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Tertiary Stress Field and Tectonic Development of the Southern Part of the Northeast Honshu Arc, Japan

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(with 2 Tables, 14 Textfigures and Appendix)

Abstract

It has been successfully proved that a dike swarm shows a preferred orientation parallel to the horizontal, maximum compressive stress (σH_{max}). Thus, it is possible to take a dike swarm as a spatial indicator of the σH_{max}-direction of the tectonic stress field during intrusion as well as a path indicator of temporal changes of tectonic development.

Seventeen dike-swarms distributed throughout the southern part of Northeast Honshu, Japan, ranging in age from the end of Oligocene to the Pliocene, have been examined. In addition, the tectonic history of the area has been studied in order to characterize these stress fields by the categories, compressional (P-type) and extensional (T-type).

The result indicates that the inner zone of NE Honshu was subjected to the T-type stress field with a N-S σH_{max} until it was replaced by the P-type field with an E-W σH_{max}. The change in type and orientation of stress field which abruptly occurred around 7 Ma b.p. affected seriously on the tectonic style of the inner zone. On the outer zone, on the other hand, no evidence was found to suggest that there had once existed any T-type field during the period concerned.

Consequently, it was made clear that the contrast of the stress field orientation between the inner and outer stress provinces sharply existed during the Miocene time probably from 21 to 7 Ma b.p. This differential buildup of tectonic stress distribution is named here as "Paired stress field". The stress history of the NE Honshu Arc, especially the occurrence and disappearance of T-type province, might be a common characteristic of the development and evolution of interarc basins.

1. Introduction

The state of stress in the Earth's crust is generally defined by gravitational stress due to the body force and tectonic stress generated by some external forces (RANALLI, 1975; MCGARR & GAY, 1978). Regional geologic structures, especially wide-spread features of tectonics, are a manifestation of the regional stress field developed in the area concerned. Therefore, it is possible to discuss the stress state by means of the characteristics of the tectonics of that province (TAKEUCHI, 1978a; MATSUDA *et al.*, 1978).

The present state of the crustal stresses can be measured by various techniques, but it is difficult to know when they originated. To restore an ancient stress field, the distribution and slip-sense of faults and igneous dikes offer very useful information. Therefore, it is necessary to determine the active ages of such tectonic elements.

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The combination of bio-stratigraphical studies, concerning mainly planktic microfossils, and the measurements of radiometric ages has gradually been accumulated (e.g. TSUCHI and others, 1979). Based on this, it becomes possible to discuss the time-stratigraphy of local geologic development by a global scale.

As a tectonophysical approach to the geohistorical study of the southern part of Northeast Honshu Arc (Fig. 1) during the late Cenozoic period, I carried out field surveys in Central Japan and tried to reconstruct the Neogene history of regional stress fields (TAKEUCHI & SAKAMOTO, 1976; TAKEUCHI, 1977; TAKEUCHI, 1978a).

For the purpose of reconstructing the past tectonic stress field to examine the stress history, I adopted what is called the "dike method" (NAKAMURA, 1977) which uses the azimuthal distribution of dikes. Some of the preliminary results from the field survey have been reported in HORI & TAKEUCHI (1977) and TAKEUCHI (1978b). Based on these field data, the present paper (1) summarizes the late Cenozoic history of the tectonic stress field in NE Honshu and (2) proposes some important problems for the geotectonical study of island arcs with special reference to the geographical and geohistorical changes in their tectonic stress field.

Generally speaking, dikes are vertical, plate-like intrusive rocks, the thickness of which is 1/100th to 1/1000th of their length (OGUSA, 1972). The other plate-like intrusive rocks formed with a little or no inclination are called sheets or sills, respectively.

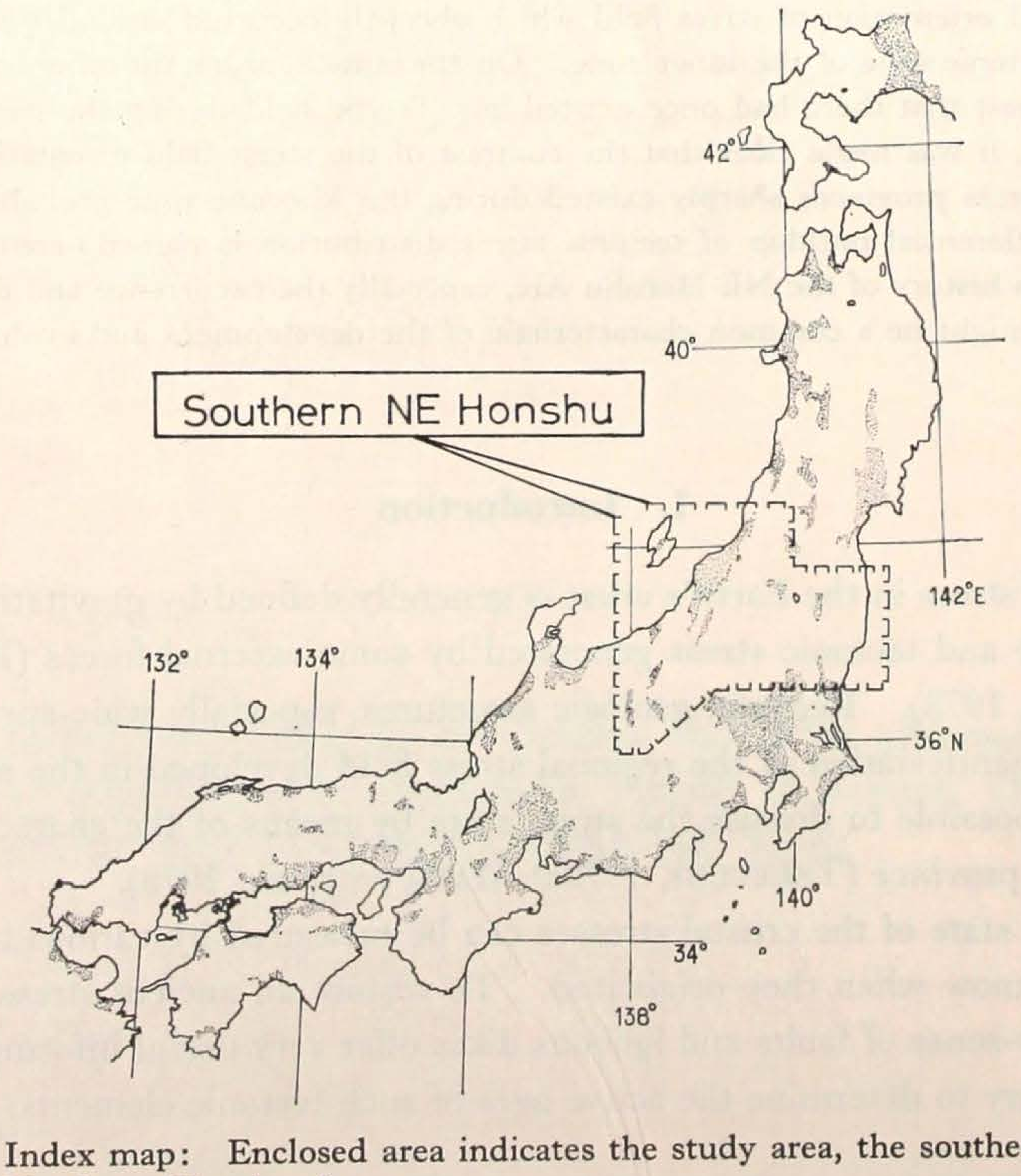

Fig. 1. Index map: Enclosed area indicates the study area, the southern part of Northeast Honshu, Japan.

As a mechanical classification, such sheet intrusives as above are formed under the static state of crustal stresses, while cone-sheets and ring-dikes with conical and cylindrical walls are formed by injection into shear fractures induced under the dynamic stresses with magma ascent and/or expansion (PHILLIPS, 1974, 1975).

The followings are the general characters of dikes involved in the mechanism of sheet intrusion that dikes intrude essentially when the magmatic pressure (P_m) exceeds the minimum (least compressive) principal stress (σ_3) and tensile strength (τ_0) of the host rock, i.e. $P_m > \sigma_3 + \tau_0$ (after ANDERSON, 1951; OGUSA, 1972; MATSUDA *et al.*, 1978; WILLIAMS & MCBIRNEY, 1979):

(1) In most case, dikes tend to show a limited spatial distribution in a certain region. In such cases, a parallel swarm with almost the same strikes in a certain direction and a radial swarm radiating from a central cone may be distinguished.

(2) Most host rocks contain such displacement as being split into two pieces and no tangential displacement.

(3) Therefore, dikes have the orientation normal to the direction of the minimum stress σ_3, that is, the one parallel to the plane defined by both the maximum (greatest compressive, σ_1) and intermediate (σ_2) principal stresses.

(4) Consequently, dikes are taken as a manifestation of tectonic stresses as well as faults. Then, from the distribution pattern of dikes it is possible to derive the dynamic situation under which intrusion took place.

2. Dike Method for Stress Field Analysis

General view of crustal stress field

The fact that the major lineaments in a given province tend to be consistent over great distances implies a uniform response of the earth's crust to large-scale tectonic forces. Some stresses of this kind may result from forces that operate on a global scale. More generally, regional stresses must result primarily from tectonic forces that act within the rigid lithosphere and are focused or modified by anisotropic structural features within the lithosphere (WILLIAMS & MCBIRNEY, 1979).

The state of stress in the earth's crust is usually defined by gravitational stress due to body force and also by tectonic stress generated by some external forces (RANALLI, 1975). At any points in the crust the stress state is locally influenced by a variation of factors, for example, such as topographic relief, geologic structure and tectonics, thermal history and so on (MCGARR & GAY, 1978).

Regarding the earth's surface as the stress-free, flat lying horizontal plane, it is accepted that one of the principal stresses is oriented vertically (σV), and the others are horizontal (σH_{max}, σH_{min}). Indeed, the observation of the present state of crustal stress indicates that the above concept is valid and that σV would be decided mainly by loading of overburden as a function of depth (MCGARR & GAY, 1978; HAIMSON, 1978). They have demonstrated the linear relationship between σV and z that follows $\sigma V = k \cdot z$, where k is a constant coefficient estimated 26.3 to 26.5 MPa/Km, respectively.

Consequently, the crustal stress field can be described by (a) orientation of horizontal deviatoric stresses and (b) magnitude ratio of horizontal principal stresses to vertical one.

Dike system and crustal stress field

As mentioned earlier, intrusive rocks formed in the deviatoric, static stress field are considered as casting of opened fractures whose wall would show the preferred orientation normal to σ_3, that is parallel to σ_1 and σ_2. Therefore, the following relationships are given:

a) Dikes, the vertical planar intrusives with the strike of σH_{max}-direction, correspond to the stress condition of $\sigma_3 = \sigma H_{min} < \sigma V$, regardless of the inequality (magnitude ratio) between σH_{max} and σV.

b) Sills, the horizontal, to the condition of $\sigma_3 = \sigma V < \sigma H_{min}$. Mechanically, let us make it a rule to name the intrusives as dike system or sill system, hereafter.

Thus, it is theoretically admitted that the distribution pattern of individual dikes of a dike system reveals the preferred orientation as an inherent character, corresponding to the principal orientation of deviatoric stress field at the time of intrusion. On reflection, when a certain directivity was recognized in the spatial pattern of dike distribution, this itself indicates that the crustal stress field at the intrusion was in a deviatoric state.

NAKAMURA (1969, 1977) proposed a new path to the practical verification of what is called as the dike method. Dikes and other planar intrusives are usually observed as "fossils" which were already consolidated at some depth, and are exposed by erosion at present. He regarded the linear arrangement of flank eruptions of a polygenetic volcano as a present expression of an active dike swarm concealed by the volcaniclastics.

According to this concept, validity of dike method can be verified as follows:

a) The orientation of tectonic stress which have existed in the recent geological time in the upper crust of volcanic regions can be identified from the distribution of flank craters indicating the trend of underground, radial, dike swarm (NAKAMURA *et al.*, 1977).

b) On purpose, the recent stress field can be estimated by various techniques; focal mechanism solutions of earthquakes, geodetic investigation of the crustal deformation, in-situ measurement of rock-stress and studies of active faults and folds.

c) Therefore, comparing of a) with b), the verification of the dike method proper may be accomplished. The recent orientation of crustal stresses in Japan, Aleutians and the conterminous United States estimated by the dike method is remarkably consistent to the result obtained using well-known methods mentioned above (NAKAMURA, 1969, 1977; NAKAMURA & UI, 1975; NAKAMURA *et al.*, 1977; TAKEUCHI, 1978; MATSUDA *et al.*, 1978; OKADA & ANDO, 1979; ZOBACK & ZOBACK, 1979).

d) Then, it is concluded that dikes commonly show the tectonophysically significant character that would reflect the condition of somewhat ambient tectonic stress field even if their spatial distribution was restricted to local areas.

e) Moreover, it should be noticed that the σH_{max}-directivity of dike system, parallel to the tectonic stresses, would commonly appear in a wide range of depth, even if the crustal stress field were in the state where the magnitude ratio of σV and σH show a reversal with depth as well as in the other deviatoric state where the inequality either $\sigma H_{max} < \sigma V$ or $\sigma V < \sigma H_{max}$ is stabilized. This is one of the major validities of the dike method as well as its plainness of dating the inferred stress system.

Based on the statements, it is impossible to distinguish the magnitude ratio of σH to σV as long as the σH_{max}-directivity is only used. While, with regard only to the stress-magnitude ratio the state of crustal stresses are tectonically classified into two types of stress field, T- and P-types (MATSUDA, 1977; MATSUDA *et al.*, 1978):

a) T-type stress field is characterized by the condition of $\sigma_1 = \sigma V > \sigma H_{max}$. The structure system characterizing this field, called extensional tectonics, consists of normal faults, regional fissure eruptions, horst-graben topography and plateau basalts. These elements indicate that the tectonism under the continued horizontal extension.

b) P-type stress field is characterized by the condition of $\sigma_1 = \sigma H_{max} > \sigma V$ and typically by thrust faults, intense folds with thrust and/or strike-slip faults and mountain-lowland topography. Those are characteristic of compressional tectonism.

Once the stress field were classified by using the characteristic structure elements as above, the orientation of all three principal stresses (σ_1, σ_2 and σ_3) are determined definitely from the σH_{max}-directivity of dike system. Therefore, it is desirable that both dike system and the other structure elements are to be compensatively used for the analy-

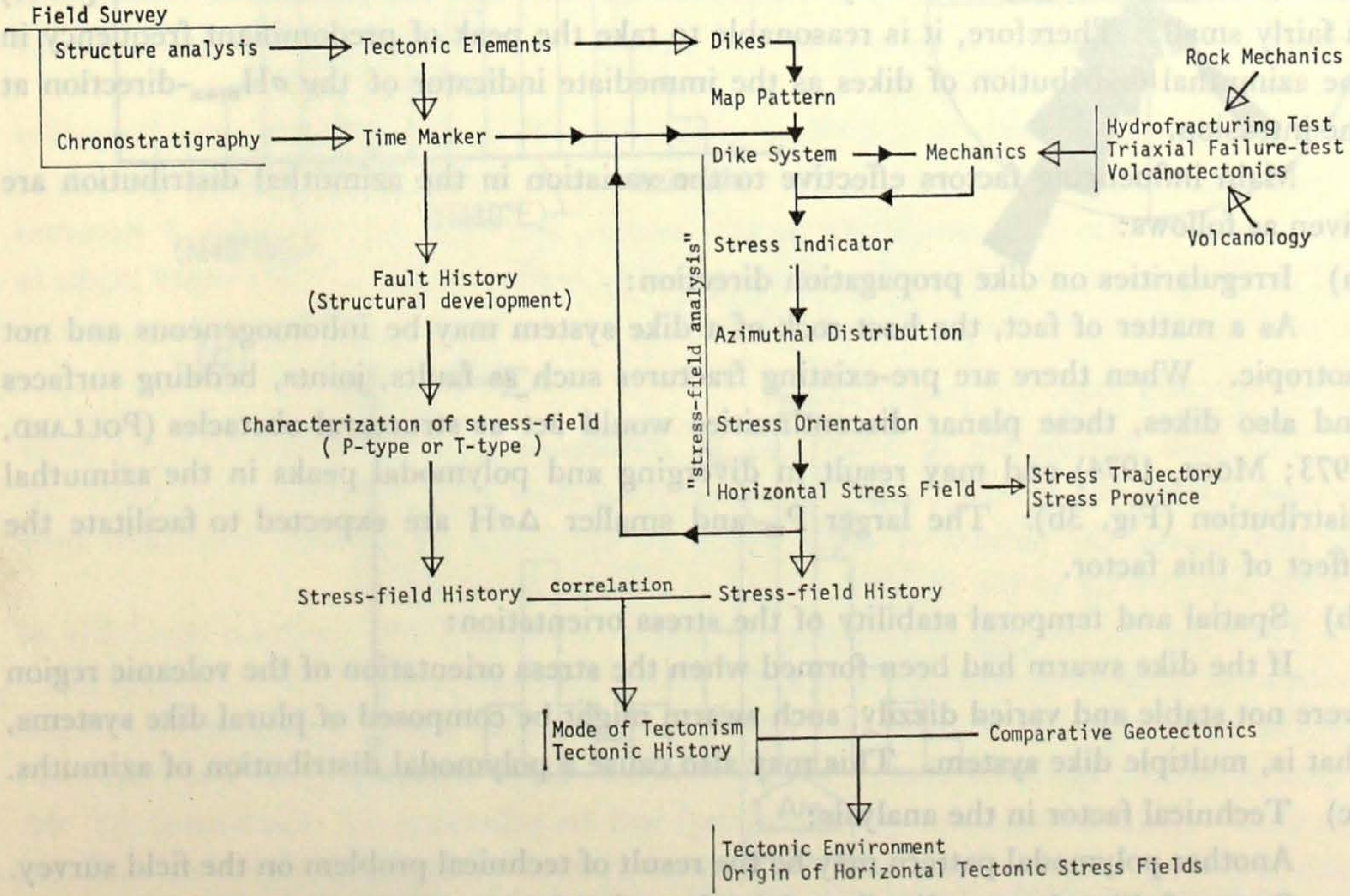

Fig. 2. Thesaurus (graphic view) of the procedure for the stress field analysis by means the dike method.

sis of tectonic stress field.

On the basis of these arguments above, summarized and shown as a graphic view in Fig. 2, the procedure of estimating the orientation or re-orientation of tectonic stress field will be presented in the following sections.

Dike method for estimation of tectonic stress orientation

Suppose an ideal dike-system that was formed under the following conditions:

(a) The brittle host rock was mechanically homogeneous with respect to the distribution of pre-existing cracks and fractures, porosity, failure strength and so on.

(b) The regional stress field at the time of intrusion was uniform in a deviatoric state.

Then, the frequency distribution of the wall-strikes of each individual dike-system is expected to show a unimodal peak indicating the σH_{max}-direction of the stress field at the intrusion (Fig. 3a). The degree of concentration is to vary under the control of the factors below:

* Horizontal stress difference ($\Delta\sigma H = \sigma H_{max} - \sigma H_{min}$)
* Magnitude of vertical stress (σV)
* Strength of the wall rock
* Toughness and stress intensity factor of induced fractures
* Pressure (P_m) and viscosity of magma fluid

According to the results in the laboratory hydrofrac experiments (HAIMSON & FAIRHURST, 1970), the σH_{max}-directivity is not missed even when the differential stress ($\Delta\sigma H$) is fairly small. Therefore, it is reasonable to take the peak of predominant frequency in the azimuthal distribution of dikes as the immediate indicator of the σH_{max}-direction at the intrusion.

Main influencing factors effective to the variation in the azimuthal distribution are given as follows:

(a) Irregularities on dike propagation direction:

As a matter of fact, the host rock of a dike system may be inhomogeneous and not isotropic. When there are pre-existing fractures such as faults, joints, bedding surfaces and also dikes, these planar discontinuities would act as structural obstacles (POLLARD, 1973; MOGI, 1974) and may result in diverging and polymodal peaks in the azimuthal distribution (Fig. 3b). The larger P_m and smaller $\Delta\sigma H$ are expected to facilitate the effect of this factor.

(b) Spatial and temporal stability of the stress orientation:

If the dike swarm had been formed when the stress orientation of the volcanic region were not stable and varied dizzily, such swarm might be composed of plural dike systems, that is, multiple dike system. This may also cause a polymodal distribution of azimuths.

(c) Technical factor in the analysis:

Another polymodal pattern may be the result of technical problem on the field survey. Some of dike-clusters distributed in the volcanic area where the volcanic activities had continued during somewhat lengthy time may lead the same result as that of the

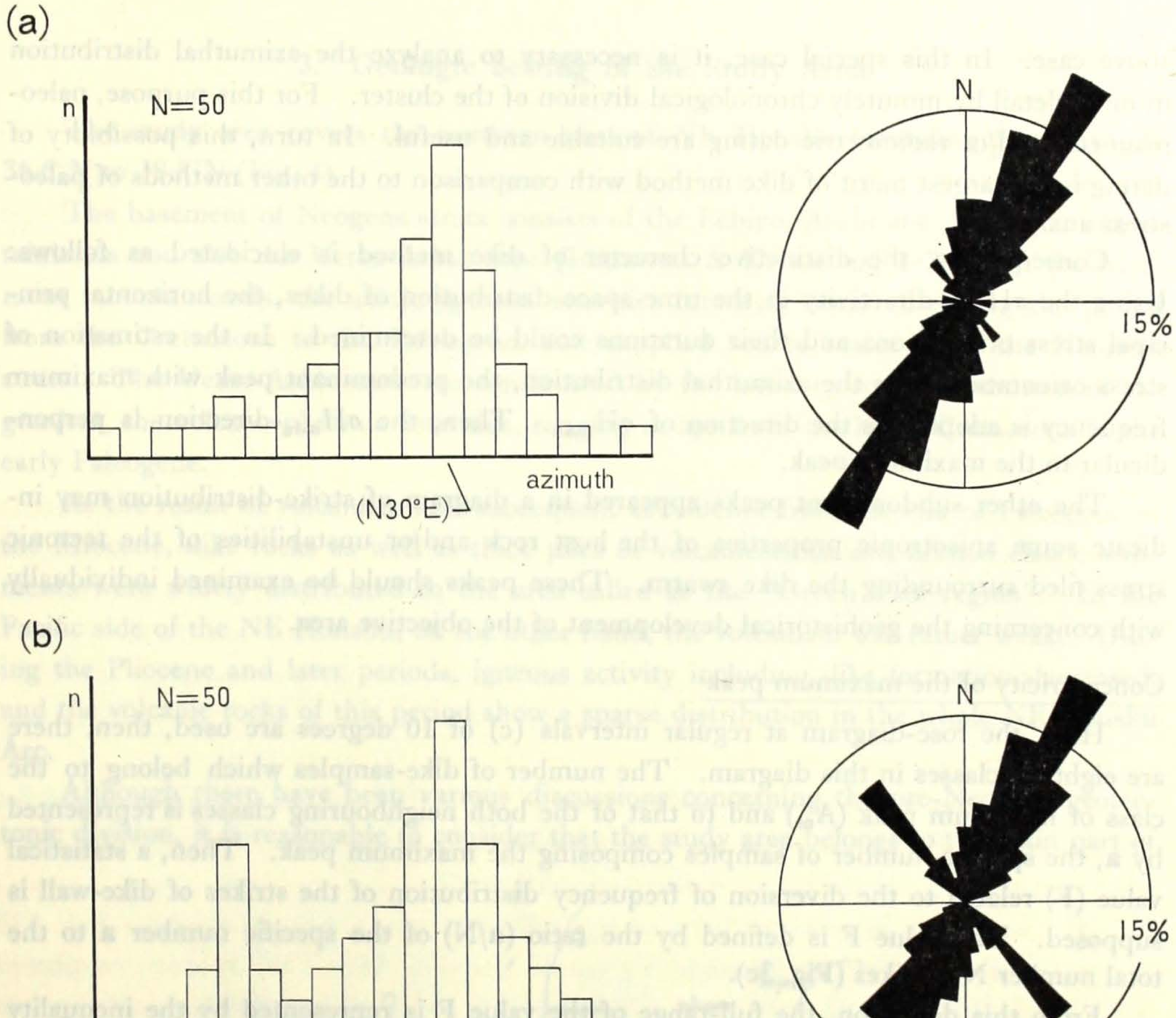

Fig. 3. Interpretative illustration of idealized dike systems and pattern index F: (a) Azimuthal distribution with a unimodal pattern, (b) Azimuthal pattern with bimodal peaks, (c) representation of concentricity (F-value) for the maximum peak A_m. $F=a/N$, where $a\equiv n_{m-1}+n_m+n_{m+1}$.

above case. In this special case, it is necessary to analyze the azimuthal distribution in more detail by minutely chronological division of the cluster. For this purpose, paleomagnetic and/or radiometric dating are suitable and useful. In turn, this possibility of dating is the largest merit of dike method with comparison to the other methods of paleostress analyses.

Consequently, the distinctive character of dike method is elucidated as follows: Using the σH_{max}-directivity in the time-space distribution of dikes, the horizontal principal stress orientations and their durations could be determined. In the estimation of stress orientation from the azimuthal distribution, the predominant peak with maximum frequency is adopted as the direction of σH_{max}. Then, the σH_{min}-direction is perpendicular to the maximum peak.

The other subdominant peaks appeared in a diagram of strike-distribution may indicate some anisotropic properties of the host rock and/or unstabilities of the tectonic stress filed surrounding the dike swarm. These peaks should be examined individually with concerning the geohistorical development of the objective area.

Concentricity of the maximum peak

Here, the rose-diagram at regular intervals (c) of 10 degrees are used, then, there are eighteen classes in this diagram. The number of dike-samples which belong to the class of maximum peak (A_m) and to that of the both neighbouring classes is represented by **a**, the specific number of samples composing the maximum peak. Then, a statistical value (F) related to the diversion of frequency distribution of the strikes of dike-wall is supposed. The value F is defined by the ratio (**a**/N) of the specific number **a** to the total number N of dikes (Fig. 3c).

From this definition, the full-range of the value F is represented by the inequality of $0<F\leq1$. That follows; (a) if the value F is near 1, the corresponding pattern of dikes comes to that of a completely parallel swarm, and (b) when the value F becomes smaller, the pattern shows non-directivity, possibly higher radiality. The other peaks in a rose-diagram can be also examined similarly.

Stress trajectory map

The local distribution of dikes may be influenced to show second or third order deviations from the primary, regional stress orientation by a structural anisotropy etc. For this reason, the pattern of dikes within an individual dike-system may show little relationship directly to the regional setting of tectonic stress field.

Then, for the purpose of assessing the spatial uniformity and temporal durability of the tectonic stress field, whether or not the inferred stress-systems from individual dike-systems have anything in common with ther orientation should be examined. Some diagrams such as age-locus chart and age-deflection chart are to be made and examined. The result of the examination (i.e. grouping) will be schematically represented by the stress trajectory maps. Comparing with stress systems inferred by the other methods using faults and folds, for example, are useful to verify and supplement the result inferred by the dike method.

3. Geologic Setting of the Study Area

The study area covers the southern part of NE Honshu extending from latitude 36.5°N to 38.5°N (Fig. 4).

The basement of Neogene strata consists of the Echigo, Asahi and Abukuma mountainlands and also the Uetsu-Ashio zone (ICHIKAWA & KITAMURA, 1978). In the basement mountainlands, the acidic igneous activities intensely occurred during the period from the Cretaceous to the Paleogene, and supplied source materials of the Neogene strata. The Uetsu-Ashio zone are constructed by the latest episode of intrusion of the granites, the volcano-plutonic activities, ranging in age from the latest Cretaceous to the early Paleogene.

As the result of volcanism and subsequent subsidence from the end of Paleogene to the Miocene, dike rocks as well as thick piles of volcaniclastics and normal clastic sediments were widely distributed in the area called as the "Green Tuff region". In the Pacific side of the NE Honshu, on the other hand, the volcanism was rather weak. During the Pliocene and later periods, igneous activity including dike formation decreased, and the volcanic rocks of this period show a sparse distribution in the whole NE Honshu Arc.

Although there have been various discussions concerning the pre-Neogene geotectonic division, it is reasonable to consider that the study area belongs to the main part of

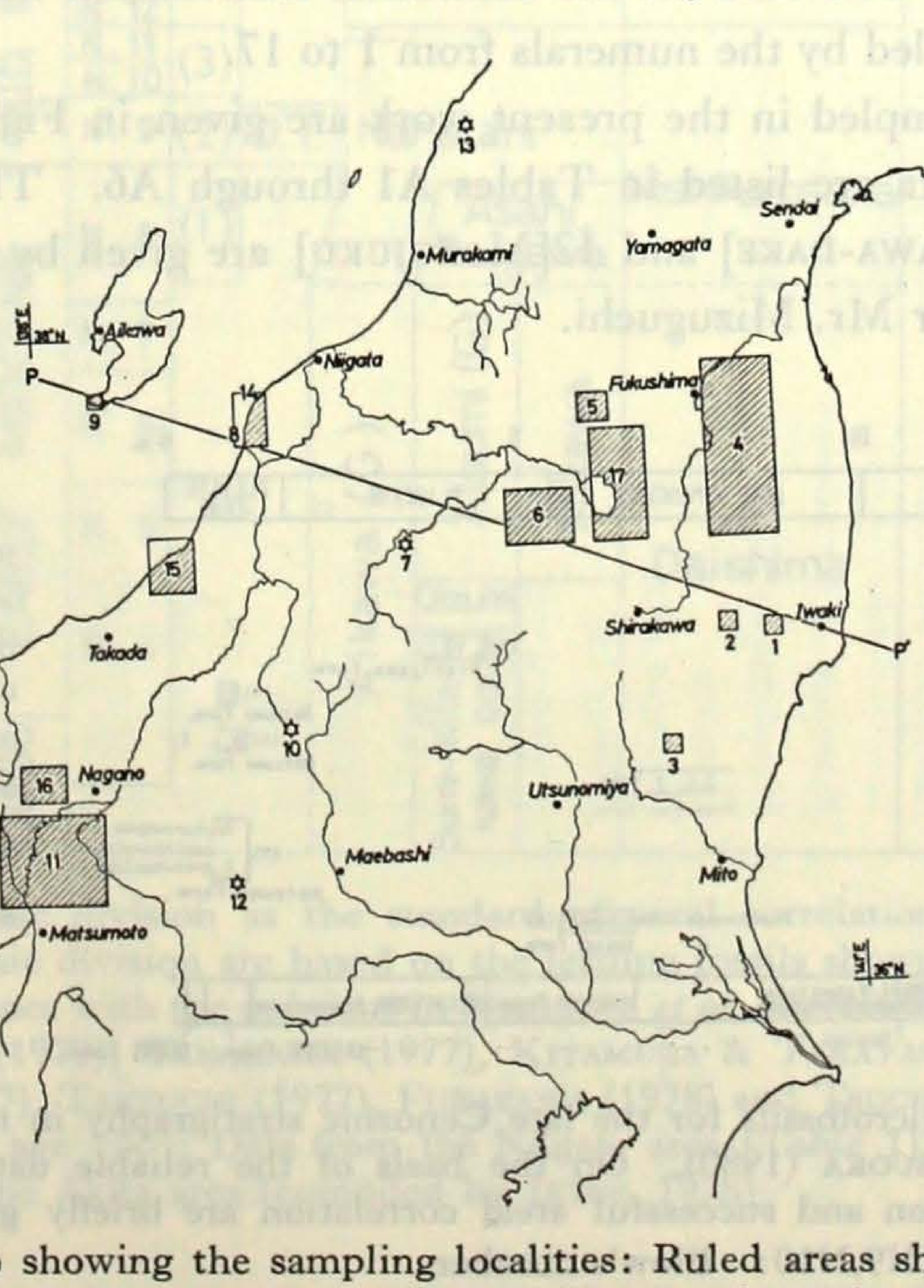

Fig. 4. Index map showing the sampling localities: Ruled areas show the localities of the dike swarms newly sampled. The dike data from the published source are indicated by stars (7,10,12). P-P' represents the profile line to which the dike data are plotted in Fig. 11.

NE Japan as long as the Neogene division is concerned (KITAMURA, 1977; ICHIKAWA & KITAMURA, 1978).

Except the easternmost district, Abukuma Mountainland, the almost whole area constructs one of the main parts of the Green Tuff region. ICHIKAWA *et al.* (1970) grouped the former area into the Outer zone of the NE Honshu Arc, and the latter into the Inner zone. The western district called the "Northern Fossa Magna region", is characterized by the intense folding of the Neogene system to form the prominent oil-producing region in Japan, that is, Niigata Oil-Gas Field.

4. Dike-Data

There are numbers of igneous dikes composed of various rock-types in the study area. Their geographical distribution is not uniform but tends to cluster as isolated swarms. The time range of main activity can be estimated on the basis of such evidences as; (a) the stratigraphic horizon of the wall rocks, (b) the horizon of unconformity underlain by the dike swarm and (c) the age of the effusive rocks with petrography similar to the dike rocks. (a) gives the oldest possible age, while (b) and (c) give the youngest and contemporary, respectively.

Table 2 shows the selected swarms each of which has almost obvious evidence for the age of intrusion. The data on the azimuthal distribution have been sampled from seventeen swarms labeled by the numerals from 1 to 17.

The dike-data sampled in the present work are given in Fig. A1 through Fig. A12 and necessary raw data are listed in Tables A1 through A6. The swarms numbered 7[TADAMI], 10[TANIGAWA-DAKE] and 12[MOTOJUKU] are given by reference, and the data of 13[ATSUMI] are after Mr. Mizuguchi.

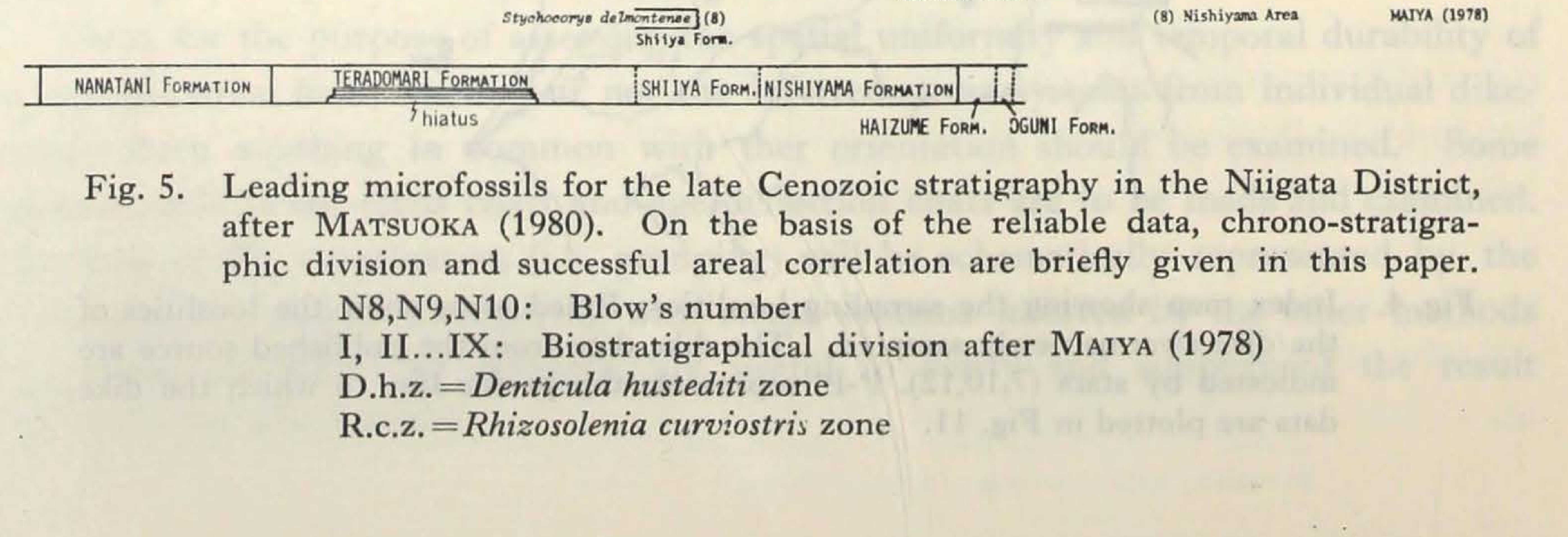

Fig. 5. Leading microfossils for the late Cenozoic stratigraphy in the Niigata District, after MATSUOKA (1980). On the basis of the reliable data, chrono-stratigraphic division and successful areal correlation are briefly given in this paper.

N8,N9,N10: Blow's number
I, II...IX: Biostratigraphical division after MAIYA (1978)
D.h.z. = *Denticula hustediti* zone
R.c.z. = *Rhizosolenia curviostris* zone

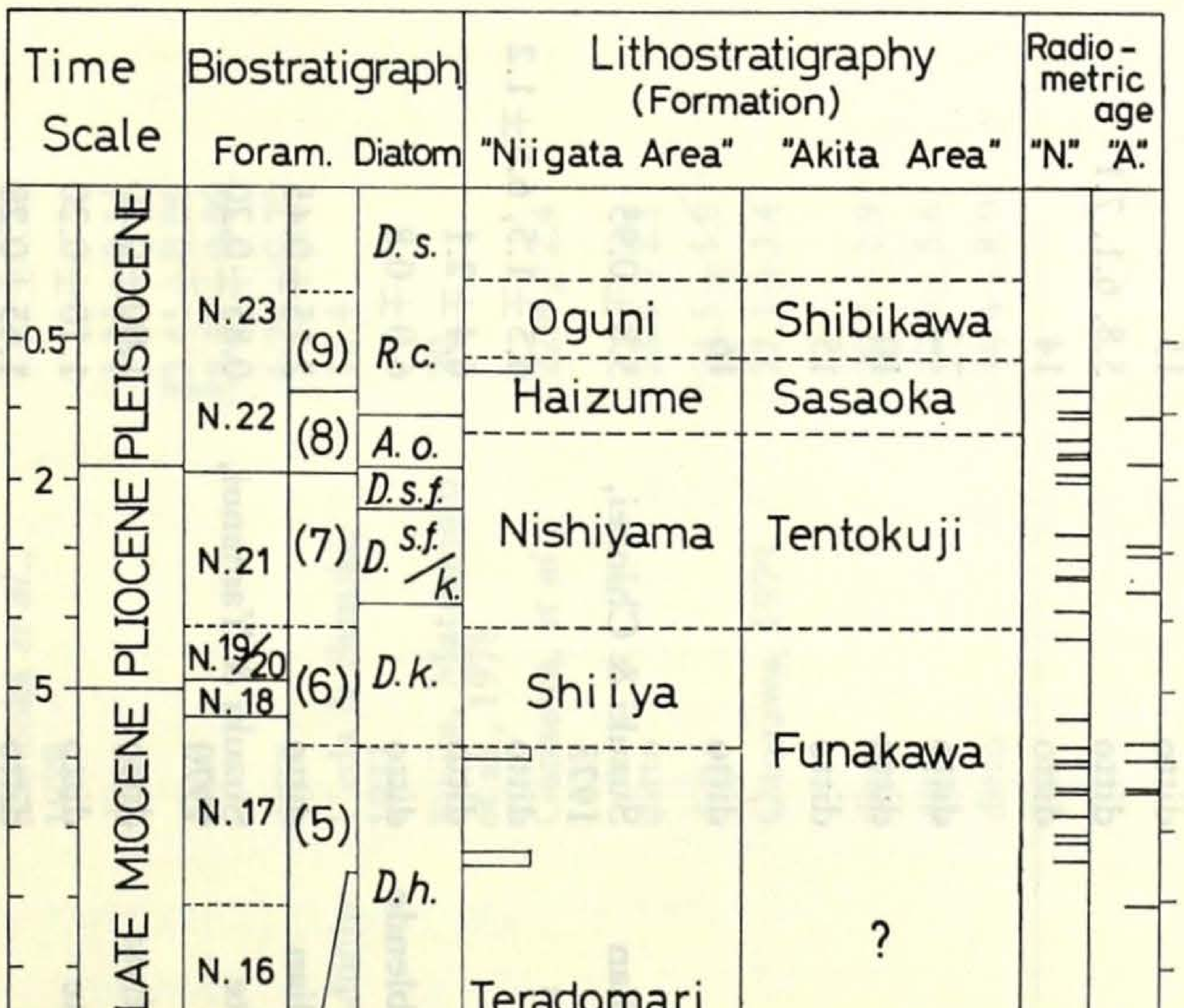

Fig. 6. Stratigraphic division as the standard of areal correlation: Time- and Biostratigraphic division are based on the leading fossils shown in Fig. 5 and also in accordance with the opinions in ICHIKAWA *et al.* ed. (1970), IKEBE *et al.* (1972), SHIMAZU (1973), TAKAHAMA (1977), KITAMURA & TAKAYANAGI (1977), SUZUKI *et al.* (1977), TAKEUCHI (1977), FUKAZAWA (1978) and TSUCHI *et al.* (1979). Radiometric age "N": Data from the Niigata area (Table 1), "A": Data obtained from the Akita area (compiled by IKEBE, 1978)

Table 1. Radiometric age data, compiled from the references related to the study area. These data are also plotted in Fig. 6.

No.	Locality and Stratigraphic Name	Horizon	Method	Author	Calculated Age (MaBP)
1	Niigata Prefecture; Nozumi coarse tuff	Teradomari F.	F-T zircon	Nishimura, 1976	7.5
2	ditto ; Yahiko trachyte	Nanatani F.	ditto	ditto	15
3	ditto ; Yagihana dacite	Shiiya F.	ditto	ditto	5.8, 6.1, 7.1
4	ditto ; Imogawa acid-tuff	Teradomari F. /Nanatani F.	ditto	ditto	14
5	ditto ; Kamitsuchikura dacite	Shiiya F.	ditto	ditto	7.2
6	ditto ; Tsuchiba trachyte	Teradomari F.	ditto	ditto	10
7	Niigata Pref. (Tanigawa) ; rhyolite	Nanatani F.	ditto	ditto	15
8	Niigata Pref. (Kamogawa) ; ditto	Tsugawa F.	ditto	ditto	16
9	Niigata Pref. (Yagihana) ; FT405MS	Nishiyama F.	F-T obsidian	Suzuki & Chinzei, 1973	5.8±0.95
10	ditto ; FT406MS-1,2	Shiiya F.	ditto	ditto	6.5±1.5, 6.8±1.2
11	ditto ; FT407	Teradomari F.	ditto	ditto	6.4±2.1
12	Niigata Pref. (Hachikoku) ; ET40MS	Nishiyama F.	F-T hornblende	ditto	6.0±0.8
13	ditto ; Konuka tuff	Tsukayama F.	F-T obsidian	ditto	2.15±0.45
14	Niigata Pref. (Tōkamachi) ; Tsukanoyama	Tsukayama F. /Oguni F.	F-T biotite	Suzuki & Yamanoi, 1970	0.85±0.20
15	ditto ; ditto	ditto	F-T amethyst	ditto	1.00±0.20
16	ditto ; Gomashio-2	Tsukayama F.	F-T biotite	ditto	1.10±0.20
17	ditto ; Uonuma pumice tuff	ditto	F-T glass	ditto	1.65±0.20
18	ditto ; Surigoma tuff	ditto	F-T biotite	ditto	1.90±0.15
19	ditto ; Konuka tuff	Tsukayama F. (lowermost)	F-T glass	ditto	2.75±0.25
20	Fukushima Pref. ; Shirakawa D1 (welded tuff)	Shirakawa F. (upper)	K-Ar	Suzuki, Yoshida & Manabe, 1977	1.4–1.6

21	ditto	;	Hotokezawa andesite welded tuff	Izumi F. (lower)	ditto	Suzuki, Manabe & Yoshida, 1977	3.8
22	Nagano Pref.	;	Minakami-yama andesite	(Shigarami F.)	ditto	Morimoto *et al.*, 1966	3.35
23	ditto	;	Kiyotaki andesite lava	ditto	ditto	ditto	5.4
24	Nagano Pref. (Asama)	;	Shiga welded tuff (dacite;AS 04-52)	Late Tertiary Volcanic Rocks	ditto	Kaneoka *et al.*, 1979	3.12±0.13
25	ditto	;	ditto; AS 04-54	ditto	ditto	ditto	3.35±0.14
26	ditto	;	Hirao Fuji H1–05	ditto	ditto	ditto	3.41±0.09 3.37±0.09
27	ditto	;	Komoro F.; KO-05	Komoro F.	ditto	ditto	4.25±0.20
28	Yamagata Pref.	;	Sanze 841	Atsumi G.	K-Ar celadonite	Ueda & Suzuki, 1973	13.4
29	Niigata Pref. (Sado)	;	(dacite)	Kimpokusan F.	K-Ar	Fujita, Matsumoto et al., 1978	20
30	ditto	;	Hanatate tuff	(Nanatani F.)	F-T zircon	Ganzawa, *et al.*, 1978	22.8±2.4
31	ditto	;	Fukutori tuff	Tsugawa F.	ditto	ditto	23.1±2.1
32	ditto	;	Tm-12 tuff	ditto	ditto	ditto	24.5±1.9
33	Niigata Pref., Asahi Mountains	;	(rhyolite tuff)	Shimoseki F.	ditto	Ganzawa, 1979	22.3±3.4
34	ditto	;	(rhyolite lava)	Asahi F.	ditto	ditto	20.7±2.9
35	ditto	;	(rhyolite tuff)	Kitaoguni F.	ditto	ditto	32.3±5.6
36	ditto	;	(rhyolite welded tuff)	Budō F.	ditto	ditto	46.4±8.0

$\lambda f(y^{-1})$: 6.85×10^{-17}

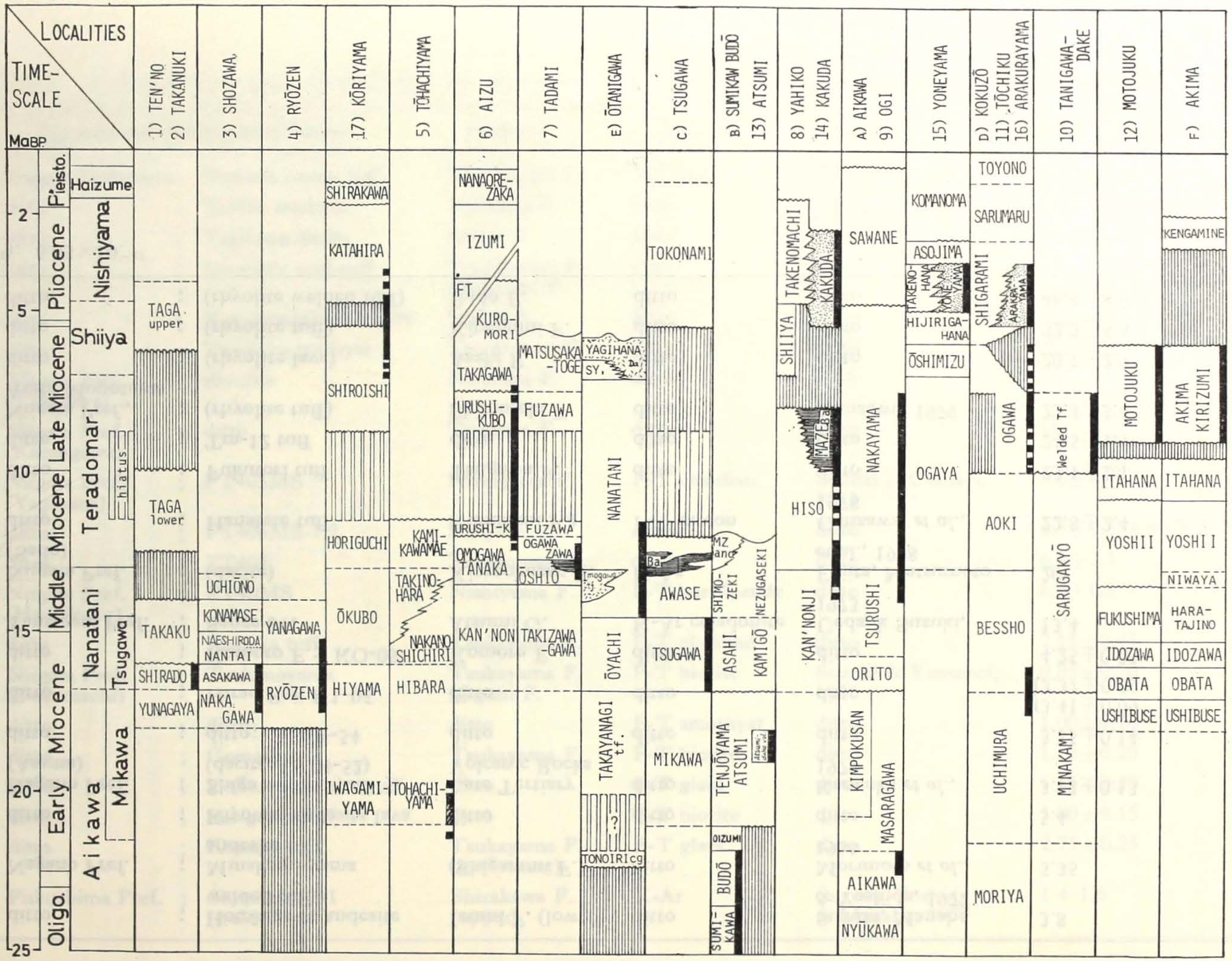

Fig. 7. Correlation table of lithostratigraphy in the southern NE Honshu.

The rose-diagrams showing the azimuthal distribution of the strikes are shown in Figs. 8a and 8b (Hori and Takeuchi, 1977), together with the loci of these swarms. Some additional swarms **a** through **f** are also tabulated in Table 2.

Chronological setting of dike swarms

Before the swarms are analysed to estimate the stress orientation, the chronological setting has to be settled with them.

Recently, Maiya (1978) has constructed the litho- and bio-straitgraphy using both planktic and benthic foraminifera, so that the rock-stratigraphy became to be regionally correlated in the whole Japan Sea side area of NE Japan with reference to the Niigata oil-bearing sedimentary basin. Thus, the most advanced and reliable, stratigraphical investigations have been carried out.

On the basis of the bio-stratigraphical examination of chronology of this district, Matsuoka (1980) has summarised the leading microfossils such as several species of planktic foraminifera, diatoms and calcareous nannoplankton by which the correlation between the relative and absolute ages could be defined (Fig. 5).

Moreover, the radiometric age data in this area have been gradually accumulated as compiled in Table 1. These radiometric ages, however, have several problems of stratigraphical assessment upon alteration and reworking (Suzuki & Chinzei, 1973; Sasajima *et al.*, 1978; Ganzawa, 1979).

According to these results as well as my field works, a chronostratigraphic division is settled as given in Fig. 6 to be used as a reference column or a time scale for the present work. The regional stratigraphic correlation among the provinces of the dike swarms is tabulated in Fig. 7, based on the leading fossils shown in Figs. 5, 6, referring to the published correlation tables and opinions in Ichikawa *et al.* ed. (1970), Ikebe *et al.* (1972), Shimazu (1973), Takahama (1976), Kitamura & Takayanagi (1977), Suzuki *et al.* (1977), Takeuchi (1977), Fukazawa (1978) and Tsuchi *et al.* (1979).

Because there has been many different opinions on the details of stratigraphy of the lower Miocene, "Lower Green Tuff", the lower parts of the columns in this table are more or less tentative. On the basis of the evidences given in the appendix, the inferred ages of formation of each dike swarm are also shown in Fig. 7.

5. Results

Azimuthal distribution:

There are many varieties among the patterns of rose-diagram, but it is clearly seen in each diagram that the azimuths of dikes tend to concentrate to a single trend. The dike swarms of Nos. 1, 3, 4, 5, 7, 10 and 13 with the F-values greater than 0.55 are characterized by the unimodal peak of dominant frequency. The other swarms of Nos. 2, 6, 8, 9, 11, 12, 16 and 17 with F smaller than 0.44 show the polymodal patterns, and their maximum peaks are less sharp. Concentricity to maximim peaks of the Pliocene swarms

Table 2. A summary of the results from the directionality analysis of dike-wall data.

LABEL	LOCALITY	DIKE ROCK	HOST ROCK	AGE	Am	N.	F.
1	Tennō	basalt	Pre-Tertiary granite	Early-Miocene	70°	55	.60
2	Takanuki	andesite	Pre-Tertiary gneiss	ditto	50°	10	.40
3	Shiozawa	porphyrite	Paleozoic shale	ditto	85°	13	.70
4	Ryōzen	andesite	granite, volcanics	ditto	−20°	197	.58
5	Tōhachiyama	propylite	Pre-Tertiary granite	ditto	−20°	23	.63
6	Southern Aizu	rhyolite	Tertiary volcanics	M.-to L.-Miocene	−10°	41	.46
7	Tadami	basalt	Miocene volcanics	Middle-Miocene	− 5°	57	.56
8	Yahiko	ditto	Miocene shale	M.-to L.-Miocene	0°	38	.29
9	Ogi-Sado	ditto	ditto	ditto	5°	50	.40
10	Tanigawadake	rhyolite	Tertiary granite	ditto	−25°	54	.80
11	Tōchiku	porphyrite	Miocene sandstone	Late-Miocene	20°	51	.39
12	Motojuku	andesite	L.-Miocene volcanics	ditto	−30°	19	.32
13	Atsumi	porphyrite	Pre-Neogene volcanics	Early-Miocene	−30°	32	.66
14	Kakudasan	andesite	Pliocene volcanics	Pliocene	−80°	30	.40
15	Yoneyama	ditto	ditto	ditto	75°	33	.42
16	Shigarami	ditto	Neogene mudstone	ditto	60°	20	.25
17	Kōriyama	ditto	Miocene sandstone	L.-Mio.to Plio.	60°	10	.40
a	Aikawa	andesite	Tertiary volcanics	Early-Miocene	−85°	—	—
b	Sumikawa・Budō	da., alkali rh.	ditto	Oligo., Early-Mio.	85°	—	—
c	Tsugawa	rhyolite	granite, Paleozoic sh.	Early-Miocene	0→40°	—	—
c′	Takizawagawa	ditto	Tertiary volcanics	E.-to M.-Miocene	~45°	—	—
d	Kokuzō	basalt	Miocene volcanics	Early-Miocene	0°	—	—
e	Ōtanigawa	rhyolite	ditto	Middle-Miocene	0°	—	—

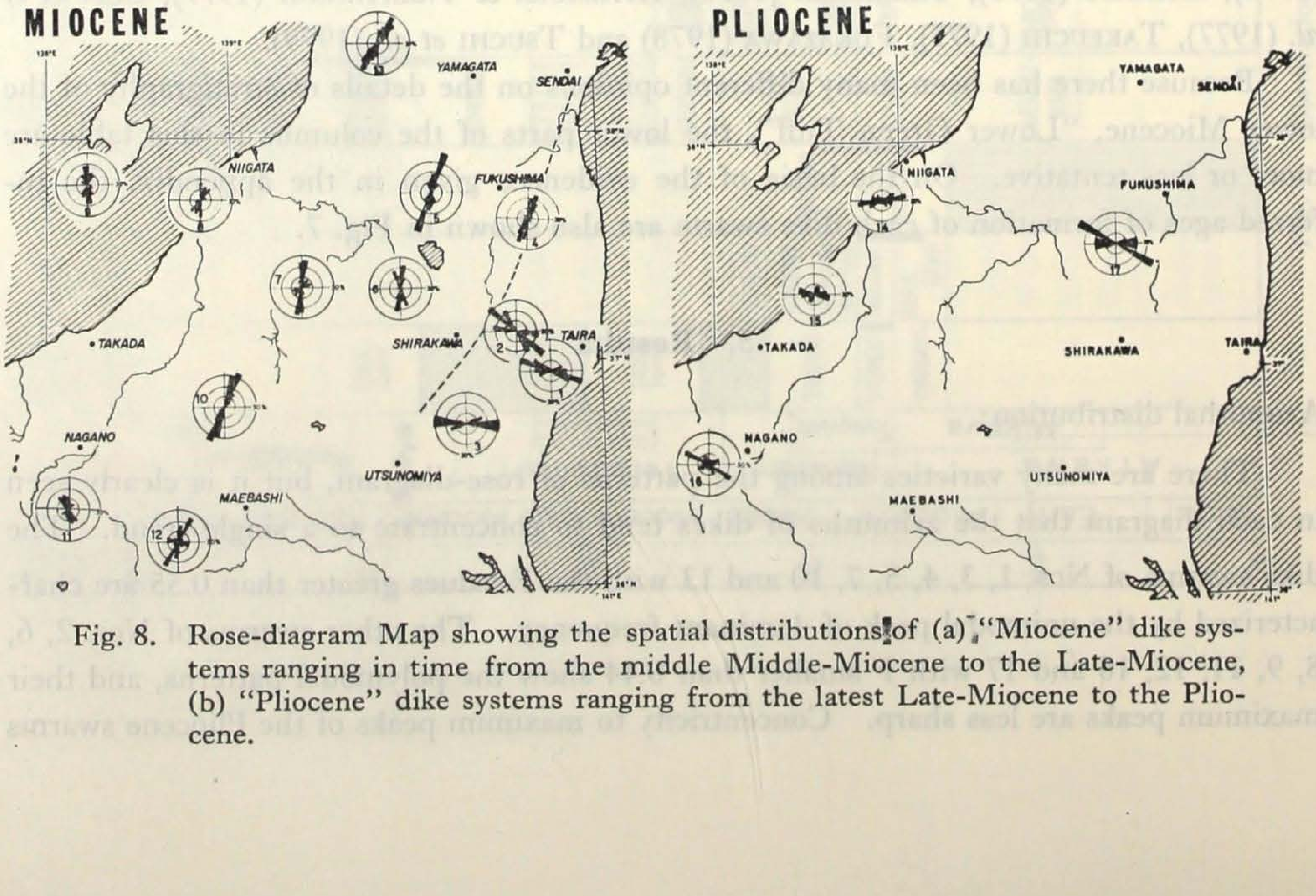

Fig. 8. Rose-diagram Map showing the spatial distributions of (a) "Miocene" dike systems ranging in time from the middle Middle-Miocene to the Late-Miocene, (b) "Pliocene" dike systems ranging from the latest Late-Miocene to the Pliocene.

labeled from 14 to 17 is lower than that of the Miocene swarms.

Judging from the rose-diagrams, most swarms can be interpreted to show that each of them constitutes a dike system, respectively. Such swarms as labeled e and 11, however, poorly fit to this interpretation.

Time-space distribution of stress systems

The distribution of the A_m-directions i.e. σH_{max}-directions is by no means uniform in both time and space. Some features of the time and spatial distribution of the stress systems are shown as the age-azimuth chart (Fig. 9) and as the age-locus chart (Fig. 10). The labels in the figures are the same as those of the dike swarm in Table 2.

Although the stress systems obtained from the A_m-direction seem non-uniform, the stress systems could be devided into several groups in terms of their ages and geography.

1) Chronological division; Stage I, II and III. (I: The earliest Early-Miocene and earlier, II: The period from the middle Early-Miocene to the earlier half of Late-Miocene, III: The end of Late-Miocene and later, mainly the Pliocene.)

Judging from Fig. 9, the boundaries among these stages are set up to be at the early Early-Miocene for the former and the late Late-Miocene for the latter.

2) Geographical division; Provinces A and B. (A: The outer zone of the southern NE Honshu, B: The inner zone.)

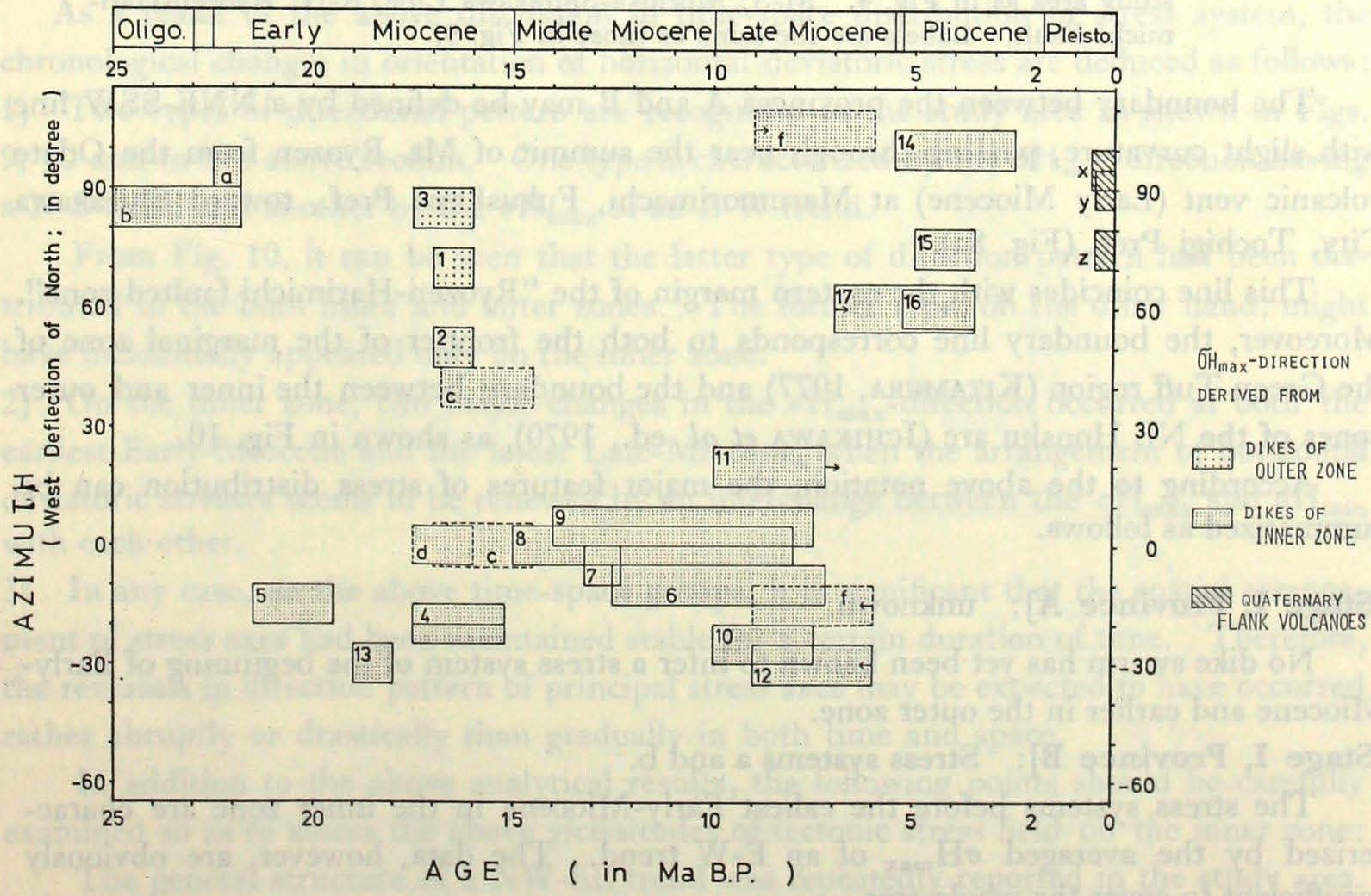

Fig. 9. Age-Azimuth chart of the inferred σH_{max}-directions: The azimuths of σH_{max} are plotted along the horizontal axis for the age of the dike system. Numerals and alphabets are the labels of the stress systems and identical to those of the dikes shown in Table 2 and Fig. 8.

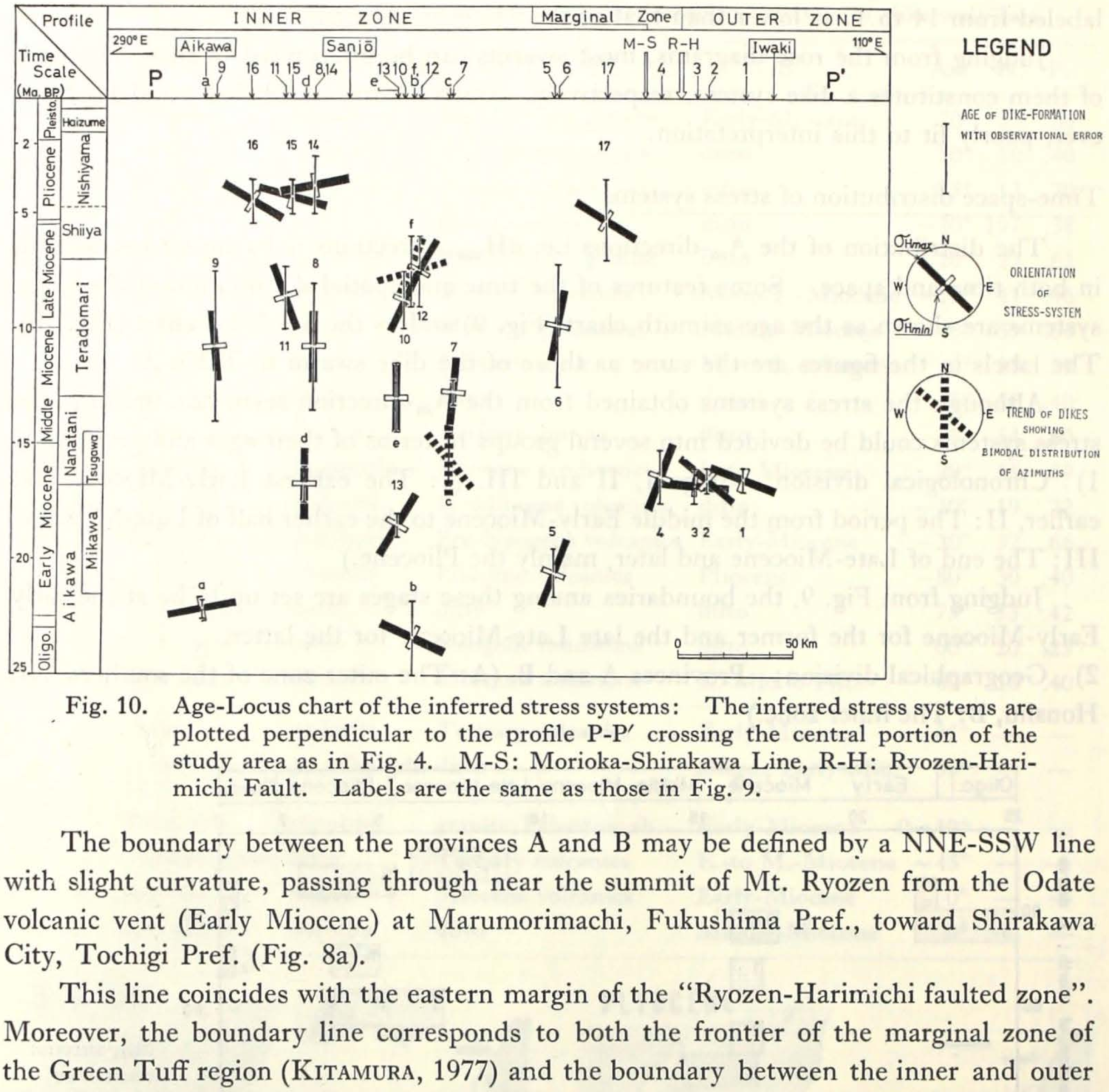

Fig. 10. Age-Locus chart of the inferred stress systems: The inferred stress systems are plotted perpendicular to the profile P-P′ crossing the central portion of the study area as in Fig. 4. M-S: Morioka-Shirakawa Line, R-H: Ryozen-Harimichi Fault. Labels are the same as those in Fig. 9.

The boundary between the provinces A and B may be defined by a NNE-SSW line with slight curvature, passing through near the summit of Mt. Ryozen from the Odate volcanic vent (Early Miocene) at Marumorimachi, Fukushima Pref., toward Shirakawa City, Tochigi Pref. (Fig. 8a).

This line coincides with the eastern margin of the "Ryozen-Harimichi faulted zone". Moreover, the boundary line corresponds to both the frontier of the marginal zone of the Green Tuff region (KITAMURA, 1977) and the boundary between the inner and outer zones of the NE Honshu arc (ICHIKAWA *et al.* ed., 1970), as shown in Fig. 10.

According to the above notation, the major features of stress distribution can be summarized as follows.

[Stage I, Province A]: unknown.

No dike swarm has yet been known to infer a stress system of the beginning of Early-Miocene and earlier in the outer zone.

[Stage I, Province B]: Stress systems a and b.

The stress systems before the ealiest Early-Miocene in the inner zone are characterized by the averaged σH_{max} of an E-W trend. The data, however, are obviously insufficient to cover the whole area.

[Stage II, Province A]: Stress system 1, 2 and 3.

The stress field on the outer zone during the stage can be represented by this group of stress systems having the common σH_{max} of WNW-ESE. The σH_{max}-directions vary from N50°W to N85°W southward in the order 2, 1 and 3 (see Fig. 9).

[Stage II, Province B]: Stress systems 4 through 13, c, d, e and f.

The stress systems of this group show the general N-S trend of σH_{max} characterizing the uppercrustal stress field of the inner zone in this stage. The orientation of the stress system seems to rotate counter-clockwise from N30°E to N20°E to N20°W westward in the order 6, 12, 10, 8, 11 and 9, as it becomes younger.

[Stage III, Province A]: No inferred stress system from dikes.

Volcanic activity in the outer zone ceased during the Stage III.

[Stage III, Province B]: Stress systems 14, 15, 16 and 17.

From the end of the Miocene (ca. 6–7 Ma b.p.) to the Pliocene and later, the stress field in the inner zone can be characterized by the family of stress systems which show the predominant E-W σH_{max}, similar to the groups [I-B and II-A]. Although the swarms of this group show a limitted and isolated distribution within the Pliocene volcanic areas, the regional tendency mentioned above is compatible with that of the Recent stress field inferred from the Quaternary flank volcanoes (NAKAMURA & UI, 1975), as shown in Fig. 9.

Vicissitude of horizontal stress-orientation

As a result of the above discussion in time-space distribution of stress system, the chronological changes in orientation of horizontal deviatoric stress are deduced as follows:

1) Two types of directional pattern are recognized in the study area as shown in Figs. 9, 10 and in the above section. One type is characterized by the σH_{max}-direction having a N-S trend and another by the σH_{max} of an E-W trend.

From Fig. 10, it can be seen that the latter type of direction pattern had been distributed in the both inner and outer zones. The former type, on the other hand, might have incidentally appeared only on the inner zone.

2) On the inner zone, two major changes in the σH_{max}-direction occurred at both the earliest Early-Miocene and the latest Late-Miocene, when the arrangement of horizontal deviatoric stresses seems to be renewed by an interchange between the σH_{max} and σH_{min} with each other.

3) In any case, on the above time-space groups, it is significant that the spatial arrangement of stress axes had been maintained stable for a certain duration of time. Therefore, the reversals in direction pattern of principal stress axes may be expected to have occurred rather abruptly or drastically than gradually in both time and space.

In addition to the above analytical results, the following points should be carefully examined so as to assess the above vicissitudes of tectonic stress field on the inner zone:

The general structure of a NW-SE trend was repeatedly reported in the study area. SHIMAZU (1973) proposed the "Tsugawa-Aizu major province" as the junction area between the main part of NE Honshu and the northern Fossa Magna region, and suggested that the general NW-SE trend in the area had commenced at the earliest Early-Miocene and that at the biginning of the Tsugawa substage they were reactivated to form sedimentary basins.

These trends are composed of Tadami-Ina Zone (SHIMADA & HIRABAYASHI, 1972), Oda-Toji Zone (SHIMAZU *et al.*, 1973), the southern margin of the Asahi Mountainland (TAKAHAMA & YOSHIMURA, 1969) and so on. According to the subsurface structure of the Natanani Formation, KATAHIRA (1969) has also suggested that the basement structure under the Niigata oil-field region has a general E-W or NW-SE trend oblique to the major structural trend of NNE-SSW, called as the Niigata trend.

So-called structural trends as above are used to be reduced from the presentday distribution of volcaniclastics or outlines of the sedimentary basin, and they do not always represent a general dike-direction. For example;

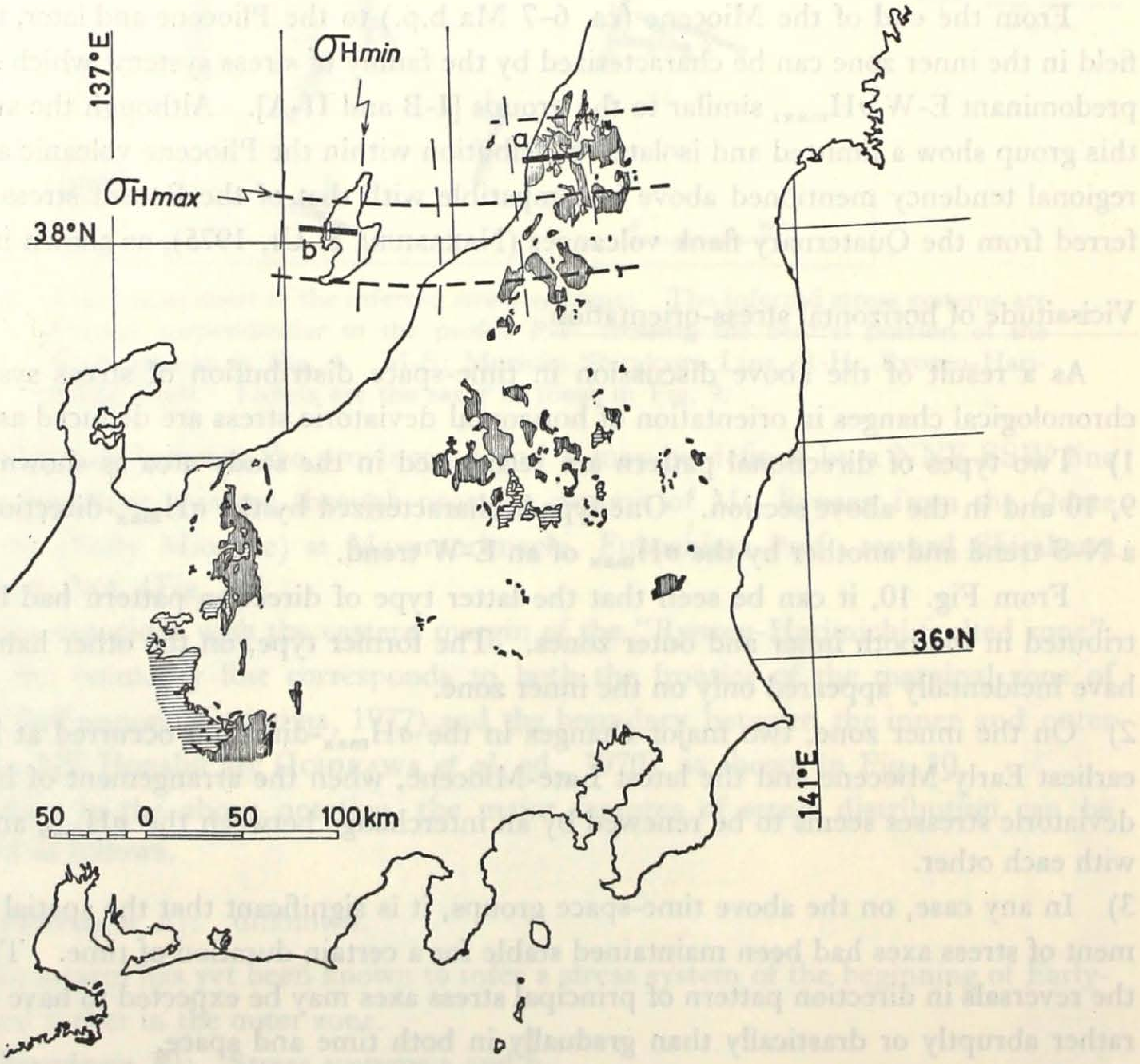

Fig. 11a Stress trajectory map (Southern NE Honshu, Stage-I) showing the stress field ranging in time from the latest Oligocene to the earliest Early-Miocene: The distribution of the both granitic rocks (vertically ruled) and acidic volcanics (horizontally ruled), ranging from the latest Cretaceous through the Oligocene, are also shown. Extensional tectonism under the T-type stress field with σH_{min} of N-S trend can be expected to have developed at least in the northern part of the area. The explanations for the representation of stress systems are the same as those in the legend in Fig. 10.

a) The lower Green Tuff beds in the Asahi district were distributed in a elongate area having a NW-SE trend, but each eruptive fissure was arranged in an echelon shape of a N-S trend as shown in TAKAHAMA & YOSHIMURA (1969).

b) The A_m-direction of the Miocene (Stage II) dikes in the Ryozen district shows such a N-S trend as described before, while the local arrangement of vents producing the volcaniclastics of Ryozen Formation shows different trend of a NW-SE direction (YASHIMA, 1962).

The analytical results of the dike-data are consistent with the opinions in SHIMAZU (1973, 1974) concerning the tectonic features of the volcanic activity during the Early-Miocene in the NE Honshu arc. He stated that the NW-SE trends represent the

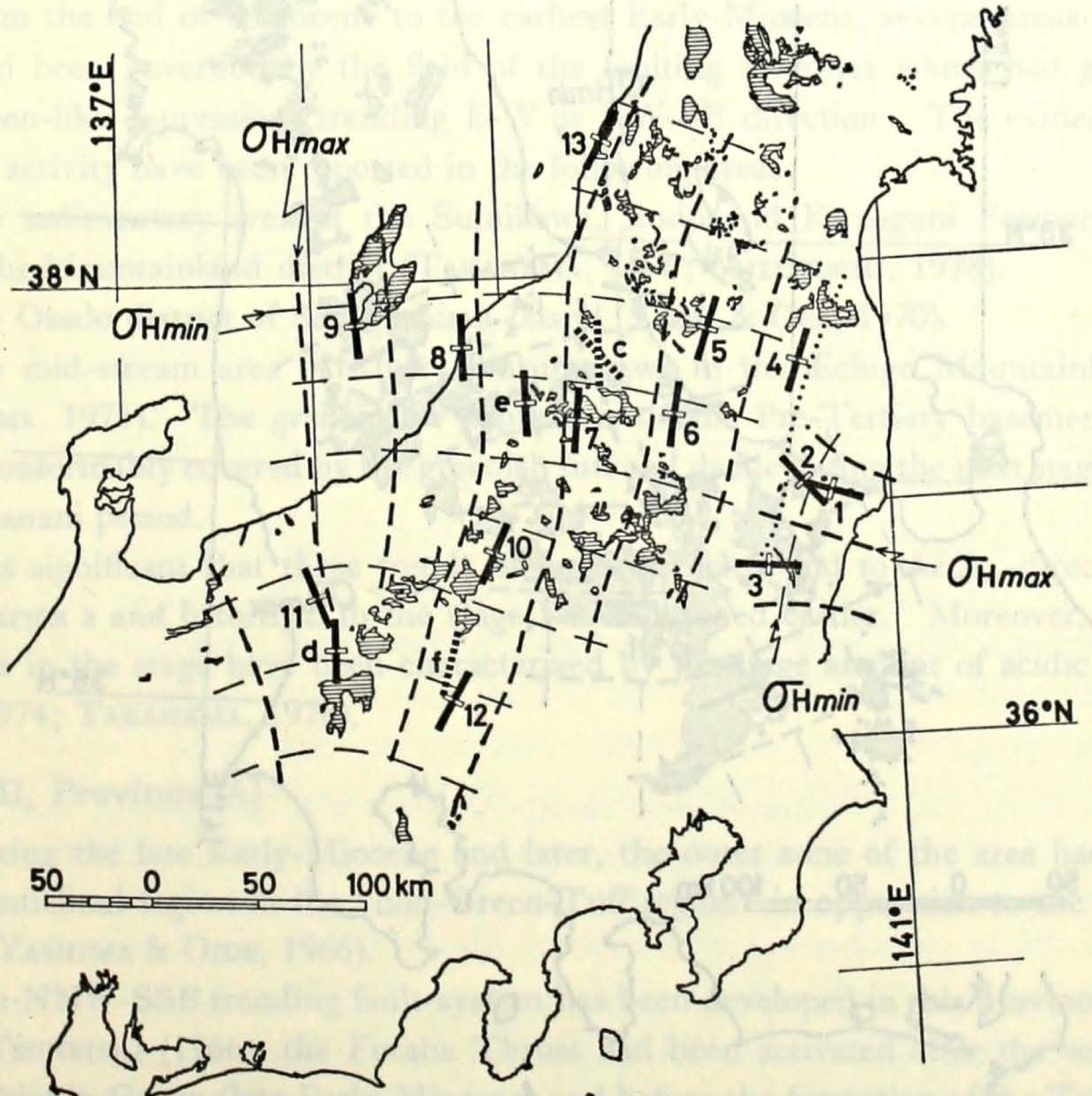

Fig. 11b Stress trajectory map (Southern NE Honshu, Stage-II) showing the stress field in the entire region of the southern NE Honshu ranging in time from the middle Early-Miocene to the early Late-Miocene. The distribution of volcanic rocks in this period are also shown: The stress field during the stage II can be characterized clearly as the "paired stress field." As in this map, σH_{max}-trend varies from an E-W trend in the outer zone(A) to a N-S trend in the inner zone(B). This spatial transition seems so abrupt that the boundary (dotted line) is able to be recognized. The T-type stress field dominates the wide region of the study area except the zone B.

principal trend of block-faulting in the basement and the N-S to NNE-SSW trends represent the dominant direction of so-called plagio-liparites (see Fig. 10).

Thus, it can be attributed to the dispersion due to reactivation of the pre-existing fractures that the irregular but remarkable trends of NW-SE to E-W shown by the rhyolite dikes had been formed only within the "Tsugawa-Aizu Province" during the latest Early-Miocene. This argument, however, is not conclusive, and more detailed analyses are necessary.

On the basis of the results and arguments in this chapter, three leaves of stress-trajectory maps are given in Figs. 11a, 11b and 11c, corresponding with the chronological division i.e. Stages I, II and III, respectively.

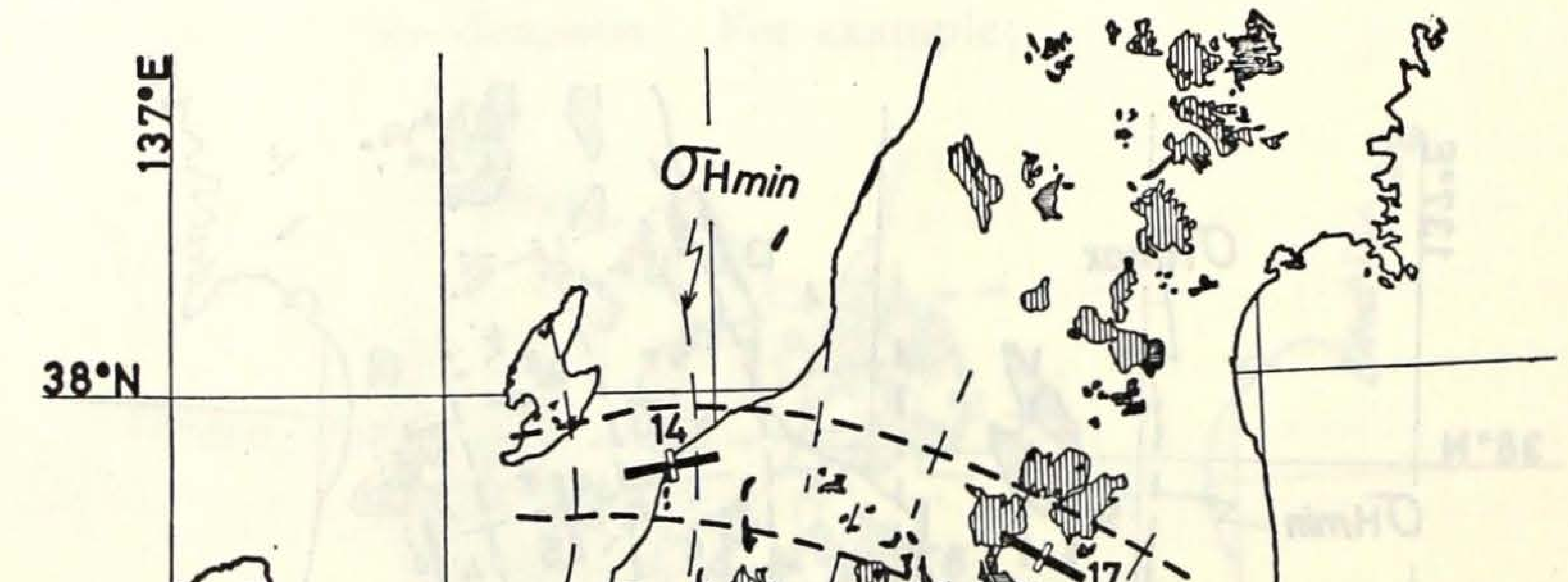

Fig. 11c Stress trajectory map (Southern NE Honshu, Stage III) showing the stress field in the inner zone, the volcanic region, during and after the latest Late-Miocene up to the Recent.

The P-type stress field has been inferred with regard to the faulting activity during the stage in the whole area including the outer zone. Therefore, a regionally uniform state is characteristic of the stress field in the whole region of the southern NE Honshu. It is significant that the pattern of σH_{max}-trajectories resembles well to those of the Present σ_1-trajectories inferred from the other known methods, geodetic measurements and focal mechanism solutions (TAKEUCHI, 1978).

6. History of the Regional Stress Field

Some data and aspects on the structural elements, except dikes, in the southern NE Honshu were presented hitherto. They are not always sufficient but useful, combined with the above dike-data for estimating the characteristics of the late Cenozoic stress field in the area. The purpose of the chapter is to correlate the stress history inferred from the dike method with that from the other structural analyses, and to classify the stress field into the T- and P-types. Brief history in the area is summarized in a similar format to that of the previous chapter.

[Stage I, Province B]

From the end of Oligocene to the earliest Early-Miocene, several areas in the inner zone had been governed by the field of the faulting activities which had given rise to the graben-like depressions trending E-W or NW-SE direction. The evidences for this tectonic activity have been reported in the following areas:

1) The sedimentary area of the Sumikawa, Budo and Kitaoguni Formations in the Asahi Mountainland district (TAKAHAMA, 1976; MIZUGUCHI, 1978).
2) The Osado district of Sadogashima Island (SAKAI & OBA, 1970).
3) The mid-stream area of River Aburumagawa in the Echigo Mountainland district (IJIMA, 1974). The graben-like depression on the Pre-Tertiary basement had been unconformably covered by the greenish tuff and dacite dating the next stage, Tsugawa-Natanani period.

It is significant that these trends of faulting correspond to the A_m-directions of the dike swarms a and b formed in the stage I as mentioned earlier. Moreover, the volcanic activities in the stage have been characterized by the huge amount of acidic rocks (SHIMAZU, 1974; TAKAHAMA, 1976).

[Stage II, Province A]

During the late Early-Miocene and later, the outer zone of the area had developed as a geanticlinal region in the "non-Green-Tuff region" in opposition to the Green Tuff region (YASHIMA & OIDE, 1966).

The NNW-SSE trending fault-system has been developed in this province. According to TSUNEISHI (1966), the Futaba Thrust had been activated after the sedimentation of the Shirado Group (late Early-Miocene) and before the formation of the Takaku Group (latest Early-Miocene).

TSUNEISHI (1974) has explained the above features of faulting as follows:

1) The NNW-SSE faults had been formed as sinistral strike-slip faults in the Cretaceous.
2) In the Miocene, these faults were rejuvenated so that the elongate graben structure with the width of 1-Km and the length of 30-Km were formed on the apex of upsqueezing due to the E-W compression.

These tectonic features are not incompatible with the averaged σH_{max} of this stage estimated by the dike method. It is conclusively suggested that the outer zone of the stage is characterized by the P-type stress field which has given rise to the E-W compressional tectonism.

[Stage II, Province B]

The inner zone in the almost entire period of the Miocene followed tectonic history characteristic of a T-type stress field, as mentioned below.

A. Sedimentation and deformation

1) According to YASHIMA & OIDE (1966), the "Yanagawa-Shirasawa line" along the western margin of the Abukuma Highlands, the southern part of the Morioka-Shirakawa tectonic line, had been a normal dip-slip fault which brought out the vertical displacement of some 1500 m during the Early- to Middle-Miocene.

2) In both the Niigata oil-field and the Hokushin districts, i.e., the Shin-Etsu sedimentary basin, fault block movements were carried during both the Mikawa and Nanatani stages (KATAHIRA, 1970; CHIGAKUKAI OF NAGANO PREF., 1962). While the movements resulted in the tectonic relief on a N-S trend, the basement relief and volcanic banks were buried as the result of the extended transgression and submergence in the same stage (KATAHIRA, 1970; IKEBE *et al.*, 1972).

In the Teradomari stage, most part of the Shin-Etsu basin performed a stable sedimentation, but the differentiation of the basin into several small basins had already commenced in the Hokushin district, resulting in the lateral changes in the facies and thickness of the strata (TAKEUCHI, 1977).

3) In the Late-Miocene, in accordance with the tendency of differentiation and scale-reduction of the sedimentary basin, such uplifted areas as the Nishikubiki zone, the Central uplift zone and the Echigo Mountain district had extended (AKAHANE, 1975; TAKEUCHI, 1977; NIIGATA PREF., 1978).

B. Volcanic activity

1) On the Motojuku, Kirizumi-Akima, Southern Aizu and Aizuyanaizu districts, the non-elongate, fault-bounded basins due to volcano-tectonic activity had been formed during the Late-Miocene (UNION OF COLLAB. RES. GROUP ON THE GREENTUFF OROGENY, 1977)

2) According to KONDA (1974) and CHIHARA (1974), basalt activity in the Teradomari stage occurred as the submarine fissure eruption at the marginal part of the sedimentary basin, although the volcanic region had extended in the almost whole area of the inner zone.

These tectonic features above A and B elucidate that the inner zone from the middle Early- to the middle Late-Miocene can be characterized by a T-type stress field. As regards to both the stage I and II, there existed the T-type tectonic stress field on the inner zone since the end of Oligocene till the end of Late-Miocene.

[Stage III, Province B]

The tectonism in the inner zone after the late Late-Miocene is considerably different from that of the earlier stages.

A. Folding and intermontane basins

According to IKEBE *et al.* (1972) and KATAHIRA (1974a, b), the first occurrence of the folded structure in the Niigata oil-field district which has been almost finished at the Oguni stage can be traced back to the Shiiya stage. The morphological features of the folding are characterized by the NNE-SSW trend, Niigata trend, and by the assymmetrical anticlines with thrust faults at the overturned east wings (UEMURA & TAKAHASHI, 1974).

In the inland area, the N-S trending intermontane basins bounded by thrusts and flexures had been formed since the end of the Late-Miocene. Some of these deformation has been active up to the Recent. TAKEUCHI (1978) examined the process and mechanism of both the above folding and the formation of intermontane basins, and showed that laterally compressive stress field was existed in the Shin-Etsu region from the end of Late-Miocene up to the Recent.

B. Pliocene volcanic activity

The Pliocene volcanic rocks tend to show somewhat localized and isolated distribution (SHIMAZU, 1974). The volcanic region had been situated at the almost central part of the sedimentary basins of the upper Neogene strata (CHIHARA, 1974). These volcanic features are different from those of the Miocene as mentioned before.

Consequently, the P-type stress field followed by the compressional tectonism of an E-W trend has been characteristic of the inner zone from the end of Late-Miocene to the present.

Recently, the data on the active faults have been sampled and accumulated rapidly from the whole Japanese Islands (e.g. MATSUDA *et al.*, 1976; OKADA & ANDO, 1979), so that the characteristics of the late Quaternary tectonics have been well elucidated. OTSUKI *et al.* (1977) have examined active faults on both the Abukuma Highlands (outer zone side) and Lowlands (inner zone side) and have pionted out the following points:

1) Most active faults of NE-SW trend are thrusts. 2) The Futaba Sheared Zone, one of the vertical faults of NNW-SSE trend, shows a component of left-lateral slip. 3) Some faults trending NW-SE are normal faults. 4) Many of these active faults formed by reactivation of the pre-existing faults and high-angled joints. 5) The inferred stress orientation from the fault-systems can be characterized by σ_1 of N45°W. Consistently, the orientations of σ_1 and σ_3 deduced by fault analysis and focal mechanism solutions and from the geodetic data are N55°W and vertical, respectively.

Such points suggest that the stress field of the Abukuma area in the later Quaternary period is characterized by the P-type field where $\sigma H_{min} \simeq \sigma V$ and that this type of stress field continued in the whole area of the southern NE Honshu during the period, regardless of the outer zone or the inner.

Correlating of the above characteristics with the inferred σH_{max} orientation by the dike method, some features of the Tertiary tectonic stress field can be pointed out as follows (Figs. 11a, b, c):

a) The regional tectonic stress field on the inner zone during the period from the end of Oligocene to the early Late-Miocene had been in a state of T-type. At the early Early-Miocene (ca. 21 Ma b.p.), the change in the arrangement of the horizontal stress axes took place: The σH_{max}-direction of the earliest Early-Miocene and earlier (Stage I) had oriented in an E-W trend, then that of the middle Early-Miocene and later period (Stage II) changed to have a N-S trend, as seen in Figs. 10, 11.

b) There existed the P-type stress field with the σH_{max} of an E-W trend in the inner zone at and after the end of Late-Miocene (Stage III). It is significant that the faulting activity in the period had been represented chiefly by the thrusting of a N-S trend in spite of the existence of pre-existing fractures and/or faults of NW-SE and NE-SW trends. Noticing the fact, it is more likely adopted that $\sigma V = \sigma_3$ in this P-type field.

c) At the late Late-Miocene (ca. 6–7 Ma b.p.) in the inner zone, the change in types of stress field from T-type to P-type took place as well as the change of the σH_{max}-orientation. According to TAKEUCHI (1977, 1978), such a drastic change can be almost correlated with the change of tectonic style in a wide sense including sedimentation, igneous activity, deformation, mineralization and so on.

d) The stress orientation on the outer zone of the study area can be characterized by the σH_{max} of E-W to NW-SE trends as long as both period from the late Early-Miocene to early Middle-Miocene (Stage II) and the late Quaternary period are concerned. Both stress states in these two periods can be classified into P-type. Because of insufficient data on dike-formation and faulting in this zone, however, it cannot be estimated (1) which of σV and σH_{min} corresponds to σ_3 and also (2) whether the P-type field had continued throughout the Cenozoic period.

Paired stress field

At least from the late Early-Miocene to the middle Middle-Miocene, two contrasting stress field coexisted in adjacent provinces of the southern NE Honshu. This differential buildup of tectonic stress distribution is named here as paired stress field.

In the inner zone, Province B, the stress field had σH_{max} of a N-S trend, while in the outer side, Province A, σH_{max} was in an E-W trend. The boundary between these provinces is nearly identical to the transitional zone between the inner and outer zones of NE Honshu arc (YASHIMA & OIDE, 1966) or to the marginal zone of the Green Tuff region (KITAMURA, 1977).

In these provinces, the spatial arrangement of horizontal principal stresses seems to have shown the lateral change as if the stress orientation had horizontally turned 90 degrees, so that the σH_{max}-trend of the outer zone is parallel to the σH_{min}-trend of the inner zone. This relationship will be discussed in the next chapter in more detail.

7. Discussion

Although there have been presented a few geohistorical studies on the Neogene stress field of Japanese Islands, it is not uncommon to show the possibility that a tectonic stress field would re-oriented drastically as well as the regional uniformity and prelonged duration (HUZITA, 1969; NAKAMURA, 1969; TAKEUCHI *et al.*, 1979).

Northeast Honshu Arc

In a major aspect, the formation and development of sedimentary basins under an E-W extensional stress field had been carried out in the ealier term of the tectonic development of the Green Tuff region of the NE Honshu, and then in the later term, many kinds of deformed structures under the E-W compressional field were completed (KITAMURA, 1979).

Some opinions* on the history of regional tectonic stress field chiefly in the northern part of NE Honshu Arc have already been proposed as follows:

a) NAKAMURA (1969) has noticed that the extensional tectonics in the Miocene period contrasts well with strong compressional tectonics in the late Quaternary, and a remarkable change in the regional stress field would be expected. Then he has made a proposal that the NE Honshu arc had been gradually drifting eastward away from the Asian continental region.

b) Uplifting in both the non-Green-Tuff region, or the outer zone, and the Backbone Range had been caused by a compressional tectonism.

c) He has considered that the temporal change in the stress field occurred not simultaneously throughout the Green Tuff region but that it occurred earlier in the area of Backbone Range than in Japan Sea side area.

d) These opinions above have been reaffirmed by KITAMURA (1979). Contrarily, FUJII (1974), ISHIHARA (1974) and HORIKOSHI (1977) have estimated simultaneously the time of re-orientation as the Late-Miocene, around 7 and 9 Ma b.p., respectively.

Comparing the above opinions with the result of the present study, the actual proofs are held to (a) and (b), but the opinion (c) cannot be supported because the time of exchange would not be traced back to the Middle-Miocene.

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* MOTOJUKU RESEARCH GROUP (1970) and FUJITA *et al.* (1974) have shown the fact that the dike systems 12 and 6 distributed in the Motojuku and the southern Aizu areas, respectively, had been closely related to doming upheavals followed by volcano-tectonic, fault-bounded depressions. On the relationship of stresses with volcano-tectonic activities, they insisted that the main tectonic force would be vertically oriented and that there was no significance of horizontal stresses.

Such a opinion, however, is one-sided and they should have noticed at least the relative magnitude between σV and σH, because if, for example, the magmatic pressure is high and σV and σH are nearly equal, magma may rise as randomly oriented dikes or cylindrical intrusions that stope their way toward the surface. In this case, normal dip-slip type of radial and/or conical faults are also expected to be accompanied (KOIDE, 1974; KAKIMI, 1978).

Moreover, the directivities shown in the distribution of dikes in those areas, formed after the doming, would rather become a strong proof of the horizontally deviatoric state of the upper-crustal stress field streached to a greater extent than that of the domed area (with radius of some 25 kilometers; KOMURO, 1978).

Moreover, such new problems are offerred as follows: 1) the axial change in horizontal stress orientation at the beginning of Early-Miocene, and 2) the paired stress field ranging at least from the late Early-Miocene to the early Middle-Miocene and 3) the stress province existed more inward of the Miocene T-type province.

Consequently, it is reasonable to estimate that the change from the T-type stress field to the P-type at least within the Uetsu sedimentary basin had been simultaneously performed at about 6 to 7 Ma b.p.

Southwestern Japan

KOBAYASHI (1977), KOBAYASHI & NAKAMURA (1978) and KOBAYASHI (1979) have analyzed the late Cenozoic stress field throughout Southwest Japan by means of the dikes, together with faults and folds. The analytical results of their study are summarized as below:

a) There had been the remarkable tendency that either σH_{max} or σH_{min} would be arranged perpendicular to the trace of Nankai Trough.

b) The temporal changes in the stress orientation are clearly different between the northern (inner) and southern (outer) belts bounded by a line near the Butsuzo tectonic line.

c) In the inner belt, three changes in orientation and type of stress field had occurred at around 21, 11 and 2 Ma b.p., but no remarkable change had been carried out in the outer belt during the Neogene period.

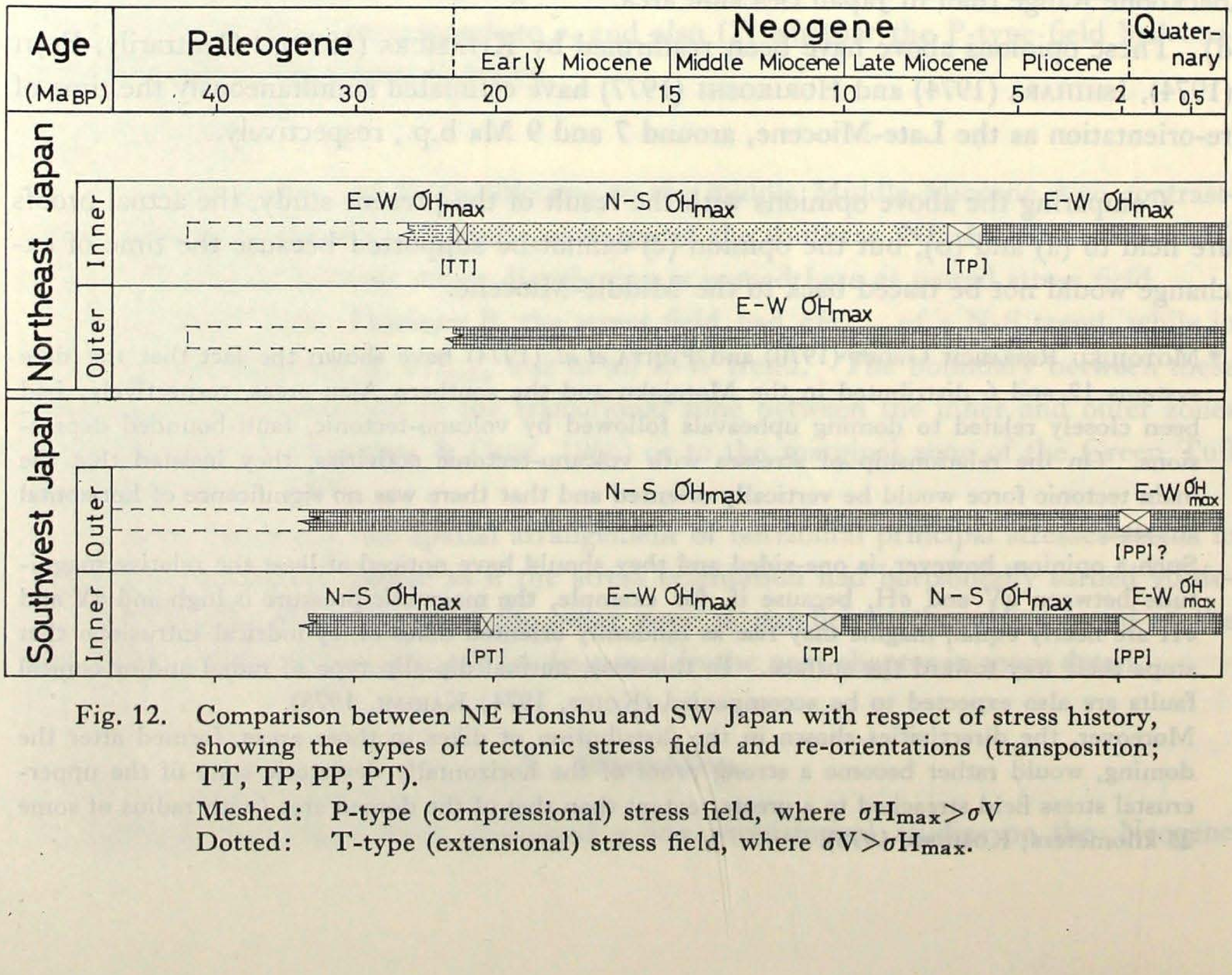

Fig. 12. Comparison between NE Honshu and SW Japan with respect of stress history, showing the types of tectonic stress field and re-orientations (transposition; TT, TP, PP, PT).

Meshed: P-type (compressional) stress field, where $\sigma H_{max} > \sigma V$

Dotted: T-type (extensional) stress field, where $\sigma V > \sigma H_{max}$.

d) The chronological changes in the stress field of SW Japan are as follows: 1) Before 21 Ma b.p., the P-type stress field with an N-S σH_{max}-trend existed in the almost whole area of SW Japan. 2) Then, between 21 and 11 Ma b.p., the paired stress field had continued. The inner belt of this period is characterized as the T-type with a N-S σH_{max}. 3) From 11 to 2 Ma b.p., the similar P-type field as that of 1) had covered again almost whole area.

Comparing the above stress field with that of the southern NE Honshu they are much different from each other in both orientation and type as shown in Fig. 12. The boundary between the two distinct stress fields is nearly identical to the Itoigawa-shizuoka tectonic line (ISTL in Figs. 13 a, b, c).

The common features seen in the both area are pointed out as follows: a) One of the horizontal principal stress would tend to be arranged nearly normal to the arc-trend. b) Several abrupt changes in both stress orientation and type of stress field can be recognized in the inner sides. c) The paired stress fields had appeared at the almost identical time, around 21 Ma b.p., although they came separately to extinction.

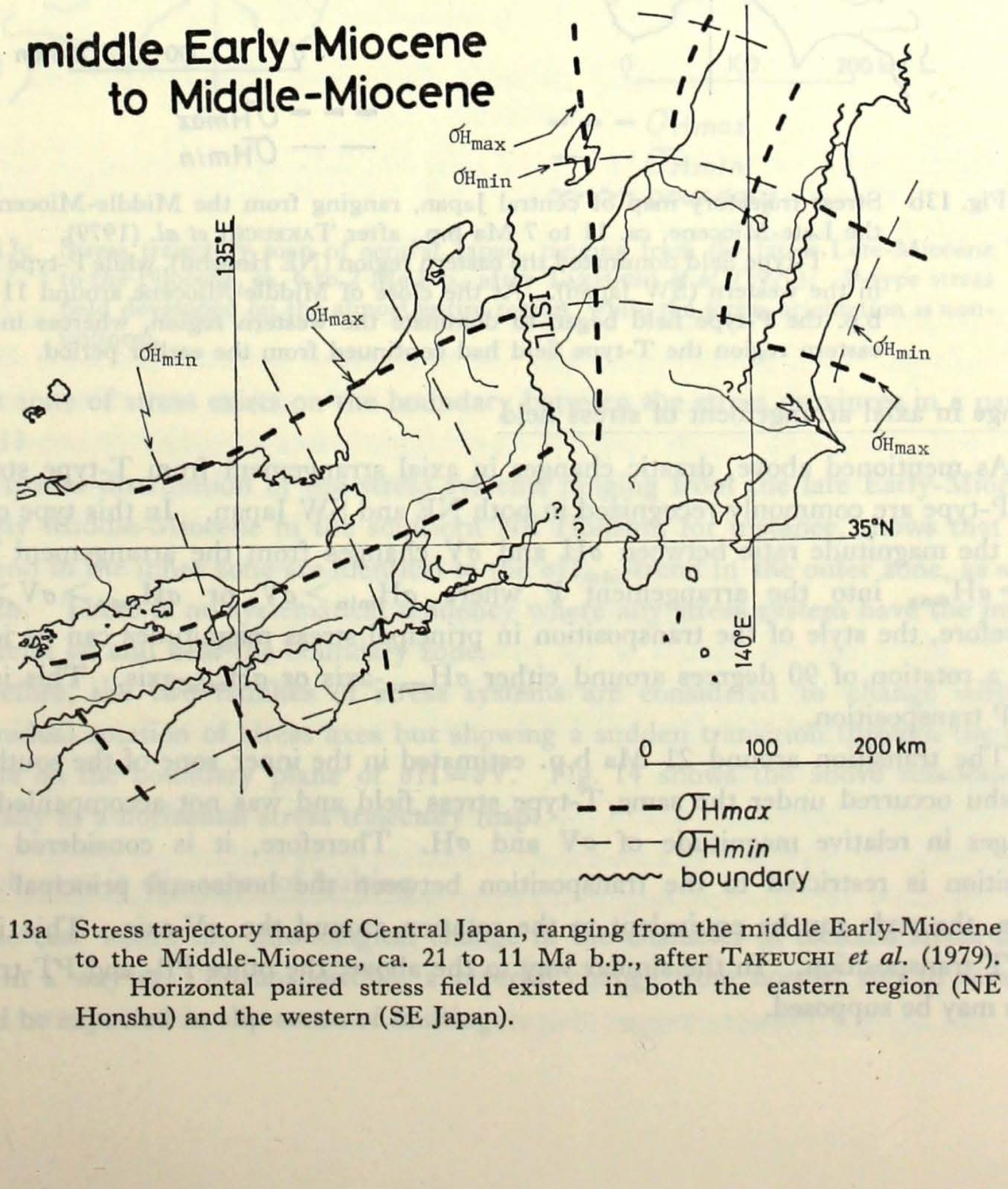

Fig. 13a Stress trajectory map of Central Japan, ranging from the middle Early-Miocene to the Middle-Miocene, ca. 21 to 11 Ma b.p., after TAKEUCHI *et al.* (1979). Horizontal paired stress field existed in both the eastern region (NE Honshu) and the western (SE Japan).

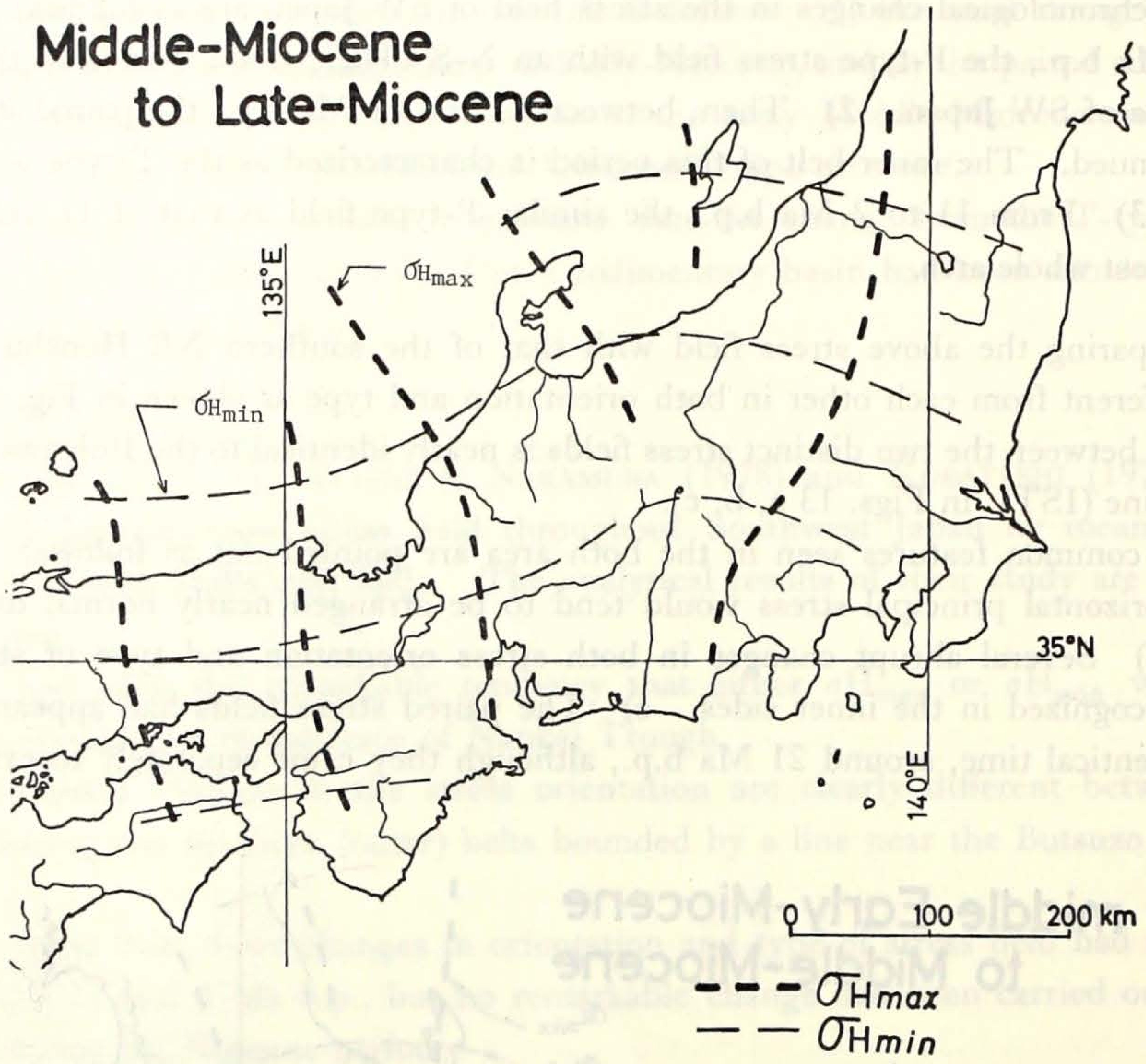

Fig. 13b Stress trajectory map of central Japan, ranging from the Middle-Miocene to the Late-Miocene, ca. 11 to 7 Ma b.p., after TAKEUCHI *et al.* (1979).
T-type field dominated the eastern region (NE Honshu), while P-type field in the western (SW Japan). At the close of Middle-Miocene around 11 Ma b.p. the P-type field began to dominate the western region, whereas in the eastern region the T-type field had continued from the earlier period.

Change in axial arrangement of stress field

As mentioned above, drastic changes in axial arrangement from T-type stress field into P-type are commonly recognized in both NE and SW Japan. In this type of transition, the magnitude ratio between σH and σV changes from the arrangement T where $\sigma V > \sigma H_{max}$ into the arrangement P where $\sigma H_{min} > \sigma V$ or $\sigma H_{max} > \sigma V > \sigma H_{min}$. Therefore, the style of the transposition in principal stress magnitudes can be identified with a rotation of 90 degrees around either σH_{max}-axis or σH_{min}-axis. This is named as TP transposition.

The transition around 21 Ma b.p. estimated in the inner zone of the southern NE Honshu occurred under the same T-type stress field and was not accompanied by any changes in relative magnitude of σV and σH. Therefore, it is considered that the transition is restricted to the transposition between the horizontal principal stresses. Then, the style can be equivalent to the rotation around the σV-axis. This is called as TT transposition. In the similar way to the above, the other PP- and PT-transpositions may be supposed.

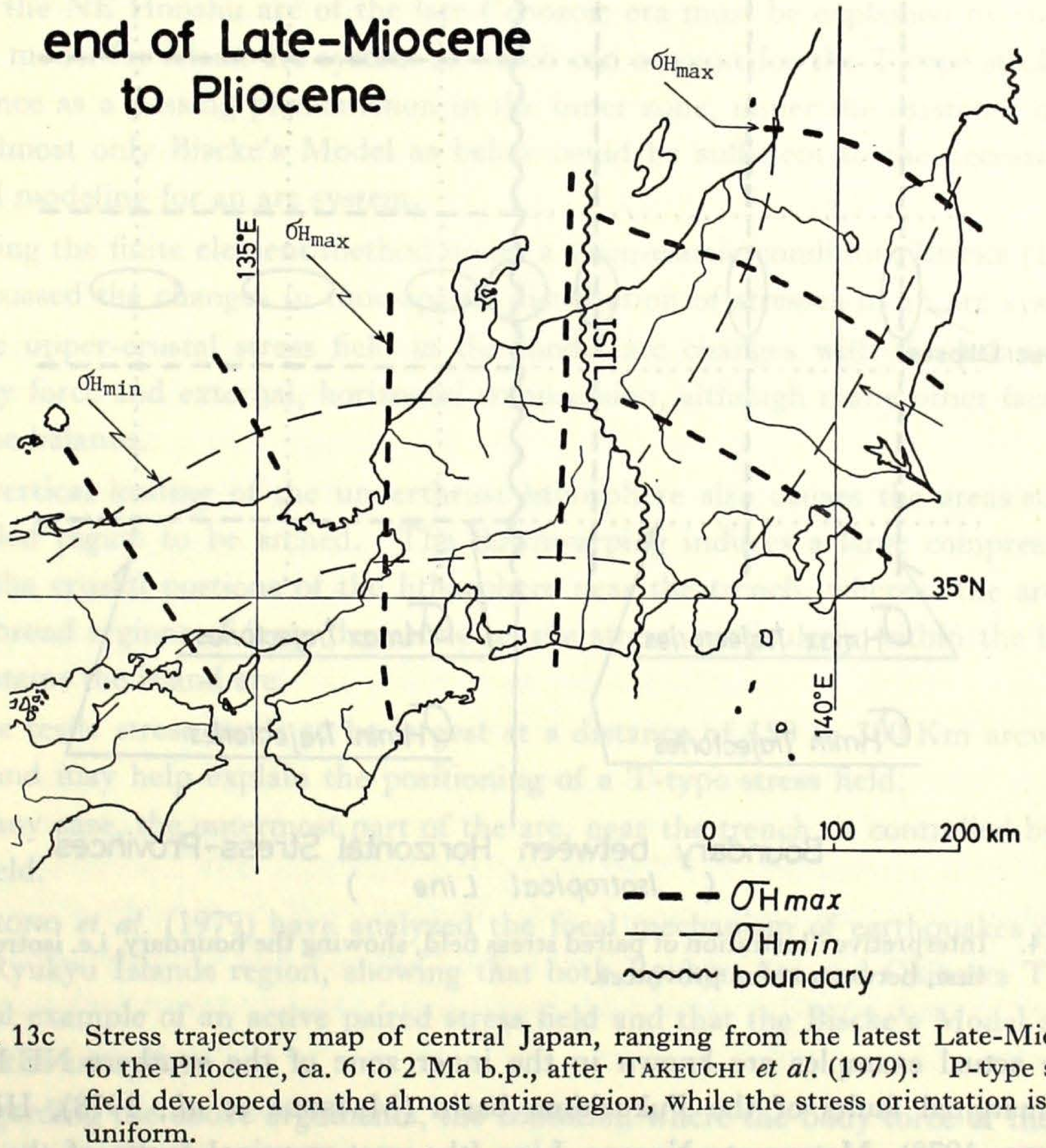

Fig. 13c Stress trajectory map of central Japan, ranging from the latest Late-Miocene to the Pliocene, ca. 6 to 2 Ma b.p., after TAKEUCHI *et al.* (1979): P-type stress field developed on the almost entire region, while the stress orientation is non-uniform.

What state of stress exists on the boundary between the stress provinces in a paired stress field?

The spatial distribution of the stress systems ranging from the late Early-Miocene to the early Middle-Miocene in the southern NE Honshu, for instance, shows that the σH_{max}-trend in the inner zone are identical to the σH_{min}-trend in the outer zone, as seen in Fig. 12b. There is no systematical tendency where any stress system have the intermediate trend on and near the boundary zone.

Therefore, the two families of stress systems are considered to change without spatial, gradual rotation of stress axes but showing a sudden transition through the isotropic state on the boundary plane of $\sigma H = \sigma V$. Fig. 14 shows the above relationship schematically as a horizontal stress trajectory map.

Reversal changes in slip-sense of faulting

In the case where the chronological change in the character of tectonic stress field occurred in a way of TP-transposition, a reversal change from normal slip to reverse slip would be expected in slip-sense of faulting.

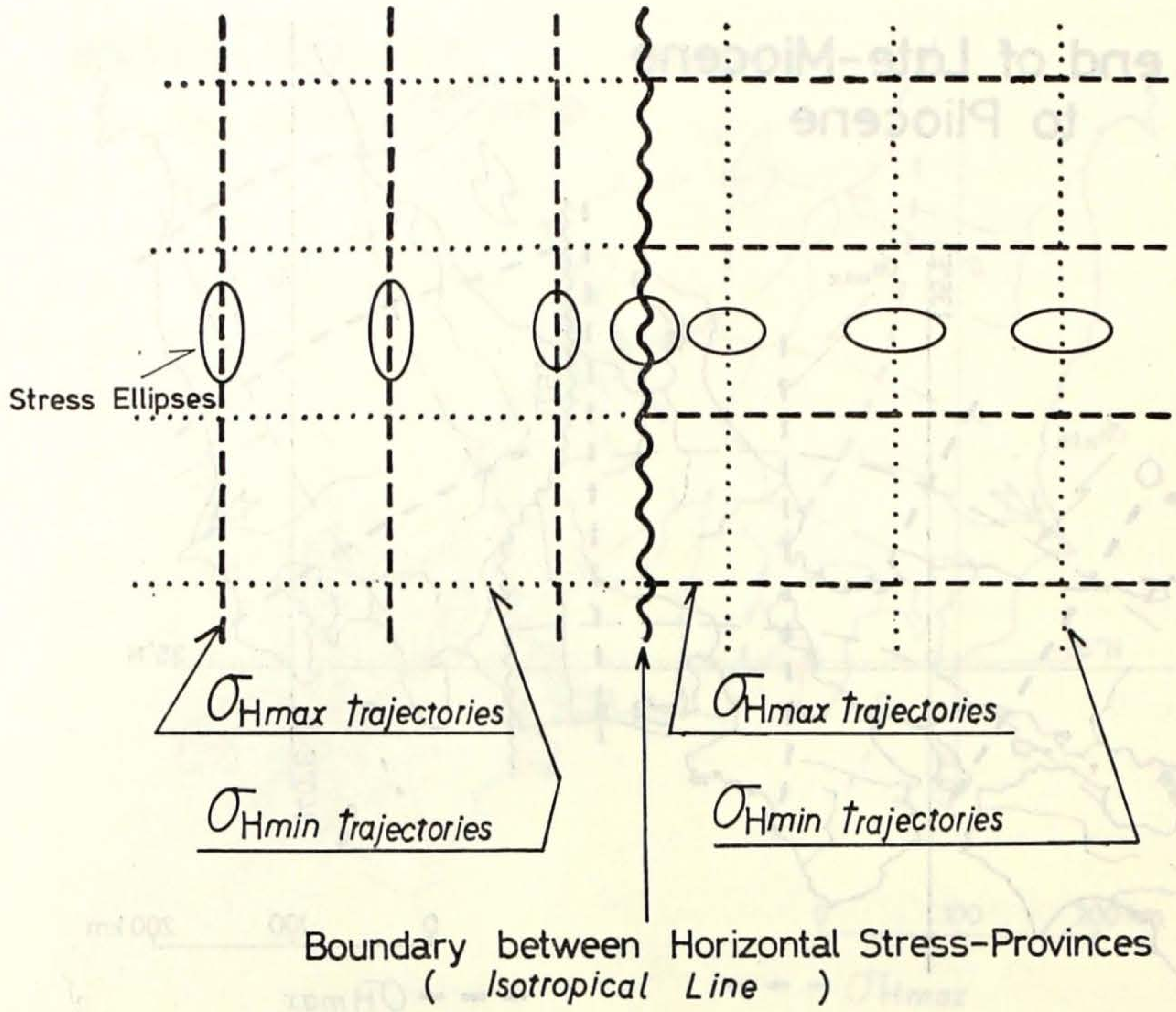

Fig. 14. Interpretive illustration of paired stress field, showing the boundary, i.e. isotropic line, between stress provinces.

Some actual examples are known in the inner zone of the southern NE Honshu; the west-marginal faults of the Fukushima basin (MATSUDA *et al.*, 1978), Himekawa Fault (SAITO, 1978), Matsumoto-Nagano Line (the west-marginal faults of the Nagano basin; TAKEUCHI, 1977), Nagatani F. (TAKEUCHI, 1979) and so on. They are observed at present as thrust or reverse fault but would have been normal fault before 6–7 Ma b.p. when the re-orientation of tectonic stresses had occurred.

Yanagawa-Shirasawa Line (the southern part of Morioka-Shirakawa tectonic line; YASHIMA & OIDE, 1966) and the northern Shibata-Koide Line (YAMASHITA, 1970) are observed as normal fault still now. However, if they are reactivated, they might show a reverse slip under the control of the Present P-type stress field. But it is not always easy for them to be recognized as reverse fault, because their ancient displacement due to normal dip-slip in the extensional tectonism under the Miocene T-type field was very large (more than 1,500 m).

The above statements mean that the faulting in the basement of the Tertiary to Quaternary sedimentary strata are caused essentially by reactivation of pre-existing faults, with the slip-sense corresponding to the state of the tectonic stress field.

On the origin of a tectonic stress field in an arc system

The above arguments suggest that the origin and development of the tectonic stress field in the NE Honshu arc of the late Cenozoic era must be explained by such an evolutional model for island arc system as which can account for the T-type stress field and subsidence as a passing phenomenon in the inner zone, under the existence of marginal sea. Almost only Biscke's Model as below could be sufficient to the necessity for mechanical modeling for an arc system.

Using the finite element method under a visco-elastic condition, BISCKE (1974, 1976) has discussed the changes in time-spatial distribution of stresses in an arc system:

1) The upper-crustal stress field in the model arc changes with the balance between the body force and external, horizontal compression, although many other factors would effect the balance.

2) A vertical loading of the underthrust lithosphere also causes the areas surrounding the loaded region to be arched. The downwarping induces a large compressive stress within the crustal portions of the lithosphere near the trench, whereas the arching may induce broad regions of large deviatoric tensile stress, particularly within the lithosphere that contains the island arc.

The tesile stress tends to be largest at a distance of 150 to 300 Km arcward of the trench and may help explain the positioning of a T-type stress field.

3) In any case, the outermost part of the arc, near the trench, is controlled by a P-type stress field.

SHIONO *et al.* (1979) have analyzed the focal mechanism of earthquakes distributed in the Ryukyu Islands region, showing that both Ryukyu Arc and Okinawa Trough are an actual example of an active paired stress field and that the Biscke's Model can be applied to the arc system.

Regarding the above arguments, the condition where the body force of the subducting slab is dominant could be expected at the time when the intra-arc basin had been formed in the NE Honshu arc. Whether or not this is true or whether another one is required cannot be known until the future study is done. The problem is what type of stress field existed backward of the inner zone of arc.

8. Summary and Conclusions

We can improve mechanical understanding relevant to geotectonic history, if the ancient state of the crustal stress are detected. The dike method is one of the way available for this purpose.

It is accepted that a dike would show a preferred orientation parallel to the principal plane of (horizontal) minimum compressive stress. Thus, it is significant that dikes could be treated as stress indicators for their surrounding rocks.

Availability of this method has been successfully examined by active and dynamic measurements of deep in-situ stresses using the hydraulic fracturing technique (e.g. HAIMSON, 1978). Owing to mechanical simplicity of dike formation, the dike method would be very useful for field geologists to induce past tectonic stress orientations.

Seventeen dike swarms distributed in the southern part of Northeast Honshu, dating from the end of Oligocene up to the Pliocene, are sampled. Each swarm can be analyzed as a dike system which had formed under a certain stress field during the same geological period. The late Cenozoic history of horizontal, deviatoric stress orientations in the studied area, are derived from the σH_{max}-directivity of the dikes.

Two types of direction-pattern are recognized in the area. The dike system of middle Early to early Late-Miocene in the western (inner) zone has a dominant N-S direction, while the one of late Early-Miocene in the eastern (outer) zone shows an E-W trend. In the inner zone, however, both of the dike system during the earliest Early-Miocene and earlier, and that formed in time from the end of Late-Miocene to the Pliocene show a direction-pattern of an E-W trend.

It is not self-evident whether the maximum principal stress σ_1 is vertical or horizontal in such stress fields. For the purpose of making a more complete description of the tectonic stress field, it is indispensable to correlate the history of horizontal stress orientations to that of structural development within the same area.

The late Cenozoic history of tectonism in the southern NE Honshu implies that two types of stress field existed in the inner zone. They are a T-type (extensional) stress field where σ_1 is vertical and a P-type (compressional) field with horizontal σ_1. The T-type field continued during a definite period from the middle Early-Miocene to early Late-Miocene, and the P-type existed in the late Cenozoic period. Moreover, the tectonic history also suggests that these fields show relatively long term stability and abrupt re-orientation.

Consequently, the analytical results of regional stress history in this area are summarized as follows:

1) A T-type stress field with σH_{min} of an E-W trend had dominated the inner zone of NE Honshu until a P-type field with an E-W σH_{max}-trend dominated the whole area at the end of Late-Miocene. In the outer zone, there was a P-type field with an E-W σH_{max}-trend at least from the Early-Miocene to the early Late-Miocene and during the late Quaternary period. The boundary between these stress provinces during the earlier Miocene nearly coincides with the transitional zone between the Outer and Inner zones of the NE Honshu arc.

2) A comparison with other island arcs as well as the northern part of NE Honshu conclusively reveals that apparently abrupt exchange in axial arrangement of principal stresses are commonly characteristic of structural development in the inner zone of island arcs.

3) In the inner zone of NE Honshu arc, the reversals of slip motion of faulting occurred at the end of Late-Miocene just at the time when the axial arrangement had been transposed in a manner of interchange between σ_3 and σ_1. Considering that such exchange in character of regional tectonic stress field was a change from the T-type into the P-

type, this might mean that there was an abrupt change from a weak horizontal compression to a strong one, that is, from a state subjected by dominant gravitational force to that of a strong horizontal force.

4) Because of insufficient data, whether or not the P-type field in the outer zone had continued throughout the entire course of the late Cenozoic period has not yet been determined. Thus, what field existed from the Late-Miocene to the Pliocene becomes a serious problem.

5) The statements mentioned above suggest that the regional stress field originated in an island arc would seemingly be controlled by the balance between gravitational loading and horizontal compressive force. As a possibility, the horizontal deviatoric state of the crustal stress field can be attributed to conditions of lithospheric convergence at the outermost margin of the arc, i.e. the plate-boundary.

This is, however, a subject for future study. The inferred stress field developed in the present paper will serve as guides and constraints in future research.

Acknowledgments

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Appendix: Analytical Description of Dike-Data

Swarm [1] ··(Fig. A1)

(1) locality; [Tenno]/(Lon. 140.7°E, Lat. 37.05°N)/the central part of the Pacific side of the Abukuma Highlands, near Iwaki City of Fukushima Pref./

The Abukuma Highlands are composed mainly of the Cretaceous plutonic rocks and the "Tankanuki metamorphic rocks". Submarine basalt volcanism of small scale took place during the period from the later Early-Miocene to the earlier Middle-Miocene, so that some hyaloclastites including pillow lavas are distributed separately in the district.

According to ISSHIKI (1974), the chemical characteristics of the above hyaloclastites are similar to those of the Hawaiian tholeiitic basalt and dissimilar to those of the known late Cenozoic volcanics on the continental side of the northeast Japan.

The dike rocks, called as the Iritono intrusives, have been considered to be related with the basalt extrusive activity (KANO *et al.*, 1973).

(2) horizon of the effusive facies; hyaloclastites in the Taira Formation of the Yunagaya Group/

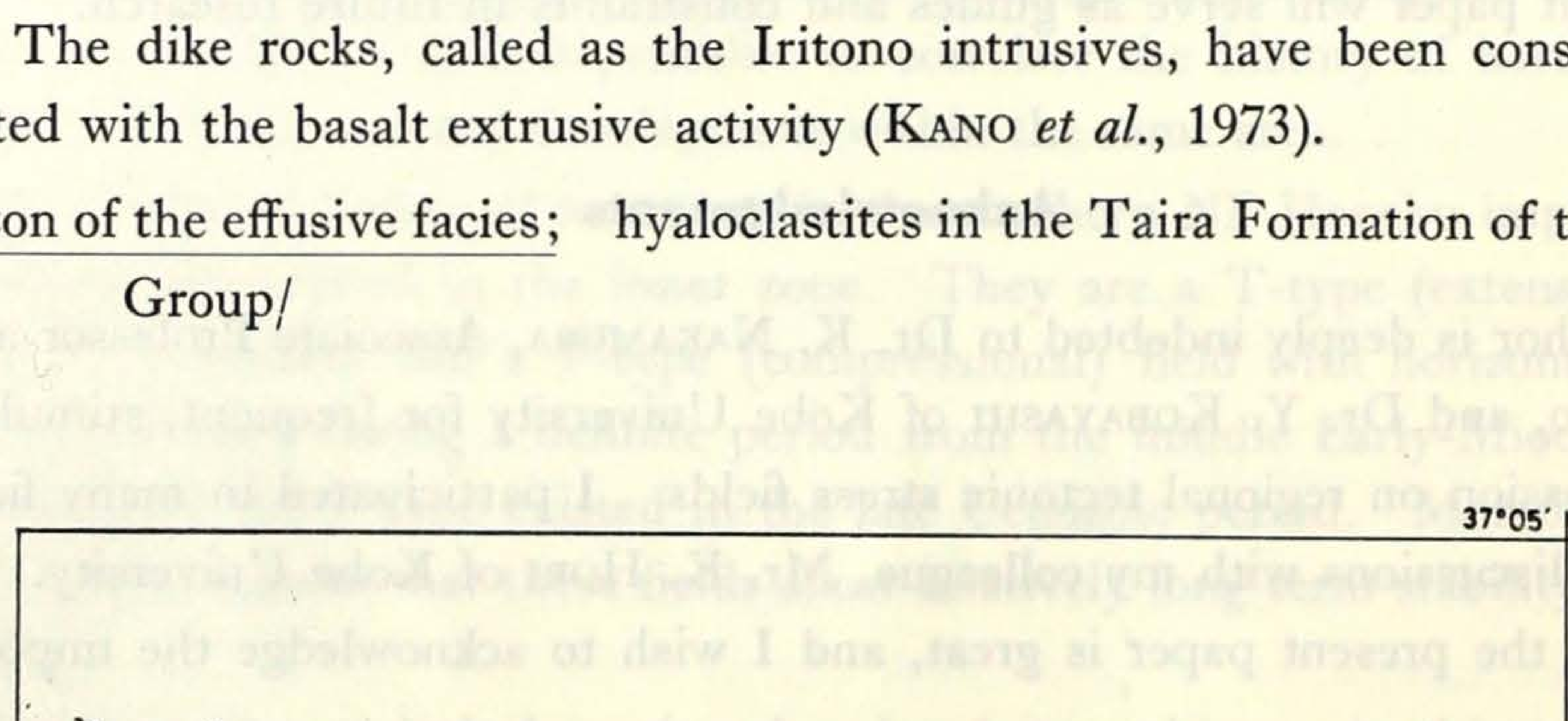

Fig. A1 Swarm [1; Tenno]

(3) age of the intrusion; late Early-Miocene (ca. 17 ~ 16 $\mathrm{Ma_{BP}}$), based on the above (2)/

(4) dike-wall data; N=55, Am=N70°W=σH_{max}, F=0.64; sampled by K. HORI and A. TAKEUCHI/

Swarm [2] ·· (Fig. A2)

(1) locality; [Takanuki]/(140.6°E, 37.1°N)/the southern part of the Abukuma Highlands, Ishikawa Country of Fukushima Pref./

In this province, the intrusive andesite with hornblende megaphenocryst with the length from 1 to 3 cm penetrate as dikes or sheets into the pre-Tertiary gneiss.

Because the lithofacies of the dikes resemble those of the Iritono intrusives, their age is assigned to that of Swarm [1].

(2) dike-wall data; N=10, Am=N50°W=σH_{max}, F=0.40; sampled by K. HORI and A. TAKEUCHI/

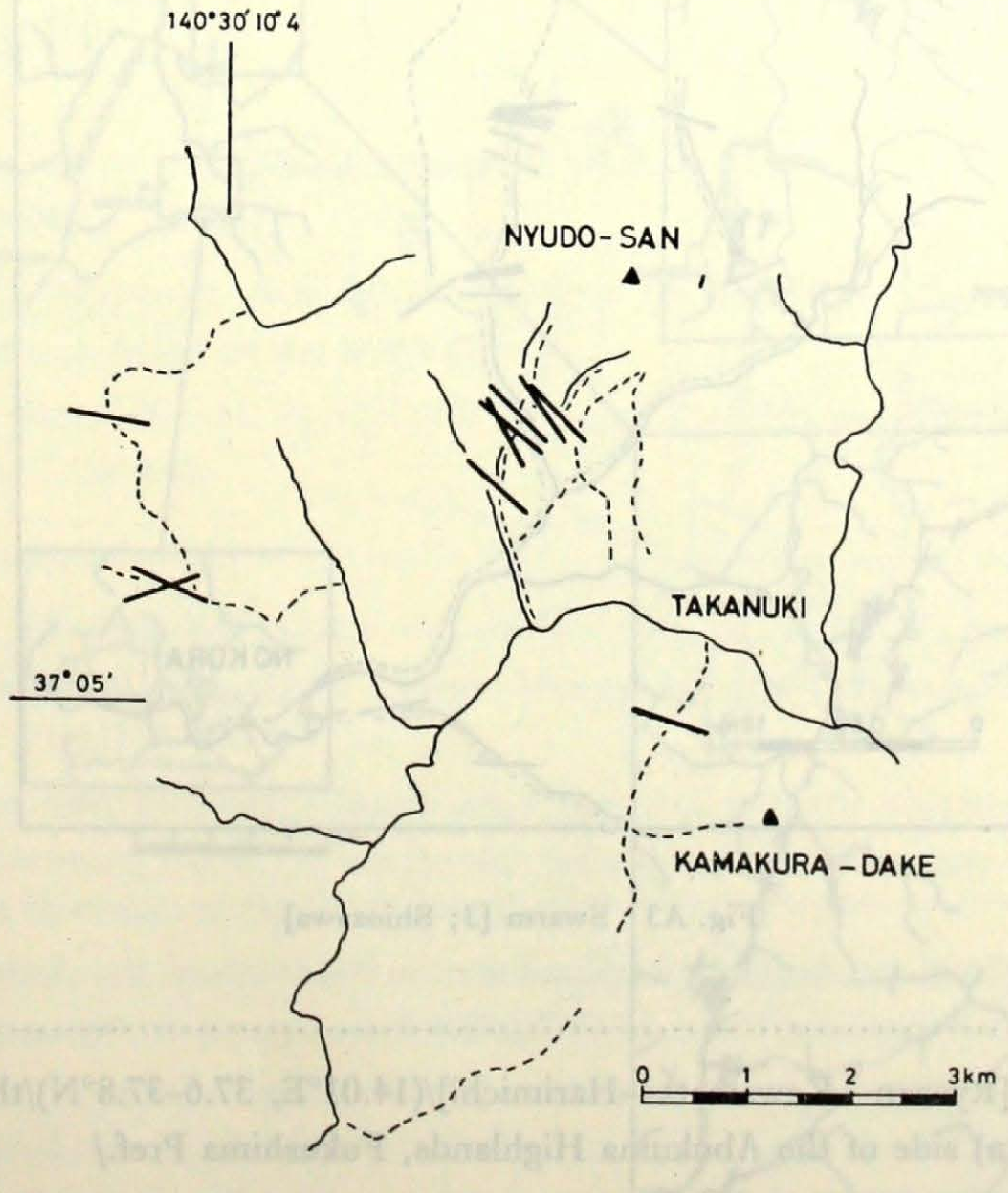

Fig. A2 Swarm [2; Takanuki]

Swarm [3] ··(Fig. A3)

(1) locality; [Shiozawa]/(140.3°E, 36.7°N)/the central part of the Yamizo Mountainland, westward of the Nantaisan Mountain, and to the southeast of Daigo City of northernmost of Ibaraki Pref./

(2) occurrence; porphyrite intruded into the Yamizo Paleozoic system/

(3) horizon of the effusives; rhyolite agglomerate in the Asakawa Formation (OTSUKI, 1975)/

(4) age of the intrusion; late Early-Miocene (ca. 17.5 ~ 16 $\mathrm{Ma_{BP}}$ in Fig. 7), based on the above (3)/

(5) dike-wall data; N=13, Am=N85°W=σH_{max}, F=0.70; sampled by K. HORI and A. TAKEUCHI/

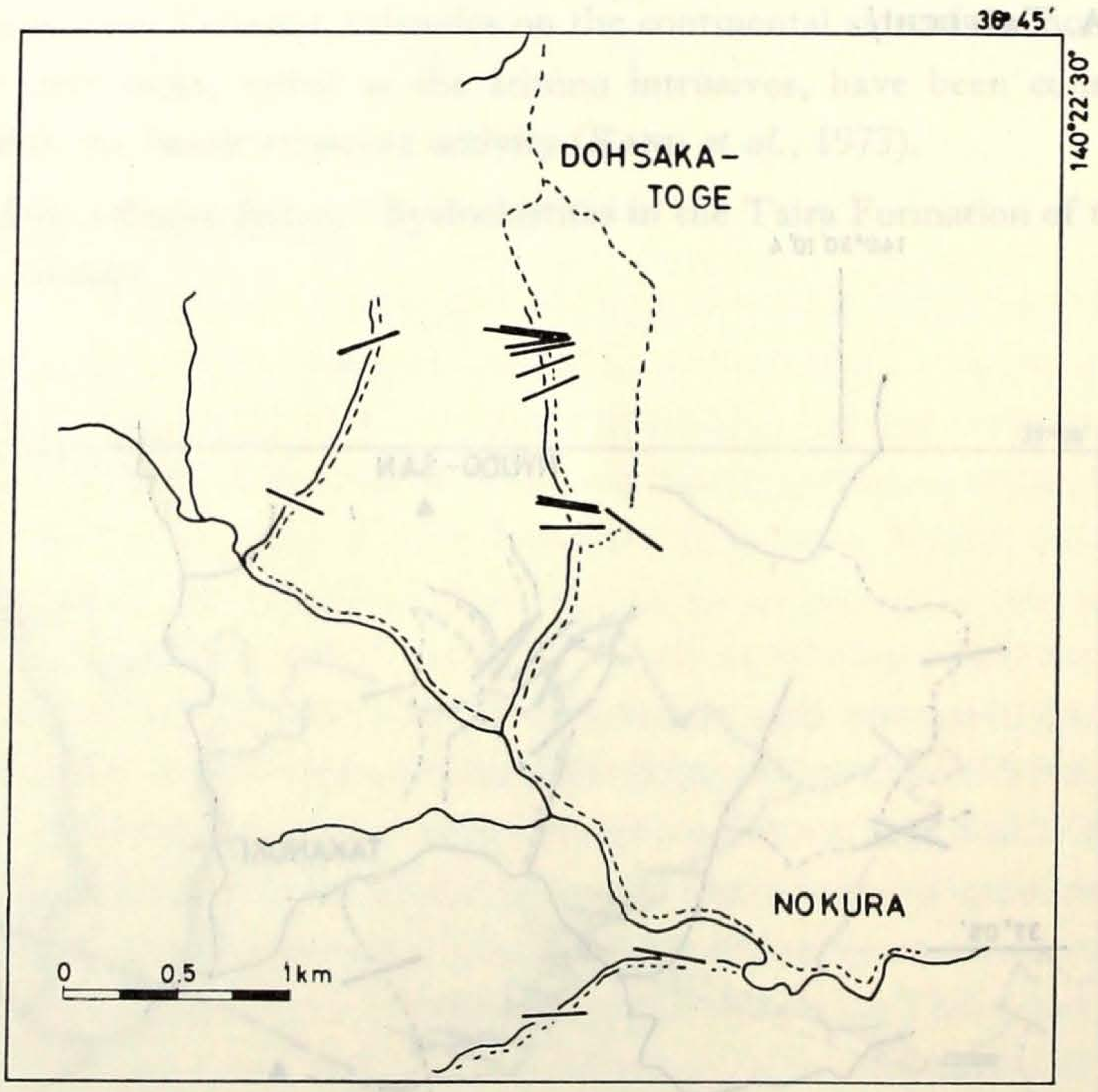

Fig. A3 Swarm [3; Shiozawa]

Swarm [4] ··(Fig. A4)

(1) locality; [Ryozen—Kawamata—Harimichi]/(14.01°E, 37.6–37.8°N)/the inland(western) side of the Abukuma Highlands, Fukushima Pref./

(2) occurrence and lithofacies; andesite and basalt dikes in the pre-Tertiary granitic rocks and in the volcaniclastics of the Ryozen Formation/

(3) horizon of the effusives; the Ryozen and Yanagawa Formation/

(4) age of the intrusion; late Early-Miocene (ca. 17.5–15 in $\mathrm{Ma_{BP}}$ Fig. 7), induced from the above (2)/

(5) dike-wall data; $N=197$, $A_m=N20°E=\sigma H_{max}$, $F=0.58$; sampled by K. Hori and A. Takeuchi/

Yashima (1962) showed that the swarm [4] was representative of the numerous dikes (more than 1,000 sheets, mainly andesite) which are distributed in an elongate area along the Ryozen–Harimichi Faults running through the Abukuma Highlands in a NNE-SSW direction with the length of about 70 Km.

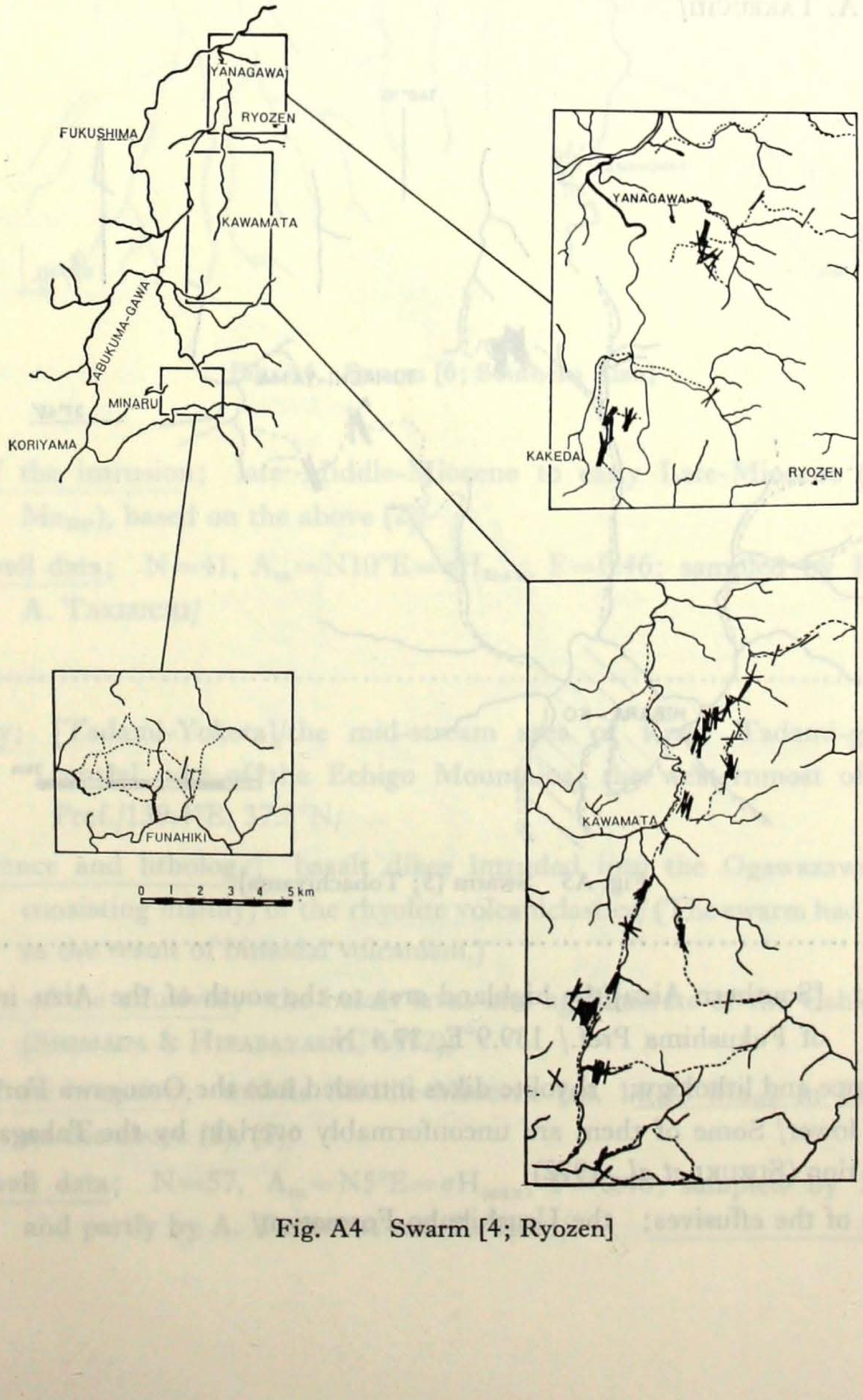

Fig. A4 Swarm [4; Ryozen]

Swarm [5] ··· (Fig. A5)

(1) locality; [Tohachiyama]/ around the Hibara pass west of the Hibara Lake, the northernmost of the central Fukushima Prefecture/ also located at the southern tip of the Ou Mountains which constructs the back bone range of the NE Honshu Arc/

(2) occurrence and lithology; propylite colored dark-blue or dark-green, penetrated into the pre-Tertiary granite/

(3) age of the intrusion; middle Early-Miocene (ca. 21.5–19.5 $\mathrm{Ma_{BP}}$ in Fig. 7), that is, the pre-propylitization (pre-Nishikurosawa) stage (HORI, 1978ms)/

(4) dike-wall data; $N=23$, $A_m=\mathrm{N20°E}=\sigma H_{max}$, $F=0.63$; sampled by K. HORI and A. TAKEUCHI/

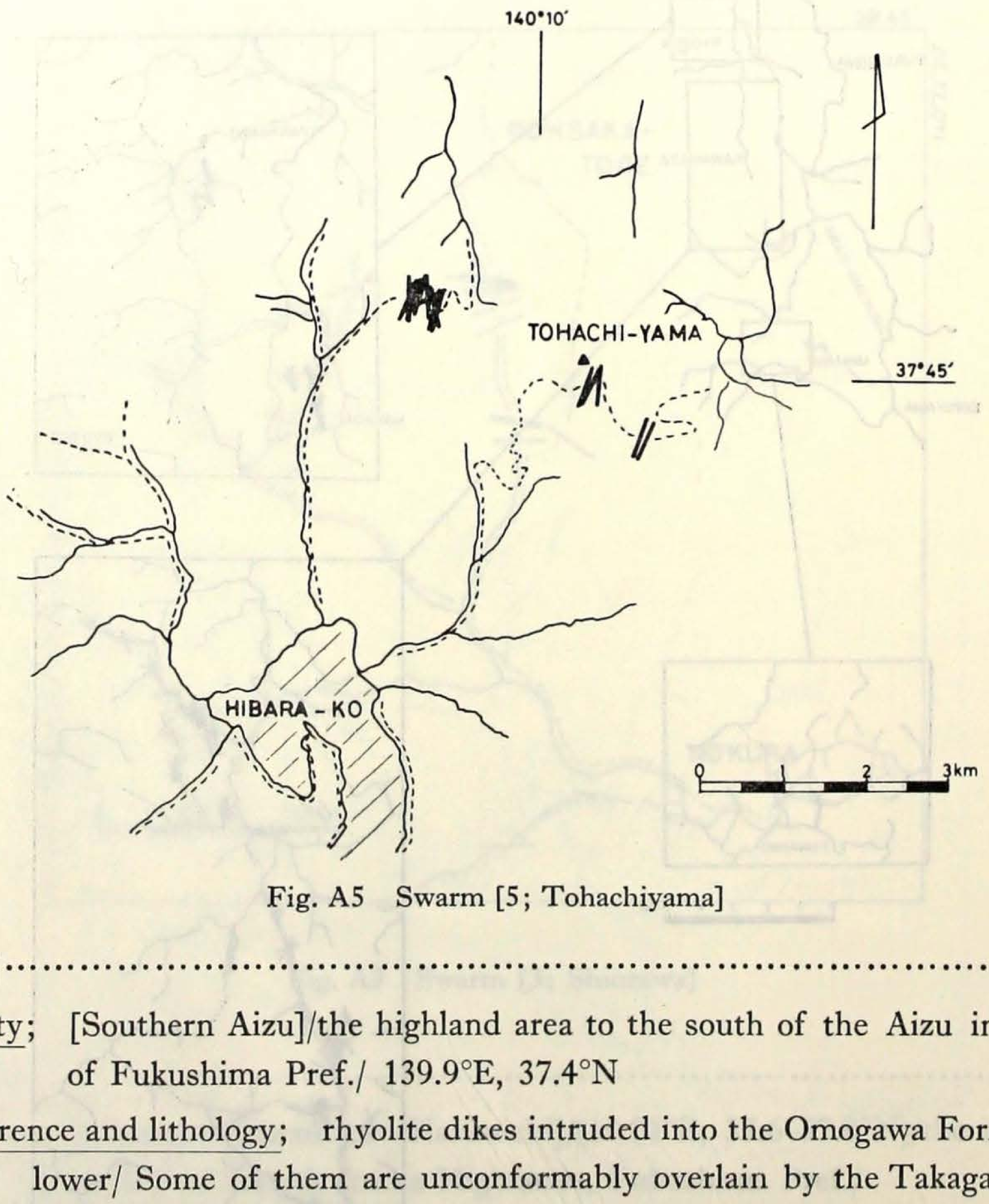

Fig. A5 Swarm [5; Tohachiyama]

Swarm [6] ··· (Fig. A6)

(1) locality; [Southern Aizu]/the highland area to the south of the Aizu inland basin of Fukushima Pref./ 139.9°E, 37.4°N

(2) occurrence and lithology; rhyolite dikes intruded into the Omogawa Formation and lower/ Some of them are unconformably overlain by the Takagawa Formation (SUZUKI *et al.*, 1972)

(3) horizon of the effusives; the Urushikubo Formation/

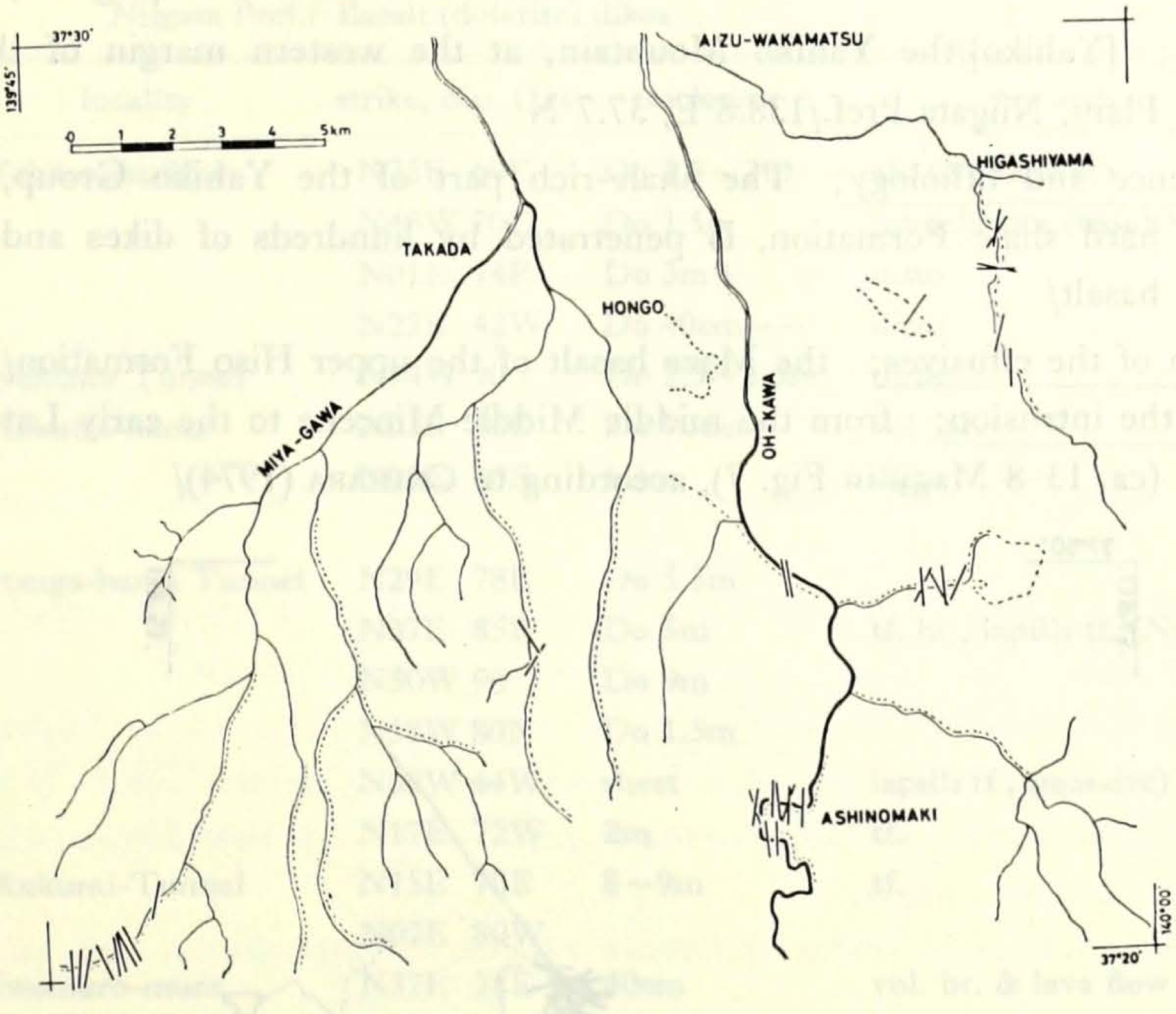

Fig. A6 Swarm [6; Southern Aizu]

(4) age of the intrusion; late Middle-Miocene to early Late-Miocene (ca. 12.5–7.5 Ma_{BP}), based on the above (2)/

(5) dike-wall data; N=41, A_m=N10°E=σH_{max}, F=0.46; sampled by K. HORI and A. TAKEUCHI/

Swarm [7]……………………………………………………………………………………

(1) locality; [Tadami-Yokota]/the mid-stream area of River Tadami-gawa at the central part of the Echigo Mountains; the westernmost of Fukushima Pref./139.4°E, 37.3°N/

(2) occurrence and lithology; basalt dikes intruded into the Ogawazawa Formation consisting mainly) of the rhyolite volcaniclastics/ (The swarm had been formed as the result of bimodal volcanism.)

(3) horizon of the effusives; the basalt lavas and agglomerate of the Oshio Formation (SHIMADA & HIRABAYASHI, 1972)/

(4) age of the intrusion; middle Middle-Miocene (ca. 14–13 Ma_{BP} in Fig. 7), based on the above (2), (3)/

(5) dike-wall data; N=57, A_m=N5°E=σH_{max}, F=0.40; sampled by M. TAKANO and partly by A. TAKEUCHI and K. HORI/

Swarm [8]··(Fig. A7, Table A1)

(1) locality; [Yahiko]/the Yahiko Mountain, at the western margin of the Niigata Plain, Niigata Pref./138.8°E, 37.7°N

(2) occurrence and lithology; The shale-rich part of the Yahiko Group, the Hiso hard shale Formation, is penetrated by hundreds of dikes and sheets of basalt/

(3) horizon of the effusives; the Maze basalt of the upper Hiso Formation/

(4) age of the intrusion; from the middle Middle-Miocene to the early Late-Miocene (ca. 13–8 $\mathrm{Ma_{BP}}$ in Fig. 7), according to CHIHARA (1974)/

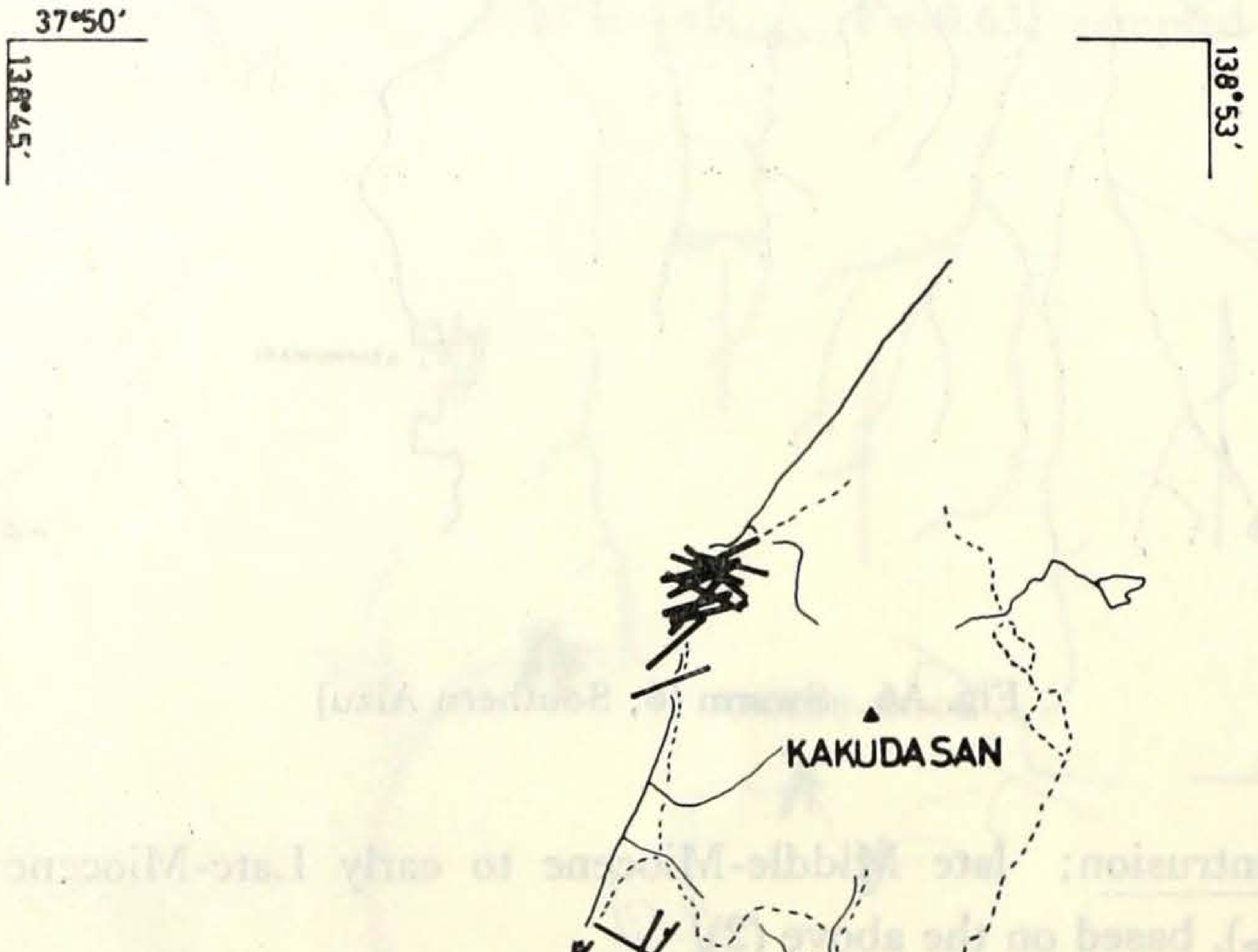

Fig. A7 Swarm [8, 14; Yahiko, Kakudasan]

Table A1 List of raw data on dike-wall (1): Swarm [8, Yahiko]/Yahiko Mountain, Niigata Pref./ Basalt (dolerite) dikes.

No.	locality	strike, dip. (°)	thickness	remarks
01	Yahiko sky-line	N25E 60E	Do 1.5 ~ 2m	sh. (N35E30W)
02		N40W 70E	Do 1.5m	pyroclastics (basalt)
03		N01E 74E	Do 3m+	ditto
04		N22E 42W	Do 40cm→ –	ditto
05	Nanaura Tunnel	N74W 90	Do 2.5 ~ 1.5m	ditto
06	Kakumi-hama	N05E 80E	Do 90cm	vol. br.
07		N05E 80E	1.3m	ditto
08				
09	Itsuga-hama Tunnel	N29E 78E	Do 5.5m	
10		N37E 85E	Do 5m	tf. br., lapilli tf. (N40E20W)
11		N50W 90	Do 9m	
12		N58W 80N	Do 1.5m	
13		N60W 44W	sheet	lapilli tf., (massive)
14		N17E 72W	2m	tf.
15	Kukumi-Tunnel	N15E 70E	8 ~ 9m	tf.
16		N02E 80W		
17	Iwamuro-mura	N37E 78E	40cm	vol. br. & lava flow (NS25W)
18		N22E 90	6m+	
101	Kakumi-hama	N40E	Data after SHIRAI *et al.* (1976)	
102		N50E	ditto	
103		N40E	ditto	
104		N70E	ditto	
105		N43W	ditto	
106		N43E	ditto	
107		N20E	ditto	
108		N55W	ditto	
109	Ishize-Pass	N12E	ditto	
110		N12E	ditto	
201	Yahiko sky-line	N05W 60W	Data after Uemura (unpublished)	
202		N70E 60N	ditto	
203		N80E 80N	ditto	
204		N65E 55N	ditto	
205		N80E 62N	ditto	
206		N50E 90	ditto	
207		N25W 62E	ditto	
208		N45W 55E	ditto	
209	Shimoyama-Tunnel	N12W 80W	1.3m	
210		N12W 80E	70cm	basalt/dacite
211		NS 90	80~60cm	

Total; 38

(5) dike-wall data; $N=38$, $A_m=N\text{-}S=\sigma H_{max}$, $F=0.29$; sampled by A. TAKEUCHI and by T. UEMURA/

"Yahiko Dome": CHIHARA (1974) has pointed out that these dikes would be related to the development of the so-called "Yahiko Dome" or "Yahiko Uplift", and offerred the excellent opinion as cited below.

> The basalt dikes seem to be radiated from the core of the dome constructed by the strata of the Yahiko Group. Regarding the variation of mineral assemblage of dike rocks, the combined process of the basalt intrusion and development of the dome structure can be explained as follows:
>
> a) The sills and sheets were formed in the muddy part in accordance with the magma ascent to accelerate the doming.
>
> b) After the muddy part had been 'saturated' with the magmatic liquid, the radial dike swarm was formed and submarine fissure eruptions occurred.
>
> c) When the folding occurred during the Pliocene and later in the Niigata Oil field, the Yahiko Dome which was already penetrated by numerous intrusives behaved as a rigid block, so that the asymmetrical anticline and the west-dipping thrusts were formed as seen at present.

The smallest F-value among the study swarms is reasonable in view of the above explanation.

Swarm [9]··(Fig. A8, Table A2)

(1) locality; [Ogi Peninsula]/the southernmost part of Sadogashima Island, Niigata Prefecture/138.2°E, 37.8°N/

(2) occurrence and lithology; basalt dikes and sheets embedded in the volcaniclastics (partially hyaloclastites) from the upper part of the Tsurushi Formation to the overlying Nakayama Formation/

The occurrence and rock-facies resemble those of the swarm [8]. Moreover, because the outcrops are located on the wave-cut bench, the sampling condition is so well that several feeder dikes of the sheets and effusives can be observed.

(3) horizon of the effusives; the Tsurushi and Nakayama Formations/

(4) age of the intrusion; from the Middle-Miocene to the early Late-Miocene (ca. 14–7.5 Ma_{BP} in Fig. 7), inferred from the above (2), (3)/

(5) dike-wall data; $N=55$, $A_m=N5°W=\sigma H_{max}$, $F=0.40$; sampled by A. TAKEUCHI/

Swarm [10]··

(1) locality; [Tanigawadake]/interior of the Shin-Shimizu tunnel on the Joetsu line of the Japan National Railway; at the boundary between the Echigo Mountains and Central Uplifting Zone in the northern Fossa Magna region/138.9°E, 36.8°N/

(2) occurrence and lithology; rhyolite dikes intruded in the granitic rocks of the Miocene

Table A.2 List of raw data on dike-wall (2): Swarm [9, Ogi]/Ogi Peninsula of Sadogashima Island, Niigata Pref./ Basalt dikes.

No.	locality	strike, dip. (°)	thickness	remarks
001	Kowashimizu	N51E 75S	6m	
002		N23E 90	2.5m	pillow lava
003		N33E 80W	3.0m	
004		N27E 53W	20~40cm	
005		N43E 90	2m	N83E73—pillow breccia
006		N35E 80W	20cm	
007		N35E 80W	2.0m	
008		N02E 90N	2.0m	
009		N13W 90	8m	
010		N07W 90	10m	
011		N07W 90	1.0m	
012		N01W 80W	2.0m	
013		N05E 90	8m × 20m	eliptical termination
014		N10E 90	2m × 100m+	with hydrothermal veins parallel to dike
015	Inugamidaira	N34W 80W	2~3m × 70m+	
016		N30W 90	1m	
017		N30W 90	1m	left lat. flt. N46E 90
018		N60W 68E	1m	
019		N80W 60E	1.8m	
020		N67W 55E	10m→ –	
021		N60W 67E	80cm	
022		N68W 90	80~10cm	
023		N13W 90	3m	
024		N03W 78E	1m	
025		N20W 90	0.6m	
026		N62W 75S	40cm	
027		N20E 90	1.5m	
028		N22E 70W	5m	
029		N30W 90	3m	right lat. flt. N50E 60S
030		N40W 69E	4m→ –	right lat. flt. {N25E 75E N28E 60S
031		N09W 70W	4m	
032		N52W 55N	10m	N57E25S bed.
033		N09W 58W	3m	
034		N10W 62W	4.5~1.8m	tf. br. ~ tf.
035		N10W 55W	1m	
036		N07W 66W	1m	
037		N20E 83E	1.2m	
038		N27E 85W	2m	
039	Shirosaki	N17E 79W	3m	
040		N87W 49W	1m	
041		N09W 80W	2.5m	
042		N01N 73W	1.8m	
043		N27W 90	2.5m	
044		N20W 80E	80cm	
045		N37W 60E	1.2m	
046		N24W 83E	1.5m→ –	
047		N13W 60W	80cm	
048		N12W 90	10cm	
049		N17E 90	80cm	

Total; 49

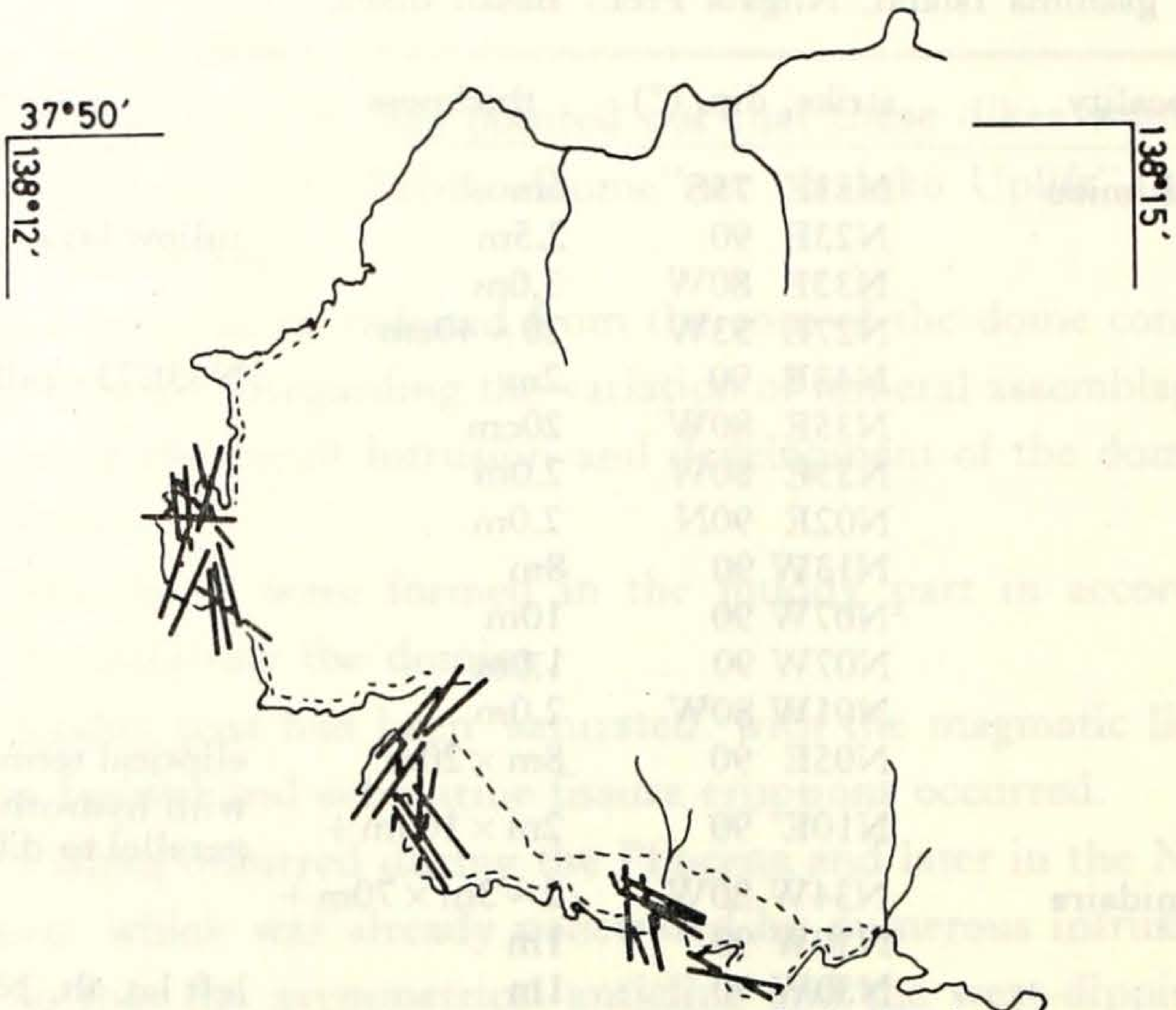

Fig. A8 Swarm [9, Ogi (Sadogashima)]

and earlier/ (A few dikes have the xenoliths of brecciated shales possibly of the Sarugakyo Group of the late Early- to Middle-Miocene age.)

(3) horizon of the effusives; probably, the Welded Tuff Formation of dacite, (Joetsu Nanbu Green Tuff Research Group, 1976)/

* K-Ar date was given to the same horizon at the Jizodake as 10 Ma$_{BP}$ in Kawano & Ueda (1964).

(4) age of the intrusion; the early Late-Miocene (ca. 10–7.5 Ma$_{BP}$ in Fig. 7), based on the above (2), (3)/

(5) dike-wall data; $N=54$, A_m=N25°E=σH_{max}, $F=0.80$; quoted from Kubo & Kizaki (1966)/

* The highest value of F can be attributed partly to the sampling condition, that is, the interior of linear tunnel.

Swarm [11]··(Fig. A9, Table A3)

(1) locality; [Tochiku]/the Hokushin district, the central part of the Chikuma Mountains at the northern part of Nagano Pref./138.1°E, 36.4°N/

(2) occurrence and lithology; mainly porphyrite and andesite dikes embedded in both

the shale-rich alternation of the Aoki Formation and the massive sandstone of the Ogawa Formation/

(3) horizon of the effusive facies; andesitic to dacitic tuffs of the lower Ogawa Formation/

(4) age of the intrusive acitvity; the Late-Miocene (ca. 10–6 Ma_{BP} in Fig. 7), estimated by TAKEUCHI (1977)/

(5) dike-wall data; $N=51$, $A_m=N20°W=\sigma H_{max}$, $F=0.39$, ($A'_m=N40°W$, $F'=0.31$); sampled by TAKEUCHI (1977)/

These dikes have been regarded as a part of volcano-plutonic complex related to the Miocene holocrystaline rocks, the radiometric dates of which were given as 7.3, 8.5 and

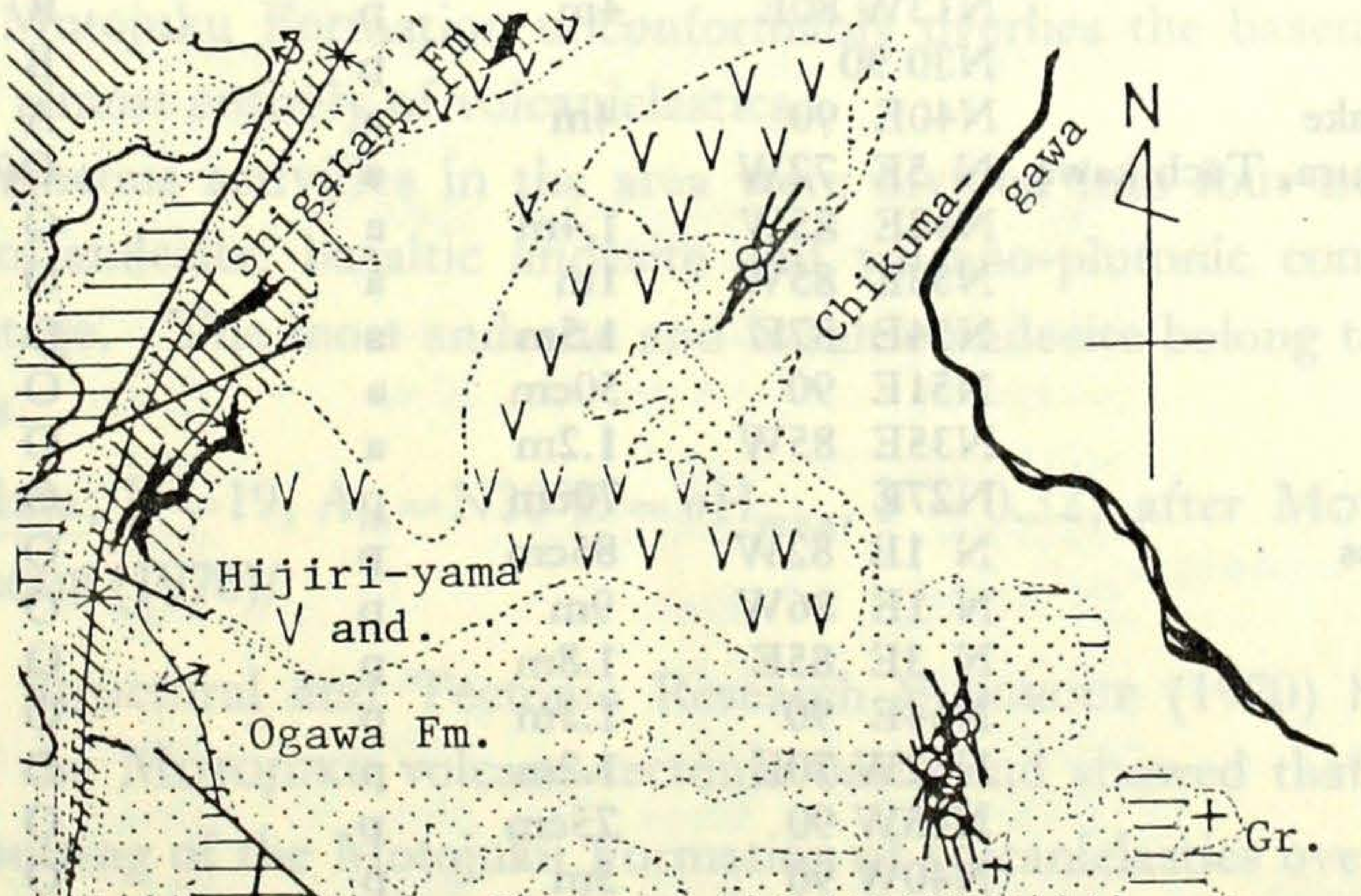

Fig. A9 Swarm [11, Tochiku]

Table A3 List of raw data on dike-wall (3): Swarm [11, Tochiku]/Tochiku area, Hokushin district of Nagano Pref./ after TAKEUCHI (1977).

No.	locality	strike, dip. (°)	thickness	dike-rock	host-rock
1	Shiga-mura, Aiyoshi.	N31W 80W	2.0m	a(andesite)	A(Aoki Fm.)
2	Aoki-Pass	N52W 77E	2m	a	A
3	Aoki-mura, Kohbo	N45W 80E		a	A
4	Shunara	N42W 87W	1.3m	a	A
5		N47W 90	3cm	a	A
6	Kamafusa	N25W 38E	30cm	a	A
7		N21W 90	4m	a	A
8		N34W 83W	55m	a	A
9	Ichinosawa	N40W 90		a	A
10		N10W 85W	1.5m	a	A
11		N28W 68W	2m	a	A, base
12	Daimyozin-dake	N20W 90	30m	p(porphyrite)	B(Bessho Fm.)
13		N30W 85W	4m	p	B
14	Mt. Fuji	N 2W 70E	8.5m	p	B
15		N13W 80E	4m	p	B
16		N30 90		p	B
17	Ogami-dake	N40E 90	4m	a	A
18	Honjo-mura, Tachikawa	N 5E 72W		a	O(Ogawa Fm.)
19		N48E 85W	1.4m	a	O
20		N53E 85W	1m	a	O
21		N54E 87E	1.5m	a	O
22		N51E 90	50cm	a	O
23		N35E 85W	1.2m	a	O
24		N27E	70cm	p	O
25	Utsu-Pass	N 1E 82W	85cm	p	O
26		N 1E 86W	9m	p	O
27		N 3E 85E	1.8m	p	O
28		N64E 90	1.3m	p	O
29		N52W 70E	1.2m	p	O
30		N45W 90	75cm	p	O
31		N40W 90	5m	p	O
32		N77W 85S	90cm	p	O
33		N45W 90	80cm	p	O
34		N39E 85S	80cm	p	O
35		N26W 82W	5m	p	O
36		N56W 90	75cm	p	O
37		N70W 48S	3.5m	p	O
38	Kamuriki-yama	N17W 86W	14cm	a	O
39		N15W 78E	15cm	d(dacite)	O
40		N43W 82W	35cm	d	O
41		N15W 85W	7.0cm	d	O
42		N 9E 80W	1.5cm	d	O
43		N21W 62W	3.5cm	d	O
44		N16W 80W		a	O
45		N13E 75S	40cm	a	O
46		N12W 73W		a	O
47		N28E 90	3m	a	O
48		N30W 76W	6m	a	O
49		N12W 90		a	O
50	Inari-yama	N 5E 64E	80cm	a	O
51		N16W 82W	20cm	a	O

Total; 51 after Takeuchi (1977)

8.6 Ma_{BP} by KAWANO & UEDA (1966) and YAMAZAKI *et al.* (1976),

Two largest peaks trending in the directions of N20°W and N40°W are shown in the rose-diagram. Their F-values are calculated as 0.39 and 0.31, respectively. Because of the largest F-value, the former is adopted here as the maximum peak, so that the σH_{max}-direction is inferred as N20°W. Moreover, the low concentricity implies that the state of stress field at the time of intrusion was so unstable that the swarm [11] are possibly composed of plural dike systems.

Swarm [12]···

(1) locality; [Motojuku]/the northeastern margin of the Kanto Mountains composed of the Chichibu Mesozoic and Paleozoic System, the Otsuki-Atokura Cretaceous system and the Lower- to Middle-Miocene series/138.7°E, 36.2°N/

(2) occurrence and lithology;

The Motojuku Formation unconformably overlies the basement rocks, and is composed almost entirely of volcaniclastics.

The igneous activities in the area were divided into four major stages. The intrusion of andesite, basaltic andesite and volcano-plutonic complex occurred in the final stage. The most andesite and basaltic andesite belong to the calc-alkaline rock series.

(3) dike-wall data; $N=19$, $A_m=N30°E=\sigma H_{max}$, $F=0.32$; after MOTOJUKU RESEARCH GROUP (1970)/

MOTOJUKU Structural and Tectonic Research SUBGROUP (1970) has discussed the development of the MOTOJUKU volcano-tectonic basin and showed that:

a) The abutting of the Motojuku Formation of volcaniclastics over the surrounding basement rocks, indicates that the effusive activity occurred after the fault-bounded angular basin had primarily been formed.

b) The secondary, circular depression occurred at the sedimentary period of the middle Motojuku Fm. The domain of the secondary depression is intruded by composite bodies of volcanic and plutonic rocks. Basaltic andesite as a cone-sheet intruded along the margin. These are immediate results of volcano-tectonism.

c) On the outer side of the above basaltic andesite, sheets and dikes of andesite developed radially. Out of the basin, there are also distributed several dikes of dacite and quartz porphyry as radial dikes.

Swarm [13]···

(1) locality; [Atsumi]/the boundary area between the Niigata Plain and the Shonai (Yamagata) Plain, i.e. the Asahi Mountains/139.6°E, 38.6°N/

(2) occurrence and lithology; porphyrite (andesite) intruding into the pre-Tertiary acid rocks, the Nishitagawa Granodiorite and the Tagawa Acid Rocks/

(3) horizon of the effusives; mainly, andesite lavas and tuff-breccias of the Atsumidake

Table A4 List of raw data on dike-wall (4): Swarm [14; Kakudasan]/North of Swarm [8, Yahiko], Niigata Pref.

No.	locality	strike, dip. (°)	thickness	dike rock	host rock	remarks
1	Tatamiura Tunnel	N70E 80 ~ 83S	9m	and. lava	vol. br.	
2		N72E 82S ~83E 72S ~73E 85S	35cm	ditto	tuff. br. vol. br.	
3		N47E 78W	8m	ditto	ditto	
4		N64W83S	1.2m	ditto	ditto	irregular
5		N82W90	20cm	ditto	ditto	ditto
6		N55 ~ 79E 85 ~ 90S	90cm	ditto		
7		N80W90	2m	ditto	ditto	irregular
8		N51 ~ 65E90	3m +	ditto	ditto	ditto
9		N25W90	2m	lava ditto ↓ br.		↓ derive
10		N65E 90	6m	lava ditto ↓ br.		
11		N66E 82N	2m	lava		
12		N78E(90)	1 ~ 2m	ditto	tf. br.	irregular
13		N81W60S	1m		ditto	
14		N66W90	60 ± 10cm		ditto	
15		N70W82N	50cm		ditto	
16		N85W80S	1.3m	and. lava		torn dike
17	Tọdai-shita	N65E 75W	90cm	ditto	ditto	
18		N79E 88W	80cm	ditto	ditto	
19	Kakuda-misaki	N38W85NE	20cm	ditto	ditto	
20		N30E 56W	65cm	ditto	ditto	↓ derive
21		N37W90	30cm	ditto	ditto	
22		N24W70SW	30cm	ditto	ditto	
23		N74E 90 ~68E 90	40cm	ditto	ditto	
24		N63E 84S ~60E 75S	1.8m 1.1m	ditto	ditto	principal dike
25	Kakuda Tunnel	N74W75N	1.3m	ditto	tf.	
26		N50W90	2 ~ 1m	ditto	ditto	irregular
27		N85W80N	4m	ditto	tf. br.	
28		N77E 71N ~81E 63N	70cm	ditto	coarse tf.	
29		ditto	1.2m	ditto	ditto	
30		ditto	2m +	ditto	ditto	

Total; 30

volcanics Formation/

(4) age of the intrusion; the middle Early-Miocene (ca. 19–18 $\mathrm{Ma_{BP}}$ in Fig. 7), referring to the above (3)/

(5) dike-wall data; $N=32, A_m=N30°E=\sigma H_{max}, F=0.66$; sampled by K. Mizuguchi/

According to Mizuguchi (1978ms), two dominant directions of high-angle joints in the granitic rocks were formed prior to dike-formation. One is NNE-SSW and another is normal to this, WNW-ESE.

The unimodal pattern of the rose-diagram (Fig. 9a) implies that the control of the stress prevented the joints of WNW-ESE trend from splitting at the time of intrusion.

Swarm [14]··(Fig. A7, Table A4)

(1) locality; [Kakuda-san]/the Kakuda Mountain, north of the Yahiko Mountain at the western margin of the Niigata Plain/138.8°E, 37.9°N/

(2) occurrence and lithology; Dikes of andesite are developed in the west (sea) side of the Kakuda Mountain/

(3) horizon of the effusives; the Kakuda Formation, which is composed of andesite

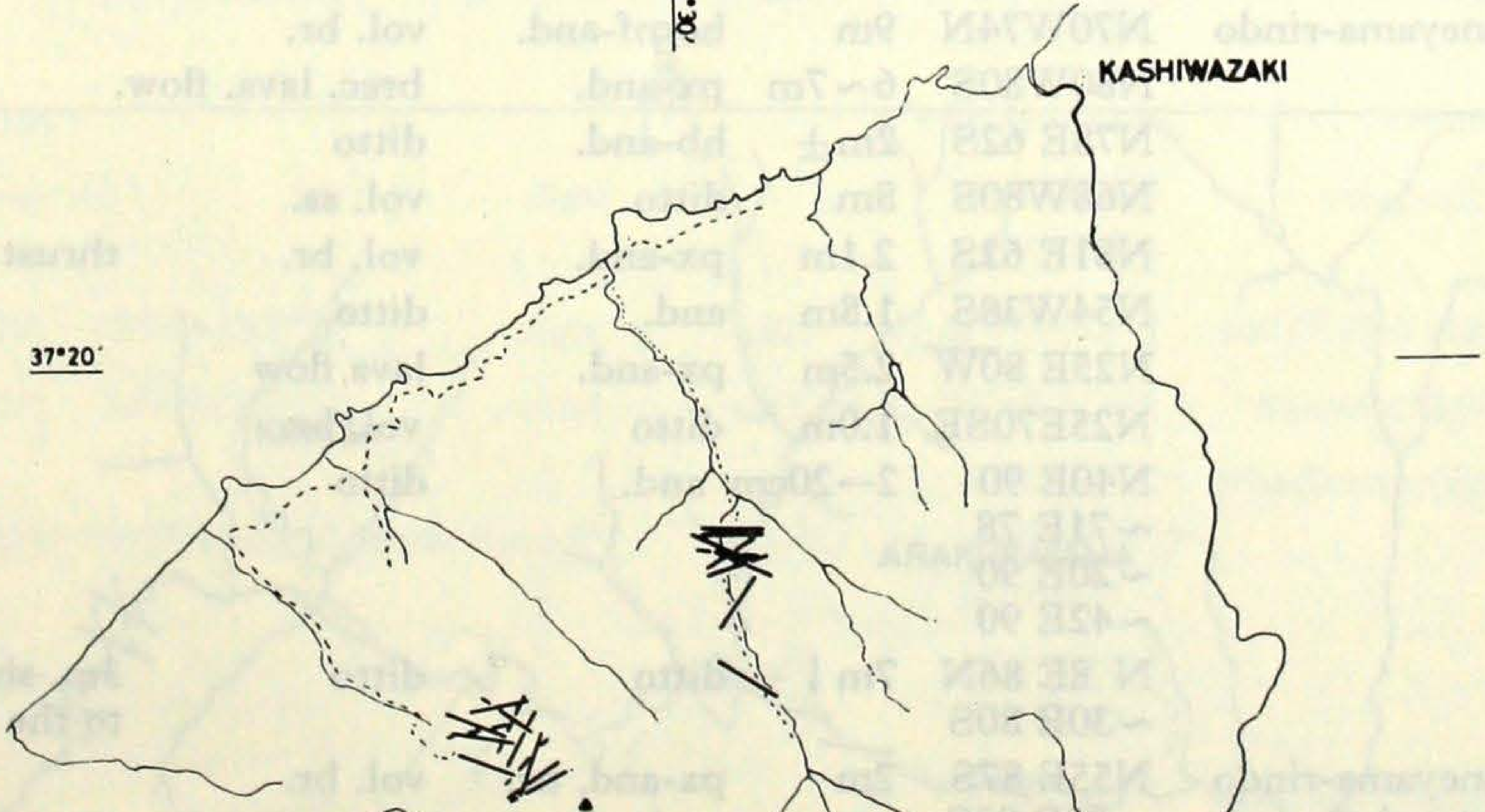

Fig. A10 Swarm [15, Yoneyama]

Table A5 List of raw data on dike-wall (5): Swarm [15, Yoneyama]/Southwest of Kashiwazaki City, Niigata Pref.

No.	locality	strike, dip.(°)	thickness	dike rock	host rock	remarks
1	Tan'ne Quarry	N58E 90	1.3m	and. brec.	lava flow	
2		N84W75S	13m	ditto	ditto	
3		N66W80S	5m	(boulder)	ditto, partially brecciated	
4		N78E 85S	5m	br. (noulder)	lava flow	
5		N75E 83S	9m	tf. br.	ditto	
6		N72W80S	4m	br.	ditto	
7	Yoneyama Dam	N28E 87S ~30E 73S	1.0m	basalt	ditto	
8		N39E 86S ~49E 79N	2.0m	basalt	basalt. lava	
9		N34E 87S ~33E 85S	90m	margin=tf.bre. dolerite	ditto	
10		N30E 85S	50cm+	ditto	ditto	
11		E36E 86W	1.5m	ditto	ditto	
12	Lake Yoneyama	N66W55N ~50W60N	3.0m	andesite	vol (tf) br.	
13	Shinsarutobibashi	N65W90	3.5m+	ditto	vol. br.	
14		E-W90	10m+	and. br	pumice tf. (ms.ss.)	
15		N87W87S	8cm	and.	ditto	
16		N85W80N	4m±	and. vesicule	vol.ss.	
17		N89W85S	10m±	and.	m~f. ss.	
18	Yoneyama-rindo	N70W74N	9m	hornf-and.	vol. br.	
19		N80W80S	6~7m	px-and.	brec. lava. flow.	
20		N78E 62S	2m±	hb-and.	ditto	
21		N68W80S	8m	ditto	vol. ss.	
22		N81E 62S	2.1m	px-and.	vol. br.	thrust (18E38E)
23		N54W38S	1.8m	and.	ditto	
24		N25E 80W	2.5m	px-and.	lava flow	
25		N25E70SE	1.0m	ditto	vol. br.	
26		N40E 90 ~71E 78 ~20E 90 ~42E 90	2→20cm	and.	ditto	
27		N 8E 86N ~30E 80S	7m ↓ —	ditto	ditto	3m. sheet derived to the west.
28	Yoneyama-rindo (last point)	N55E 87S ~55E 85S	2m	px-and. br.	vol. br.	
29		N58E74NW ~63E 82SE	70cm	ditto	ditto	vertical striation
30	Echigo Noda	N75W90	10m+	hb-and.	lava flow	
31	Sarukeyama	N85W90 ~73E 80S	50cm	ditto	lava flow put in ss. N84E40N	
32	Kuroiwa Quarry	N82W60~80S ~80E 90 ~51W80NE ~69W80N	20m± ↑ — ↓ 50m	basalt	ms & ss f. alt. N64E 30N N84E 24N	
33		N82W90	50m+	hb-and.	ss & ms alt.	

Total; 33

lavas (partially with pillow structures) and tuff breccias/

The volcaniclastic rocks are interfingered with mudstone and sandstone alternation of the Takenomachi Formation.

(4) age of the intrusion; the Pliocene (ca. 5.5–2.5 $\mathrm{Ma_{BP}}$ in Fig. 7), referring to the above (3)/

(5) dike-wall data; $N=30$, $A_m=\mathrm{N80°E}=\sigma H_{\max}$, $F=0.40$; sampled by A. TAKEUCHI/

Swarm [15]···(Fig. A10, Table A5)

(1) locality; [Yoneyama]/the southwest margin of the Niigata Plain, near Kashiwazaki City of Niigata Pref./138.5°E, 37.3°N/

(2) occurrence and lithology; Andesite dikes embedded in the Pliocene volcaniclastic rocks of the Yoneyama Formation./

According to CHIHARA (1974), the volcanic products composed of olivine-, pyroxene- and hornblende-andesites have repeatedly accumulated. The extrusives are partially covered unconformably by the Asojima Formation.

(3) age of the intrusion; the early Pliocene (ca. 5–3.5 $\mathrm{Ma_{BP}}$ in Fig. 7), inferred from the above (2)/

(4) dike-wall data; $N=33$, $A_m=\mathrm{N75°W}=\sigma H_{\max}$, $F=0.42$; sampled by A. TAKEUCHI/

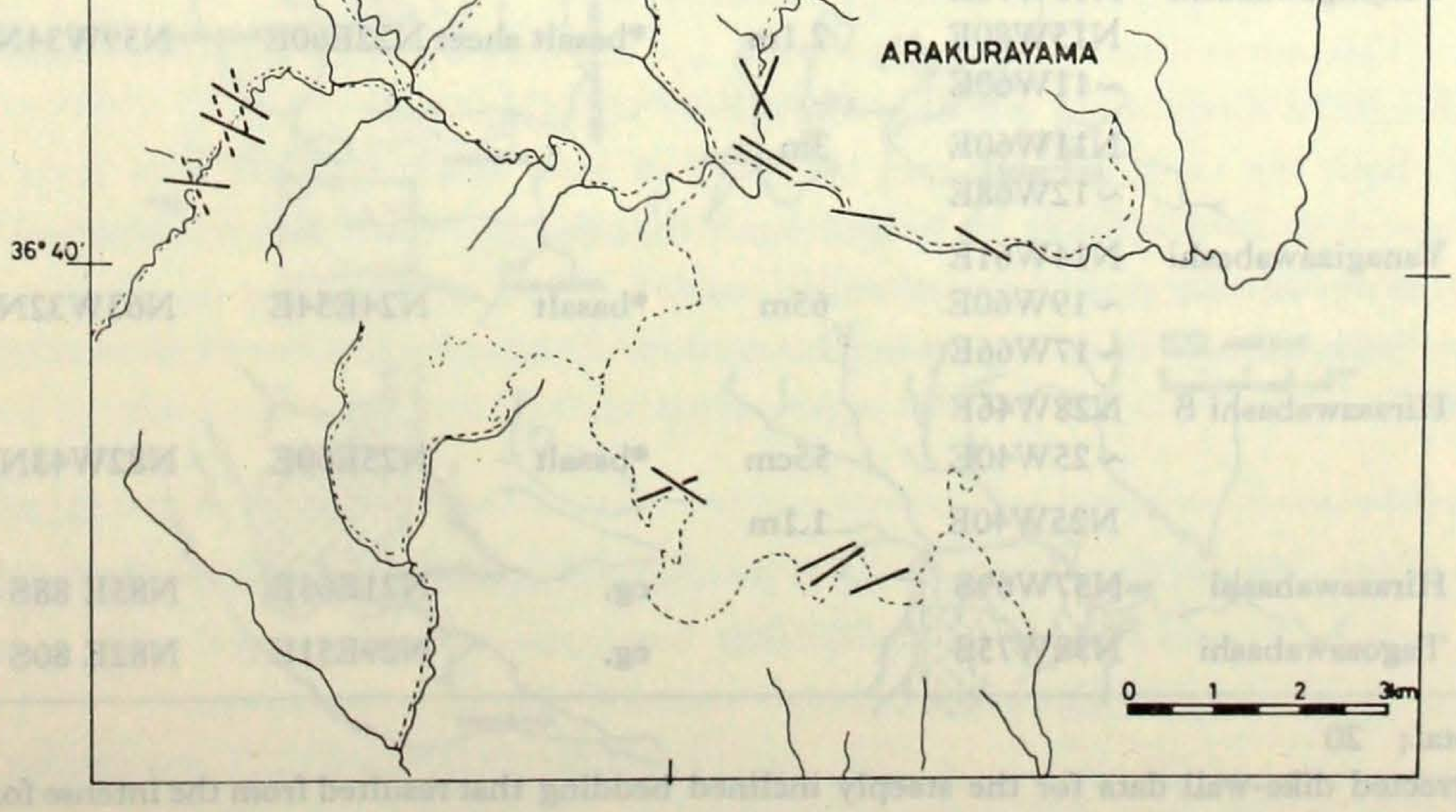

Fig. A11 Swarm [16, Shigarami]

Table A6 List of raw data on dike-wall (6): Swarm [16, Shigarami]/Around Mt. Arakurayama, Hokushin district of Nagano Pref.

No.	locality	strike, dip.(°)	thickness	dike rock	host rock	remarks
1	Momio	N 6E 80W ~66E 82N ~88E	5m+	and.	ms. flat 20°−	
	Momio Ubakubo	N85W		pumice.		
2	Kodeya	N60E 80W ~66E 80W	7m	and.	flat	N50E joint
3		N53E 70S	8m+	and.	flat	
4	Ajimame	N57W80S~90	10m±	and.	ms. flat	
5		N35~71~80E 50~60N	curved contact 10m±		ms. flat	gabbroic inclus. N76W63N
6	Uoyama	N60W90	40m 360m long	basalt HA(tholeiite)		
7		ditto				
8	Okinasa	N37W90 ~20W90	2m	and.		
9		N20E 60W	4m	and.	ms.	
10	Togeshita	N85E 53N ~87W75N	5m	and.	ss. ms.	
	Kuroiwa	sill (~sheet)				early Pleist.
11	Mujinagoro	N42W90 ~75W90		and.	ms.	neck
12	Hodai NW750m	N11W70W	6m	and.	N70E54NW	N25W63W(*)
13	Kakehudazawa	N11W60W	20m	and.	N53E52NW	N50W53W(*)
14	Tenjingawabashi	N13W70E N15W80E ~11W60E	2.1m	*basalt sheet	N22E60E	N59W34N(*)
15		N11W60E ~12W68E	3m			
16	Yanagizawabashi	N14W61E ~19W60E ~17W66E	65m	*basalt	N24E54E	N63W32N(*)
17	Hirasawabashi S	N28W46E ~25W40E	55cm	*basalt	N25E60E	N82W43N(*)
18		N25W40E	1.1m			
19	Hirasawabashi	N57W69S		cg.	N21E63E	N85E 88S (*)
20	Tagosawabashi	N38W75S		cg.	N29E51E	N82E 80S (*)

Total; 20

* corrected dike-wall data for the steeply inclined bedding that resulted from the intense folding after the intrusion.

Swarm [16]··(Fig. A11, Table A6)

(1) locality; [Shigarami]/around Mt. Arakurayama at the northern part of the Chikuma Mountains, Nagano Prefecture/138.0°E, 36.2°N/

(2) occurrence and lithology; Dikes distributed in the province consist mostly of calc-alkaline andesite and high-alumina tholeiite (TAKESHITA, 1975). They intruded into the volcaniclastics and lavas called as the Togakushi (or Arakurayama) Volcanics, and into the clastic sediments of the Neogene.

(3) horizon of the effusives; The Togakushi Volcanics are the extrusive rocks related to the dike swarm, and they are intercalated with the mudstones and sandstones of the Shigarami Formation.

(4) age of the intrusion; the early Pliocene (ca. 5.5–3.5 Ma_{BP} in Fig. 7), referring to the above (2), (3)/

The Kiyotaki Andesite Lava, the horizon of which is equivalent to that of the lower Togakushi Volcanics, are dated by K-Ar method as 5.4 Ma_{BP} (MORIMOTO *et al.*, 1966).

(5) dike-wall data; $N=20$, $A_m=N60°W=\sigma H_{max}$, $F=0.35$; sampled by A. TAKEUCHI/

Swarm [17]··(Fig. A12])

(1) locality; [Koriyama]/the upland of the southern margin of the Ou Mountain Range,

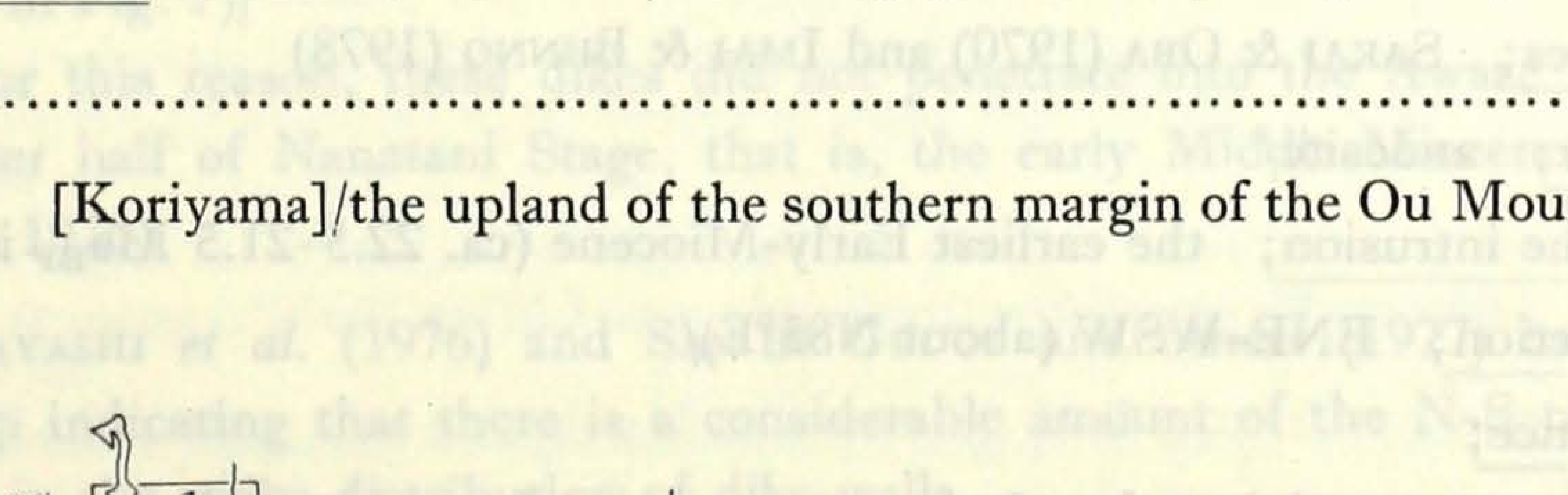

Fig. A12 Swarm [17, Koriyama]

between the Lake Inawashiro and the Koriyama basin at the west side of the Abukuma River Lowlands, Fukushima Pref./140.2°E, 37.0°N/

(2) reference; HORI, K. (1978ms)

(3) lithology; andesite dikes and sheets embedded in the Horiguchi, Okubo and Itaya Formations/

(4) horizon of the effusives; The fresh 'Later Andesite', which is clearly distinguished from the propylites in the province, unconformably covers the Horiguchi formation and lower and is unconformably underlain by the Shirakawa Formation.

(5) age of the intrusion; from the late Late-Miocene to the early Pliocene (ca. 7–4 Ma_{BP} in Fig. 7), based on the above (4)/

(6) dike-wall data; $N=10$, $A_m=N60°W=\sigma H_{max}$, $F=0.40$; sampled by K. HORI/

Swarm [a]……………………………………………………………………………………

(1) locality; [Aikawa]/the southwestern part of Osado area of the Sadogashima Island, Niigata Prefecture; north of the Swarm [9, Ogi]/138.2°E, 38.1°N/

(2) references; SAKAI & OBA (1970) and IMAI & BUNNO (1978)

(3) lithology; andesite/

(4) age of the intrusion; the earliest Early-Miocene (ca. 22.5–21.5 Ma_{BP} in Fig. 7)/

(5) A_m-direction; ENE–WSW (about N85°E)/

(6) Occurrence;

a) An intense activity of andesite accompanied by epithermal vein mineralization occurred during the end of the sedimentary period of Aikawa Formation. All the champion veins run nearly E-W.

b) Most vein fissures are perhaps tension cracks.

c) This mineralization was preceeded by the formation of the dike-swarm, the dominant direction of which is in an E-W trend.

d) Both the Ogiri-Torigoe and Heiko Fault vein fissures would have been right-lateral strike-slip faults as judged from the distribution of the surrounding rocks and the striations on the vein walls.

e) Such tectonic features can be observed in the lowest Miocene strata of the whole Sado area.

Swarm [b]……………………………………………………………………………………

(1) locality; [Budo]/the Japan Sea side of Asahi Mountains of the northernmost of Niigata Pref./139.5°E, 38.9°N/

(2) reference; TAKAHAMA (1976)

(3) occurrence and lithology; rhyolite dikes (altered) in the Sumikawa Formation composed of lavas, tuff breccias and welded tuffs, mainly of two-pyroxene an-

desite/

The volcanic activity was accompanied by the faulting of WNW-ESE trend, resulting in several graben-like basins where the Budo, Sumikawa and Kitaoguni Formations accumulated.

(4) age of the intrusion; the earliest Early-Miocene and/or earlier (older than about 22 Ma_{BP} in Fig. 7)/

(5) dike-wall data; $A_m \doteqdot N85°W \doteqdot \sigma H_{max}$

Swarm [c]……………………………………………………………………………………

(1) locality; [Tsugawa]/the central part of the Echigo Mountains, west of the Aizu Basin; the eastern margin of Niigata Pref./139.5°E, 37.7°N/

(2) references; ABE & SHIMAZU (1976), WAKABAYASHI *et al.* (1976) and SAN'IN Green-Tuff Research GROUP and others (1977)/

(3) lithology; rhyolite so-called as the plagio-liparite/

(4) age of the intrusion; Tsugawa Stage, i.e. the late Early-Miocene (ca. 17–14.5 Ma_{BP} in Fig. 7)/

For this reason, these dikes did not penetrate into the Awaze Formation of the later half of Nanatani Stage, that is, the early Middle-Miocene (ABE & SHIMAZU, 1976).

WAKABAYASHI *et al.* (1976) and SAN'IN GROUP and others (1977) has shown the geologic map indicating that there is a considerable amount of the N-S to NNW-SSE components in the strike-distribution of dike-walls.

The NW-SE or E-W direction of dike intrusion are remarkable, and parallel to the trend of the eastern margin of the Tsugawa sedimentary basin.

Swarm [c′]……………………………………………………………………………………

(1) locality; [Takizawagawa]/to the south of the Swarm [c], the western margin of Fukushima Pref./

SHIMADA & HIRABAYASHI (1972) and HAYAKAWA *et al.* (1974) stated that the rhyolite dikes of NW-SE trend, called as the Yokota Rhyolite, was cut by another rhyolite dikes formed later in the direction of an N-S trend. The age of the Yokota Rhyolite was considered by them to be the late Takizawagawa stage, that is, the early Middle-Miocene.

Swarm [d]……………………………………………………………………………………

(1) locality; [Kokuzo]/the southern part of Chikuma Mountains, the central part of Nagano Pref., constructed mainly by the lower Green Tuff beds which are intruded by the Miocene Granitic rocks/138.2°E, 36.3°N/

(2) reference; UTASHIRO *et al.* (1958)

(3) lithology; basalt dikes developed in the Green Tuff beds including hyaloclastites/

(4) horizon of the effusive facies; the Kokuzo Basalt emplaced between the uppermost of the Uchimura Formation and the lowermost of the Bessho Formation/

(5) age of the intrusion; the late Early-Miocene (ca. 17.5–16 Ma_{BP} in Fig. 7), judging from the above (4)/

(6) dike-wall data; $N \geq 300$, $A_m \doteqdot$ N-S $\doteqdot \sigma H_{max}$/The spatial distribution shows a sub-parallel to sub-radial pattern.

Swarm [e]··

(1) locality; [Otanigawa]/around the type locality of the Nanatani Formation, south-east of Kamo City of Niigata Pref./139.1°E, 37.4°N/

(2) reference; SHIMAZU *et al.* (1976)

(3) occurrence and lithology; basalt dikes and sheets as a result of bimodal volcanism, intruding into the tuffs and tuff breccias of the Otanigawa Formation, i.e. the lower Nanatani shale Formation/
(multiple dikes of dolerite and rhyolite)

(4) age of the intrusion; the early Middle-Miocene (ca. 14.5–11.5 Ma_{BP} in Fig. 7)/

(5) dike-wall data; $N=7$, A_m of an N-S trend/

Swarm [f]··

(1) locality; [Akima, Kirizumi]/the upstream area of River Kirizumigawa at the western part of Gumma Pref.; the east of Mt. Asama-yama/138.7°E, 36.4°N/

(2) reference; AKIMA Collaborative Research GROUP (1976)

(3) occurrence and lithology; andesite dikes penetrating into the Mizuya tuff breccia, the Yunosawa lava and tuff breccia and the Dozen lava and tuff breccia Members of the lower part of the Kirizumi Formation/

(4) age of the intrusion; the Late-Miocene (ca. 9–6 Ma_{BP} in Fig. 7)/

(5) A_m-direction; The dikes in this area show two dominant directions of N20–10°E and N80–70°E, and the latter trend coincides with that of a zone of alteration.

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