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Wrench Fault Tectonics of the Median Tectonic Line and Deformation of the Cretaceous Izumi Group in West Kinki, Southwest Japan

Takao MIYATA*

(with 2 Tables and 32 Figures)

Abstract

The geologic structure of the Cretaceous Izumi Group in west Kinki, Southwest Japan was investigated in order to clarify the movement picture of the Median Tectonic Line (MTL) during post-Cretaceous ~ pre-Middle Eocene time (ca. 65 ~ 50 Ma).

It is concluded that the Paleogene movement along the MTL in west Kinki has more predominant left-lateral strike-slip component than the dip-slip one on the basis of the analysis of strain picture (left-hand en echelon upright folds, right-hand en echelon faults of Riedel-shear type, mode of boudinage structure, and wide shear zone). The amount of the left-lateral wrenching is estimated at about 15 km.

Judging from the geologic information obtained also in east Chubu and Kyushu, the pre-Middle Miocene MTL of Southwest Japan can be synthetically explained by a predominant left-lateral wrenching. This displacement sense on the MTL is opposite to the late Quaternary right-lateral strike slip. The amount of displacement of the left-slip is large as compared with that of the late Quaternary right-slip.

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* Institute of Geosciences, College of Liberal Arts, Kobe University, Kobe 657, Japan.

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Introduction

The Median Tectonic Line (MTL) is the first class fault dividing Southwest Japan into the Inner zone and the Outer zone. It extends for about 1,000 km from Kyushu to Kanto. It was once divided by YABE (1959) into three sections: east, middle and west. According to ICHIKAWA (1978a), the MTL is divided into four segments from the west to the east: I. Kyushu, II. Shikoku and west Kinki, III. east Kinki and Chubu, and IV. north Kanto (east of the Itoigawa-Shizuoka Tectonic Line). They are furthermore subdivided into eight subsegments. Nature of faulting differs from segment to segment.

The uppermost Cretaceous Izumi Group (Campanian ~ Maastrichtian) is distributed in a narrow zone along the MTL in the segment II (Fig. 1a). The MTL (s. str.) in this segment is a boundary fault between the Izumi Group (on the north) overlying the Ryoke metamorphic belt and the Sambagawa metamorphic belt (on the south). The faulting on the MTL is considered to have caused during post-Cretaceous ~ pre-Middle Eocene time (ca. 65 ~ 50 Ma ago), as will be discussed in III. 1.2.

In order to clarify the nature of faulting on the MTL during post-Cretaceous ~ pre-Middle Eocene time, I investigated the MTL and deformed structures of the Izumi Group in west Kinki (Fig. 1b): (1) the western part of the Izumi Mountain-range (ICHIKAWA and MIYATA, 1973; MIYATA, 1975, 1978) and (2) eastern part (MIYATA *et al.*, 1974) of the Izumi Mountain-range. Details in the latter area will be reported by RESEARCH GROUP for MTL in WEST KINKI (1980 in preparation). In west Kinki, the Izumi Group has been investigated by EHARA (1921), KOBAYASHI (1931), MATSUMOTO (1954,

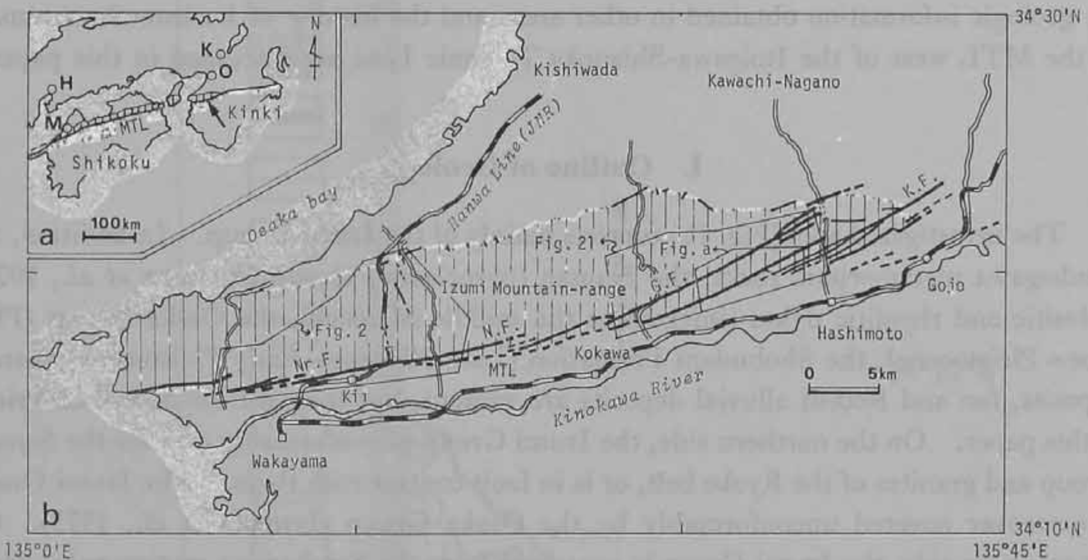

Fig. 1. Index map showing the distribution of the Izumi Group.
a) MTL: Median Tectonic Line, Dotted part: Sambagawa metamorphic rocks, Lined part: Izumi Group, Arrow: Investigated area (Izumi Mountain-range), K: Kyoto, O: Osaka, H: Hiroshima, M: Matsuyama.
b) Nr.F.: Narutaki fault, N.F.: Negoro fault, G.F.: Gojodani fault, K.F.: Kongo fault, Lined part: Izumi Group, Fig. a: Location of MIYATA *et al.* (1974).

1959), ICHIKAWA and MAEDA (1958a, 1958b, 1963, 1966), HORII (1958, 1959), ICHIKAWA and OHASHI (1965), TANAKA (1965), ICHIKAWA (1968), ISHIGAMI and YOSHIMATSU (1972) and others, while the MTL has been investigated by KAWADA (1939), HUZITA (1969), ICHIKAWA (1968), OKADA and SANGAWA (1978) and others.

The MTL have been studied and discussed by many geoscientists since it was named "Grosse Medianspalte" by NAUMANN (1893). The MTL has a long history which began at least in the late Mesozoic (for a review and summary of the earlier works, see MINATO *et al.*, 1965; ICHIKAWA *et al.*, 1970; SUGIYAMA, 1973). Four phases of faulting on the MTL were once distinguished by KOBAYASHI (1941): Kashio phase, Ichinokawa phase, Tobe phase and Shobudani phase. The MTL during post-Cretaceous ~ pre-Middle Eocene time, dealt with in this paper, corresponds to the so-called Ichinokawa phase, redefined by NAGAI (1958). Hitherto, for the movement on the MTL at that time, two different interpretations have been proposed: (1) the relative subsidence of the Ryoke metamorphic belt covered with the Izumi Group against the Sambagawa metamorphic belt, by a normal fault, dipping northward (cf. YABE and OZAKI, 1961), and (2) the relative upthrusting of the Sambagawa metamorphic belt against the Izumi Group from the south to the north with a low-angle dip (cf. YABE and OZAKI, 1961; NAGAI, 1973). However, these interpretations are not based on the tectonic analysis of strain picture along the MTL, but they are based on the assumption that the MTL at that time was essentially a dip-slip faulting.

The purpose of the present study is to clarify the movement picture of the MTL during Paleogene (pre-Middle Eocene) time on the basis of the tectonic analysis of strain picture (en echelon folds, en echelon faults, boudinage structure and wide shear zone), which was recorded in the Izumi Group along the MTL in west Kinki. Furthermore, the geologic information obtained in other areas and the history of horizontal movement on the MTL west of the Itoigawa-Shizuoka Tectonic Line are discussed in this paper.

I. Outline of Geology

The investigated area (Fig. 1b) consists mainly of the Izumi Group. In addition, the Sambagawa metamorphic rocks, the Sennan (pyroclastic) Group (YAMADA *et al.*, 1979), andesitic and rhyolitic dykes (inferred as the middle Miocene), the Osaka Group (Pliocene ~ Pleistocene), the Shobudani Formation (Late Pliocene ~ Early Pleistocene), terrace deposits, fan and Recent alluvial deposits are present, but they will be described briefly in this paper. On the northern side, the Izumi Group unconformably overlies the Sennan Group and granites of the Ryoke belt, or is in fault contact with them. The Izumi Group is moreover covered unconformably by the Osaka Group (ITIHARA *et al.*, 1975). On the southern side, the Izumi Group is separated from the Sambagawa metamorphic rocks by the MTL. The distribution of the Sambagawa metamorphic rocks is restricted within scattered narrow areas along the MTL, because the Sambagawa metamorphic rocks are extensively overlain by the Shobudani Formation and terrace and fan deposits. An exception is found at on the western part of Hashimoto City (MIYATA *et al.*, 1974), where sheared Sambagawa metamorphic rocks are exposed rather extensively. Some dykes are emplaced along and adjacent to the MTL. Dykes, trending about N 50°E, are developed adjacent to the MTL in the central part of the Izumi Mountain-range (ICHIKAWA *et al.*, 1976). They are commonly small, but attain sometimes to the thickness of 800 m. They may be correlated with some volcanic rocks of the Ishizuchi Group in Shikoku (HORIKOSHI, 1964) and the Takami-yama acidic volcanics in central Kinki, which is correlated with the Muro Group (UMEDA *et al.*, 1968). These Groups are referred to Middle Miocene in age (10 ~ 15 Ma ago) (cf. IKEBE *et al.*, 1973). The Shobudani Formation is composed mainly of gravels, sands, silts, and clays. The *Metasequoia* fauna and vivianite were found in this Formation (see MATSUSHITA, 1962, 1971). The fluvial terrace deposits consist chiefly of subrounded to subangular gravels, derived dominantly from the Izumi Group, subordinate amount of silts and clays. OKADA and SANGAWA (1978) divided the terrace deposits into the highest, high, middle and low ones. The fan deposit is locally developed along the southern foot of the mountain-range.

The Izumi Group in the western part of the Izumi Mountain-range forms a major asymmetrical syncline (Figs. 2 and 3). The axial trace is extended as far as about 15 km to the west. On the east, the syncline changes gradually into a homocline. In the area occupied by the southern limb of the syncline, the strata of the Izumi Group strike N-S to N 50°W and dip northeastward at an angle of 30~60°, while in the area of the northern limb and of the homocline, the strata strike generally N 50~80°E and dip southeastward at an angle of 30~70°. The strata of the Izumi Group become younger to the east. They are overturned, dipping northward at a high-angle, in the area adjacent to the MTL.

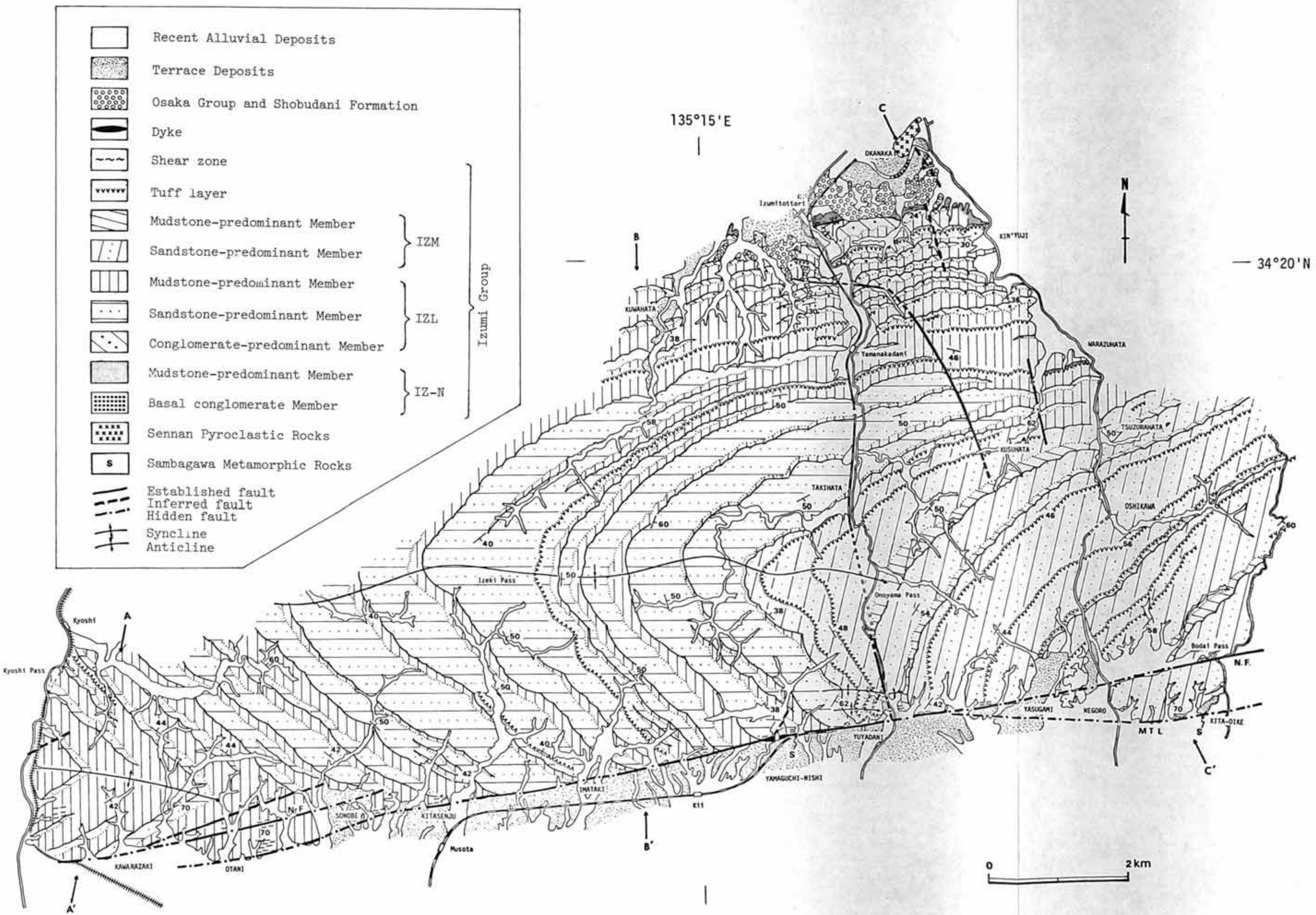

Fig. 2. Geologic map of the western part of the Izumi Mountain-range.
MTL: Main fault of the Median Tectonic Line, N.F.: Negoro fault, Nr.F.: Narutaki fault.

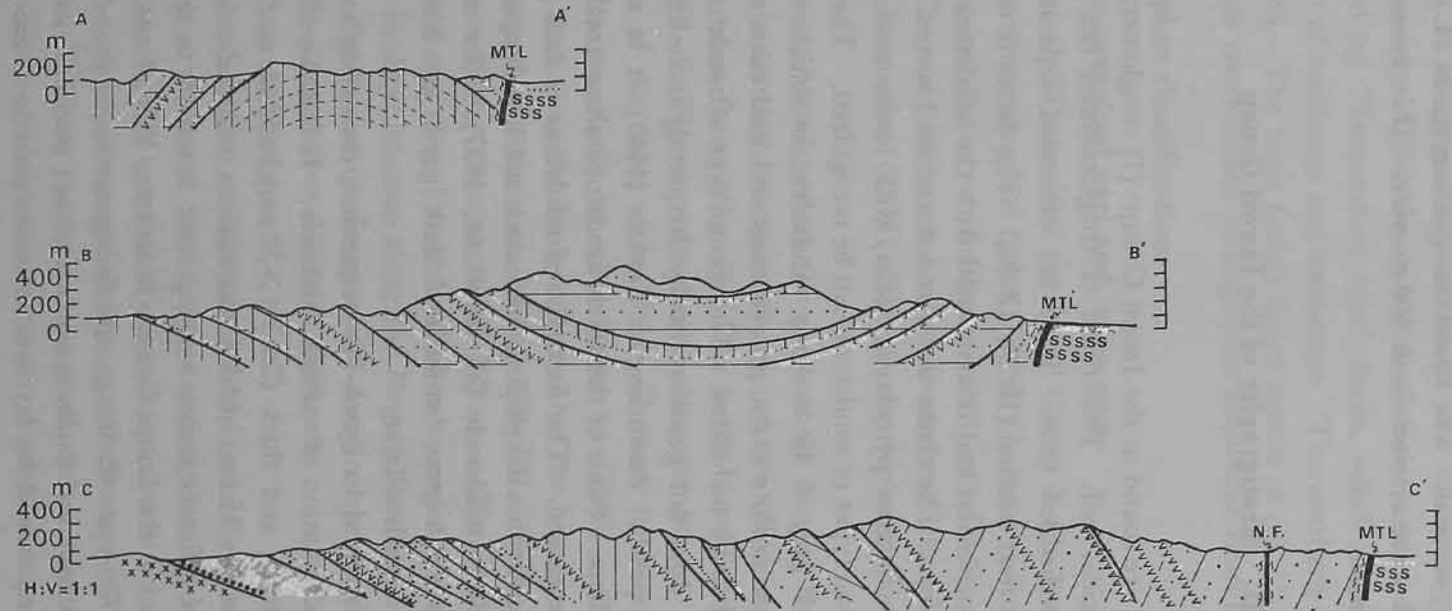

Fig. 3. Geologic profiles in the western part of the Izumi Mountain-range. For location and legend see Fig. 2.

On the other hand, the MTL runs through the southern foot of the Izumi Mountain-range along the north side of the River Kinokawa (Fig. 1). The fault trace of the MTL trends in a E-W to N 80°E direction. The fault plane dips generally northward at angles ranging from 50° to nearly vertical. The Izumi Group along the MTL is strongly sheared. The shear zone in broad sense attains about 600 m wide. It is unconformably overlain by the Shobudani Formation.

II. Stratigraphy of the Izumi Group

1. Lithofacies

The following rocks are found in the Izumi Group: (1) conglomerate, (2) sandstone, (3) mudstone and (4) acidic tuff. Two types of conglomerates can be discriminated: the basal ones and interbedded ones. They are discussed separately. The former will be described in the next section (II. 2), IZ-N_{α}. The latter is developed well at a basal part of cyclic sedimentation and is associated with the sandstones. Some of them show a graded stratification. The clasts are rounded and well sorted. They are dominantly composed of the Sennan pyroclastic rocks, with lesser amounts of sandstone, mudstone and chert. Two types of sandstone can be recognized. The first type is a fine to medium grained, dark grey or brown-grey sandstone, in which vertical grading is general. Sole marks such as flute casts, groove casts and load casts are commonly observed. It is considered to be turbidites. The second type of sandstone is thick, coarse grained, pale green and does not grade vertically, frequently including lithic fragments of granule size and mud patch. According to TANAKA (1965), it is not turbidite, but is regarded as fluxoturbidites. Some of the thick sandstone show amalgamations. Two types of mudstone are descerned. The first type of mudstone is dark grey to light grey, clayey to silty grained, sometimes developing lamination and Lebensspuren. The second type of mudstone is pebbly mudstone (cf. CROWELL, 1957). The acidic tuffs, being characteristically dark greenish-grey, brown and dark grey, are interbedded here in 22 horizons and will be described later.

The Izumi Group is mainly a flysch-like sequences, consisting essentially of sandstone and mudstone in alternation of various thickness. It is conveniently divided into massive ($t>2$ m) sandstone, and thick ($2\text{m}>t>30$ cm)-bedded, medium ($30\text{ cm}>t>15$ cm)-bedded, and thin ($t<15$ cm)-bedded alternations of sandstone and mudstone.

Sedimentary cycles of different orders ranging from hundreds to thousands of meter in thickness are developed in the Izumi Group (ICHIKAWA, 1960; ICHIKAWA and OHASHI, 1965; TANAKA, 1965). They are thinning- and fining-upward types, which is composed of the sandstone-predominant and mudstone-predominant members in ascending order, where the former is characterized by layers of massive sandstone and thick-bedded alternation, and the latter is characterized by massive mudstone, medium-bedded and thin-bedded alternations, respectively.

The Izumi Group can be classified into five facies: (a) "Kasayama type" facies, consisting of the thick conglomerate and sandstone, (b) "Azenotani type" facies, composed mainly of predominant massive mudstone, in addition to the thin-bedded alternation of sandstone and mudstone, (c) "Kin'yuji type" facies, which are characterized by the thick-bedded alternation of conglomerate, sandstone and mudstone, (d) "Warazuhata type" facies, composed mainly of thin-bedded and medium-bedded alternations of sandstone and mudstone, and (e) "Tsuzurahata type" facies, which consist chiefly of the thick-bedded alternation of sandstone and mudstone. The northern marginal facies are composed of (a) and (b). The main (axial) facies consist of (c), (d) and (e). The (a), (b), (c), (d) and (e) form continuously stratigraphic sequences from the north to the south.

2. Stratigraphic classification

2.1. Northern marginal part and main part

ICHIKAWA *et al.* (1979) classified the Izumi Group in the Izumi Mountain-range into three facies: (1) northern marginal facies (IZ-N), (2) main facies and (3) southern facies. The northern marginal facies are further divided into IZ-N_α, IZ-N_β and IZ-N_γ from the lithofacies. The main facies are further divided into the Shindachi Formation (IZL 1~9), the Iwade Formation (IZM1~8) and the Kokawa Formation ("IZU"1~3) in ascending order.

The Izumi Group, developed on the north of the Negoro faults in this area, is composed of strata of the northern marginal facies and two (Shindachi Formation and Iwade Formation) of the main facies (Fig. 4). The latter is subdivided stratigraphically into IZL1~9 and IZM1~7 (Fig. 4), respectively, along the Negoro Route with reference to sedimentary cycles of the order of hundreds of meter in thickness. This kind of the symbol corresponds essentially to what ICHIKAWA (1960) and ICHIKAWA and OHASHI (1965) used in the area along the Neogro Route, but the notation IZ-N and IZL1~9, are due to a later revision (ICHIKAWA *et al.*, 1979). The IZL, developed at the west of Negoro Route, can be shown under notation IZL0, IZL-1,... The stratigraphic division of the Izumi Group in this area (Fig. 5) is described in ascending order.

IZ-N: (Type locality; Mutsuo along the Negoro Route)

The IZ-N is distributed in the northern marginal part of the area from Mutsuo to Izumitottori. It attains about 340 m in thickness.

IZ-N_α (20 m+in thickness):

The IZ-N_α is the basal conglomerate bed, unconformably covering the Sennan (pyroclastic) Group on the north, but the plane of unconformity cannot be observed directly here, because most of this member is extensively covered by terrace and Recent alluvial deposits. The plane of unconformity is well developed at the east of the Negoro Route, for example, Takihata pond, Inakura pond, Sobura etc. (cf. ICHIKAWA and OHASHI, 1965). The clasts of conglomerates are rounded and poorly sorted. Clast size is pebble to cobble, sometimes boulder clasts are composed predominantly of acidic pyroclastic rocks, sandstone and mudstone. A thin acidic tuff layer (t_5) is intercalated in the conglomerate. This corresponds to the "Kasayama type" conglomerate.

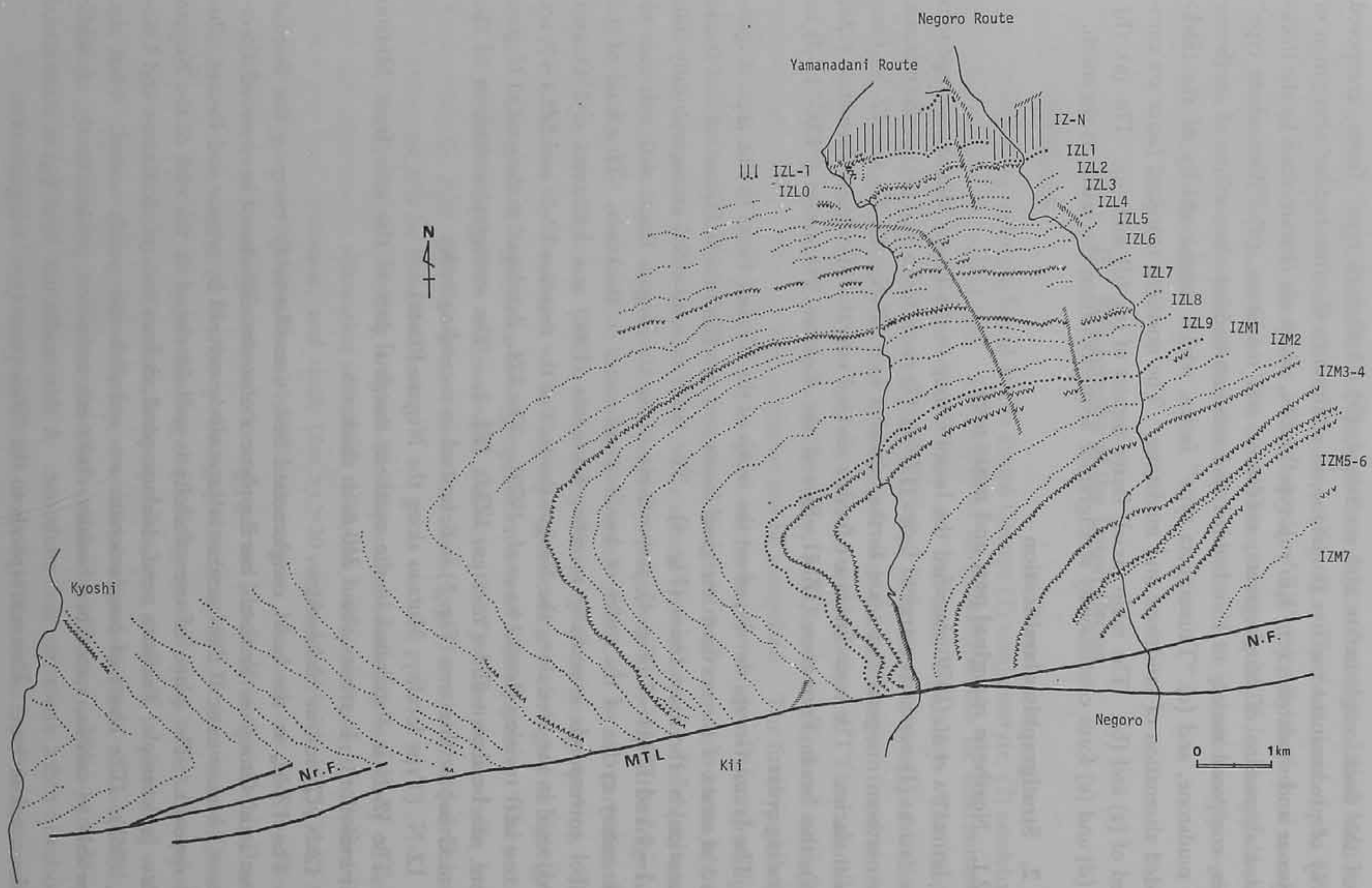

Fig. 4. Map showing sedimentary cycles of the Izumi Group in the western part of the Izumi Mountain-range.

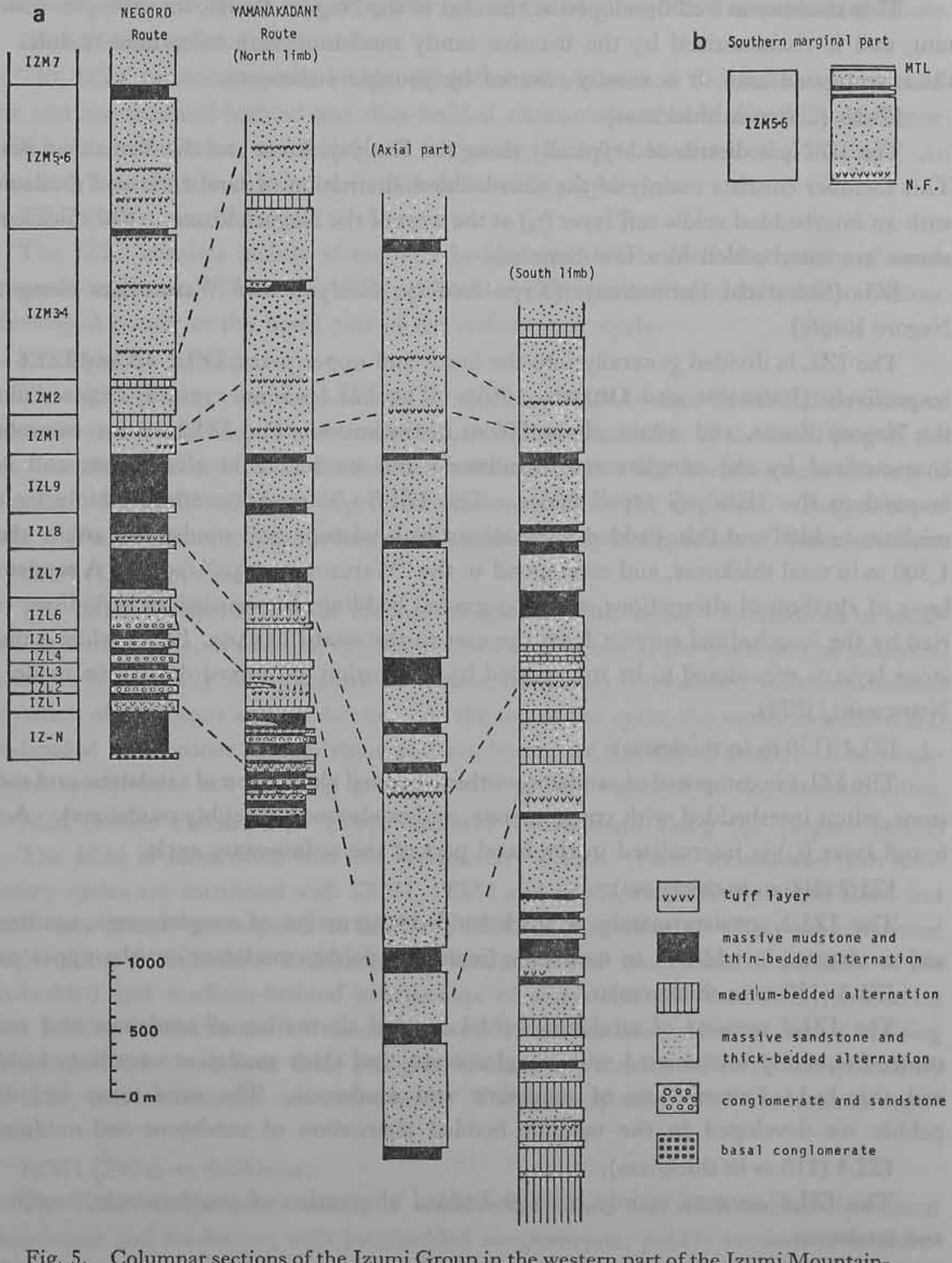

Fig. 5. Columnar sections of the Izumi Group in the western part of the Izumi Mountain-range.

a) Northern marginal and main part.

b) Southern part (south of the Negoro fault).

IZ-N_β (100 m in thickness):

This member is well developed at the east of the Negoro Route, for example, Azeno-tani, and is characterized by the massive sandy mudstone with calcarious nodule. In the investigated area, it is mostly covered by younger sediments.

IZ-N_γ (220 m in thickness):

The IZ-N_γ is distributed typically along the Kin'yuji River and the Yamanaka River. This member consists mainly of the thin-bedded alternation of sandstone and mudstone, with an interbedded acidic tuff layer (t_6) at the west of the Negoro Route. The thick sand-stones are interbedded in a few horizons.

IZL (Shindachi Formation): (Type locality; Kin'yuji and Warazuhata along the Negoro Route)

The IZL is divided generally into the lower and upper parts, IZL1 ~ 5 and IZL6 ~ 9, respectively (ICHIKAWA and OHASHI, 1965). The IZL1 ~ 5 are typically exposed along the Negoro Route, and attain about 600 m in thickness. The IZL1 ~ 5 are commonly characterized by the conglomerate, sandstone and mudstone in alternation, and correspond to the "Kin'yuji type" facies. The IZL6 ~ 9 are characterized mainly by the medium-bedded and thin-bedded alternations of sandstone and mudstone, attain about 1,300 m in total thickness, and correspond to the "Warazuhata type" facies. A sandstone layer of rhythmical alternations, showing graded bedding, is regarded as turbidites, carried by the longitudinal current from the east to the west (TANAKA, 1965), while a mud-stone layer is considered to be transported by suspension (cf. mixed deposition model by NISHIWAKI, 1978).

IZL1 (130 m in thickness):

The IZL1 is composed of sandstone ~ thick-bedded alternation of sandstone and mud-stone, often interbedded with conglomerate, and mudstone (or pebbly mudstone). Acid-ic tuff layer (t_8) is intercalated in the basal part of the sedimentary cycle.

IZL2 (100 m in thickness):

The IZL2 consists mainly of thick-bedded alternation of conglomerate, sandstone and mudstone, in addition to mudstone (including pebbly mudstone) at the upper part.

IZL3 (130 m in thickness):

The IZL3 consists of sandstone ~ thick-bedded alternation of sandstone and mud-stone, frequently intercalated with conglomerate, and thick mudstone ~ medium-bedded and thin-bedded alternations of sandstone and mudstone. The sandstones including pebble are developed in the medium-bedded alternation of sandstone and mudstone.

IZL4 (110 m in thickness):

The IZL4 consists mainly of thick-bedded alternation of conglomerate, sandstone and mudstone.

IZL5 (140 m in thickness):

The IZL5 consists of sandstone ~ thick-bedded alternation of sandstone and mud-stone, frequently intercalated with conglomerate, and massive mudstone ~ medium-bedded and thin-bedded alternations of sandstone and mudstone. The sandstones including pebbles are developed in the medium-bedded alternation of sandstone and mudstone. Two acidic tuff layers (t_9 and t_{10}) are found along the Yamanakadani Route.

IZL6 (240 m in thickness):

The IZL6 is characterized by the thick-bedded alternation of sandstone and mudstone and the medium-bedded and thin-bedded alternations of sandstone and mudstone. Thick-bedded sandstones are developed frequently in a few horizons near the top. An acidic tuff layer (t_{11}) is developed in this sedimentary cycle.

IZL7 (360 m in thickness):

The IZL7 consists mainly of medium-bedded and thin-bedded alternations of sandstone and mudstone. However, the thick-bedded alternation of sandstone and mudstone is developed poorly at the basal part of the sedimentary cycle.

IZL8 (260 m in thickness):

The IZL8 is also composed mainly of medium-bedded ~ thin-bedded alternation of sandstone and mudstone, in addition to thick-bedded alternation at the basal part of the cycle, but the thick-bedded sandstones are interbedded in a few horizons near the top of the cycle. An acidic tuff layer (t_{12}) is intercalated within the sequence. Fragments of oyster shells are contained in medium-bedded alternation at the south of Yamanakadani.

IZL9 (430 m in thickness):

The IZL9 consists mainly of medium-bedded and thin-bedded alternations of sandstone and mudstone, in addition to thick-bedded sandstones at the basal part of the cycle. It changes horizontally into dominant sandstone, frequently intercalated with thin-bedded alternation of sandstone and mudstone. At the top of the cycle, the medium-bedded and thin-bedded alternations of sandstone and mudstone are developed poorly. The thick-bedded sandstones, not showing graded bedding, are regarded as the fluxoturbidites.

IZM (Iwade Formation): (Type locality; Tsuzurahata along the Negoro Route)

The IZM is subdivided into five sedimentary cycles. First, second and fifth sedimentary cycles are correlated with IZM1, IZM2 and IZM7, respectively, while third and fourth ones almost correspond to IZM3-4, IZM5-6, respectively. They are composed mainly of the thick-bedded alternations of sandstone and mudstone, in addition to the thin-bedded and medium-bedded alternations of sandstone and mudstone, and attain about 3,700 m in thickness. A sandstone layer of alternations, showing graded bedding and sole marks such as flute casts and groove casts, are considered to be transported by a turbidity current from the east to the west. They correspond to the "Tsuzurahata type" facies.

IZM1 (290 m in thickness):

The IZM1 also consists mostly of massive sandstone and thick-bedded alternation of sandstone and mudstone, with interbedded conglomerate, pebbly mudstone, medium-bedded and thin-bedded alternations. At the top of the cycle, the medium-bedded ~ thin-bedded alternation of sandstone and mudstone (including pebbly mudstone) are developed poorly. Two acidic tuff layers (t_{13} and t_{14}) are interbedded at the lower part of the cycle. Sole marks such as flute casts, groove casts and load casts are well developed.

IZM2 (250 m in thickness):

The IZM2 also consists dominantly of sandstone ~ thick-bedded alternation of sandstone and mudstone, with interbedded conglomerate and medium-bedded alternation of sandstone and mudstone. At the top of the cycle, the mudstone ~ medium-bedded alternation are poorly developed.

IZM3-4 (1,100 m in thickness):

The IZM3-4 consists mainly of the thick-bedded alternation of sandstone and mudstone, with frequently interbedded mudstone, rhythmic thin-bedded and medium-bedded alternations. Three acidic tuff layers (t_{15}, t_{16} and t_{17}) are developed.

IZM5-6 (1,050 m in thickness):

The IZM5-6 also consists mainly of sandstone ~ thick-bedded alternation of sandstone and mudstone. Three acidic tuff layers (t_{18}, t_{19} and t_{20}) are interbedded.

IZM7 (1,020 m in thickness):

The IZM7 is also composed mainly of sandstone ~ thick-bedded alternation of sandstone and mudstone, with interbedded medium-bedded and thin-bedded alternations of sandstone and mudstone. It is developed typically at the east of Negoro Temple.

2.2. Southern part (south of the Negoro fault)

The Izumi Group of the southern marginal part, where is bounded by the Negoro fault on the north and by the main fault of the MTL on the south, is composed mainly of the thick-bedded alternation of sandstone and mudstone, in addition to the medium-bedded and thin-bedded alternations of sandstone and mudstone, with one layer of acidic tuff (t_s). It attains about 800 m in thickness (Fig. 5b) and can be correlated stratigraphically with the Middle Subgroup, probably IZM5-6 on the basis of the characteristic of acidic tuff as will be seen later. The Izumi Group of this part is generally sheared along the above-mentioned two faults.

2.3. Facies change

Using tuff layers as a key bed, it has been recognized that a remarkable lateral facies change took place from the SW (main part) to the NE direction (northern marginal part) in the Izumi Group of the Izumi Mountain-range (ICHIKAWA, 1960; ICHIKAWA and OHASHI, 1965; TANAKA, 1965; MIYATA and ICHIKAWA, 1971; SHINOHARA, 1977). The northern marginal facies are composed of (a) "Kasayama type" and (b) "Azenotani type," while the main facies consist of (c) "Kin'yuji" type, (d) "Warazuhata type" and (e) "Tsuzurahata type", as mentioned in II. 1. Fig. 6 shows the lateral variation of the Izumi Group in the western part of the Izumi Mountain-range. From SW to NE, the facies change of [(e)]-(d)-(c)-(b)-(a) is recognized in IZL1 ~ 5. Furthermore, SHINOHARA (1977) discreminated the following four types of lateral variation: 1) (e)-(d)-(b)-(a) in IZL6 ~ 9, 2) (e)-(c)-(b)-(a) in IZM 1 ~ 2, 3) (e)-(c)-(c')-(a) in IZM3 ~ 4, and 4) (e)-(c')-(a) in IZM 5 ~ 8, where (c') means the "Chichioni type," consisting of the alternation of thick-bedded conglomerate and very thin-bedded mudstone.

The migration of the "Warazuhata type" takes place from W to E into the younger

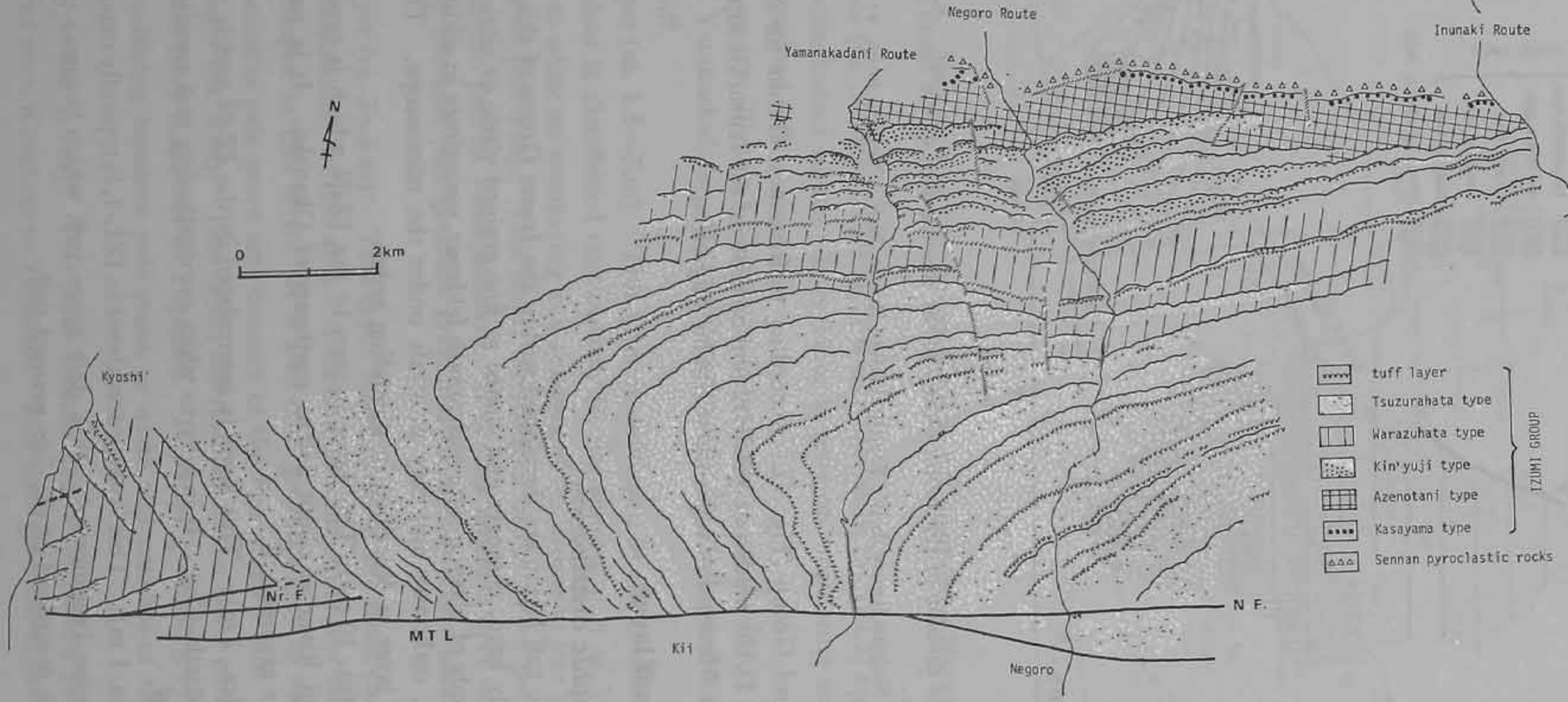

Fig. 6. Facies map of the Izumi Group in the western part of the Izumi Mountain-range.

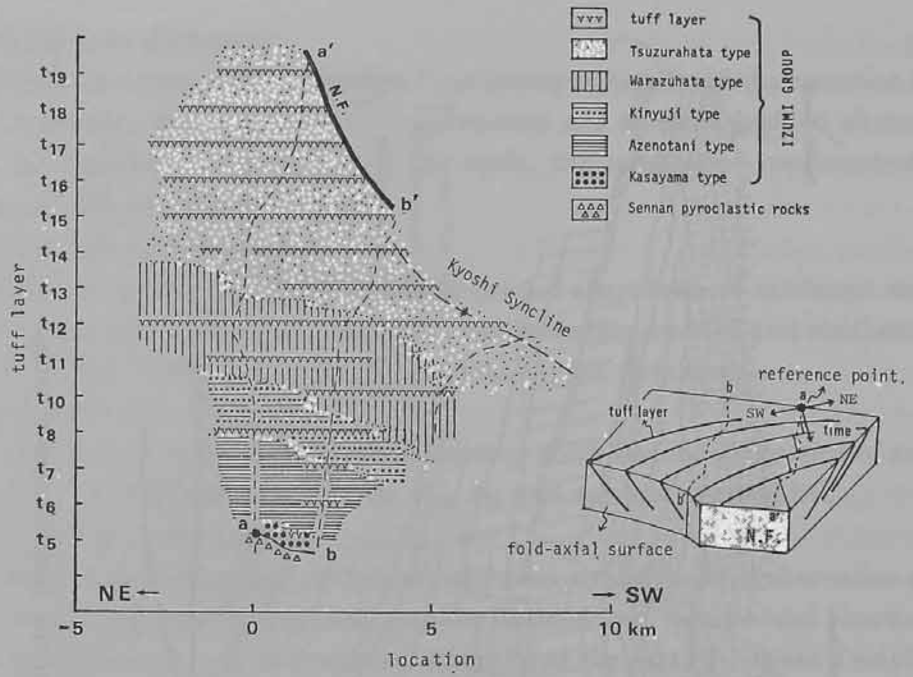

Fig. 7. Facies division of the Izumi Group of the western part of the Izumi Mountain-range.
a-a': Negoro Route, b-b': Yamanakadani Route, N.F.: Negoro fault, *: Reference point.

strata of the Izumi Group (Fig. 7). According to RESEARCH GROUP for MTL in WEST KINKI (1978, Fig. 1), the mudstone-predominant member of the Izumi Group in the eastern part of the Izumi Mountain-range has a similar migration.

3. Acidic tuff layer

3.1. Stratigraphic distribution

The 17 acidic tuff layers are developed within the Izumi Group of this area (Fig. 8). They are generally hard, compact and coarse to fine grained vitric or vitric crystal tuffs, composed commonly of glass, quartz and potash feldspar, sometimes in addition to microcline, plagioclase, carbonate and clay minerals under the microscope. The occurrence of individual tuff layer is described in ascending order.

t_5 tuff layer (ca. 10 cm): This layer is seen in the IZ-N which is typically exposed along the Kin'yuji River at about 250 m southeast of Okanaka. It is pale green and consists of the fine grained tuff.

t_6 tuff layer (ca. 2 m): This layer is intercalated in the IZ-N and is well observed at Izumitottori, Misaki-Cho. It is grey to white on weathering and consists of medium to fine grained tuff.

t_7 tuff layer (ca. 1 m): This layer, intercalated in IZL-1, is typically exposed along the Yamanaka River near Izumitottori. It is dark green tuff, which becomes white grey on weathering, and is composed of the fine grained tuff.

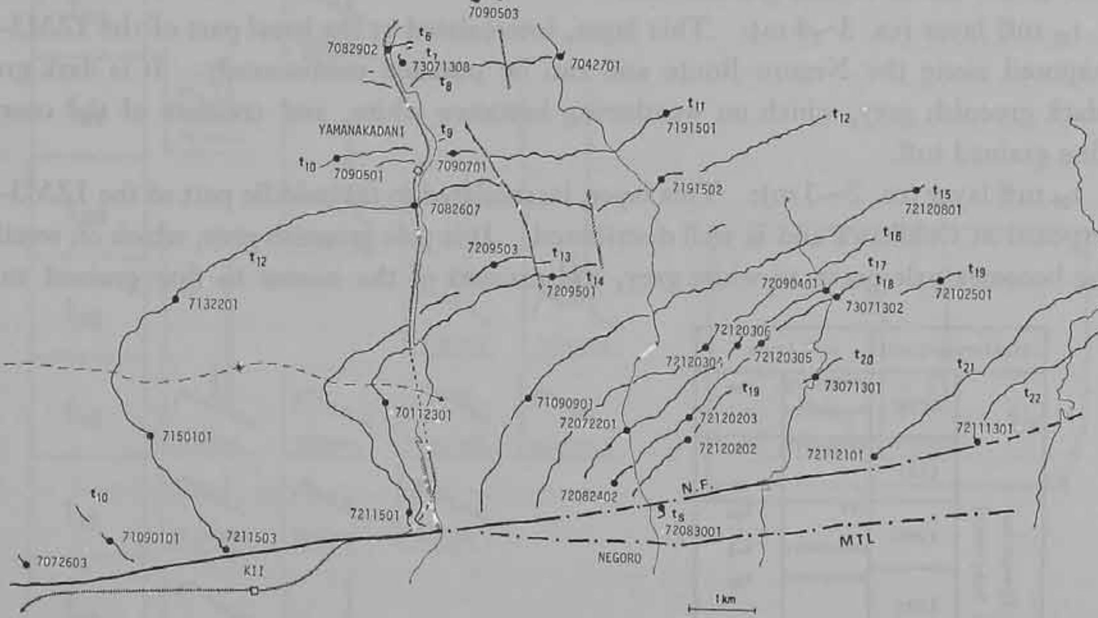

Fig. 8. Map showing distribution of acidic tuff layers (after MIYATA, 1978).

t_8 tuff layer (ca. 30 cm): This layer is intercalated in the IZL1, and is well observed along the Yamanakadani Route. It is white to grey on weathering and consists of the coarse to fine grained tuff.

t_9 tuff layer (ca. 20 cm): This layer is intercalated in the lower part of the IZL5 at the east of Yamanakadani. It is white on weathering and consists of the medium to fine grained tuff.

t_{10} tuff layer (ca. 1.5∼3 m): This layer is developed in the middle part of the IZL5 at Yamanakadani is distributed continuously in the western part of Yamanakadani. It is pale green to white on weathering and consists of the coarse to fine grained tuff.

t_{11} tuff layer (ca. 3 m): This layer, intercalated in the upper part of the IZL6, is seen in the eastern part of Yamanakadani. It is dark greenish grey to dark grey, which on weathering becomes pale greenish grey, and consists of the medium to fine grained tuff.

t_{12} tuff layer (ca. 3∼5 m): This layer, intercalated in the basal part of the IZL8, is distributed continuously in this area. Sometimes slump structures and parallel laminations are developed in this layer. It is also dark greenish grey to dark grey which on weathering becomes pale green and consists of the fine grained tuff.

t_{13} tuff layer (ca. 2 m): This layer, intercalated at the basal part of the IZM1, is well distributed from Kusuhata to Yuyadani. It is dark greenish grey to dark grey tuff, which on weathering becomes pale green to white and consists of the medium to fine grained one.

t_{14} tuff layer (ca. 2.5 m): This layer, intercalated in the middle part of the IZM1, is also distributed from Kusuhata to Yuyadani. It is dark greenish to dark grey and is composed of the coarse to fine grained tuff.

t_{15} tuff layer (ca. 3∼4 m): This layer, intercalated at the basal part of the IZM3-4, is exposed along the Negoro Route and can be pursued continuously. It is dark grey to dark greenish grey, which on weathering becomes white, and consists of the coarse to fine grained tuff.

t_{16} tuff layer (ca. 2∼3 m): This layer, intercalated in the middle part of the IZM3-4, is exposed at Oshikawa and is well distributed. It is pale greenish grey, which on weathering becomes pale green to white grey, and consists of the coarse to fine grained tuff.

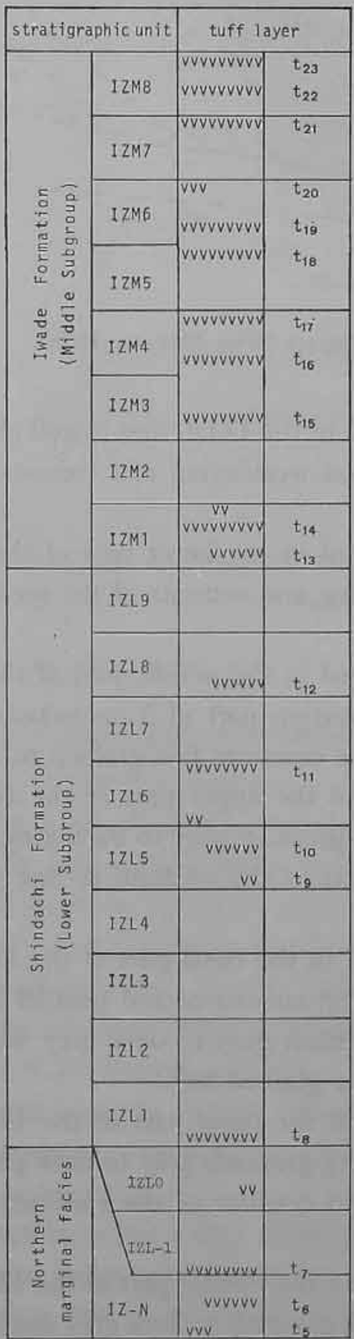

Fig. 9. Stratigraphic distribution of acidic tuffs in the Izumi Group in the western part of the Izumi Mountain-range.

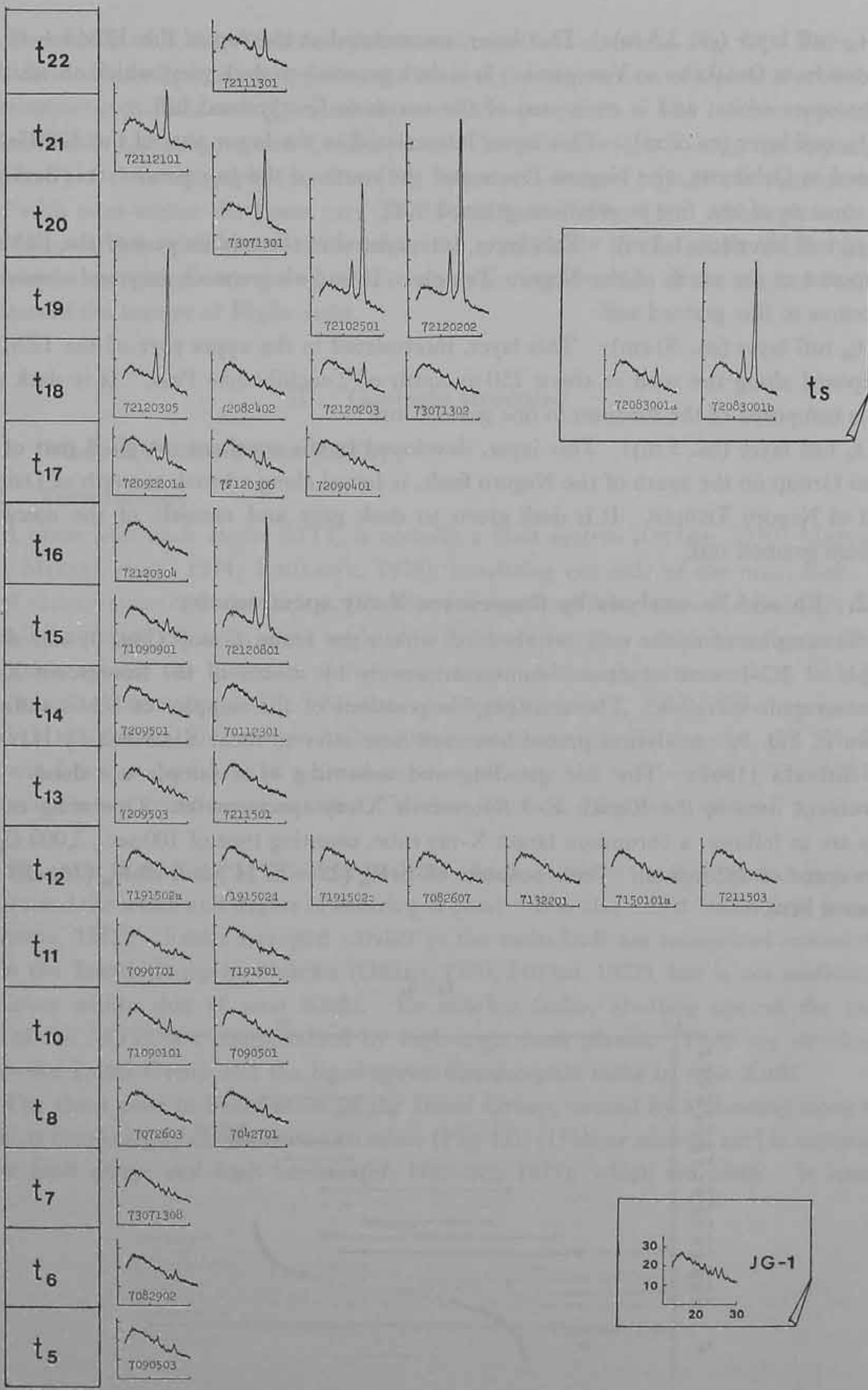

Fig. 10. Fluorescent X-ray spectrographic patterns for Rb and Sr. For locality numbers see Fig. 8.

t_{17} tuff layer (ca. 3.5 m): This layer, intercalated at the top of the IZM3-4, is distributed from Oshikawa to Yasugami. It is dark greenish to dark grey, which on weathering becomes white, and is composed of the coarse to fine grained tuff.

t_{18} tuff layer (ca. 2 m): This layer, intercalated in the lower part of the IZM5-6, is exposed at Oshikawa, the Negoro Route and the north of the Juji pond. It is dark grey and consists of the fine to medium grained tuff.

t_{19} tuff layer (ca. 1.5 m): This layer, intercalated in the middle part of the IZM5-6, is exposed at the north of the Negoro Temple. It is dark greenish grey and consists of the coarse to fine grained tuff.

t_{20} tuff layer (ca. 80 cm): This layer, intercalated in the upper part of the IZM5-6, is exposed along the road at about 250 m south of Tsuchibotoke Pass. It is dark grey and is composed of the medium to fine grained tuff.

t_s tuff layer (ca. 5 m): This layer, developed in the southern marginal part of the Izumi Group on the south of the Negoro fault, is found along a brook at south of Daimon pond of Negoro Temple. It is dark green to dark grey and consists of the coarse to medium grained tuff.

3.2. Rb and Sr analysis by fluorescent X-ray spectrometry

38 samples of acidic tuffs interbedded within the Izumi Group (Fig. 9) and also a sample of JG-1 were examined semiquantitatively by means of the fluorescent X-ray spectrographic methods. The stratigraphic positions of the samples of acidic tuffs are shown in Fig. 9. Analytical procedures used here refer to those described by HATTORI and SHIBATA (1967). The fine grinding and mounting of a sample are done. The instrument used is the Rigaku K-3 fluorescent X-ray spectrometer. Operating conditions are as follows; a chromium target X-ray tube, counting time of 100 sec., 2,000 c.p.s., chert speed of 1/2 in/min. Peak position of SrK_α ($2\theta=25°11'$) and RbK_α ($2\theta=26°58'$) are used here.

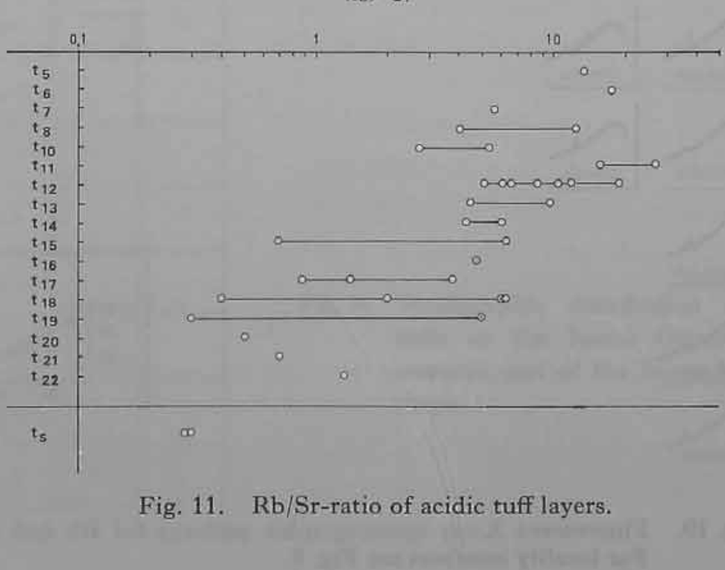

Fig. 11. Rb/Sr-ratio of acidic tuff layers.

The results of X-ray diffraction patterns obtained are shown in Fig. 10. The acidic tuff is divided broadly into two types on the basis of the comparison of a peak of strontium: (1) strontium-rich tuffs and (2) relatively strontium-poor tuffs. The former type is recognized in the t_{15}, t_{18}, t_{19}, t_{20} and t_s tuff layers. The tuffs developed within the upper part (IZM3∼7) of the stratigraphic position (Fig. 9) are said to show high Rb/Sr-ratio as compared with ones within the lower part (IZM1 and lower) (Fig. 11). Although each tuff has a considerably wide range of the ratio, the t_s tuff layer in the south of the Negoro fault can be correlated with the t_{19} tuff layer on the northern side of the Negoro fault on the basis of the feature of Rb/Sr-ratio.

III. Geologic structure

1. Median Tectonic Line (MTL)

1.1. Terminology

A great fault such as the MTL is actually a fault system (Okada, 1970; Matsuda, 1973; Miyata *et al.*, 1974; Ichikawa, 1976), consisting not only of the main fault, but also of various types of faults such as (1) those arranged parallel to the main fault, (2) those which is branching off at an acute angle with the main fault, in addition to those making high angle against the direction of the main fault. Although terms such as "Median shear zone" (Makiyama, 1951), "Median zone" (Matsushita, 1962), "Median tectonic zone" (Matsushita, 1971), and so on have been used sometimes in the past, the "Median Tectonic Line" is used here in a broad sense to indicate the fault system. The Median Tectonic Line in broad sense is called "Median Tectonic Line fault system" by Okada (1970).

The main fault of the MTL is the boundary fault, of which the fault trace is generally straight and the width and degree of shearing is great. It is also called "main fault strand" (Matsuda, 1973). Faults arranged parallel to the main fault are recognized remarkably within the Izumi Group in Shikoku (Okada, 1970; Suyari, 1972), but is not ascertained by author within that of west Kinki. En echelon faults, abutting against the main fault of the MTL, are characterized by high-angle fault planes. They are developed within the Izumi Group and the Sambagawa metamorphic rocks in west Kinki.

The shear zone in broad sense of the Izumi Group, caused by a shearing along the MTL, is conveniently divided into two zones (Fig. 12): (1) shear zone (s. str.) is composed of the fault gouge and fault breccia (cf. Higgins, 1971), which are black. It attains

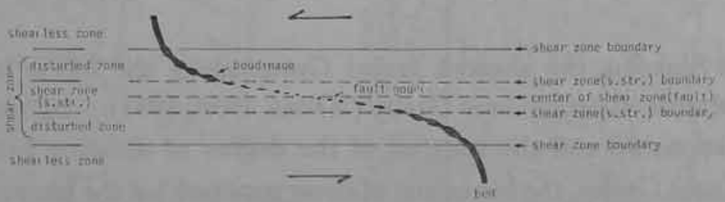

Fig. 12. Schematic illustration showing division of a shear zone (s.l.)

abut 100 m (Fig. 16). Most individual tectonic fragments of rocks, contained within the shear zone (s. str.), are from granule to cobble size. And (2) disturbed zones has characteristic structures such as boudinage structures and folds of small-scale, associated with bedding slips and shears. It attains about 500 m in width. The two zones differ obviously in the degree of shearing.

1.2. Stage of activity

Four stages of the MTL in Kinki are conveniently indicated by the uncomformities and the contrast of the effect of shearing between juxtaposed beds (or rocks) on faults: (1) late Mesozoic (pre-Campanian) time, (2) Campanian ~ Maastrichtian time, (3) Paleogene ~ early Miocene (probably pre-Middle Eocene) time, and (4) late Quaternary time. Although a stage between (3) and (4) is ascertained in Shikoku (cf. SUYARI and AKOJIMA, 1973), it is not dealt with in this paper, because no positive record is found at present in Kinki. Stage (4) may embrace more than one substage of different nature (cf. OKADA and SANAGAWA ,1978; SANGAWA, 1977); but its subdivision is not the main theme of the present paper. This paper deals mainly with the MTL during stage (3) in view of the following geologic relationship.

(1) The uppermost Cretaceous Izumi Group is strongly sheared along the main fault of the MTL. Shear zone (s.1.) is unconformably overlain by the Shobudani Formation, for example, at Umehara (about 500 m west of the southwest end of the geologic map shown in Fig. 2) and at about 500 m west of Yuyadani (Fig. 2). Thus, construction of the broad shear zone (s.1.) of the Izumi Group was essentially of pre-Shobudani age. Because boudinage structures and small-scale folds are developed in the broad shear zone (s.1.), they are said to be of pre-Shobudani age. Also, en echelon faults developed within the Izumi group are said to be pre-Shobudani age, because individual shear zone (s. l.) of en echelon faults (e.g. Negoro fault in Fig. 15 and S-5 fault in Fig. 21) are unconformably covered by the Shobudani Formation. However, the Quaternary faulting, which cuts the Shobudani Formation, is really recognized along the MTL in west Kinki. A young fault gouge is developed generally in this case.

(2) Dykes (middle Miocene) are emplaced sometimes along and adjacent to the MTL in west Kinki. Some dykes are generally in contact with the strongly sheared part of the Izumi Group. The degree of shearing of the Izumi Group is very high and extensive as compared with that of the dyke. Judging from the contrast of the effect of shearing between the Izumi Group and the dyke, the shear zone (s.str.) of the Izumi Group is further considered to have been mainly formed by a faulting prior to the intrusion of dykes.

(3) In west Shikoku, the sheared Izumi Group along the MTL is unconformably overlain by the Middle Eocene Kuma Group (NAGAI, 1958, 1973). In consideration of the stratigraphic relationship and the contrast of the degree of shearing between the Izumi Group and the Kuma Group, the formation of shear zone (s.1.) of the Izumi Group is regarded as being essentially during post-Cretaceous ~ pre-Middle Eocene time (ca. 65 ~ 50 Ma).

Fig. 13. Map showing localities of outcrop of a shear zone (s. str.) along the MTL.

1.3. Description of characteristic fault features

Fig. 13 shows locality of outcrops where fault products were observed along the MTL (s. str.) in the western part of the Izumi Mountain-range. Here, the MTL is divided conveniently into three segments. Brief description of outcrops follows.

Segment A: Segment A is situated between Kawarazaki and Kita-Senju. The main fault of the MTL and two branch faults are developed here. At the following localities of branch faults, both sides of the fault are composed of the Izumi Group. One of the branch faults, branching off from the main fault, extends through the north of Otani (Locs. 2a, 3a and 3b) to Okubo (Locs. 4a and 4b).

Narutaki fault, another branch fault, can be traced through the north of Otani (near Loc. 2b), Locs. 5b and 6, the north of Isao (Loc. 7) and farther to the east over about 5 km.

Loc. 1: At Kawarazaki, there is a black fault gouge, which has originated in the mudstone of the Izumi Group.

Loc. 2a: The mudstone and the thin-bedded alternation of sandstone and mudstone of the Izumi Group are strongly sheared, and the small-scale rock fragments are aligned in the E-W direction.

Locs. 3a and 3b: The fault gouge of several tens of meters in width is seen at the west and east of the pond.

Loc. 5b: Fault gouge of the Izumi Group is more than 20 m in width.

Locality of the main fault of the MTL is not clear here, for a lack of the outcrop of the Sambagawa metamorphic rocks, but is presumed to pass from Otani through Sonobe and Isao to Kita-Senju, judging from the distribution of the fault gouge of the Izumi Group at the following localities.

Loc. 5a: The fault gouge of the Izumi Group is widely developed. The arrangement of tectonic fragments within the fault gouge has a strike of N 70°E and a dip of about 80°N.

Loc. 9a: On the small stream floor, the fault gouge of the Izumi Group is unconformably covered with the terrace deposit.

Loc.10a: At Kita-Senju about 500 m north of the Musota Station of the Hanwa line (Japan National Railway), a shear zone (s. str.) of the Izumi Group has been once observed along the width of roughly 80 m, when housing sites were constructed. The disturbed Izumi Group on the north, has a strike of N 58°E and a dip of 54° N, and consists of the thin-bedded alternation of sandstone and mudstone with a thin acidic tuff layer. Farther to the east (Loc. 10b), the shear zone (s. str.) is unconformably covered by gravels. The gravels of the middle terrace deposit are gently inclined southward for 10~20°.

Segment B: Segment B is located between Kita-Senju and Yuyadani, east of the segment A. The main fault of the MTL can be traced clearly on air-photographs.

Loc.11: At Imataki, the fault gouge of the Izumi Group is exposed on the road side.

Loc.12: There is a geologic information from vertical drilling, suggesting that the fault plane of the main fault dips northward at an average angle of about 55° (cf. ICHIKAWA and MIYATA, 1973). During the construction of the Kinki Expressway in 1972 the fault gouge was observed at Locs. 13a to 17.

Locs.18a and 18b: Approximately east-west trending dyke of hornblende andesite is emplaced within the fault gouge of the Izumi Group. It is about 15 m wide and about 250 m

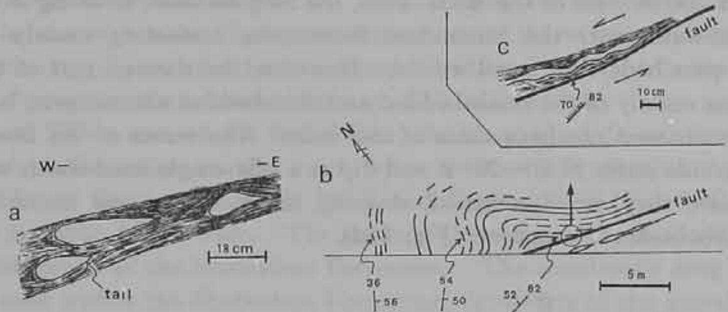

Fig. 14. Sketches showing structures within a shear zone (s.str.)
a) Tectonic fragments of sandstone (Izumi Group) within the shear zone (s.str.) in the E-W direction at Loc. 18a in Fig. 13.
b) Minor fold within the medium-bedded alternation of sandstone and mudstone in the NW-SE direction at Loc. 31 in Fig. 13.
c) Thin-bedded sandstone is boudinaged at the same locality as (b).
Sketches (b) and (c) are regarded as structures related to a left-hand simple shear along a fault.

long at the west (Loc. 18a) and east (Loc. 18b) of the Nanase River. The effect of shearing of the Izumi Group is far stronger and more extensive than that of the dyke. In the shear zone (s. str.), the subrounded rock fragments are observed frequently. On the east-west trending outcrop, heads of the asymmetric elongated ellipsoids orient westward (Fig. 14a).

Loc. 19: At Kamikurotani, there is an outcrop about 2 m in width of the Sambagawa metamorphic rocks, consisting mainly of the pelitic and psammitic schists. They strike N 52° W and dip 68° northwestward. Further to the north, a wide zone of fault gouge of the Izumi Group is developed.

Loc. 21: At Yuyadani, the black fault gouge of the Izumi Group attains more than 80 m in width, and is covered with the terrace deposit. At present, this outcrop is difficult to observe due to a dense vegitation.

Segment C: Segment C is situated between Yuyadani and Higashi-Sakamoto and consists of the main fault of the MTL on the south and the Negoro fault, the latter of which branches off from the main fault of the segment B. The Negoro fault can be traced from Locs. 22 to 29, while the fault products along the main fault can be seen at Locs. 30 to 33.

Loc. 22: On the north of Yama, the shear zone of the Izumi Group in roughly east-west direction, consisting of the thick-bedded alternation of sandstone and mudstone, is observed. The bedding plane of the Izumi Group has a strike of N 20° E and a dip of 80° E.

Loc. 23: At about 150 m west of Hara, the similar sheared part of the Izumi Group is exposed about 100 m in width.

Loc. 25: At Yasugami, black fault gouge along the Negoro fault is about 4 m wide. The sheared part of the Izumi Group, consisting mainly of the thick-bedded alternation of sandstone and mudstone, is developed along the brook until about 250 m further south of the fault gouge. It strikes N 80°W to N 84° E and dips 70° to nearly vertical northward or southward. The northward-dipping beds are overturned. Here, the Izumi Group is extensively covered by the younger terrace deposit. On the north of the fault gouge, the sheared part of the Izumi Group, partly with the thin-bedded and medium-bedded alternations of sandstone and mudstone, strikes N 45°~60° E and dips 70° to near vertical northward or southward. The northward-dipping beds are also overturned.

Loc. 26a: At about 200 m west of the Bodai Pass, the Negoro fault, trending N 62°E and dipping 60° southward, cuts the Shobudani Formation, consisting mainly of gravel, sand, silt and peat beds with fossil woods. However, the sheared part of the Izumi Group, consisting mainly of the thick-bedded and thin-bedded alternations, is distributed along the southern and northern sides of the fault. The strata of the Izumi Group on the southern side strike N 50～70° E and dip at a high-angle southward, while on the northern side, they are overturned, dipping north. They are unconformably overlain by the Shobudani Formation (Fig. 15d).

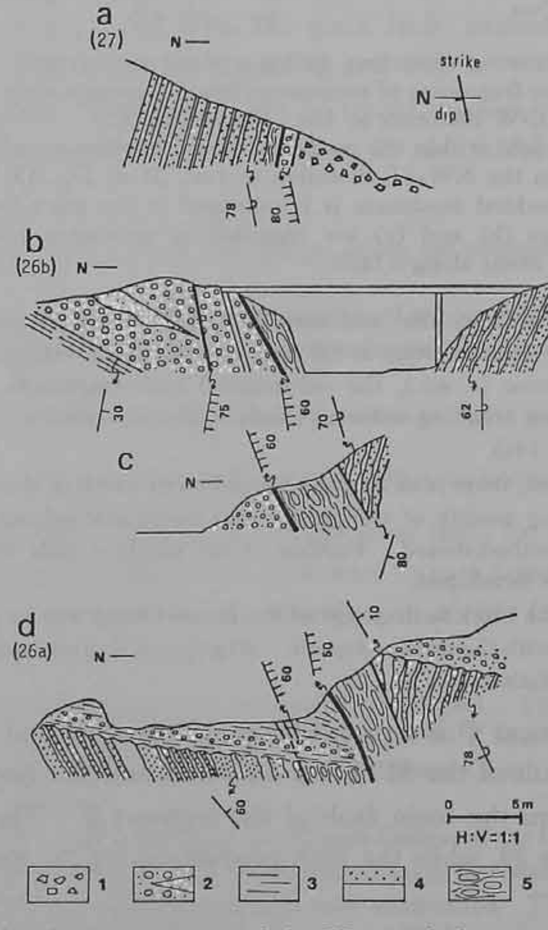

Fig. 15. Sketches showing occurrences of the Negoro fault.
1: Talus deposit, 2 and 3: Shobudani Formation (2: Gravel (partly sand), 3: silt), 4: Alternation of sandstone and mudstone (Izumi Group), 5: Sheared part of the Izumi Group. For locality numbers see Fig. 13.

Loc. 26b: At the Bodai Pass, the Shobudani Formation, consisting mainly of gravel, sand and silt beds, unconformably covers the Izumi Group. A tectonic slice of the Shobudani Formation is sandwiched between two branch faults of the Negoro fault. The Negoro fault proper (or the southern branch fault) trends N 82° E and dips 60° southward. The sheared part of the Izumi Group hangs over the Shobudani Formation on the south by a reverse fault (Figs. 15b and 15c). The fault breccia, which had originated in the Izumi Group, is about 5 m wide, while the young fault gouge on the fault plane is about 10 cm in width. The Shobudani Formation is hardly sheared and only a small-scale drag caused by the faulting is recognized. The fault on the north trends roughly E-W and dips 75° to nearly vertical southward. This fault runs between the Shobudani Formation and the Izumi Group on the eastern side of cutting site, while it runs within the Shobudani Formation on the western side of the cutting. The young fault gouge on the fault is about 10∼17 cm wide, while the sheared part of the Izumi Group on the north attains about 10 m in width.

Loc. 27: At about 500 m east of the Bodai Pass, the overturned Izumi Group hangs over the Shobudani Formation on the south by a reverse fault parallel to the bedding plane of the Izumi Group, striking N 78° E and dipping 80°N (Fig. 15a). The young fault gouge is about 14 cm wide. The sheared part of the Izumi Group is covered partly with the gravel of the Shobudani Formation. The small-scale drag caused by the faulting is seen within the Shobudani Formation, consisting of the gravel and silt beds with fragments of fossil wood.

Loc. 28: At Nishi-Yamada, the fault gouge is developed about 3 m wide within the massive sandstone of the Izumi Group along the brook. The bedding plane of sandstones strikes N 82° E and dips 64° northward.

Loc. 29: At about 1 km northwest of the Sakura pond, the fault gouge of the Izumi Group is seen about 2 m wide along the brook. The sheared strata of the Izumi Group, consisting of the medium-bedded and thick-bedded alternations of sandstone and mudsone, strike N 72°E and dip 74° northward.

Loc. 30: At Negoro, the sheared part of the Izumi Group is exposed owing to the construction of housing sites. The fault gouge of the Izumi Group attains about 100 m in width.

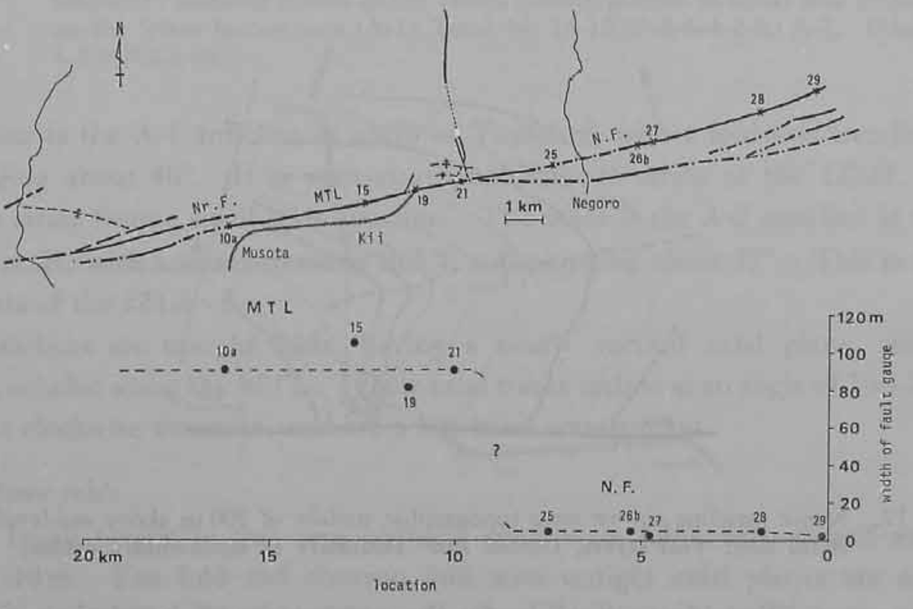

Fig. 16. Width of fault gouge along the MTL.
MTL: Main fault of the MTL, Nr.F.: Narutaki fault, N.F.: Negoro fault.

To the north, the disturbed zone, accompanied with the boudinag estructure, is developed. The strata of the Izumi Group strike N 70°W and dip 70° northward.

Loc. 31: At about 300 m northeast of Yamada, the sheared part of the Izumi Group is exposed owing the construction of housing sites. The black fault gouge of the Izumi Group, striking N 88°E and dipping 60° northward, is seen in the width of about 50 m on the N-S profile. To the north, the disturbed zone of the Izumi Group, striking N 58°E and dipping 82° southward, is characterized by the boudinage structure. On the NW-SE profile, a minor fold was observed within the disturbed Izumi Group (Fig. 14b). Fold-axial trace trends NWN-SES at an oblique angle to the fault trend. Small-scale boudinage structures (Fig. 14c) are developed within the northern limb of the fold near the fault plane.

Loc. 32: At about 200 m west of Kita-Ohike, there is a small-scale outcrop of the dark bluish fault gouge of the Sambagawa metamorphic rocks, accompanied with mica mineral and fragments of quartz vein. This gouge is covered with the terrace deposit.

Loc. 33: At about 150 m west of Higashi-Sakamoto, there is a new outcrop of the sheared Izumi Group, consisting of the black fault gouge and the disturbed zone. The former, striking N 76°E and dipping 60° northward, is roughly 100 m wide. The latter, accompanied with the boudinage structure, strikes N 70°W and dips 70° northward.

2. Deformation of the Izumi Group

2.1. Folds

2.1.1. *Major syncline*

The Izumi Group (IZL1 ~ 9 and IZM1 ~ 2) in the west of this area forms a major syncline. This syncline can be traced from Onoyama Pass, Wakayama City, westward for more than 15 km long into Ishibashi, Misaki-Cho, Osaka Prefecture. At the west of this area, this syncline gradually becomes a part of synclinorium. As the syncline is well seen along the river and road (Route 26) at Kyoshi, Misaki-Cho (ICHIKAWA,

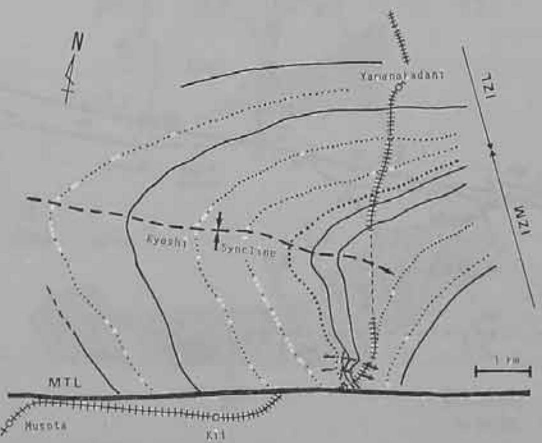

Fig. 17. Major syncline shown on a topographic surface of 200 m above sea-level. Solid line: Tuff layers, Dotted line: Boundary of sedimentary cycles.

1968), the name "Kyoshi syncline" is, for the convenience of description, given to it. The trace of axial surface, eliminating the effect of topography, shown a nearly straight E-W trend (Fig. 17). This syncline is analyzed using the acidic tuff as a key bed. The axis has a trend of S 80° E ~ E and a plunge of about 38~42°. Strike and dip of strata of the northern limb of the syncline are in harmony with those of a homocline in the eastern part of this area. The Kyoshi syncline becomes open eastward and becomes obscure eastward. The fold-axis is not cut directly by the MTL (MIYATA and ICHIKAWA, 1971).

2.1.2. *Anticlines along the MTL*

Two small-scale anticlines (Fig. 18), having a half-wavelength of 0.5 ~ 2.5 km, are developed in the Izumi Group along the MTL in the western part of the Izumi Mountain-

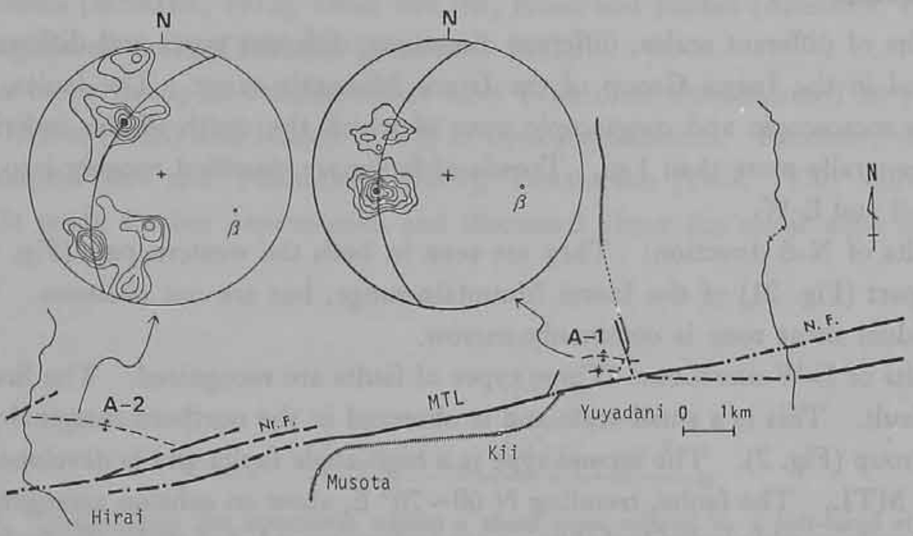

Fig. 18. En echelon folds and en echelon faults in the western part of the Izumi Mountain-range.
MTL: Main fault of the MTL, Nr.F.: Narutaki fault, N.F.: Negoro fault, π-diagrams: Bedding planes of the Izumi Group, plotted in equal area projection on the lower hemisphere (A-1: Total 44, 14-12-10-8-6-4-2-0, A-2: Total 50, 6-5-4-3-2-1-0).

range. One is the A-1 anticline at north of Yuyadani, with a fold-axis trending S80°E and plunging about 40°. It is seen stratigraphically in strata of the IZM1. On the south, the strata form a small-scale syncline. The other is the A-2 anticline at the north of Kawarazaki, with an axis trending S65°E and plunging about 37°. This is recognized in strata of the IZL3 ~ 5.

The anticlines are upright folds, having a nearly vertical axial plane, and are arranged en echelon along the MTL. Their axial traces incline at an angle of 10~20° to the MTL in a clockwise direction, and are a left-hand arrangement.

2.1.3. *Minor folds*

The Izumi Group in this area contains small-scale folds with a half-wavelength less than 10 m. Fan fold and chevron fold with upright axial planes are sometimes found near the MTL. Upright folds with sharp hinges and planar limbs, which are observed at the west side of Mikasa pond along the Route 26, have nearly horizontal fold-axes, trending S72°W. These axes incline at angles of about 15 ~ 20° to the branch fault of the MTL. This relationship is similar to one between the small-scale anticlines and the main fault of the MTL.

Another folds are generally open concentric folds having inclined axial planes. Fold-axes trend generally N30~70°E and nearly horizontal. On account of these folds, the strata on the southern limb are often overturned, so that they are inverted locally. But details are not dealt with here, because they are not related to the main theme of the present paper.

2.2. Faults

Faults of different scales, different directions, different types and different ages are recognized in the Izumi Group of the Izumi Mountain-range. The faults, here dealt with, are mesoscopic and megascopic ones of which the width of the individual shear zone is generally more than 1 m. Trends of faults are classified roughly into two directions, N-S and E-W.

Faults of N-S direction: They are seen in both the western part (Fig. 2) and the eastern part (Fig. 21) of the Izumi Mountain-range, but are not common. The width of individual shear zone is commonly narrow.

Faults of E-W direction: Three types of faults are recognized. The first type is a normal fault. This is a small-scale and is observed in the northern marginal part of the Izumi Group (Fig. 2). The second type is a high-angle faults and is developed typically near the MTL. The faults, trending N 60$\sim$70° E, show en echelon arrangements (Fig. 21). They have wide individual shear zones and are regarded as strike-slip faults as will be discussed in IV. The third type is a reverse fault. It trends in a E-W to WNW-ESE direction, and is generally a boundary fault between the Izumi Group (or the Sambagawa metamorphic rocks) and the Shobudani Formation (or terrace deposits). With two reverse faults, the Izumi Group, the Sambagawa metamorphic rocks and the Shobudani Formation form a piled structure form north to south. The effect of shearing of the Izumi Group (or the Sambagawa metamorphic rocks) is stronger and more extensive than that of the Shobudani Formation.

IV. En echelon folds and en echelon faults along the MTL

1. Terminology and previous work

The formation of en echelon folds has been demonstrated experimentally by TOKUDA (1926). En Echelon folds, arranged generally oblique to the wrench fault, have been discussed by MOODY and HILL (1956). They used the term "drag fold" in their case. Subsequently, the experimental approaches for the formation of folds related to the wrench fault were made by PAVONI (1961) (cf. GARFUNKEL, 1966) and WILCOX *et al.* (1973). According to them, the axial traces of en echelon folds are arranged at an angle of 30$\pm$15° to the main fault direction, in a clockwise (left-hand) or counterclockwise (right-hand) direction, caused either by the left-lateral or right-lateral wrenching, respectively (Fig. 19). There are many reports about folds related to the wrench fault, for example, en echelon folds along Alpine fault, New Zealand (BISHOP, 1968), Anaco

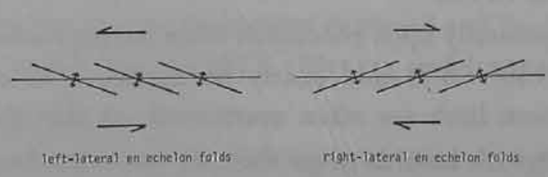

Fig. 19. Patterns of en echelon folds related to a wrenching.

fault, Venezuela (MURANY, 1972), Dead Sea rift, Israel and Jordan (AHARONI, 1966) and Newport-Inglewood fault, California (HARDING, 1973).

On the other hand, en echelon faults have been once demonstrated by FUJIWARA (1924), H. CLOOS (1928) and RIEDEL (1929) in their experiments. Recently, SKEMPTON (1966), MORGENSTERN and TCHALENKO (1967), TCHALENKO (1968, 1970) and WILCOX *et al.* (1973) made further experiments and discussed about the shear zone structures (Fig. 20).

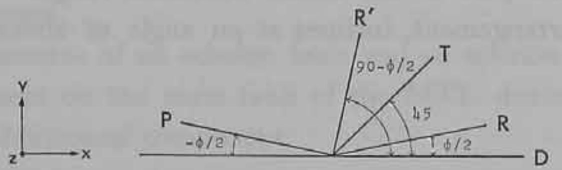

Fig. 20. Terminology for structures within a shear zone related to a left-hand simple shear.
D: Principal displacement shear, P: Thrust shear, R: Riedel shear, R': Conjugate Riedel shear, T: Tension fracture, ϕ: Peak angle of shearing resistance.

Riedel shears: The Riedel shears(R) typically lie en echelon, inclines at an acute angle of about $\phi/2=10\sim30°$ to the general direction of relative movement, where ϕ means the peak angle of shearing resistance and is about 24°. They are accompained ideally by conjugate Riedel shears(R'), at an angle of about $90°-\phi/2=70\pm10°$ to the general direction of relative movement, but this type of shears(R') is poorly formed and then has a small amount of displacement.

Thrust shears: Shear planes have an orientation opposite to the Riedel shears, i.e. at an acute angle of about $-\phi/2$ to the direction of movement. They are denoted by the letter P.

Principal displacement shear: Continuous shear plane lying in the general direction of movement is the principal displacement shear(D). According to SKEMPTON (1966), the principal displacement shear (or principal slip surface) is used (1) when slips become concentrated along displacement shears, which are defined as shorter shear planes lying parallel or subparallel with the general direction of movement, (2) when the displacement shears become continuously clear with increasing movement.

Tension fractures: The tension fractures (or normal faults) (T), are formed when the confining pressure is small. They develop at an angle of about 45° to the direction of movement.

En echelon Riedel shears are arranged in a counterclockwise (right-hand) or clockwise (left-hand) direction, caused by the left-lateral or right-lateral wrenching, respectively. The Riedel shears have the same sense of strike slip as that of the principal displacement shear. The superficial en echelon arrangement of Riedel shears have been recognized in the earthquake faults associated with a strike-slip component, for example, the Dasht-e Bayaz erathquake fault (August 31, 1968), Iran (TCHALENKO and BERBERRIAN, 1975) and the Hauytapallana fault (Pariahuanca earthquake, July 24 and October 1, 1969), Central Peru (PHILIP and MEGARD, 1977). The similarities in oblique en echelon pattern taking place on the shear box experiment, clay experiment and earthquake fault, is interpreted as indicating similarities in the deformation mechanism (TCHALENKO, 1970).

2. Results and discussion

En echelon folds and en echelon faults are developed in the Izumi Group along the main fault of the MTL (Figs. 18 and 21). As discussed in III.1.2, they are concerned with the deformation which took place after the deposition of the Izumi Group and prior to the deposition of the Shobudani Formation, probably prior to the deposition of the Kuma Group in west Shikoku.

En echelon folds are the small-scale upright anticlines, A-1 and A-2 as described in III. 2.1, in the western part of the Izumi Mountain-range. The anticlines show a left-hand en echelon arrangement, inclines at an angle of about 10～20° to the main fault of the MTL.

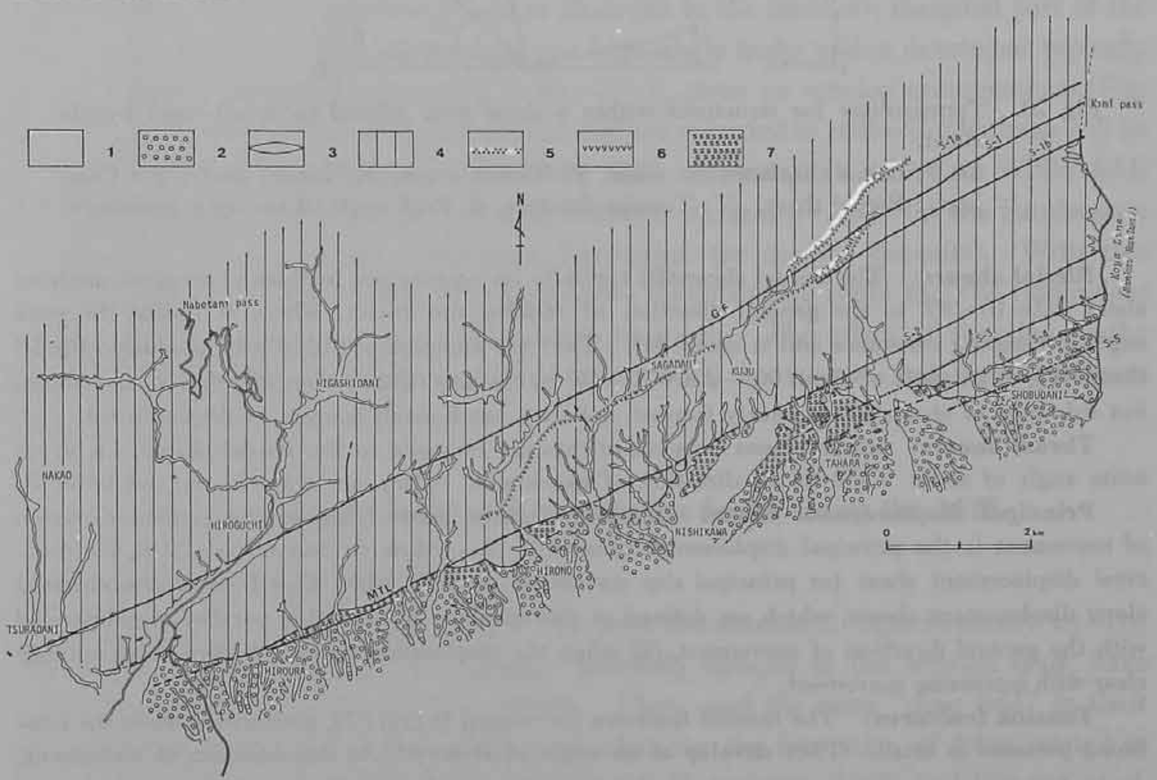

Fig. 21. En echelon faults along the MTL in the eastern part of the Izumi Mountain-range (after MIYATA *et al.*, 1974; RESEARCH GROUP for MTL in WEST KINKI, 1978).
1: Recent alluvial deposits, 2: Terrace deposits and Shobudani Formation, 3: Dykes, 4–6: Izumi Group (particularly, 5: Coarse-grained sandstone, 6: Tuff), 7: Sambagawa metamorphic rocks, MTL: Main fault of the MTL, G.F.: Gojodani fault, S-1～S-5: Fault noted by MIYATA *et al.* (1974). For location see Fig. 1b.

En echelon faults are composed of the following individual fault, branching off from the main fault (ICHIKAWA and MIYATA, 1976; MIYATA *et al.*, 1974): e.g. Narutaki fault, Negoro fault, Gojodani fault, faults of S-2～S-5 etc. They are high-angle faults, accompanied with wide shear zone. The Negoro fault shows a left-lateral strike separation of about 0.5 km on the basis of the correlation between tuffs cut by this fault, as mentioned in II. 3.2. Also, the Gojodani fault reveals the left-lateral strike separation of about 1.3 km on the basis of the tectonic feature of the fault and the correlation between characteristic tuffs and sandstone beds cut by this fault (RESEARCH GROUP for MTL in WEST KINKI, 1978, 1980 in preparation). Individual fault of Riedel-shear type shows a right-hand en echelon arrangement, inclined at an acute angle of about $10\sim20°$ to the main fault. According to OKADA and SANGAWA (1978), the late Quaternary right-lateral horizontal displacements are also recognized along the Negoro fault and Gojodani fault. Therefore, the amounts of the ancient left-lateral horizontal displacement are considered to be larger than the above-noted figures.

Judging from the patterns of en echelon folds and en echelon faults, it is concluded that the faulting movement on the main fault of the MTL during Paleogene time has a prominent left-lateral horizontal component.

V. Boudinage structure along the MTL

1. Terminology and previous work

The term "boudinage structure" as introduced by LOHEST *et al.* (1909) refers to the sousage-like structure of segments of layers in cross section. Each segment is called a boudin. These terms used are descriptive. As to the process of formation of boudins, the term "boudinage" is used (RAMSAY, 1967). According to RAMSAY (1967), the boudinage structure is always separated into a number of boudins, whereas the pinch-and-swell structure is continuous. However, the term "boudinage structure" is used here in a wide sense and no strict separation is set between them.

The cross-sectional shape of boudins varies widely. It is divided typically into four types: (1) lenticular (lens-like), (2) rectangular, (3) barrel-shaped, and (4) rhomboidal (rhombic and lozenge-shaped) boudins (cf. RAMBERG, 1955; WHITTEN, 1966; STRÖMGÅRD, 1973). Boudins of lenticular, rectangular and barrel-shaped types may be equivalent to those of flow, fracture and combination between flow and fracture, respectively, of the scheme by SMITH (1975). The rhomboidal boudins is well known as a tectonic lens (UEMURA, 1965).

The descriptive terminology used for the boudin is shown in Fig. 3 of MIYATA (1975). The terms used in JONES (1959) is essentially followed, except for the term "length" which is applied in the sense of RAMBERG (1955).

The three dimensional shape of boudins is divided essentially into two types (Fig. 22): (1) type I, which has one neckline and is known as cylinder-shaped boudin (CLOOS, 1947), and (2) type II, which is segmented in two directions to produce fairly equidimensional boudin, e.g. chocolate tablet boudin (WEGMANN, 1932), barrel-shaped boudin (COE, 1959), disk-like boudin (RAMBERG, 1955), pillow-like boudin (JONES, 1959) and so on.

Most of the earlier works on boudinage structures have been summarized by WHITTEN (1966). As for recent works on this subject, one can recognize two standpoints. One is the works on boudinage structures, dealt with the stress, mechanical properties

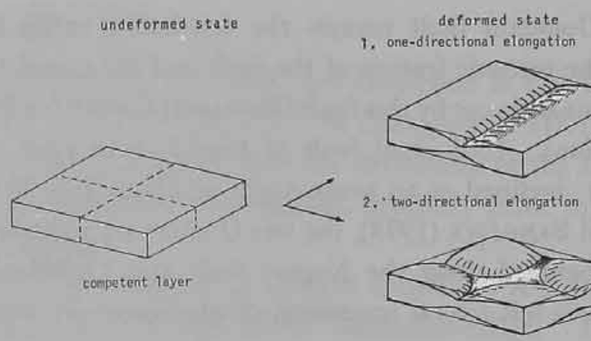

Fig. 22. Three-dimentional geometry of boudinage structures.

of layer, and/or strain (or strain-rate) related to the formation of boudins (e.g. RAMERG, 1955; RAST, 1956; UEMURA, 1965; VOIGHT, 1965; PATERSON and WEISS, 1968; SCHWERDTNER, 1970; STEPHANSSON and BERNER, 1971; STRÖMGÅRD, 1973; MIYATA, 1975; RONDEEL *et al*, 1975; EKSTRÖM, 1975; SMITH, 1975, 1977). The other is the papers, discussed the orientation and shape of the strain ellipsoid using boudinage structures (e.g. FLINN, 1962; RAMSAY, 1967; TALBOT, 1970; UMEMURA, 1973; SANDERSON, 1974).

The boudinage structure in the Izumi Group was already discussed in the previous papers (MIYATA, 1975). Some of the results will be cite and have together with additional discussion.

2. Distribution and occurrence

Boudinage structure is found in sandstone layers of various thickness, which are in alternation with mudstone layers. As is clear from Fig. 23, the boudinage structure is

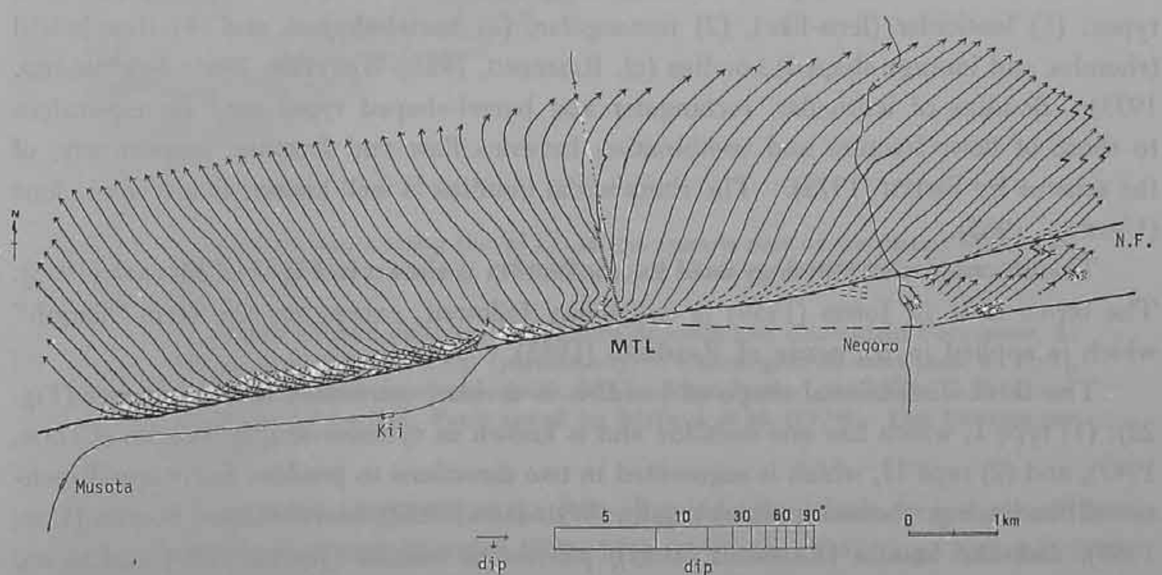

Fig. 23. Strike line map of the Izumi Group along the MTL.
Short dashed lines: Overturned beds, Dotted part: Distribution of boudinage structures. The strata dip to the right side of the arrow.

not related with any stratigraphically limited part of the Izumi Group. The boudinage structure cannot be found in the whole part of northern limb and the main part of the major syncline, but developed in the disturbed zone along the MTL. Furthermore, the boudinage structure is not developed in the normal sequence of the Izumi Group to the north of the disturbed zone.

Formation of boudinage is limited commonly in the domain in which the strike of the Izumi Group in the disturbed zone is (a) parallel to subparallel or (b) inclined clockwise to the trend of the MTL, but is hardly found in the domain in which the strike of the Izumi Group is (c) normal to subnormal or (d) inclined counterclockwise to the trend of the MTL (Fig. 23).

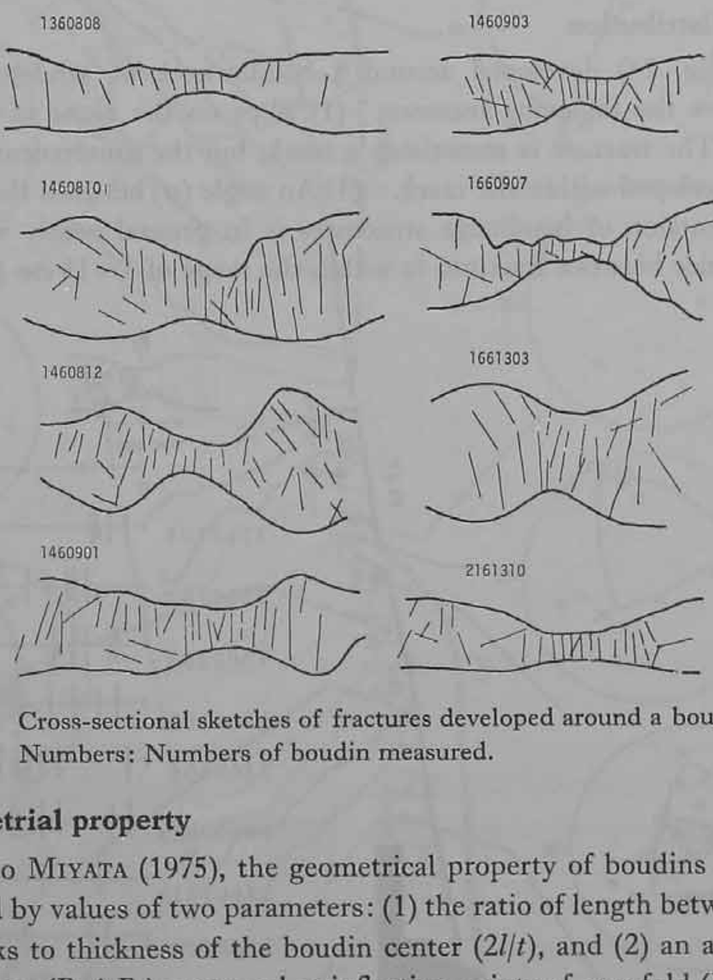

Fig. 24. Cross-sectional sketches of fractures developed around a boudin-neck. Numbers: Numbers of boudin measured.

3. Geometrial property

According to MIYATA (1975), the geometrical property of boudins in a cross-section can be expressed by values of two parameters: (1) the ratio of length between neighbouring two boudin-necks to thickness of the boudin center ($2l/t$), and (2) an angle between two surface inclinations ($B_1 \wedge B_2$) measured at inflection points of scar fold (Fig. 27). Length of boudins versus thickness of boudins shows a linear trend of increasing length of boudins with increasing thickness of boudins. Values of $2l/t$ on E-W direction and on N-S direction are average 2.6 and 2.7, respectively. The majority of 2ψ-value is greater than 90°. The mean value of 2ψ is within the range of $115 \sim 120°$. The boudin of the lenticular type of the Izumi Group along the MTL is characterized by the ratio of $1.5 < 2l/t < 5.0$ with means values of 2.6 and 2.7.

The similar relationship has been recognized in the rectangular type ($1.3<2l/t<4.0$ with a mean ratio of 2.3, after UEMURA, 1965), and in the barrel-shaped type ($2.3<2l/t<4.0$ with a mean value at about 1.9, after RONDEEL and VOERMANS, 1975) from field data. It can be considered that boudins have dominant lengths just as folds have dominant wavelengths. According to SMITH (1975, 1977), the $2l/t$ may be related to the viscosity ratio between the boudin and surrounding incompetent layers for boudinage.

The three dimentional shape of boudins in the Izumi Group is the disk-like in the Type II. Ratio of longer axis of a disk-like boudin to its shorter axis is within the range of $1.3\sim1.9$ (MIYATA, 1975). Judging from this, the deformation of the Izumi Group, which formed the boudinage structure along the MTL, is considered to be a flattening type ($0<k<1$) according to FLINN (1962).

4. Strain distribution

Fractures (Fig. 24) developed around a boudin-neck of sandstone beds of the Izumi Group have the following features: (1) Slips on the plane of fractures are not recognized. (2) The fracture is sometimes a crack, but the simultaneously recrystallized mineral is not developed within the crack. (3) An angle (α) between the plane of a fracture and the orientaion of boudinage structures is in general nearly vertical (Fig. 25). And (4) the distance between fractures is within the range of $1\sim15$ cm (Fig. 26).

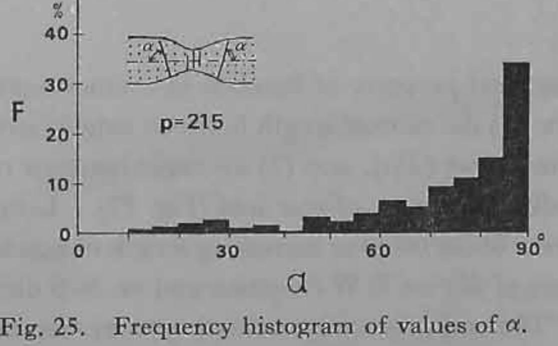

Fig. 25. Frequency histogram of values of α.

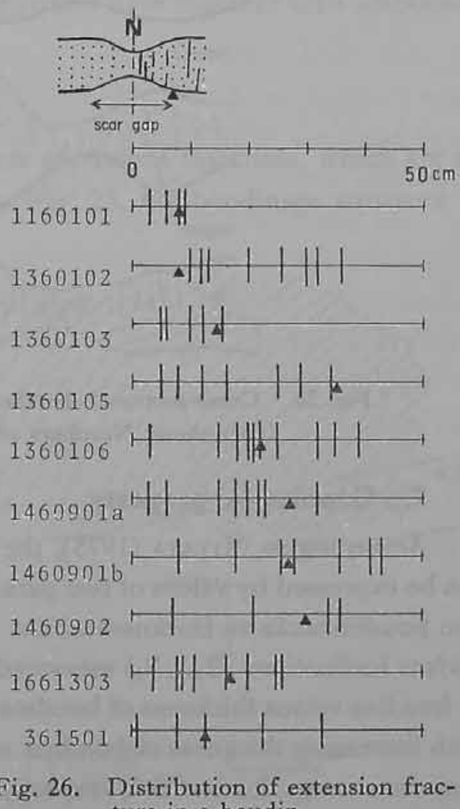

Fig. 26. Distribution of extension fracture in a boudin.
Triangle: Half length of scar gap, N: Center of a boudin-neck, Numbers: Numbers of boudin measured.

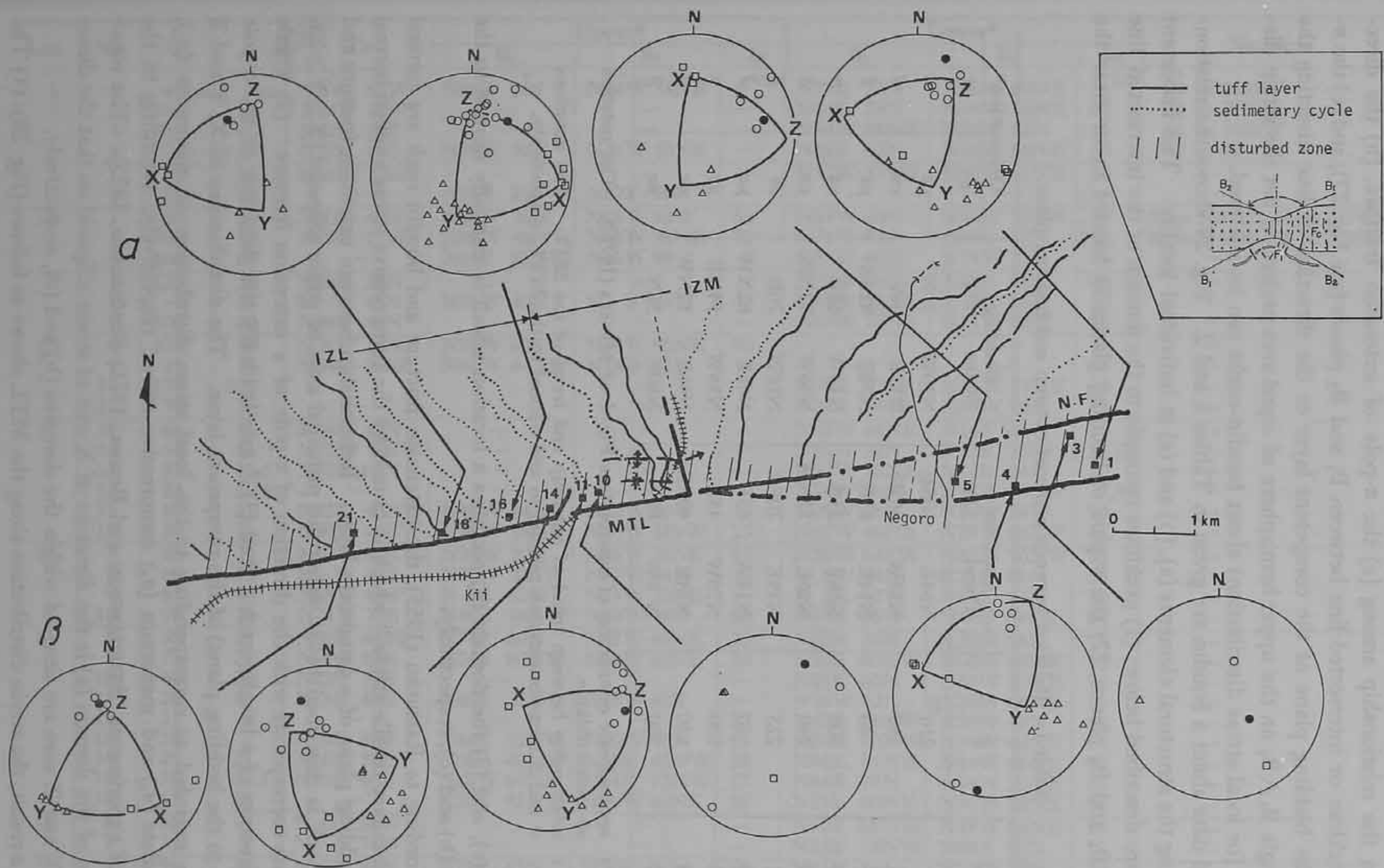

Fig. 27. Upper hemisphere equal area sterographic projection of boudinaged elements.
X, Y, Z: Axes of strain ellipsoid (X≥Y≥Z), Open square: π-pole of extension fracture developed in a boudin-neck, Black triangle: Neckline (or intersection line between B_1 and B_2 planes), Open circle: Direction of line bisecting an obtuse $B_1 \wedge B_2$, Black circle: π-pole of a bedding plane, Numbers: Localities of analysis of boudins. For explanation of α and β see Table 1.

From the relationship among (a) the π-pole of extension fracture, (b) the direction of neckline or intersected line between B_1 and B_2 planes (see Fig. 27), and (c) the π-ploe of the bedding plane of the competent layer or the direction of line bisecting the obtuse angle $B_1 \wedge B_2$ on the upper hemisphere of equal area projection net the strain distribution (or local stress distribution) about boudin-necks can be analyzed.

Field data about a boudin are given in Tables 1 and 2. Fig. 27 shows the relationship among the structural elements (a), (b) and (c) at individual locality. The important features are described below: (1) necklines reconsile to the domain of the intersceted line between B_1 and B_2 planes, (2) the π-ploe of bedding planes is located in or near the domain (c), and (3) the domain (a) occupies a location which is mutually normal to the domains (b) and (c), respectively.

Table 1. Relation between plane of outcrop and bedding plane.

Loc.	δ	Outcrop Trend	Outcrop Dip	Bedding Strike	Bedding Dip	Orientation* ϕ	Orientation* γ
1	210^m	N64°E	50°SE	N70°W	70°N	*yz*	α
3	540	N14W	66W	N12E	4W	*xz*	β
4	80	N14E	65E	N78E	82SE	*yz*	β
5	300	N68E	85S	N10W	60E	*yz*	α
10	240	N26E	72NW	N36W	72NE	*yz*	β
11	225	N39E	70SE	N16W	70E	*ob*	β
14	30	N18W	65E	N66E	62NW	*yz*	β
16	100	N70W	45S	N56W	54NE	*xz*	α
18	130	N54E	40SE	N66E	52NW	*xz*	α
21	300	N 6W	80W	N80E	52N	*yz*	β

* ϕ : approximate orientation of outcrop (see Fig. 3 of MIYATA [1975]). The notation *ob* means oblique.
γ : relationship between trend of outcroup and trend of the MTL. The notations α and β mean orientation parallel to and normal to the MTL, respectively.

According to RAMBERG (1955), the extension fracture and boudin neck are formed by a "secondary tensile stress," which is caused by the compressive stress applied normal to the bedding plane of a competent layer. Relationship between extention fracture and boudin-neck is described below using the principal axes of strain ellipsoid ($X \geq Y \geq Z$): (1) X axis corresponds with the direction of π-pole of a extension fracture. (2) Y axis is the direction of a boudin-neck. And (3) Z axis is ideally the direction of the π-pole (normal to the bedding plane) of the competent layer. The distributions of X, Y and Z axes are regarded as corresponding to the local stress distribution of minimum (σ_3), intermediate (σ_2) and maximum (σ_2) compressive stress, respectively, according to the results of experiments (STEPHANSSON and Berner, 1971; STRÖMGÅRD, 1973). The mean direction of the domain (a) is the direction of X axis of strain ellipsoid so that the direction of Y and Z axes are situated within the domains (b) and (c), respectively.

As a result, the strain distribution along the MTL shows as follows (Fig. 28): (1) The

Table 2. Measurement of boudins.

Loc.	No.	$2l$	t	Fc	Upper*			Lower*			Neckline
					B_1	B_2	$2g$	B_1	B_2	$2g$	
1	1	45cm	7cm	N20°E 60°W	N80°E 24°S	N64°W 54°NE	—cm	N78E 24N	N66W 60NE	—cm	22° to N51°W
	2	105	20	N54W 20SW	—	—	—	N84E 24N	N56W 50NE	68	28 to N50W
	3	135	46	N22E 86E	—	—	—	N34W 58NE	N76W 62N	—	48 to N26W
	4	73	35	N20E 84E	N70W 32N	N41W 50NE	—	N86E 42N	N28W 66NE	45	62 to N-S
3	1	72	15	N56E 70SE	—	—	—	N57W 33SW	N66W 41NE	26	—
	2	51	12	—	N76E 24S	N62E 70NW	—	—	—	—	—
4	1	80	35	N20E 40N	N84W 70N	N86W 88W	60	N84W 80N	N46W 78SW	90	50 to N61W, 48 to N74W
	3	200	50	N19E 75W	N80W 60N	N66W 78NE	70	N71W 80S	N68E 62N	110	48 to N44W, 58 to N76W
	4	160	60	—	N64E 52NW	N66W 90	5	N83W 40N	N74W 72N	6	—
5	1	125	30	N80E 58N	—	—	—	N70W 60N	N14E 48E	40	—
	3	—	35	E-W 45N	N76W 40N	N-S 84W	—	N48W 22NE	N 9E 78E	50	—
	4	100	30	N89E 42N	—	—	—	N60W 70NE	N11W 82W	35	—
10	8	170	50	N36W 10NE	N72W 62S	N40W 80NE	90	—	—	—	—
	9	31	11	N84E 36SE	N48W 44NE	N14W 52E	—	—	—	14	—
	10	170	100	—	—	—	—	N38E 50SE	N64W 74NE	90	—
	11	70	25	—	—	—	—	N28E 28SE	N84W 86S	52	—
11	11	63	11	N74E 42N	—	—	—	N48W 44NE	N16E 68W	16	—
	12	55	15	N52W 30SW	—	—	—	N80W 22N	N12E 76W	17.5	—
	13	37	11.5	N72E 62N	—	—	—	N43W 58NE	N12E 74W	30	—
	14	23	10.5	—	—	—	—	N74W 50N	N28W 84SW	7.5	—
	15	67	21	N32E 40NW	N48W 44NE	N20W 76W	—	N70W 38N	N10W 74W	70	—
	16	59	21	N30W 60SW	N48W 38NE	N30W 54SW	25	N62W 46NE	N28W 46SW	45	—
14	7	85	38	N52W 70SW	N20W 20E	N66W 79NE	15	N28W 64SW	N48E 70NW	72	—
	8	65	52	E-W 42S	N30W 32SW	N82W 64N	—	N 6W 44N	N74E 66N	55	—
	9	65	40	N68W 60S	N 6E 62W	N54W 70NE	—	N 2E 32W	N84E 44N	54	—
	10	98	23	N74W 70S	N90E 39NW	N80W 48N	60	N10E 68W	N44E 88SE	60	—
16	8	30	17	N30E 64SE	N74E 60N	N32W 40NE	21	N80E 70N	N20W 54E	16	—
	9	75	22	N 4W 82E	N34E 60NW	N48W 62NE	34	N56E 60NW	N60W 60NE	30	—
	10	40	22	N22E 72E	—	—	—	N84E 60N	N34W 50NE	35	—
	11	20	14	N 4E 80E	N60E 38NW	N18W 42E	—	N76W 62N	N26W 66NE	—	—
	12	21	9	—	—	—	17	N42E 76NW	N70W 48N	16	—
	13	30	7	N 6E 62E	N44E 52NW	N70W 48N	16	N54E 60NW	N46W 40NE	17	—
	14	29	21	N 6E 84E	N66E 48NW	N50E 48NW	28	N66E 64NW	N44W 66NE	27	—
	15	30	23.5	N16E 68E	N28W 64NE	N14E 72NW	27	N84E 78N	N54W 70NE	35	—
	16	65	26	—	N30E 42NW	N46W 46NE	56	N58E 60NW	N50W 52NE	54	—
18	6	35	17	N 6E 80W	—	—	—	N62E 68NW	N48W 60NE	17	—
	7	26	7	N-S 74W	—	—	—	N58E 78NW	N88E 84N	15	—
21	1	36	33	N 8E 80E	N76E 82N	N70E 36N	30	N74E 76N	N72W 30N	20	—
	2	25	8.5	N16E 84E	N22E 44W	N60W 34NE	15	—	—	—	—
	3	15	4.5	N64E 42SE	N69E 58N	N42E 36NW	14	N80E 60N	N82W 40N	7	—
	4	25	6	N36E 60SE	—	—	—	N78E 52N	N56W 32NE	10	—

* see Fig. 27b.

For notations Fc, B_1 and B_2 see Fig. 27b. Notations $2l$, t and $2g$ mean length and thickness of a boudin and scar gap, respectively.

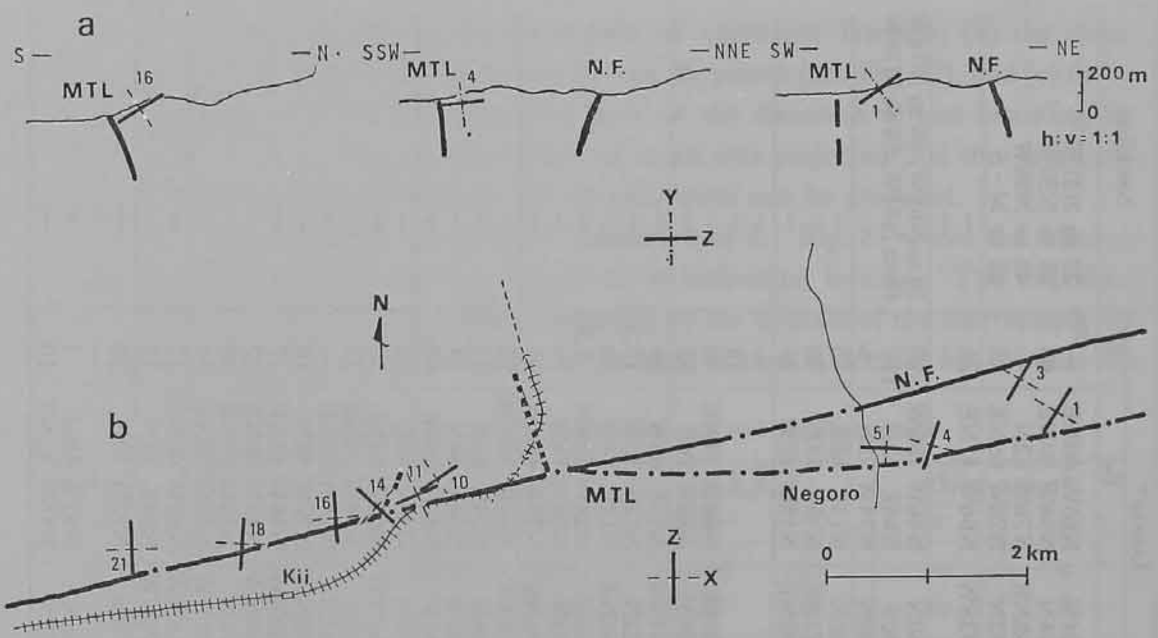

Fig. 28. Distribution of axes of strain ellipsoid (X≥Y≥Z)
a) Pofile section on ZY-plane, MTL: Main fault of the MTL, N.F.: Negoro fault, Numbers: Localities of analyzed boudins in Fig. 27.
b) Distribution of XZ-plane.

X axis is almost horizontal and trends nearly E-W to NW-SE. (2) The Y axis plunges northward at an angle ranging from 60° to nearly vertical. And (3) the Z axis takes the orientation striking N-S to N 20°E, and nearly horizontal to dipping about 30° southward. This result does not contradict with the strain distribution resulting from the left-hand simple shear along the MTL.

5. State of strain

MIYATA (1975) discussed that value of quadratic elongation (λ), obtained at several localities in the segment B along the MTL, shows the range of $1.1 \sim 3.0$ (exceptionally 9.1), and also, varies in the wide range within individual outcrop. This range shows the strain state of the typical boudin in the disturbed zone along the MTL.

Fig. 29 shows the relationship between the quadratic elongation (λ) in a boudin and the distance (δ) from the MTL. From Fig. 29, it can be seen that the maximum value of quadratic elongation about boudins within the disturbed zone has a tendency to decrease with an increase of the distance from the MTL. In another word, it is inferred that the boudinage structure of the Izumi Group within the disturbed zone becomes less significant with an increase of the distance from the MTL. Farther from the MTL to the north, the Izumi Group changes gradually to the normal sequence without boudinage.

Based on the analysis of mircofabrics in the granite of the Ryoke belt in central Kinki, HARA and YOKOYAMA (1974), and HARA *et al.* (1977) discussed that the ductile shear zone (ca. 6.5 km wide) along the MTL of the pre-Izumi time (Fig. 32) is characterized by

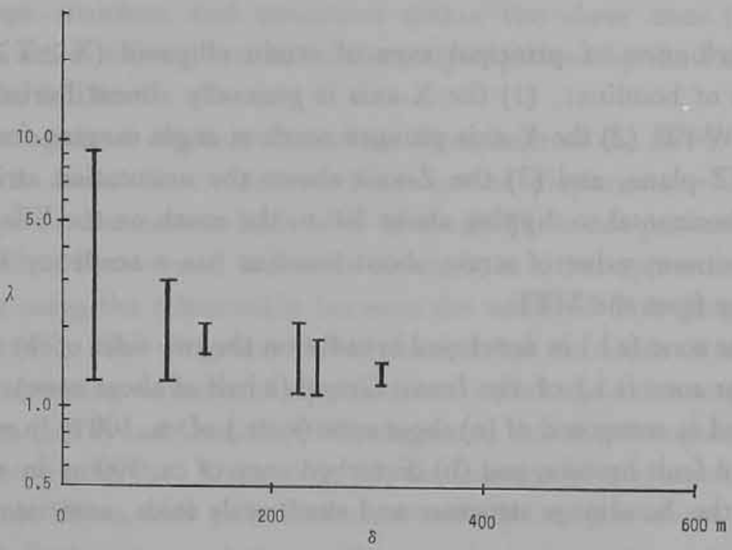

Fig. 29. Relationship between quadratic elongation (λ) and distance (δ) from the MTL (after Miyata, 1975).

a continuous increase of the shear strain toward the MTL from the north. The present result obtained in west Kinki for post-Izumi time shows essentially the similar tendency as that by Hara *et al.* (1977). The strain features along the MTL of post-Izumi time can be also attributed to a simple-shear mechanism (cf. Ramsay and Graham, 1970).

VI. Movement picture of the MTL in Southwest Japan

1. West Kinki

From the detailed field examination, it has been verified that the structural elements—folds, faults and boudins—are developed in the Izumi Group along the MTL. They can be regarded as the most salient structures related to the faulting on the MTL. As a result of tectonic analysis on them, it has become clear that the MTL along the southern margin of the Izumi Mountain-range has a strain picture as follows:

1) En echelon folds show a clockwise (left-hand) distribution pattern (Miyata, 1972; Ichikawa and Miyata, 1973, 1976).

2) En echelon faults of Riedel-shear type show a counterclockwise (right-hand) distribution pattern (Miyata *et al.*, 1974; Ichikawa and Miyata, 1976).

3) Left-lateral strike separations, as described in IV, are recongnized along the Negoro fault (Miyata, 1978) and Gojodani fault (Research Group for MTL of West Kinki, 1978), on the basis of the correlation between characteristic tuffs and/or sandstone beds cut by these faults.

4) The boudinage structure is developed commonly within the disturbed zone where the strike of the bedding plane of the Izumi Group is parallel to subparallel or inclined clockwise to the MTL, but is hardly recognized in the domain where the strike of bedding plane of the Izumi Group is normal to subnormal or inclined counterclockwise to that

of the MTL.

5) The distribution of principal axes of strain ellipsoid ($X \geq Y \geq Z$) is obtained from the analysis of boudins: (1) the X-axis is generally almost horizontal and trends nearly E-W to NW-SE, (2) the Y-axis plunges north at angle ranging from 60° to nearly vertical on the YZ-plane, and (3) the Z-axis shows the orientation striking N-S to N 20°E and nearly horizontal to dipping about 30° to the south on the YZ-plane.

6) The maximum value of strain about boudins has a tendency to decrease with increasing distance from the MTL.

7) The shear zone (s.l.) is developed broadly on the two sides of the main fault of the MTL. The shear zone (s.l.) of the Izumi Group (a half of shear zone) attains to about 600 m in width and is composed of (a) shear zone (s.str.) of ca. 100 m in width, consisting of fault gouge and fault breccia, and (b) disturbed zone of ca. 500 m in width, which is characterized by the boudinage structure and small-scale folds, associated with bedding slips and shears.

8) The fault plane of the main fault of the MTL dips generally northward at angles ranging from 55° to nearly vertical.

These features are concerned with the deformation which took place after the deposition of the Campainan～Maastrichtian Izumi Group and is prior to the Middle Miocene, probably prior to the Middle Eocene, as mentioned in III. 1.2. Judging synthetically from the above-noted strain picture, it can be concluded that the movement picture of the Paleogene MTL in west Kinki is more prominent left-lateral strike-slip than the dip-slip. The formation of deformed structures such as en echelon folds, en echelon

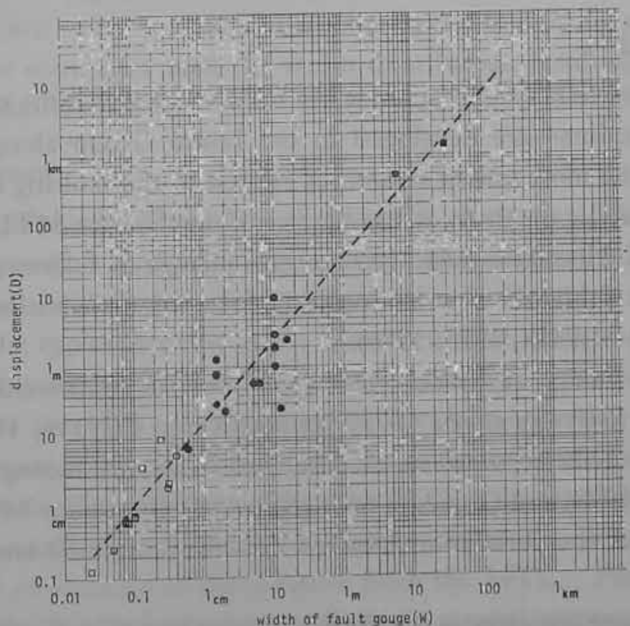

Fig. 30. Relationship between amount of displacement and width of fault gouge. Open square: Mean value of Engelder's (1974) data, Black circle: Minor faults within the Izumi Group, Black square: En echelon faults (Negoro fault and Gojodani fault) along the MTL.

faults, boudinage structure and structures within the shear zone (s.str.), which was recorded in the Izumi Group, can be consistently explained by the Paleogene left-lateral wrenching on the MTL.

Next, the amount of displacement of the main fault of the MTL in west Kinki will be discussed. A direct determination of amount of displacement is difficult, because any geologic marker common to both sides of the MTL is not preserved along the main fault of the MTL. However, it is able to estimate, as a first approximation, the amount of displacement using the relationship between the width of fault gouge and the amount of displacement (Fig. 30). Engelder (1974) pointed that the width of fault gouge tends to increase with increasing amount of displacement under the microscopic level. Subsequently, MIYATA (1978) and OTSUKI (1978) suggested that it is recognized through microscopic to megascopic levels. Using Fig. 30, the amount of displacement relative to the fault gouge of ca. 100 m wide (a half of shear zone [s. str.]) is about 7.5 km. By symmetry the total displacement relative to the two shear zones (s. str.) of both the Izumi Group and the Sambagawa metamorphic rocks is estimated at about 15 km.

2. East Chubu

The MTL forms a convex to the north across the eastern part of Southwest Japan. The Akaishi Tectonic Line and Komyo fault, branching off from the MTL, extend to the south (Fig. 31). The left-lateral strike slips along the Akaishi Tectonic Line and

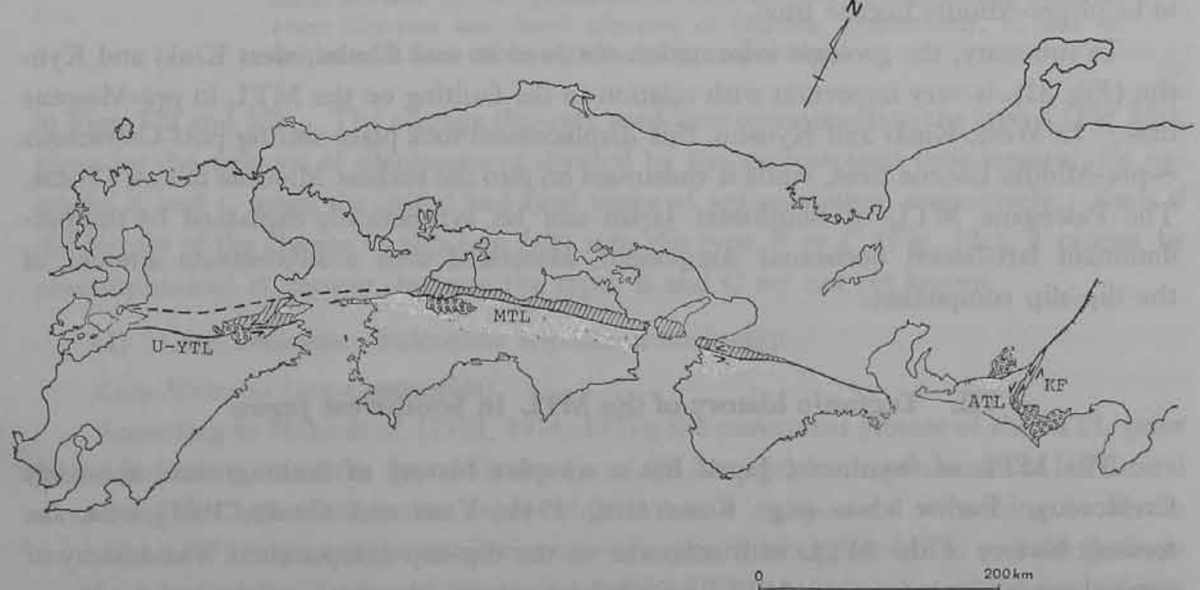

Fig. 31. Left-lateral wrenching along the MTL in Southwest Japan.
ATL: Akaishi Tectonic Line, KF: Komyo Fault, U-YTL: Usuki-Yatsushiro Tectonic Line, Dotted part: Sambagawa metamorphic rocks, Lined part: Upper Cretaceous strata, Circles: Miocene volcanics and/or sediments, Arrow: Sense of displacement.

the MTL in east Chubu are suggested by MAKIYAMA (1951) and KIMURA (1959). Recently, MATSUSHIMA (1973), MATSUSHIMA and SAKAMOTO (1976) and TSUNEISHI *et al.* (1975) discussed the left-lateral strike slips on the Akaishi Tectonic Line and Komyo fault. Total offset of the Butsuzo Tectonic Line, which is a boundary fault between the Chichibu belt and the Shimanto belt, is estimated at about 65 km along the Akaishi Tectonic Line and Komyo fault. This great amount of displacement can be considered to have caused also along the main fault of the MTL in east Chubu, because the Akaishi Tectonic Line and Komyo fault are regarded as Riedel shears branching off from the MTL. According to KIMURA (1959), MATSUSHIMA (1973) and TSUNEISHI *et al.* (1975), the age of the left-lateral wrenching on the MTL, Akaishi Tectonic Line and Komyo fault is regarded as pre-Middle Miocene time. The "Oligocene" or earliest Miocene Wada Formation is joined this deformation.

3. Kyushu

According to TERAOKA (1970), the MTL in Kyushu joints the Usuki-Yatsushiro Tectonic Line toward southwest. The Usuki-Yatsushiro Tectonic Line has a predominant left-lateral strike slip on the basis of structural pattern of en echelon folds, which were recorded in the Turonian-Santonian Onogawa Group (TERAOKA, 1977). The age of the left-lateral strike-slip faulting is the pre-Miocene, because the Usuki-Yatsushiro Tectonic Line does not cut the overlying Miocene volcanic rocks at the Sobosan District. As a comparison with the geologic relationship of Ishizuchi, west Shikoku, the age is estimated to be of pre-Middle Eocene time.

In summary, the geologic information obtained in east Chubu, west Kinki and Kyushu (Fig. 31), is very important with relation to the faulting on the MTL in pre-Miocene time. In West, Kinki and Kyushu, this displacement took place during post-Cretaceous ~pre-Middle Eocene time, while it continued on into the earliest Miocene in east Chubu. The Paleogene MTL of Southwest Japan can be synthetically explained by the predominant left-lateral horizontal component, associated with a subordinate amount of the dip-slip component.

VII. Tectonic history of the MTL in Southwest Japan

The MTL of Southwest Japan has a complex history of faulting since the early Cretaceous. Earlier ideas (e.g. KOBAYASHI, 1941; YABE and OZAKI, 1961) were the tectonic history of the MTL with reference to the dip-slip component. The history of vertical component along the MTL in Shikoku has been discussed and revised by NAGAI (1973), SUYARI and AKOJIMA (1973) and TAKAHASHI (1977) and others. However, recent views (since 1966) about movement on the MTL differ significantly from earlier ones. There are some geologic information of strike slip: (1) on the late Quaternary MTL in Shikoku and west Kinki (e.g. KANEKO, 1966; OKADA, 1968, 1970, 1973; HUZITA, 1969), and (2) on the pre-Quaternary MTL in Kinki and west Chubu (e.g. ICHIKAWA and MI-

YATA, 1973; HARA *et al.*, 1973; HAYASHI, 1978). The tectonic hisotry of the MTL with reference to the strike-slip component was synthesized by ICHIKAWA (1976, 1978a, 1978b).

The history of horizontal movement on the MTL is outlined below and is shown

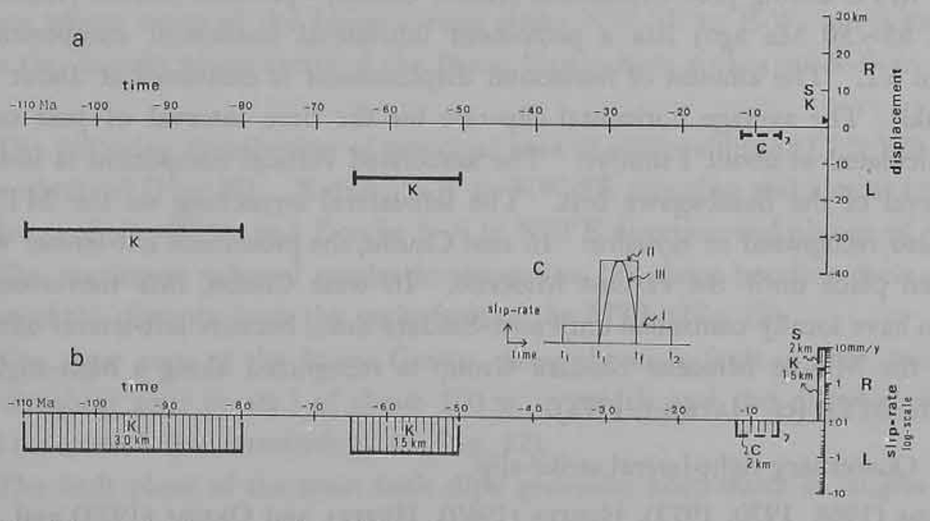

Fig. 32. Tectonic history of the MTL of Southwest Japan with reference to the strike slip.
a,b) R: Right-lateral strike slip, L: Left-lateral strike slip, C, K, and S: Data concerned with the MTL in the Chubu, Kinki and Shikoku Districts, respectively, Lined part: Amount of displacement.
c) Reference slip-rate. I: Average slip-rate, given by the amount of displacement divided by the geohistorical time interval ($t_1 \sim t_2$), II and III: Average slip-rate and dated slip-rate of faulting, respectively, t_i and t_f: Initial and final times of a faulting, respectively.

in Figs. 32a and 32b. The average slip-rate used here corresponds to the type A (Fig. 32c), given by the amount of displacement divided by the geohistorical time interval, for example, t_1 and t_2 mean the initial and final times of sedimentation, respectively. Even if the history of the change in slip-rate falls into the type B or C (Fig. 32c), it cannot be overemphasized at present, because the types B and C are not yet known.

(1) Late Mesozoic ~ Paleogene left-lateral strike-slip

Late Mesozoic (pre-Campanian)

According to HARA *et al.* (1973, 1974, 1977), the movement picture of the MTL prior to the sedimentaion of the Izumi Group (~ca. 80 Ma ago) has a predominant left-lateral wrenching in Chubu and farther west, while it has a right-lateral wrenching in Kanto on the basis of analyses of the microstructure of mylonite along the MTL and the geologic structure (en echelon folds and en echelon faults of Riedel-shear type) of the Sambagawa belt. According to them, the different sense of wrenching on the MTL is caused by non-uniform compression from the southern side. Initiation of the MTL is regarded as probably the early Cretaceous (ca. 110 Ma ago) (cf. HARA *et al.*, 1973). The amount of horizontal displacement within the ductile shear zone of the MTL in pre-Campanian age is estimated at about 30 km in east Kinki (HARA and YOKOYAMA, 1974; HARA *et al.*, 1977).

The average horizontal slip-rate for the time interval of past ca. 110∼80 Ma is calculated at about 1 mm/yr or more in east Kinki Fig. 32b.

Paleogene (*pre-Middle Eocene*)

The MTL during post-Cretaceous (Izumi Group)∼pre-mid-Eocene (Kuma Group) time (ca. 65∼50 Ma ago) has a prominent left-lateral horizontal component as described in VI. The amount of horizontal displacement is estimated at about 15 km in west Kinki. The average horizontal slip-rate for the time interval of past ca. 65∼50 Ma is calculated at about 1 mm/yr. The associated vertical component is indicated by an upheaval of the Sambagawa belt. The left-lateral wrenching on the MTL at this time is also recognized in Kyushu. In east Chubu, the prominent left-lateral wrenching have taken place until the earliest Miocene. In west Chubu, this movement is considered to have locally continued until post-Shidara time, because left-lateral offset (about 2 km) of the Middle Miocene Shidara Group is recognized along a high-angle branch fault of the MTL (cf. HAYASHI, 1978).

(2) Quaternary right-lateral strike-slip

OKADA (1968, 1970, 1973), HUZITA (1969), HUZITA and OKUDA (1973) and MATSUDA (1973) suggested that the right-lateral strike slip took place along and adjacent to the main fault of the MTL in the late Quaternary (1∼0.5 Ma ago) in Shikoku and west Kinki (segment II). According to OKADA (1968, 1973), the maximum amount of horizontal displacement is the order of several kilometers. The horizontal slip-rate for the past 10^5 year is estimated at about 6∼9 mm/yr in Shikoku and 1∼2.8 mm/yr in west Kinki (OKADA and SANGAWA, 1978). The active right-lateral strike-slip faulting has continued with an approximately constant or a gradually accelerated slip-rate. Through the amount of vertical displacement differs from place to place, probably because of a transcurrent buckling, its value is a fifth to tenth against that of horizontal displacement.

In summary, the following two points were verified as shown in Fig. 32a: (1) Through the long history of the MTL, the strike slip changed from the left-lateral in pre-Quaternary time to the right-lateral in late Quaternary, especially in segment II. And (2) the amount of the pre-Quaternary left-slip is larger than that of the late Quaternary right-slip.

Conclusion

It is concluded that the movement on the MTL during post-Cretaceous∼pre-Middle Eocene (ca. 65∼50 Ma ago) time in west Kinki has more predominant left-lateral horizontal component than the vertical one on the basis of the analysis of strain picture, which was recorded in the Izumi Group, as listed below.

1) En echelon folds, with axial traces aligned obliquely to the trend of the main fault of the MTL (Fig. 18), show the left-hand arrangement.

2) En echelon faults of Riedel-shear type along the Izumi Mountain-range (Figs.

18 and 21) take the right-hand arrangement.

3) The Negoro fault and the Gojodani fault (Riedel-shear type) show the left-lateral strike separations (Figs. 8 and 21).

4) Along the MTL, the boudinage structure is developed commonly within the disturbed zone where strata of the Izumi Group strike NW-SE to E-W, but is hardly recognized in the domain where strata of the Izumi Group have strikes on N-S to NE-SW (Fig. 23).

5) The following distribution of principal axes of strain ellipsoid ($X \geq Y \geq Z$) about boudins is obtained (Fig. 28). X-axis: E-W to NW-SE direction and almost horizontal, Y-axis: plunge of 60∼90°N, and Z-axis: N-S to N20°E direction and plunge of 0∼20°S.

6) The maximum value of quadratic elongation (λ) about boudins decreases with an increase of the distance from the main fault of the MTL (Fig. 29).

7) The shear zone of the Izumi Group along the main fault is wide, being composed of the shear zone (s. str.) of about 100 m in width and the distributed zone of about 500 m in width (for terminology see Fig. 12).

8) The fault plane of the main fault dips generally northward at angles ranging 55° to nearly vertical.

The formation of deformed structures (left-hand en echelon folds, right-hand en echelon faults of Riedel-shear type, boudinage structure, and wide shear zone) can be consistently explained by the left-lateral strike-slip faulting of the Paleogene MTL. The amount of displacement is estimated at about 15 km along the main fault of the MTL in west Kinki.

A left-lateral strike-slip faulting has been clarified also on the Akaishi Tectonic Line and the Komyo Fault (cf. MATSUSHIMA, 1973; TSUNEISHI *et al.*, 1975) in east Chubu, and on the Usuki-Yatsushiro Tectonic Line, branching off from the MTL, in Kyushu (cf. TERAOKA, 1977). Thus, the Paleogene MTL of Southwest Japan can be synthetically explained by the prominent left-lateral strike-slip faulting.

In the tectonic history of the MTL, with reference to the strike-slip component, the similar sense of displacement has been reported along the early Cretaceous (pre-Campanian) MTL in Shikoku, Kinki and Chubu (e.g. HARA *et al.*, 1973) and along the post-Miocene MTL in west Chubu (HAYASHI, 1978). In west Kinki and Shikoku, the right-lateral strike-slip faulting took place in late Quaternary age (e.g. OKADA, 1968; HUZITA, 1969). However, the amount of the pre-Quaternary left-slip is larger than that of the late Quaternary right-slip.

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