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64. *Ground Cracks at Matsushiro Probably of Underlying Strike-slip Fault Origin, I—Preliminary Report.*

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1. Introduction

The Matsushiro earthquake swarm[1] which broke out at the beginning of last August reached a culmination both in seismicity[2] and in the rate of associated vertical and horizontal ground deformation[3] this April. During the culminate period, four linear ground fissure zones which are arranged *en echelon* in a narrow area were formed successively in the epicentral area. The cracks and fissure zones seem to have resulted from an underlying strike-slip fault. The inferred fault agrees well with the one expected from focal mechanism studies of the earthquake swarm[1] in the sense of its horizontal movement and also explains qualitatively the extensional deformation of ground as revealed by electro-optical measurement[4].

This paper describes the ground cracks and fissure zones as in early June, 1966 and gives preliminary results of measurements of the rate and direction of opening of the ground cracks.

2. Surface geology of the fissured area

The four fissure zones are distributed in a narrow area, 0.3 km wide

1) The Party for Seismographic Observation of Matsushiro Earthquakes and the Seismometrical Section, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network, Part 1", *Bull. Earthq. Res. Inst.*, **44** (1966), 309.

2) ———, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network (7th report)", *Monthly meeting of E.R.I.*, May 24, 1966.

3) T. HAGIWARA, J. YAMADA and M. HIRAI, "Observation of Tilting of the Earth's Surface at Matsushiro (4th report)", *Monthly meeting of E.R.I.*, May 24, 1966.

The Party for electro-optical measurement, "Electro-optical Measurement in Northern Shinshu (4th report)", *Monthly meeting of E.R.I.*, May 24, 1966.

4) K. KASAHARA and A. OKADA, "Electro-Optical Measurement of Horizontal Strains Accumulating in the Swarm Earthquake Area (1)", *Bull. Earthq. Res. Inst.*, **44** (1966), 335.

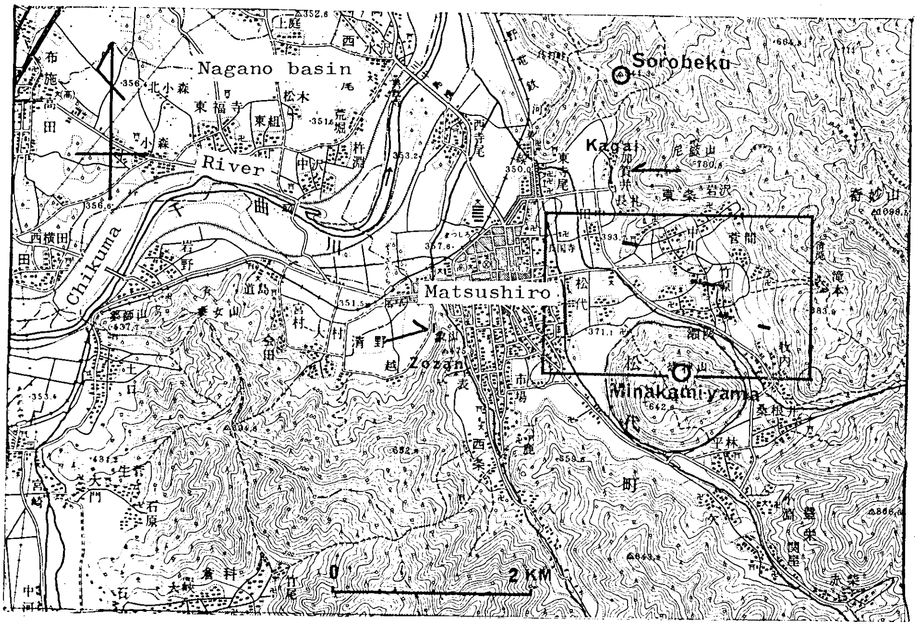


Fig. 1. Index map. Fissure zones are indicated by thick lines. Rectangle is the area covered by Fig. 2. Thick lines indicated by arrows outside the rectangle are those formed by slow landslide.

and 1.8 km long, lying north and northeast of the base of Minakami-yama lava dome. The dome, which rises steeply above the surrounding lowlands, lies almost directly over the epicentral area of the Matsushiro earthquake swarm (Fig. 1). Most of the fissured area is on the floor of the broad valley, at the mouth of which the town of Matsushiro is situated. The upper reaches of the valley are extensively covered by coalescing alluvial fans while the lower portion extending to the Nagano basin has a flat surface probably of back swamp of the Chikuma River.

Fig. 2 shows the geomorphology of the fissured area on a larger scale. The area is underlain mainly by the coalescing alluvial fans (Fig. 7) formed between the Minakami-yama lava dome (hornblende bearing augite-hypersthene andesite) and the highlands to the east and north which are underlain predominantly by shale intruded by a complex of hornblende porphyrite and fine grained diorite.[5] The three older fans extending from

5) R. MORIMOTO, I. MURAI, T. MATSUDA, K. NAKAMURA, Y. TSUNEISHI and S. YOSHIDA, "Geological Consideration on the Matsushiro Earthquake Swarm since 1965 in Central Japan", *Bull. Earthq. Res. Inst.*, **44** (1966), 423.

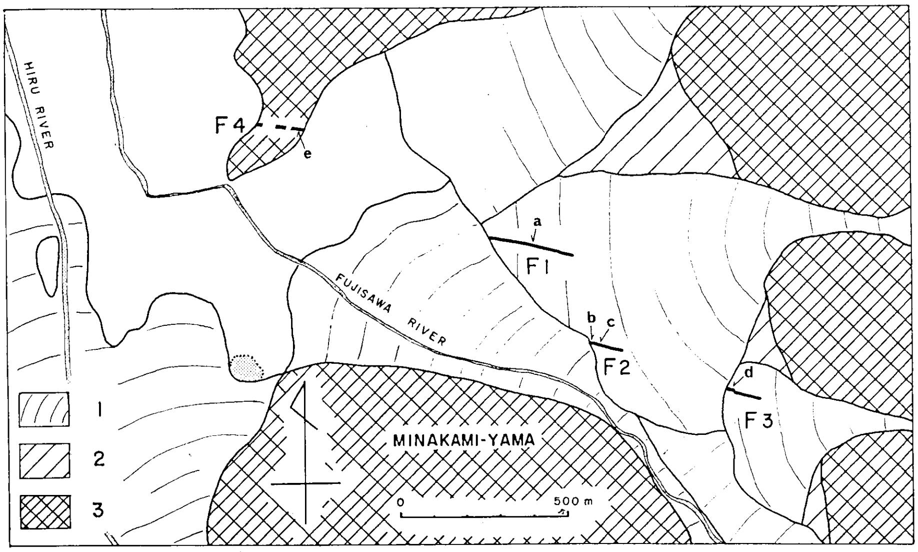


Fig. 2. Distribution of fissure zones (F_1—F_4). 1: fan, 2: talus slope, 3: mountainland, blank: flat low land. a—e: localities where horizontal movement of ground has been measured. Cf. Fig. 7.

the east with slopes of as much as 10 degrees, consist of a muddy surface layer a few metres thick overlying coarse rubbly fan deposits. On the other hand, the alluvial fan of Fujisawa River just north of Minakami-yama is gentler in slope; it consists of gravelly deposits covered by surface soil less than one metre in thickness.

The outline of the fans shown in figure 2 is easily recognized in the field and on aerial photographs. The northwestern part of the mapped area is a low flat flood plain that is utilized for paddy-fields (Fig. 7).

The maximum thickness of the underlying valley-fill deposits is estimated at several tens to a hundred metres on the basis of topographic consideration. The thickness of 57 m was measured by the electrical resistivity method[6] along the N-S line through locality **a** of F_1 (Fig. 2).

3. Description of the Fissure Zones

The length, date of discovery of cracks and also dates when further opening was observed and when our measurements began are listed in

6) K. KAWADA, "Electric Resistivity Measurement along and across a Ground Fissure in the Matsushiro Area", *Monthly meeting of E.R.I.*, May 24, 1966.

Table 1. The date of actual formation of the cracks is not certain but would be earlier than the date they were found, except for F_1 which cuts across a road 3 m wide and a farmer's garden (Fig. 5). After cracks were found, further opening was observed by naked eye and later by measurements of displacements between reference marks set in cement on either side of the cracks.

Table 1.

Name and locality of fissure zones	Length (m)	Date of		
		Find (1966)	Further opening observed by naked eye	Beginning of measurement
F_1,. Takehara	275	Jan. 21	end of Feb., Apr. 17	Apr. 22
F_2, Seseki	190	Apr. 17		May 19
F_3, (Mulberry field)	100	Apr. 25(17?)	Apr. 25 ~ May 17	May 19
F_4, (Ikeda shrine or Tamayori-hime shrine)	65+(150+)	May. 18		June 10

The following features are common to the four fissure zones:

1) The zones are almost linear, they are a few to several metres in maximum width, and they have nearly the same strike. They are arranged *en echelon* in an area extending in a N60°W direction.

2) Each fissure zone consists of short parallel cracks of 0.2 to 3 m long and 0.2 to 7 cm wide arranged *en echelon* in the respective fissure zones. The angle between a fissure zone and component cracks is about 35° (Figs. 3 and 4).

3) The horizontal movement represented by individual fissure zones is not a mere opening but includes a left-lateral component which is apparently clear from the *en echelon* arrangement of constituent cracks and is also demonstrated by our measurement. Dip slip component has not yet been observed, except in the one case which is regarded as a local disturbance.

4) Separation across cracks, density of component cracks, and horizontal movement are largest in the central part of a fissure zone. On the other hand, the ends of the fissure zones are comprised of only one or two

cracks, the amount of dislocation being far smaller. This is best observed at fissure zones F_1 and F_2.

5) Location of the fissure zones is apparently controlled by surface geology. Zones F_1, F_2 and F_3 terminate at the western margins of alluvial fans. Zone F_4 is expressed only in surface soil on hill but does not extend to wet low land.

6) Although the distribution of the fissure zones is controlled by surface geology, their trend is nearly parallel to the maximum inclination of the ground surfaces. Among the four fissure zones, F_4 differs from the rest in that it was formed across a low hill consisting of consolidated Miocene shale and associated porphyrite whereas the other three are formed on alluvial deposits.

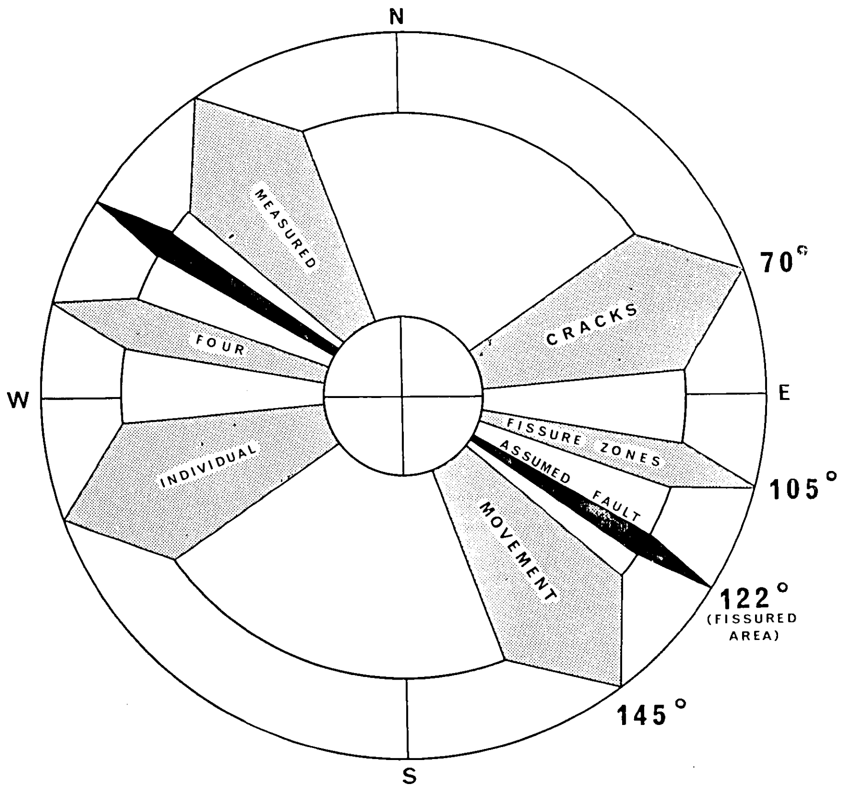
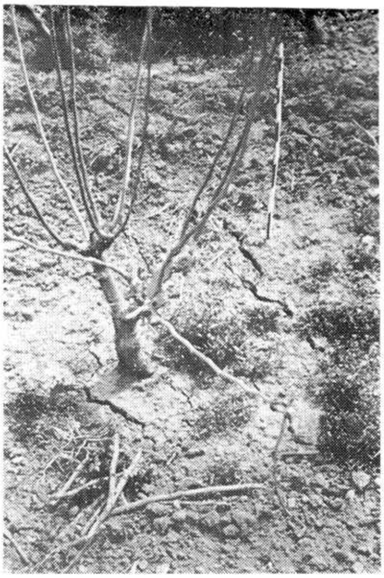


Fig. 3. Directions of individual cracks, four fissure zones, assumed fault (fissured area) and measured movement direction of fissure zones.



a.

b.

Fig. 4. a: Cracks arranged *en echelon* in mulberry field (F_1). Scale (1 m) indicates direction of the fissure zone. b: one of the widest cracks of F_3 (Locality **d**). Width of scale 16 mm.

Fig. 3 shows the direction of individual cracks, trend of the four fissure zones, the inferred strike of the underlying fault, and the direction of opening movement. The last of these is determined from measurements to be described in the next section.

4. Measurement of the rate and direction of movement

The dislocation and its rate along fissure zones have been measured at five localities (**a-e**, Fig. 2). This report presents only the results at locality **a** as they cover the longest time period and are representative of those at the other localities. These will be described in a later report.

Locality **a** is nearly at the centre of zone F_1 where it intersects a house and its garden (Fig. 5). The displacement in the fissure zone is distributed among many cracks on the ground surface, but is concentrated into one or a few cracks where the fissure zone cuts through concrete slabs on the ground. Along four cracks (A, B, C and D; Fig. 5) on the concrete slabs, simple reference points were set up to measure the displacement. Each of these comprises four points, being a few tens of centimetres apart, so located that two are on the same side of the crack (Figs. 6, 8 and 9).

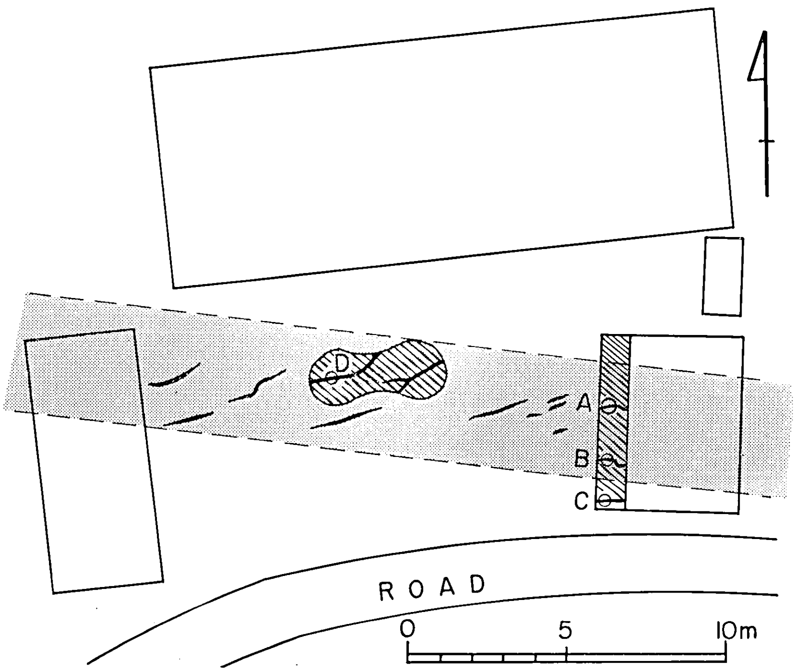
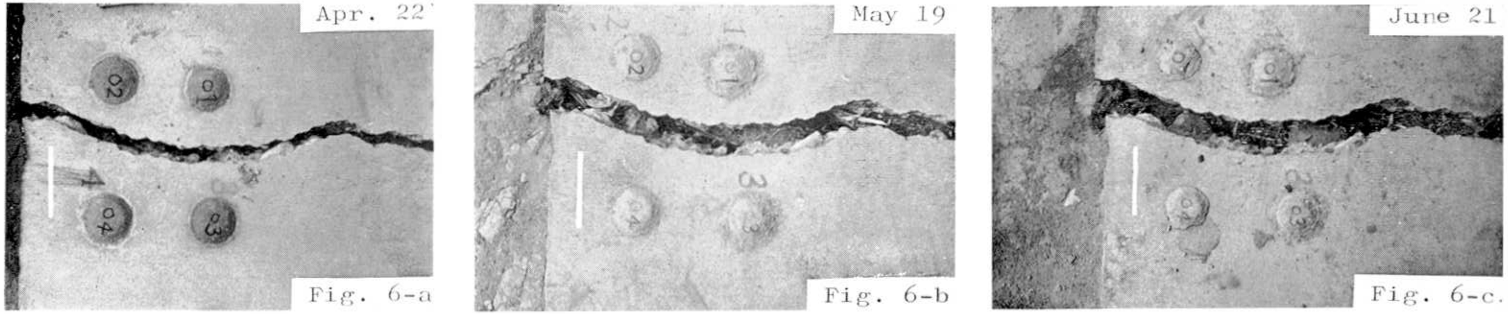


Fig. 5. Sketch map of locality a in Fig. 2. Stippled area: fissure zone, thick line: cracks, hatched area: concrete slab, A～D: sites where the measurement has been conducted. Rectangles are houses made of wood.

The concrete slab, on which A, B and C are situated, covers the whole width of fissure zone F_1. The sum of measured displacements on A, B and C, therefore, would represent the net movement in the fissure zone. Because the slab on which D lies, covers most, but not all the width of the fissure zone, the movement shown by the set D will represent only part of the net movement in the zone.

At each set of four points, four distances were measured to the nearest 1 mm between the points on opposite sides of the cracks. The rate and direction of movement of the southern two points (I and II, Figs. 8 and



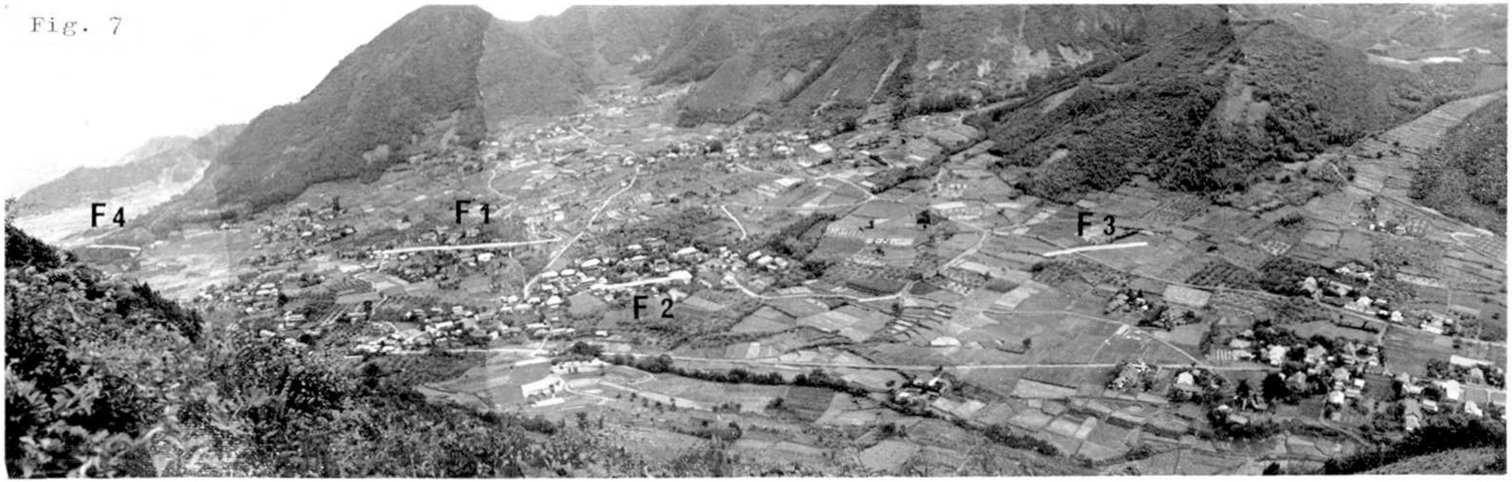


Fig. 6. Growing cracks on concrete slab at A of locality **a**. White lines are 10 cm. In the centre of small mounds there are pinpoints between which distance has been measured. The shape of square of Fig. 6-a is reproduced in upper right of Fig. 8.

Fig. 7. Fissured area viewed from the eastern top of Minakami-yama. Four linear fissure zones (F_1—F_4) are indicated. Cf. Fig. 2.

9) relative to base lines connecting the northern two points of A and D are shown in Figs. 8 and 9 for the period from April 22nd to June 6th. As the amount of movement of B and C cracks during the period of our measurement (B: May 20th-June 6th, C: April 22nd-June 21st) was so small (on the order of a mm), the measurement at B and C are not presented.

These results show:—

1) The NW-SE direction of the movement is almost the same during the observed period as was expected by the *en echelon* arrangement of cracks in fissure zones.

The curves of displacement vectors are slightly concave northeast. This is tentatively interpreted as the combined result of the change of direction itself and local rotation of the concrete slab. Rotation of the concrete slabs on both sides of crack A is observable even with the naked eye.

2) The rate of movement is regarded as almost continuous and not stepwise in time units of one day and with the precision of measurement used. For shorter time units and with more precise methods, the movement would probably be stepwise. This is suggested by the observation that just after a greater earthquake a sudden opening of the crack was noticed as shown in Table 1.

3) The amount of movement represented by set A (Fig. 8) is greater than that by set D (Fig. 9), but the general tendency is quite similar. This is what was to be expected, as stated earlier, because of the differing widths of concrete slabs at the two localities.

4) The rate of movement has become progressively smaller. It was 1.40 mm/day at A and 0.87 mm/day at D toward the end of April, and in June dropped off to one third and one half respectively.

5. Discussion

It appears difficult to attribute the formation of cracks and fissure zones described in the previous sections to landsliding or simple ground upheavals. The landslide hypothesis can not account for the direction of fissure zones which is generally in the direction of the maximum surface inclination.

In the epicentral area many cracks of greater dimension have been formed that are associated with slow progressive landslides since the beginning of the present earthquake swarm. Those at Nuruyu, 9.5 km NE of Minakami-yama, at Kagai and at Zozan (Fig. 1) are of this type.

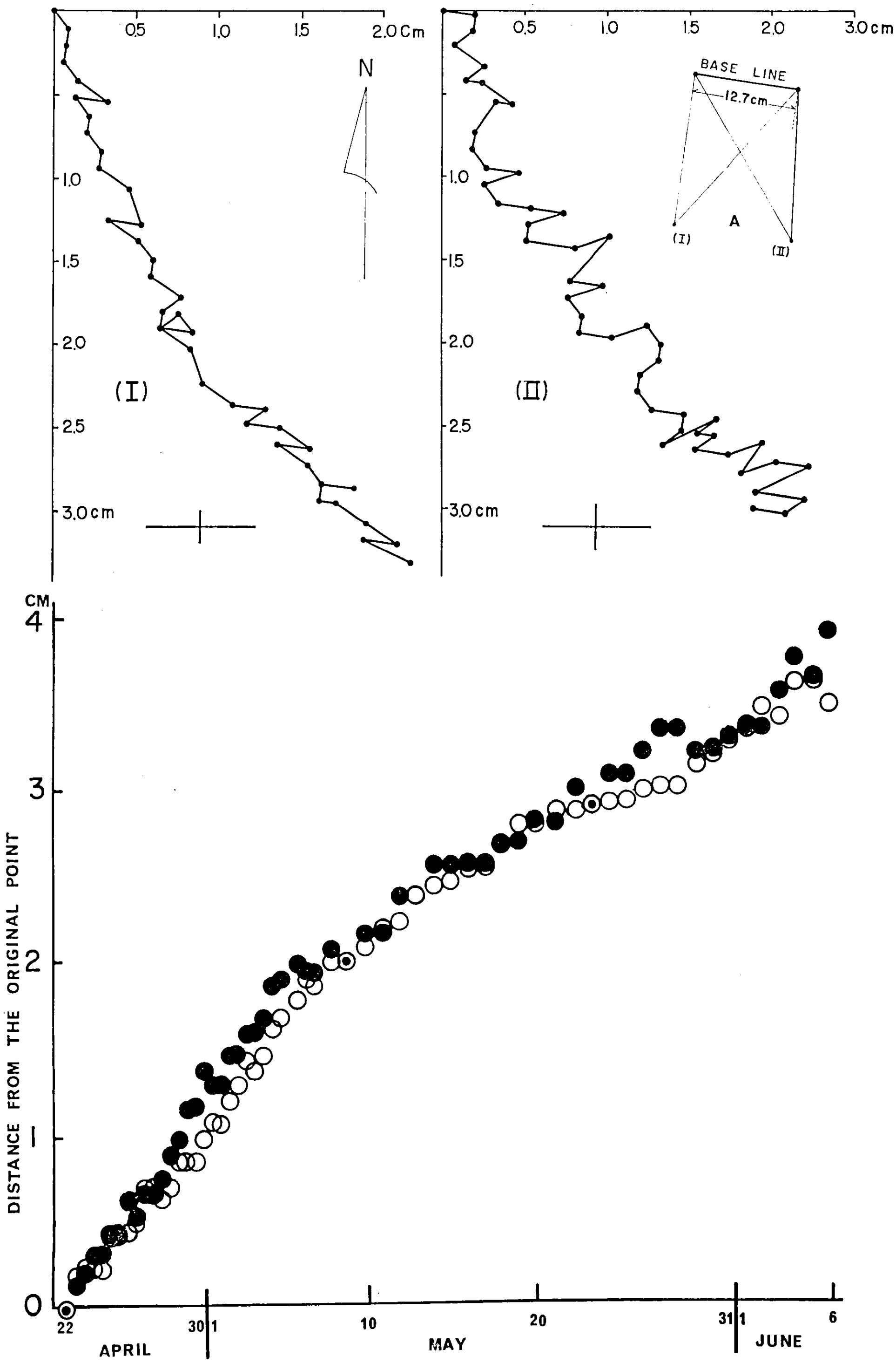


Fig. 8. Result of measurement of crack A (Fig. 5) in locality a of F_1.

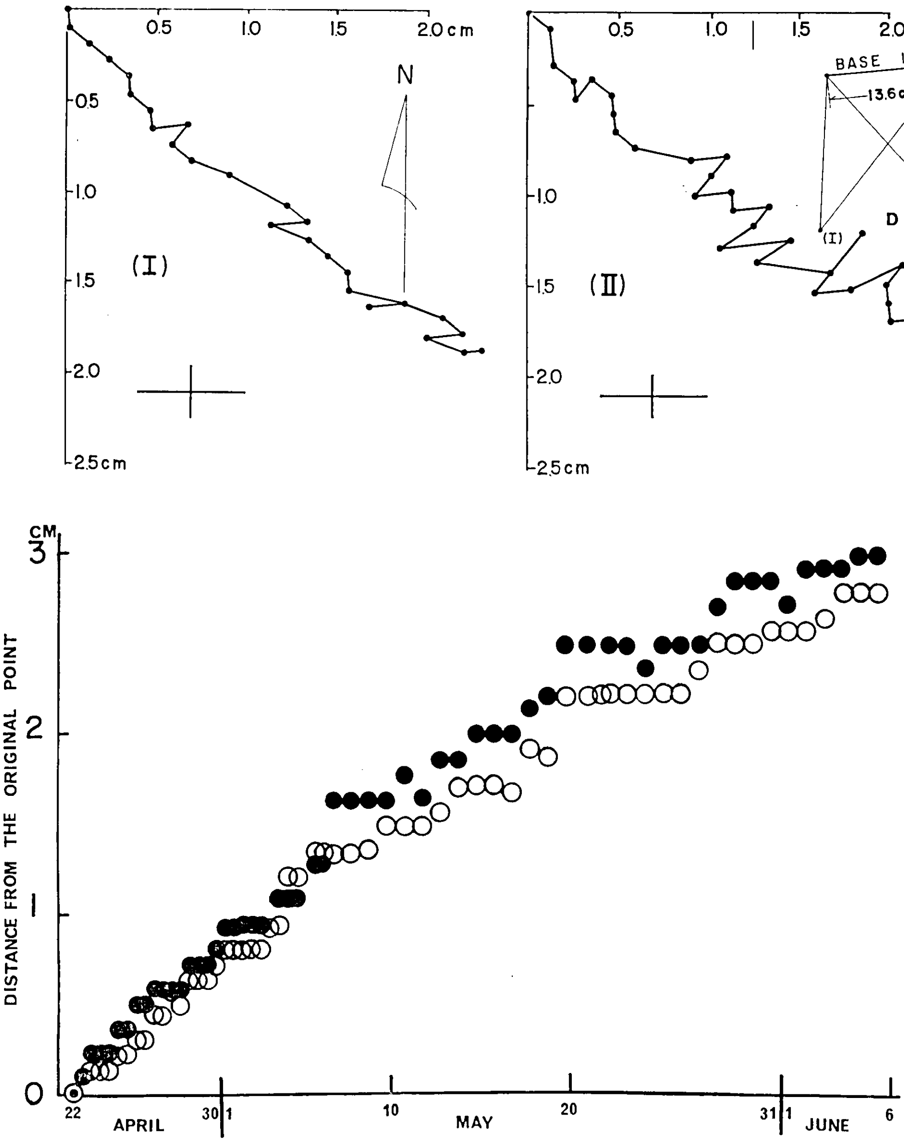


Fig. 9. Result of measurement of crack D in locality a of F_1.

In the upper graphs (I) and (II) are horizontal displacement vectors of two points referring to base line which connects another two points on the opposite side of cracks. Two flat crosses indicate the possible range of error of each point. Lower graphs show amount of movement of the points whose displacement vectors are shown in I and II. Solid and open circles correspond to (I) and (II), repectively.

They are all parallel to contour lines and component cracks are not arranged invariably *en echelon.* A hypothesis of simple upheaval does not adequately explain the left-lateral strike-slip component of movement on cracks in the fissure zones or the fact that the zones trend mainly in a WNW-ESE direction (Fig. 3).

A third hypothesis, which seems most likely at present, is that there is an active fault or a zone of faults in the basement rocks (probably Miocene shale intruded by porphyrite-diorite complex) just beneath the fissured area which has a component of left-lateral movement. According to this explanation, *en echolen* arranement of individual cracks in a fissure zone and the four fissure zones in the fissured area are regarded as shear phenomenon reflecting movement of bed rock faults. They are comparable to feather joints which are frequently observed in hard rocks which have undergone differential movement. Also, the movement of the fissure zones as described in section 4 must be intimately related to one or more concealed bedrock faults. From the directions of the measured left-lateral movement and separation of surface cracks, the inferred fault should have a horizontal axis of maximum compression in an E-W direction.

The fault hypothesis seems to be more plausible when the results of electro-optical measurement and of push-pull distribution of the present earthquakes are taken into account. By the electro-optical measurement[7)], the accumulated amount of N-S extensional strain from October, 1965 (Minakami-yama ~ Sorobeku, Fig. 1) across the fissured area attained 0.8×10^{-4} in March, 1966. Actual fractures between the two stations would be expected. Further, the direction of minimum compressive stress as expected by the measurement is N-S, which is nearly the same as that expected by the trend of the assumed fault. Push-pull distribution of initial motion of the Matsushiro earthquakes[8),9)] is quadrantal with the horizontal maximum compressive stress axis in an E-W direction. One of the two nodal lines which are thought to represent potential directions of shear fracture at the hypocentre, nearly coincides with the fault direction suggested by this study.

Thus, the stress system inferred both by the geodetic and first motion studies is consistent with the fault hypothesis. If the Matsushiro earth-

7) K. KASAHARA and A. OKADA, *loc. cit.*, 4).

8) The Party for Seismographic Observation of Matsushiro Earthquakes and the Seismometrical Section, *loc. cit.*, 1).

9) M. ICHIKAWA and T. ISHIKAWA, *Annual Meeting, Seismological Society of Japan*, May 25, 1966.

quake swarm keeps its activity, additional parallel faults with the same sense of displacement and/or conjugate right lateral faults may possibly be expected to occur in the epicentral area.

6. Concluding remarks

Four ground fissure zones a few hundreds of metres in length, which were formed in the epicentral area during a culminate period of the Matsushiro earthquake swarm, are best interpreted as a surface manifestation of new movement on an underlying strike-slip fault. Preliminary result of measurement of the surface ruptures indicates left-lateral displacement along NW–SE trending fissured area which corresponds closely with the movement direction expected by geodetic measurements across the area and with one of the nodal lines derived from first motion studies of the earthquakes.

In conclusion the writers are grateful to Mrs. M. Saito of Matsushiro for her help in making daily measurements of crack movements. They are also indebted to Prof. T. Kimura, Assoc. Prof. T. Matsuda and Dr. G. Plafker for their critical reading of the manuscript. Part of the present study was supported by a grant given by the Ministry of Education.

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64. 横ずれ断層によると考えられる松代の地割れ群 I

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松代群発地震は1966年4月にこれまでのうち最大の活動を示した．この時期に震央域内の長さ1.8 km，巾 0.3 km の細長い地域に4個のそれぞれ直線的な地割れ帯が形成され，発達を続けている．4月末から6月初めにかけてこれら地割れ帯に対して変位の速さと方向の観測が開始された．

本稿では1966年6月までの地割れ群の性質と観測結果の一部とを報告し，この地割れ群が恐らく地下の左横ずれ断層の動きの地表的表現であることを論じた．

震央地域には本稿で扱った地割れの他に，加賀井・象山・温湯などにゆるやかな地辷りによると考えられる地割れがある．両者の相違を列挙すると，

（本稿で扱った地割れ）	（地辷りによると考えられる地割れ）
等高線と無関係，あるいは直交し，山地をも横切る．	背後に山地，前面に低湿地をもった山麓緩斜面に生じ，等高線と平行．

垂直落差はない.	地形的にひくい方がおちている.
地割れ帯中の割れ目が全体を通して同方行に雁行.	一般に雁行しない. また雁行しても向きは一様ではない.
地割れ帯は直線的.	等高線にそって曲る.

等である. 特記すべきは地辷りによると考えられる地割れは, それと平行して約 50m 位はなれた低地側に, もり上る地帯が生ずることである.

本稿で扱った地割れ帯はほぼ N60°W 方向の細長い地域内に配列し, Fig. 3 に示すように変位には左横ずれの成分がある. 個々の地割れ帯は数多くの雁行配列した小さな割れ目よりなる. 地割れ帯の長さは 100～300m (Table 1) で, 個々の割れ目は長さ数 m 以下である. それらの方向は 4 つの地割れ帯を通してよくそろっており, その関係は Fig. 3 に示されている.

以上の性質はゆるやかな地辷りに起因する地割れとしては説明できないし, また単なる土地の隆起を考えても説明がむずかしい. 現在のところ, 地割れを生じている細長い地域ののび, N60°W の方向に地下の基盤岩中に左横ずれ断層が生じつつあり (1 つではなく同センスの小さな断層が密集しているのかもしれない) その地表での現われが羽毛状の地割れであると考えるのが一番もっともらしい. この考えはほぼ東西水平方向に最大圧縮応力を想定する点で松代地震の発震機構とよく一致する. また光波測量基線の 1 つ (皆神山——可候峠) が推定断層をよこぎり, 著しいのびを示していることも少くとも定性的に矛盾はない.

地割れ帯は巾数 m 程度で, その巾の中に多数の平行な割れ目を含むが, たまたま地割れ帯全体を被うコンクリートのたたきを横ぎるような場合には地割れ帯中の割れ目はごく小数になり, その動きが地割れ帯全体の動きに近いものを示していると考えられる.

Fig. 8 および Fig. 9 は, F_1 地割れ帯の地点 a (Fig. 2, 5) において, ともにコンクリートたたきの上に生じた A および D 割れ目の動きを示したものである. A 割れ目 (Fig. 6) はほぼ地割れ帯全体を被うコンクリートたたきの上にあり, 同じたたき上の B および C 割れ目は測定を開始してからはほとんど変化がない. 従って測定期間中の A 割れ目の動きは, ほぼ a 地点における F_1 地割れ帯の動きをあらわしていると考えることができる. これに対して Fig. 9 に示した D 割れ目の動きは, 割れ目のできているたたきが地割れ帯全体を被っていないので F_2 地割れ帯の動きの一部をあらわしていると考えられる.

Fig. 8 および 9 に示された A および D 割れ目の動きの傾向はよく似ている. その大きさは A の方が大きく, 前にのべたことから期待されるものと一致している. 動きの方向は北々西～北西 (南々東～南東) である (Fig. 3). 動きの早さは 4 月下旬に 1.4mm/day 程度であったものが 6 月上旬には 1/3 程度に減少し, この期間における地震活動度の減少と対応しているようにみえる.

謝辞: 松代町竹原の斉藤まき江氏には毎日の測定をしていただいた. また松代町役場の方々にはいろいろ便宜を提供していただいた. 記して厚く御礼申し上げたい.