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Origin of the Median Tectonic Line

By

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with 58 Text-figures

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Abstract

The southern maginal region of the HT/LP Ryoke metamorphic belt is characterized by a mylonite zone and nappe structures. The tectono-metamorphic history in the southern margin of the Ryoke belt, and the initial stage of formation of the Median Tectonic Line (MTL) were studied at the middle-southern region along the MTL in the Chubu district. Four phases of deformation can be recognized in this region. The first deformation (D1) formed the S1 foliation. The structural features of D1 can not be clearly identified. The metamorphic conditions during D1 were assumed to be medium pressure in the Mikawa Plateau. Extensive growth of porphyroblasts occurred after D1 and before D2 (inter-D1-D2) under non-deformational conditions. The metamorphic conditions changed with a remarkable decrease in pressure from D1 to inter-D1-D2. The D2 deformation was penetrative and involved pressure-solution, resulting in a distinct foliation (S2), which is typically observed in the Ryoke metamorphic rocks. The metamorphic conditions changed with a distinct increase in temperature from inter-D1-D2 to D2. The oldest plutonic mass of the Older Ryoke granites (the Kamihara tonalite) was deformed during D2. The D3 deformation formed a large-scale recumbent fold during the earlier stage of D3. During the later stage of D3, the deformation was concentrated in the lower structurally portions, resulting in the formation of the large-scale mylonite zones and nappe structures. The mylonite zones are developed horizontally and have a top to the west shear sense. The high temperature portion of the Ryoke belt was emplaced onto the low temperature portion. The second older plutonic mass of the Older Ryoke granites (the Tenryukyo granite) were emplaced and deformed during D3. The D3 deformation occurred with distinct decrease in temperature and pressure. The intrusion of the Younger Ryoke granites took place after D3. The D4 deformation is characterized by the formation of the nappe complex and crush melange. The nappe structures of D4 characteristically contain the rocks formed on the surface and rocks derived from other terrane. During the later stage of D4, the Ryoke nappe complex was thrust over the Sambagawa rocks. After the coupling of the Ryoke belt and the Sambagawa belt, the high-angle MTL was formed with a sinistral strike-slip component, resulting in the formation of upright folds.

D1, inter-D1-D2, and D2 are typical of the Ryoke belt, and are the result of regional metamorphic processes. Whereas D3 and D4 are characteristic of the southern margin of the Ryoke belt and represent a distinct decrease in temperature and pressure. The initial stage of the MTL is correlated with the D3 and D4 tectonism, and occurred with the uplift of the Ryoke belt from depth and the transportation of the Ryoke belt toward the south. The western portion of the Ryoke belt was uplifted at about 90 Ma and was followed by the uplift of the eastern portion at 60 Ma. The high-angle MTL and the upright folds postdate the tectono-metamorphic processes of the Ryoke belt and the formation of the initial MTL as a horizontal shear zone.

CONTENTS

I. Introduction

Since Lapworth's (1985) initial description of mylonites in the Moine Thrust zone, it have been recognized that mylonite indicate zones of concentrated deformation. Mylonitic rocks occur in all tectonic setting such as plate boundaries and plate interiors (Tullis *et al.*, 1982). They appear to be generally associated with faults or shear zones. In recent years, mylonitic rocks have attracted much attention from the viewpoint of their microstructures, deformation mechanisms, geometry, and tectonic setting.

Mylonitic rocks are exposed along the Median Tectonic Line (MTL), a major tectonic feature dividing Southwest Japan into the Inner and the Outer Zones (Fig. 1). These mylonites have been discussed from various viewpoints for a long time. The MTL has a long and complicated history dating back to the Late Mesozoic, and even today certain parts remain very active faults. According to the latest summary of displacement history of the MTL by Ichikawa (1980), the initial stage of the MTL is interpreted to have been a ductile shear zone in the southern margin area of the Ryoke belt. During the first half of the 1980's, the initial shape of the MTL was interpreted to be a strike-slip fault (e.g. Hara and Yokoyama, 1974; Hara *et al.*, 1977, 1980b; Takagi, 1983, 1984, 1985, 1986). Recently, some important data has been collected from the southern margin of the Ryoke belt, clarifying that the mylonite zone was originally formed with a flat-lying attitude by Ohtomo (1988, 1991), Yamamoto and Masuda (1987), Michibayashi and Masuda (1988) and Sakakibara et al., (1989). Additionally, it was reported by Ohtomo (1986, 1987, 1989), Sakakibara *et al.* (1989), Hayasaka *et al.* (1989) and Okamoto *et al.* (1989) that the Ryoke metamorphic and igneous rocks along the southern margin of the Ryoke belt were developed as nappes. These data support the idea that the MTL was developed with horizontally during the early stage of its generation history.

During the Cretaceous, the Ryoke belt (composed of granites and high-temperature metamorphic rocks) and the Sambagawa belt (composed of high-pressure metamorphic rocks) were formed separately, at a great distance from one another. Specifically, the former was on the continental side of a volcanic front and the later was in a subduction zone. Both metamorphic belts were joined by subsequent tectonic events. During late Cretaceous or early Paleogene, the present zonal structure of Southwest Japan appears to have been nearly completed. The formation of this initial stage of the MTL seem to be a critical event in the structural development of Southwest Japan. Recently accumulated information on microfossils, structure, and radiometric dating demand the reexamination of the initial stage of the MTL as well as the tectonic processes of Southwest Japan.

Until the first half of the 1980's, studies of the initial stage of the MTL had been done mainly on the granite mylonite. However, the origin of the initial MTL must be understood in accordance with the geotectonic history of the Ryoke metamorphic belt. One of the critical studies may be to clarify the tectono-metamorphic processes of the southern marginal shear zone of the Ryoke belt. In this paper, I use geologic, metamorphic, structural and geochronological data to study the tectonics related to the initial stage of the MTL. As the deformation of initial stage of the MTL is interpreted to have recorded deep-seated deformation of the Ryoke belt, an analysis of the southern shear zone of the Ryoke belt has been performed in this study. The field location of this study area is situated in the middle - southern part of the Ryoke belt along the MTL in the Chubu district. In this area, the MTL runs approximately NE-SW and is essentially vertical, although there is the another MTL, which is a thrust toward the Sambagawa belt. This area was not affected by intense disturbance during Neogene. Most of the area is occupied by granites and high-grade

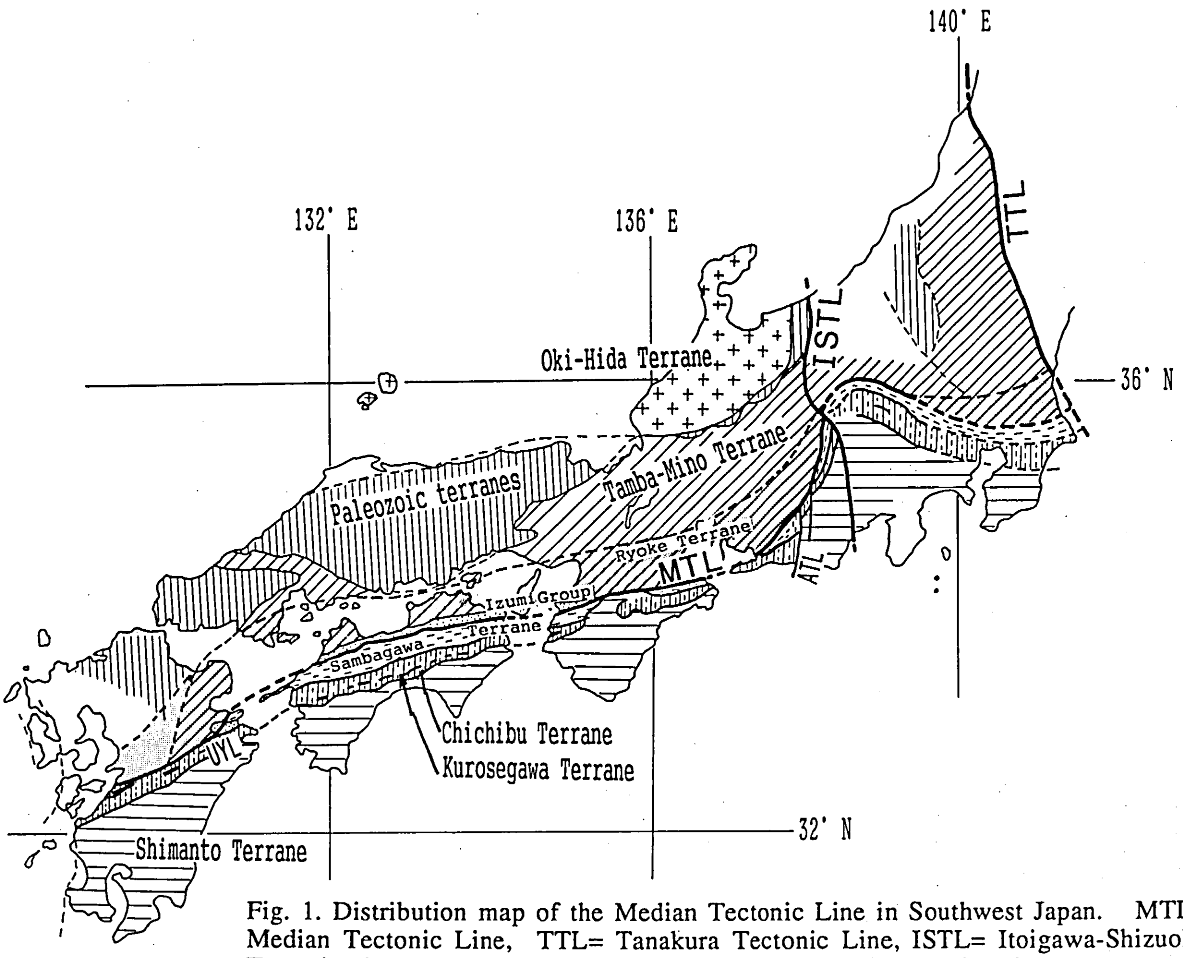


Fig. 1. Distribution map of the Median Tectonic Line in Southwest Japan. MTL= Median Tectonic Line, TTL= Tanakura Tectonic Line, ISTL= Itoigawa-Shizuoka Tectonic Line, ATL= Akaishi Tectonic Line, UYL= Usuki-Yatushiro Line.

gneisses, as well as the mylonitic rocks that were derived from them. In the thrusting part sedimentary rocks, volcanic rocks and a great volume of cataclastic rocks are also found. Such units are not found in other areas along the MTL. It must be very important to clarify the geologic meaning of the peculiar units in the southern margin of the Ryoke belt, in order to understand the tectonics related to the formation of the MTL.

In this paper, I will first analyze the metamorphic and deformational history of the shear zone along the southern margin of the Ryoke belt in the Sakuma area (Fig. 2). Next, the mylonite zone of the Tenryukyo granite in the Hoji Pass area will be described and discussed to clarify the profile of the shear zone (Fig. 2). Then, the macroscopic geologic structures of the southern marginal shear zone and the adjacent high-grade gneiss region will be analyzed to clarify the structural development related to the formation of the southern marginal shear zone. Rb-Sr ages of some of the granitic rocks were determined to understand their origins. Finally, using the metamorphic and deformational history, as well as the geologic structure of the Ryoke belt, the formation processes of the initial stage of the MTL will be clarified in terms of the geotectonic history of Southwest Japan. I will show that the initial stage of the MTL was a flat-lying shear zone which was the result of the concentration of deformation in the Ryoke belt, as well as uplift and transportation to the oceanic side of the Ryoke metamorphic belt.

II. Outline of research history

The MTL has a complicated displacement history. Since Naumann (1893), the displacement history of the MTL has been described and discussed by many authors. Kobayashi (1941) divided the faulting along the MTL into the following four phases: the Kashio phase of late Mesozoic, the Ichinokawa phase, the Tobe phase, and the Shobudani phase of post-Plio-Plistocene. The age of the second phase and that of the third phase were revised by Nagai (1958) discovering middle-upper Eocene strata in Shikoku - the Ichinokawa phase is post-Cretaceous - pre-middle Eocene and the Tobe phase is post-Eocene - pre-Miocene.

Recently Ichikawa(1980) described five stages of displacement along the MTL as follows -

Stage 1: early(-"middle") Cretaceous stage. Left- lateral shearing from Kyushu to Chubu and right-lateral shearing in Kanto, forming an embryo syntaxis structure in the Chubu and Kanto district.

Stage 2: early Paleogene stage (65-50 Ma). Left-lateral faulting from Kyushu to Chubu accompanied by left-lateral branch faults.

Stage 3: late Paleogene - early Miocene stage (50-20 Ma). Small-scale reverse faulting in some regons from Kyushu to Chubu and left-lateral faulting in the eastern part of the Chubu district.

Stage 4: middle Miocene - Pliocene stage (15-2 Ma). local displacement of a dip-slip nature.

Stage 5: late Quaternary stage. Right-slip faulting in

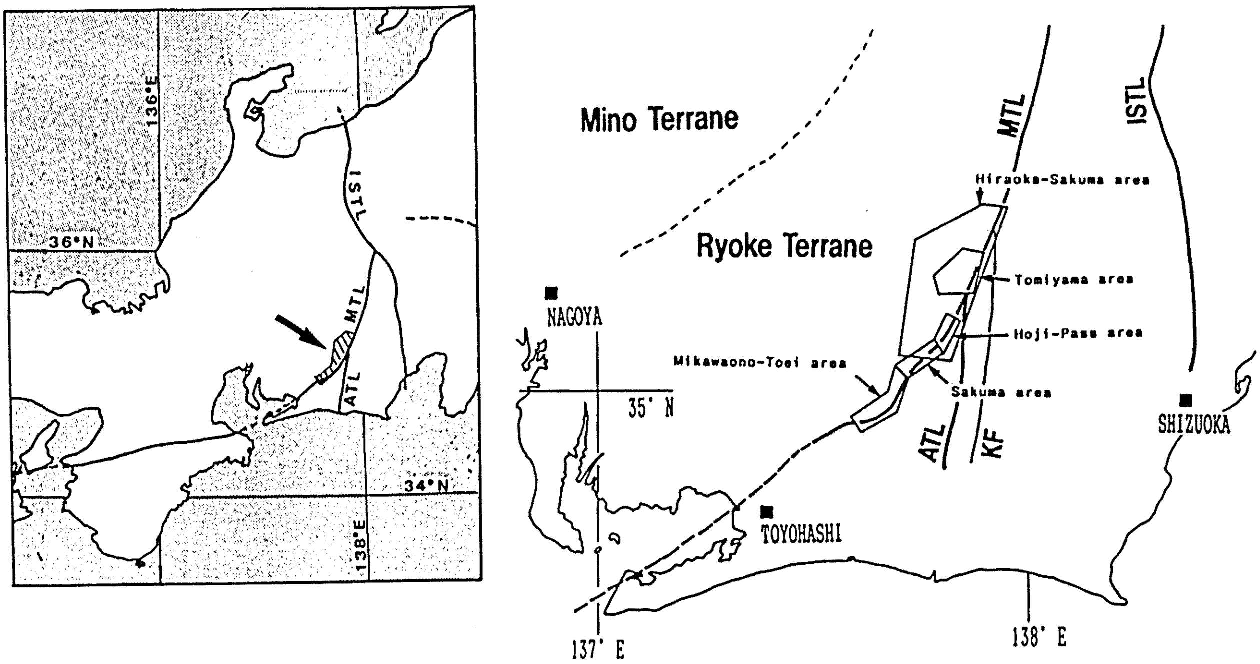


Fig. 2. Index map showing the location of investigated areas in the Chubu district, which are presented in this paper. MTL= Median Tectonic Line, ISTL= Itoigawa-Shizuoka Tectonic Line, ATL= Akaishi Tectonic Line, KF= Komyo fault.

the eastern part of Shikoku and western Kii Peninsula

The initial stage of the MTL is clearly found in rocks in the southern marginal area of the Ryoke belt as ductile deformation. Harada (1890) named the rocks of this initial stage, exposed along the MTL in the upper reaches of Tenryugawa River, "Kashio gneiss". Since then, the "Kashio gneiss" along the MTL has been studied by many geologists from the viewpoint of its protolith, petrogenesis, and structural relationship to the MTL. Up to the 1970's, the "Kashio gneiss" had been interpreted as rocks produced by protoclastic deformation of granitic intrusives along the MTL (e.g. Sugiyama, 1939, 1973; Hayama *et al.*, 1963; Hayama and Yamada, 1973, 1980). But Echigo and Kimura (1973) and Yoshida and Masaoka (1973) regarded the "Kashio gneiss" as mylonitic rocks. Echigo and Kimura (1973) interpreted the mylonitization as not due to strike-slip faulting but due to dip-slip faulting resulting from maximum compressive stress perpendicular to the MTL. Additionally Hara and Yokoyama(1974) determined that granites along the MTL as having two types of foliation, defined by preferred orientation of mafic minerals and by preferred orientation of recrystallized quartz grains. The former foliation, which is interpreted to have formed during the magmatic stage, is oblique to the latter, which is interpreted to have developed during ductile shearing along the MTL. Additionally, based on the fabric analysis of recrystallized quartz grains, these worker also showed that the "Kashio gneiss" is a mylonite.

Since Lapworth's (1885), classification of texturally distinctive rocks associated with fault zones has been tried by many authors (e.g. Waters and Cambell, 1935; Hsu, 1955; Christie, 1960, 1963; Reed, 1964; Spry, 1969; Higgins, 1971; Sibson, 1977; Tullis *et al.*, 1982; Takagi, 1982; Wise *et al.*, 1984). Up to the 1970's, mylonite had been thought to be formed dominantly by cataclasis. Since then, several developments have allowed new insights into the formation of mylonite, owing to new instruments, such as transmission electron microscopy, chemical analysis techniques for fine-grained rocks, and experimental deformation apparatus capable of producing deformation microstructures identical to those of naturally deformed rocks. It is now generally believed that mylonite is the result of crystal plastic deformation of constituent minerals associated with dynamic recovery and recrystallization.

Simultaneous with these studies of fault rocks in other parts of the world, studies on mylonite have also begun by Japanese geologists, for example, Hara et al. (1973), Yoshida and Masaoka (1973) and Ehiro et al. (1979). The following studies largely contributed to the tectonic setting and formation mechanisms of mylonite along the MTL. Hara et al. (1977, 1980b) proposed a movement-strain picture of a ductile shear zone (MTL) during mylonitization. Kosaka (1980) described many ductile-brittle microstructures of the mylonitic rocks along major faults in Japan, such as the Hatagawa fault, the Futaba fault, and the MTL. Kosaka (1980) estimated the physical conditions of deformation of these faults by comparing microstructures from high-temperature deformation experiments on quartz aggregates with those of natural mylonites. Geologic and detailed petrographic studies of mylonitic rocks along the MTL in several regions have also been made by Takagi (1983, 1984, 1985, 1986). From the orientation of stretching lineations and asymmetric microstructures observed in the mylonites, it was suggested by Hara and Yokoyama (1974), Hara *et al.*, (1977, 1980a) and Takagi (1984, 1985, 1986) that left-lateral strike-slip shearing with a subordinate component of vertical-slip took place during mylonitization.

Hara *et al.* (1977, 1980a) called the mylonite zone along the MTL, "the southern marginal shear belt of the Ryoke metamorphic terrane", and proposed the following geotectonic model of the mylonite zone as the initial stage of the MTL. The shear belt was produced through the process of formation of Fossa Magna syntaxis under non-uniform compression from the side of the Pacific Ocean. The stress concentration along the southern margin of the Ryoke belt responsible for the generation of the shear belt occurred when Fossa Magna syntaxis was produced to some extent and the shear movement of dip-direction began around its axial zone. This is because the major structure of the Inner Zone is characterized by left-hand, echelon, upright folds in the west wing of Fossa Magna syntaxis and right-hand, echelon folds in the east wing. Hayama and Research Group for the Hiki Hills (1985) found granite mylonite exposed along the MTL in the east wing of Fossa Magna syntaxis in the northeastern marginal area of the Kanto Mountains. Takagi and Nagahama (1987) determined that the mylonite experienced sinistral shear movement, like the Hiji tonalite in the Chubu district. Takagi(1985, 1989) proposed the tectonic setting of the mylonitic rocks combined with Ichikawa's (1970) model for tectonic generation of the MTL. Specifically, the Hiji tonalite was deformed by deep-seated sinistral quasi-plastic shear movement with a minor amount of vertical-slip before the formation of Fossa Magna syntaxis. However, this initial shape of the mylonite zone has never been proven. All of the previous work interpreted the mylonite zone as a strike-slip shear zone. But the initial orientation of the mylonite zone appears to have been different from the previously proposed model, according to my detailed geologic investigation. It has been determined that the mylonite zone was formed as a flat-lying shear zone in the Mikawaono-Toei, the Sakuma, the Hoji Pass area (Ohtomo, 1986, 1987, 1988), the Misakubo area (Yamamoto and Masuda, 1987), the Kamimura area (Michibayashi and Masuda, 1988), and the Kayumi area (Sakakibara *et al.*, 1989). Ohtomo (1987a & b) has analyzed the deformation and metamorphic history of the southern marginal shear zone of the Ryoke belt. The deformation and metamorphism in the southern marginal shear zone was developed together with the central part of the Ryoke belt during the earlier phases. Later phase deformations occurred in a non-penetrative fashion in the Ryoke belt and were mainly concentrated in the southern region, forming localized mylonite zones. The southern marginal shear zones represent the initial shape of the MTL. The Ryoke metamorphic and igneous rocks along the southern margin of the Ryoke belt were also developed as nappes. These have been reported in the Mikawaono-Toei area (Ohtomo, 1986, 1989), the Kayumi area (Sakakibara *et al.*, 1989), the Asaji area (Hayasaka *et al.*, 1989), and the Kosa area (Okamoto et al., 1989).

III. Geologic setting

The Ryoke metamorphic belt situated in the north of the MTL is a belt consisting of high-temperature type metamorphic rocks and granitic rocks of Cretaceous age. This belt corresponds to the southern front of Cretaceous acidic magmatism in the Inner Zone of Southwest Japan. The protoliths of the Ryoke metamorphic rocks have been generally interpreted to be a southern extension of the Jurassic and earliest Cretaceous accretionary complexes of the Tamba-Mino Terrane. In Kyushu, however they partially contain Paleozoic terranes (Okamoto *et al.*, 1989), proving that the Ryoke metamorphic belt was developed in a direction parallel to the arrangement of terranes of the Outer Zone, cutting across the arrangement of terranes of the Inner Zone (Fig. 1).

The MTL is placed at the southern boundary of the now-observed Ryoke metamorphic belt. In the western half of the MTL, late Cretaceous marine sediments (Izumi Group) are extensively developed, covering the Ryoke granites and mylonites along the MTL. But in the eastern part of Kii Peninsula and the Chubu district, mylonitic rocks along the MTL are well exposed, displaying their initial characteristics. Geological, structural and petrological studies on the mylonitic rocks along the MTL have been carried out by the author in some areas, Mikawaono-Toei, Sakuma, the Hoji Pass, and Tomiyama (Fig. 2). The data from these areas will be described and discussed first.

IV. Sakuma area

A. Outline of geology

The geology of the Ryoke belt in the Sakuma area has been studied by several workers. Geologic maps of the area have been compiled by Hayama *et al.* (1963), Okusa (1964), Sugiyama (1973), Ohtomo (1987a & b) and Ui *et al.* (1988). Mylonites exposed along the Urakawa and the Nakabe routes have been studied by Hara *et al.* (1977, 1980b), Hayama and Yamada (1980), Ui *et al.* (1988) and Takagi and Ito (1988). The Ryoke metamorphic rocks were described by Kutsukake (1977).

Figure 3 illustrates the geologic map and cross sections of the Sakuma area based on the work of the present author. As shown in Figure 3, there are two lines of the MTL in the study area. One is a NE-SW trending high-angle fault between Nakabe and Kawakami. The other between Izumma and Kawakami, is a thrust with a NE-SW trend and NW dip. The latter is on the southern side of the former and juts out into the Sambagawa belt. The latter low-angle thrust type MTL is cut by the former high-angle MTL. Additionally, both are cut by NW-SE trending high-angle faults. Rocks of the Ryoke belt exposed in the Sakuma area are divided into three units (Fig. 3), the Aikawa tonalite, the metamorphic rocks which were derived from sedimentary rocks, and the Tenryukyo granite. They are all in fault contact with or unconformably covered by the Eocene-Miocene Shidara Group (Hayashi and Koshimizu, 1992). Around Izumma, the Shidara Group covers both the Aikawa tonalite and the Sambagawa metamorphic rocks across the low-angle thrust type MTL, and the distribution of the Shidara Group is cut by the high-angle MTL.

B. Major geologic structure

In previous work (Hayama *et al.*, 1963, Okusa, 1964, and Sugiyama, 1973), the geologic structure of rocks of the Ryoke belt in the area was regarded as a NE-SW trending zonal structure along the MTL. Recently, a detailed investigation of the geology of this area (Ohtomo, 1987a & b) has determined that rocks of the Ryoke belt are developed as nappes. In the area, the Aikawa tonalite and the Ryoke metamorphic rocks form nappes. In the southwestern part of the area, the Aikawa tonalite nappe structurally underlies the Ryoke metamorphic rock nappe (Figs. 3and 4). The thrust between the Aikawa tonalite and the Ryoke metamorphic rocks is cut by a backthrust in the west of Urakawa. Additionally, the Aikawa tonalite nappe

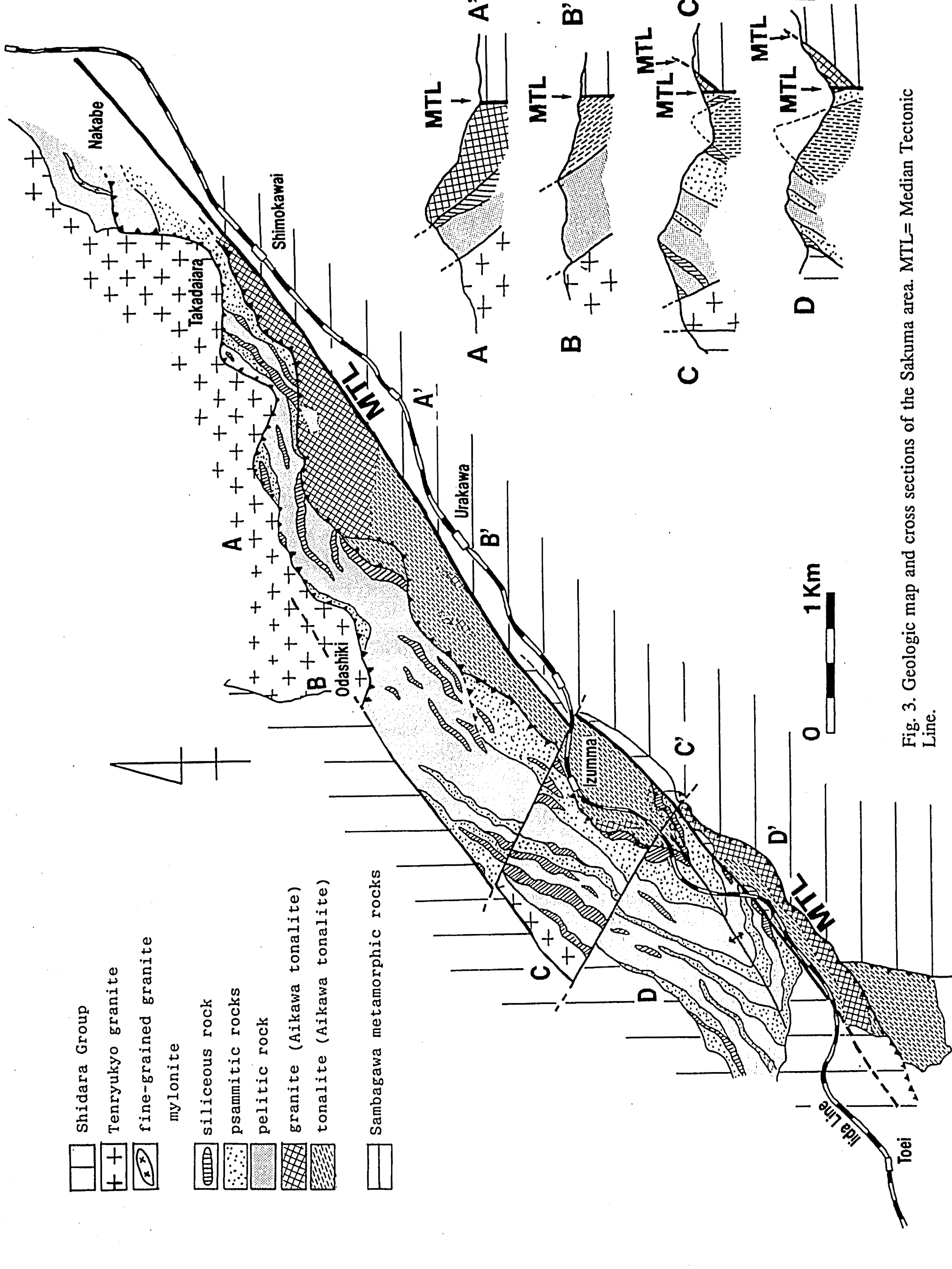


Fig. 3. Geologic map and cross sections of the Sakuma area. MTL= Median Tectonic Line.

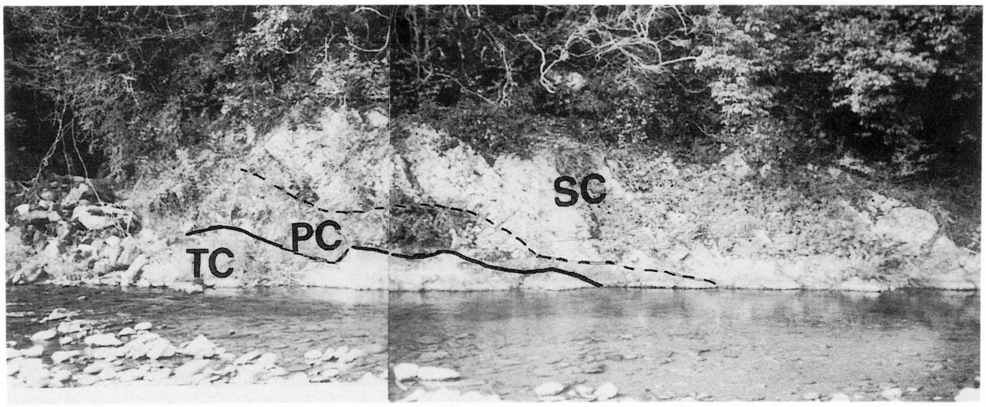


Fig. 4. Photograph of the low-angle fault divided the Aikawa tonalite nappe and the Ryoke metamorphic rock nappe. Cataclasite of the Aikawa tonalite (TC) is fault contact with cataclasite of the pelitic schist (PC). The outcrop locates along the River Aikawa to the west of Izumma. SC= cataclasite of the siliceous schist.

is thrust over the Sambagawa metamorphic rocks, forming the low-angle thrust type MTL. In the northeastern area, the Aikawa tonalite nappe is thrust over the Ryoke metamorphic rock nappe, which itself is thrust over the Tenryukyo granite. These thrusts are assumed to be backthrust. Cataclasite zones are developed around the nappe boundaries. These zones are several tens of meters in thickness. The nappes are folded in an upright fashion with a NE-SW trend.

C. Rock types and petrography

1. Ryoke metamorphic rocks

The Ryoke metamorphic rocks in this area consist mainly of schists with a subordinate amount of gneiss. They are derived from sedimentary rocks such as pelitic, psammitic, and siliceous rocks and show well-developed foliations and lineations.

In the northwest of Nakabe, pelitic and siliceous gneisses crop out on a small-scale, being intruded by the Tenryukyo granite. The foliation and lineation of the Tenryukyo granite are parallel to the metamorphic rocks. The Tenryukyo granite and gneisses underlie the schist nappe. Mineral assemblages of pelitic and psammitic gneisses:

1. cordierite + biotite + muscovite + K-feldspar + plagioclase + quartz
2. biotite + muscovite + K-feldspar + plagioclase + quartz
3. cordierite + biotite +muscovite + plagioclase + quartz
4. garnet + biotite+muscovite+plagioclase + quartz
5. biotite + plagioclase + quartz

Fine-grained granites, several tens of meters thick, are interlayered with pelitic gneiss. They all are distinctly mylonitized. Their mylonitic foliation and lineation are concordant with these of the mylonitic part of the Tenryukyo granite (Fig. 5e,f,g & h). The fine-grained granite appears to have been affected by the same ductile deformation as the Tenryukyo granite and metamorphic rocks.

The Ryoke metamorphic rock nappe consists mainly of pelitic, psammitic, and siliceous schists. Intrafolial folds are often found in the nappe (Fig. 6). The stretching lineation is generally parallel to their axis. Mineral assemblages of pelitic and psammitic schists are:

1. cordierite + biotite + muscovite + K-feldspar + plagioclase + quartz
2. cordierite + garnet + biotite + muscovite + plagioclase + quartz
3. garnet +biotite+K-feldspar+plagioclase + quartz
4. garnet + biotite + muscovite + plagioclase + quartz
5.garnet+ muscovite+ K-feldspar + plagioclase + quartz6. biotite + muscovite + K-feldspar + plagioclase + quartz
7. sillimanite + biotite + plagioclase + quartz
8. biotite + muscovite + plagioclase + quartz

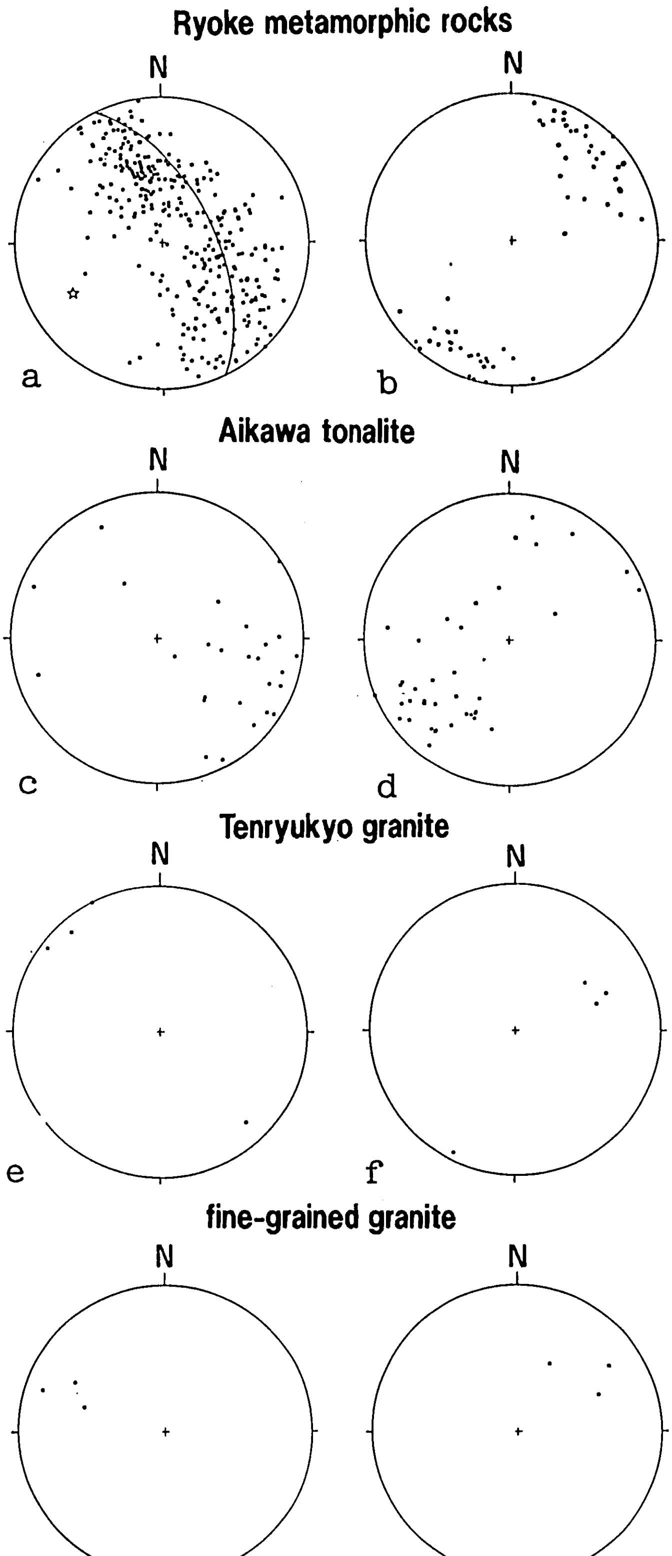
Sillimanite, garnet, and cordierite are found as porphyroclasts. Some grains of K-feldspar and biotite are also texturally porphyroclastic. The schistosity and stretching lineation are expressed by a preferred orientation of biotite and/or muscovite flakes. Mylonitic textures such as S-C structures, pressure shadows, and mica fish were observed under the microscope (Fig.11). Such microstructural evidence suggests that the metamorphic rocks underwent shear deformation. Pelitic gneisses are rarely found as small-scale lenses in schists, suggesting that the gneisses are relicts which escaped shear deformation. Mineral assemblages of the pelitic gneisses are:

1.sillimanite(fibrolite) + andalusite +cordierite + garnet + biotite + muscovite + K-feldspar + plagioclase + quartz
2. andalusite + cordierite + biotite + muscovite + K-feldspar + plagioclase + quartz

The stretching lineation of the schists has a NE-SW trend (Fig. 5b). Along the River Aikawa, their schistosity (Fig. 5a) forms an ENE-WSW trending upright fold with an axis that plunges toward the WSW at a low angle (Figs. 3 and 5a). Mesoscopic open folds and kink folds (Fig. 7) are observed around the axial part of the upright fold.

2. Aikawa tonalite

The Aikawa tonalite (Ohtomo,1990) is mainly exposed from Takadaira to the south of Izumma. On the northwestern side of the high-angle MTL, the tonalite is situated under the nappe of the Ryoke metamorphic rocks (Fig. 4). On the southeastern side, it overlies the



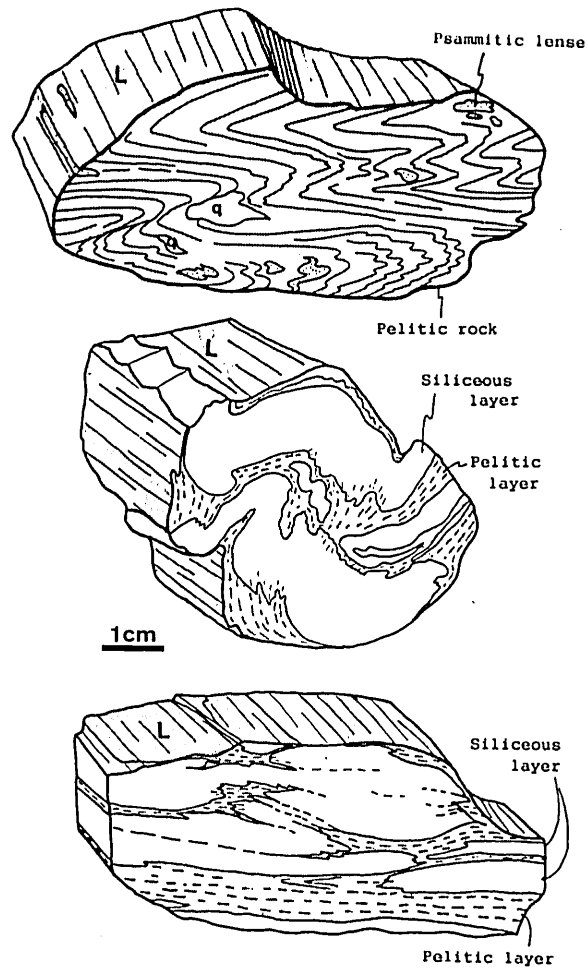
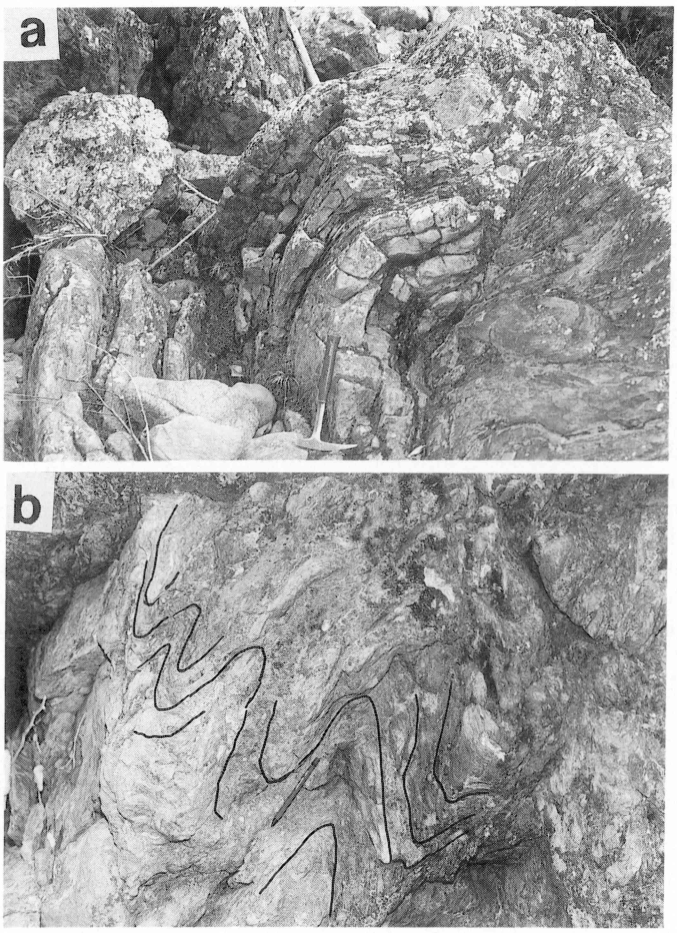


Fig. 6. Sketches of the F3-folds. L= L3-lineation, q= Quartz vein.

Fig. 5. Equal area plots for data from the Sakuma area. (a) Schistosity (S3) of the Ryoke metamorphic rocks. The upright fold axis, defined by the distribution of S3, is shown by the open star. (b) Stretching lineation (L3) of the Ryoke metamorphic rocks. (c) Mylonitic foliation (Sm) of the Aikawa tonalite. (d) Mylonitic lineation (Lm) of the Aikawa tonalite. (e) Mylonitic foliation of the Tenryukyo granite to the northwest of Nakabe. (f) Mylonitic lineation of the Tenryukyo granite to the northwest of Nakabe. (g) Mylonitic foliation of the fine-grained granite. (h) Mylonitic lineation of the fine-grained granite.

Sambagawa metamorphic rocks as a nappe. Around its boundary, the Aikawa tonalite was affected by strong cataclastic deformation. Around Izumma, the Aikawa tonalite is unconformably covered with rhyolitic tuff of the Shidara Group, which is cut by the high-angle MTL.

The Aikawa tonalite is a mylonitic rock derived from tonalite and granite. Mylonite derived from tonalite is dominant in the area from Izumma to Urakawa. Granitic mylonite is more abundant in the area from Urakawa to Takadaira. Basic inclusions are common in the tonalite. Mylonite derived from the tonalite is composed of quartz, plagioclase, biotite, hornblende, ±K-feldspar with accessory sphene, allanite, epidote, zircon and apatite. The granitic mylonite always consists of quartz, K-feldspar, plagioclase and biotite with the same kinds of accessory minerals as those of the tonalite.



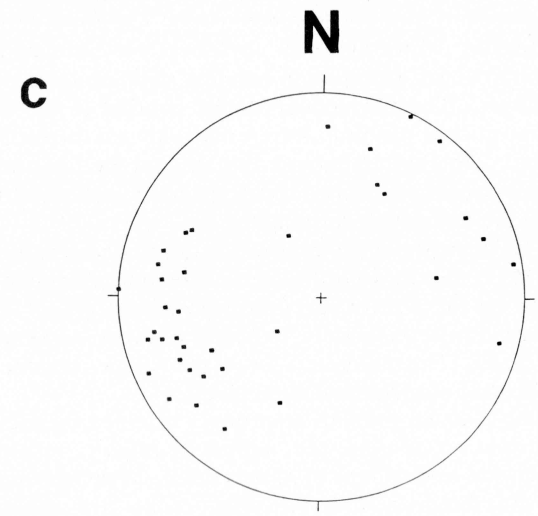


Fig. 7. (a)(b) Minor folds developed around the axial region of the upright fold along the River Aikawa. (c) Equal area plots showing the axis of the minor fold.

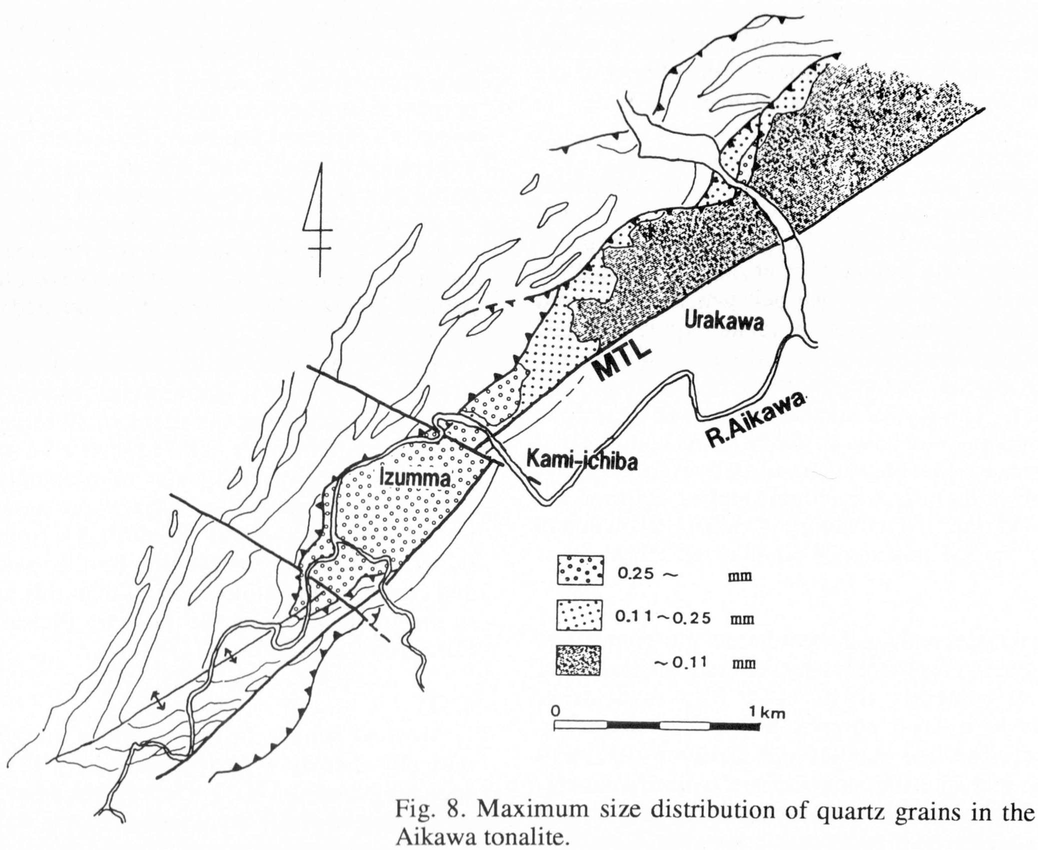


Fig. 8. Maximum size distribution of quartz grains in the Aikawa tonalite.

Mylonitic foliation (Sm) and lineation (Lm) are developed in strongly deformed rocks. The Sm is defined by preferred dimensional orientation of elliptical porphyroclasts and fluxion banding with elongate pressure shadows. The Sm appears to be parallel to the original compositional banding. Intrafolial folds are often observed in the mylonites. Although the Sm and the Lm are not so clear in weakly deformed rocks, the basic inclusions in these rocks are elongated, defining the Sm.

The intensity of mylonitization does not increase toward the MTL, but in a northeasterly direction along the MTL, based on the size of recrystallized quartz grains (Fig. 8). Ultramylonite is widely exposed between Urakawa and Takadaira. The mylonitization of the Aikawa tonalite seems to decrease at lower structural levels.

The Aikawa tonalite is strongly affected by cataclastic deformation around the nappe boundary, resulting in cataclasite several tens of meters thick. Mylonites overlying the Sambagawa metamorphic rocks are remarkably deformed by cataclasis. A cataclasite zone situated around the nappe boundary also forms an upright fold. The orientation pattern of the Sm and the Lm are illustrated in Figure 5c & d. Mylonites overlying the Sambagawa metamorphic rocks are unconformably covered with rhyolitic tuff of the Shidara Group.

3. Tenryukyo granite

The Tenryukyo granite is exposed in the northern part of the field area. It intrudes into pelitic gneisses to the northwest of Nakabe, but is typically in thrust contact with schists. It mainly consists of granite with a subordinate amount of granodiorite. The main rock facies is a coarse-grained biotite granite with K-feldspar phenocrysts. Medium-grained hornblende-biotite granodiorite is a marginal facies, several meters thick, exposed along the wall boundary. The Tenryukyo granite is affected by mylonitic deformation forming mylonitic foliation which cuts across the rock facies. The orientation patterns of the Sm and the Lm are illustrated in Figure 5e & f.

D. Deformation and metamorphic history

The succession of metamorphism in the regional metamorphic belts has been generally distinguished on the basis of the timing relations between the growth of metamorphic minerals and deformation. The tectono-metamorphic history of the Ryoke belt was first analyzed based on data for microstructures of metamorphic minerals from the southwestern part of the Mikawa Plateau, the Chubu district, by Seo and Hara (1980), Seo *et al.* (1981), and Seo (1985). The Ryoke southern marginal shear zone has been interpreted to have a much more complicated polyphase deformation history (modified from Ohtomo, 1987a & b), representing distinct episodes of deformation (D1, D2, D3, D4, etc.). The history of mineral growth and deformation in the Sakuma area is summarized below.

1. D1

In pelitic gneisses, andalusite, cordierite, muscovite, and K-feldspar occur as porphyroblasts, containing inclusions of other kinds of minerals (Fig. 9a & b). Andalusite, cordierite, and K-feldspar porphyroblasts show a zoning, defined by inclusion-free mantles and inclusion-rich cores (Fig. 9a). The inclusion-free mantles are typically narrow. Some of the inclusion minerals, such as muscovite and biotite, have a preferred dimensional orientation forming a schistosity (S1) (Fig. 9a & b). The schistosity (S2), deflected around porphyroblasts and oblique to, and discontinuous with, S1 (Fig. 9a & c), indicates that the deformation D1, related to the formation of S1, occurred before the appearance of the porphyroblasts. S1 is the earliest deformation microstructure which was recognized in the metamorphic rocks of the area. Stable mineral assemblages from the D1 event include muscovite and biotite in pelitic rocks.

2. Inter-D1-D2

Porphyroblastic growth of andalusite, cordierite, K-feldspar, muscovite, and biotite occurred after D1 and before D2. These porphyroblasts grew helicitically over earlier fabrics (S1) (Fig. 9a & b). Inclusion-rich cores were formed under static condition during this inter-D1-D2 phase.

The euhedral garnets with normal zoning have inclusion-rich radial zones separated by inclusion-free sectors. The inclusions are oriented along rational crystallographic directions. The garnets are comparable to those described by Seo and Hara (1983). It can be assumed that these garnet formed under non-deformational conditions (cf. Rast and Sturt, 1957; Seo and Hara, 1983). Stable mineral assemblages in the inter-D1-D2 phase include andalusite, K-feldspar, muscovite, biotite, garnet, and cordierite in the pelitic rocks. The inter-D1-D2 phase corresponds to the second phase in the Mikawa Plateau after Seo and Hara (1980) and Seo *et al.* (1981).

3. D2

The gneisses typically display a dominant foliation (S2). S2 is defined by a preferred orientation of fine-grained biotite flakes (Fig. 9c). The biotite flakes are generally free from inclusions, unlike the porphyritic biotite. The metamorphism related to the crystallization of the biotite flakes occurred simultaneous to the deformation related to the formation of S2. Inclusion-free mantles of porphyroblasts such as cordierite, K-feldspar, and andalusite occur in a direction parallel to S2 and are typically absent in a direction normal to S2, due to pressure solution. These porphyroblasts also display pressure shadows which were developed under a maximum compression direction normal to S2. Interstitial cordierite and K-feldspar, which do not contain inclusions, also exist and have elongated shapes parallel to S2. Any lineation associated with S2 is not definitive.

S2 folds, as intrafolial folds on the mesoscopic scale, are ascribed to D2. Their axial plane cleavages are characterized by concentrations of fibrolite (Fig. 9d & e). Wintsch and Andrews (1987) proposed a pressure solution process for the development of monomineralic folia of fibrolites that crosscut and anastomose around feldspar and biotite. Stable mineral assemblages from the D2 event include K-feldspar, muscovite, biotite, garnet, sillimanite, and cordierite in pelitic rocks. D2 in this area corresponds to the fourth phase in the Mikawa Plateau after Seo and Hara (1980) and Seo *et al.* (1981).

4. D3

Most of schists in the southern marginal shear zone typically display a strong schistosity (S3), as well as a stretching lineation (L3). During the earlier stage of D3, S3 was produced under conditions of biotite stability condition. In biotite-muscovite schists, biotite grains are divided into

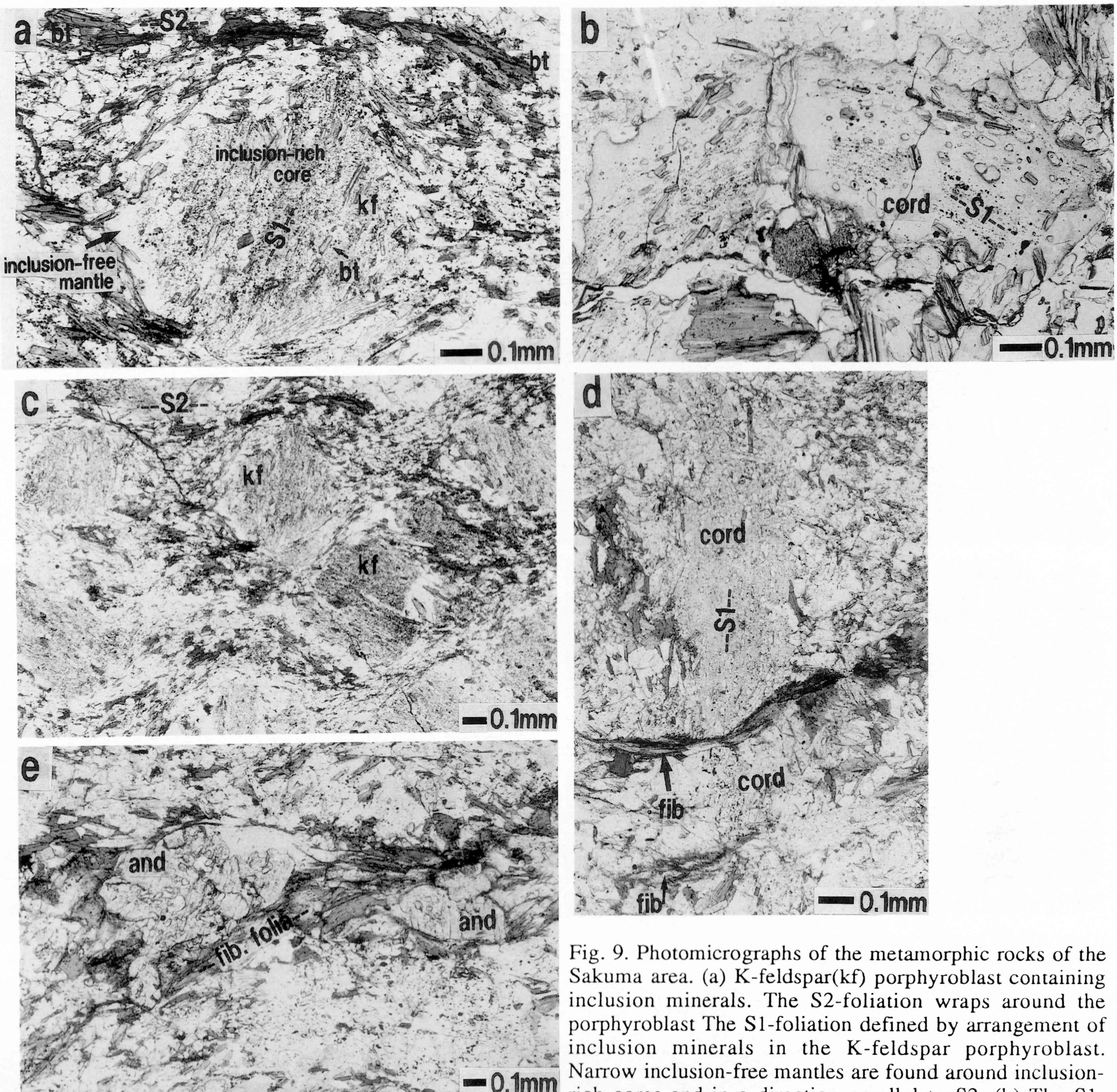


Fig. 9. Photomicrographs of the metamorphic rocks of the Sakuma area. (a) K-feldspar(kf) porphyroblast containing inclusion minerals. The S2-foliation wraps around the porphyroblast The S1-foliation defined by arrangement of inclusion minerals in the K-feldspar porphyroblast. Narrow inclusion-free mantles are found around inclusion-rich cores and in a direction parallel to S2. (b) The S1-foliation defined by arrangement of inclusion minerals in the cordierite porphyroblast. (c) The S2-foliation wrapping around the K-feldspar porphyroblasts. The S1-foliations in the K-feldspar porphyroblasts have random orientation due to the rotation during D2. (d) Fibrolite (fib) forming axial plane cleavage in axial region of F2. Fibrolite (fib) folia crosscutting a porphyroblast of cordierite (cord). (e) Folia of fibrolite cutting an andalusite (and) porphyroblast.

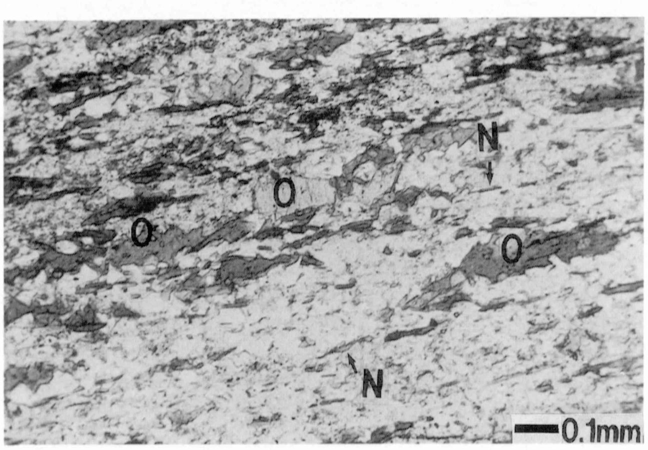


Fig.10. Photomicrograph showing preferred orientation of biotite forming S3. Old biotite grains(o) have a preferred dimensional orientation. While new biotite grains(n) have both a preferred dimensional and lattice orientation.

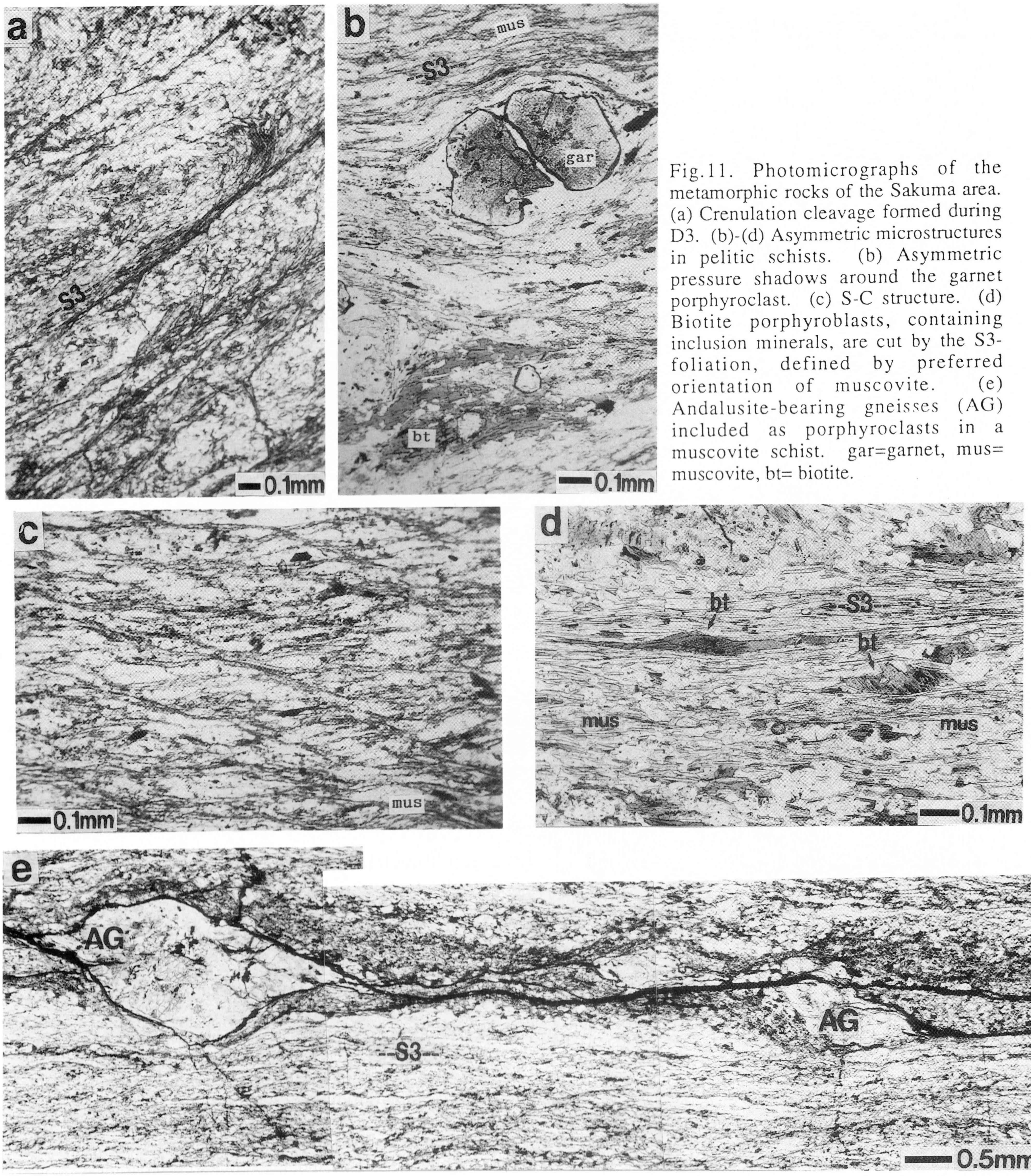


Fig.11. Photomicrographs of the metamorphic rocks of the Sakuma area. (a) Crenulation cleavage formed during D3. (b)-(d) Asymmetric microstructures in pelitic schists. (b) Asymmetric pressure shadows around the garnet porphyroclast. (c) S-C structure. (d) Biotite porphyroblasts, containing inclusion minerals, are cut by the S3-foliation, defined by preferred orientation of muscovite. (e) Andalusite-bearing gneisses (AG) included as porphyroclasts in a muscovite schist. gar=garnet, mus= muscovite, bt= biotite.

two groups - old and new biotite grains (Fig. 10). The old biotite grains are typically parallelogram shape with rather ragged and ill defined grain boundaries. They show evidence of intragranular deformation forming markedly undulatory extinction. Some of the old biotites have their (001) plane oriented at high angles to S3 (Fig. 10). They do not show preferred lattice and dimensional orientation. While new biotite grains are thin flakes with sharp grain boundaries, elongated parallel to (001), and have preferred dimensional and lattice orientations. Thus, it has been concluded that the old grains appeared before the D3 phase, while the new grains grew during the D3 phase. According to Mancktelow (1979) and Seo and Hara (1980), it can be further assumed that the new biotite grains grew during a pressure solution phase event of the old biotite grains. Microprobe analyses of both types of biotites showed that the new grains are a slightly lower in TiO_2 than the older grains (Fig. 12). Perhaps the new grains grew under lower temperature condition than the older grains (cf. Guidotti, 1984). Stable mineral assemblages in the earlier stage of

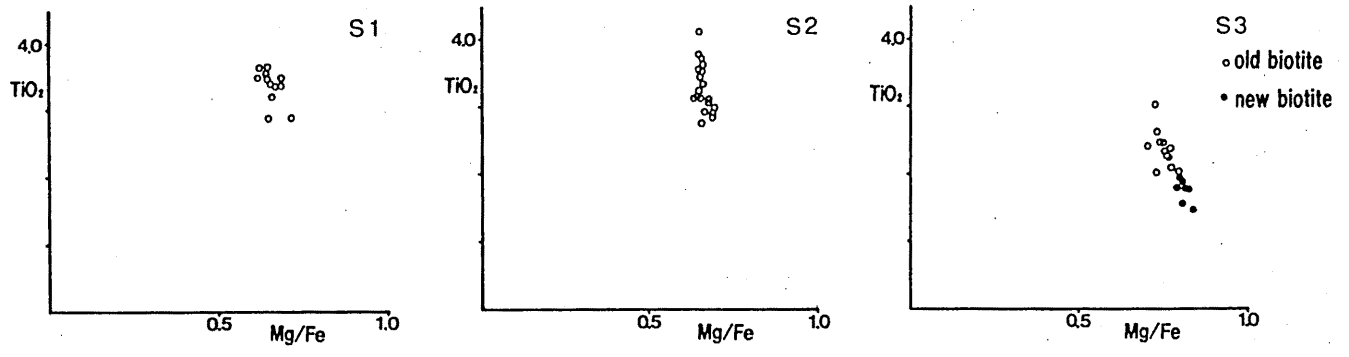


Fig.12. TiO_2 - Mg/Fe diagrams for biotite in the metamorphic rocks from the Sakuma area.

the D3 event include muscovite and biotite in the pelitic rocks. Garnet, K-feldspar, cordierite, and andalusite, as well as old biotite grains, typically remained as relicts.

Crenulation folds (F3) of on S3 were formed during the later stage of D3 (fig. 6). Typically, in the axial regions of F3, S3 is strongly crenulated, with crystals, such as muscovite and biotite in microlithon that are bent and broken in the crenulation hinges (Fig. 11a). Along its crenulation cleavage muscovite has a preferred dimensional orientation. The rocks most strongly deformed during D3 were completely converted to muscovite schist (fig. 11d). These muscovite schists have asymmetric microstructures such as pressure shadows and S-C structures, typically found in most other mylonites (Fig. 11b & c). The lower structural portion of the metamorphic rocks has been especially strongly deformed during D3 to the southwest of Izumma. Muscovite schists rarely contain original rock fragments of the andalusite-bearing gneiss (Fig. 11e). The schists are found as a block of ultramylonite in the Aikawa tonalite. S3 of the muscovite schists is parallel to the Sm of the ultramylonite. It seems probable that the muscovite schists and the ultramylonite have been affected by D3, resulting in the formation of S3 and Sm, respectively. Stable mineral assemblages developed during the later stage of the D3 event include muscovite, chlorite, and sphene in pelitic rocks. Microprobe analysis of muscovites suggests that S3 muscovites have a lower Al_2O_3 content than the older muscovites (Fig. 13), due to lower temperature conditions. Garnet, K-feldspar, cordierite, andalusite, and biotite remained as relicts.

5. D4

The deformation of the D4 phase is characterized by cataclasis. These cataclasites are related to the formation of nappes, which are shown in Figure 3 This event was not accompanied by extensive recrystallization and growth of metamorphic minerals. The unfolding of the later phase upright fold shows that the nappe piles have a flat-lying structure. At this time, the Aikawa tonalite was thrust over the Sambagawa rocks. Additionally, backthrusts between the Aikawa tonalite and the schists and between the schists and the Tenryukyo granite also occurred after the formation of nappe piles. The Aikawa tonalite, schists and Tenryukyo granite were remarkably crushed in the regions of nappe boundaries and backthrusts. Mafic minerals and plagioclase in cataclasites are replaced by carbonate and clay minerals.

6. Later phase structures

After D4, upright folding occurred. This event was not accompanied by extensive recrystallization nor by growth of metamorphic minerals. Mesoscopic minor folds, which were developed around the axis of the upright folds (Fig. 7),

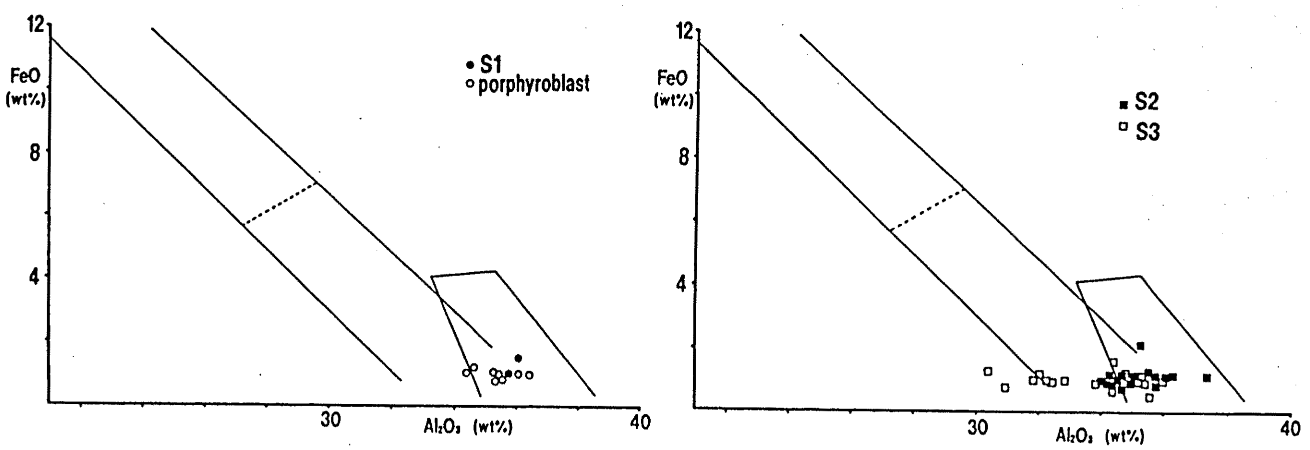


Fig.13. Diagrams for compositional variation of muscovite in the metamorphic rocks from the Sakuma area.

Table 1. Relationship between stable mineral assemblage and deformation in the Sakuma area.

deformation		stable mineral assemblages
D1	formation of S1	Qz+Pl+Mus+Bt
	formation of porphyroblast	Qz+Pl+Mus+Bt+Kf+Cord+And+Gar
D2	formation of S2	Qz+Pl+Mus+Bt+Kf+Cord+And+Gar+Sil
D3	formation of S3 and L3	(early stage) Qz+Pl+Mus+Bt (late stage) Qz+Pl+Mus+Chl+Sphene
D4	formation of cataclasite	Qz+ carbonate and clay minerals

Qz=quartz, Pl=plagioclase, Mus=muscovite, Bt=biotite, KF=K-feldspar, Cord=cordierite, And=andalusite, Gar=garnet, Sil=sillimanite.

are characterized by flexural slip. These upright folds seem to have been formed as echelon folds along the high-angle MTL.

E. Geotectonic history of the Sakuma area

The following geotectonic history of the Sakuma area is based on the above data.

(1) The S1-schistosity was formed during D1.

(2) Porphyroblasts such as K-feldspar, cordierite, andalusite, biotite, muscovite, and garnet grew under non-deformational condition during the inter-D1-D2 phase.

(3) The S2-schistosity and the F2-folds were formed during D2. The D2 deformation seems to be penetrative type.

(4) The S3-schistosity and the F3-folds were formed during D3. The deformation of D3 was concentrated in the lower structural level of the Ryoke metamorphic rocks and the Aikawa tonalite during the later stage of D3. D3 occurred during retrograde metamorphism. The mineral assemblages of the rocks strongly affected by D3 experienced metamorphism under low-temperature conditions, which resulted in the disappearance of the K-feldspar, cordierite, andalusite, garnet and biotite.

(5) The nappe piles, as well as the cataclasite zone, were formed during D4. The low angle MTL thrust, along which the Ryoke units thrust over the Sambagawa metamorphic rocks, were formed during the D4 deformation. Additionally, the formation of backthrusts with cataclasite zones occurred during D4.

(6) The high-angle MTL and the upright folds with NE-SW trends were formed after D4.

(7) The Eocene-Miocene Shidara Group unconformably covered the Ryoke units and the Sambagawa metamorphic rocks.

(8) The high-angle MTL was displaced again, and the distribution of the Shidara Group was cut by the MTL.

V. Hoji Pass area

A. Outline of geology

There are only a few studies of the geology of the Ryoke belt in the Hoji Pass area. Geologic maps have been compiled by Hayama *et al.* (1963) and Hayama and Yamada (1980). Mylonite, exposed between the Nihonsugi Pass and Misakubo, has also been reported by Hara *et al.* (1980b). Recently, a mylonite zone in the Tenryukyo granite has been studied by Ohtomo (1988).

A new detailed geologic map of the Ryoke belt has been completed as shown in Figure 14. Rocks of the Ryoke belt exposed in the area consist of a mylonitic facies of the Hiji tonalite (Hayama and Yamada, 1980), metamorphic rocks derived from sedimentary rocks, and the Tenryukyo granite. The Ryoke rocks are in contact with the Sambagawa metamorphic rocks (Fig. 14). The boundary between these two is the MTL, which is a high-angle fault with a NE-SW trend. NW-SE trending high-angle faults, N-S trending, and NE-SW trending thrusts cut across the Ryoke rocks. There are cataclasite zones, several meters thick, around these thrusts. These faults all seem to be cut by the MTL (Fig. 14).

B. Major geologic structure

In previous work (Hayama *et al.*, 1963), the geologic structure of the Ryoke rocks in the area was regarded as a NE-SW trending zonal structure paralleling the MTL. Recently, a detailed investigation of the geology (Ohtomo, 1988) revealed that the Ryoke rocks were developed as nappes. Mylonites derived from the Hiji tonalite, the Ryoke metamorphic rocks, and the Tenryukyo granite are arranged in nappe piles, in ascending structural order and in tectonic contact with one another. There is no cataclasite zone around the boundaries between nappes. All of the nappes forms NE-SW trending upright folds.

C. Rock types and petrography

1. Ryoke metamorphic rocks

The Ryoke metamorphic rocks of this area are exposed in a long, narrow area along the MTL. They mainly consist of schists with a subordinate amount of gneiss. They are derived from sedimentary rocks such as pelitic, psammitic, and siliceous rocks. The schists are of lower-metamorphic

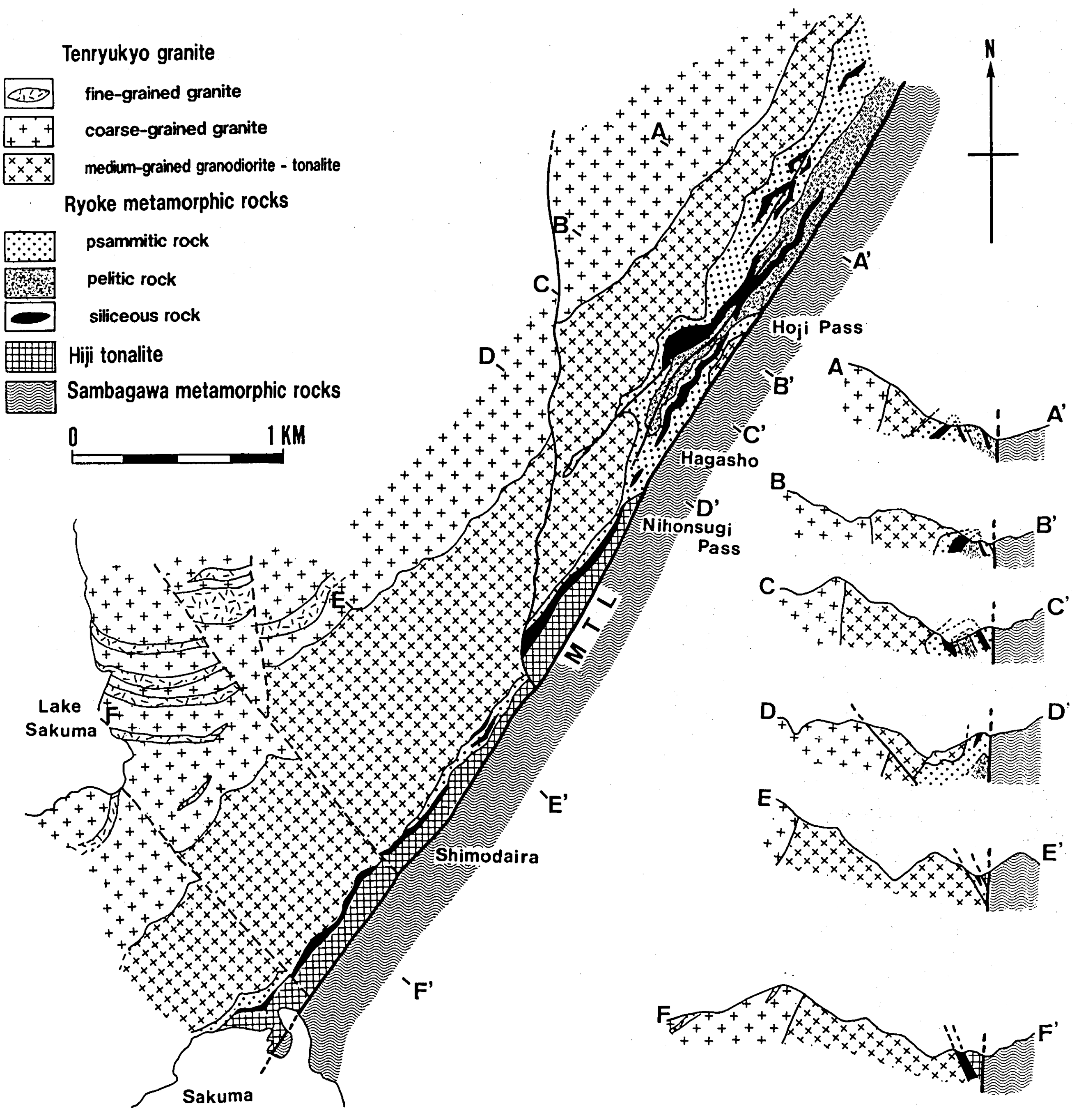


Fig. 14. Geologic map and cross sections of the Hoji Pass area. MTL= Median Tectonic Line.

grade, having a phyllitic appearance.

To the north of Hagasho, psammitic schist, interbedded with thin siliceous schist, lies on pelitic schist. These schists are widely exposed in this region, but to the south are only several tens meters thick and are very narrow. These southern schists mainly consist of psammitic and siliceous schists. From Simodaira to Sakuma, they overlie the mylonite derived from the Hiji tonalite and is structurally below the Tenryukyo granite. The boundaries between the schists and these granites are NE-SW trending, east-dipping faults. The Hiji tonalite and the Tenryukyo granite show no intrusive relationship with the metamorphic rocks. They all are considered to be originally in tectonic contact with one another. Mineral assemblages of pelitic and psammitic schists are:

1. andalusite + cordierite + biotite + muscovite + plagioclase + quartz
2. andalusite + muscovite + plagioclase + quartz
3. garnet + biotite + muscovite + plagioclase + quartz
4. biotite + muscovite + plagioclase + quartz
5. biotite + plagioclase + quartz
6. muscovite + plagioclase + quartz

A well-developed schistosity and a stretching lineation are typically observed in the schists (Fig. 16c & d). The

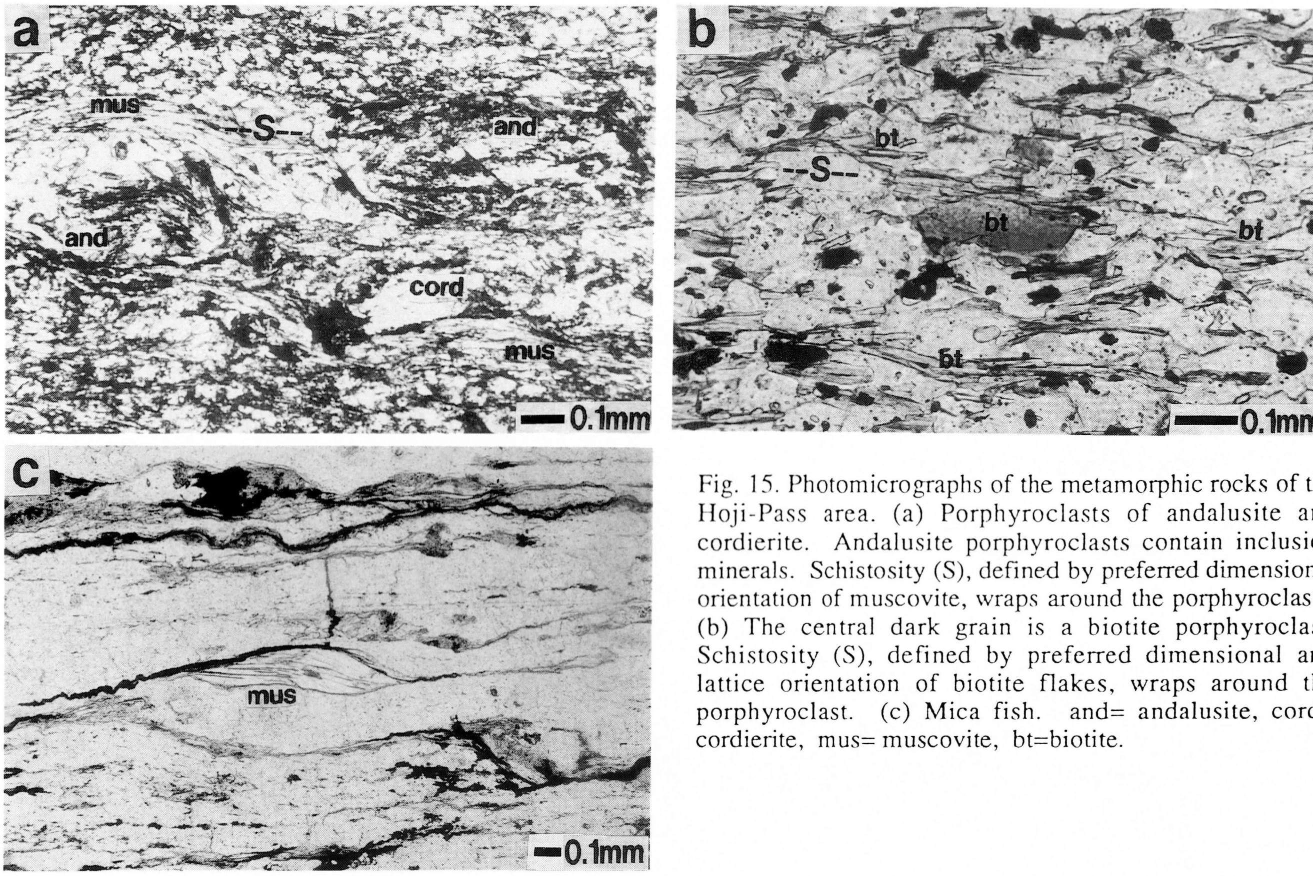


Fig. 15. Photomicrographs of the metamorphic rocks of the Hoji-Pass area. (a) Porphyroclasts of andalusite and cordierite. Andalusite porphyroclasts contain inclusion minerals. Schistosity (S), defined by preferred dimensional orientation of muscovite, wraps around the porphyroclasts. (b) The central dark grain is a biotite porphyroclast. Schistosity (S), defined by preferred dimensional and lattice orientation of biotite flakes, wraps around the porphyroclast. (c) Mica fish. and= andalusite, cord= cordierite, mus= muscovite, bt=biotite.

schistosity is mainly defined by preferred lattice and dimensional orientation of muscovite. In some schists, it is also defined by preferred lattice and dimensional orientation of finer grained biotite flakes (Fig. 15b). Andalusite, garnet, cordierite, and some biotite occur as porphyroclasts (Fig. 15a & b). Mylonitic structures such as S-C structure, pressure shadow, and mica fish (Fig. 15c) have been observed under the microscope. Micro-structural evidences suggests that the schist underwent a shear movement. Crenulation folds of the schistosity are typically occur and their axes are parallel to the stretching lineation.

The gneisses are mainly exposed in a limited area around Sakuma. A gneiss sample was obtained from a point near the Tenryukyo granite in the north of Hoji Pass. Mineral assemblages of the pelitic and psammitic gneiss are:

1. garnet + biotite + muscovite+ K-feldspar + plagioclase + quartz
2. biotite + cordierite + K-feldspar + plagioclase + quartz
3. biotite + muscovite + plagioclase + quartz

Garnet occurs as a porphyroblast. The gneissosity is typically weak and defined by preferred dimensional orientation of biotite. The schistosity of the metamorphic rocks is represented by an upright fold which has a NE-SW trend (Fig. 16c). The axis of the fold plunges toward the NE at a low-angle. The stretching lineation plunges toward the NE or SW at a low angle (Fig. 16d).

2. Mylonite derived from the Hiji tonalite

The mylonite is exposed in a long, narrow area along the MTL from Sakuma to the Nihonsugi Pass. Hayama and Yamada (1980) interpreted the mylonite as the mylonitic

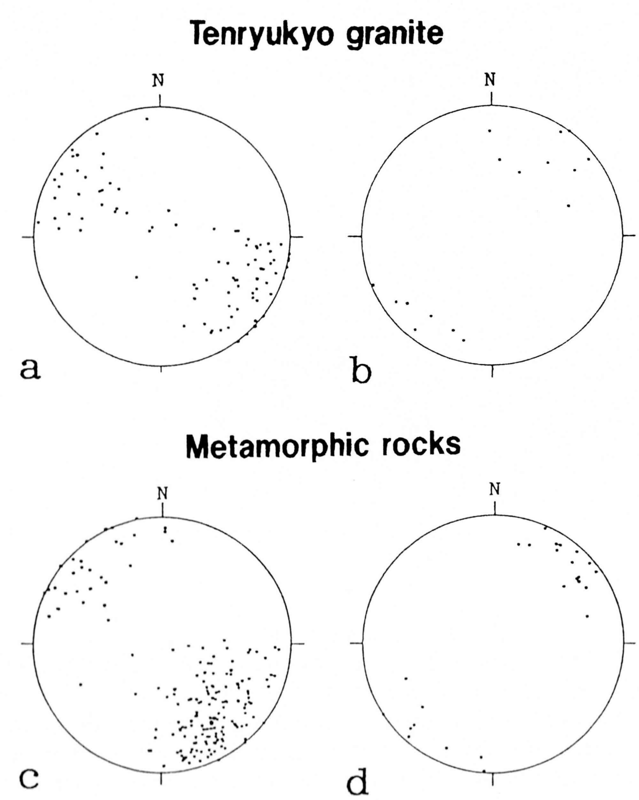


Fig. 16. Equal area plots showing the orientation data in the Hoji Pass area. (a) Mylonitic foliation of the Tenryukyo granite. (b) Mylonitic lineation of the Tenryukyo granite. (c) Schistosity of the metamorphic rocks. (d) Stretching lineation of the metamorphic rocks.

facies of the Hiji tonalite in their geologic map of the Urakawa - Wada area.

The mylonite is mainly composed of ultramylonite derived from tonalite and granite. The tonalite mylonite is composed of quartz, plagioclase, biotite, hornblende, ±K-feldspar, with accessory sphene, allanite, epidote, zircon, and apatite. Granite mylonite typically consists of quartz, K-feldspar, plagioclase and biotite with the same kinds of accessory minerals as those of tonalite. Well-developed mylonitic foliation (Sm) and lineation (Lm) are observed. Both mylonites have been affected by cataclastic deformation.

3. Tenryukyo granite

The Granite, widely exposed in the area, is the Tenryukyo granite, a very large plutonic body 30 km x 7.5 - 2 km with an elongated shape parallel to the MTL. The granite in this region consists of three rock facies (Fig. 14) - (1) medium-grained hornblende-biotite granodiorite, located on the margin of the granite body, (2) coarse-grained biotite granite, situated on the inside of the granite body, and (3) fine-grained biotite granite dykes. The granodiorite facies is generally massive in the part which is free from mylonitization. It mainly consists of plagioclase, quartz, K-feldspar, biotite, and hornblende with accessory zircon, apatite, and ilmenite. The coarse-grained granite facies mainly consists of plagioclase, quartz, K-feldspar, and biotite with accessory zircon, apatite, and ilmenite. This facies is generally characterized by large porphyritic K-feldspar and a low percentage of hornblende. It has a weak foliation, in the part which is free from mylonitization. The fine-grained granite dykes are typically oriented with a NE-SW trend, a west dip and are subparallel to the boundary between the medium-grained granodiorite facies and the coarse-grained granite facies.

The Tenryukyo granite typically contains xenoliths of metadiabase. These xenoliths have two different forms - 1) an elongate form, which is parallel to the foliation of host rock, and 2) a rounded form. The granite also contains rare pelitic and psammitic gneiss xenoliths.

To the north of the Nihonsugi Pass and Sakuma, the Tenryukyo granite is significantly affected by ductile deformation, resulting in both mylonitic structures of constituent minerals and mylonitic foliation (Sm) and lineation (Lm). The Sm is plotted in Figures 16a and 17 and the Lm is plotted in Figure 16b. The Sm is represented by an upright fold with a NE-SW trend. The axis of the fold plunges toward the NE - NNE at a low angle. The Lm plunges toward the NE or SW at a low angle. The mylonitization of the Tenryukyo granite is described in detail in the following section.

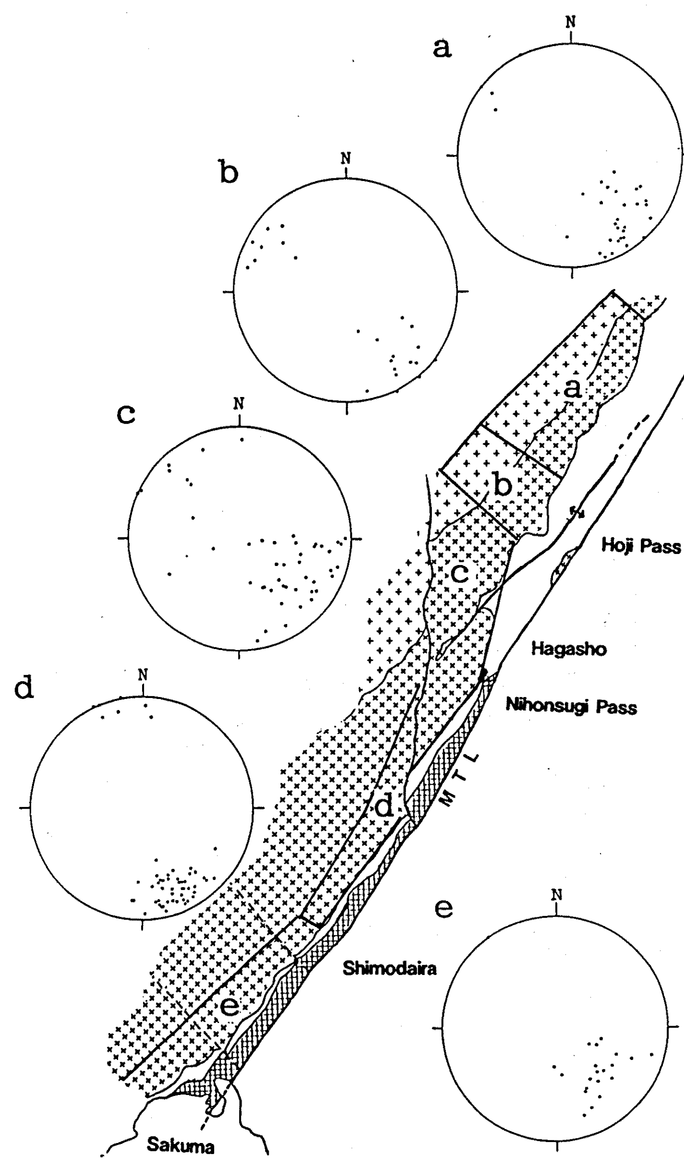


Fig. 17. Equal area plots showing the orientation data for mylonitic foliation of the Tenryukyo granite at the Hoji Pass area.

D. Mylonitization of the Tenryukyo granite

1. Distribution of mylonitic rocks

The eastern portion of the N-S trending, east-dipping thrust contains two mylonite zones in the granite. One of these mylonite zones is located in the medium-grained granodiorite facies, and the other zone is in the coarse-grained granite facies. There is a slightly-deformed medium-grained granodiorite facies, several tens of meters thick, between the two mylonite zones. Figure 24 illustrates the distribution of the mylonitic rocks in the area. To the west of the thrust, there is a mylonite zone in the coarse-grained granite facies along the boundary between the coarse-grained granite and the granodiorite facies. The medium-grained granodiorite facies is not affected by remarkable mylonitic deformation.

The mylonitic rocks frequently have a distinct mylonitic foliation (Sm) and stretching lineation (Lm). The Sm is mesoscopically defined by fluxion banding, elongation of quartz pools (Fig. 18b), and dimensional preferred orientation of elliptical porphyroclasts.

Figure 17 illustrates the orientation pattern of the Sm for the mylonitic rocks. Around Hagasho, the Sm is represented by a NE-SW trending upright fold. Unfolding the upright fold symmetrically around its axial surface, the Sm forms a nearly flat-lying structure.

2. Asymmetric microstructures

Recently Several types of asymmetric microstructures

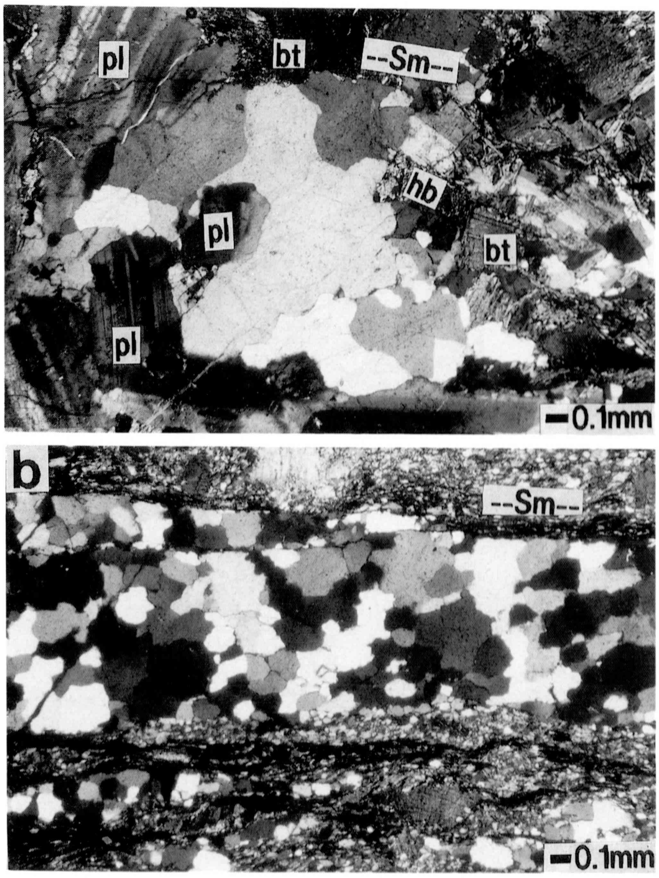


Fig. 18. Photomicrographs of two quartz textures - quartz grains as individual crystals and "quartz pool" as individual domain occupied by quartz grains and bounded by other minerals. XZ section. (a) Quartz in slightly mylonitized granite. (b) Quartz in strongly mylonitized granite. Sm= mylonitic foliation, pl=plagioclase, bt=biotite, hb= hornblende.

(such as pressure shadows, displaced broken grains, mica fish, and obliquity of elongate recrystallized quartz) were comprehensively discussed by Simpson and Schmid (1983), Lister and Snoke (1984), Hanmer (1984) and others. These microstructures are considered to be useful in determining the sense of shearing in deformed rocks. Takagi (1984, 1985) and Takagi and Ito (1988) described such microstructures in the granite mylonite along the MTL in the Takato and Kayumi areas. The asymmetric microstructures are also typically observed in the XZ sections of the mylonitic rocks in the Hoji Pass area. Asymmetric pressure shadows typically occur as "wings" on plagioclase or K-feldspar porphyroclasts. In mylonites derived from coarse-grained, K-feldspar-porphyritic granite, asymmetric pressure shadows around K-feldspar porphyroclasts are typically observed both mesoscopically and microscopically. Displaced broken grains of plagioclase and K-feldspar porphyroclasts are also observed in the mylonites (Fig. 19a). Biotite or muscovite fish is not only observed in the granite mylonites but also in the mylonites derived from metamorphic rocks (Fig. 15c). The shape of recrystallized quartz grains in these mylonites is typically equant (Fig. 18b). The recrystallized quartz grains rarely show elongate fabrics oblique to the Sm (Fig. 19b).

Asymmetric microstructures which are useful in determining the sense of shear have been analyzed at 28 locations of the Tenryukyo granite and metamorphic rock mylonites. Unfolding the upright folds which postdate the mylonitization, the shear sense indicates that the structural upper units were displaced to SW relative to the lower structural units, although there is one exception.

3. Deformation of quartz

The quartz in the granite mylonites is recognized as having two distinct textures (Sakurai and Hara, 1979; Hara *et al.*, 1980a): quartz grain, as individual crystal distinguished from each other by high-angle boundaries, and "quartz pool" which is defined as individual domain occupied by quartz grains and bounded mainly by other minerals (Fig. 18a & b).

The quartz pools are commonly considered to be the result of magmatic crystallization-induced micro-structures, initially formed as single quartz grains (Fig. 18a). Their average shapes are assumed to be approximately comparable with the strain ellipsoid. The spatial variation in the average shapes of quartz pools has been analyzed on outcrops of the Tenryukyo granite along a route between the Hoji Pass and Tomiyama, in order to determine the spatial variation of strain mode (Fig. 20). Measurements of the average shapes were made on 7-15 pools in the XZ plane and in the YZ plane. Figure 24 clearly shows that there are two strongly-mylonitized regions - one in the medium-

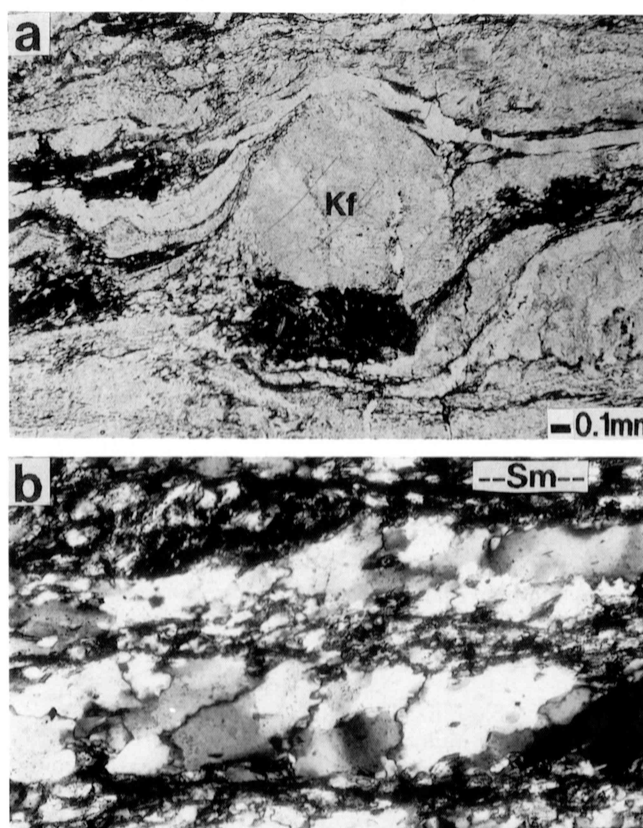


Fig. 19. Photomicrographs of asymmetric microstructures in the Tenryukyo granite. XZ section. (a) Asymmetric pressure shadows around a K-feldspar porphyroclast. (b) Recrystallized quartz grains showing elongate fabric oblique to the Sm. Kf= K-feldspar.

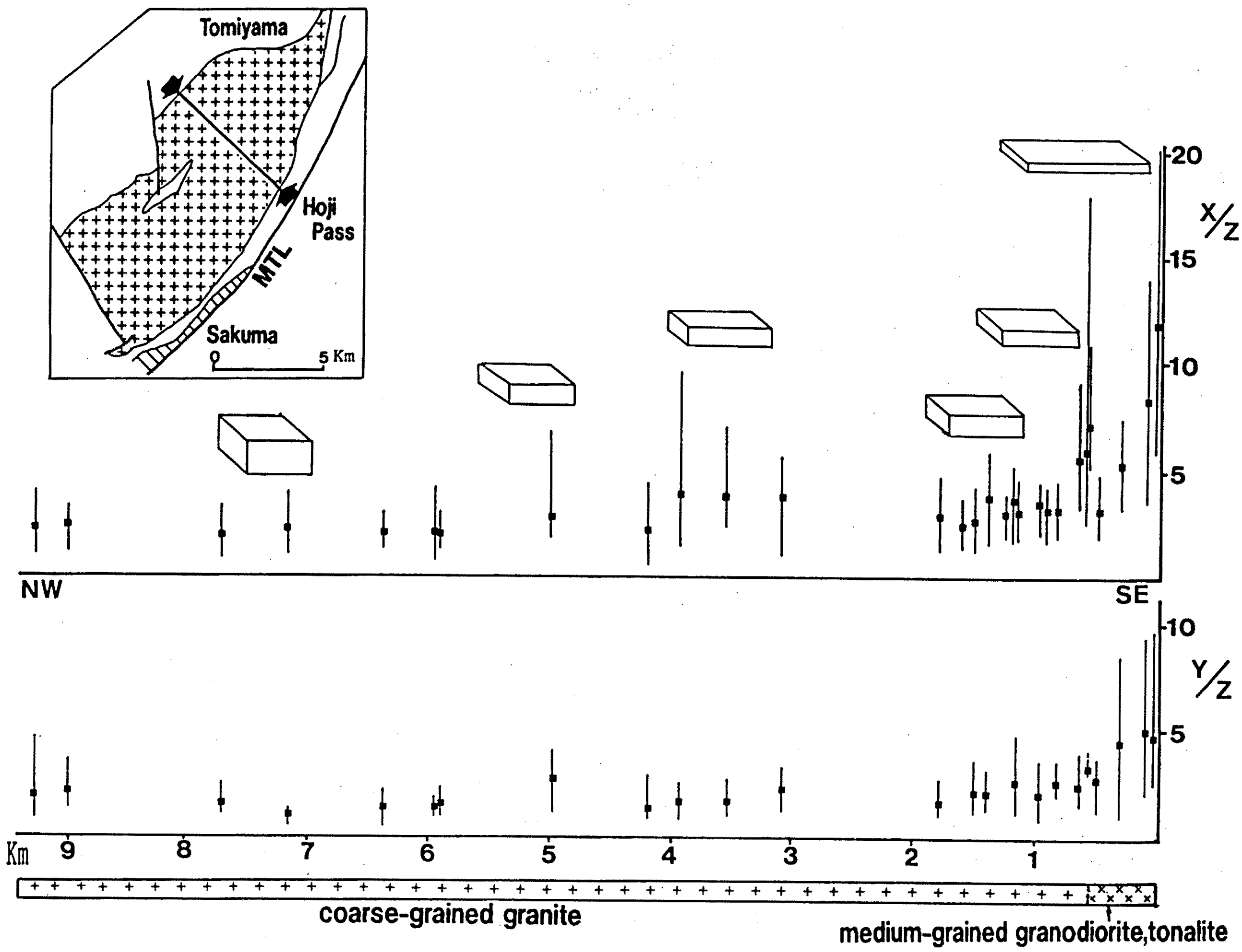


Fig. 20. Diagrams showing the spatial variation in mean aspect ratio for quartz pools of the Tenryukyo granite.

grained grano-diorite facies, and the other in the coarse-grained biotite granite facies. The former is situated at a lower structural level and seems to have a higher strain magnitude than the latter.

The areal variation data for each quartz pool in the XZ and YZ planes is displayed in Figure 21. These measurements were made on four rock types of medium-grained granodiorite facies, which were divided with reference to the degree of mylonitization: meso-scopically strongly mylonitized rock, well- mylonitized rock, intermediately mylonitized rock and weakly-mylonitized rock. Two samples were analyzed for each rock type. The shape of each pool is assumed to approximate an ellipse and its area has been measured by $s = \pi ab$, where a is the long diameter of the ellipse and b is the short diameter. Figure 21 shows that the area occupied by quartz pools is reduced as mylonitization becomes stronger. Under the microscope, the quartz pools, in strongly mylonitized rock, are intercalated with some thin layers, composed of fine-grained recrystallized plagioclase and K-feldspar. This type of microstructure is not observed in the intermediate and weakly-mylonitized rocks. Perhaps pressure solution and/or division of the quartz pools, by kinking, occurred during mylonitization.

The average three-dimensional shapes of quartz pools are displayed on a Flinn diagram (1962) (Fig. 22). These

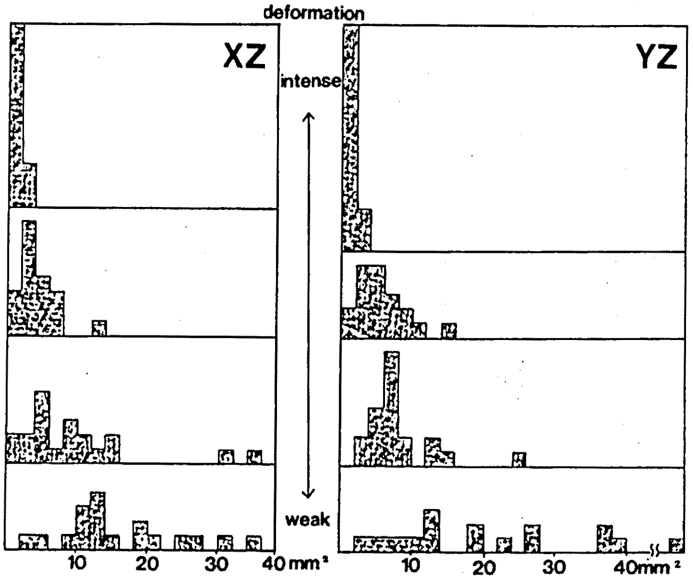


Fig. 21. Histograms showing the areal variation for quartz pools in the Tenryukyo granite at the Hoji Pass area.

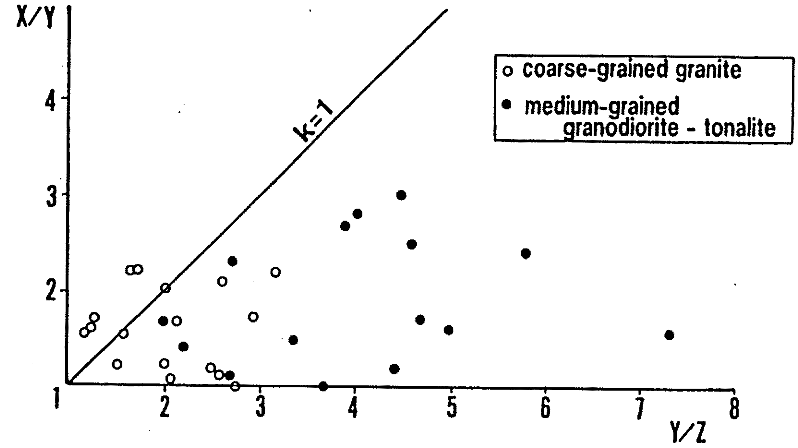


Fig. 22. Flinn diagram for quartz pools of the Tenryukyo granite at the Hoji Pass area.

have been estimated on the basis of the XZ plane data and YZ plane data. Various shapes of quartz pool with a wide range of k value occur from samples of the non-mylonitized or weakly-mylonitized granite. But the average quartz pool shape from mylonitized granite is flattened ribbon. In the mylonites from lower structural levels, quartz pools have k values of 0.9<k<0.3. In the mylonites from higher structural levels, they have k values of 0.8<k<0.6. This suggests that the strain mode of quartz, in the deformation related to formation of the mylonitic foliation, is of flattening strain. According to Takeshita and Wenk (1988), quartz polycrystals become softer during flattening strain at low temperature and during elongation strain at high temperature. Toriumi (1985) described the strain mode of quartz in the Ryoke belt as an elongation strain. However, as already pointed out by Sakakibara *et al.* (1989) in the Kayumi area, the strain mode for quartz pools in this area is not an elongation strain.

Quartz pools in the Tenryukyo granite typically consist of many quartz grains which were produced by dynamic recrystallization (Fig. 18a & b). The size of the recrystallized quartz grains has been measured on the XZ plane in several locations. The mean grain size is given by

$$\bar{s} = \left(\prod_i^n a_i b_i\right) / n,$$

where a_i is the long diameter of recrystallized quartz grain, b_i is the short diameter and n is observation number(50). The mean grain size clearly changes from the northwestern margin of the Tenryukyo granite toward the southwestern

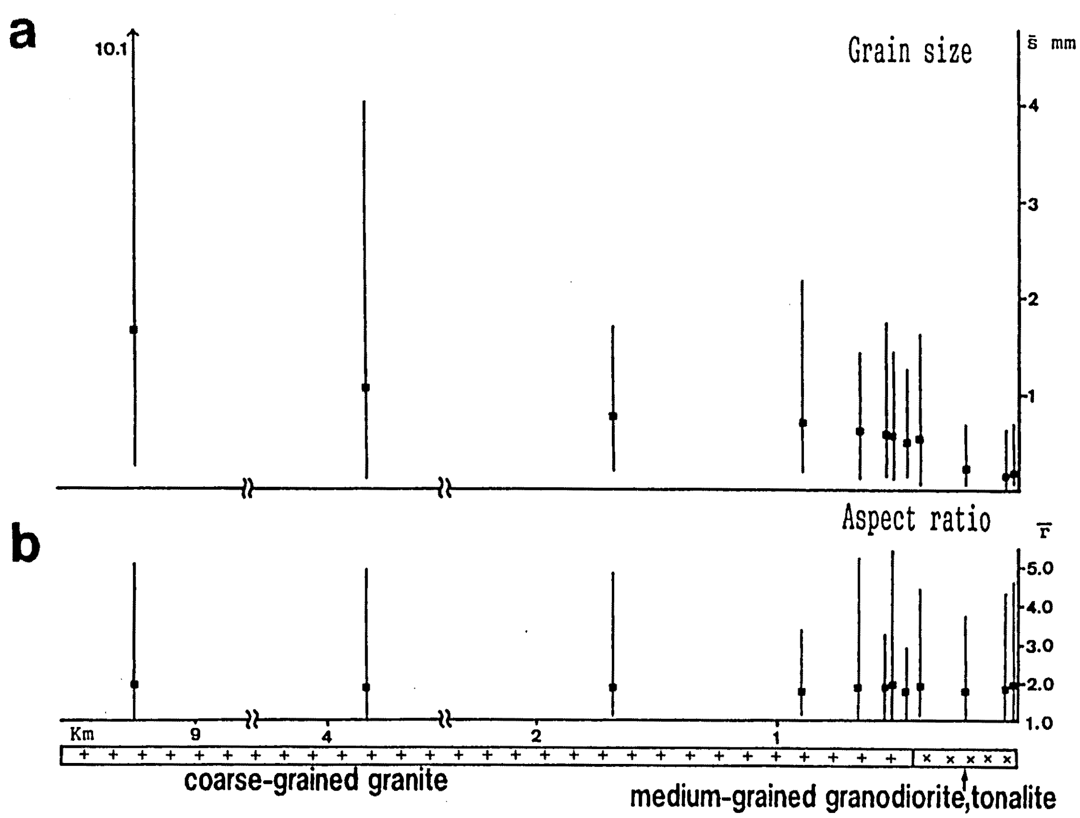


Fig. 23. Data for recrystallized quartz grains on the Tenryukyo granite. (a) Grain size (b) Aspect ratio.

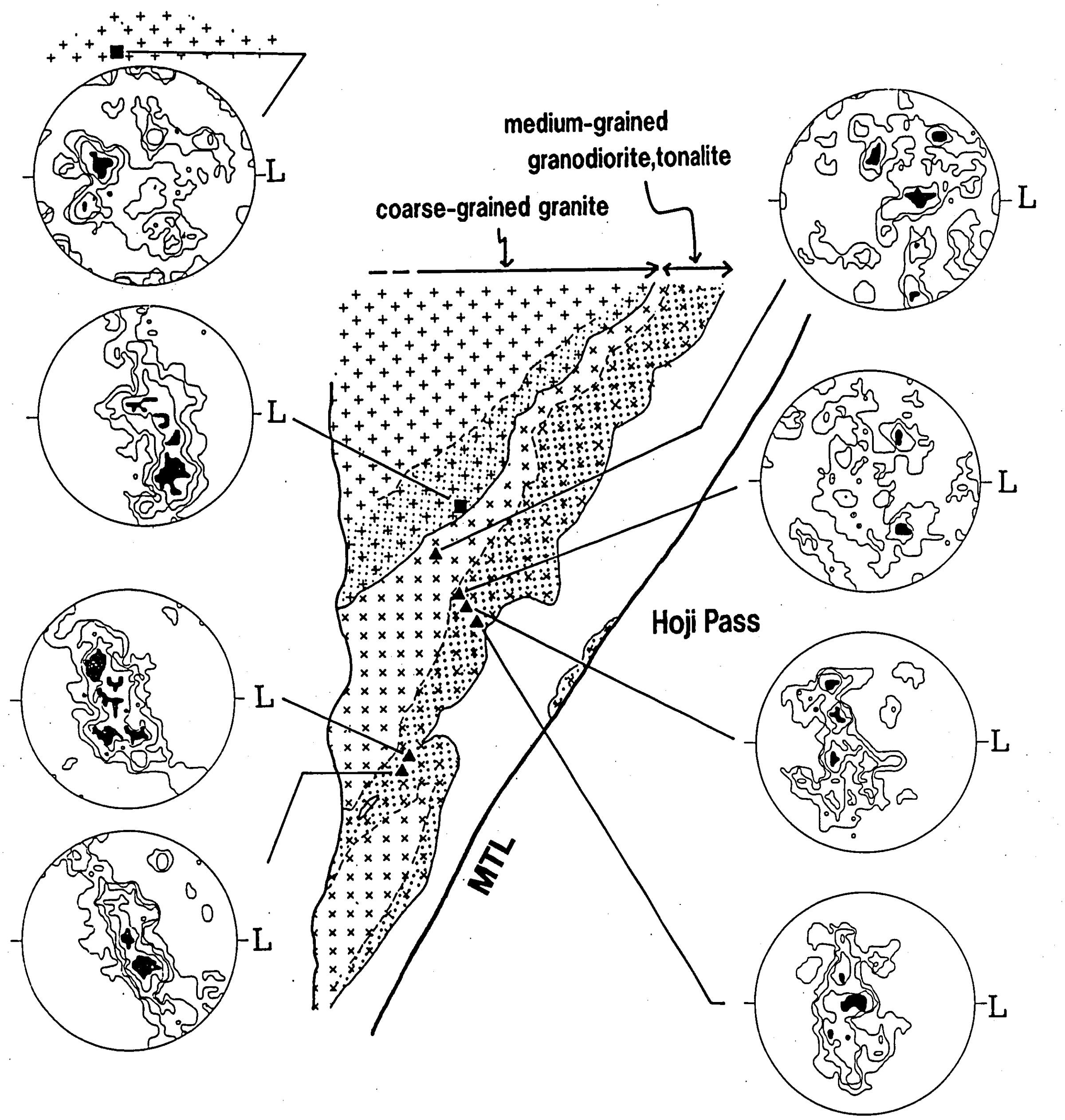


Fig. 24. Distribution of the strongly mylonitized zones (dotted area) and the quartz c-axis fabrics of the Tenryukyo granite at the Hoji Pass area.

margin (Fig. 23a), with an abrupt decrease at about 500 m from the southeastern boundary. Additionally from this location the mean grain size seems to decrease slightly toward the southeastern boundary. This result is essentially the same as that by Hara *et al.* (1977, 1980b) and Takagi (1984, 1985).

Figure 23b illustrates the distribution of the mean aspect ratio (r) of recrystallized quartz grains. The mean aspect ratio is given by

$$r=(\sum_{i}^{n} a_i/b_i)/n,$$

where a_i is the long diameter of the recrystallized quartz grain, b_i is the short diameter, and n is the observation number(50). The ratio seems to be almost constant over the entire granite mass. The shape of quartz is essentially equidimensional and polygonal, correlating with P-type quartz defined by Masuda and Fujimura (1981) (Fig. 18a & b). This result is the same as Takagi's (1984, 1985).

The strain modes, inferred from the distribution of the aspect ratio of quartz grains, do not appear to correspond with those determined by the average three-dimensional shapes of quartz pools. As elongated quartz grains, which are oblique to the Sm, are rarely observed in P-type grains (Fig. 19b), it is inferred that the P-type quartz grains have been transformed by resetting of the 'finite strain clock' due to recrystallization in the later stage.

4. c-axis fabrics of recrystallized quartz

Quartz pools in the Tenryukyo granite consist of many quartz grains which were produced by dynamic recrystallization (Fig. 18a & b). Some c-axis fabrics of these quartz grains are given in Figure 24. They show a dominance of crystal plastic processes during the deformation of the quartz.

The types of c-axis preferred orientation depend on - (1) the intracrystalline deformation mechanisms (i.e. operative slip systems and relative importance of climb and cross-slip), (2) the deformation regime, and (3) the intensity of deformation (cf. Lister and Hobbs, 1980). In order to determine whether deformation was coaxial or non-coaxial and to understand the variations in the deformation intensity, a c-axis fabric analysis of quartz grains was undertaken on some of the Tenryukyo granite illustrated in Figure 24.

In strongly-mylonitized zones, quartz grains display single girdles or incomplete type I crossed girdles with dominant girdles leading to a marked asymmetry with respect to the Sm (Fig. 24). Specifically, the c-axis fabrics from the samples of the lower strongly mylonitized zone in the southwest of the Hoji Pass are strongly asymmetrical with respect to the Sm. Some of these seem to be associated with a Y-maximum. However, the c-axis fabrics from the samples of the weakly mylonitized zone do not show any distinct pattern. A preferred orientation of the c-axis becomes more intense with increasing shear strain and finite strain toward the strongly-mylonitized zones, showing a gradual change of the fabric pattern (Fig. 24). By analogy with other fabric studies in non-coaxial environments (e.g. Burg and Laurent, 1978; Lister and Price, 1978; Lister and Williams, 1979; Lister and Hobbs, 1980; Behrmann and Platt, 1982; Bouchez *et al.*, 1983; Simpson and Schmid, 1983; Evans and White, 1984; Lister and Snoke, 1984, etc.), the sense of c-axis fabric asymmetry in these rocks with respect to the mesoscopic foliation indicates a left-lateral shear. This sense of shear is consistent with the other asymmetric microstructures which have been described. Quartz fabrics from other areas of the Ryoke belt have been analyzed (Hara and Yokoyama, 1974; Hara *et al.*, 1977, 1980b; Hayashi and Takagi, 1987; Sakakibara *et al.*, 1989), with essentially the same result as this study.

The fabric patterns in this region suggest that the prismatic plane, as well as the basal and the rhombic planes, played an important role in an active glide system during deformation of quartz in the Ryoke belt (Lister and Hobbs, 1980). This result agrees with data from Sakakibara *et al.* (1989).

Sakakibara *et al.*'s (1989) work in the Kayumi area suggest that the strain modes inferred from the c-axis fabrics in this area do not correspond with those defined by the average three-dimensional shapes of quartz pools. As previously discussed, the quartz fabric pattern is sensitive to changes in movement during the closing stages of deformation. Thus, the analyzed c-axis fabrics may only be the result of the later stage deformation of mylonitization of the Tenryukyo granite.

5. Profile of the mylonite zone in the Tenryukyo granite

On the basis of the analysis of the strain mode of quartz pools, the distribution of the average grain size, the quartz aspect ratio, and the quartz c-axis fabrics, the profile of the mylonite zone in the area is explained as follows. The basal portion of the Tenryukyo granite forms a non-uniform horizontal shear zone, which experienced a top to the southwest shear (Fig. 25). This non-uniform shear zone macroscopically consists of two parallel strongly mylonitized zones. The strain mode is approximately one of flattening, based on the average shapes of quartz pools. According to the data for the c-axis fabrics and grain size reduction of recrystallized quartz, the deformation in the later stage became simple shear and was concentrated in the southwestern margin of the Tenryukyo granite. The Tenryukyo granite was tectonically emplaced on the metamorphic rocks.

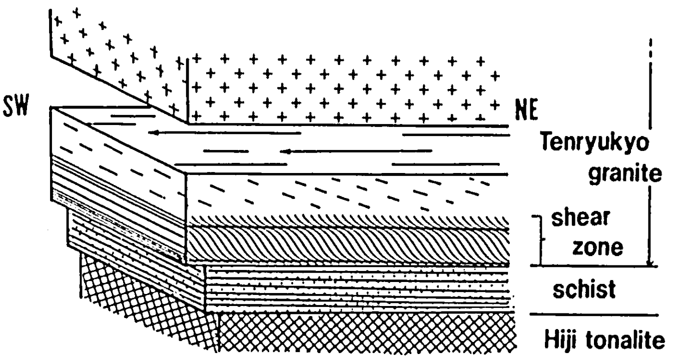


Fig. 25. Schematic diagram showing the development of shear zones of the Tenryukyo granite in the Hoji Pass area.

E. Geotectonic history of the Hoji Pass area

The following tectonic history of the area is based on the geological and structural data discussed above.

(1) The Tenryukyo granite intruded into the gneisses.
(2) The Tenryukyo granite was strongly mylonitized forming a non-uniform horizontal shear zone. The deformation was mostly concentrated in a narrow zones of the basal part of the granite. The upper structurally portion was displaced toward the southwest along the horizontal shear zone. The Ryoke metamorphic rocks were affected by deformation at low temperature condition which resulted in the disappearance of garnet and andalusite. The mylonitization occurred during retrograde metamorphism and the formation of nappe structures. This deformation is comparable with D3 in the Sakuma area.
(3) Upright folds with a NE-SW trend were formed.
(4) Thrust with a N-S trend and high-angle faults with a NW-SE trend occurred. Finally, the MTL formed, cutting across the other faults.

VI. Hiraoka-Tomiyama area

A. Outline of geology

The Hiraoka-Tomiyama area is located approximately 4 km from the MTL. According to the metamorphic facies map of Suwa (1961), the central culmination axis of the Ryoke metamorphic belt is located in this area. Geological and petrological studies of the Ryoke belt around Lake Sakuma have been performed by many workers. The Plutonism Research Group of Hokkaido University (1964, 1965) have studied the geologic structure of the

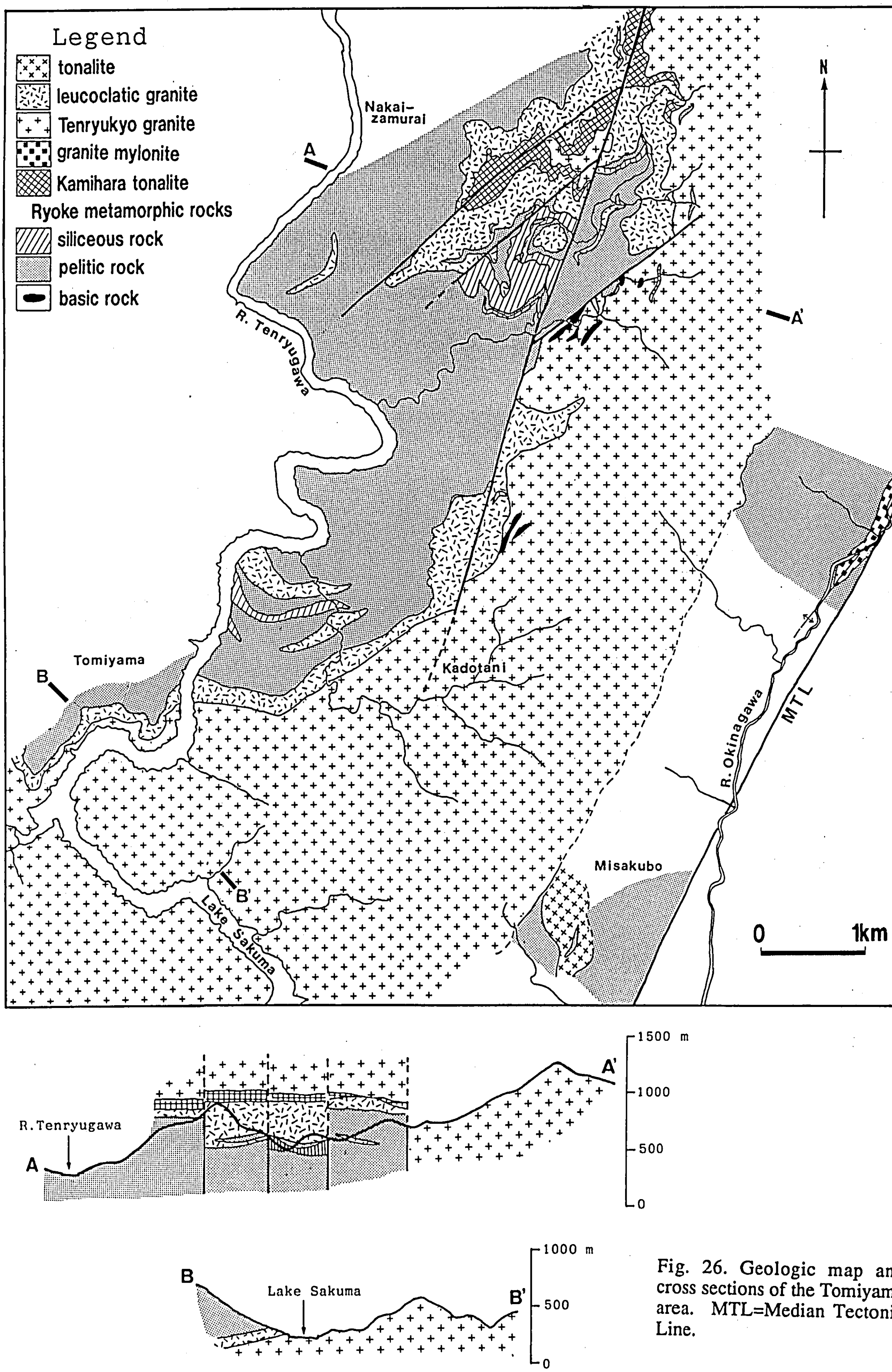


Fig. 26. Geologic map and cross sections of the Tomiyama area. MTL=Median Tectonic Line.

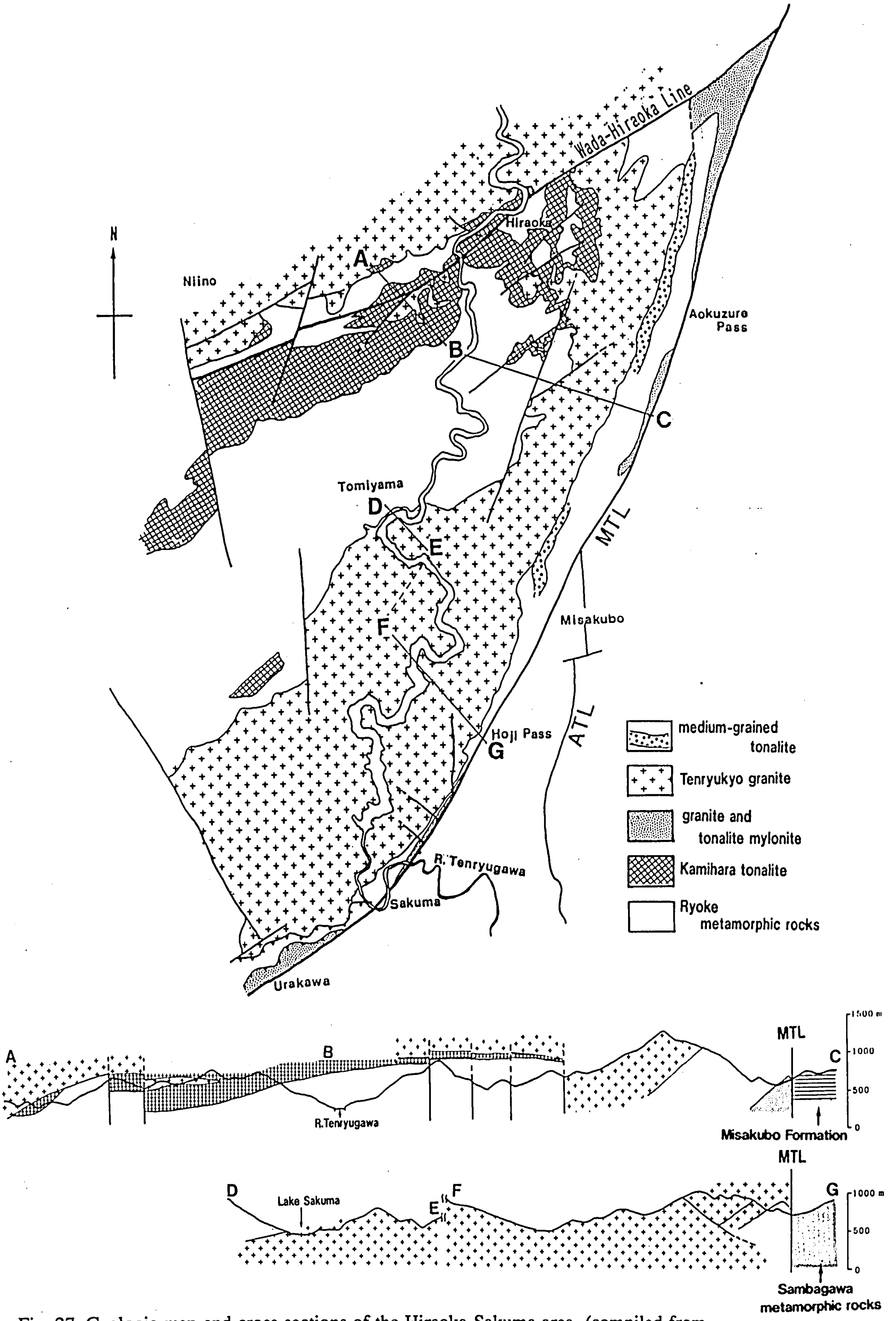


Fig. 27. Geologic map and cross sections of the Hiraoka-Sakuma area. (compiled from Togashi (1987); Yamada et al. (1974); Fig.26. in this paper). MTL= Median Tectonic Line, ATL= Akaishi Tectonic Line.

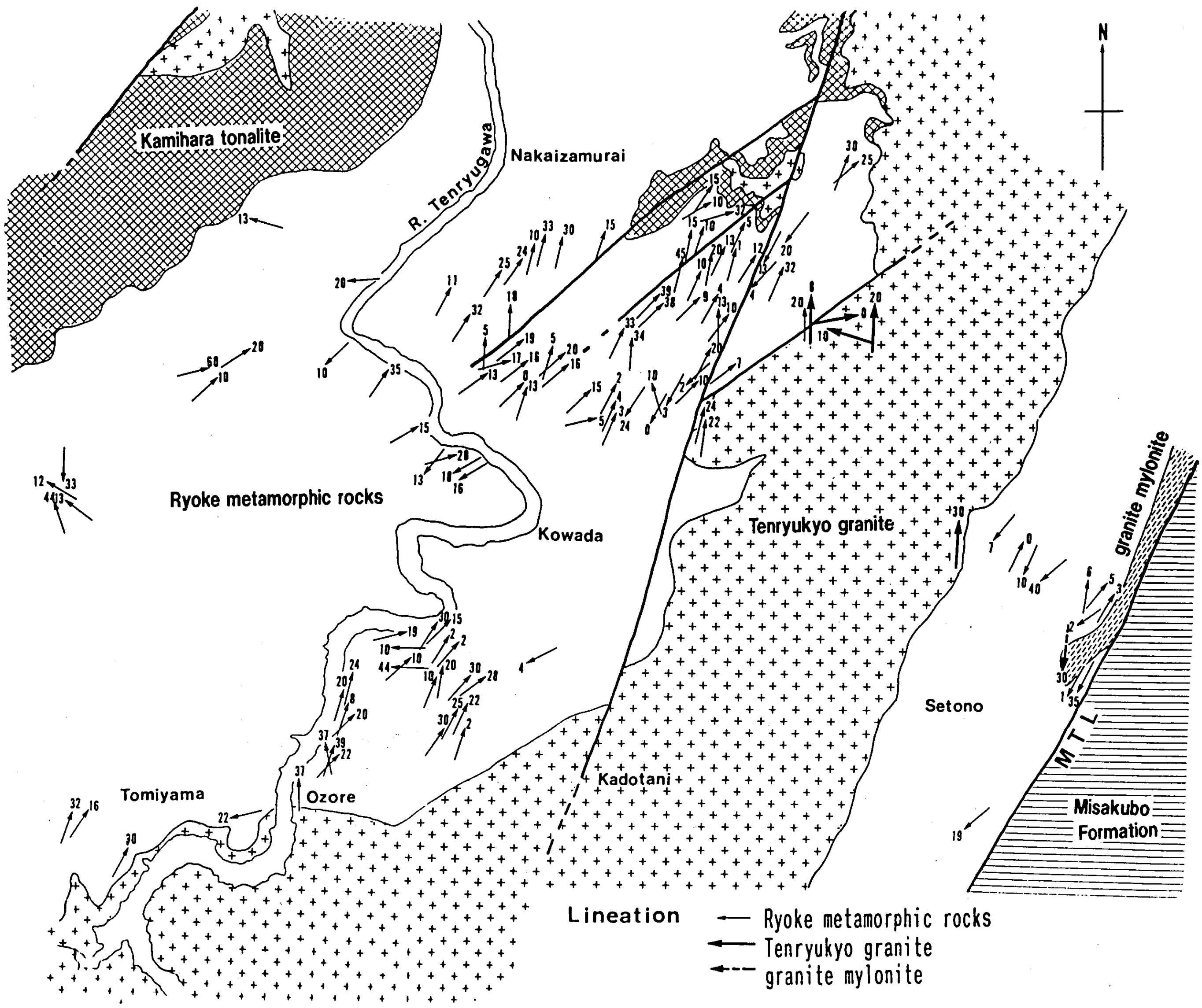


Fig. 28. Diagram of the orientation of stretching lineation of the metamorphic rocks in the area from Nakaizamurai to Tomiyama

metamorphic and granitic rocks around Lake Sakuma. Geological, petrological, and Rb-Sr geochronological studies of the granitic rocks exposed in the Niino area, in the northern part of the Hiraoka-Tomiyama area, were performed by Kagami (1968, 1973). The petrography, chemistry, and mineralogy of the metamorphic rocks in this area were also described by Kutsukake(1977). The metamorphic grade in the Hiraoka-Kadotani area was examined in detail from petrological data of the metamorphic minerals in pelitic gneisses by Yokoi (1983). Recently, the geologic structure of the older granite and metamorphic rocks in the Hiraoka area was also analysed by Togashi(1987). Additionally, Ohtomo (1991) has recently studied the geologic structure of the Hiraoka-Sakuma area, concluding that the nature of the deformation relates to the formation of the southern marginal shear zone. The Ryoke rocks exposed in the Tomiyama area, are divided into four units (Fig. 26) - metamorphic rocks (derived from sedimentary rocks), the Kamihara tonalite, fine-grained leucogranite, and the Tenryukyo granite.

B. Major geologic structure

In previous work (the Plutonism Research Group of Hokkaido University, 1964, 1965), the geologic structure of the Ryoke rocks in the area had been characterized as a flat-lying structure of the metamorphic rocks and the Kamihara tonalite, with a steeply dipping structure of the Tenryukyo granite. Togashi (1987) has pointed out that the metamorphic rocks, the Kamihara tonalite, and the Tenryukyo granite have a stratified structure, forming a NNE-SSW trending upright fold.

Figure 26 is a geologic map from the area around Lake Sakuma between Nakaizamurai and Tomiyama. Figure 27 is a geologic map along the River Tenryugawa between Hiraoka and Sakuma compiled from the data of my investigation, Togashi (1987) and Yamada *et al.* (1974). In northern Nakaizamurai, a stratified structure exists with the Kamihara tonalite overlying the metamorphic rocks, and Tenryukyo granite lying above the Kamihara tonalite. But, in southern Tomiyama, the Tenryukyo granite lies below the metamorphic rocks. In this region, the Ryoke rocks form a

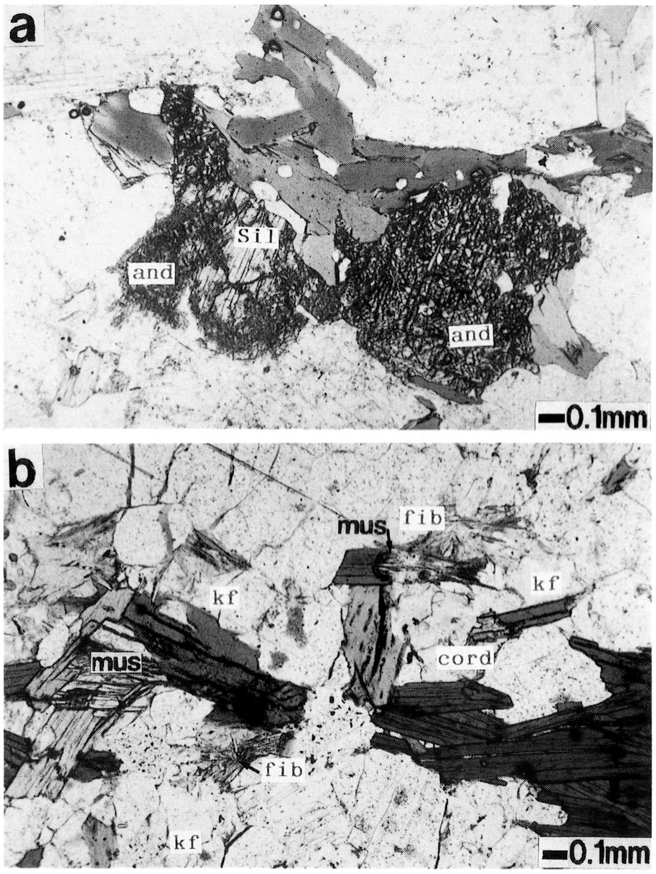


Fig. 29. Photomicrographs of pelitic gneisses with andalusite(and), sillimanite(sil), and fibrolite(fib) in the Hiraoka-Tomiyama area. (a) Sillimanite occurs in contact with andalusite and was converted from andalusite. (b) Fibrolite occurs with K-feldspar(kf). cord=cordierite, bt=biotite, mus=muscovite.

recumbent fold with a N-S trending axis and a W dipping axial plane. The axis of recumbent fold is not parallel to the NE-SW stretching lineation (Figs. 28 and 35). NE-SW and ENE-WSW high-angle faults were produced after the formation of the recumbent fold.

C. Rock types and petrography

1. Ryoke metamorphic rocks

The Ryoke metamorphic rocks are surrounded by the Tenryukyo granite and are widely exposed in the central part of the Hiraoka-Sakuma area (Fig. 27). They mainly consist of pelitic gneisses with a subordinate amount of siliceous gneisses and basic metamorphic rocks. Siliceous gneisses contain some psammitic gneisses. Well-developed gneissosity and stretching lineation are typical of these gneisses. Intrafolial folds exist and have axes that are parallel to the stretching lineation (Fig. 33).

The mineral assemblages of pelitic gneisses are:

1. sillimanite ± andalusite +cordierite + biotite + muscovite + K-feldspar + plagioclase + quartz
2. sillimanite ± andalusite + biotite + muscovite + K-feldspar + plagioclase + quartz
3. cordierite + garnet + biotite + muscovite + K-feldspar + plagioclase + quartz
4. cordierite + biotite + muscovite + K-feldspar + plagioclase + quartz
6. garnet + biotite + muscovite + K-feldspar + plagioclase + quartz
3. biotite + muscovite + K-feldspar + plagioclase + quartz
7. biotite + muscovite + plagioclase + quartz

Andalusite, cordierite, sillimanite, and garnet are found as porphyroblasts. Sillimanite occurs in contact with andalusite and its crystallographic c-axis coincides with that of andalusite in the southwestern part of the field area (Fig. 29a). In contrast to this, fibrolite is not in contact with andalusite and sillimanite, but occurs with K-feldspar in the north-western part of the area (Fig. 29b). According to Yokoi (1983), sillimanite was converted from andalusite, but fibrolite was produced by decomposition of muscovite with quartz (Yokoi, 1983). Additionally, the distribution coefficient of Fe and Mg, between biotite and cordierite, decreases continuously from the south-eastern region to the northwestern region. Therefore Yokoi (1983) concluded that the metamorphic grade increases from the southeast to the northwest in the Hiraoka-Kadotani area. This suggests that the downward structural increase of the metamorphic grade is harmonic with the major geologic structure.

Pelitic gneisses typically show a gneissosity. The gneissosity is mainly defined by preferred dimensional and lattice orientations of strongly elongated platelets of biotite. This is comparable with the S2 foliation in the Sakuma area. Intrafolial folds are frequently open or tight in shape and observed in the hinge area of the recumbent fold. They are not accompanied by axial plane cleavage but by a stretching lineation, which is well- developed around the hinge of the recumbent fold but relatively ambiguous clear developed in the northern area.

Figure 34 shows quartz c-axis fabrics of a folded siliceous gneiss. The quartz c-axis fabric in the fold limb shows random orientation, but in the hinge have a pattern that is mainly related to crystal plastic processes during the folding. The pattern of the latter indicates that the lineation corresponds to the X-direction.

2. Kamihara tonalite

The Kamihara tonalite is mainly exposed in the area from Hiraoka to Niino. It is a sheet-like body intercalated with pelitic gneisses. According to Togashi (1985, 1987), the Kamihara tonalite is mainly composed of medium-grained hornblende-biotite tonalite with subordinate amounts of hornblende-biotite granite and granodiorite with K-feldspar porphyroblasts which were formed by metasomatism of the Tenryukyo granite. The Kamihara tonalite consists mainly of plagioclase, quartz, biotite, hornblende, clinopyroxene, ±K-feldspar with accessory zircon, allanite, apatite and ilmenite.

This tonalite has a well-developed gneissosity which is parallel to that of the surrounding gneisses (Figs. 31 and 32a). The tonalite gneissosity is characterized by an elongation of the basic inclusions and an alignment of the mafic minerals (Fig. 30a & b). Mafic minerals such as biotite and hornblende form aggregates and have a shape alignment as a result of the deformation. The quartz domains are weakly elongated. The Kamihara tonalite around Uedaira, near the axis of the recumbent fold, does not only have a strong gneissosity but also a stretching lineation which is defined by an elongation of quartz domains and aggregates of mafic minerals. The stretching

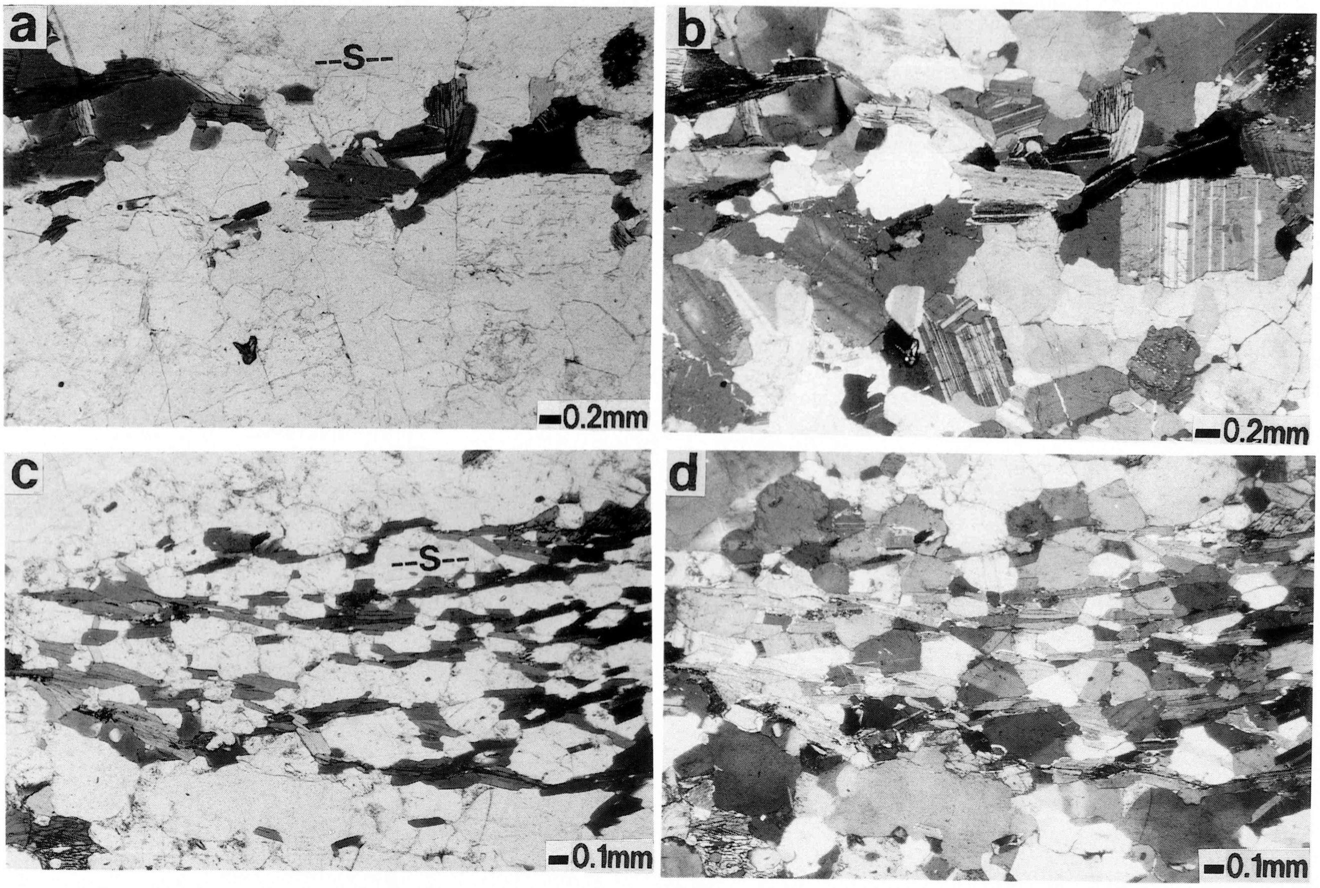


Fig. 30. Photomicrographs of the Kamihara tonalite. (a)(b) The typical Kamihara tonalite with gneissosity (S) defined only by shape orientation of mafic minerals. (c)(d) The Kamihara tonalite involved in the axial region of the recumbent fold shows well-developed gneissosity (S). (a)(c) open nicols, (b)(d) crossed nicols.

lineation of the Kamihara tonalite is parallel to that of the gneisses (Figs. 28 and 32b). Near the axis of the recumbent fold, strongly-deformed facies, with several cm in thickness, were occurred in the Kamihara tonalite (Fig. 30c & d). According to Kagami (1968), there are neither facies variations in the Kamihara tonalite near the wall rocks, nor veins, derived from the Kamihara tonalite, in the wall rocks.

3. Tenryukyo granite

The Tenryukyo granite is widely exposed in the Hiraoka-Sakuma area (Fig. 27). It is a large body, 36 Km x 7.5 - 2 Km, and is elongated parallel to the MTL. Unfolding the recumbent fold, it is considered to be a large sheet-like body.

The Tenryukyo granite in this area consists of coarse-grained biotite granite and medium-grained hornblende-biotite granodiorite and tonalite. The coarse-grained biotite granite characteristically contains porphyritic K-feldspar. These lithofacies grade into each other. The Tenryukyo granite often includes xenoliths of metadiabase and gneisses. Most of them are rounded. The Tenryukyo granite mainly consists of plagioclase, quartz, K-feldspar, biotite, and hornblende with accessory zircon, apatite, and ilmenite. Foliation is developed in the axial part of the recumbent fold and around the boundary of the Tenryukyo granite. It is defined by the arrangement of elongated quartz pools and of biotite flakes.

4. Fine-grained leucogranite

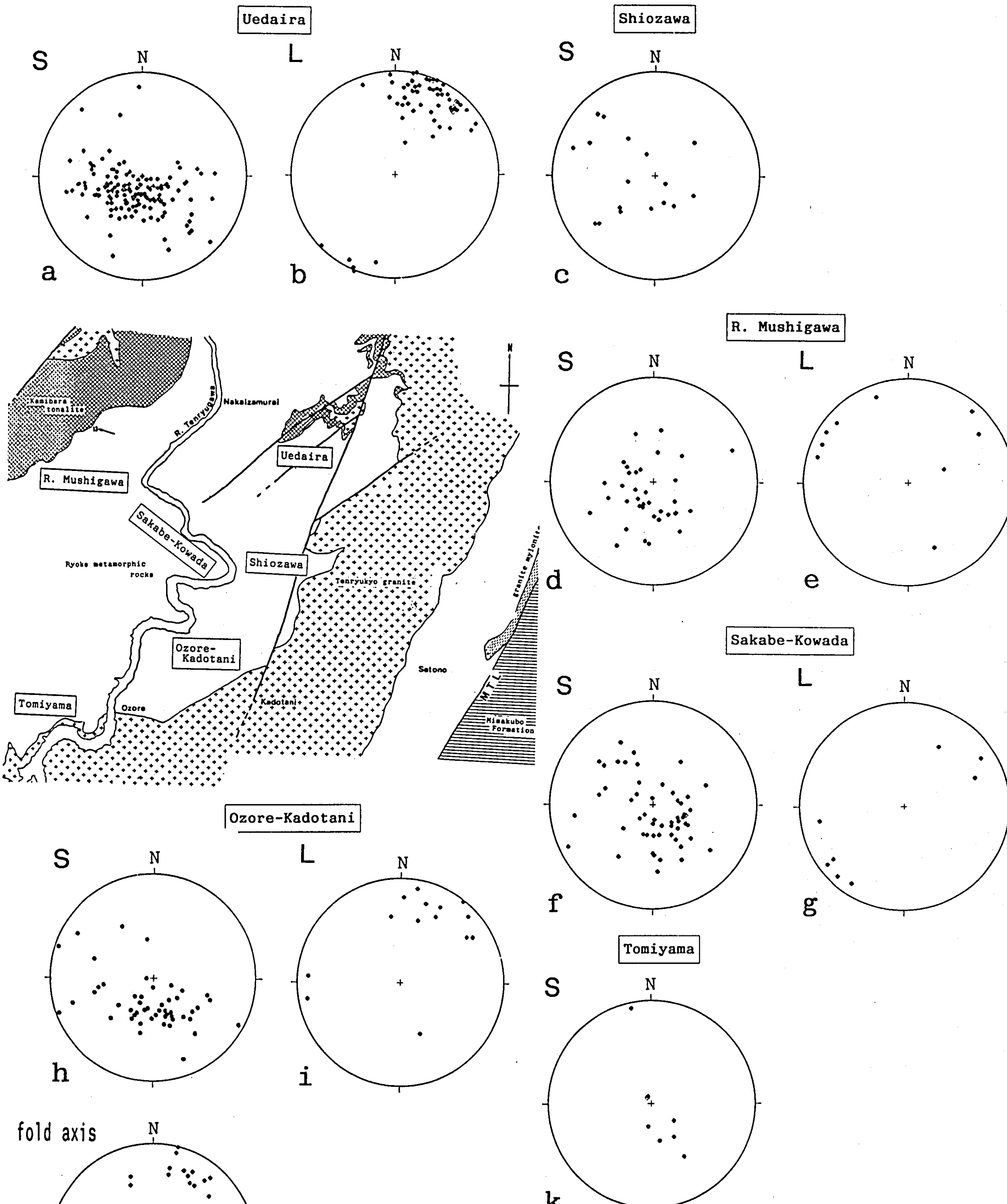
The fine-grained leucogranite is mainly exposed in the areas around the axis of the recumbent fold and between the Tenryukyo granite and the gneisses (Fig. 26). The leucogranite intrudes the Tenryukyo granite, Kamihara tonalite, and gneisses. Xenoliths of surrounding gneisses are typical. Many of them are partly assimilated by the leucogranite.

The leucogranite mainly consists of quartz, K-feldspar, plagioclase, biotite, and muscovite with accessory zircon, apatite and ilmenite. Cordierite also exists in minor amounts. The foliation in the granite, which is weakly developed (Fig. 32e), is defined by the arrangement of biotite and xenoliths, and seems to be parallel to the mass boundary.

D. Deformation history of the Hiraoka-Sakuma area

On the basis of the geological and structural features mentioned above, two deformation phases can be distinguished: 1) "the first phase", resulting in the formation of the gneissosity; and 2) "the second phase", resulting in the formation of the recumbent fold.

The first phase deformation is related to the formation of a gneissosity of the metamorphic rocks. The gneissosity is defined by a preferred dimensional and lattice orientation of



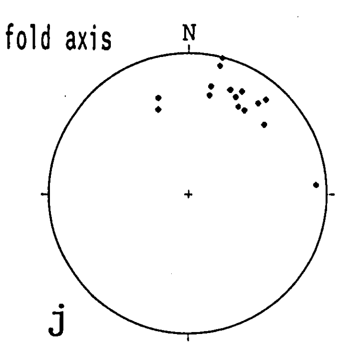
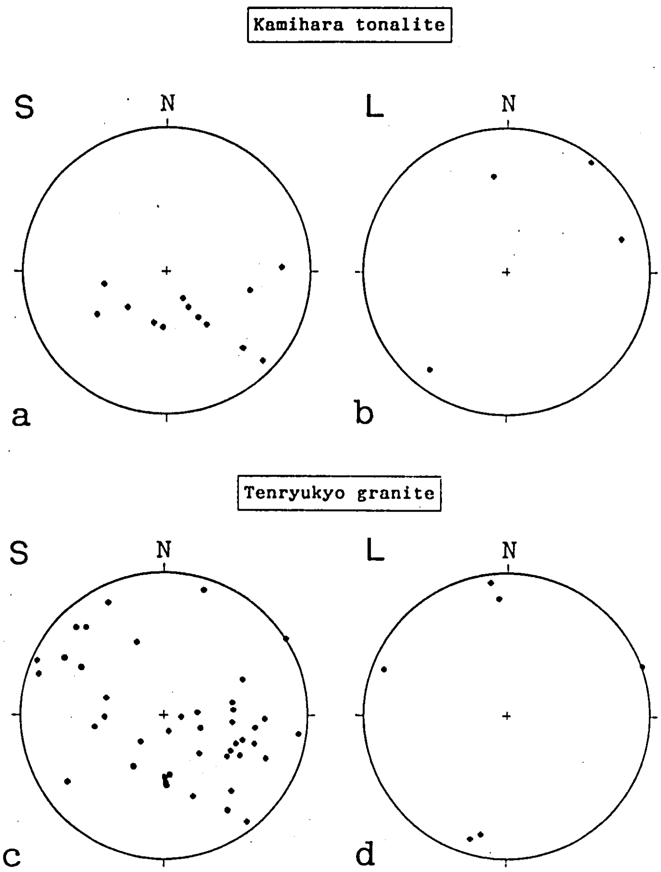


Fig. 31. Index map for the location of the data described in the diagrams a to k and equal area plots showing the orientation data for the metamorphic rocks of the Hiraoka-Tomiyama area. (a), (c), (d), (f), (h) and (k) are of gneissosity. (b), (e), (g) and (i) are of stretching lineation. (j) is of minor fold axes around Ozore-Kadotani.



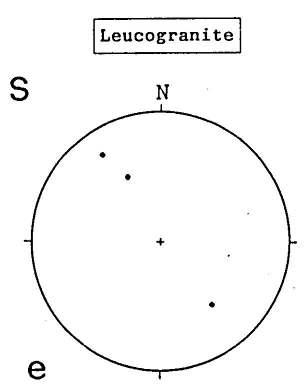


Fig. 32. Equal area plots showing the orientation data for the Kamihara tonalite, the Tenryukyo granite and the leucogranite. (a), (c) and (e) are of the foliation. (b) and (d) are of stretching lineation.

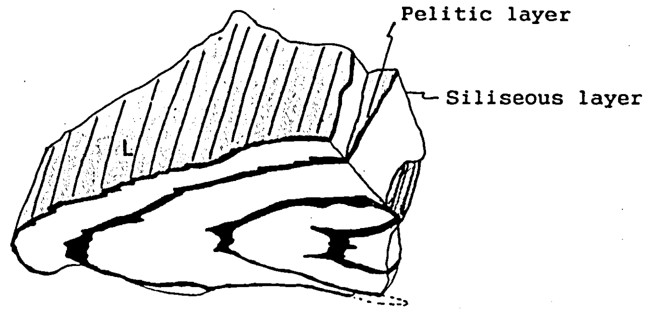


Fig. 33. Sketch of an intrafolial fold of the metamorphic rocks of the Tomiyama area. L= stretching lineation.

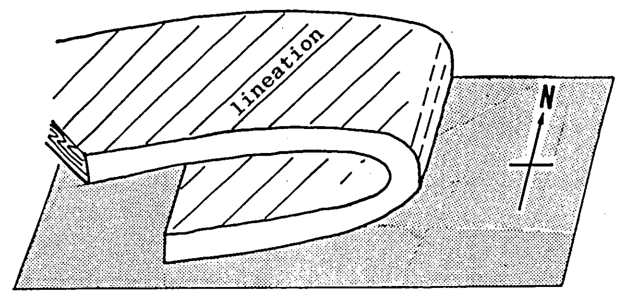


Fig. 35. Schematic diagram showing the orientation relation of some structural elements in the recumbent fold of the Hiraoka-Sakuma area. The axis of the recumbent fold is not parallel to the stretching lineation, or the axis of the intrafolial fold.

biotite flakes which are free from inclusions. There is no lineation of the gneissosity. The metamorphism, related to the crystallization of biotite flakes, occurred simultaneous to the deformation related to the formation of the gneissosity. On the basis of the deformation history analyzed in the Sakuma area, the gneissosity and its genesis are correlated with S2 and D2, respectively. Pelitic rocks mainly contain andalusite, sillimanite, K-feldspar, cordierite, biotite, and muscovite. The metamorphism associated with the

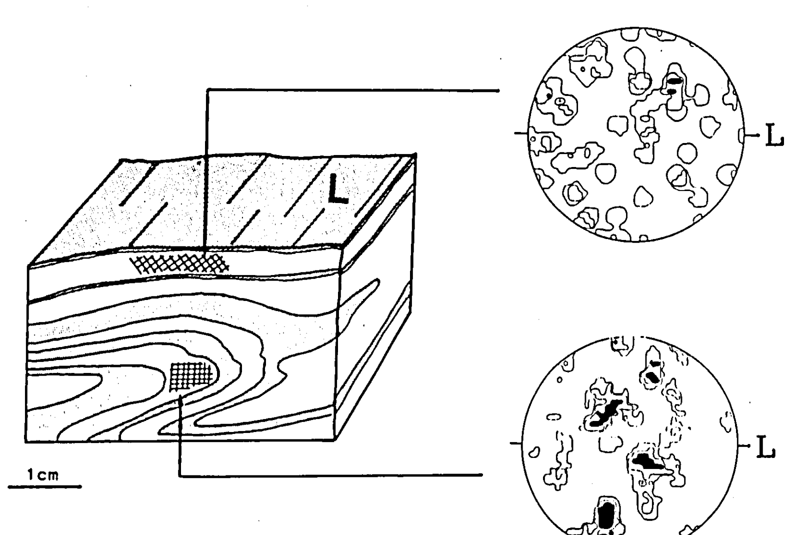


Fig.34. Sketch of an intrafolial fold of a siliceous gneiss of the Tomiyama area and c-axis fabrics of quartz grain in the fold. L= stretching lineation.

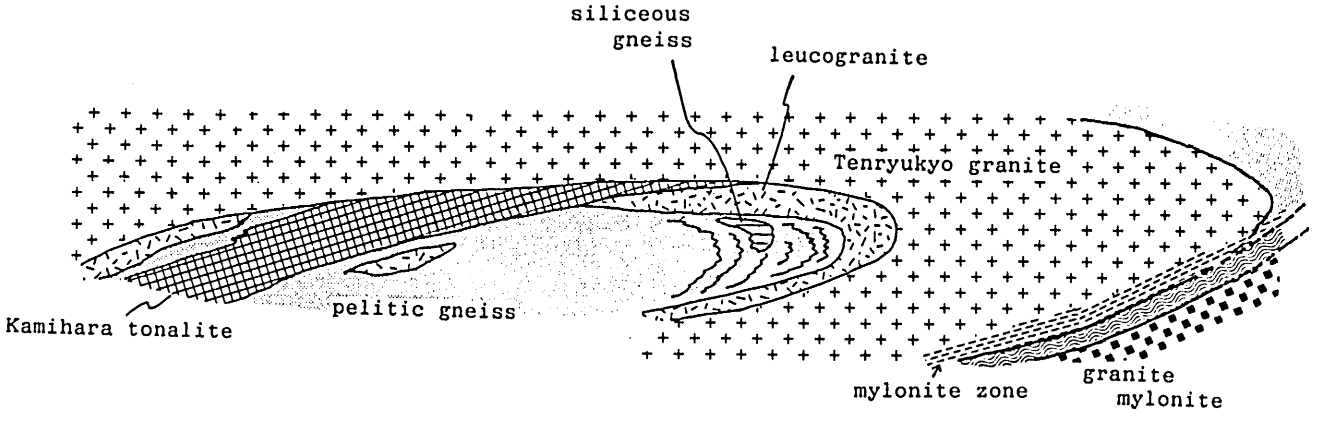


Fig. 36. Schematic diagram of a profile of the recumbent fold in the Hiraoka-Sakuma area.

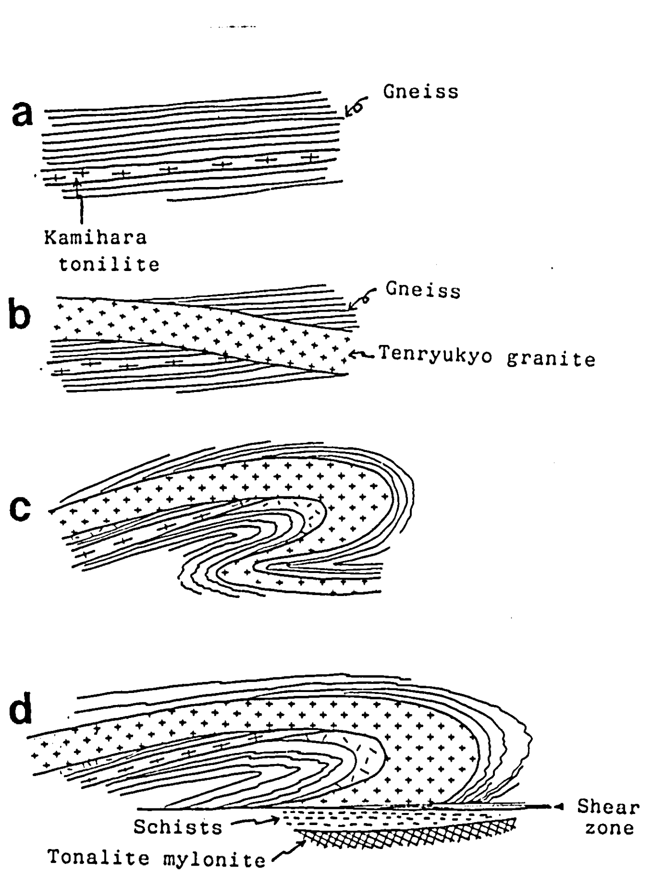


Fig. 37. Schematic diagram showing the stages of the formation of the recumbent fold of the Hiraoka-Sakuma area. (a) The Kamihara tonalite and the Ryoke metamorphic rocks (gneisses) deformed, forming gneissosity (b) The Tenryukyo granite intruded into the Ryoke metamorphic rocks (gneisses) and the Kamihara tonalite as a sheet-like body.(c) Recumbent folding. (d) In the later stage of the formation of the recumbent fold, a non-uniform shear zone was produced along its lower limb, giving rise to tectonic contact with the underlying metamorphic rocks (schists) and tonalite mylonite.

formation of the gneissosity occurred under upper amphibolite facies and is correlated with a period of the highest temperature of the Ryoke metamorphism. According to Yokoi(1983), fibrolite-bearing pelitic gneisses occur extensively in the northwestern area, except for those adjacent with the Tenryukyo granite. Additionally, the distribution coefficient of Fe and Mg between biotite and cordierite decreases from the southeast to the northwest. These facts show that the metamorphic grade increases from the southeast to the northwest. Specifically, the downward structural increase in the metamorphic grade is harmonic with the major geologic structure of the metamorphic rocks surrounded by the Tenryukyo granite.

The well-developed gneissosity of the Kamihara tonalite is approximately parallel to and continuous with that of the surrounding metamorphic rocks (Togashi, 1987), suggesting that the gneissosity of the Kamihara tonalite and metamorphic rocks was formed in the same deformation phase. The Kamihara tonalite is interpreted to have intruded the Ryoke metamorphic rocks before or during D2.

The second phase deformation in the Hiraoka-Sakuma area resulted in the formation of a recumbent fold of the Tenryukyo granite. S2, stretching lineation and axis of intrafolial folds are plotted in Figures 28, 31and 32. The fold axis of the recumbent fold has N-S trend and gently plunges toward the north. In the southern part of the area, the stretching lineation is well-developed unlike in other areas. As the Plutonism Research Group of Hokkaido University (1964, 1965) pointed out, gneisses have two types of lineations which trend to N-S and NE-SW. The stretching lineation of gneisses and of the Kamihara tonalite runs generally NE-SW. In the Tenryukyo granite, the lineation trends in some places to N-S, parallel to the axis of the recumbent fold. The NE-SW trending lineation is interpreted to be related to the maximum elongation during the folding.

In the Misakubo and the Sakuma-Hoji Pass areas, the southern marginal shear zone is developed on the lower limb of the recumbent fold (Figs 27 and 36). The lineation in the southern shear zone is subparallel to the stretching lineation in the gneisses in the Hiraoka-Tomiyama area. The recumbent fold and the shear zone seem to have grown progressively in the same movement picture. The earliest stage of formation of the recumbent fold was followed by that of the shear zone on its lower limb, and that of

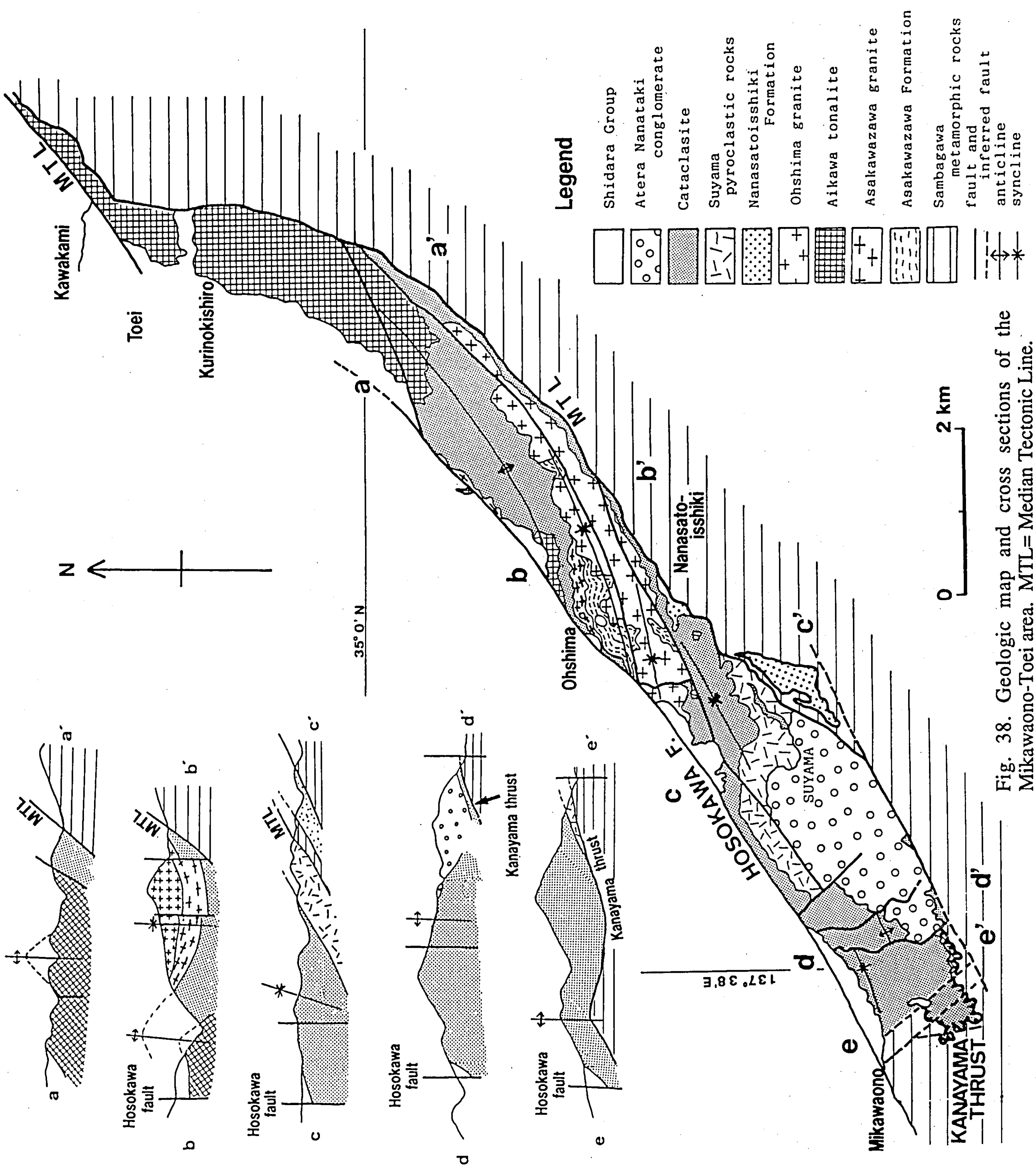


Fig. 38. Geologic map and cross sections of the Mikawaono-Toei area. MTL= Median Tectonic Line.

underlying geological structure (Fig. 37). The formation of the recumbent fold is correlated to the D3 event.

VII. Mikawaono-Toei area

A. Outline of geology

In the Mikawaono-Toei area, the MTL is a sharply curved line, and the Ryoke belt juts out onto the Sambagawa belt (Fig. 38). In this area, pre-Miocene rocks of the Inner Zone are exposed in a long, narrow area bounded by faults. The jutting domain is separated on the northwest from the Eocene-Miocene Shidara Group by the Hosokawa fault, and on the southeast from the Sambagawa metamorphic rocks by the MTL and the Kanayama thrust (Ohtomo, 1990). In this area between Nosaka and Toei and along the Hosokawa fault, the pre-Miocene rocks are unconformably covered by the Shidara Group.

The geology of the jutting domain has been studied by Saito (1955), Ui (1980), Hara *et al.* (1980b), Yamada *et al.* (1987), Ui *et al.* (1988) and Ohtomo (1986, 1989, 1990), analyzing its complicated nature. Saito (1955) pointed out that rocks of this area consist of the Suyama Formation, the Kochi Formation, and mylonites derived from igneous and sedimentary rocks. Ui (1980) studied the area between Mikawaono and Kurosawa, showing the distribution of various rock units - the Atera Nanataki conglomerate, the Suyama pyroclastic rocks, the Kochi Formation, and granite cataclasite. He called the area between the Hosokawa fault and the MTL, a lenticular "disturbed zone", because of the complicated association of the various rocks. Hara *et al.* (1980b) divided rocks in the Suyama district, into the Kochi Formation, mylonitized Ryoke rocks, and the Suyama Formation. Yamada *et al.* (1987) divided rocks in the area between Mikawaono and Ohshima, into the Atera Nanataki conglomerate, the Suyama pyroclastic rocks, cataclastic rocks derived from the Mitsuhashi granite and the Kiyosaki granite, mylonite derived from the Hiji granodiorite, and the Kochi Formation. Fission-track ages of zircons of the Suyama pyroclastic rocks have been measured to be 65 Ma. Additionally, Ohtomo(1990) divided rocks in the jutting domain into 8 units (Fig. 38) - the Aikawa tonalite, the Nanasatoisshiki Formation, the Suyama pyroclastic rocks, the Asakawazawa granite, the Asakawazawa Formation, the Ohshima granite, cataclasites, and the Atera Nanataki conglomerate. The geologic map and cross sections of the Mikawaono-Toei area are shown in Figure 38.

B. Major geologic structure

Hara *et al.* (1980b) pointed out that the MTL in the area is inclined toward the north at low angles. Recently a detailed investigation of the geology of this area (Ohtomo, 1986, 1989, 1990) has revealed that pre-Miocene rocks, expect for the Atera Nanataki conglomerate, are piled as nappes. Around Suyama, the Nanasatoisshiki Formation, the Suyama pyroclastic rocks, cataclasites and the Ohshima granite are arranged in nappe piles in ascending order. In the area from Ohshima to Toei, the Aikawa tonalite, the cataclasites, the Asakawazawa granite, the Asakawazawa Formation, and the Ohshima granite are also piled as nappes in ascending order. The pile nappes were thrust over the Sambagawa metamorphic rocks. The pile nappe units and their basal thrust were respectively named the Ryoke nappe complex and the Kanayama thrust by Ohtomo (1990). The Ryoke nappe complex is unconformably covered by the Atera Nanataki conglomerate. All of the nappes form E-W trending upright folds. The half wave-length of the folds ranges from several hundreds of meters to 1 km (Fig. 38). A schematic profile, displaying the tectonic superposition of the Ryoke nappe complex and the Sambagawa belt in this area, is illustrated in Figure 39.

C. Rock types and petrography

1. Aikawa tonalite

The Aikawa tonalite (Ohtomo, 1990), is mainly exposed from the south of Nosaka to Kawakami and to the east of Ohshima. Additionally, on the north side of the Hosokawa fault, it is exposed only in a small area, and is unconformably covered by the Shidara Group, 2 km northeast of Ohshima.

The Aikawa tonalite is composed of mylonitic rocks, mainly derived from tonalite with subordinate granite. Basic inclusions are typically observed in tonalite. The tonalite mylonite is composed of quartz, plagioclase, biotite, hornblende, ±K-feldspar with accessory sphene, allanite, epidote, zircon and apatite. The granitic mylonite consists

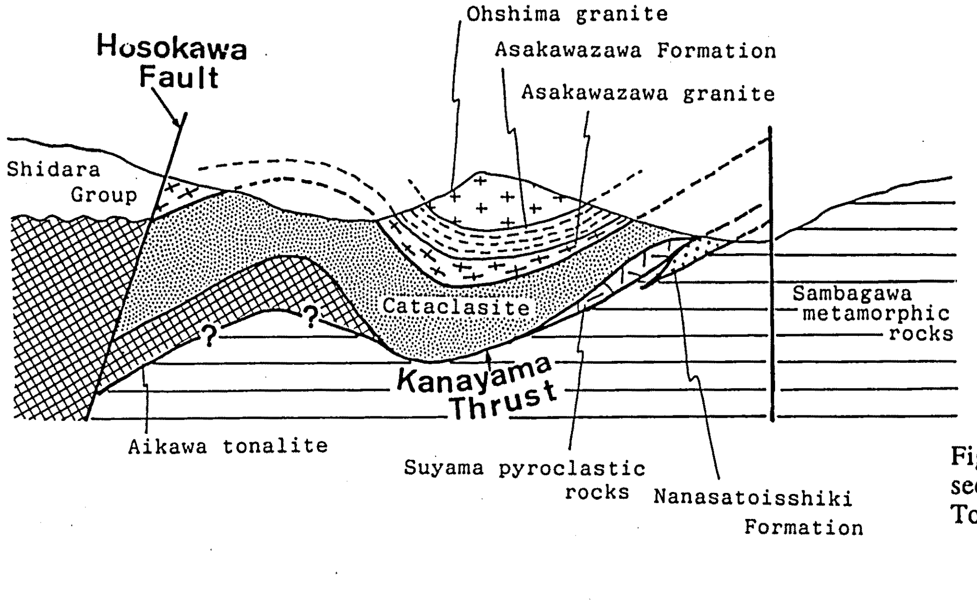


Fig. 39. Schematic geologic section of the Mikawaono-Toei area

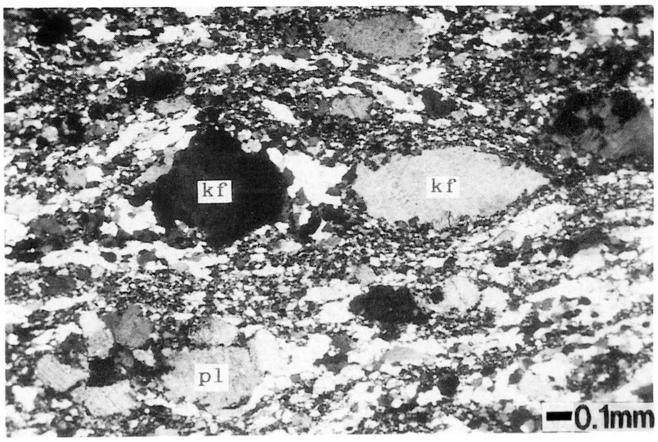


Fig. 40. Photomicrograph of a granite mylonite in the Aikawa tonalite. K-feldspar and plagioclase porphyroclasts are surrounded by fine, recrystallized grains of feldspar and quartz. kf= K-feldspar, pl= plagioclase.

of quartz, K-feldspar, plagioclase, biotite with the same kinds of accessory minerals as those of the tonalite.

In the strongly deformed rocks, mylonitic foliation (Sm), defined by a dimensional preferred orientation of elliptical porphyroclasts (Fig. 40), and fluxion banding, with elongated pressure shadows, are developed. The Sm is usually parallel to the original compositional banding. Basic inclusions are elongated parallel to the Sm. Intrafolial folds are often observed in the banded mylonites. Axial planes of the folds and elongation directions of the recrystallized quartz grains around their hinges are parallel to the general trend of the Sm, suggesting that the intrafolial folds formed during mylonitization. The stretching lineation (Lm) is defined by preferred dimensional orientation of biotite. But in weakly deformed rocks, the Sm and the Lm are not clear.

A NE-SW trending fault runs through Nosaka. The tonalite mylonites with a small amount of granitic mylonite are exposed on the northern side of the fault (Fig. 41a). The intensity of mylonitization increases toward the east and the

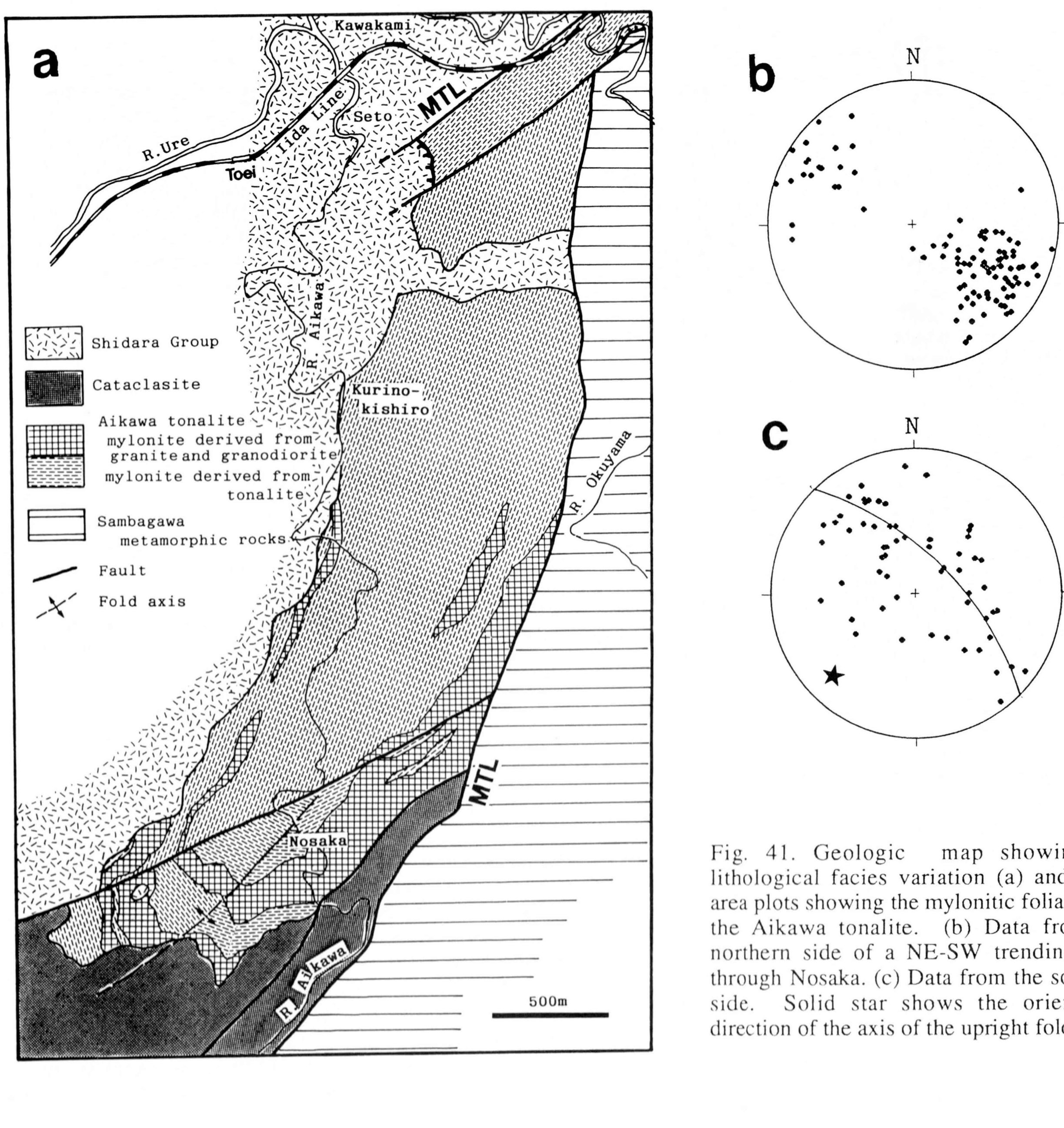


Fig. 41. Geologic map showing the lithological facies variation (a) and equal area plots showing the mylonitic foliation of the Aikawa tonalite. (b) Data from the northern side of a NE-SW trending fault through Nosaka. (c) Data from the southern side. Solid star shows the orientation direction of the axis of the upright fold.

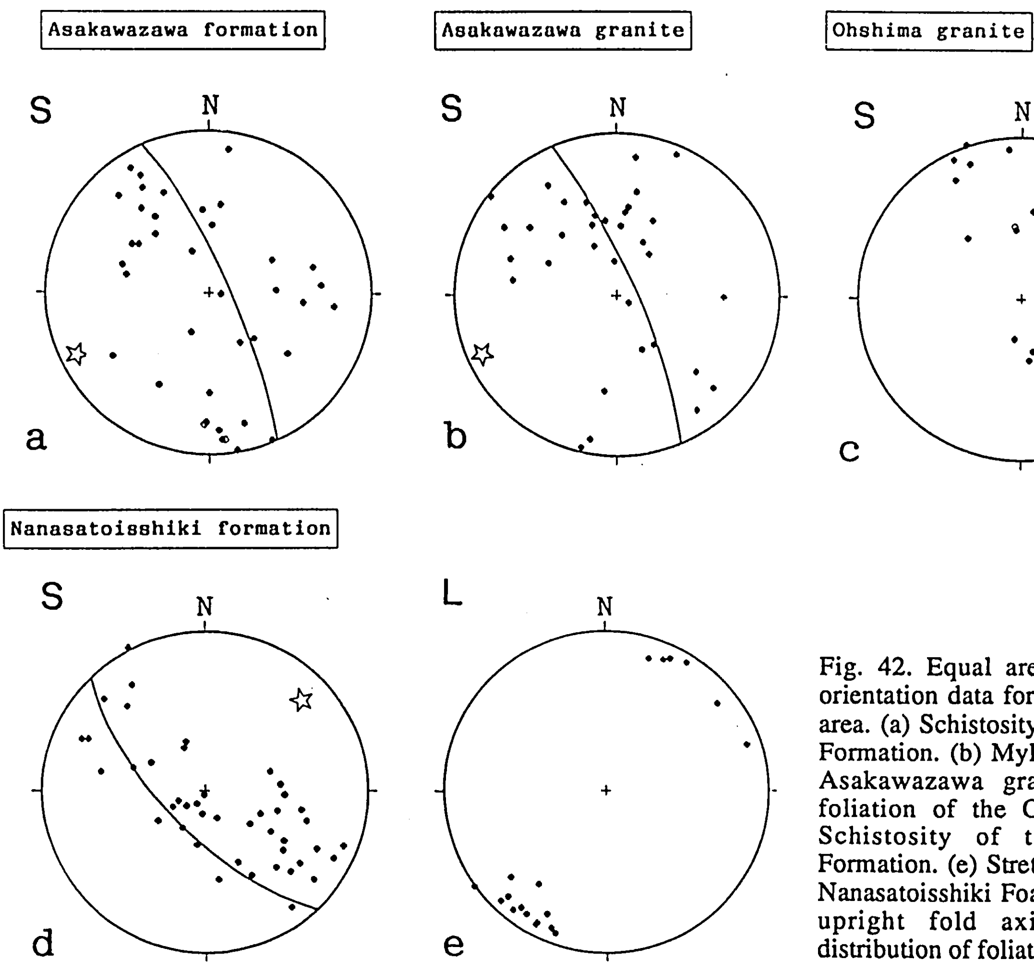


Fig. 42. Equal area plots showing the orientation data for the Mikawaono-Toei area. (a) Schistosity of the Asakawazawa Formation. (b) Mylonitic foliation of the Asakawazawa granite. (c) Mylonitic foliation of the Ohshima granite. (d) Schistosity of the Nanasatoisshiki Formation. (e) Stretching lineation of the Nanasatoisshiki Foation. Open star= the upright fold axis defined by the distribution of foliation.

west. Strongly-mylonitized rocks are exposed along the MTL. Granitic mylonites are more extensively exposed on the southern side of the fault (Fig. 41a). In general, mylonitization on the southern side of the fault is stronger than in the northern side. In the eastern part of Ohshima, ultra-mylonite is exposed separately in the cataclasite zone. On the northern side of the fault in Nosaka and the east of Ohshima, rhyolitic tuff of the Shidara Group unconformably covers the Aikawa tonalite (Fig. 38).

The Aikawa tonalite is underlain by the cataclasite zone to the south of Nosaka and to the east of Ohshima. To the south of Nosaka, the lithologic arrangement of the Aikawa tonalite is distinctly cut by the cataclasite zone (Fig. 41a). The uppermost part of the Aikawa tonalite near the cataclasite zone is affected by cataclastic deformation. This evidence shows that the Aikawa tonalite is in thrust contact with the cataclasite zone.

Figure 41b & c illustrates the orientation pattern of the Sm on the northern and the southern sides of the fault. The Sm of the former trends to the NE-SW and dips toward the north or the south. But the Sm of the latter plots on a great circle. In the geologic map (Fig. 41a), the lithologic arrangement of the Aikawa tonalite and the foliation of cataclasite overlying the tonalite (Fig. 46) also form a NE-SW trending antiform, which plunges toward the NE at a low angle. From these facts, it is concluded that the Aikawa tonalite and cataclasites form an upright fold after the formation of the cataclasite zone.

2. Nanasatoisshiki Formation

The Nanasatoisshiki Formation (Ohtomo, 1990), is exposed to the east of Suyama and in Nanasatoisshiki (Fig. 38). It had been regarded as a part of the Kochi Formation by Saito (1955), Ui (1980), Hara *et al.* (1980b), and Yamada *et al.* (1987). However, the Kochi Formation (Saito, 1955), does not only contain sedimentary rocks but also a large-volume of cataclasites derived from various rocks. Additionally, the Kochi Formation exposed around Kochi consists of cataclasites derived from sedimentary rocks and granite. Ohtomo (1990) separated the non-metamorphosed sedimentary rocks (sandstone, mudstone, and conglomerate) from the cataclasites, and called them the Nanasatoisshiki Formation.

To the east of Suyama, the Nanasatoisshiki Formation forms a thin nappe intercalated in the Sambagawa metamorphic rocks (Fig. 38), and mainly consists of sandstone with subordinately mudstone. Around Nanasatoisshiki, it is exposed between the MTL and the cataclasite zone (Fig. 38), and is composed of mudstone and conglomerate. The bedding of the Nanasatoisshiki Formation is represented by NE-SW trending upright folds with half wavelengths of 100 m (Fig. 42d). The sandstone of the Nanasatoisshiki Formation is lithic arenite. Detrital grains of sandstone are composed of quartz, plagioclase, K-feldspar, garnet, allanite, granite, mudstone, siliceous mudstone, sandstone, chert, psammitic schist, and altered volcanic rocks.

Well-developed foliation and lineation are observed in most places. In the sandstone, foliation and lineation are defined by the elongated shape of the detrital grains, the anastomosing cleavage folia, and the shape orientation of the white mica (Fig. 43a & b). The detrital grains are clearly elongated parallel to the lineation. The lineation is especially well-developed in the mudstone that is intercalated in the sandstone. On the plane parallel to the lineation, mica beards are closely intergrown. Mica flakes in these beards are fine-grained white mica, strongly oriented parallel to the mean cleavage direction. In mudstone, the foliation is defined by cleavage seams and a preferred lattice orientation of white mica. Recrystallized minerals and peak widths at the half height of the carbonaceous material (Fig. 49 and 50a) indicates that the Nanasatoisshiki Formation was metamorphosed under pumpellyite-prehnite facies.

The conglomerate to the south of Ohshima consists of pebbles of sandstone (arkose), siliceous mudstone, non-deformed granite, plagioclase-porphyry, andesite lava, rhyolitic tuff, recrystallized chert, and quartz rock of recrystallized grains. The cleavage is quite weakly-developed.

The quartz veins, less than 1 cm thick, are typically observed in sandstone and mudstone. The veins are folded with their axial surface parallel to the mean cleavage direction. The prehnite veinlets are also observed under the microscope. The above geological observation suggests that the Nanasatoisshiki Formation was deformed under low-temperature conditions, resulting in the formation of cleavage folia and seams due to pressure solution mechanisms.

3. Suyama pyroclastic rocks

The Suyama pyroclastic rocks (Ui, 1978), are a part of "the cataclastic rocks derived from igneous rocks" by Saito (1955) and "mylonitized Ryoke rocks" by Hara *et al.* (1980b). Ui (1977), Nakai (1977), and Suzuki and Kato (1978) found acid pyroclastic rocks in "the cataclastic rocks" by Saito (1955). Nakai (1977) correlated these to the Sen-nan rhyolites in the Kii Peninsula. According to Yamada *et al.* (1987), the fission-track ages of zircons from the Suyama pyroclastic rocks gave ages of 65.2±3.9 Ma and 58.0±3.9 Ma. Both of these ages are considerably younger than the age of the Sen-nan Rhyolites. The age data of the Suyama pyroclastic rocks were interpreted in terms of the eastward migration of the late Cretaceous acid volcanism in the Ryoke belt (Yamada *et al.*, 1987).

The Suyama pyroclastic rocks are exposed around Suyama (Fig. 38). Their distribution is bounded by the

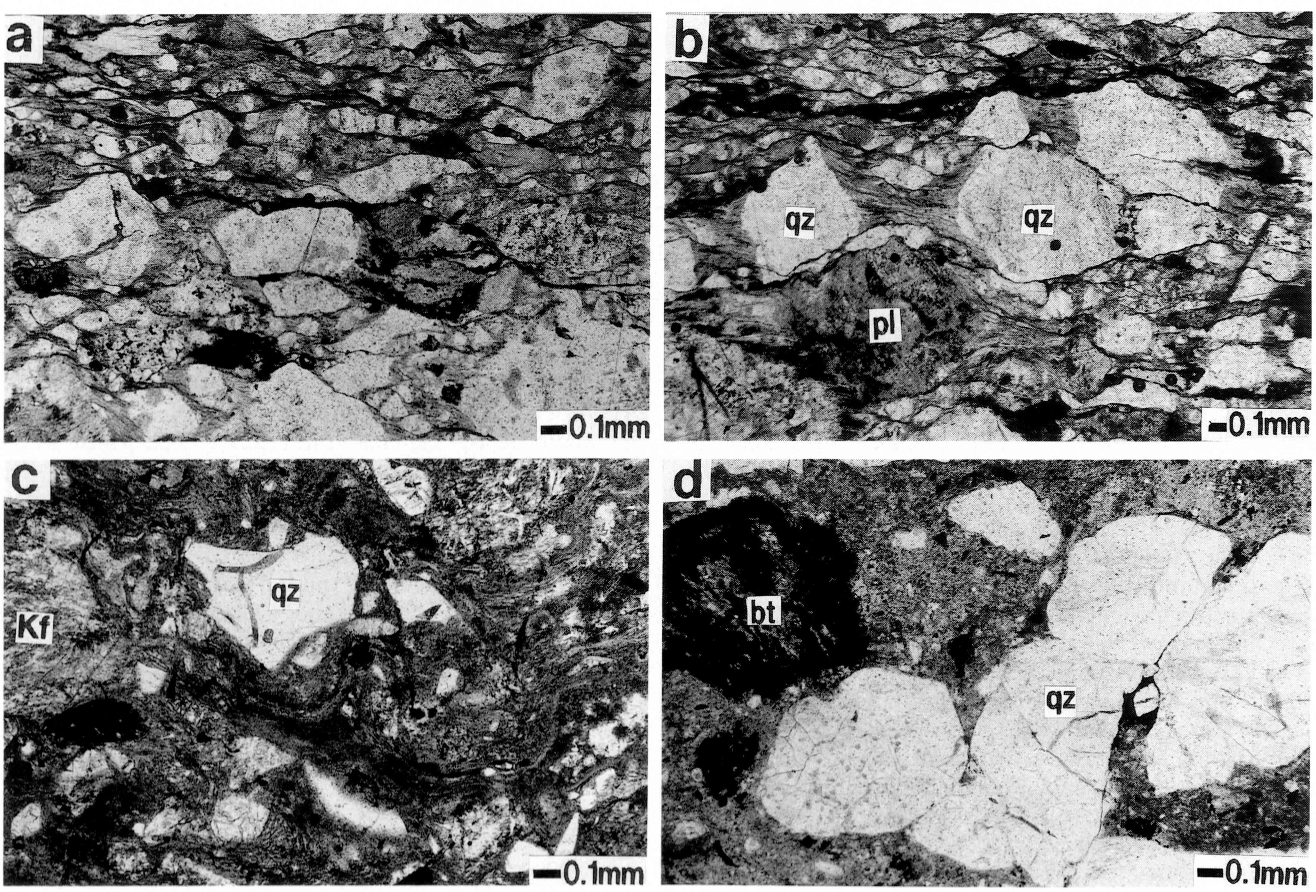


Fig. 43. Photomicrographs of the Nanasatoisshiki Formation and the Suyama pyroclastic rocks. (a)(b) Deformed sandstone in the Nanasatoisshiki Formation. XZ section. (a) The anastomosing, dark cleavage folia wrap around the detrital grains. (b) The mica beards formed between detrital grains. Mica flakes in the beards are strongly oriented parallel to the mean cleavage direction. (c)(d) Rhyolitic tuff in the Suyama pyroclastic rocks. (c) Rarely observed welded texture. (d) Typically massive tuff. qz= quartz, kf= K-feldspar, pl= plagioclase, bt= biotite.

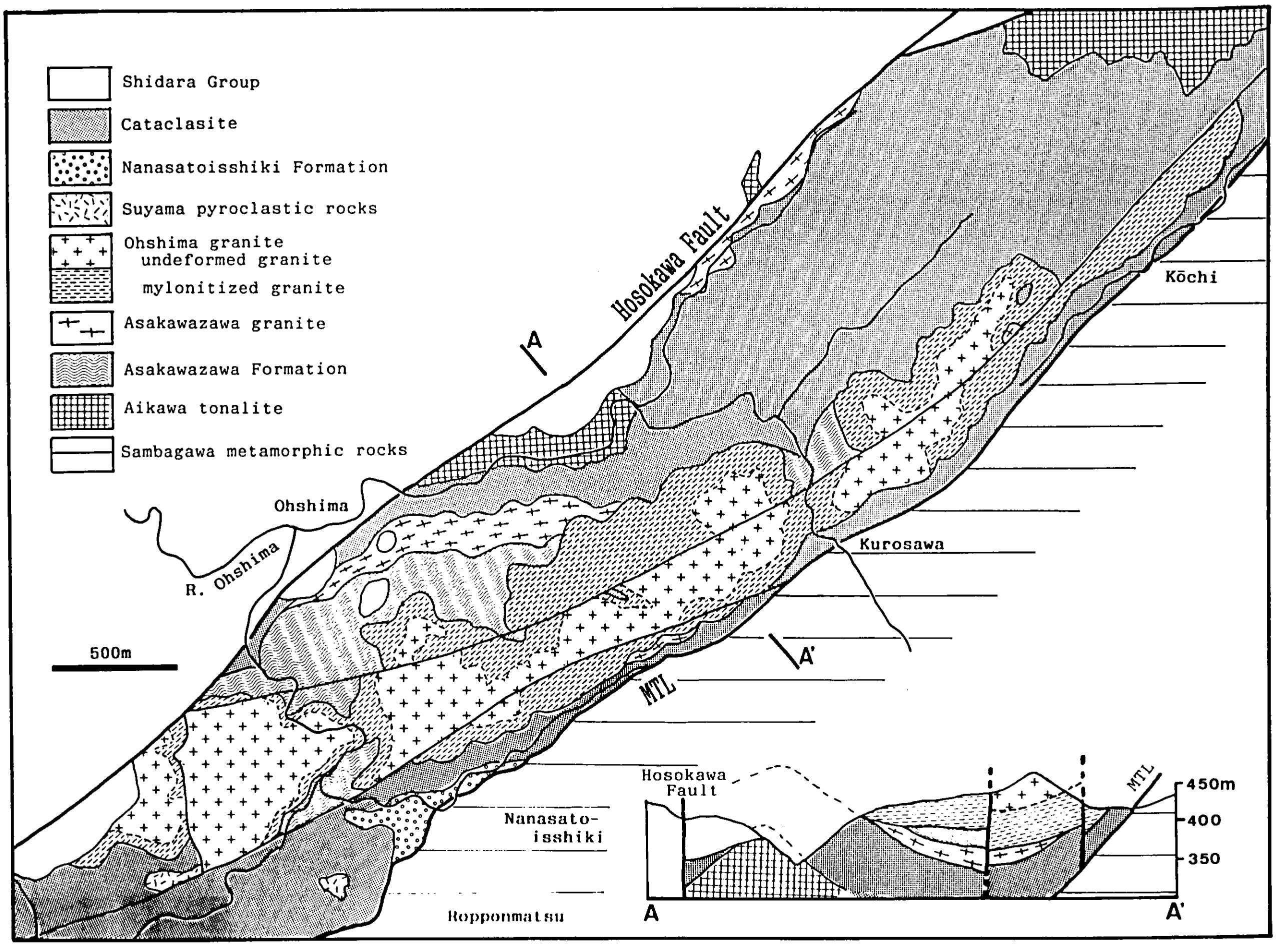


Fig. 44. Geologic map and cross section showing the distribution of mylonitic facies of the Ohshima granite.

MTL on the southern side, and cut and underlain by the cataclasite zone on the northern side. The Suyama pyroclastic rocks are unconformably covered by the Atera Nanataki conglomerate (Fig. 38). They consist mainly of rhyolitic tuff. They seem to be massive and frequently contain accidental rock fragments, sandstone, and siliceous mudstone. It is unusual to observe a welded texture in them. The Suyama pyroclastic rocks are affected by thermal metamorphism, resulting in the formation of muscovite as a metamorphic mineral and mosaic textures of quartz and feldspar in the matrix. Granite porphyries, found to the north of Suyama, are inferred to be small masses intruded into the Suyama pyroclastic rocks. Their matrix also has a mosaic texture of quartz and feldspar, and the grain boundaries between phenocryst and matrix are complicated and not clear. The granite porphyries are also metamorphosed.

After the thermal metamorphism, the Suyama pyroclastic rocks and associated the granite porphyries underwent distinct cataclastic deformation. Some cataclasite zones, several tens of meters thick, were formed in the Suyama pyroclastic rocks.

4. Asakawazawa granite

The Asakawazawa granite (Ohtomo, 1990), is mainly exposed to the south of Ohshima along the Hosokawa fault (Fig. 38). It had been regarded as a part of "the cataclastic rocks derived from igneous rocks" by Saito (1955), "granite cataclasite" by Ui (1980), "mylonitized Ryoke rocks" by Hara *et al.* (1980b), and mylonites derived from the Hiji granodiorite by Yamada *et al.*(1987). The Rb-Sr whole-rock isochron ages are 152 Ma and 62 Ma (Fig. 55). This age problem of the granite will be discussed in the following section.

The Asakawazawa granite forms a nappe (Fig. 38). The Asakawazawa granite nappe underlies both the Asakawazawa Formation and the Ohshima granite nappes, and is cut by the underlying cataclasite zone (Fig. 38).

The Asakawazawa granite mainly consists of granite with subordinate tonalite. It has a mylonitic foliation (Sm) and lineation (Lm), and consists of quartz, K-feldspar, plagioclase, and biotite with accessory zircon, apatite and opaque minerals. Most of the biotite was replaced by chlorite. The Sm is characterized by layering of alternating quartz and feldspar layers (Fig. 45a). The quartz has well-developed ribbon structures with some recrystallized new grains (Fig. 45c). The ribbon boundaries are irregular and serrate. The elongate grains are oriented oblique to the Sm. Plagioclase and K-feldspar are recrystallized to a fine-grained mosaic with subgrains along the host grain margin (Fig. 45b), suggesting that the recrystallized grains formed by a progressive misorientation of subgrains.

Figure 42b is a π-diagram for the Sm of the Asakawazawa granite. The orientation pattern indicates a

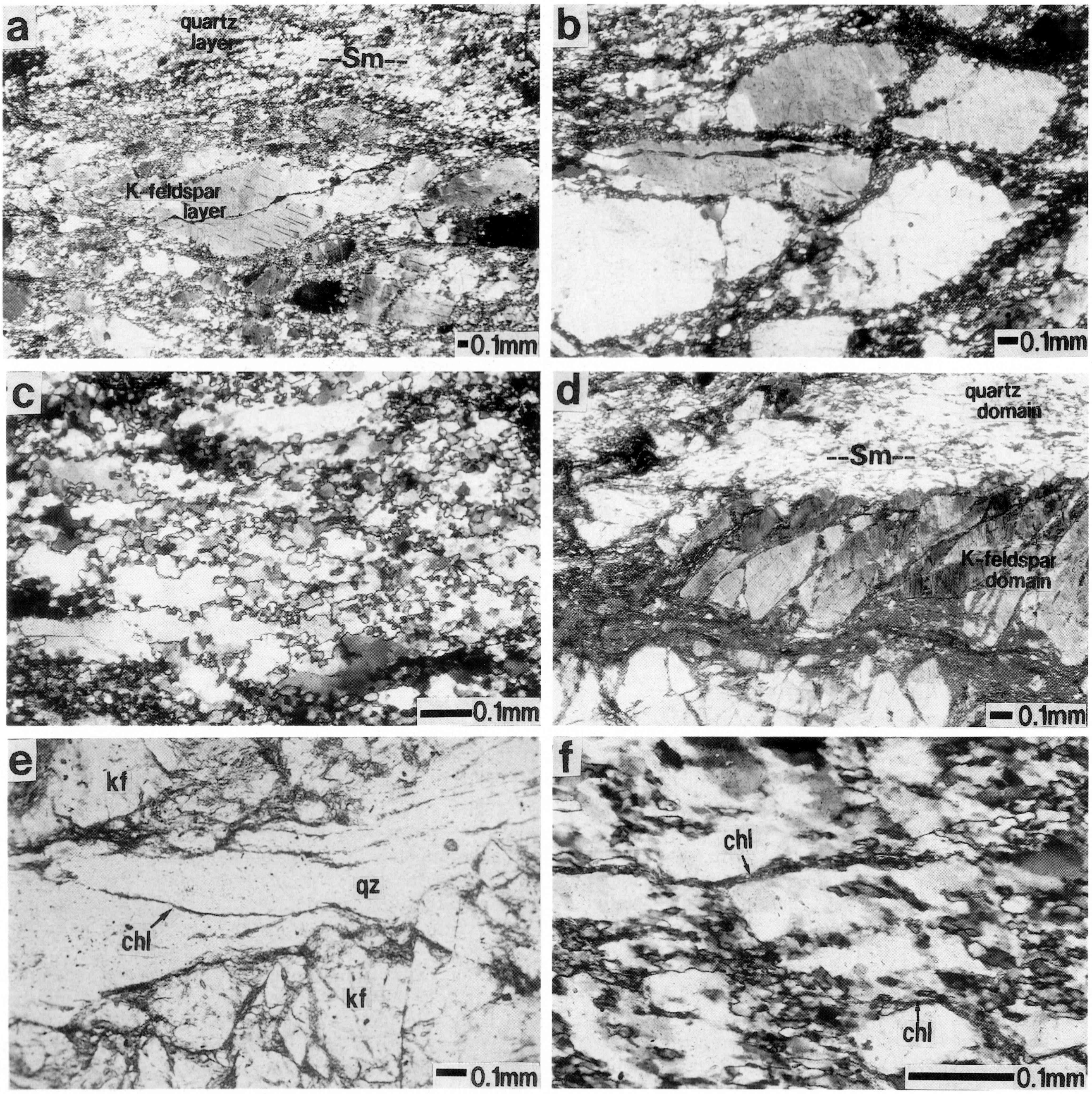


Fig. 45. Photomicrographs of the Asakawazawa granite and mylonitic facies of the Ohshima granite. (a-c) Granite mylonite in the Asakawazawa granite. (a) The Sm defined by layering of quartz and K-feldspar. (b) K-feldspar layer. Fine, recrystallized grains with subgrains wrap around porphyroclasts. (c) Quartz layer. Ribbon boundaries are irregular. (d-f) Granite mylonite in the Ohshima granite. (d) The Sm defined by an elongation of quartz and K-feldspar domains. (e) Grain size reduction of K-feldspar grains due to microcracking and microfaulting. Fine, recrystallized chlorite in a quartz domain have a preferred orientation. (f) Quartz layer. Grain size reduction due to deformation bands. kf= K-feldspar, Qz= quartz, chl= chlorite.

fold structure with an axis gently plunging toward the WNW.

5. Asakawazawa Formation

The Asakawazawa Formation (Ohtomo, 1990), is mainly exposed to the south of Ohshima (Fig. 38). It has been regarded as a part of "the cataclastic rocks derived from sedimentary rocks" by Saito (1955), part of the "granite cataclasite" by Ui (1980), part of "mylonitized Ryoke rocks" by Hara *et al.* (1980b), and part of the Kochi Formation by Yamada *et al.* (1987).

The Asakawazawa Formation forms a nappe, and is composed of pelitic and siliceous schists. Well-developed schistosity, defined by preferred orientation of very fine-

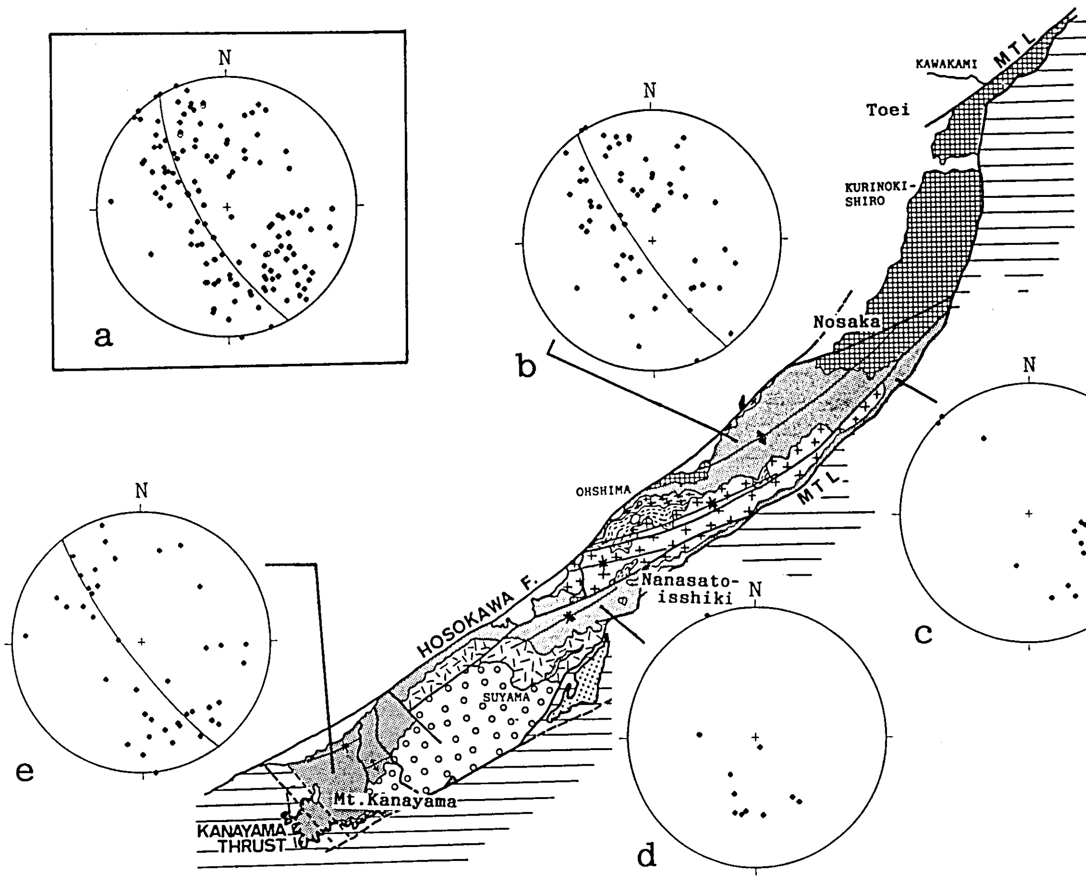


Fig. 46. Equal area plots showing the orientation for foliation of the cataclastic rocks of the Mikawaono-Toei area. (a) Synoptic diagram. (b) Data for the eastern part of Ohshima. (c) Data along the MTL from Nanasatoisshiki to Nosaka. (d) Dta for the southwestern part of Nanasatoisshiki. (e) Data around Mt. Kanayama.

grained flaky minerals such as muscovite and chlorite, is distinctly observed. The schistosity seems to be parallel to the bedding plane in most areas, and seems to be parallel to the Sm of the Asakawazawa granite. Because of its mineral assemblages and peak widths at half heights of carbonaceous materials (Figs. 49 and 50a), the Asakawazawa Formation is interpreted to have been metamorphosed under middle - upper greenschist facies condition. The Asakawazawa Formation appears to have undergone mylonitization with the Asakawazawa granite.

6. Ohshima granite

The Ohshima granite (Ohtomo, 1990), is exposed along ridges from southern Ohshima to Kochi. It has been regarded as a part of "the cataclastic rocks derived from igneous rocks" by Saito (1955), part of the "granite cataclasite" by Ui (1980), part of "mylonitized Ryoke rocks" by Hara *et al.* (1980b), and part of the cataclastic rocks derived from the Mitsuhashi granite by Yamada *et al.* (1987).

The distribution pattern of the Ohshima granite (Fig. 38) indicates that it forms a nappe over the Asakawazawa Formation and the Asakawazawa granite. It is a coarse-grained, massive biotite granite. The Rb-Sr mineral age of the feldspars in the Ohshima granite is 79 Ma (Fig. 53). This age problem will be discussed in the later. The Ohshima granite mainly consists of quartz, K-feldspar, plagioclase, and biotite with accessory zircon, apatite, and opaque minerals. Though quartz grains show undulatory extinction, the upper portion of the granite nappe has a non-deformed texture. Thus the Ohshima granite is interpreted to have been mylonitized along the nappe boundary (Fig. 44). The strongly mylonitized rocks frequently have a mylonitic foliation (Sm). The Sm is defined by an elongation of quartz domains and by a layering of quartz and feldspars domains (Fig. 45d).

Quartz grains are deformed predominantly by intracrystalline slip, producing a well-developed ribbon structure with deformation bands at a high angle to ribbon boundaries (Fig. 45f). Plagioclase and K-feldspar grains show grain size reduction by microcracking and microfaulting (Fig. 45e). Microfaults occur at a high - middle angle to the Sm. The progressive rotation of microfault-blocks resulted in a greater physical separation of feldspar fragments along the Sm with an increase in the bulk strain. In the strongly-deformed rocks, biotite has disappeared and fine-grained chlorite and sericite were produced with their (001) planes subparallel to the Sm (Fig. 45e). Mylonites of the Ohshima granite appear to have been produced under lower-greenschist facies condition during a nappe-forming event.

7. Cataclasite zone

Cataclasites are widely exposed in this area. They form a zone which is several hundred meters thick (Fig. 38). Some small scale cataclasite zones, several tens of meters thick,

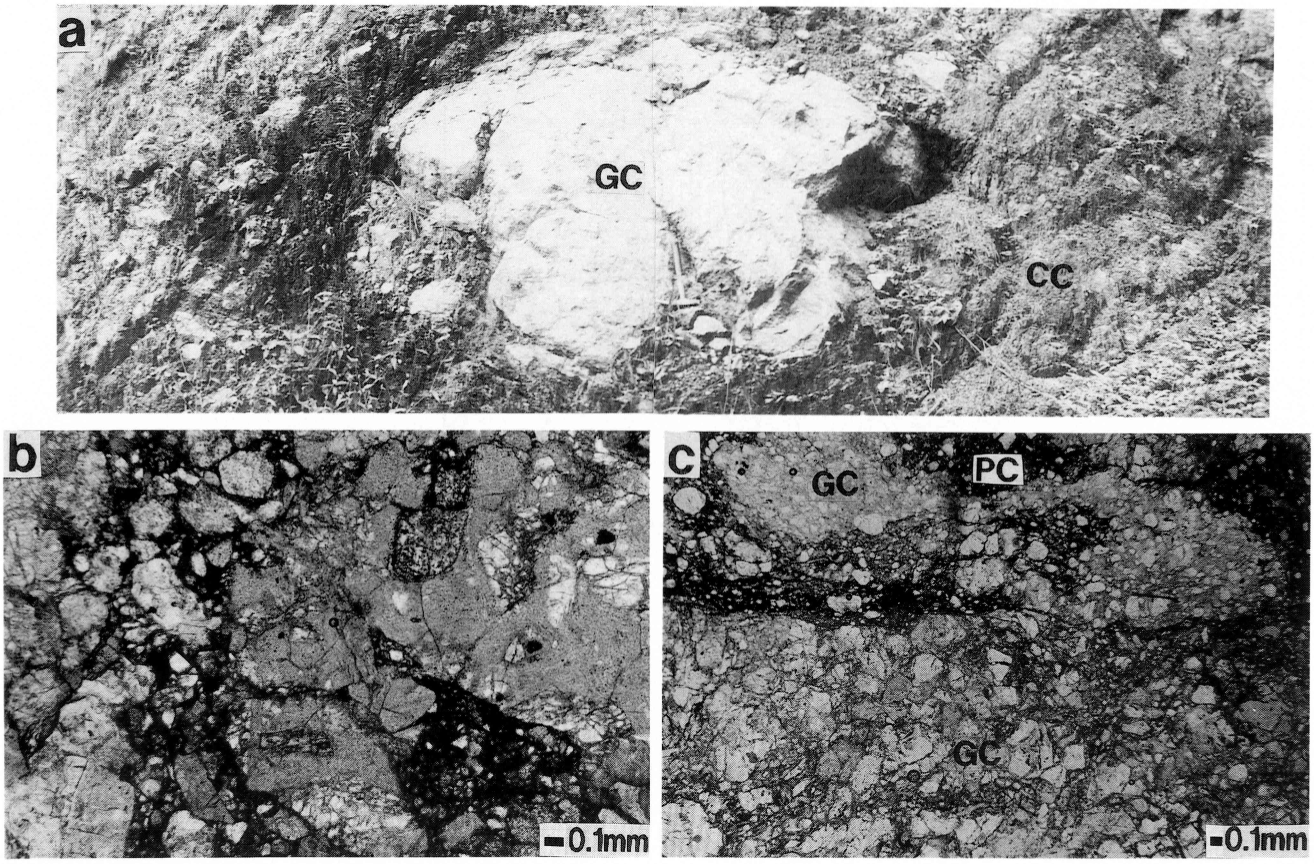


Fig. 47. Photograph and photomicrographs of cataclasites in the Mikawaono-Toei area. (a) Granite cataclasite (GC) included in cataclasite of clastic rocks (CC). (b) Cataclasite derived from granite porphyry. (c) Cataclasite of pelitic rock (PC) included in granite cataclasite (GC).

were formed locally in the other nappes. Ui (1980) called the cataclasites zone around Mt. Kanayama a "chaotic body", because it is not a bedded sequence of sedimentary rocks but a tectonically disturbed body. The original rocks of the cataclasites consist of various rock types - granite, granitic mylonite, pyroclastic rocks, granite porphyry, pelitic schist, sandstone, mudstone, and conglomerate. The cataclasites of granite, pyroclastic rocks, and mudstone are predominant, and of granitic mylonites are also usually found.

Figure 46 displays π-diagrams for the foliation defined by compositional banding, orientation of slabs, and cleavage in the cataclasite zone. The orientation patterns indicate a fold structure with an axis gently plunging toward the NE.

The cataclasites consist of a coarse-grained clasts and fine-grained matrix. Some clasts are also cataclastic rocks. These range from a few millimeters to several hundreds of meters in length (Fig. 47).

The exact contact between the cataclasite zone and the Aikawa tonalite, the Asakawazawa granite, the Asakawazawa Formation, the Ohshima granite, the Nanasatoisshiki Formation, and the Suyama pyroclastic rocks has not been located, but the distribution of the cataclasite zone appears to be oblique to the structural trend of the nappe piles. The cataclasite zone is unconformably covered by the Atera Nanataki conglomerate.

Cataclasites derived from granite are pale green or white and massive in appearance. These consist of fragments of minerals and rock fragments in a fine-grained matrix. The shapes of the fragments are mostly angular to subangular, but are locally subrounded (Fig. 47c). The fine-grained matrix is a material in which granite has been crushed to very small fragments. Cleavage lamellae are not typically developed in the matrix, though only weakly-developed cleavage lamellae are locally observed. The matrix is typically replaced by calcite.

Cataclasites, derived from granite mylonites and acidic pyroclastic rocks, are white and massive in appearance. These consist of rock fragments in a fine-grained matrix. The shapes of the fragments are mostly angular to subangular but are locally subrounded. The fine-grained matrix is a material in which granite mylonite or pyroclastic rocks has been crushed to very fine fragments. Cleavage lamellae are not commonly developed in the matrix. Most of the cataclasites derived from acidic pyroclastic rocks were affected by remarkable silicification. The matrix has been partially replaced by calcite.

Cataclasites derived from mudstone and sandstone have a block-in-matrix structure, containing various clasts in a mudstone or sandstone matrix. The clasts are rounded to subrounded, and consist of granite, granitic mylonite, pyroclastic rocks, granite porphyry, and their cataclasites. The fine-grained matrix is a material in which mudstone and sandstone has been crushed to very small fragments. The matrix was injected along fractures of the clasts. The cataclasites with an unfoliated matrix occur in some places,

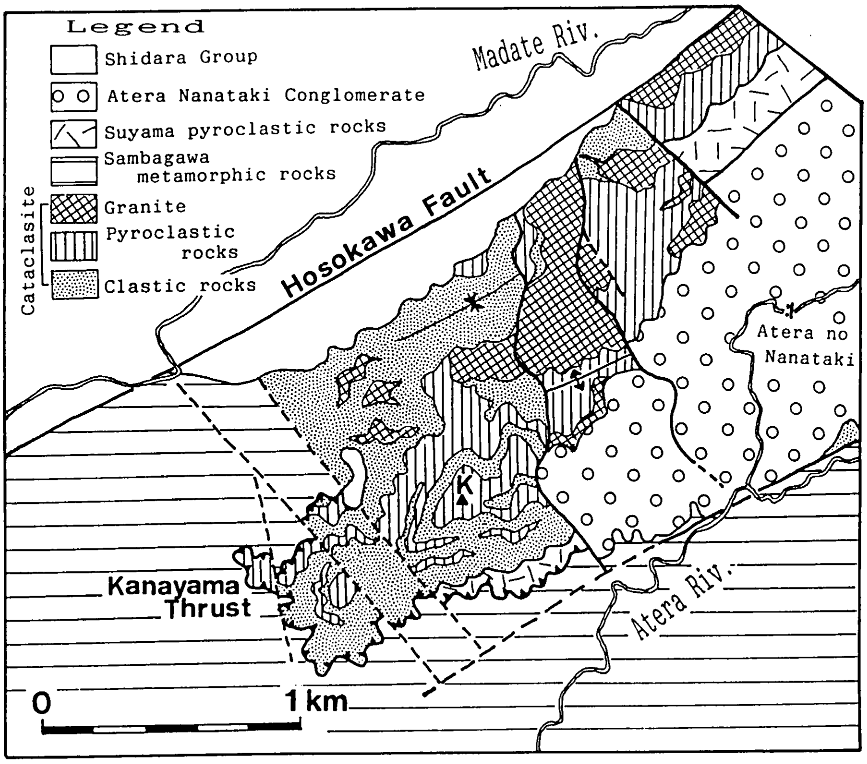


Fig. 48. Lithologic map showing the distribution of original rocks in the cataclasite zone around Mt. Kanayama(K).

having an appearance like a pebbly mudstone. Most of the cataclasites have a well-developed foliation. The foliation is defined under the microscope by cleavage lamellae. The clasts are blocks or slabs and have a pinch and swell structure, as well as boudinage. The long axes of the clasts are oriented parallel or subparallel to the foliation of the matrix. The matrix behaves in a more ductile way. The clasts are usually white and massive. Because they have been greatly altered, their origin is difficult to determine. The clasts appear to have been derived from the Asakawazawa Formation, the Asakawazawa granite, the Suyama pyroclastic rocks, and the Ohshima granite. Carbonate and clay minerals occur in the matrix.

Figure 48 is a detailed lithologic map of the original rocks of cataclasites around Mt. Kanayama. Although granite cataclasites, pyroclastic rock cataclasites, and clastic rock cataclasites seem to be piled from upper to lower structural level, granite cataclasites and pyroclastic rock cataclasites are developed in an interfingered fashion, and are intermingled with clastic rock cataclasites. This complex structure can be observed from the mappable to the microscopic scale. The cataclasite zone is interpreted to be a crush mélange.

8. Atera Nanataki conglomerate

The Atera Nanataki conglomerate was originally called the Nanataki conglomerate by Yoshida and Suzuki (1952). Since then, Saito (1955) named this formation the Suyama Formation, and Ui (1980) called it the Atera Nanataki conglomerate, describing the characteristic features of this formation. Ui(1980) correlated the Atera Nanataki conglomerate to the Upper Cretaceous Subgroup of the Izumi Group with reference to its lithologic features. Following Ui(1980), conglomerates around Suyama are called the Atera Nanataki conglomerate in this paper.

The Atera Nanataki conglomerate is composed mainly of conglomerate with subordinate amounts of sandstone. The clasts are mostly of pebble to cobble size, sometimes attaining boulder size. They are rounded or subrounded, are ill-sorted, and are composed of rhyolitic and rhyodacitic tuff, andesite lava, granite porphyry, massive granite, gabbro, arkose sandstone, mudstone, and siliceous rocks. Clasts of acidic tuff, granite porphyry, and sedimentary rocks (especially sandstone) are predominant. Most of acidic tuff, granite porphyry, and mudstone have been affected by thermal metamorphism, resulting in the formation of metamorphic minerals such as cordierite and garnet. The siliceous mudstones include radiolarian remains, which were converted to quartz aggregates, due to thermal metamorphism. There are various kinds of sandstone gravels such as massive sandstone, laminated sandstone, and deformed sandstone. Some sandstones, which are deformed forming cleavages, resemble the Nanasatoisshiki Formation. Some gravels of acidic tuff and granite porphyry seem to have been derived from the Suyama pyroclastic rocks. Gravels from coarse-grained, massive granite are often found at the northern margin of the conglomerate. Gravels of granite mylonite and gneiss have not been found. Clasts of basic schist like the Sambagawa metamorphic rocks are only found in a few locations along the Atera River. The matrix of the conglomerate is generally arkosic arenite. The Atera Nanataki conglomerate is dark reddish in color, due to volcanic rock fragments with a large amount of reddish opaque minerals. Ui (1980) stated that the Atera Nanataki conglomerate is about 400 m thick. It unconformably lies on the Suyama pyroclastic rocks and the cataclasite zone to the east and north of Suyama and around the Atera River.

Yoshida and Suzuki (1952) and Saito (1955) pointed out that the conglomerate contains pebbles derived from the Sambagawa metamorphic rocks. However, such pebbles can not be found except for a small amphibolite. There is no sufficient evidence that the conglomerate unconformably lies on the Sambagawa metamorphic rocks. Around the

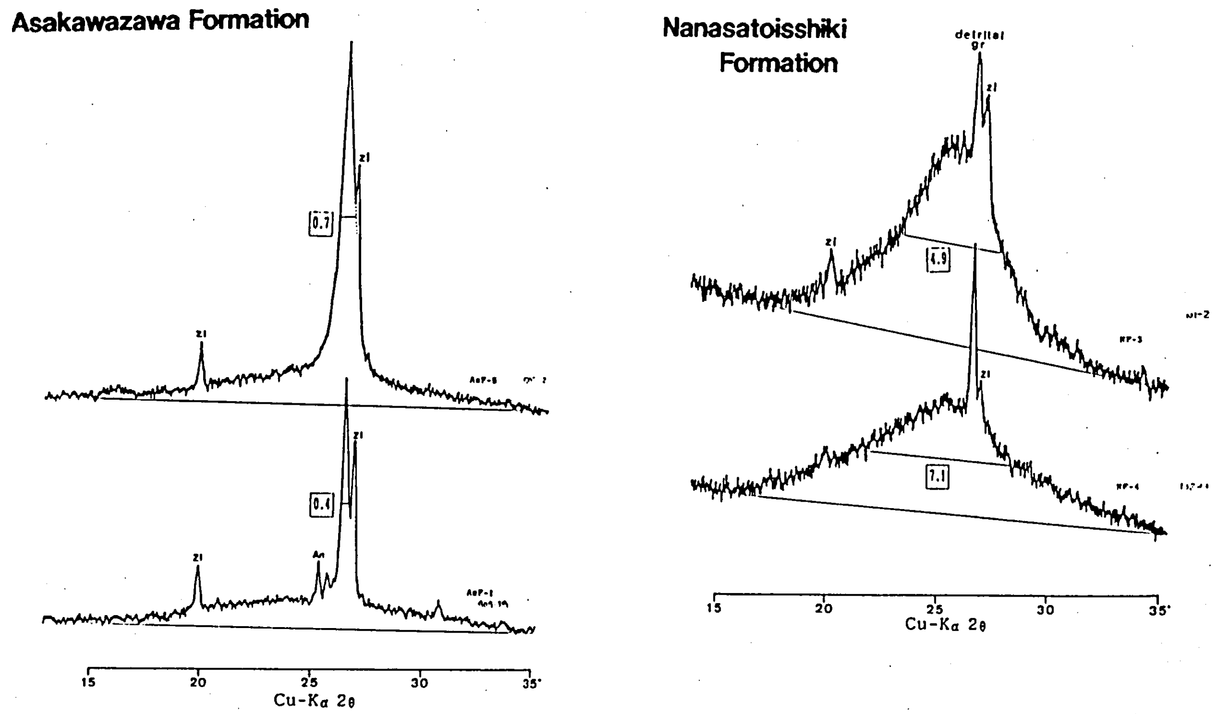


Fig. 49. Representative X-ray diffractograms of carbonaceous material in pelitic rocks of the Asakawazawa Formation and the Nanasatoisshiki Formation. Numbers in the squares are peak widths at half height in degrees 2θ. Zi= zircon, An= anatase.

Atera River, the Atera Nanataki conglomerate lies on the cataclasite, which overlies the Sambagawa rocks. The basal part of the conglomerate is not disturbed. The sedimentation of the Atera Nanataki conglomerate appear to have occurred after the cataclasite zone was emplaced on the Sambagawa rocks. The Suyama pyroclastic rocks, unconformably covered by the conglomerate, have fission track ages of 65 and 58 Ma. The sedimentation of the conglomerate seems to have occurred after latest Cretaceous, probably in Paleogene. Ui's (1980) opinion that the Atera Nanataki conglomerate is correlated to the Upper Cretaceous Izumi Group is thus in question.

9. Eocene-Miocene Shidara Group

In this area, rhyolitic tuff, tuff breccia, sandstone and shale of the Shidara Group, as well as andesite dykes, are exposed. All of the Shidara Group have been known as middle Miocene formation. Recently, the lower part of the Shidara Group was determined to be the Paleogene formation by evidences of fission-track ages of Oligocene from rhyolitic tuff and Eocene molluscs (Hayashi and Koshimizu, 1992). Around Ohshima and Kurinokishiro, the pyroclastic rocks unconformably lie on the cataclasite, the Asakawazawa Formation, the Asakawazawa granite, and the Aikawa tonalite (Figs. 38, 41a and 44). While sandstone, shale, and rhyolitic tuff unconformably covers the cataclasite around Hosokawa (Figs. 38 and 48). There are some andesite dykes which intruded into the nappes.

D. Graphitization of carbonaceous material in the Asakawazawa Formation, the Nanasatoisshiki Formation and the cataclasite zone

Sedimentary rocks generally contain carbonaceous material. The carbonaceous material recrystallizes to form graphite structures with an increase in diagenesis and metamorphism. Studies of the transformation is called graphitization. The carbonaceous material in regional and contact metamorphic rocks has been done by many workers (e.g. Landis, 1971; Grew, 1974; Tagiri & Tsuboi, 1979; Tagiri, 1981, 1985; Itaya, 1981; Okuyama-Kusunose & Itaya, 1987),because of the usefulness of the graphitization process as an indicator of relative metamorphic temperature (in the greenschist facies and lower-temperature metamorphic rocks).

The Asakawazawa and the Nanasatoisshiki Formations of the nappe complex appear to have been metamorphosed at low-grade, resulting in the formation of white mica and chlorite as metamorphic minerals. Biotite does not occur. Graphitization of carbonaceous material in the Asakawazawa formation and the Nanasatoisshiki formation were analyzed to determine their metamorphic grades. Additionally, graphitization of cataclasite derived from pelitic rocks were analyzed to discern their origins. Carbonaceous material was separated from silicate minerals by a method modified after Itaya (1981) and Tagiri (1981, 1985).

1. Analytical method

The X-ray powder diffractometer was controlled as follows - a Cu-Kα of 20 KV 15mA, a Ni-filter, a 1°-0.3mm-1° slit, a scanning rate of 1°/min, and a chart speed of 10 mm/min. The d_{002} of graphite was measured and the diffractometer was run between 15° and 35°. The peak-value(2θ) and the half height width of the carbonaceous material were obtained from each X-ray diffractogram. Each diffractogram was calibrated with a silicon standard. The 2θ position and width of the (002) refraction were

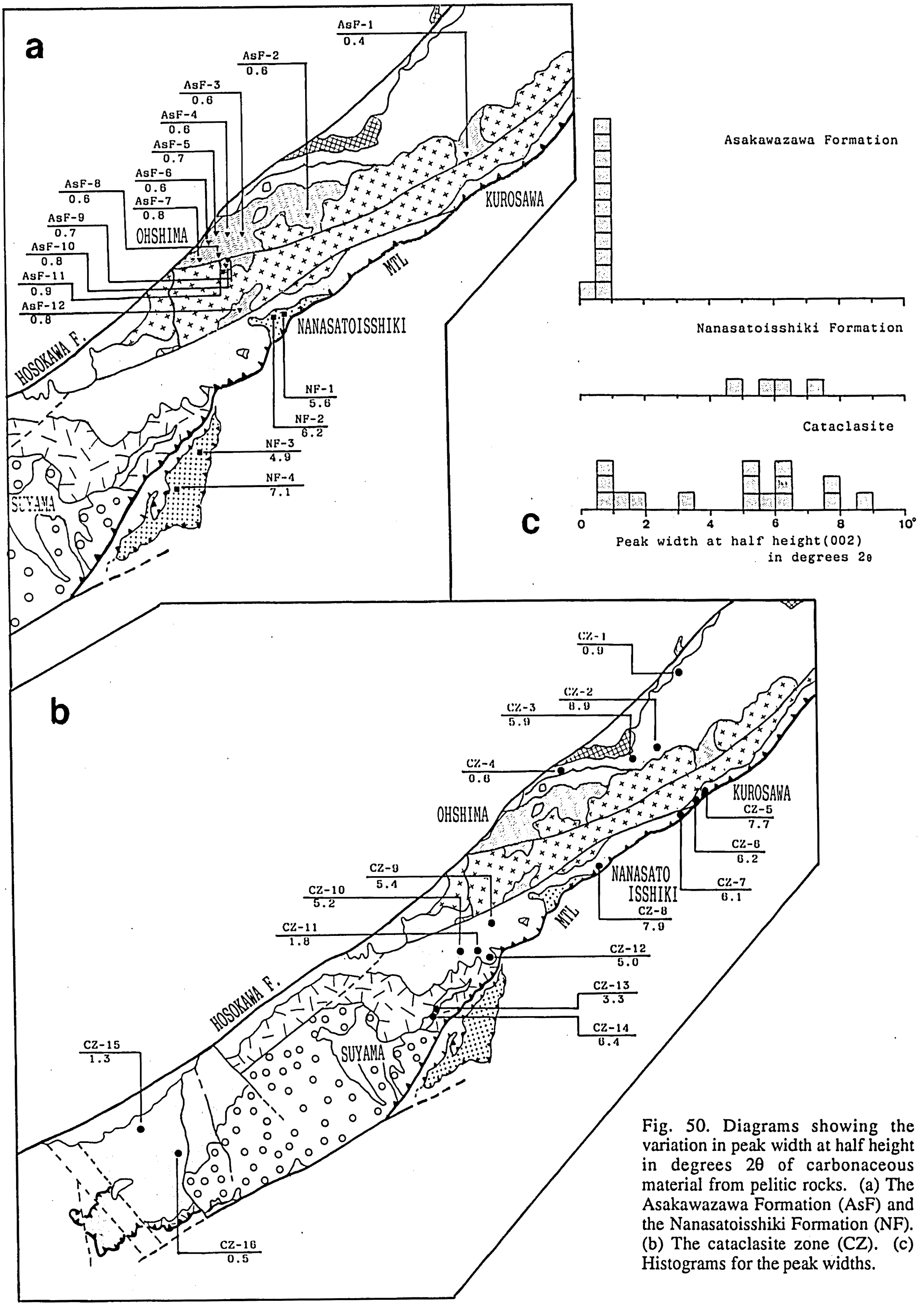


Fig. 50. Diagrams showing the variation in peak width at half height in degrees 2θ of carbonaceous material from pelitic rocks. (a) The Asakawazawa Formation (AsF) and the Nanasatoisshiki Formation (NF). (b) The cataclasite zone (CZ). (c) Histograms for the peak widths.

Table 2. X-ray data of carbonaceous material from pelitic rocks in the Asakawazawa Formation, the Nanasatoisshiki Formation and the cataclasite zone.

sample No.	2θ	d_{002}	Peak width (°2θ)
Asakawazawa Formation			
AsF-1	26.50	3.36	0.4
AsF-2	26.50	3.36	0.6
AsF-3	26.50	3.36	0.6
AsF-4	26.50	3.36	0.6
AsF-5	26.50	3.36	0.7
AsF-6	26.50	3.36	0.6
AsF-7	26.40	3.38	0.8
AsF-8	26.50	3.36	0.6
AsF-9	26.45	3.37	0.7
AsF-10	26.55	3.36	0.8
AsF-11	26.40	3.38	0.9
AsF-12	26.45	3.37	0.8
Nanasatoisshiki Formatiom			
NF-1	25.20	3.53	5.6
NF-2	25.10	3.55	6.2
NF-3	25.50	3.49	4.9
NF-4	25.10	3.55	7.1
Cataclasite zone			
CZ-1	26.55	3.36	0.9
CZ-2	24.90	3.58	8.9
CZ-3	25.10	3.54	5.9
CZ-4	26.55	3.36	0.6
CZ-5	24.90	3.58	7.7
CZ-6	25.22	3.53	6.2
CZ-7	25.20	3.53	6.1
CZ-8	24.70	3.60	7.9
CZ-9	25.70	3.47	5.4
CZ-10	24.40	3.51	5.2
CZ-11	26.20	3.40	1.8
CZ-12	26.01	3.42	5.0
CZ-13	25.90	3.44	3.3
CZ-14	25.25	3.53	6.4
CZ-15	26.60	3.35	1.3
CZ-16	26.50	3.36	0.5

measured at half the peak height on the diffractogram. The interplanar spacing d_{002} was calculated from the 2θ values.

2. Result

Typical X-ray diffractograms from 15° to 35° 2θ Cu-Kα of the carbonaceous material in the Asakawazawa and the Nanasatoisshiki Formations are shown in Figure 49 The locations of the samples from the Asakawazawa and the Nanasatoisshiki Formations and their peak width at half height in 2θ are shown in Figure 50a. The data of 2θ, d_{002}, and peak width at half height in 2θ are given in Table 2. The acid insoluble mineral is mostly zircon, which is found in most of the samples. Anatase, rutile, and tourmaline are found in some samples.

From the Asakawazawa Formation, the diffraction pattern of the carbonaceous material has only one sharp (002) peak of graphite located at a higher 2θ with a swelled background (Fig. 49). Its peak width at half height and d_{002} range from 0.4(2θ) to 0.9(2θ) and from 3.36A to 3.38A, respectively.

In Figure 49, the diffraction patterns of carbonaceous material in the Nanasatoisshiki Formation have two peaks - one is a sharp peak corresponding to (002) peak of well-ordered graphite, and the other is a diffuse peak located at a lower 2θ than the (002) peak. For the diffusive peak, its peak width at half height and d_{002} range from 4.9(2θ) to 7.1(2θ) and from 3.49A to 3.55A, respectively. The sharp, but weak, (002) peak of graphite in the Nanasatoisshiki Formation can be attributed to relict well-ordered graphite of detrital origin. The presence of both a sharp and diffuse peak in the X-ray diffractogram was also reported for carbonaceous material in some Japanese Paleozoic slates (Fujinuki *et al.*, 1974), Mesozoic shales (Tagiri & Tsuboi, 1979), and the Sambagawa metamorphic rocks (Itaya, 1981). Mixing of the detrital well-ordered graphite in the pelitic rocks of the Nanasatoisshiki Formation suggests that the carbonaceous material was supplied from high-temperature metamorphic rocks.

Histograms of peak width at half height from X-ray diffractograms in the Asakawazawa Formation and the Nanasatoisshiki Formation are shown in Figure 50c. Distribution of d_{002} of carbonaceous material in the Asakawazawa Formation is entirely different from that in the Nanasatoisshiki Formation

The graphitization of carbonaceous material chiefly depends not on the pressure but on the temperature and the duration of metamorphism. In the Sambagawa metamorphic belt, the carbonaceous material in the pelitic schists approaches well-ordered graphite only at a temperature near the biotite isograd (Itaya, 1981). In other regional metamorphic terrains, the Wakatipu schists in New Zealand (Landis, 1971) and rocks in the Narragansett basin of New England, U.S.A. (Grew, 1974), well-ordered graphite appears at a metamorphic grade corresponding to the biotite zone. On the other hand, in the Miyamori contact aureole in Northeast Japan, well-ordered graphite appears only in the sillimanite zone.

In the Asakawazawa Formation, the carbonaceous material is well-ordered graphite or slightly less ordered graphite. It suggests that the metamorphic grade in the Asakawazawa Formation is correlated with the upper to middle greenschist facies, as compared with the graphitization of carbonaceous material in the Sambagawa metamorphic rocks by Itaya (1981). On the other hand, the diffraction pattern of the Nanasatoisshiki Formation mainly has a diffuse peak, and shows that the carbonaceous material consists of a mixture of small grains of different crystallinity. The crystallographic data obtained through the bulk X-ray diffraction can be considered as average values, and suggest that the crystallinity of carbonaceous material is weak. It suggests that the metamorphic grade in the Nanasatoisshiki Formation can be correlated with prehnite-pumpellyite facies.

The locations of the samples from the cataclasite zone and their peak width at half height are shown in Figure 50b. The data of 2θ, d_{002}, and peak width at half height are given in Table 2. A histogram of peak width at half height of the carbonaceous material from pelitic rocks of the cataclasite zone is shown in Figure 50c. Its peak width at half height and d_{002} range from 0.5(2θ) to 8.9(2θ) and from 3.36A to 3.58A, respectively. This suggests that pelitic rocks with various degrees of graphitization occur in the cataclasite zone. It can be inferred that some of the pelitic rocks with well-ordered graphite were derived from the Asakawazawa Formation, and those with the diffuse diffraction peaks were derived from the Nanasatoisshiki Formation. But some pelitic rocks have moderate diffraction peaks, the origin of which remains unknown. As the pelitic rocks are associated with cataclasites derived from acid volcanic rocks, it might be concluded that the original rocks were affected by thermal metamorphism, simultaneous with the Suyama pyroclastic rocks. The data for graphitization of the cataclasite also supports the conclusion that the cataclasite zone is a crush melange which includes various kinds of rocks.

E. Rb-Sr ages of the Ohshima granite, the Aikawa tonalite and Asakawazawa granite

Some granitic rocks, the Ohshima granite, the Aikawa tonalite, and the Asakawazawa granite, are found in the Ryoke nappe complex in the Mikawaono-Toei area. Rb-Sr whole-rock and mineral isochron ages of the granitic rocks were measured to determine their origins.

1. Analyzed samples

Samples from the Ohshima granite, Aikawa tonalite, and Asakawazawa granite were collected at the locations shown in Figures 51 and 52. A whole-rock sample was analyzed from the Ohshima granite. This sample was slightly-deformed as evident by the deformation lamellae in quartz. Some biotites were replaced by chlorite. K-feldspar and plagioclase were separated from this sample for age determination.

Two samples, AiT-1 and AiT-2, were taken from the Aikawa tonalite. Both have a compositional layering with thicknesses of about several cm, and a mylonitic structure. The mylonitic foliation is subparallel to the layering. The AiT-1 sample is divided into five whole-rock samples (AiT-1A - E), which were each collected from different layers. The layer from AiT-1A looks like a dyke, which may have predated the mylonitization, as inferred from the granitic mylonite inclusions and the continuous mylonitic foliation. A whole-rock sample, AiT-2A , was taken from the sample AiT-2, for measuring a mineral isochron age. K-feldspar and plagioclase were separated from the AiT-2A layer. These mineral samples are composed of a mixture of porphyroclasts and fine, recrystallized grains. A whole-rock sample of AiT-2B, was also analyzed.

Nine whole-rock samples of the Asakawazawa granite were analyzed. Five samples (AsG-2, 4, 5, 6 and 15) were taken from the upper portion of the nappe (Fig. 52). Two minerals (plagioclase and K-feldspar), which were separated from AsG-5, were also analyzed. The lower portion of the nappe is strongly affected by cataclastic deformation which postdated the mylonitization. In order to investigate the effect of cataclastic deformation, four samples (AsG-7, 8, 11 and 12) were also collected from the lower cataclastic portion.

2. Analytical techniques

The seventeen whole-rock and six mineral samples, described above, were analyzed isotopically. Rb and Sr concentrations were determined by X-ray fluorescence and by isotopic dilution method using a ^{87}Rb-^{86}Sr mixed spike. Rb and Sr were separated following the procedures described by Kagami *et al.* (1982, 1987). Mass spectrometric analyses were made using a MAT261 mass spectrometer in the Institute for Study of the Earth's Interior at Okayama University. The ^{87}Sr/^{86}Sr ratios were normalized to ^{86}Sr/^{88}Sr=0.1194.

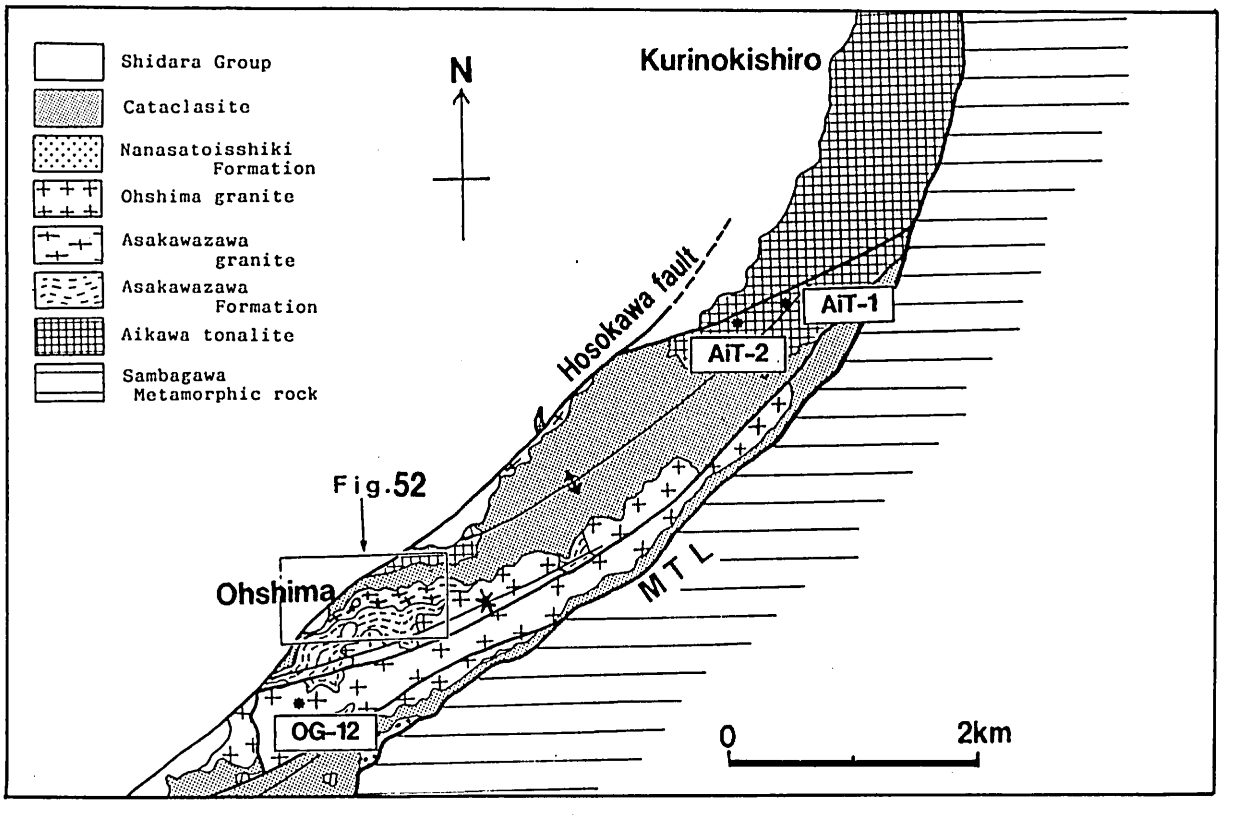


Fig. 51. Location map of the analyzed Rb and Sr samples from the Aikawa tonalite (AiT) and the Ohshima granite (OG).

Table 3. Rb-Sr data of the Ohshima granite, the Aikawa tonalite and the Asakawazawa granite.

sample		Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$*
Ohshima granite					
Q1-12	Whole-rock	90.3	174.3	1.4988	0.70890(2)
Q1-12	K-feldspar	281.9	131.4	6.2135	0.71419(1)
Q1-12	Plagioclase	69.2	272.3	0.7352	0.70801(2)
Aikawa tonalite					
AiT-1A	Whole-rock	53.0	315.0	0.4870	0.70748(3)
AiT-1B	Whole-rock	67.2	195.1	0.9967	0.70818(3)
AiT-1C	Whole-rock	60.0	338.9	0.5122	0.70762(2)
AiT-1D	Whole-rock	75.9	190.3	1.1535	0.70831(1)
AiT-1E	Whole-rock	78.0	192.2	1.1745	0.70826(2)
AiT-2A	Whole-rock	94.3	231.4	1.1795	0.70900(1)
AiT-2A	K-feldspar	122.7	254.8	1.3939	0.70931(2)
AiT-2A	Plagioclase	37.4	187.5	0.5766	0.70852(2)
AiT-2B	Whole-rock	90.0	405.9	0.6419	0.70865(2)
Asakawazawa granite					
AsG-2	Whole-rock	111.2	188.2	1.7094	0.70970(2)
AsG-4	Whole-rock	75.5	325.1	0.6721	0.70750(1)
AsG-5	Whole-rock	86.6	209.8	1.1936	0.70850(1)
AsG-5	K-feldspar	266.9	173.9	4.4426	0.71132(2)
AsG-5	Plagioclase	39.1	182.8	0.6188	0.70791(2)
AsG-6	Whole-rock	69.1	171.8	1.1639	0.70851(1)
AsG-7	Whole-rock	94.6	150.5	1.8190	0.70873(1)
AsG-8	Whole-rock	64.4	368.6	0.5053	0.70758(1)
AsG-11	Whole-rock	64.5**	232.6**	0.8023	0.70785(2)
AsG-12	Whole-rock	103.5**	280.9**	1.0661	0.70806(1)
AsG-15	Whole-rock	71.9**	207.3**	1.0035	0.70800(2)

* Numbers in parentheses for the $^{87}Sr/^{86}Sr$ ratios refer to the 2σ error in the last digit. ** Rb and Sr by XRFS; others by isotopic dilusion.

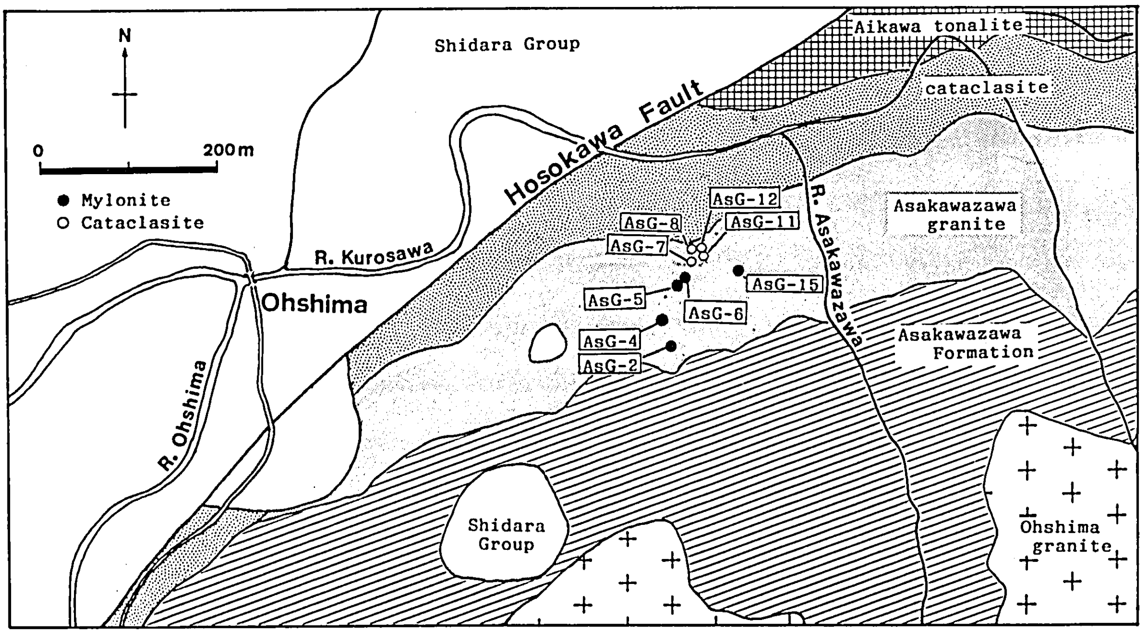


Fig. 52. Location map of the analyzed Rb and Sr samples from the Asakawazawa granite (AsG).

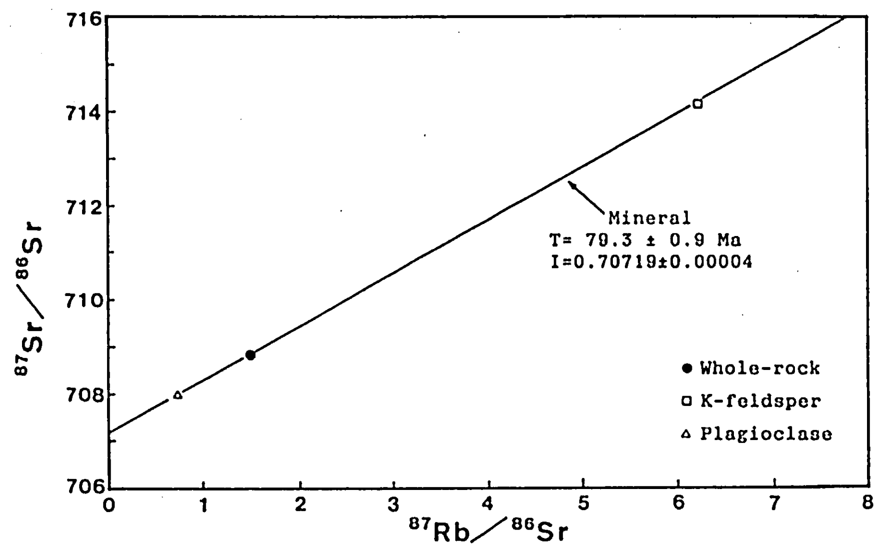


Fig. 53. Rb-Sr isochron diagram for the Ohshima granite.

The Sr isotopic ratios for NBS987 were measured seven times during this study. The average ratio was 0.710252±0.000015(2σ). Rb-Sr whole-rock isochron ages were calculated using the equation of York (1966) and $\lambda^{87}Rb=1.42\times10^{-11}y^{-1}$ (Steiger and Jäger, 1977).

3. Results

The Rb-Sr data are given in Table 3 and isochron diagrams in Figures 53, 54 and 55. The following age calculations have been made:

a. Ohshima granite

Mineral samples (K-feldspar and plagioclase) and a whole-rock sample form an isochron which indicates an age of 79.3±0.9 Ma with a MSWD (mean square of weighted deviates) of 0.0169 and a SrI ($^{87}Sr/^{86}Sr$ initial ratio) of 0.70719±0.00004(2σ).

b. Aikawa tonalite

As AiT-1A looks like the mylonite derived from a dyke before mylonitization, the data of AiT-1A is excluded from the regression. The four remaining data of sample AiT-1 define an isochron age of 72.3±14.1 Ma (MSWD=0.0717) with a SrI of 0.70711±0.00020(2σ). The data of the whole-rock sample AiT-2A and mineral samples of K-feldspar and plagioclase define an isochron age of 65.9±14.6 Ma (MSWD=0.1969) with an SrI of 0.70801±0.00017(2σ). The data of AiT-2B also plot near the mineral isochron. There are very large 2σ errors on the intercept. Thus these ages overlap with one another at 2σ level.

c. Asakawazawa granite

The whole-rock samples fall into two distinctive groups. One group defines an isochron corresponding to an age of 151.6±18.3 Ma (MSWD=0.2748) with an SrI of 0.70597±0.00031(2σ), whereas the other group gives an good-fit isochron indicating an age of 61.5±1.4 Ma (MSWD=0.0157) and an SrI of 0.70714±0.00002(2σ). The former was taken from the upper portion of the Asakawazawa granite nappe, the latter from the lower portion affected by cataclastic deformation.

The data of the mineral samples (K-feldspar and plagioclase) and the whole-rock sample for AsG-5 define an isochron age of 62.2±3.0 Ma (MSWD=0.1344) with an SrI

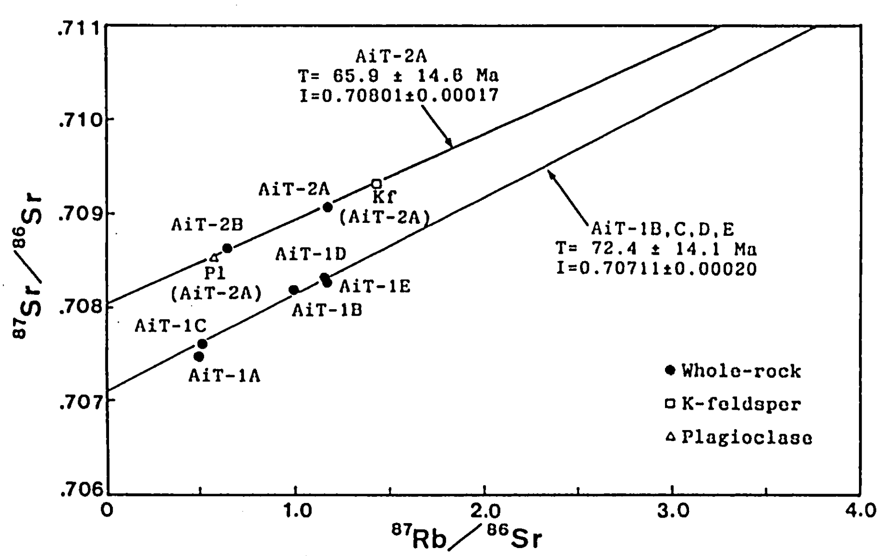


Fig. 54. Rb-Sr isochron diagram for the Aikawa tonalite.

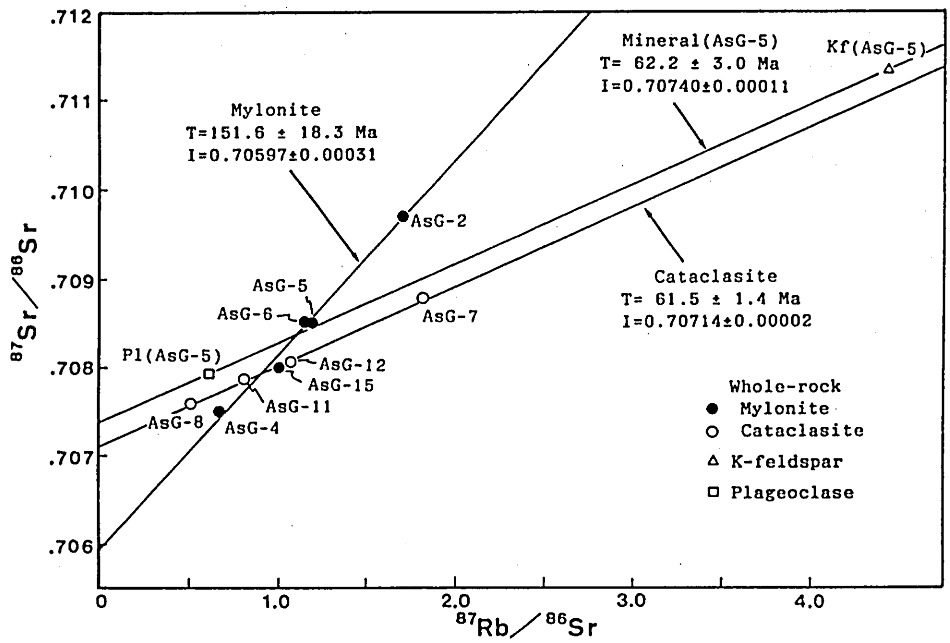


Fig. 55. Rb-Sr isochron diagram for the Asakawazawa granite.

of 0.70740±0.00011(2σ). This is similar to the age obtained from the whole-rock isochron age of the lower cataclastic portion of the granite.

4. Interpretation of Rb-Sr isotopic ages of the granitic rocks

a. Ohshima granite

The mineral isochron age of 79.3 Ma was obtained for the Ohshima granite. Mineral ages represent either the time of crystallization of a mineral, the cooling to a temperature, at which point the mineral becomes a closed system, or a later metamorphic event. As the analyzed sample escaped from mylonitization along the nappe boundary, its mineral age of 79.3 Ma is considered to represent either the time of crystallization or that of cooling. The non-mylonitized part of the Ohshima granite is generally massive without gneissose structure, which is characteristic of the older Ryoke granites. The SrI of 0.70719 for the granite is within the range for that of other Ryoke granites. Thus, the Ohshima granite is regarded as one of the younger Ryoke granites.

b. Aikawa tonalite

A mineral isochron age of 65.9 Ma and a whole rock isochron age of 72.3 Ma were obtained for different samples of Aikawa tonalite.

There is a possibility that the whole rock isochron age is closely related to the time of formation of a suit of comagmatic rocks in the Aikawa tonalite. But it is doubtful that it actually recorded this date because, under upper amphibolite facies condition, the Aikawa tonalite underwent mylonitic deformation involving dynamic recrystallization and drastic grain size reduction. Such deformation increases intracrystalline strain energy and enhances intracrystalline diffusion (Cohen, 1970; Brodie, 1980 etc.). Additionally, grain size reduction may greatly increase diffusion along grain boundaries (*cf.* Beach, 1980).

In the Takato area K-Ar ages from 56 to 38 Ma have been reported for the Hiji tonalite (mylonite) which is correlated with the Aikawa tonalite (Shibata and Takagi, 1988). But the K-Ar ages of the Katsuma quartz diorite, which intruded the Hiji tonalite subsequent to mylonitization, are 70 Ma (hornblende) and 63 Ma (biotite). Because of a whole rock Rb-Sr age of about 90 Ma from the non-mylonitized Hiji tonalite from a selected area (Yamana *et al.*, 1983), the main stage of mylonitization is interpreted to have occurred between 90-70 Ma (Shibata and Takagi, 1988). Additionally, a non-deformed younger Ryoke granite of 87.7 Ma intruded into mylonite in Awaji Island, mylonitization is considered to have occurred before 87.7 Ma (Takahashi, 1992). I thus cannot regard the isochron ages of 72.3 Ma and 65.9 Ma as mylonitization ages. The AiT-2 sample, carrying the mineral isochron age of 66 Ma, contains low-grade mineral alterations (for example saussuritization of plagioclase and chloritization of biotite). These ages may have been produced by a resetting of the Rb-Sr isotopic systems due to a low-grade geological event after mylonitization. An exact interpretation of the age data from the Aikawa tonalite remains undetermined.

c. Asakawazawa granite

The whole-rock age of 151.6 Ma from the upper mylonitic portion is considered to be related to the time of mylonitization according to the following argument. The analyzed Asakawazawa granite has a penetrative mylonitic deformation, which resulted in dynamic recrystallization of its constituent minerals and drastic grain size reduction. Both plagioclase porphyroclasts and dynamically recrystallized plagioclase in the granite facies have the same chemical composition (An_{13-17}). The cores of the plagioclase in the granitic rocks of the Ryoke belt generally have an content of more than 30 percent (e.g., Yamada *et al.*, 1977). The chemical composition of the plagioclase in the Asakawazawa granite may have greatly changed during mylonitization. The K-feldspar porphyroclasts have a composition of Or_{84-97}, while the dynamically recrystallized K-feldspar have Or_{94-97} compositions. The latter also changed composition during mylonitization. As mentioned above, the mineral constituents in the Asakawazawa granite appears to have undergone modification in their chemical compositions during mylonitization, due to intracrystalline diffusion. Diffusion along grain boundaries also may have been greatly increased by grain size reduction (*cf.* Beach, 1980). Thus, the process of mylonitization may have induced resetting of the Rb-Sr whole-rock system (*cf.* Smalley *et al.*, 1983). However, the time of intrusion is not likely to be much older than 151.6 Ma, because dynamic recrystallization of plagioclase occurs at a temperature higher than 500°C (*cf.* Tullis and Yund, 1977), and the granite was still at relatively high temperature during the mylonitization. Based on these ideas, it can be assumed that the time of the intrusion of the Asakawazawa granite is late Jurassic.

Additionally, the whole-rock age of 61.5 Ma from the lower cataclastic portion of the Asakawazawa granite is remarkably younger than the one from the upper mylonitic portion. According to Smalley *et al.* (1983), the Rb-Sr whole-rock system can be reset even by relatively low-grade geological events. The whole-rock age of 61.5 Ma is considered to be related to the resetting of the Rb-Sr whole-rock system during cataclastic deformation following the formation of the nappe complex. The minerals, which were separated from AsG-5 yield an isochron age of 62.3 Ma. The mineral age from the upper mylonitic portion of the Asakawazawa granite is similar to the whole-rock age from the lower cataclasite. The mineral isochron age of 62.4 Ma may also be a result of a resetting of the Rb-Sr system. Therefore, it is interpreted that the jointing of the Ryoke belt and of the Sambagawa belt, which followed the formation of the Ryoke nappe complex, occurred at the time of early Paleogene.

E. Geotectonic history of the Mikawaono-Toei area

The following geotectonic history of the Mikawaono-Toei area is based on the above data.

(1) The Asakawazawa granite was mylonitized during the latest Jurassic age. The Aikawa tonalite was mylonitized before 72 Ma. The intrusion of the Ohshima granite occurred at about 79 Ma. The Suyama pyroclastic rocks were produced at about 65 Ma.

(2) The Asakawazawa Formation, the Asakawazawa granite, the Aikawa tonalite, the Ohshima granite, the Suyama pyroclastic rocks, and the Nanasatoisshiki Formation were transported as nappes, resulting in the formation of crush melange and thrusting of the nappe complex over the Sambagawa belt.

(3) The Atera Nanataki conglomerate was deposited on the Ryoke nappe complex.

(4) NE-SW trending upright folds were formed.

(5) The Eocene-Miocene Shidara Group unconformably covered the Ryoke rocks and the Sambagawa metamorphic rocks.

(6) The Hosokawa faults, with a NE-SW trend, was formed.

VIII. Tectonic synthesis and P-T-D path of the Ryoke belt

As mentioned before, the geotectonic history of the southern margin of the Ryoke belt has been described and discussed in the Sakuma, the Hoji Pass, the Tomiyama Hiraoka, and the Mikawaono-Toei areas (Ohtomo, 1986, 1987a & b, 1988, 1989). The tectono-metamorphic process of the main Ryoke belt had been described by Seo and Hara (1980), Seo *et al.* (1981), Seo (1985) and Nureki *et al.* (1982) and Yuhara (1990). In this chapter, the tectono-metamorphic history of the Ryoke belt will be discussed on the basis of the metamorphic and structural data of the main and the southern marginal regions.

1. D1

D1, related to formation of the S1-schistosity, is the earliest phase deformation in the Ryoke belt. The S1-schistosity is recognized as preferred dimensional orientation of inclusion minerals in porphyroblasts - K-feldspar, cordierite, and andalusite. S1 indicates that a metamorphism associated with the D1 tectonism occurred before the formation of these porphyroblasts. The structural features correlated with S1 were described in detail in the Mikawa Plateau (Seo and Hara, 1980;Seo *et al.*, 1981). They were also described in the Shishijima area, Seto Inland Sea (Nureki *et al.*, 1982), the Sakuma area (Ohtomo, 1987a & b; this study), and the Ina area (Yuhara, 1990). Seo *et al.* (1981) found that staurolite has a preferred dimensional orientation with other inclusions in biotite and andalusite porphyroblasts. The mineral assemblages in pelitic rocks during the D1 phase include biotite+muscovite+plagioclase +quartz in the Sakuma area, staurolite+biotite+garnet in the Mikawa Plateau, and biotite+muscovite+plagioclase+quartz in the Shishi-jima area. Though, staurolite is only found in the Mikawa Plateau in the Ryoke belt, Seo *et al.* (1984) assumed that staurolite was present during the D1 phase, because the zincian hercynite in pelitic gneisses was recrystallized at the expense of staurolite, based on the microscopic structure and the chemistry of the hercynite and the presence of sillimanite in the Uo-shima area, Seto Inland Sea.

From the Fe^{2+}- Mg^{2+} distribution, between garnet and staurolite (Perchck, 1977), included in andalusite porphyroblasts, the metamorphic temperature and pressure of D1 have been estimated by Seo (1985) to be 490 to 520°C and 3.3 to 3.8 Kb. But the mineral assemblage of staurolite, garnet, biotite, muscovite, and quartz and the lack of andalusite and cordierite, appear to be comparable with medium-pressure Barrovian metamorphism. Additionally, on the base of the fact that fibrolite was formed after S1 and before the formation of porphyroblasts, Seo *et al.* (1981) pointed out that the first phase metamorphism with D1 was medium-pressure metamorphism (Fig. 56).

S1 has been observed not only in the main Ryoke belt - the Mikawa Plateau, Seto Inland Sea, and the Ina area, but also in the southern margin of the Ryoke belt, the Sakuma area. S1 seems to be a characteristic deformation phase of the Ryoke belt.

2. Inter-D1-D2

Extensive growth of porphyroblasts occurred after D1 and before D2. Means and Paterson (1966), Etheridge *et al.* (1974) and Tullis (1976) showed experimentally that biotite flakes which appear under deformation condition have a dimensionally preferred orientation with their (001) normal to the axis of maximum shortening. Seo and Hara (1980) showed that the lattice fabrics for the biotite porphyroblasts (A-biotite) produced during the inter-D1-D2 phase is not coincident with their dimensional fabric, which shows a

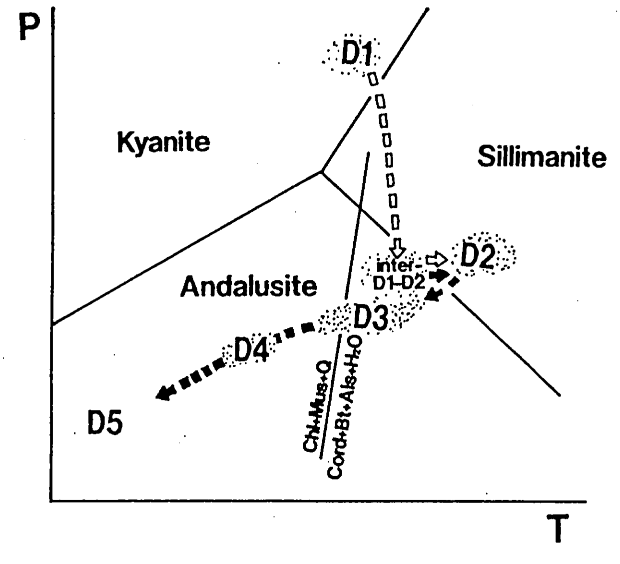


Fig. 56. The P-T-D history of the Ryoke belt in the Chubu district.

distinct preferred orientation parallel to the wrapped schistosity(S2). From these microstructures of the biotite porphyroblasts, Seo and Hara (1980) suggest that the porphyroblasts grew under non-deformational conditions.

The metamorphic features correlating to the growth of the biotite porphyroblasts in the Mikawa Plateau have not only been observed in the southern margin, but also in other areas of the Ryoke belt. The reported mineral assemblages of porphyroblasts during the inter-D1-D2 phase include andalusite+cordierite+K-feldspar+garnet+biotite in the Mikawa Plateau (Seo *et al.*, 1981), andalusite+cordierite+K-feldspar+garnet in the Sakuma area (Ohtomo, 1987a & b; this paper), and sillimanite+andalusite in the Hiraoka-Kadotani area (Yokoi, 1983). From the Fe^{2+}-Mg^{2+} distribution between cores of garnet grains and porphyroblastic biotite grains (*cf.* Thompson, 1975; Perchuk, 1977), the metamorphic conditions of this phase has were estimated by Seo (1985) to be about 500 - 550°C and 3Kb. According to Seo (1985) and Seo *et al.* (1981), the unusual fibrolite is included in andalusite porphyroblasts. It is clear that the fibrolite predates the metamorphism of the inter D1-D2 phase. It does not show preferred dimensional orientation unlike the cases of other inclusion minerals formed during the D1 phase. Seo *et al.* (1981) suggested that, when passed from the first metamorphic phase of D1 to the second metamorphic phase of inter-D1-D2, the metamorphic condition changed through the sillimanite stability field and that the appearance of staurolite occurred as a result of the reaction of chlorite+muscovite=staurolite+biotite+quartz+H_2O (Hoschek, 1969) in the kyanite stability field. It is inferred that the metamorphic conditions changed with the remarkable decreasing of pressure from the D1 phase to the inter-D1-D2 phase (Fig. 56).

3. D2

A distinct foliation(S2) is now typically observed in the Ryoke metamorphic rocks. In biotite gneiss and schists, S2 is characterized by a preferred dimensional and lattice orientation of biotite. Seo and Hara (1980) discussed the development process of schistosity in biotite schist in the Mikawa Plateau. The formation of C-biotite flakes [small recrystallized biotites found in A-biotite flakes (biotite porphyroblasts produced during the inter D1-D2 phase)], was induced by their intra-crystalline slip-deformation in the third phase. In the fourth phase, B-biotite and muscovite flakes, which show preferred lattice and dimensional orientation defining the schistosity (S2), resulted from the deformation with pressure solution under maximum compression normal to S2. The shift of deformation mechanisms from the third phase (formation of C-biotite) to the fourth phase (formation of S2) is considered to have occurred with a decrease of strain rate (Seo and Hara, 1980).

The D2 deformation was penetrative and was accompanied by pressure-solution. It occurred through-out the Ryoke belt and produced a penetrative foliation (S2) without lineation. Biotite and muscovite formed during the D2 phase have a preferred dimensional and lattice orientation. Garnet and K-feldspar, without S1 inclusion minerals, crystallized in elongated shapes parallel to S2. Inclusion-free mantles of porphyro-blastic K-feldspar, biotite, and muscovite were also developed normal to S2. The D2 deformation was associated with the formation of the F2 fold. In hinges of microscopic F2 fold, axial plane cleavage of fibrolite was rarely produced, resulting from pressure solution.

A large-scale conversion of the geologic structure in the Ryoke belt occurred during the D2 phase. For example, in the Mikawa Plateau, metamorphic rocks of the andalusite zone presently overlie those of the sillimanite zone. This structural arrangement was produced during the third phase (an earlier stage of D2 in this paper) between the second metamorphic phase (inter-D1-D2 in this paper) and the fourth metamorphic phase (D2 in this paper) (Seo and Hara, 1980). During the first and second metamorphic phase (D1 and inter-D1-D2 in this paper), the metamorphic mineral assemblage of the andalusite zone provides a higher metamorphic temperature than the sillimanite zone. Rocks from the andalusite zone were placed in a lower tectonic position than the sillimanite zone.

Using various geothermometer and geobarometer, the metamorphic conditions of D2 have been estimated by Seo (1985) to be 420 - 530°C in the low-grade part and about 600°C and 2.5 - 3Kb in the high-grade part of the Mikawa Plateau. Similar metamorphic conditions have been estimated by many investigators (for example, Ono, 1977a & b; Kutsukake, 1977; Hayama, 1981; Morikiyo, 1984, 1986; etc.), though they did not analyzed the timing of appearance of minerals. Ono (1977a & b), Hayama (1962, 1964) and Seo (1985) assumed that the metamorphism during the D2 phase occurred under low-P_{H_2O} conditions. The metamorphism during the D2 phase reached higher-amphibolite facies condition in the culmination field. It is assumed that the metamorphic conditions changed with the distinct increasing of temperature from the inter-D1-D2 phase to the D2 phase (Fig. 56). The Kamihara tonalite around Hiraoka, which is correlated with the first phase granitic mass of plutonism of the Ryoke belt was deformed with the surrounding metamorphic rocks during the D2 phase.

4. D3

The D3 deformation is related to the formation of the large-scale recumbent fold and the large-scale ductile shear zones. The recumbent fold, which was formed in the early stage of D3, is developed with a N- NNE-trending axis and a W-dipping axial-plane in the Hiraoka-Tomiyama area, involving the older Ryoke granites - the Kamihara tonalite (the first-phase granitic mass of the Ryoke belt) and the Tenryukyo granite (the second-phase granitic mass). The Tenryukyo granite was deformed by D3 but not by D2, suggesting that it was emplaced during the period between the D2 phase and the D3 phase. The formation of the recumbent fold was associated with a maximum elongation shown by the NE-trending stretching lineation, which is oblique to the NNE-trending fold axis.

During the later stage of D3, the deformation was concentrated to the lower portion of structural level resulting in the formation of a ductile shear zone. It occurred under amphibolite facies to lower-greenschist facies condition. The ductile shear zone is considered to be a horizontal shear zone with top to the west shear in the Kayumi area, the Kii Peninsula (Sakakibara *et al.*, 1989), and with top to southwest shear in the Chubu district (Ohtomo, 1987a, 1988; Yamamoto and Masuda, 1987; Michibayashi and Masuda, 1988; etc.). As the MTL in the Chubu district was bent during Miocene, the shear sense of both regions have been regarded to be same. In the latest stage of D3, nappe structures were formed in the southern margin of the Ryoke belt. In the Hoji Pass area, the Tenryukyo granite nappe overlies the lower-grade metamorphic rock nappe which overlies the granite and tonalite mylonite nappe. The metamorphic condition during the D3 phase changed from amphibolite-facies to lower-greenschist facies (Fig. 56). Namely D3 occurred with a distinct decrease of temperature and pressure.

5. D4

The D4 deformation is characterized by the formation of the nappe complex and the crush melange. The deformation structures during the D4 phase are clearly found in the Mikawaono-Toei area and the Sakuma area.

During the early stage of D4, the nappe complex was formed in cataclastic fashion. In the Sakuma area, the metamorphic rock nappe is in cataclastic thrust contact with the granite and tonalite mylonite nappe (the Aikawa tonalite).

In the Mikawaono-Toei area, tonalite mylonite (the Aikawa tonalite), non-metamorphic rocks (the Nanasato-isshiki Formation), pyroclastic rocks of upper Cretaceous age (the Suyama pyroclastic rocks), granite mylonite of 152 Ma (the Asakawazawa granite), pelitic schist (the Asakawazawa Formation), and granite of upper Cretaceous age (the Ohshima granite) form nappe piles. During nappe forming events, the 79Ma Ohshima granite formed a mylonite zone under the lower greenschist facies conditions, along the nappe boundary. A strongly-developed cleavage was formed in the Nanasato-isshiki Formation under prehnite-pumpellite facies conditions. This evidence suggests that the nappe complex was formed at a shallow crustal level.

During the later stage of D4, the nappe piles were thrust over the Sambagawa metamorphic rocks, with the formation of crush melange in the Mikawaono-Toei area. The Aikawa tonalite directly overly the Sambagawa metamorphic rocks in Izumma to Kawakami. In the Sakuma area, backthrusting also occurred at this stage. The sense of thrusting during the D4 phase has not been yet determined. the D4 event was not accompanied by remarkable recrystallization and grain growth of constituent minerals, although only carbonate and clay minerals were produced in the crush melange. The D4 deformation is characterized by cataclastic features. The formation of crush melange is considered to have occurred during the latest Cretaceous, on the basis of the whole rock isochron age of the cataclasite derived from the Asakawazawa granite.

6. D5(formation of the high angle MTL and upright folds)

After the thrusting with the formation of crush melange, a high-angle fault and upright folds were formed. The high-angle fault is the main fault of the present MTL. The upright folds are comparable with the folds widely developed in Southwest Japan. Their axial trace have a left-hand arrangement to the main the MTL fault (e.g. Hara *et al.*, 1977, 1980b). It is interpreted that the upright folds were developed as echelon folds with a left-lateral strike-slip component related to the high-angle MTL . In the western part of Kii Peninsula, echelon folds are developed with other deformation structures such as echelon faults, boudinage structures, and shear zones in the Izumi Group (Miyata, 1980 ; Miyata *et al.*, 1980). In the Chubu district, the formation of the upright folds predate the sedimentation of the Eocene-Miocene Shidara Group. In the western Kii Peninsula, the event took place after the sedimentation of the Izumi Group (80-65 Ma) and before middle Miocene (probably before middle Eocene) (Ichikawa, 1980). Previous work suggest that the MTL, with a left-lateral strike-slip component, was formed during Paleogene (pre-middle Eocene).

The upright folds are not accompanied by the development of axial-plane cleavages and remarkable recrystallization of constituent minerals. They formed by flexural-slip. Minor faults also typically occur along their axial-plane. The upright folds postdate the tectono-metamorphic process of the Ryoke belt.

VIIII. Tectonic Implications

A. Origin of the older rocks along the MTL

Recently, some older rocks have been discovered in some places along the MTL. Permian granite and its related metamorphic rocks, accompany Late Cretaceous sediments, as nappes overlying the Sambagawa metamorphic rocks, have been discovered in the northern margin of the Kanto Mountains (Ono, 1983; Hayama and Research Group for the Hiki Hills, 1985; Hayama *et al.*, 1987; Takagi *et al.*, 1989). In the Mikawaono-Toei area, the Chubu district, the Asakawazawa granite, with a mylonitization age of 152 Ma has been discovered (Ohtomo and Kagami, 1990; this paper). The granite is a member of nappe complex in southern margin of the Ryoke belt.

In the Sambagawa metamorphic belt on western Shikoku, the Karasaki mylonite contains 160Ma relict amphibolite, and is intermingled with the Futami nappe schists, which are situated in the uppermost structural level of the Sambagawa megaunit (Takeda *et al.*, 1987). According to Hara *et al.* (1990), the Futami nappe and the Karasaki mylonite were transported onto the Sambagawa schists during the earlier stage of the Ozu phase. Additionally, the older rocks have been discovered even in the Ryoke belt. Kagami *et al.* (1987) determined that the arc-type gabbro and metadiabase in the Ryoke belt of Kii Peninsula and Seto Inland Sea, are of Permian age.

Most of the original rocks of the Ryoke metamorphic rocks are of Late Jurassic - earliest Cretaceous accretionary complexes of the Mino-Tamba Terrane. The Ryoke metamorphism has therefore been considered to have occurred during middle-late Cretaceous before the sedimentation of the Cretaceous Izumi Group. However, the original rocks of the Sambagawa metamorphic rocks have been assumed to be accretionary complexes of Early Cretaceous age by Hara *et al.* (1990). Thus, it can be concluded that the older rocks, distributed along the MTL, were obviously formed before the end of the sedimentation of the original rocks of the metamorphic rocks on both sides of the MTL.

Hayama (1989, 1991) have pointed out that these older rocks were developed as continental, Paleo-Ryoke land. The Paleo-Ryoke land was first proposed by Ichikawa (1964) to have been developed along the southern side of the Ryoke belt. Additionally, Hara *et al.* (1990,1991) pointed out that the plutonism and tectonism related to the Karasaki mylonite occurred in the Paleo-Ryoke land. It was also suggested that the overlying nappes containing the Karasaki mylonite were transported onto the Sambagawa schists, when the structural relationship between the Sambagawa Terrane, and the northern Chichibu, and Kurosegawa Terranes was produced during the earlier stage

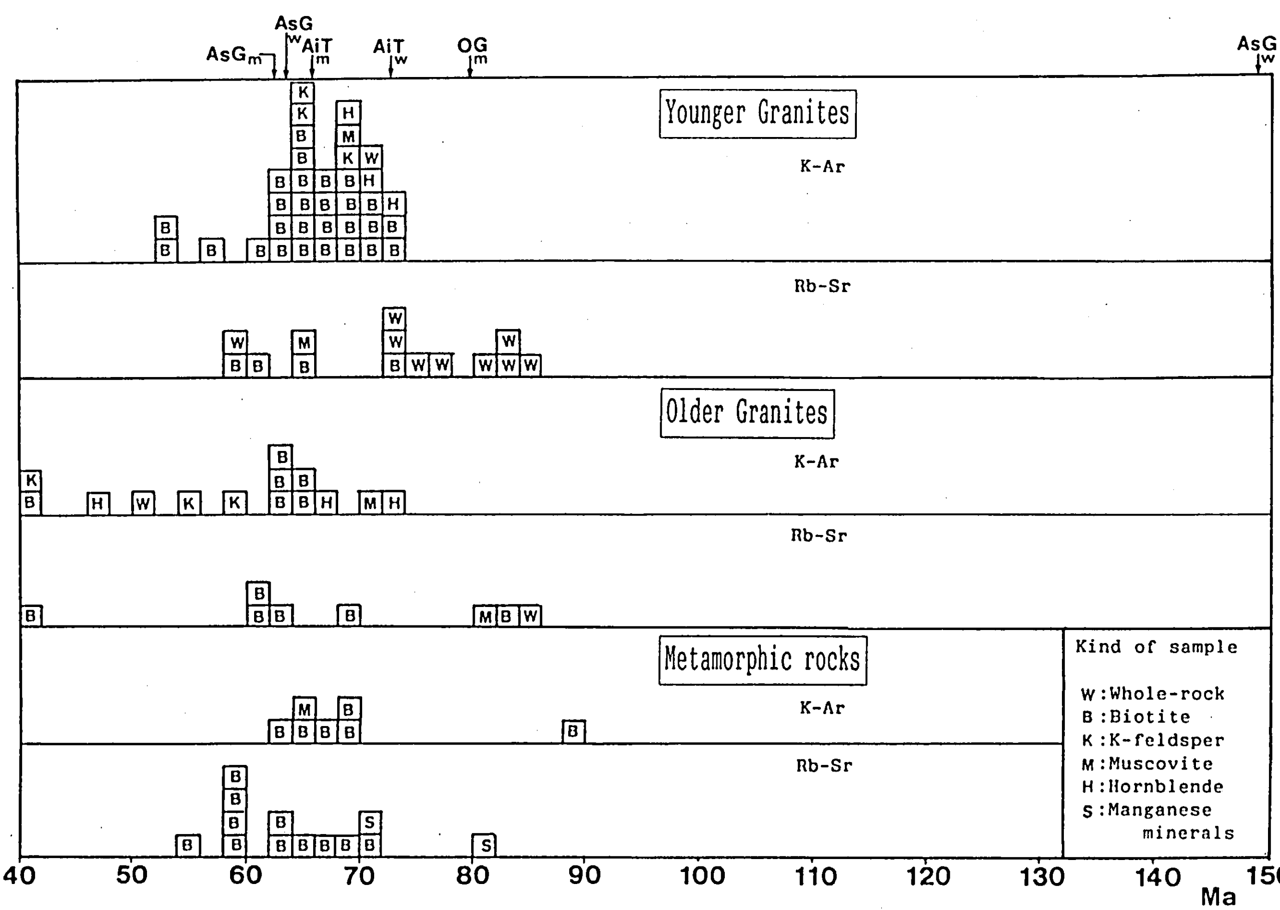


Fig. 57. Rb-Sr and K-Ar age histograms for the metamorphic rocks, the older granites and the younger granites in the Ryoke belt of the Chubu district. Compiled from Kagami (1973), Nakai (1982), Okano (1982), Sato et al. (1991), Shibata et al. (1979), Shibata and Ishihara (1979), Shibata and Takagi (1988), Uchiumi et al. (1990), Yamada et al. (1977), Yamana et al. (1983) and Geological Survey of Japan (1982). Arrow=age data of this study (OG=Ohshima granite, AiT=Aikawa tonalite, AsG=Asakawazawa granite, w=whole-rock isochron, m=mineral isochron)

Table 4. K-Ar ages and Rb-Sr mineral ages of biotite, muscovite, K-feldspar and hornblende from the metamorphic rocks, Older granite, and Younger granite in the Ryoke belt from Yanai to Chubu (compiled from Geological Survey of Japan, 1982; Okano, 1982, Okano and Honma, 1983; Sato *et al.*, 1991; Shibata and Takagi, 1988; Takahashi, 1992; Uchiumi *et al.*, 1991). bt=biotite, mus=muscovite, kf=K-feldspar, hb=hornblende.

	metamorphic rock		Older granite		Younger granite	
	K-Ar age	Rb-Sr age	K-Ar age	Rb-Sr age	K-Ar age	Rb-Sr age
Yanai	-	95,102(bt) 92(mus)	-	90-91(bt)	84,85(bt)	87,89(bt)
Takanawa Peninsula	-	-	-	-	87(bt)	-
eastern Shikoku	-	-	-	-	75-87(bt)	-
Awaji Island	-	-	72-88(bt) 89(hb)	84(bt) 99(kf)	70,80-86 (Bt) 88,90(Hb)	-
Kii Peninsula	-	-	-	71(kf)	69,73-77, 98(bt)	69,81(bt) 70-71(mus) 71,83(kf)
western Chubu	63-68(bt)	68(bt)	70(mus)	80(mus)	62-71(bt) 73(hb)	73(bt)
eastern Chubu	64,68,88 (bt)	55-70(bt)	52-65(bt) 66,72(hb)	61-69,83 (bt)	58-65(bt) 71(hb)	58-66(bt)

of the Ozu phase. While Maruyama *et al.* (1990), Isozaki and Maruyama (1990), and Isozaki *et al.* (1991) proposed the tectonic model that the Chichibu and the Kurosegawa Terranes of the Outer Zone of Southwest Japan are derived from the Inner Zone, the Chichibu terrane (except for the Sambosan belt) is a southern continuation of the Mino-Tamba terrane, and the Kurosegawa terrane is a tectonic outlier of the Paleozoic terranes. But the Permian and Jurassic rocks along the MTL are structurally located between the Ryoke and the Sambagawa terrane - the Paleo-Ryoke land. Additionally, the basic rocks of 250 Ma are included in the original rocks of the Ryoke metamorphic rocks, and the older rocks along the MTL are mixed with the Ryoke rocks in the Mikawaono-Toei area. It has been assumed that the Kurosegawa rocks, as nappes of the uppermost structural level of the Outer Zone, are not derived from the Inner Zone, but the Paleo-Ryoke land (Hara *et al.*, 1991). The origin of the older rocks along the MTL is assumed to have been derived from the Paleo-Ryoke land. Collision of a continent (Paleo-Ryoke land) and the Jurassic accretionary complex of the Inner Zone have been also proposed by Ichikawa(1981), Komatsu(1988) and other workers. The formation of the 152 Ma Asakawazawa granite is considered to clearly show that the Ryoke belt was the field of the collision of the Tamba-Mino Terrane and the Paleo-Ryoke land.

B. Time of mylonitization

The formation of the southern marginal shear zone of the Ryoke belt has been assumed to have occurred during early Late Cretaceous age after the intrusion of the older Ryoke granites, and before the intrusion of the younger Ryoke granite and the sedimentation of the Izumi Group. The exact radiometric ages, showing the intrusion of the older granite, have not yet been determined. From the Yanai district to the Chubu district, K-Ar ages of the older Ryoke granites are the same as the surrounding metamorphic rocks (Table 4). Both ages are inferred to be cooling age. K-Ar ages of the older Ryoke granites are often younger than those of the San-yo granites, which intruded the Ryoke granites, (e.g. Okano and Honma, 1983). In the Takato area, the Chubu district, K-Ar ages of the mylonite, derived from the older Ryoke granites (Shibata and Takagi, 1988), and Rb-Sr mineral ages of biotite of the Ryoke metamorphic rocks (Okano, 1982) are younger than the younger Ryoke granites which were not affected by mylonitization. This evidence also suggests that radiometric ages of the older granites do not show their formation age, but their cooling age.

Figure 57 shows K-Ar and Rb-Sr ages of the older Ryoke granites, the younger Ryoke granites and the metamorphic rocks. Except for the Rb-Sr whole-rock ages of the younger granites, most of them range from 70 to 60Ma. For the younger granites, Rb-Sr whole-rock ages, as the time of emplacement, are older than K-Ar and Rb-Sr mineral ages. These facts suggest that 70-60 Ma was the time of cooling related to uplifting. From the Yanai district to the Chubu district, the cooling ages show an eastward younging polarity. Thus, it can be assumed that the Ryoke metamorphic field was uplifted at the earlier stage in the western area than in the eastern area. In the Chubu district, K-Ar ages and Rb-Sr mineral ages of the Ryoke rocks range from 70 to 60 Ma. In the Mikawaono-Toei area, crush melange was formed at about 62 Ma. This fact suggests that the metamorphic field of the Ryoke metamorphic terrane in the Chubu district was greatly uplifted during the D4 phase. The uplifting of the Ryoke metamorphic field in the Yanai district occurred at about 90 Ma on the basis of the cooling

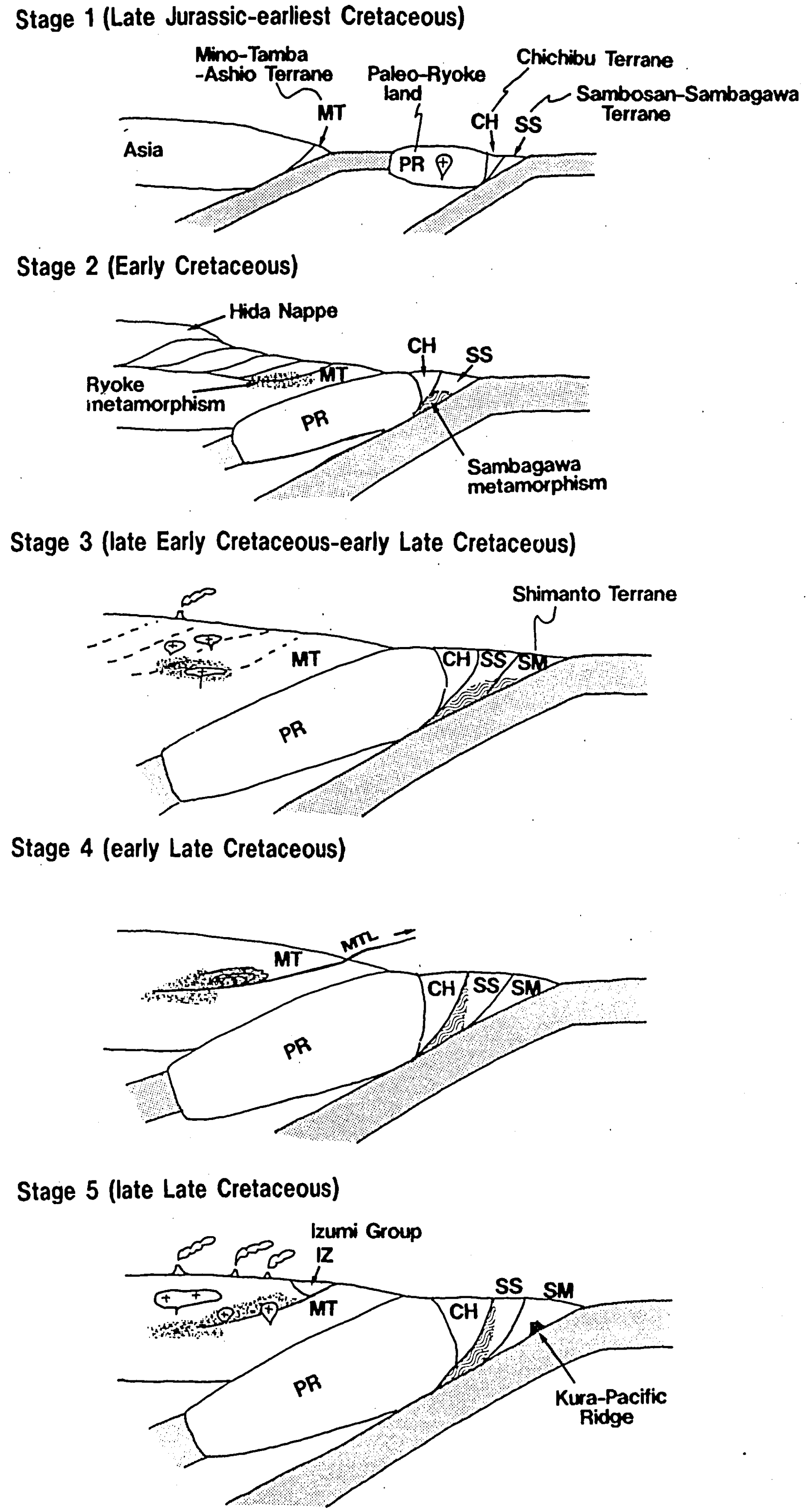
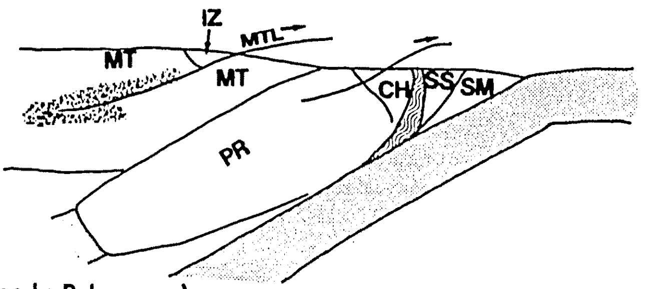


Fig. 58. Diagrams showing the tectonic evolution of Southwest Japan during late Jurassic to early Paleogene.

Stage 6 (latest Late Cretaceous-earliest Paleogene)



Stage 7 (early Paleogene)

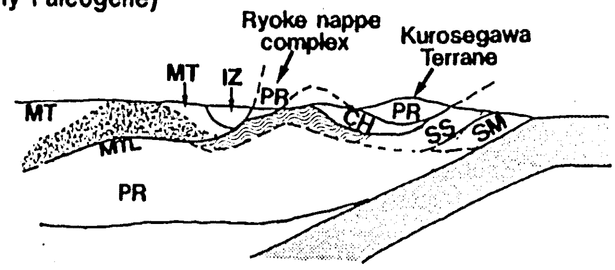


Fig. 58. continued.

ages. On the Awaji Island, non-mylonitized 87.7 Ma (K-Ar age) younger Ryoke granite intruded the mylonite, and the mylonitization has also been assumed to be older than 87.7 Ma (Takahashi, 1992). The Ryoke metamorphic field in the Yanai district and Awaji Island may have been uplifted during the D3 phase. In the western part of the Ryoke belt, the main uplifting stage is comparable with mylonitization in the southern marginal shear zone . The uplifting of the Ryoke metamorphic field began at about 90 Ma.

C. Geotectonic history of the Ryoke belt

The formation of the Ryoke metamorphic belt and origin of the MTL in the tectonic history of Southwest Japan may thus be summarized as follows (Fig. 58).

Stage 1(Late Jurassic-earliest Cretaceous)

This stage is represented by the formation of accretionary complexes (the Mino-Tamba Terrane) of Late Jurassic-earliest Cretaceous ages in the southern front of Asia (the Hida continent). The original rocks of the Ryoke metamorphic rocks are part of the Mino-Tamba Terrane. The formation of the accretionary complex continued to earliest Early Cretaceous (Wakita, 1988). This was followed by the collision of the Paleo-Ryoke land, where granite intrusion and mylonitization during Jurassic age occurred, forming the Asakawazawa granite mylonite and Karasaki Mylonite. In the southern front of the Paleo-Ryoke land, accretionary complexes of Jurrasic-late Cretaceous ages (the Chichibu-Shimanto Terranes) were produced.

Stage 2(Early Cretaceous)

This stage is represented by the collision of the Paleo-Ryoke land with the continental margin of Asia, which occurred at the ending of the formation of the Mino-Tamba Terrane and the formation of nappe piles of the terranes in the Inner Zone.

The early Cretaceous Tedori Group unconformably covering the Hida Terrane, contains gravels derived from the Jurassic accretionary complex (Saida, 1987; Takeuchi and Takizawa, 1990). This evidence suggests that the formation of the Hida nappe also occurred during Early Cretaceous before the Jurassic accretionary complex furnished the fragments to the Tedori Group. Hara *et al.* (1991) suggested that the nappe piles of the terranes in the Inner Zone and Hida nappe were formed by the collision of the Paleo-Ryoke land in the continental margin of Asia.

The tectonic thickening of the Inner Zone was induced by this collision. The metamorphism associated with D1 in the Ryoke metamorphic rocks is assumed to be ascribed to this tectonic thickening. During the D1-D2 phase after these events, the Ryoke metamorphic field was uplifted under static conditions.

Stage 3(late Early Cretaceous-early Late Cretaceous)

This stage is represented by intense magmatism related to the older Ryoke granites and metamorphism associated with the D2 deformation.

Stage 4(early Late Cretaceous)

This stage is characterized by the uplifting of the Ryoke metamorphic belt. The time of uplifting shown by the cooling ages of the Ryoke rocks appears to have begun at an earlier age in the western part of the Ryoke belt than in the eastern part. The uplift of the Ryoke belt occurred with southward thrusting, which contained a large sinistral component. The thrusting formed the recumbent folds and the southern marginal shear zone. Tectonics of this stage have been described by Hara *et al.* (1991) as the Fd-phase forming large-scale drag folds in the Yanai area. The Ryoke metamorphic belt was transported a long way toward the south during this stage. The central high-temperature part of this belt was emplaced onto the non-metamorphic and weakly metamorphosed rocks of its southern outside (Fig. 58).

Stage 5(late Late Cretaceous)

This stage is represented by the intrusion of the younger Ryoke granite. In this stage, the most intense magmatism extended to all over the Inner Zone accompanying the southward migration of the magmatic front (Fig. 58). This event is assumed to be related to the subduction of the Kula-Pacific ridge at about 85-80 Ma which was pointed by Kiminami *et al.*(1990).

Stage 6(latest Late Cretaceous - earliest Paleogene)

The earlier part of this stage is represented by the southward thrusting of the Ryoke belt and Paleo-Ryoke land from the Inner Zone to the Outer Zone. The intense uplifting of the Ryoke metamorphic field occurred with the formation of nappe complex and crush melange at the later part of this stage. The rocks of the Paleo-Ryoke land, situated in the area between the Ryoke metamorphic terrane, the Sambagawa metamorphic terrane, and the Upper Cretaceous sediments, were transported onto the Jurassic-Cretaceous accretionary complexes of the Outer Zone, forming the Kurosegawa Terrane nappes.

Stage 7(early Paleogene)

This stage is represented by the formation of the high-angle MTL. Left-lateral strike slip faulting along the MTL was associated with echelon folding. The faulting occurred before the sedimentation of the Eocene Kuma Group.

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