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19. *High Angle Reverse Faultings in the Interaxial Zone of Active Folds in the Inner Belt of Northeast Japan.*

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Abstract

A precise level net covering the folded area of about $10 \times 20\,\mathrm{km}^2$ near Ojiya, Niigata Prefecture, Northeast Japan was set up in 1967–1968. A remarkable vertical crustal movement was found to have a wavelength of several kilometers by the relevelings in 1978. The anticlinal uplift and the corresponding synclinal subsidence with a noticeable asymmetric feature about the fold axes were found to be concordant with the underlying Neogene and Quaternary fold structures. The fault plane solution of a local earthquake located in the area shows a high angle reverse faulting with the strike in a NNE-SSW direction parallel to the fold axes as confirmed for the active faults in the area. The result shows a common feature to the source mechanism of big earthquakes in the inner belt of Northeast Japan represented by the Niigata earthquake of 1964. Considering the seismotectonic environment in the area, the releveling data was analysed by applying the static dislocation theory.

It was found from the analysis that the asymmetric mode of movement could be explained by a reverse faulting in the interaxial zone of fold structure as expected from the seismological evidences. The preferred fault parameters of the model were as follows: a rectangular surface of horizontal length 10 km, width 4 km, dip 85° embedded in an elastic half space with the top of the fault at a depth 1 km below the earth's surface and dip slip motion 2.5 cm on the fault surface with the strike in a NNE-SSW direction.

The seismic moment $Mo_L = 3.3 \times 10^{23}$ dyne·cm was obtained from the fault parameter determination. Cummulative seismic moment $\sum Mo_S$ from a magnitude-moment relation was estimated from the seismicity data for the specified folded area in the period corresponding to the releveling data. The cumulative seismic moment $\sum Mo_S$ was compared with Mo_L by introducing the quantity $\alpha=(Mo_L-\sum Mo_S)/Mo_L$ ($0\leqq\alpha\leqq1$), which varies depending on the ratio of the aseismic slip to the total fault surface displacement. The dominant role of the aseismic slip on the fault surface in the process of active folds near Ojiya was suggested from the estimation of α being nearly equal to 1, though the time interval of the releveling data was too short to make a conclusive discussion. In the other folded areas, however, some of the concealed faults in the interaxial zone seemed to be inherited to produce a dip-slip motion accompanied by a moderate earthquake of magnitude M of 5–6, resulting in α being nearly equal to zero, though the detailed discussion on this matter should be reserved for future studies because of a lack of data.

1. Introduction

Regarding tectonic development of fold structure in the present and the latest geologic time, pioneer work was done by OTUKA (1941). Comparisons were made of vertical crustal movements as revealed by precise relevelings with the deformations of river terraces and underlying Neogene and Quaternary fold structures in the inner belt of Northeast Japan (Fig. 1). It was pointed out from the evidence that both deformed terraces and vertical displacement of bench marks were concordant with underlying fold structures. This is interpreted to mean that some of the fold structures indicated by Neogene and Quaternary strata are still active at present.

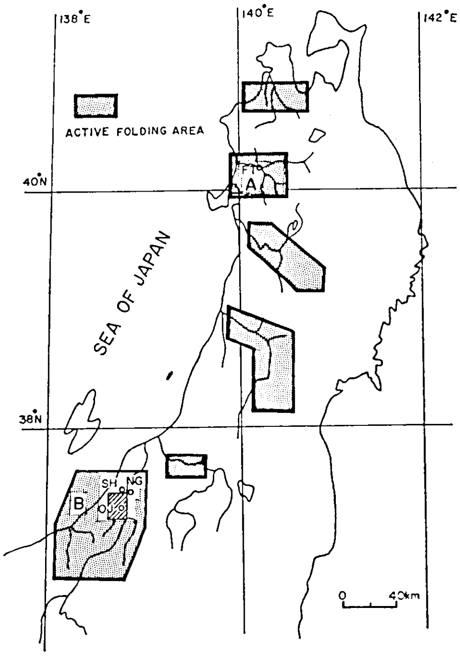


Fig. 1. Active folding areas in the inner belt of Northeast Japan (hatched zones). Active folding areas along the Yoneshiro river, Akita Prefecture (A) and the Shinano river, Niigata Prefecture (B). FT: Futatsui, SH: Sekihara, NG: Nagaoka, OJ: Ojiya. The Ojiya active folding area is indicated by the shaded zone.

The Ojiya active folding area, Niigata Prefecture, Northeast Japan (Fig. 2) occupies a southern part of of a Miocene to Quaternary basin with its center of subsidence about 50 km north-northeast of Ojiya.

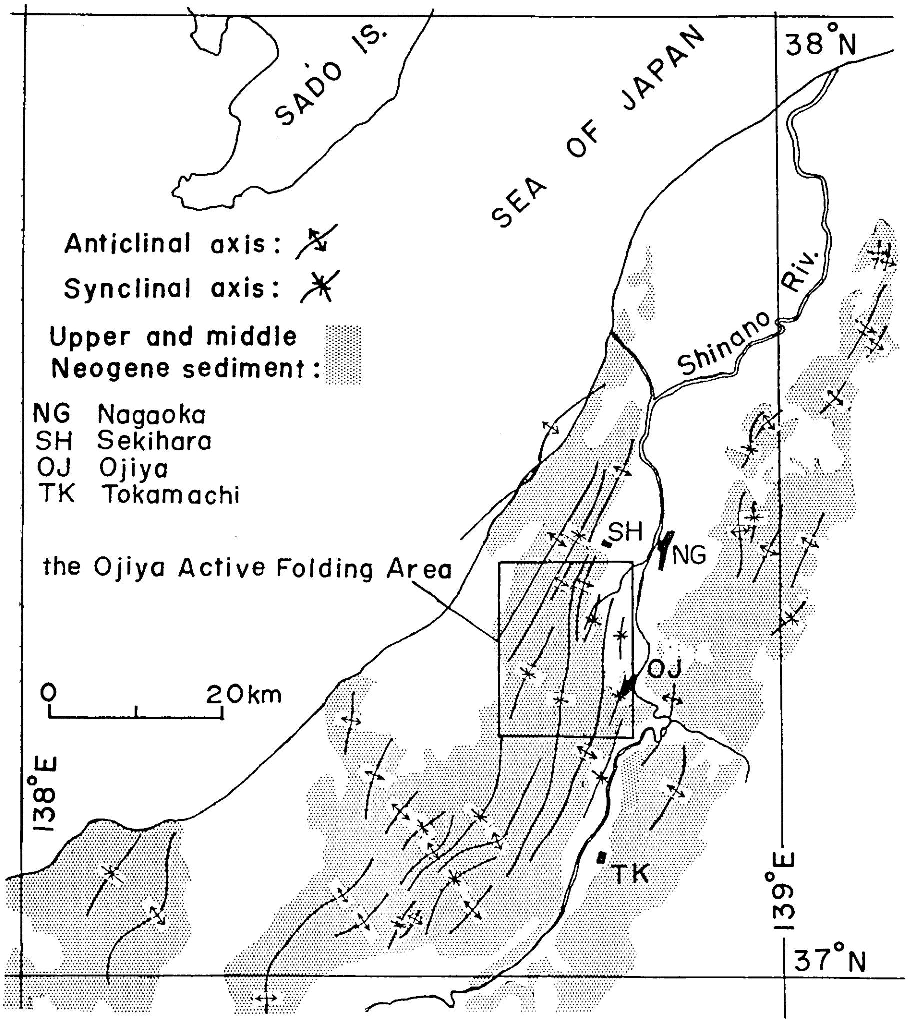


Fig. 2. Location of the Ojiya active folding area enclosed in a rectangle with the indication of the anticlinal and the synclinal axes.

During the late Quaternary period, a subareal drainage system has developed due to a general uplift of the entire basin. The Ojiya active folding area is now located along the lower stream of the northward flowing Shinano river, one of the largest rivers in Japan. The Quaternary strata have been affected by remarkable deformation since the last 10^5–2×10^6 years resulting in the folding of several kilometers with the NNE-SSW trending axis. A flight of river terraces of a comparatively large area is distributed along the Shinano river. Some of the terraces show a distinct deformation after their formation, as indicated by a wavy profile. The degree of deformation of these terrace surfaces is proportional to their age and the direction of tilt is the same as that of the Quaternary strata beneath the terraces. The inclination of the river terraces can be attributed mainly to the accumulation of tectonic deformation since the time when the terraces were initially formed.

The paper studies vertical crustal movement as detected by the relevelings in the active folding area near Ojiya. Geological and semismological features are correlated with the releveling results. The distribution, the direction of strike and the type of active faults are referred to the map complied by the Research Group for Active Faults of Japan (THE RESEARCH GROUP FOR ACTIVE FAULTS OF JAPAN, 1980). The microearthquake observation in the area shows that most of the earthquakes near Ojiya have occurred in swarms with a distribution striking in a NNE-SSW direction (HOKUSHIN OBSERVATORY OF MICRO-EARTHQUAKES and CRUSTAL DEFORMATION, E. R. I. (EARTHQUAKE RESEARCH INSTITUDE, TOKYO UNIVERSITY), 1980, 1981). The fault plane solution of a local earthquake indicates the high angle reverse faulting with the strike parallel to the lineation of the epicentral distribution. The releveling result shows an asymmetric mode of movement with a large velocity gradient on the order of 10^{-6} per year on the eastern wing of the anticline. From the geological, seismological and geodetic evidences, it is shown that the high angle reverse faulting is a plausible explanation of the characteristic mode of movement.

2. Releveling results

The change of the height of bench marks on the level route from Ojiya to Tokamachi along the banks on the Shinano river (Fig. 2) for the period of 1897–1927 indicated the subsidence of a synclinal axis to the south of Ojiya, which was interpreted as an evidence of active folds in the area (OTUKA, 1941). In the succeeding course of the study, a direct approach was made by MIYAMURA and OKADA (1956) and SUGIMURA and NAKAMURA (1956) to detect the active fold movements by setting up bench marks on a transversal route crossing the fold structures. The fundamental features including the amplitude and the wavelength of the fold movement were measured for the period of 1958–1967. The result gave the maximum rate of tilt of the order of 10^{-6} per year, which is significantly higher than the average rate of the secular movements in Japan, which are mostly on the order of 10^{-7} per year (MIZOUE, 1967, 1968, 1969).

In order to have sufficient data to compile a detailed map of the fold movements in the area of about $10\times 20\,\mathrm{km}^2$ near Ojiya, a level net was newly set up in 1967–1968 with the installation of 63 bench

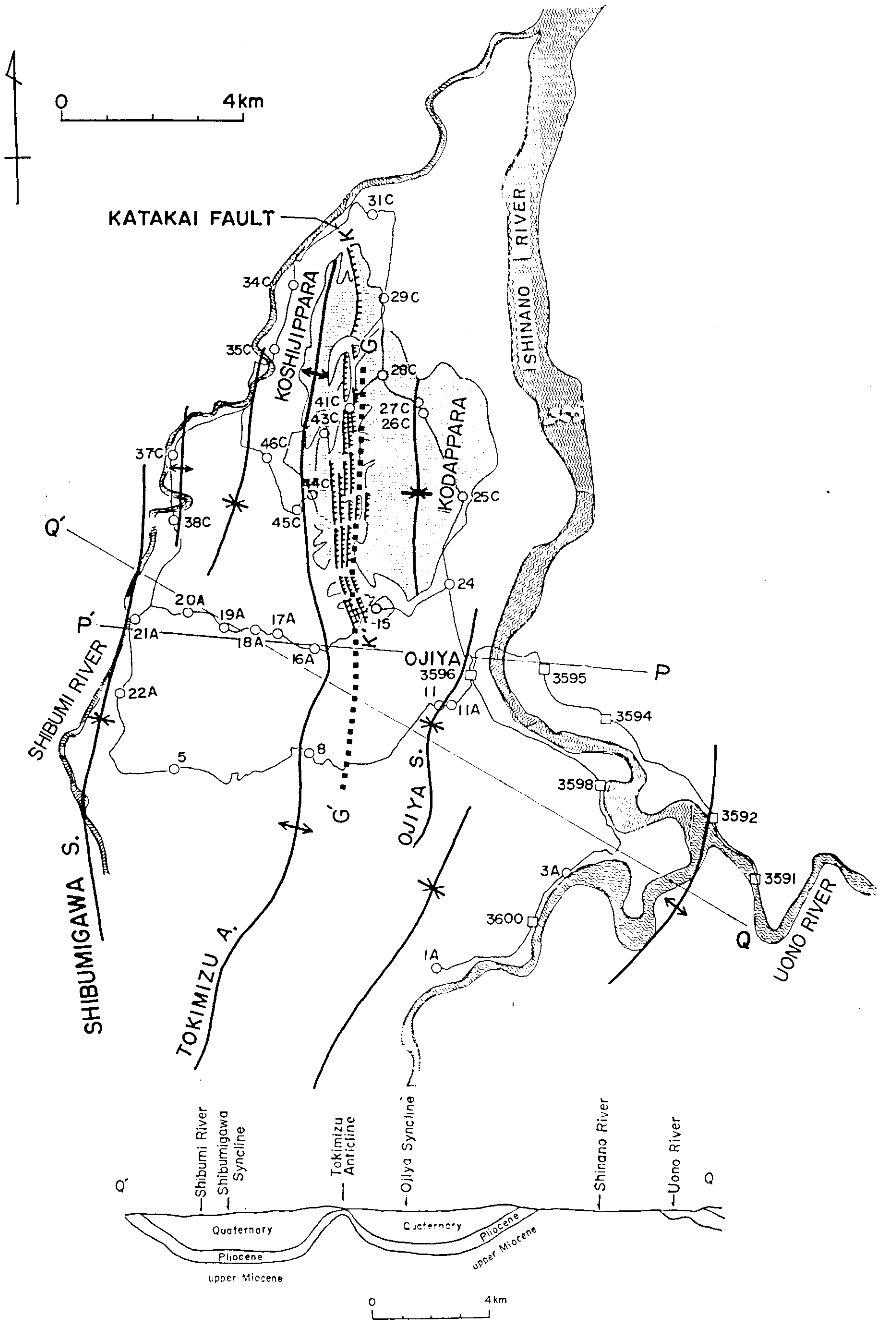


Fig. 3. Index map showing location of bench marks (circle for E.R.I. and square for G.S.I. (Geographical Survey Institude), leveling route (thin solid lines), axes of the Tokimizu anticline and the Shibumigawa and the Ojiya synclines (thick sinuous lines with a pair of arrows), two river terraces (Koshijippara and Kodappara as mentioned in the text), the Katakai fault (KK′), the cross-sectional line PP′ for the profile in Fig. 7 and the lineation of crustal deformation GG′ in the interaxial zone. The geological cross section along the line QQ′ is shown in the lower figure.

marks. The fold axes were crossed by the four different level routes linked in loops (Fig. 3). The net was releveled in October 1978. The bench marks kept in proper condition all through the 10 year period since 1968 were found to total 37.

The north-northeastward tilt of the Quaternary strata in the folded area near Ojiya has been confirmed from geological and geomorphological evidence (NAKAMURA, 1957; NAKAMURA and OTA, 1968). The average rate of the tilt during the past 10^5 years was about 0.2 mm/km·year from the inclination of the river terrace surfaces of the Koshijippara and Kodappara (Fig. 3). On the other hand, the corresponding tilt rate from the releveling data for 1969–1978 is 0.195 mm/km·year. The good agreement of the tilt rate at present and during the past 10^5 years indicates that the regional tilt movement is progressive and of tectonic origin (MIZOUE, NAKAMURA and IZUTSUYA, 1980).

A remarkable undulatory mode of movement with a wavelength of several kilometers was observed for the period of 1968–1978 superimposing on a regional tilt towards the NNE direction associated with the secular mode of subsidence of the Niigata basin (Fig. 6–(a)). The anticlinal uplift near Ojiya showed a noticeable asymmetric pattern about the strike of the fold axis to be concordant with the deformed river terraces and underlying Quaternary fold structures (MIZOUE *et al.*, 1980). In the central and the southern parts of the level net, the undulatory movement was found to have a wavelength of about 8–9 km and a peak to peak amplitude of 15 mm as shown in Fig. 6–(a). The largest velocity gradient of 1.3×10^{-6} per year was found in the eastern wing of the Tokimizu anticline or in the interaxial zone between the Tokimizu anticline and the Ojiya syncline, the geological cross section of which is shown along the line QQ′ in Fig. 3 (MIYASHITA *et al.*, 1970).

3. Active fault and microearthquake activity

The Research Group for Active Faults in Japan complied the results on the studies of active faults in Japan with sheet maps and inventories (THE RESEARCH GROUP FOR ACTIVE FOLDS OF JAPAN, 1980). The Katakai fault (KK′ in Fig. 3), as named by the Group, was identified as an active fault on the eastern wing of the Tokimizu anticline with a strike in a NS direction and had a fault length of about 7 km. The trace of the Katakai fault coincides with the zone of large velocity gradient of deformation running along the line GG′ (Fig. 3). The upheaval of the western block of the Katakai fault was about 100 m higher than that of the eastern block. It was estimated from the topographical features that the rate of the relative displace-

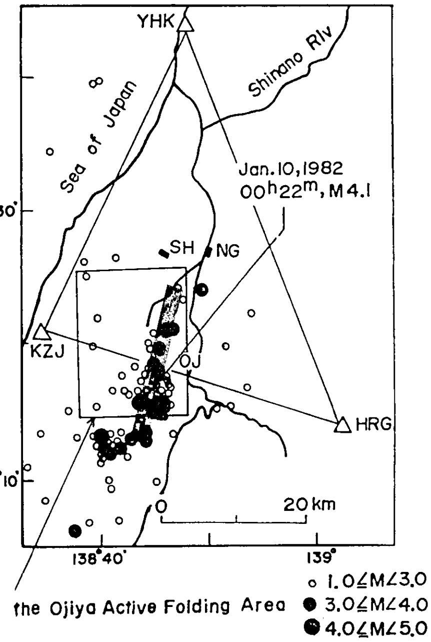


Fig. 4. Microearthquake distributuon in the southern Niigata basin for the period of the swarm activities near Ojiya; (I) July–Oct., 1979, (II) Feb.–Jun., 1981 and (III) Oct., 1981–Jan., 1982 with the event of Jan. 10, 1982 (M 4.1) for which the fault plane solution is given in Fig. 5. The seismic stations YHK (Yahiko), KJZ (Kashiwazaki) and HRG (Hirogami) are shown by triangles. The Ojiya active folding area is enclosed by a rectangle as in Figs. 1 and 2. The hatched zone striking in the NNE-SSW direction through Ojiya (OJ) corresponds to the Katakai fault (KK′ in Fig. 3) and also to the zone of the large velocity gradient of deformation (GG′ in Fig. 3).

ment of the two blocks is about 1 m per 10^3 years (OTA, 1969).

During the period from July, 1979 to May, 1982, noticeable earthquake swarms occurred near Ojiya with their epicentral distributions trending approximately in the NNE-SSW direction (HOKUSHIN OBSERVATORY OF MICROEARTHQUAKES AND CRUSTAL DEFORMATION, E.R.I., 1980, 1981). The swarm activities attained their peaks in the intermittent periods of (I) July–Oct., 1979, (II) Feb.–Jun., 1981 and (III) Oct., 1981–Jan., 1982 as shown in Fig. 4. In each of the sequences of the activity, the epicenters were concentrated in areas of about 10–15 km in length and 3–4 km in width. A fault plane solution was obtained for one of the representative events in the activity based on the data of the microearthquake observation network in the central and northeast Japan. The result was nearly identical with that of the Niigata earthquake (AKI, 1966) as shown in Fig. 5.

The microeathquake activity in relation to the active fault is sum-

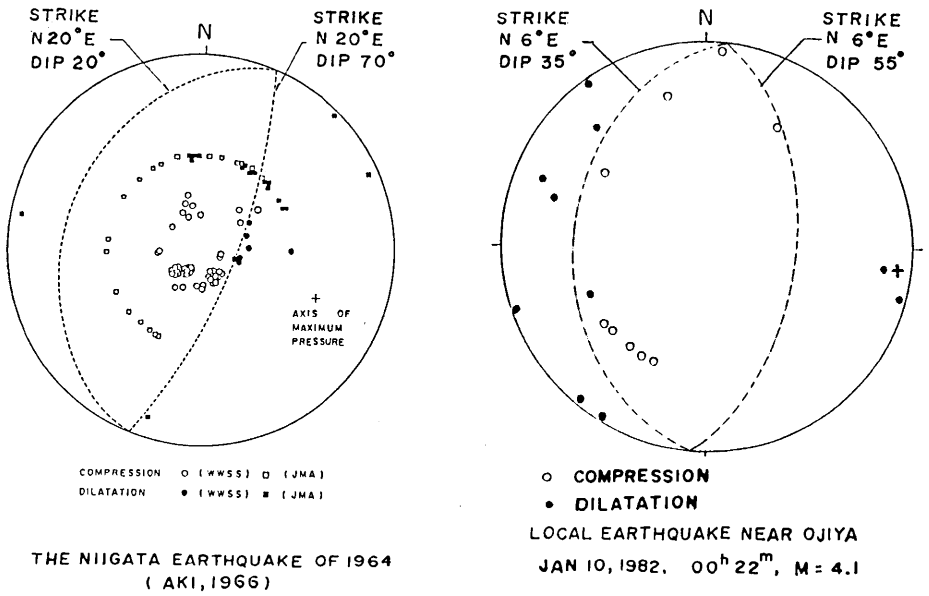


Fig. 5. Fault plane solutions from the initial motion of the P-waves for the Niigata earthquake (M 7.5) in 1964 (left) and the local earthquake near Ojiya (M 4.1) in 1982 (right) with the equal area projection on the upper focal hemisphere. Note that both of the earthquakes are of the similar type of reverse faultings.

merized as follows:

i) The epicentral distribution of microearthequakes indicates a linear arrangement of the N-S to NNE-SSW direction along the trace of the Katakai fault (Figs. 3 and 4).

ii) The fault plane solution of a local earthquake on the Katakai fault shows a high angle reverse faulting as in the case of the Niigata earthquake of 1964 caused by the regional tectonic stress prevailing in the inner belt of Northeast Japan (Fig. 5).

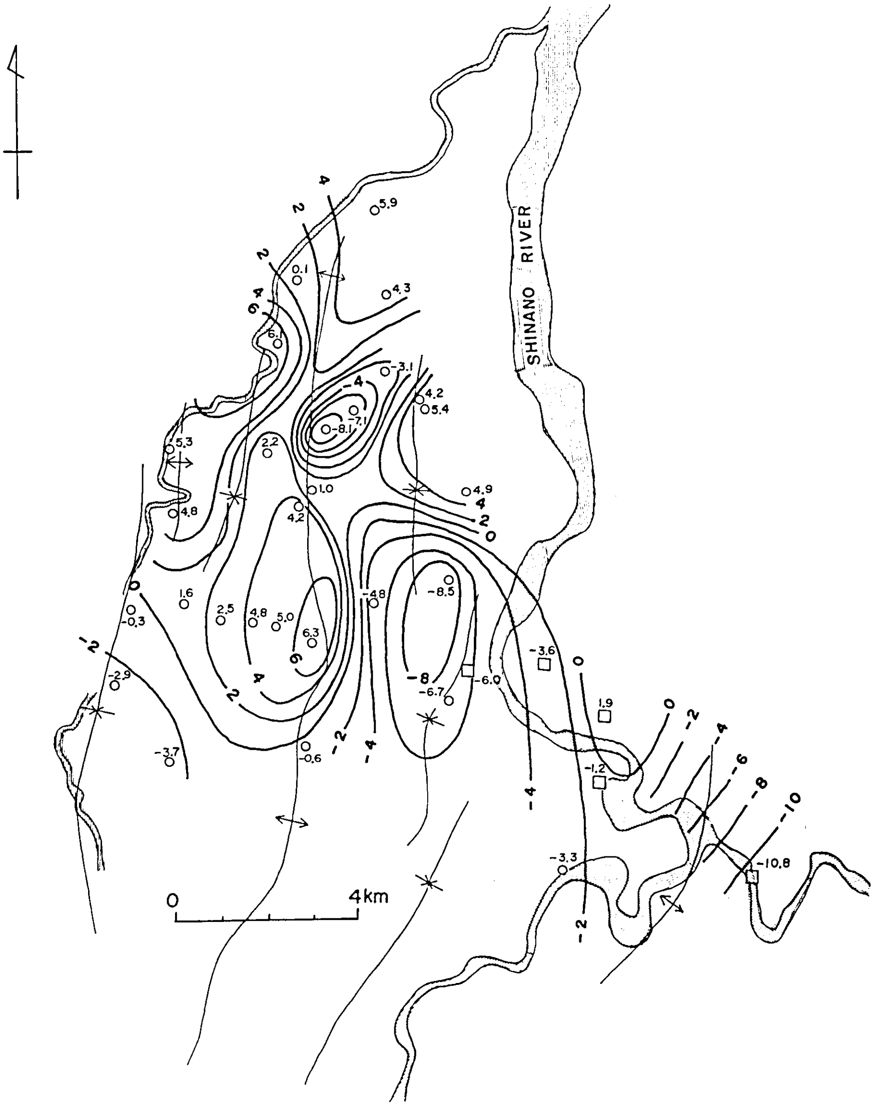
iii) It is highly possible from the evidence that the earthquake swarms in the area is related to the high angle reverse faulting of the Katakai fault with a common type of tectonic process as in the case of the Niigata earthquake (HIRASAWA, 1965; AKI, 1966).

4. Ananalysis

The statistic, elastic dislocation theory (MARUYAMA, 1964) is applied for the releveling data analysis. The fault surface is given by a rectangular surface of horizontal length L, width W and dip D embedded in an elastic half space with the top of fault at a depth H below the free surface.

The fault parameters are determined by fitting the observed pattern to the calculated one for the next three cases with different fault lengths L 4, 10 and 15 km, each of which is evaluated in the following manner:

i) L: 4 km, the length of the interaxial zone of the acute velocity gradient,

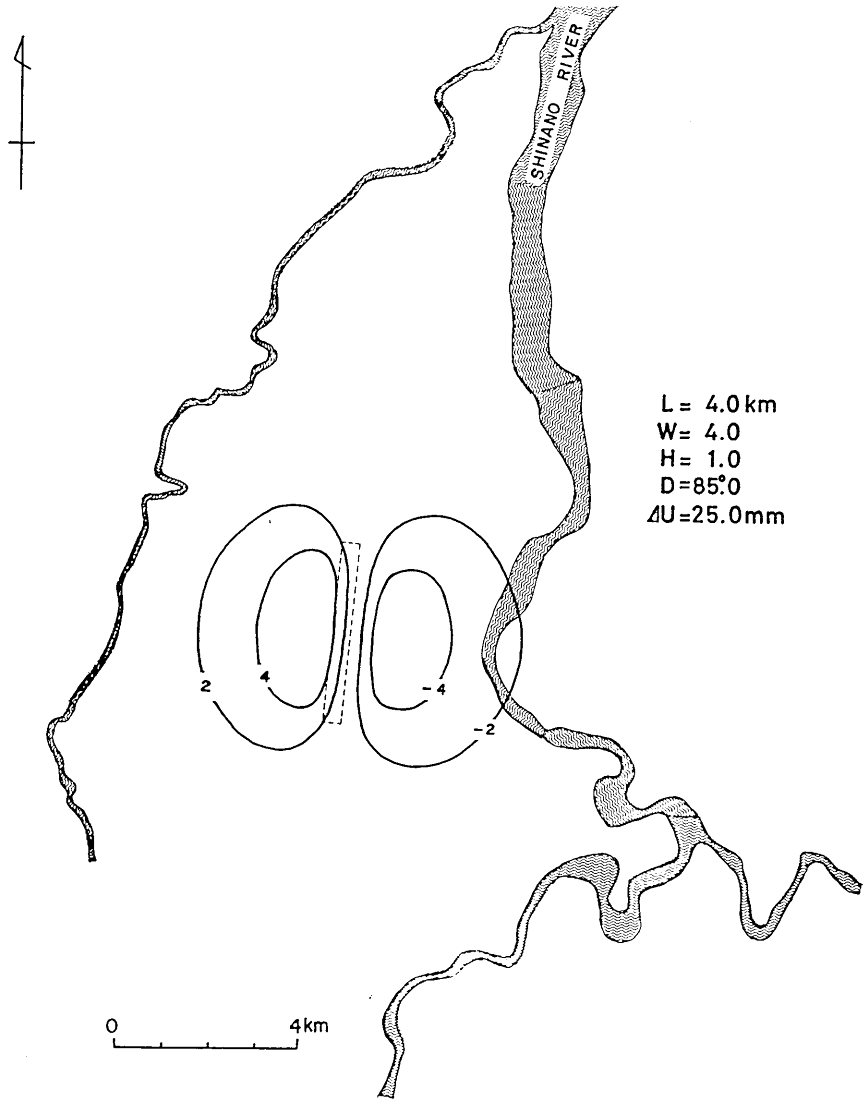


(a)

Fig. 6-(a). Observed result of the distribution of the undulatory mode of vertical crustal movement (adjusted for the period of Jan. 1, 1969-Dec. 31, 1978) as indicated by the contour lines of a 2 mm interval and the corresponding height change (in mm) of bench marks (circle for E.R.I. and square for G.S.I. bench marks).

ii) L: 10 km, the length of the lineament of the epicentral distribution of microearthquakes and
iii) L: 15 km, the length of the smoothed line of segment of the axis of the Tokimizu anticline.

Calculated results are shown in Figs. 6-(b), 6-(c) and 6-(d). The calculated and observed data are compared along the cross-sectional line PP′ on which the location of bench marks is projected (Figs. 1 and 7). The model with the fault length of L 4 km gives very small displacement over the entire cross-sectional line PP′. On the other

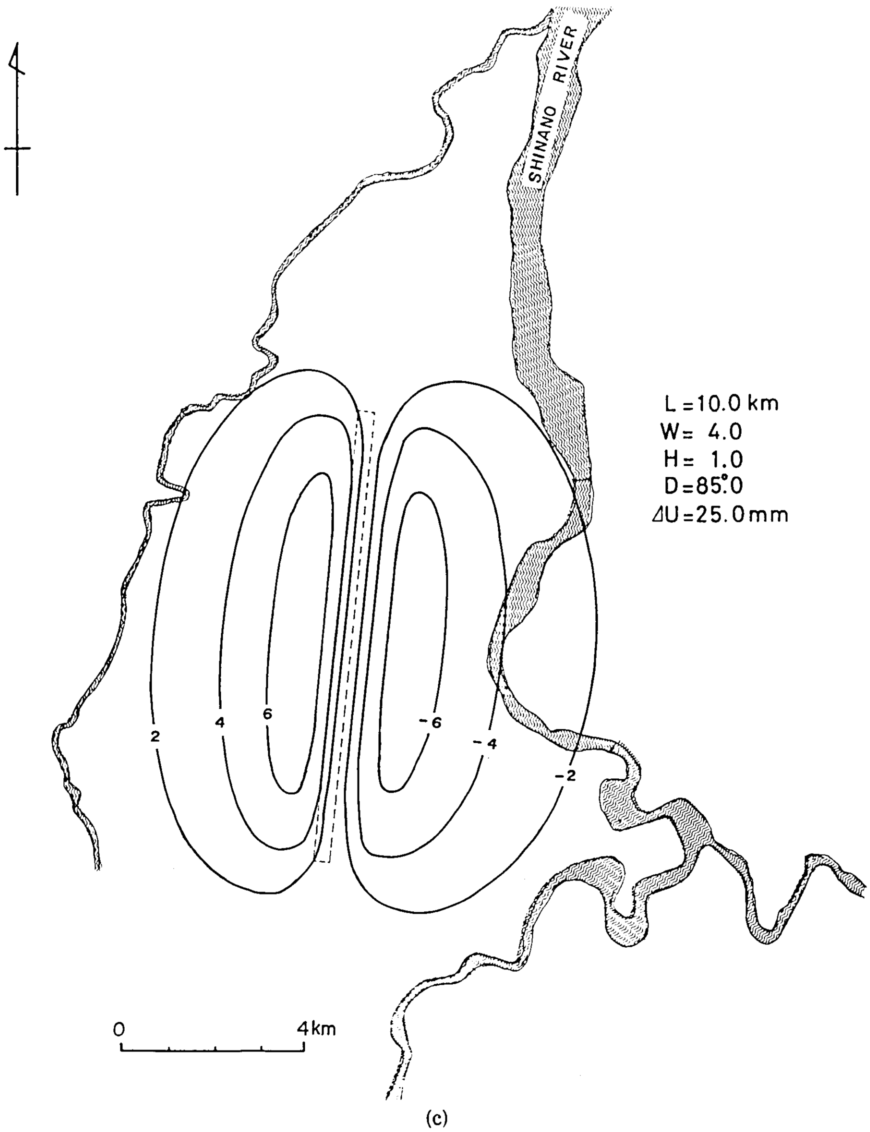


(b)

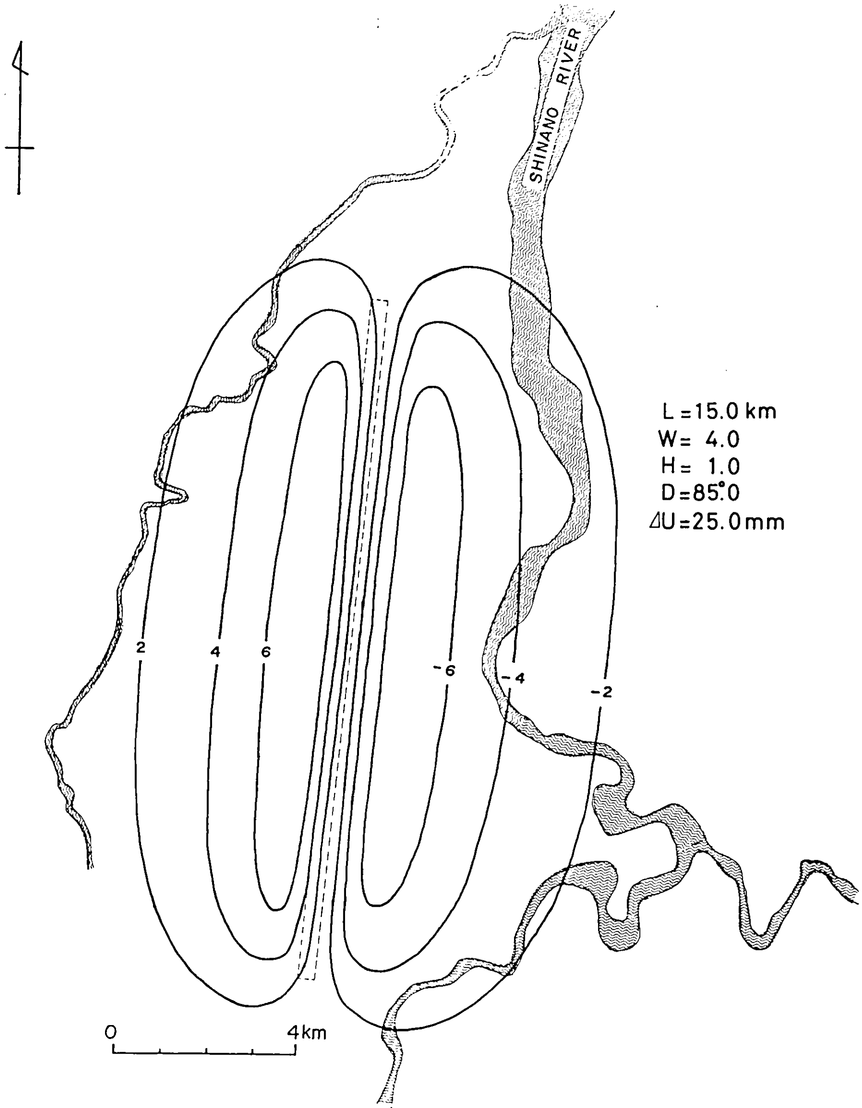
hand, the results for L 15 km gives an very large displacement in the northern and the southern end of the fault. Thus, the preferred fault parameters are as follows: a length L 10 km, width W 4 km, dip angle D 85°, depth of the top of the fault surface H 1 km and displacement on the fault surface ΔU 2.5 cm.

From the fault parameter determination, the following points can be noted.

i) The fault length is nearly equal to the length of the lineament of the epicentral distribution of microeathquakes in the swarm



(c)



(d)

Figs. 6-(b), (c) and (d). Calculated results of the vertical crustal movement. The fault length L is taken as 4, 10 and 15 km for the cases (b), (c) and (d), respectively. The vertical movement on the surface is shown by the contour lines of a 2 mm interval. The fault surface is shown by a rectangle projected on the earth's surface (dashed line). The preferred fault length L is 10 km.

activity along the Katakai fault.

ii) The type of the fault is a high angle reverse faulting with the dip angle 85° towards the west striking in the N-S to NNE-SSW direction.

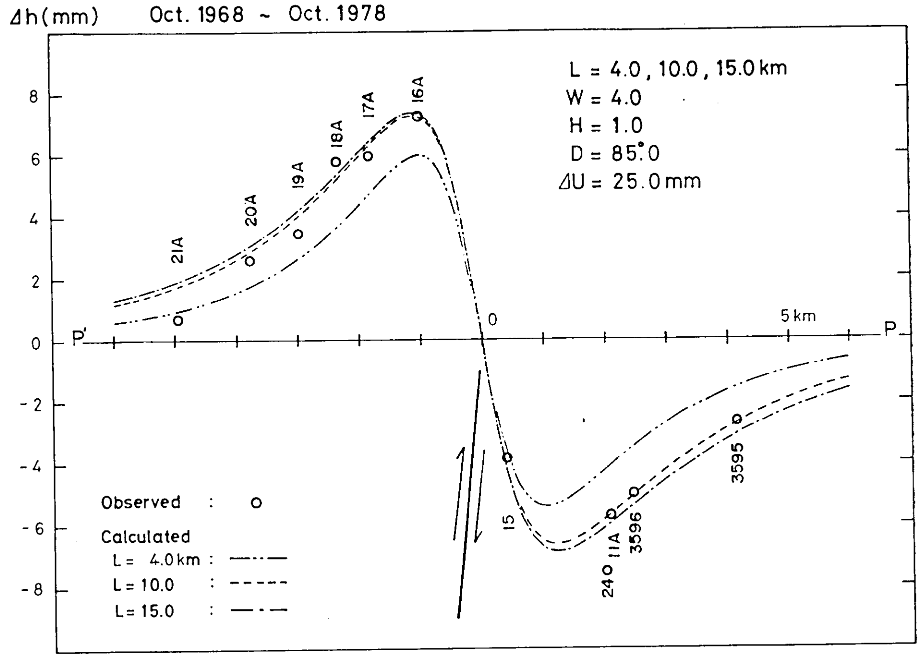


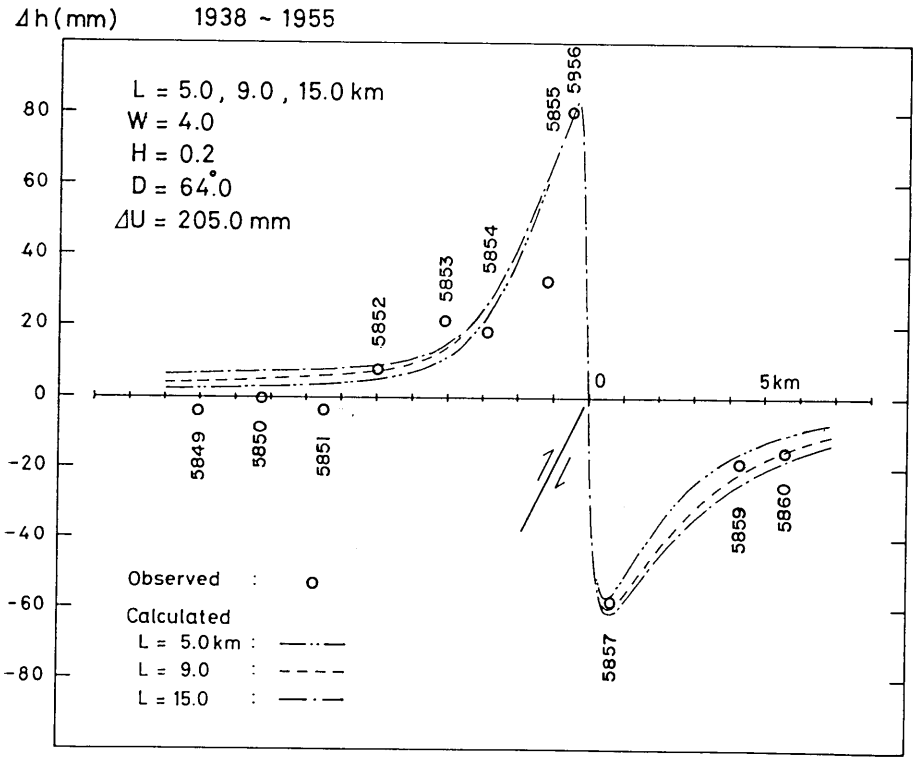
Fig. 7. Observed and calculated movements along the profile PP′ in Fig. 3 and the related faulting. The observed data is shown by empty circles. The calculated results are given for the three different models with fault lengths L of 4, 10 and 15 km, the width W of 4 km, the dip of 85°, the top of the fault at depth H of 1 km and the dip-slip motion ΔU of 2.5 cm striking in the NNE–SSW direction.

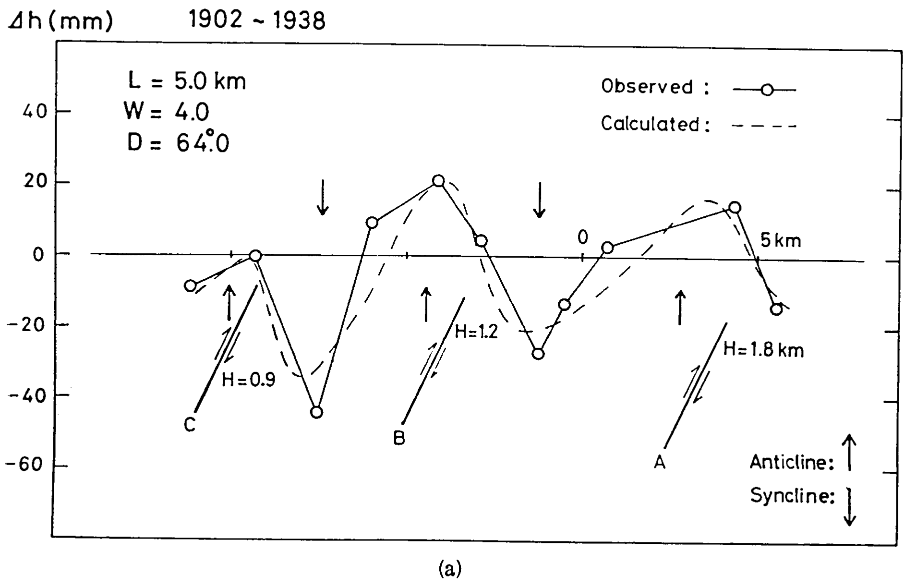
iii) The depth of the fault plane is very shallow judging from the small values of H 1 km and W 4 km.

iv) The time rate of the displacement on the fault surface ΔU 2.5 cm per 10 years is in the same order of magnitude as that of the Katakai fault on the order of 1 m per 1000 years for the geological time interval (OTA, 1969).

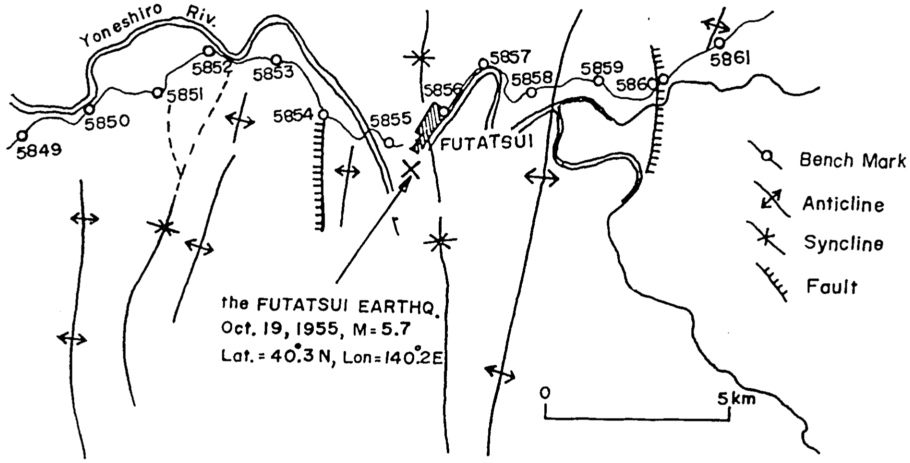
5. Seismicity and the rate of the fault movement

The cumulative seismic moment $\sum Mo_S$ as derived from the empirical relation of magnitude M and semismic moment Mo_S in the form of $\log Mo_S = aM + b$ is compared with the seismic moment Mo_L as obtained from the releveling data. The coefficients a and b are given as 1.5 and 16.0, respectively (AKI, 1972). The partition of the seismic and aseismic components of the fault displacement can be evaluated from a comparison in the following way. When the total slip on the fault surface ΔU_L and the seismic slip component ΔU_S are given for a specified fault with the length L and the width W, we have $Mo_L =$


Δh (mm)
1938 ~ 1955
L = 5.0, 9.0, 15.0 km
W = 4.0
H = 0.2
D = 64.0°
ΔU = 205.0 mm
80
60
40
20
0
-20
-40
-60
-80
5849
5850
5851
5852
5853
5854
5855
5956
5857
5859
5860
0
5km
Observed :
Calculated
L = 5.0km :
L = 9.0 :
L = 15.0 :


Δh (mm)
1902 ~ 1938
L = 5.0 km
W = 4.0
D = 64.0°
Observed :
Calculated :
40
20
0
-20
-40
-60
0
5km
H=0.9
H=1.2
H=1.8 km
C
B
A
Anticline:
Syncline:

(a)



(b)

Fig. 8-(a). Observed and calculated movements associated with the Futatsui earthquake (M 5.7) of 1955 and the related faulting. The movement is calculated for the three different models with fault lengths L of 5, 9, 15 km, widths W of 4 km, the dip D of 64°, tops of the faults at depth H of 0.2 km and dip-slip motions ΔU of 20.5 cm striking in a N-S direction (upper figure). The movement for 1902–1938 is simulated by applying an interaxial fault system consisting of the three high angle reverse faultings of (A), (B) and (C) parallel in their strikes with ΔU of 13 cm (lower figure).

Fig. 8-(b). The level route corresponding to the results in Fig. 8-(a) with the indication of the anticlinal and synclinal axes. The epicenter of the Futatsui earthquake (M 5.7) of 1955 is shown by a cross with an arrow (after MIYAMURA and OKADA, 1956).

$\mu \cdot A \cdot \Delta U_L$ and $Mo_S = \mu \cdot A \cdot \Delta U_S$, where μ is rigidity and $A = L \cdot W$ is the area of the fault surface. In case the slip ΔU_L is totally attributed to the seismic one, Mo_L should be equal to $\sum Mo_S$. With an increase of the aseismic component of the slip, the seismic component will take a smaller part in the total amount of slip, resulting in the decrease of $\sum Mo_S$ relative to Mo_L. On the contrary, if the slip is totally attributed to an aseismic one the cumulative seismic moment $\sum Mo_S$ will come to be equal to zero, while Mo_L remains at a finite value.

For the comparison of the two components of slip, we introduce a quantity as given by

$$\alpha = (Mo_L - \sum Mo_S)/Mo_L = (\Delta U_L - \Delta U_S)/\Delta U_L$$

which should be in the range of $0 \leqq \alpha \leqq 1$ depending on the relative amount of aseismic component of faulting.

In the period from October, 1968 to October, 1978, for which the releveling data is available in the major part of the level net near Ojiya, the following two earthquakes were located in the folded area by JMA:

October 02, 1974, 37.23°N, 138.70°E, h 20 km, M 3.9,
September 12, 1978, 37.27°N, 138.68°E, h 0 km, M 2.6.

The cumulative seismic moment $\sum Mo_S$ for the two events is given as 7.2×10^{21} dyne·cm. With $Mo_L=3.3\times10^{23}$ dyne·cm, equivalent to M 5.0, for the faulting in the interaxial zone ($L=10$ km, $W=4$ km, $\Delta U=$ 25 mm, $\mu=3.3\times10^{11}$ dyne·cm), we have $\alpha=0.98$. The result leads to the conclusion that the high rate of movement in the interaxial zone as compared with weak seismic activities can be attributed to a fault creep with an occasional occurrence of earthquake swarms.

6. Interaxial faulting related to moderate sized earthquakes

Some of the moderate sized local earthquakes in the folded areas in the inner belt of Northeast Japan were accompanied by remarkable crustal movements as detected by relevelings. Typical examples can be seen in the cases of the Sekihara earthquake of 1927, M 5.4, the Nagaoka earthquake of 1961, M 5.2 and the Futatsui earthquake of 1955, M 5.7. Due to the lack of detailed data of these earthquakes, a discussion on the feature of faultings of these earthquakes can be no more than a speculation. It should be noticed, however, that releveling data is available along the routes perpendicular to the general trend of the fold axes. It is very likely for these earthquakes to be located in the interaxial zones of active folds judging from the characteristic pattern of the change of hights of bench marks in relation to the locations of the epicenters and fold axes. As an argument by analogy of the faulting in the active fold area near Ojiya, it will be assumed in the following discussion that the earthquakes occurring in the interaxial zones are related to high angle reverse faultings striking in the direction parallel to the fold axes.

Among the three exemplified earthquakes, the Futatsui earthquake is the only case whose seismic movement is detected by the relevelings with bench marks set up at 2 km intervals. The Futatsui earthquake occurred on October 19, 1955 with its epicenter at 40.3°N, 140.2°E near Futatsui, Akita Prefecture, Northeast Japan (Fig. 8-(b)). The characteristic mode of the asymmetric movement for the period of 1938–1955 (Fig. 8-(a)) suggests a concealed seismic faulting in the interaxial folded zone along the Yoneshiro river, though neither a seismic nor a geological fault was found in the area (MIYAMURA and OKADA, 1956). The fault length of the earthquake is assumed to be about 9 km based on the report of the diameter of the aftershock area (SHIMA and SHIBANO, 1956). The surface displacement is calculated for the three cases of L 5, 9 and 15 km. It is assumed that the fault strikes in a N–S direction following the general trend of the fold axes. The preferred fault parameters of the model are as follows: a length L of 15 km, width W of 4 km, dip D of 64°, depth of the top of the fault H of 0.2 km, and dip-slip ΔU of 20.5 cm. The seismic moment Mo_L for the result is 4.1×10^{24} dyne·cm whereas the cumulative seismic moment $\sum Mo_S$ is 3.5×10^{24} dyne·cm from M 5.7 for the Futatsui earthquake. Thus, we have α nearly equal to 0 indicating that most of the total slip for 1938–1955 in the area near Futatsui is of seismic origin.

The mode of movement for 1902–1938 has a different pattern from that of 1938–1955. As a speculation, the movement of 1902–1938 can be explained if we assume a system of the three high angle reverse faultings in the interaxial zones of the folding area as shown in the lower figure of Fig. 8-(a).

7. Conclusions

The precise level net covering the folded area of about 10×20 km^2 near Ojiya, Niigata Prefecture, Northeast Japan was set up in 1967–1968. The releveling result for a decade is available for a detailed study on the characteristic mode of vertical crustal movement in relation to the geological and seismological evidences. A remarkable undulatory mode of movement with wavelength of several kilometers was detected superimposing on the regional tilt in a NNE direction. The anticlinal uplift near Ojiya shows a noticeable asymmetric pattern about the strike of the fold axes to be concordant with the deformed river terraces and undulatory Quaternary fold structures. A large velocity gradient of more than 10^{-6} per year was found in the eastern wing of the Tokimizu anticline.

Based on the geological and geomorphological evidences, the acute deformation in the eastern wing of the Tokimizu anticline can be correlated with the Katakai fault which has been identified as an active fault with an offset of vertical displacement of about 100 m. Microearthquake observation has disclosed the fact that the epicentral distribution in the area shows a characteristic linear arrangement which agrees well with the trace of the Katakai fault. The movement of the fault is found to be a high angle reverse faulting from the fault plane solution of a local earthquake. Considering the type of faulting and the geometry of the fault as suggested from the geological and seismological evidence, the releveling result is analysed by introducing the static elastic dislocation theory. It is found from the analysis that the high angle reverse faulting is a plausible explanation of the characteristic mode of movement.

The seismic moment as derived from the releveling data is compared with the cumulative seismic moment from seismicity data in the area. The dominant role of the aseismic slip to the total fault surface displacement is confirmed by the comparison. The time rate of vertical displacement for the Katakai fault of about 1 m per 1000 years from geomorpholocical evidences can be compared with dip-slip movement of the fault of 2.5 cm per 10 years from the releveling data. It is remarkable that the time rate of movement is in the same order for both the geological and geodetic time intervals.

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19. 東北日本内帯の活褶曲翼部における高角逆断層運動

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新潟県小千谷地域に設置された水準点の変動を解析した．当地域の変動モードは北向きの全般的な傾動と波長数キロメートルの波状変動とに分離される．後者は褶曲軸について非対的な隆起，沈降を示す．この特長的な変動の原因について活断層および微小地震活動と対応させることにより一つの解釈を与えた．すなわちこの変動は，地殻浅所における褶曲軸翼部での高角逆断層によるものであろうということである．なお，求められた断層変位速度と当地域の地震活動とを比較することによりこの変動が主として aseismic slip によるものらしいということを指摘した．また小千谷の例に対し，主として地震にともなう変動の例として二ツ井地震 (1955 年，*M* 5.7) の例をとりあげた．