes. Briefly, there are two alternative interpretations possible for the present problem: (1) the outflow may be interpreted as the result of crustal fracturing, or (2) the water may be a generator of the crustal deformations and earthquakes. Taking these hypotheses into consideration, though not discriminating them conclusively, Nakamura and Tsuneishi attributed the deformations and the areal water outflow to the increasing fluid pressure associated with the development of brittle fracturing under the tectonic stress of east-west compression.

The Geographical Survey Institute and the Earthquake Research Institute have conducted gravity surveys extensively in the seismic area. Especially in the central part of the area, they repeated the surveys for several times in order to discover secular changes which might occur in relation to the swarm activity. Fig. 13 reproduces Harada's illustration (1968), which plots the observed gravity change at the Matsushiro first-order gravity station against the ground uplift. Observational error is supposed as 0.02 mgal or

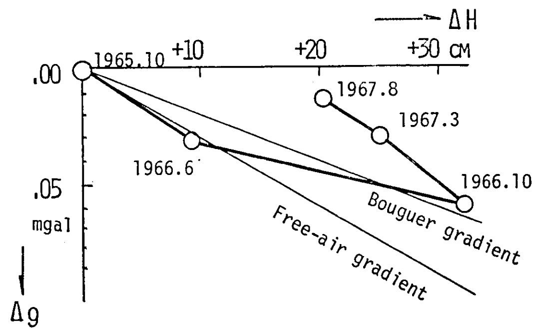

Fig. 13. Changes in gravity (Δg) and elevation (ΔH) observed at the Matsushiro first-order gravity station (after Y. Harada, G.S.I.).

less in this case, so that we may accept the gravity changes as significant. The free-air gradient in the figure represents the vertical movement of the station with the underlying mass unchanged. In other words, we shall observe the gravity change along this line if the crust is inflated as a result of bulk increase due to fracturing. The change from 1965.10 to 1966.6 might be explained by this mechanism. Suppose the 10 cm uplift is gained by fracturing of rocks within the depth of 5 km from the surface. Then the average porosity increase is expected to be $10^{-5} \sim 10^{-4}$. This order of magnitude is reasonably understood referring to the data of laboratory rock tests. The change from 1966.6 to 1966.10 seems more difficult to explain. The most popular explanation for the Bouguer gradient would be a land upheaval due to magma injection from the adjacent areas. But, this hypothesis hardly holds in the present case, because various sorts of evidence seem to contradict magma's action as the principal driving force to the swarm activity (f.i. Rikitake et al., 1967). Density increase of fractured rocks by water saturation seems to be a more likely mechanism, although it is still too small to explain the observations. Density increase of rocks due to bulk compression, and decrease of the mountain-body attraction associated with water outflow might be the other factors. But further examinations are needed to draw proper conclusions. The changes to 1967.3 and to 1967.8 are along the free-air gradient from 1966.10. It also indicates that the rock density was increased by some unknown causes at the stages of land subsidence.

As a whole, the process in the period 1965.10—1967.8 has left no effective gravity change at this station notwithstanding a considerable amount (+20 cm, approximately) of residual displacement. In other words, there have been some unknown effects in this locality, causing an additional gravity exactly as much as to compensate the gravitational effect by the free-air uplift. Mass increase under the station may be the simplest explanation for the present effect, but the writer would like to leave its mechanism or other possibilities (f.i. water flow from highlands to low lands) open to question.

5. Energy account

Hagiwara and his group have continued laborious statistics on the energy release since the installation of their temporary seismic stations. Later, they published a summary of their seismometrical work (f.i. Hagiwara and Iwata, 1968), in which they totaled the seismic energy which was released during the respective stage of the swarm as given in Table 2. The total energy release throughout these stages is then estimated at 1.6×10^{21} ergs, approximately. According to their interpretation, this amount of energy is equivalent to that of one earthquake of magnitude 6.4 or so.

Another principal factor in the seismic energetics is the energy change associated with crustal movements. For example, land upheavals (or subsidences) will certainly gain (or lose) gravity potential at the expense of energy from the other sources.

Table 2. Account of various sorts of energy.

Seismic (total)	$1,661\times10^{18}$ ergs
Stage I	250 〃
〃 II	841 〃
〃 III	392 〃
〃 IV	124 〃
〃 V	51 〃
Land upheaval (total)	17,000 〃
Regional	10,000 〃
Local	7,000* 〃

* Decreasing since Oct. '66.

We have observed a considerable magnitude of land movements in and around Matsushiro as shown in Fig. 12. Therefore, we may approximately account for the energy by introducing several assumptions. The lower set of energies in Table 2 gives the results referred to in the data in Fig. 12, where we assume that the movements appear only in the depth range of 0～5 km, getting their amplitude reduced linearly with depth, from the surface value down to zero at 5 km.

Table 3. Possible strain energy in source volume.

e	10^4	10^3	10^2 erg/c.c.
eV	20,000	2,000	200×10^{18} ergs

($V=30\times15\times5$ km$^3\fallingdotseq2\times10^{18}$ c.c.)

It is notable in the table that the potential energy change, which is ten times as large as the released seismic energy, is associated with the present movements. In other words, the energetic aspect of the swarm cannot be explained unless the mechanisms of large energy supply are understood.

The possible strain energy supply from a unit volume of the crust is generally believed to be the order of magnitude, 10^3 ergs. Therefore, the crustal volume of $30\times15\times5$ km^3, which approximately represents the source dimensions of the Matsushiro swarm, may supply 2×10^{21} ergs to its maximum. Simple comparison of this figure with the released seismic energy (1.6×10^{21} ergs) might lead us to a misunderstanding as if the present activity had been maintained by a supply of the strain energy, which was accumulated precedently in its source volume. As known from the previous discussion, the Matsushiro swarm is hardly maintained by such a local source if the energy consumption due to the land upheavals is taken into account. Perhaps the strain energy supply on a regional scale must be provided to account for the energetics of the present event.

6. Processes and background of the Matsushiro swarm (review)

The source mechanisms have been discussed, in the foregoing sections, from the seismological and geodetic points of view. Indeed, this extra-

Table 4. Research by various groups and summary of the results.

	Problem	Author	Summary of results
EARTHQUAKE	Seismic activity	HAGIWARA et al.	Mode of development (Space/time) energy, mechanism
	〃 〃 (micro)	〃 〃	New activity in adjacent area
	〃 〃 〃	HORI	Inactivity 〃 〃 〃
	Source mechanism	ICHIKAWA	E-W compression
	Source parameter	KASAHARA	Low stress drop
DEFORMATION	Horiz.: Triangulation	G. S. I.	Buried fault (cf. model)
	Geodimeter	KASAHARA et al.	E-W compr., stages of development
	Surface fractures	NAKAMURA et al.	Buried fault, 〃 〃 〃
	Vert.: Leveling	GSI/TSUBOKAWA et al.	Upheaval, stages of development
	Tiltmeter	HAGIWARA	SEE-up, 〃 〃 〃
	Associated:		
	Geomagnetism	RIKITAKE et al.	Local decrease of ΔF (Oct. '66)
	Gravity	TSUBOKAWA	Local increase of Δg_0 (Dec. '65-Dec. '66)
	Water	MORIMOTO et al.	Deep origin, correlation to seismicity and deformations
BACKGROUND	Structures: Seismic prospecting	G. S. J.	
	Geophysical prospecting	SEYA/ONO	Gravity/geoelectrical structure
	Boring	TAKAHASHI et al.	200 m. (test)
	Geological	MORIMOTO et al.	Quaternary tectonics under E-W compr.
	〃	MATSUDA et al.	No evidence for pre-existing fault
	Rocks: Laboratory test	HOSHINO et al.	Brittle, minor fractures before yielding
	Fracture system	MURAI	Two systems

ordinary event has strongly and widely attracted the interest of scientists. Articles, which have been published on the various aspects of the present activity, doubtlessly amount to close on a hundred, excluding engineering ones. The writer extracts several representative ones for the purpose of reviewing the present status of research on this particular event. Table 4 lists these articles together with summaries of their results.

It is almost established that the regional crustal stress in the E-W compressional sense is the basic driving force for the present activity. Studies on the focal mechanism (Ichikawa, 1967), horizontal crustal

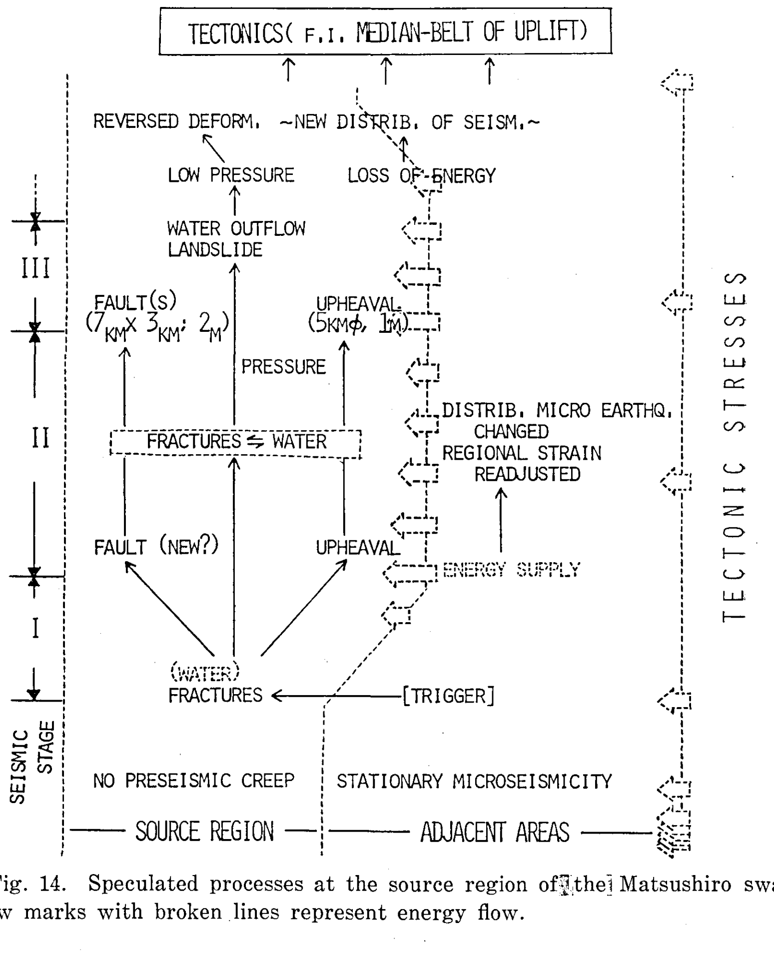

Fig. 14. Speculated processes at the source region of the Matsushiro swarm. Arrow marks with broken lines represent energy flow.

movements (Kasahara et al., 1968), and surface evidence for the ground fractures (Tsuneishi and Nakamura, 1970) support this idea equally well. Secular changes in the local geomagnetic field seem to be consistent with the present idea (Rikitake et al., 1967), too. The absolute magnitude of this crustal stress is beyond our estimation, at present. But, it would not have dropped so seriously on the regional scale, since the seismic stress drops are very low (see Section 1), and the activity seems to be fed by a capacious source (see Section 5).

In Fig. 14 are drawn the sequential features of the Matsushiro swarm, assigning each half of the trace space to the source region and the adjacent region, schematically.

Few data are available for the preseismic stage. It is presumed, however, that the future earthquake fault was not creeping at this stage. This is concluded from the comparison of the Geodimeter surveys with the old triangulation. As given in Table 5, extension or contraction of

Table 5. Changes in the base-line length observed by triangulations and Geodimeter surveys.

Period	Sorobeku-Minakamiyama	Zozan-Minakamiyama	Remarks
1904-1966	+126 cm	−26 cm	Triangulation
1965-1966	>116	−22	Geodimeter

the base-lines which appeared between 1904 and 1966 are well explained by the deformations after the beginning of the activity, suggesting no significant movements between 1904 and 1965. This evidence is also consistent with the report by Matsuda (1967) that he has observed no significant signs of a pre-existing fault in the area of the present faulting, either topographically or geologically. If this is accepted, then we shall arrive at very notable conclusion that we have been observing the birth of an absolutely new fault there.

The first stage of activity involves several interesting but difficult problems. Most puzzling of them is, perhaps, why the swarm has started at the moment and the location as observed. Leaving the triggering mechanisms for future studies, the writer would like to remark that the new fault production seems to have started as early as in November, 1965. Geodimeter surveys in that period have registered small but significant changes in the respective base-lines (Kasahara et al., 1968). Judging from the subsequent studies, they are probably the signs of the young fault with several centimetres offset.

It is unknown whether or not the underground water has participated essentially in fracturing since the earlier period. As discussed in Section 4, the mode of gravity changes seem to support fracturing under a dry or, at least, unsaturated condition.

The second stage is characterized by a high seismic activity with extensive development of the epicentral area, but it was less active than the third stage with respect to crustal deformations. As discussed previously, there are two alternative understandings of the water's role in the swarm processes—supposing water outflow, respectively, as the result or the cause of crustal fracturing. It is difficult to discriminate one from another, but the writer considers whether the two factors are equally primary. That is to say, fracturing and water liberation couple positively with one another, thus causing explosive acceleration of the swarm activity at the respective climax.

Incidentally, the discussion in Section 5 concluded that a considerable amount of strain energy is supplied from the adjacent areas to maintain the active swarm processes. It is natural from this point of view, that we observe reduced seismicity in the adjacent areas (Hori, 1967) or extraordinary land movements on a regional scale (Fig. 12, left).

The third stage is characterized by predominant earth deformations and areal water outflow, which finally triggered disasterous landslides. The dimensions of 7 km × 3 km (offset: 2 m) and 10 km × 10 km (maximum upheaval: 1 m) are assigned to the two principal factors of deformations, faulting and doming up, respectively.

Drastic changes in the activity occurred in October, 1966, when various components of deformations turned into reversal modes simultaneously, together with the seismicity reduction. According to A. Okada (personal communication), for example, the vertical deformation recovered for 15~20% of the previous uplift, in the next several months after the reversal, and is almost ceasing its activity as far as the recent data are concerned. This mode of recovery is also the case of the horizontal movements, although less percentage of the previous extension (f.i. of the Sorobeku base-line) was recovered. This movement does not mean, necessarily, reversal of the falting from left-lateral to right-lateral. As discussed by Tsuneishi and Nakamura (1970), the observed north-south contraction is interpreted, more reasonably, by the closing of the fracture zone due to decreasing in the fluid pressure. The fault is believed to be moving inactively, with its left-lateral sense unchanged.

Hoshino and Nagumo (1967) worked out a series of laboratory tests on the rock specimen from the seismic region, and found that the swarm shocks may be interpreted as a group of minor fractures preceding the yielding. The fracture systems in the epicentral area have been analysed geologically by Murai (1967), who concluded that one of the three predominant sets of fracture or joint systems is consistent with the E-W compressional stress which reasonably explains the focal mechanisms, faultings, as well as the basic features of the recent tectonics in the present district.

The writer previously referred to Matsuda (1967) who suggested the newness of the present faulting. But, it does not mean, necessarily, that the Matsushiro activity is the first swarm that occurred in the present province. On the contrary, local history doubtlessly proves a repetition of a similar event there. This is also indicated by the fact that the present swarm area trends to depelop along the so-called Median Belt of Uplift (Nakamura, 1969).

Another evidence for close coupling of the present activity to the geologic or tectonic backgrounds is seen in the focal distribution of swarms referred to in the crustal structures. As discovered by Asano et al. (1960), who worked out a series of seismic prospectings across the epicentral area, the Median Belt of Uplift is exhibited well by the narrow belt of the bed rock (velocity: 6 km/sec) being uplifted for about 3 km, along the present unit. It is extremely interesting and suggestive that the swarms are concentrated mainly in this block, judging from the cross-sectional view of the epicenters distribution.

The Disaster Prevention Research Center has now conducted a deep drilling in Matsushiro planning to reach the raised bed rock at its shallowest part. We shall have more definite data about the conditions and materials in the source region after getting this project completed. Field experiments by Suyehiro (1968) and Asano et al. (1970) seem interesting, too, as these are new approaches to the physics of the seismic processes. They respectively studied seismic signal dissipation and wave velocities across the epicentral region and found out significant changes in these quantities during the swarm. If further improvements could be made on these techniques, it is hoped that we shall have more detailed knowledge about the physical mechanisms of the seismic activity.

Incidentally, the Matsushiro swarm is now ceasing from the long-continued activity, and is providing us with a lot of valuable data and experiences through wide-scale expeditions. It is just a local event from the energetic points of view. But, there have been and will be few earthquakes of this magnitude so stimulating to seismology as this is.

7. Remark and acknowledgement

In the above, the writer has developed his idea on the physical processes at the source region of the Matsushiro swarm. The speculative model thus proposed seems to have no serious inconsistency to the primary sorts of information about the present event. However, the writer does not deny the possibility of an alternative solution ; he rather hopes that the present solution would be replaced by someone else in future for better understanding of the Matsushiro swarm.

Dr. T. Kizawa of the Meteorological Research Institute of J. M. A., who collected the J. M. A.'s seismograms of the Matsushiro swarm, kindly offered the necessary copies for the writer's study. Drs. R. Sato and H. Kanamori of the University of Tokyo gave to the writer valuable suggestions on surface wave analyses. Dr. A. Sugimura read the manuscripts critically and gave the writer useful advices from tectonic points of view. His sincere thanks go to these colleagues. The writer is also thankful to Miss M. Hirai and Miss N. Kanaya for their assistance in computation as well as in preparation of the manuscripts.

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31. 松代地震の震源過程

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松代地震群の震源パラメーターを Aki や Brune の方法によって推定した．資料として岐阜におけるウィーヘルト地震計の記録を用いたが，それは皆神山麓に推定される潜在断層のほぼ真横の方位に同地が位置し，しかも非常にきれいな Love 波が記録され解析に好都合であったからである．

このようにして求めた結果によると，マグニチュード 4～5 くらいの地震でモーメントは 10^{22}～10^{23}dyne・cm 程度になる．

一方，三角測量をはじめ各種の調査資料に基づいて震源域地下に潜在すると思われる断層のパラメーターを求めた．表層下に位置する横ずれ型断層の模型を適用して見ると，今回のそれは約 3 km・幅(深さ)と，ずれの量，2 m ほどの横ずれ断層が地表下数百 m のところまで来ているらしい．その長さはおよそ 7 km であり，位置および方位は既に知られているように皆神山麓の北西をかすめて北西—南東に延びている．

さきに求めた震源モーメントも併用して，この断層が群発地震に併なってどう発達して来たかを模型的に合成して見た結果は，さきに光波測量によって明らかにされた可候基線の変動ともかなり調和するようである．

さらに，松代地震に関する各種の調査資料を整理綜合して，今回の地震動の経過や背景についても簡単な考察を試みた．
