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Geological and Petrological Studies on the Hiroshima Granite in the Togouchi-Yuu-Takehara District, Southwest Japan*

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The main purpose of this paper is throwing light on the mechanism of emplacement of the Hiroshima granite and on the space problem of volcano-plutonism in the Inner Zone of Southwest Japan during the late Cretaceous. In order to discuss these problems which are classical and have so far been unsolved, the author has selected the Togouchi-Yuu-Takehara district as a granite field of the San-yo zone. In the southern end of the district, the granite is in contact with Ryoke granitic and metamorphic rocks formed in 10km depth of crust, and in the central area it intruded into pre-Cretaceous sedimentary rocks and into both the sedimentary rocks and Cretaceous surficial volcanic rocks in northern and eastern areas. The author have investigated the granite distributed in the Togouchi area and another several areas in the district, focuing mainly on contact feature between the granite and wall rocks and internal structure of the granite mass. As a result, it is clarified that throughout the district the Hiroshima granite is not a uniform mass but a mass formed by accumlation of layered bodies of granitic rocks. In the mass, rather mafic granite as granodiorite or hornblende granite occurs overlying rather felsic granite as medium to coarse-grained biotite granite. The forming order of them is closely connected with the stratigraphical sequence of the Cretaceous volcanic rocks. As a whole, it can be regarded that the Hiroshima granite is a large tabular mass gently dipping toward the south, and that the Hiroshima granite passively intruded along the fracture zone gently dipping southward, and at the head of the zone the Cretaceous volcanic activities took place. Additionaly, the stress field during and after the emplacement of granodiorite in the Togouchi area has been analysed based upon microfabric and homogenization temperature of fluid inclusion planes in quartz. Finally, the author propose flat-dike type mass for the emplacement mechanism of a large granite mass.

I. Introduction

Late Cretaceous to Palaeogene igneous rocks as acidic volcano-plutonic association are widely developed in the Inner Zone of Southwest Japan. They in Chugoku Province have been classified into three E−W trending zones, based on ages of activity and modes of occurrence: Ryoke zone, San-yo zone and San-in zone from south to north (Fig. 1).

Radiometric ages of the granitic rocks in the San-yo zone widely range from 70Ma to 103Ma showing a cluster around 85Ma (Fig. 2) (Geological Survey of Japan, 1982; Higashimoto et al., 1983, 1985, 1986). Such an age variation may show that in the San-yo zone there are many masses with different intrusion ages, but it is also found even within a small mass. There is little difference in radiometric ages between the granitic rocks of the San-yo zone and those of the Ryoke zone but radiometric ages of the granitic rocks of the San-in zone are clearly younger than those of the other

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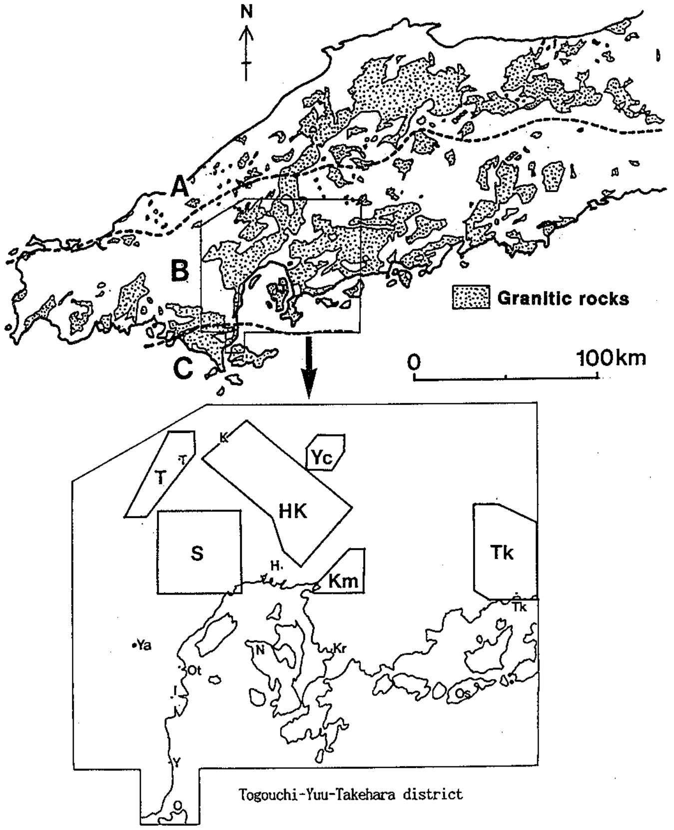

Fig. 1. Diagram showing the distribution of granitic rocks in Chugoku Province and the location of the studied area.

A: San-in zone
B: San-yo zone
C: Ryoke zone
HK: Hiroshima-Kake area
Km: Kumano area
S: Saeki area
T: Togouchi area
Tk: Takehara area
Y: Yachiyo area
H: Hiroshima
I: Iwakuni
K: Kake
Kr: Kure
N: Nomizima
O: Oshima
Os: Osakishimozima
Ot: Otake
T: Togouchi
Tk: Takehara
Y: Yuu
Ya: Yasaka-kyo

zones. According to Ishihara (1977), the granites in the San-yo zone and the Ryoke zone are largely of ilmenite-series, and those in the San-in zone commonly of magnetite-series.

Since Kojima et al. (1959) called medium-grained to coarse-grained granitic rocks developed in the southern halves of Hiroshima Prefecture and Okayama Prefecture the Hiroshima granitic complex, the granitic rocks in the San-yo zone have been called as a whole the Hiroshima Granite. On the other hand, granitic rocks in the Ryoke zone have been called the Ryoke Granite (younger and older), and those in the San-in zone the San-in Granite.

As summarized by Murakami and Imaoka (1986), studies on volcanic and granitic rocks in the San-yo zone have been done, in attempting to clarify their magma types and petrological characteristics based mainly on their mineralogy and petrochemistry and the history of volcano-plutonic activities. The intrusion and emplacement mechanisms of the granitic rocks have so far scarcely been analyzed. The main purpose of this paper is throwing light on the mechanism of emplacement of the Hiroshima Granite and on the space problem of volcano-plutonism in the Inner Zone of Southwest Japan during the late Cretaceous.

Because the way of intrusion of a granite mass and its lithology are closely reflected on the formation history of the mass, it is considered to be essentially important for the present author's purpose to clarify not only geological and structural features but also lithological and mineralogical changes within the mass. Therefore, the author believes that the accumulation of detailed geological data as well as petrological and mineralogical data must give a first step to the success in solution of above—mentioned problems. In order to analyze the problems the author has selected the Togouchi-Yuu-Takehara district as a granite field (here called T-Y-T district) to study. The

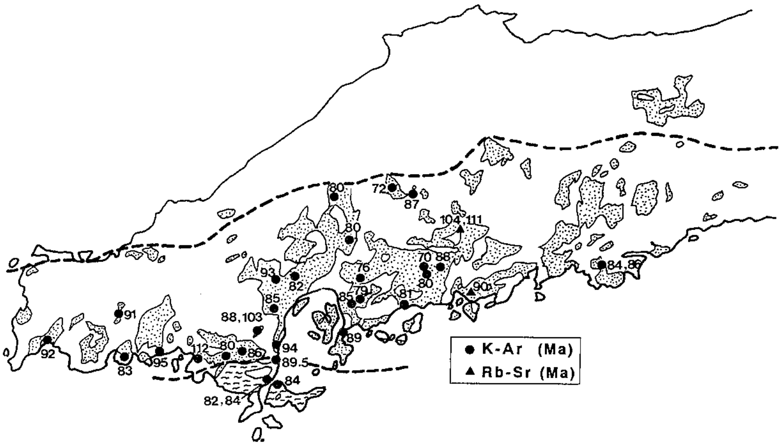

Fig. 2. Spatial variation of the radiometric ages of granitic rocks in the San-yo and Ryoke zones. (compiled from Geological Survey of Japan, 1982; Higashimoto et al., 1983, 1985, 1986)

T-Y-T district is situated around Hiroshima City, extending about 91km from south to north, and about 74km from east to west, in the central Chugoku Province (Fig. 1).

Pre-Cretaceous formations and late Cretaceous to Paleogene igneous rocks of the San-yo zone are widely developed in the T-Y-T district as shown in Fig. 3. In the southern margin of the district occur the Ryoke metamorphic rocks and the Ryoke Granite. The Cretaceous to Paleogene igneous rocks of this district consist mainly of rhyolitic and granitic rocks. The latter show commonly a disconcordant relation to the country rocks such as pre-Cretaceous formations and Cretaceous volcanic rocks (Fig. 4). Yoshino and Hayashi (1979) reported that the boundary surface between a granite and its host rocks in the Yasaka-kyo area situated in the southern part of the T-Y-T district is also disconcordant, showing "step-like structure" characterized by the repetition of a steep wall contact and a nearly horizontal roof contact.

Such a step-like structure has been reported in the other areas in the world, for example, Myers (1975) showed in the Coastal Batholith (Mesozoic to Tertiary) in Peru that granitic bodies are characterized by a steep wall contact and a gentle roof contact. Takahashi, M (1985) also reported that Miocene Okueyama pluton in Kyushu Province has the similar boundary with rhyolitic host rock to that in the Coastal Batholith.

In order to discuss the intrusion mechanism of granite, it is necessary to begin with the clarification of the structural relationship between granite and its country rocks in the T-Y-T district. Next, as for the internal structure of the granitic rocks of the T-Y-T district, some authors have suggested that the granitic rocks do not occur as a uniform mass, but are consisted of several granitic rock bodies which vary in lithology and activity stages.

Tomonari (1984) subdivided the granitic rocks cropping out in the Middle Belt of Palaeozoic Terrane in Hiroshima Pref. (equivalent to Maizuru Terrane) into four different types of Mannari, Asida, Mikawa and Hirotani, based mainly on lithological difference. Suzuki, T (1986) subdivided the granitic rocks in the northwestern area of the T-Y-T district into Kake granite, Mugitani granodiorite and Togouchi granodiorites, each of which was subdivided further into two or three facies based on lithological characteristics. Yoshino and Hayashi (1989) clarified that the Togouchi granodiorites (Suzuki, T., 1986) is composed of six different facies which are diorite porphyry, granodiorite porphyry, granite porphyry, quartz diorite, granodiorite and granite.

As for the relationship among each rock body constituting a granitic mass, the following studies have been done. Hara (1955) showed that granite in the Hata area is composed of fine-grained facies, medium- to coarse-grained facies, and that each of which occurs as a layered body. Yoshida

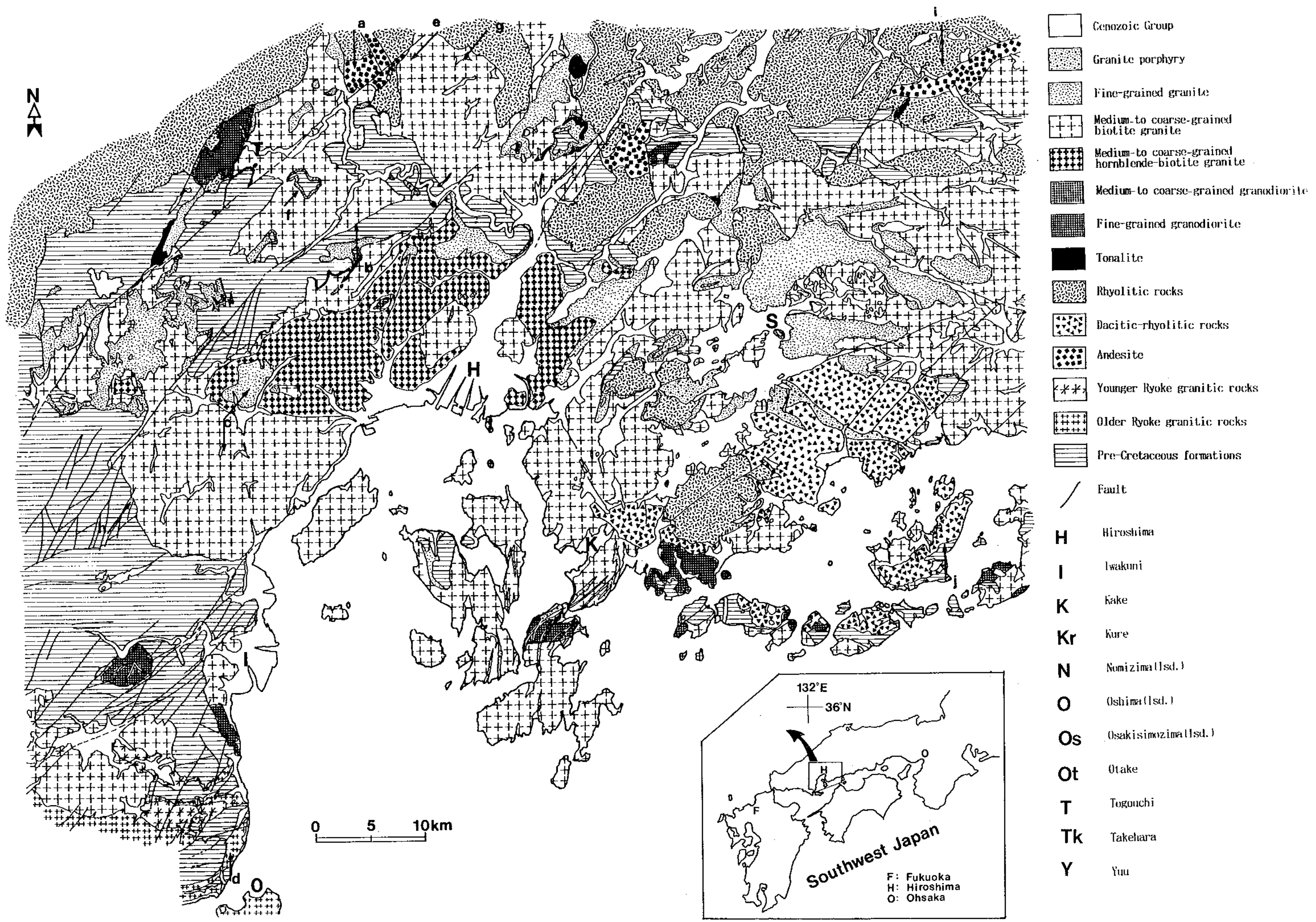

Fig. 3. Geological map of the Togouchi—Yuu—Takehara district, southwest Japan.
(compiled from Hara, 1955; Yoshino & Hayashi, 1979; Yoshida et al., 1985; Suzuki,T., 1986; Yamada et al., 1986; Takahashi, Y. et al., 1989; Yoshino & Hayashi, 1989; Hayashi, 1989; Takahashi, Y 1991; Hara et al., 1991 and the present author's data)

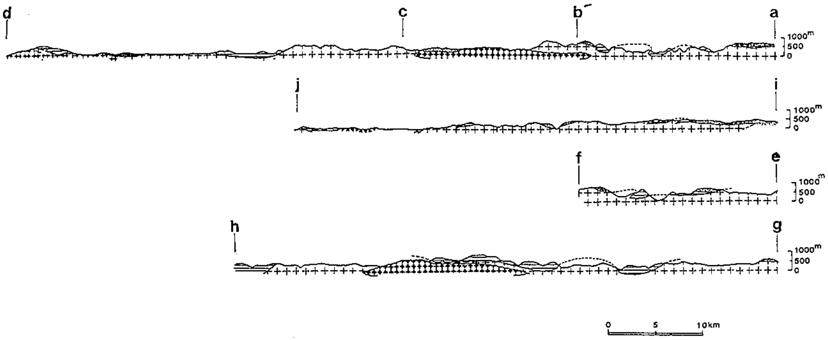

Fig. 4. Geological profiles of the Togouchi-Yuu-Takehara district.
See Fig. 3 for legend and location of the profiles lines.

et al. (1985) reported that granite in the Takehara area is consisted of coarse-grained facies, medium-grained facies and fine-grained facies, and that each of which occurs as layered body. In the Tsuta area of the district, Takahashi,Y et al. (1989) showed that granite is constructed by six different types of granitic rocks which are granophyric granite, fine-grained biotite granite, fine- to medium-grained biotite granite, medium-to coarse-grained biotite granite, medium-grained hornblende-biotite granite and quartz diorite, and that each of which occurs as a layered body. Takahashi,Y (1991) also showed that granite in the Hiroshima area situated on the east of the Tsuta area is constructed by three different granitic rocks which are fine-grained biotite granite, medium-to coarse-grained biotite granite and medium-grained hornblende biotite granite, and showed that each of which occurs as a layered body. In an every study mentioned above, it has been clearly shown that a coarse-grained granitic rock body tends to occupy lowermost level of a large mass, and a fine-grained one the uppermost level. Furthermore, it is notable that the hornblende biotite granite formed in earlier stage occupies relatively upper level of a large mass.

In the problem of intrusion mechanism of granite, it is more necessary to understand tectonic significance of such layered structure of a granitic mass as mentioned above, which can be attributed to results of either fractionation of a single magma within a pluton or accumulation of several plutons individually intruded. Therefore, it is the most important theme to clarify features of the layered structure of the granitic mass (Hiroshima Granite) in the T-Y-T district.

In the northwestern area of the T-Y-T district, many faults are developed in NE−SW trend (Yamada et al., 1986) (Fig. 3). Such NE−SW trending faults distinctively appear in pre-Cretaceous formations and Cretaceous volcanic rocks, but they are obscure in the granitic rocks in some places. It is noticeable that the dominant boundaries between the granitic rocks and their country rocks which are regarded as intrusion contact, are sometimes in NE−SW trend and placed in the extension of such NE−SW trending faults, e.g. near Kabe, in the west of Saeki. It has been suggested by some authors that fault or faulting played an important role in the intrusion processes of granitic rocks as, for example, the Coastal Batholith in Peru (Pitcher and Bussell, 1977), the Main Donegal Granite in Ireland (Hutton 1982), the Central Extremadura batholith in Spain (Castro, 1985) and the biotite granite at Strontian in Scotland (Hutton, 1988).

Therefore, in the district it becomes also to be a more important theme to clarify relation not only between geological structure and shape of a granitic mass, but also between the shape and internal structure of the mass.

For the purpose mentioned above, the author selected the Togouchi area situated in the northwestern margin of the T-Y-T district to study further in detail, in which a northern limit of the granitic mass exists, and the granitic rocks are in contact with either pre-Cretaceous formations or Cretaceous volcanic rocks.

In the area, geological structure, lithological feature and mineralogy, internal structure and shape of the granite mass have been investigated. The area is considered to be situated near the boundary between the San-yo zone and the San-in zone (Ishihara, 1977). Suzuki,M. (1987) stated that the Togouchi granodiorites belongs to magnetite-series granite. Therefore, these studies in the area are also helpful for understanding the zonal arrangement of granitic rocks in Chugoku Province.

With reference to the study of the area, the granitic rocks in the other six areas in the T-Y-T district than the Togouchi area have been investigated and reviewed (Fig. 1). As a result, the megascopical shape and internal structure of the granitic rocks and structural relationship between the granitic rocks and country rocks throughout the T-Y-T district will be clarified (Figs. 3 and 4). Additionally, the fabrics of fluid inclusion planes in quartz grains will be also analyzed to clarify the deformation history of the granitic rocks during cooling.

Based on the results from the studies mentioned above, the problem on the emplacement mechanism of the granitic rocks will be discussed.

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II. Outline of Geological Framework

The pre-Cretaceous rocks as country rocks for Cretaceous igneous rocks in the T-Y-T districts have been classified into five units with reference to age and lithology. Akiyoshi Terrane rocks as a Permian accretionary complex, Maizuru Terrane rocks as a latest Permian accretionary complex, Suo Tarrane rocks as a high P/T rocks of Triassic age and upper unit Mikawa Group and lower unit Kuga Group of the Kuga-Tamba-Mino-Ashio Tarrane rocks as Jurassic accretionary complex (cf. Ichikawa, 1990). These units are respectively developed as flat-lying nappes, which are folded in upright fashion and gentle form with E−W trending axes (Kojima, 1953; Hara et al., 1979; Nishimura, 1990). The upper members of nappes such as Akiyoshi Tarrane nappe and Maizuru Tarrane nappe are distributed in the northwestern and southeastern part of this district, while the lower member such as Mikawa nappe and Kuga nappe in the southern part and central part along the River Ohta (Fig. 3). The southern extension of the Kuga nappe corresponds to the metamorphic rocks of the Ryoke zone (Higashimoto et al., 1983).

Volcanic rocks in San-yo zone which consist of andesite, dacite, rhyolite and their tuffaceous equivalents, are widely distributed in the San-yo zone. They are divided into four groups formed by a series of Cretaceous to Paleogene igneous activity, Kanmon, Shunan, Hikimi and Abu Groups in the order of younging. Their distribution areas are roughly arranged into two E—W trending zones (Fig. 5). The one (northern volcanic zone) is placed along the Chugoku Mountains, being in the northern outside of the distribution zone of Cretaceous granitic rocks mentioned above. The other (southern volcanic zone) is placed along northern coast of Seto inland sea on the east of Hiroshima City. The northern volcanic zone contains the Sandan-kyo block and Takada block after Yoshida (1961), and the southern volcanic zone the Akitsu-Sensui block also after him.

Andesitic rocks and rhyolitic rocks with great volume of their tuffaceous equivalents in the T-Y-T district have been called by Yoshida (1961) Kisa andesite and Takada rhyolites respectively. The Takada rhyolites have an either conformable or unconformable relationships to their underlying Kisa andesite (Yoshida, 1964). Thereafter the Kisa andesite was correlated with the Shunan Group, while the Takada rhyolites with the Hikimi and Abu Groups (Iizumi et al., 1985).

The Kisa andesite had been considered to developed near the southern margin of rhyolitic rocks of the northern volcanic zone as shown in Geological map of Hiroshima Pref. (1963). But, Hayama et al., (1975) suggested that pyroclastic rocks in Osakisimozima Island situated in the southern volcanic zone is possibly correlative with the Kisa andesite. The Takada rhyolites are mainly developed in the northern volcanic zone, consisting mostly of rhyolite and its tuffaceous equivalents, while these in southern volcanic zone consist mainly of dacite and its tuffaceous equivalents (Higashimoto et al., 1985; Yamada et al., 1986).

Yoshida (1964) pointed out that Takada rhyolites are composed mainly of dacitic and rhyolitic pyroclastic formations, frequently intercalated by their equivalent lavas, but the detailed volcano-stratigraphy has not yet been established.

Kawahara and Bammoto (1983) reported an alternation of tuffaceous sandstone and shale intercalated in rhyolitic rocks of the Sandan-kyo block about 8 kilometers north of Kake, showing that it contains *Cunninghamia* cone of Hetonaian. Kawahara (1978) reported the rhyolitic rocks in Mihara belonging to the Akitu-Sensui block are interstratified with subaqueous deposit. Aki Research Group (1983) clarified that the rhyolitic rocks in east of Kure are divided into six formations characterized by dacitic to rhyolitic tuff and interstratified clastic deposit, and suggested

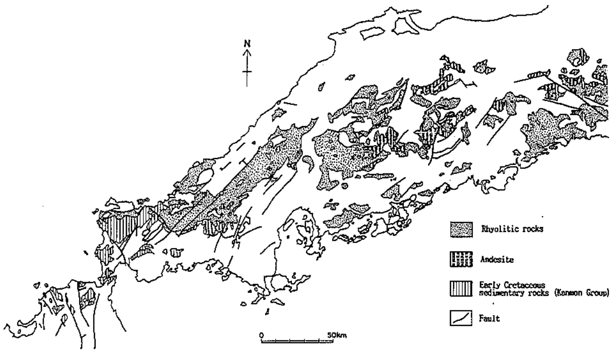

Fig. 5. Distribution of late Cretaceous to early Palaeogene igneous rocks in Chugoku-Kyushu Province.
(compiled from Geological Survey of Japan, 1982 and Hayashi, 1989)

that they, as a whole, form a gentle basin structure whose long axis is in E—W trend. The volcanic activities for the formation of the Takada rhyolites appear to have mainly taken place on land (Yoshida, 1964). Concerning to the forming process of these volcanic rocks, Murakami (1974) suggested, on the basis of mode of occurrence, feature of accumulation, mineralogical characteristics and so on, that rhyolitic rocks of the Hikimi Group containing the Sandan-kyo block were accumulated in an E—W trending fissure with volcanic activities.

Granitic rocks in Chugoku Province, which range from diorite to granite in composition, are widely distributed along the northern coast of Seto Inland Sea, and being traced to the northern area of Kyushu Province. They have been so far assumed to occur as stock and/or batholith with various sizes (Murakami, 1981). However their shapes and internal structures have not yet been clearly presented.

In the T-Y-T district, around Hiroshima City, there exists the largest exposure (Hiroshima granite batholith) of the granitic rocks in the San-yo zone, which have been considered to form a large batholith (Fig. 1). They postdate the pre-Cretaceous rocks and Cretaceous volcanic rocks belonging to the Takada rhyolites and Kisa andesites, showing disconcordant relation with their country rocks (Fig. 4).

Although almost all granitic rocks distributed in the T-Y-T district have been considered to be involved in the Hiroshima granite batholith, they have been divided into some masses with reference to lithofacies and intrusion relation. Suzuki, T (1986) classified granitic rocks in east of Kake into three masses based upon their intrusion relation, Kake granite, Mugitani granodiorite and Togouchi granodiorites, each of which was subdivided further into two or three facies based on lithological characteristics. The Togouchi granodiorites is the earliest one among the granitic masses in the area. He regarded the granodiorites as a member of the Central plutonic rocks group after Kojima et al., (1959), Yoshida (1961) and Tomonari (1984). Yoshino and Hayashi (1989) clarified that the Togouchi granodiorites is composed of six different facies which are diorite porphyry, granodiorite porphyry, granite porphyry, quartz diorite, granodiorite and granite. Hara (1955) clarified that the Hiroshima granite batholith in the Hata area on the northeast of Kabe is divided into three units in lithofacies, fine-grained adamellite facies, granodiorite facies and coarse-grained granite facies with pinkish K-feldspar, and that these units form a nearly flat-lying structure. Yoshida et al. (1985) classified the Hiroshima granite batholith in the Takehara area on the basis of lithofacies into three units, fine-grained aplitic granite, medium-grained granite and coarse-grained granite with pinkish K-feldspar. They also show that these units occur as flat-lying layered masses and the fine-grained aplitic granite is situated in the uppermost structural level.

In the Tsuta and Hiroshima areas placed in the northwestern part of the T-Y-T district, recently Takahashi, Y. et al., (1989) and classified the Hiroshima granite batholith into six masses which are granophyric granite, fine-grained biotite granite, fine- to medium-grained biotite granite, medium- to coarse-grained biotite granite, medium-grained hornblende-biotite granite and quartz diorite, with reference to lithological feature, showing these masses form a flat-lying layered structure and the fine-grained granite is placed in the uppermost structural level. Subsequently in the Hiroshima area on the east of the Tsuta area, Takahashi,Y. (1991) also classified the Hiroshima granite batholith into three masses of fine-grained biotite granite, medium- to coarse-grained biotite granite and medium-grained hornblende biotite granite, showing that these masses form a flat-lying layered structure and that the fine-grained granite is placed in the uppermost structural level.

III. Distribution and Structure of the Igneous Rocks in the Togouchi Area

A. General Geology

Fig. 6 illustrates the distribution of the pre-Cretaceous rocks, Cretaceous volcanic rocks and granitic rocks in the Togouchi area. The pre-Cretaceous rocks are grouped into two formations. The one is pebbly mudstone with various-scaled olistoliths of sandstone and chert, and the other is mudstone accompanied with green rocks. Both of formations are developed in E—W trend, and their boundary is placed near Hosomidani (Yamada et al., 1986). Recently Kusumi et al. (1989) have pointed out that both formations contain radiolarian fossils of Jurassic age, showing that these belong to the accretionary complexes of the Kuga-Tamba-Mino Terrane.

In the Togouchi area Cretaceous igneous rocks are widely distributed, though small bodies of tonalite appear in its southern part. Granitic rocks consist of granodiorite, porphyritic granite, medium-grained granite and fine-grained granite containing aplite (Hayashi, 1989). The porphyritic granite is a dike. Roughly speaking, Cretaceous volcanic rocks of this area belong to the Sandan-kyo block of Takada rhyolites, being widely developed in its western and northwestern part. They are also developed as a roof pendant for the granitic rocks near Mt. Ichima (Figs. 6 and 7).

B. Distribution of rhyolitic and plutonic rocks

1. Rhyolitic rocks

In the Togouchi area, rhyolitic rocks show an extensive distribution as illustrated in Fig. 6. Yoshida(1964) pointed out that the rhyolitic rocks in the northwestern area of the T-Y-T district consist mainly of rhyolitic pyroclastic rocks, and he called them Sandan-kyo formation. The Sandan-kyo formation is considered to belong to the Hikimi Group (Iizumi et al., 1985; Yamada et al., 1986), which is one of the main constituent of Cretaceous volcanic rocks in Chugoku Province (Fig. 5). Rhyolitic rocks in the Togouchi area occupy the eastern margin of such a large volcanic mass. In the Geological map of Hiroshima Pref. (1963), it is shown that the rhyolitic rocks in this area are intruded by granite porphyry in the vicinity of Uchinashi, and that the granite porphyry is in fault contact with the Hiroshima Granite. Yoshino and Hayashi (1989) pointed out that the rhyolitic rocks are traced over the River Ota at the north of Seizui to the top of Mt.Ichima, and are in contact with the Jurassic accretionary complex with a NW—SE trending boundary surface which dips steeply to the south. The distribution of the rhyolitic rocks extends around the top of Mt.Ichima (Fig. 6).

On the northwestern slope of Mt.Ichima, the rhyolitic rocks are traced as narrowly elongated body of 200 meters in width from north of Seizui to near the top of Mt.Ichima, and at a height of 1000 meters, they are developed in horizontal fashion. On the bed of the River Ota is developed a boundary between the rhyolitic rocks and the Jurassic accretionary complex, having a chilled margin of 2 to 3 meters wide. At height of 800 meters, on the southeastern slope of Mt.Ichima, their distribution is nearly horizontal. The northeastern end of their distribution is marked near Tabuki, and the eastern end is in the west of Tabuki, where the rhyolitic rocks are in contact with granodiorite at low angles and in fault contact with the Jurassic accretionary complex at high angles. The southwestern end of their distribution is near the head of the Sakaidani gorge, showing that they are in contact with chert of the Jurassic accretionary complex at high angles, and are horizontally distributed at a height of 950 meters (Fig. 7).

On the west of Tabuki, a road-cut exposure shows that the rhyolitic rocks are in contact with chert of the Jurassic accretionary complex at high angles, where they become finer in grain size towards the contact suggesting the existing of chilled margin. Recrystallized biotite is found in muddy-beds in the chert, suggesting a contact metamorphic effect. Generally, the rhyolitic rocks near the contact

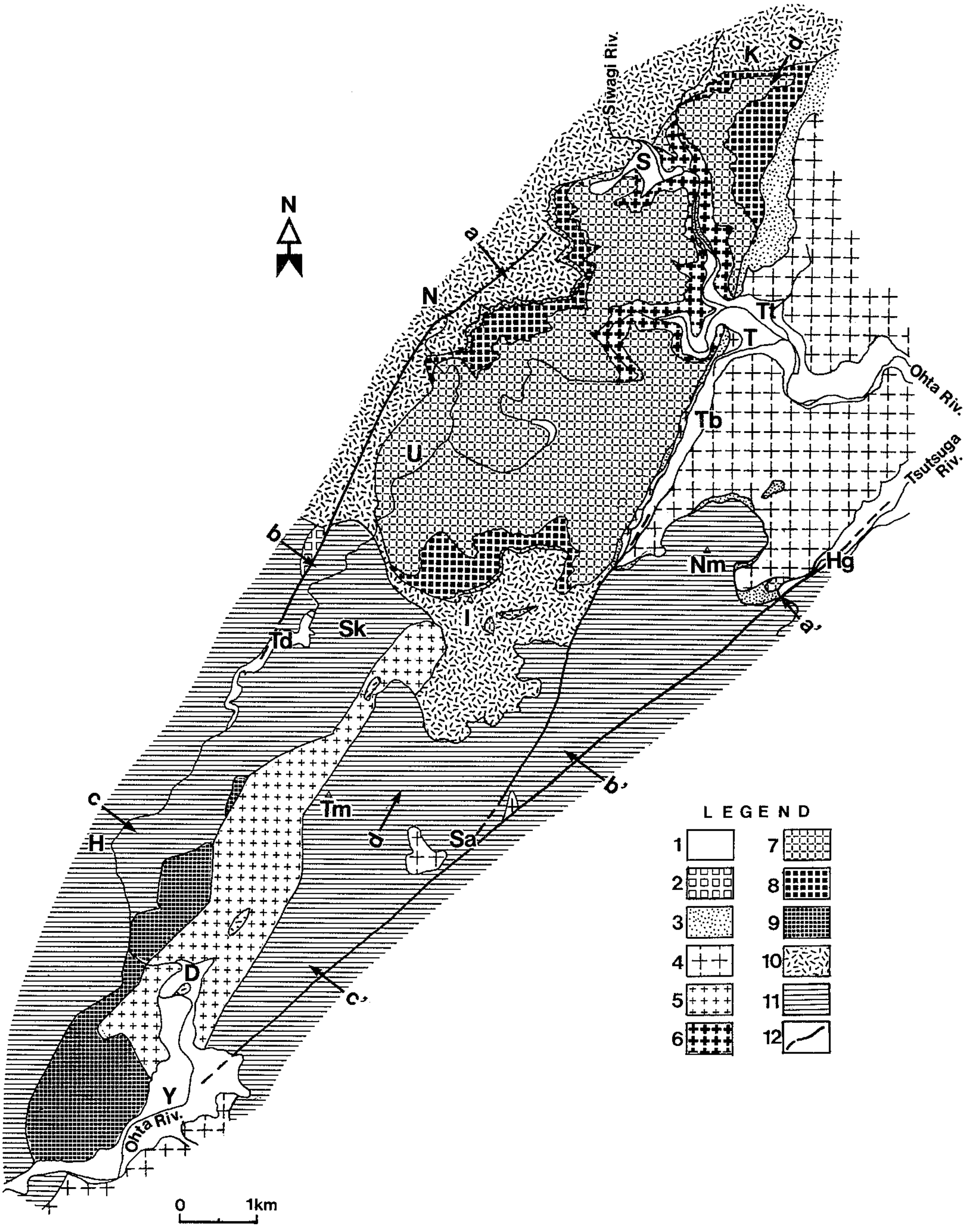

Fig. 6. Geological map of the Togouchi area placed in the northwestern marginal part of the Togouchi-Yuu-Takehara district, southwest Japan.

1: Quaternary, 2: granite porphyry, 3—9: Hiroshima granites, 3; fine-grained granite and aplitic rocks, 4; medium-grained granite, 5; porphyritic granite, 6—8; granodiorite (6,7 and 8; lower, middle and upper lithologic facies respectively, See text in detail), 9; tonalite, 10: Takada rhyolitic rocks, 11: pre-Cretaceous Yoshiwa formation, 12: fault. D: Dani, H: Hosomidani, Hg: Hagiwara, I: Mt.Ichima, K: Kajinoki, N: Nasu, Nm: Mt.Nabe, S: Shiwagi, Sa: Sakahara, Sk: Sakaidani T: Togouchi, Tb: Tabuki, Td: Tateiwa dam, Tm: Mt.Tateiwa, Tt: Tsubutani, U: Uchinashi, Y: Yoshiwa.

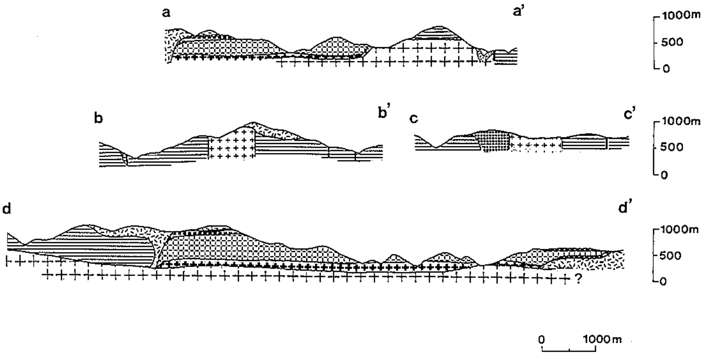

Fig. 7. Geological profiles of the Togouchi area.
See Fig. 6 for legend and location of the profile lines.

with the Jurassic accretionary complex, which is at high angles, tend to be finer-grained. On the eastern to southeastern slope of Mt.Ichima, many rhyolitic dikes, which are of 1 to 2 meters in width, appear in the Jurassic accretionary complex. Rhyolitic rocks in the Togouchi area have so far been considered by Yoshida (1964) and Kawahara (1989) to consist of the accumulation of dacitic and rhyolitic pyroclastic rocks. On the basis of the above described geological evidences, however, it would be said at least that some parts of rhyolitic rocks are intrusive.

2. Plutonic rocks

According to Geological map of Hiroshima Pref. (1963) granitic rocks in the Togouchi area consist of biotite granite and hornblende-biotite granodiorite or quartz diorite. Yamada et al. (1986) said that these are divided into 3 types, First type [hornblende-biotite granodiorite (granophyric)], Second type [hornblende-biotite granodiorite and biotite granodiorite to granite], and Third type [biotite granite or hornblende-biotite granite]. The author, based mainly upon their mode of occurrence, has newly classified them into tonalite and the following 4 types of granitic rocks. The granitic rocks are granodiorite, porphyritic granite, medium-grained granite and fine-grained granite or aplite. Tonalite corresponds to the First type by Yamada et al. (1986), a part of the granodiorite to the Second type, and the remaining part of the granodiorite, porphyritic granite, the medium-grained biotite granite and fine-grained to the Third type.

a. Tonalite

Tonalite occurs an elongated body with NE−SW trend in the north of Yoshiwa. It is also found as small bodies which appears to be orientated on a line along the northeastern extension of this body (Fig. 6). They intrude into the Jurassic accretionary complex with high angle boundaries. On the River Ota, is found porphyritic granite intruding into the tonalite with high angle boundaries (Fig. 7).

b. Granodiorite

Granodiorite occurs as an elongated body in NE−SW trend from near Mt.Ichima to near Kajinoki (Fig. 6). Suzuki,T (1986) called this rock “Togouchi granodiorites”, and classified it into granodioritic rock facies and granophyric rock facies. The author has clarified that the granodiorite consists of three lithofacies which are intergradationally changed into each other. The first is fine-grained porphyritic, the second medium-grained porphyritic, the third coarse-grained equigranular.

Except for its southeastern part, the granodiorite intrudes into the rhyolitic rocks. In the sub-area from Uchinashi to Shiwagi, it is in contact with rhyolitic rocks with two different fashions. The one is gently dipping contact surface and the other is steeply dipping contact surface. In the sub-area from Shiwagi to Kajinoki, the granodiorite horizontally overlies the rhyolitic rocks. Detailed description of the contact feature will be presented in the section IIIC.

In its southeastern part, the granodiorite is in contact with medium-grained granite and fine-grained granite with low angle contact surfaces. The exact boundary between the granodiorite and the medium-grained granite is not clearly exposed. The granodiorite near the medium-grained granite is characterized by the occurrence of K-feldspar rich veins, which are inferred to have been derived from the latter, suggesting that the latter intrudes into the granodiorite.

The granodiorite has a vertical lithological change. As mentioned before, it consist of three different lithofacies such as fine-grained, medium-grained and coarse-grained granodiorites. These three types granodiorites have also different types dark inclusions in descending order of structural order (Fig. 6), though, strictly speaking, one lithofacies is not distinctly to develop only in one structural level. Below about 400 meters, in the northwestern slope of Mt. Ichima, is developed the coarse-grained granodiorite, and in a level from about 400 meters to about 850 meters occurs the medium-grained granodiorite, which shows a decrease of grain size as the altitude becomes higher. In the level from about 850 meters to about 1000 meters is found the fine-grained granodiorite. It is occasionally in contact with the rhyolitic rocks. But the fine-grained granite or aplite frequently occurs as thin layered body between the fine-grained granodiorite and the rhyolitic rocks (Fig 8).

Under a level below about 400 meters in Nasu-Shiwagi sub-area, is developed the coarse-grained granodiorite. In a level from about 400 meters to about 600 meters occurs the medium-grained granodiorite. Like the case of Mt.Ichima sub-area its grain size decreases as the altitude becomes higher. In a level from about 600 meters to about 670−680 meters is developed fine-grained granodiorite as a layer of 20 to 30 meters thick. However, in outcrops cannot always be observed ascertained boundaries between the different lithofacies zones.

In the medium-grained granite appears also occasionally a lithological change such as that of the granodiorite. Near roof contact around Mt.Nabe porphyritic texture is distinctly developed.

c. Medium-grained granite

Medium-grained granite is one of the typical constituents of the Hiroshima Granite. It is distributed mainly from Kajinoki to Togouchi-Hongo, in the northern part of the Togouchi area (Fig.6). In the area from Hagiwara to Sakahara, medium-grained granite is found as small bodies aligned in NE−SW trending intruding into the Jurassic accretionary complex. On the river bed of the River Shiwagi, a small exposure of medium-grained granite is found in fine-grained granite.

The distribution of the medium-grained granite extends with a distance of about 10 kilometers and NE−SW trend from the studied area to Kake Town (Fig. 3). Namely, it can be regarded as an elongated body aligned in NE−SW trend. As mentioned before, It is intruded into the granodiorite, and around Mt.Nabe, into the Jurassic accretionary complex with a nearly horizontal contact at a

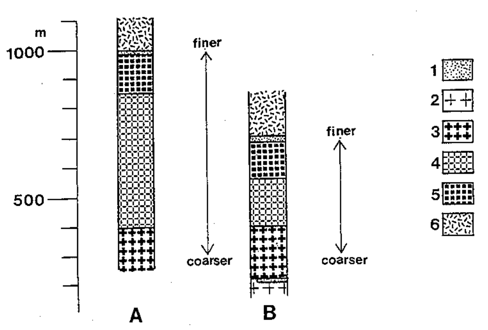

Fig. 8. Schematic diagram illustrating the vertical variation of lithofacies in the granodiorite.
A: Mt.Ichima sub-area, B: Shiwagi-Nasu sub-area.
1:fine-grained granite or aplitic rocks, 2: medium- to coarse-grained granite, 3−5: granodiorite (3; lower lithologic facies, fine-grained porphyritic facies, 4; middle lithologic facies, medium-grained porphyritic or equigranular facies, 5; upper lithologic facies, coarse-grained equigranular facies), 6: rhyolitic rocks.
Numbers (meters) show altitude above sea level.

height of 800 meters, in which a thin layer of fine-grained granite is found on the top of the granite. While, the southern end of the granite in Hagiwara shows a contact to the complex whose plane is steeply dipping to the west (Fig. 7).

d. Porphyritic granite

Porphyritic granite is distributed from Dani to Sakaidani as a narrow body elongated in NE−SW trend. It is intruded into the Jurassic accretionary complex, rhyolitic rocks and tonalite. The contact plane between the tonalite and the Jurassic accretionary complex is generally at high angles. It is running in two different trends, NE−SW trend and NNW−SSE trend. But, in the head of Sakaidani, the contact plane between this rock and the rhyolitic rocks is changed in orientation to be nearly horizontal. (Figs. 6 and 7)

In porphyritic granite near Dani are found small bodies of rhyolitic rocks sporadically aligned in NE−SW trend. Their mode of occurrence suggests that they are xenolith. Judging from such shape characteristics and its relations to the host rocks, the porphyritic granite seems to be a large-scale dike.

e. Fine-grained granite and aplite

Fine-grained granite is exposed in small bodies scattered along the boundary between the granodiorite and the medium-grained granite (Fig. 6). In Tsubutani, it occurs as a comparatively large body elongated in NE−SW trend. As mentioned before, near the top of Mt.Ichima and the Nasu−Shiwagi sub-area, it occurs as a thin body intercalated between the rhyolitic rocks and the granodiorite. Near the top of Mt.Nabe, the fine-grained granite occurs as a thin body intercalated between the medium-grained granite and the Jurassic accretionary complex. In the south of Shiwagi, fine-grained granite and aplite are found on the river bed of the River Shiwagi. In the granodiorite occurring above the river bed are also found many horizontal dikes of fine-grained granite which are 10cm to 1.5m in thickness. These fine-grained granites are comparable with the thin bodies developed along the boundaries between the medium-grained granite and the granodiorite, and between the granodiorite and the rhyolitic rocks mentioned above. The fine-grained granite and aplite are considered to be intruded into both of the granodiorite and medium-grained granite (Fig. 7).

f. Granite porphyry

Granite porphyry occurs as a small body in the north of Seizui. It is intruded into both of the Jurassic accretionary complex and the rhyolitic rocks (Fig. 6).

Summing up the above description, the granitic rocks in the studied area are regarded to have been formed as a series of plutonism of five rock types, tonalite, granodiorite, porphyritic granite, medium-grained granite and fine-grained granite in the order of younging.

C. Geological structure

In the Togouchi area, it has been revealed that granodiorite occurs as a layered body with near flat-lying lithological variation, being intruded by underlying the medium-grained granite. The contact plane between the former and the latter is also near horizontal, suggesting that the medium-grained granite as the most dominant constituent of the Hiroshima Granite underlies with great extent throughout the area (Fig. 7).

Detailed geological mapping reveals that mesoscopic contact relationship between the granodiorite and the rhyolitic rocks is characterized by the repetition of roof contact (flat-lying contact) and wall contact (steeply dipping contact). In this paper, such a contact structure is called the "step structure". Though analogous step structure is also for the medium-grained granite and porphyritic granite, it appears most distinctly for granodiorite.

In the Uchinashi-Kajinoki sub-area, the step structure is well developed. From Uchinashi to Nasu, the granodiorite is in a wall contact with the rhyolitic rocks. The wall is in NE−SW trend. From the south of Uchinashi to the top of Mt.Ichima, the trend of the wall contact changes from NE−SW to NNW−SSE. From Nasu to Shiwagi, the granodiorite shows a roof contact with the rhyolitic rocks at a height of 650 to 700 meters. Strictly speaking, the contact plane is not horizontal but dips very gently toward NE. In the northwestern end of the roof contact, it changes into the wall contact, whose plane is developed in NE−SW trend. This wall contact is regarded to be continued to that found at Shiwagi. Near the top of Mt.Ichima there is a roof contact, which continues to the wall contact extending from near Tabuki (Figs. 7 and 8). Therefore, It can be said that the boundary structure of the granodiorite in the studied area is characterized by the large-scale step structure going down to the northwest as the repetition of pairs of roof contact and wall contact.

Although most of contact planes between the granodiorite and the rhyolitic rocks are irregular in outcrops even for the wall contact, these appear to be commonly sharp zig-zag boundary. Therefore, the contact planes appear to be controlled by planes of fracturing of wall rocks.

Though the porphyritic granite is dominantly in steep wall contact with the Jurassic accretionary complex, which is in NE−SW trend and NW−SE trend, the top of its body at Sakaidani is in a nearly horizontal roof contact with the rhyolitic rocks. The medium-grained granite also shows the steep wall contact and nearly horizontal roof contact with country rocks, suggesting that its emplacement mechanism is essentially the same as that of the granodiorite.

In the sub-area from Shiwagi to Kajinoki, the granodiorite overlies on the rhyolitic rocks. The grain size of the granodiorite becomes not only finer toward the contact with the rhyolitic rocks, but also toward the upper part of the body (Fig. 7, d−d'profile). The exposure at Kajinoki contains a distinct contact surface between the fine-grained granodiorite and rhyolitic rocks. Judging from these facts, it can be regarded that the granodiorite occurs as a horizontal tabular body intruding the rhyolitic rocks. Because this sub-area is situated in the northern margin of the granodiorite, and also in the northern margin of the Hiroshima Granite, it can be said that the above described modes of occurrence of the granodiorite and others is the clearest evidence available to understand the marginal shape of the Hiroshima Granite, and to clarify the essential features of the intrusion mechanism of the Hiroshima Granite.

IV. Petrography of Igneous Rocks in the Togouchi Area

Petrographical features of main igneous rocks in the Togouchi area are described and discussed in this chapter.

A. Rhyolitic rocks

The rhyolitic rocks in the Togouchi area are almost massive and homogeneous, showing only weak sign for flow and bedded structures. There matrices are gray or dark gray in color. Phenocryst is mainly composed of euhedral or subhedral quartz, plagioclase, K-feldspar, biotite and/or green hornblende whose grain sizes are from 0.5 millimeters to several millimeters. Allanite, zircon and apatite occur in accessory amounts. Rock fragments can rarely be found.

The rocks close to granodiorite show thermal metamorphic feature as follows. Fine-grained recrystallized biotite frequently occurs not only in a matrix but also replacing phenocryst of biotite and hornblende. Phenocrystic hornblende is completely or partially replaced by aggregate of fine-grained biotite and actinolite. Recrystallized quartz and feldspars whose grain size is about 0.02

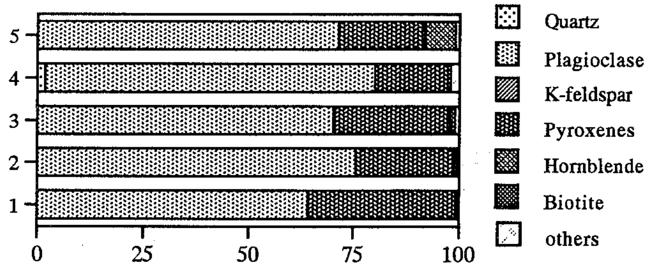

Fig. 9. Modal variation of constituent minerals in the tonalite.

millimeters are found in phenocrysts of feldspars. In such thermally metamorphosed rocks the matrix is changed to holocrystalline texture in which quartzo-feldspathic minerals of about 0.02 millimeters partly appear showing a granoblastic texture. In some cases, matrix-forming minerals become coarse-grained up to 0.1 millimeters in diameter. Moreover andalusite is sometimes crystallized. It has been found in specimens obtained from near the top of Mt.Ichima and a river bed of the River Ota near the west of Uchinashi. On the western slope of Mt.Ichima, garnet has also been found as one of thermally metamorphic minerals (Suzuki,M., Hayashi and Yoshimura, 1992).

Many rhyolitic dikes are observed in the Jurassic accretionary complex on the eastern slope of Mt.Ichima, and their phenocrysts and matrix-forming minerals are rather fine-grained in size.

B. Plutonic rocks

1. Tonalite

The size of the constituent minerals of the tonalite body is rather small, and its lithofacies varies in wide range. The rock is massive and dark greenish gray in color, and shows more or less porphyritic texture. Foliation and linear structure cannot be observed in outcrops. In the marginal zone of the body, close to the Jurassic accretionary complex, there is finer-grained facies whose grain size are finer than 0.5 millimeters. In the central part of the body, there is medium-grained facies whose grain size is from 1 millimeters to 3 millimeters in diameter and additionally, gabbroic pegmatite pools, whose grain sizes reach to 3 centimeters in length, are sometimes found. Average content ratio of colored minerals is about 30 percent throughout the body (Fig. 9). The tonalite is mainly composed of plagioclase, green hornblende, biotite, clinopyroxene and orthopyroxene, regardless of lithofacies. Quartz rarely occurs in small amount, and apatite, zircon and Fe-Ti oxide occur in accessory amounts.

Orthopyroxene and clinopyroxene are frequently enclosed in hornblende, and are partially converted into uralite. Hornblende is replaced by the aggregate consisted chiefly of actinolite, chlorite and epidote. Furthermore, biotite is partially replaced further by chlorite. Plagioclase occurs in two different forms. One occurs as subhedral or anhedral crystal with polysynthetic twin. It has rather weak zonal structure. Another is comparatively large crystal which occurs in the form of euhedral or subhedral phenocryst showing distinct zonal structure. Its grain size ranges from 2 millimeters to 3 millimeters. Quartz appears as a interstitial crystal (PlateI-1). The conversion phenomena found mainly in hornblende and pyroxenes are regarded to be caused by the intrusion of the porphyritic granite mentioned later.

Kojima (1964) pointed out that mafic plutonic rocks accompanied with the Hiroshima Granite are closely related with the felsic activity. According to his opinion, the present body is regarded as such the case. The tonalite may be cognate with dark inclusion in the granodiorite as will be shown later.

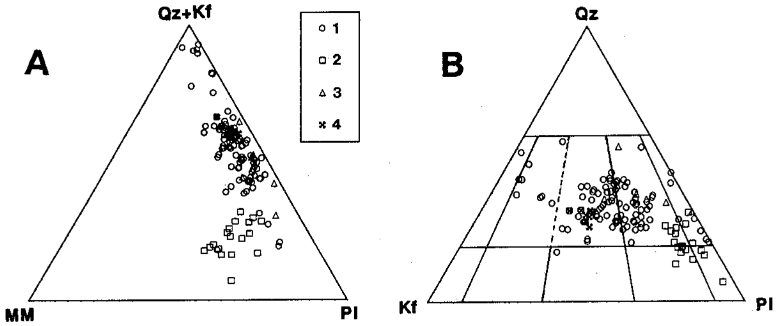

Fig. 10. Modal Qz+Kf−MM−Pl (A) and Qz−Kf−Pl (B) diagrams for granitic rocks in the Togouchi area.
Qz: quartz, Kf:K-feldspar, Pl:plagioclase, MM:mafic minerals
1: granodiorite, 2: dark inclusion, 3:porphyritic granite, 4:medium-grained granite.

2. Granodiorite and its associated dark inclusion

a. Granodiorite

Yoshino and Hayashi (1989) classified the granodiorite into six types based upon the petrographical characteristics. It seems for the author to be more available to classify the rock into three lithofacies types as follows.

The granodiorite is generally massive and glomeroporphyritic. Its mafic minerals are commonly found as mineral clusters whose grain sizes are from about 3 millimeters to 6 millimeters. The granodiorite contains a lot of dark inclusions, but any other rock fragment except for dark inclusions is not found.

Constituent minerals are mainly plagioclase, quartz, K-feldspar, hornblende and biotite. Allanite, zircon, apatite, sphene and Fe-Ti oxide occur in accessory amounts. Secondary minerals are actinolite, chlorite, epidote and some biotite. Modal Qz+Kf−MM−Pl and modal Qz−Kf−Pl are shown in Fig. 10. Modal analysis has been done by a common method using thin sections as well as by the image processing method using rock slabs, which has been proposed by Hayashi and Suzuki (1990). Color index are commonly about 10, but in some specimens the index reaches to about 20. Many specimens are dotted in "granodiorite" and "quartz-adamellite" region, and some other specimens in "granite" and "monzonite" regions.

Plagioclase occurs in two forms. One occurs all over the rock as subhedral or anhedral crystal with polysynthetic twin. It has rather weak zonal structure. Another is fairly large crystal which occurs in the form of euhedral or subhedral phenocryst, whose grain size ranges from 1 millimeters to 5 millimeters. It has distinct zonal structure in which the composition varies from andesine in the core to oligoclase in the rim. Their detailed chemical data will be presented in the Chapter V.

Myrmekite is commonly found in quite small amount. In general, K-feldspar is almost anhedral perthite, and it appears often as an intergrowth with quartz forming micrographic texture. Small anhedral K-feldspar grains are also sometimes found along cleavage of large plagioclase grains. Quartz generally occurs as anhedral crystal. But coarse-grained anhedral quartz occurs often forming intergrowth with K-feldspar. Hornblende is almost green in color. In some specimens, the rim is replaced by biotite. Cummingtonite is rarely found replacing orthopyroxene.

As mentioned in Chapter III, the granodiorite shows remarkable lithological variation. Generally speaking, the lithofacies varies from fairly coarser-grained equigranular to finer-grained porphyritic texture. Therefore six rock types classified by Yoshino and Hayashi (1989) are grouped into the following three lithofacies types, based mainly upon the grain size and texture as well as the mineral composition. These types of lithofacies are developed in the granodiorite body, forming "stratigraphical" horizons each of which is namely flat-lying, and so named the lower, middle and upper lithofacies respectively. The lithofacies changes from the coarse-grained equigranular one in the lower horizon, through medium-grained porphyritic one in the middle horizon, to the fine-grained porphyritic one in the upper horizon. It is noticeable that these three lithofacies occupy the different levels in the body. Mineral compositions of the lower, middle and upper lithofacies are similar to each other.

The lower lithofacies:

Texture of the lower lithofacies of the granodiorite is closely similar to the general type granite, though it is more or less porphyritic (Plate I-2) and coarse-grained micrographic texture is frequently developed in this type (Plate I-3). Average grain size is 2 to 4 millimeters. As mentioned above, it is notable that small anhedral K-feldspar is sometimes scattered as a pockmark crystal along cleavages in large plagioclase grains (Plate I-4). Occasionally it is developed cutting across the grain boundary of plagioclase. It seems likely that such the K-feldspar was produced by permeation of potassium along the cleavage of plagioclase which was opened by deformation. Near the bottom part of the lower lithofacies which is placed closely to the medium-grained granite, the granodiorite is intruded by a lot of flaky veins of pink K-feldspar. These veins are ascribed to micro-fracturing of the lower lithofacies.

The middle lithofacies:

The middle lithofacies rocks are characterized by the porphyritic texture (Plate I-5). Grain size of phenocryst minerals is 1 to 5 millimeters in diameter, and of matrix-forming minerals is 0.02 millimeters to 0.2 millimeters. The former appears to show occasionally rounded shape. The matrix ranges from 40% to 60% in volume. Fine-grained micrographic texture is frequently found in matrix (Plate I-6). The middle lithofacies is the main constituent in the granodiorite body.

The upper lithofacies:

The upper lithofacies rocks have a distinct porphyritic texture (Plate I-7). Phenocrysts of 2 to 4 millimeters are found in their matrix consisting of mineral grains of 0.05 to 2 millimeters. These phenocrysts occur generally in rounded shape. The grain size of matrix-forming minerals is finer than that in the middle lithofacies. Fine-grained micrographic texture frequently appears in the matrix. A few amount of K-feldspar is rarely found in interstitial fashion, as seen in the rock of chilled margin (Plate I-8). In this lithofacies, such rocks as diorite porphyry are also sometimes found especially close to the dark inclusion.

b. Dark inclusion

Dark inclusion is commonly accompanied with the granodiorite, and sometimes with the porphyritic granite and medium-grained granite. It is commonly irregular in shape, varying in size (length of long axis) from few millimeters to several meters. Small-sized fragments of dark inclusion are often scattered around large ones. Dark inclusion tends to occur with concentration in flat-lying zones in the central and marginal parts of the granodiorite body. For instance, it is found as a wide zone in the level of higher than 600 meters on the northwestern slope of Mt.Ichima, and as a narrow zone lying horizontally at a height of 550 meters in near Shiwagi. In the body near Togouchi, however, dark inclusion is scarcely found.

Constituent minerals of dark inclusions are mainly plagioclase, green hornblende and biotite.

Sphene, apatite, allanite, zircon and Fe-Ti oxide are in an accessory amounts. Quartz and K-feldspar are occasionally accompanied. Actinolite, chlorite and biotite are found as secondary minerals. Both plagioclase and hornblende are classified into two populations with reference to grain size; one is fine-grained ranging from 0.2 to 0.5 millimeters in length, and the other is coarse-grained with about 1 millimeters in length. Generally, plagioclase of both types appears as tabular crystal, showing zonal structure of which cores consist of andesine, and rims of oligoclase. In the dark inclusion, occasionally appears plagioclase ranging from 1 millimeters to 4 millimeters in a length. Such the plagioclase has also distinct zonal structure, and is very similar to that of the host granodiorite in grain size and compositional range. Biotite with length larger than 3 centimeters is sometimes found in needle-like shape.

The lithofacies of dark inclusion appears to change in response to surrounding to the three lithofacies of the granodiorite body. Namely, it is roughly classified into three types of lithofacies, lower type, middle type and upper type. The upper lithofacies, the middle lithofacies and the lower lithofacies of granodiorite shows a tendency to be accompanied with the upper type, the middle type and the lower type of dark inclusion. These three types of dark inclusion are described in detail in the following section. Roughly speaking, from the lower to upper types via the middle type, the rock changes from angular to rounded in shape, and from coarser-grained heterogeneous to finer-grained homogeneous in texture.

The lower type:

The boundary between the dark inclusion and the host granodiorite is not distinct but rather intergradational. Rocks, which seem to be comparable with granodiorite but are highly richer in mafic minerals than it, are found with obscure outlines (Plate II-1). Such rocks are also referred to the one type of dark inclusion.

The lower type is constituted by two components, which are distinguished from each other with reference to grain size; one consists of minerals of finer than 0.5 millimeters, and another of coarse-grained minerals which range from 0.5 millimeters to 1 millimeters. The latter component frequently sporadically occurs in the former. Phenocryst-like plagioclase often appears. Quartz and K-feldspars are often found in interstitial fashion forming intergrowth with each other (Plate II-2). Dioritic to granodioritic veins and pools frequently appear with various scales in this type of dark inclusion. The constituent minerals of such the rocks are comparable in size with these of the host granodiorite. Pools are often linked with each other by veins. The formation of the veins and pools is ascribed to fracturing of dark inclusion.

The middle type:

The middle type is the dominant one of dark inclusion and occurs in the middle lithofacies of granodiorite body. It is compact and massive with a few patches consisted of coarse-grained minerals. The type dark inclusion is more melanoclatic than the lower type one. It tends to be rounded in shape. The boundaries between the middle type rocks and the host granodiorite are distinct, as observed along them, the mineral grains of the latter are incorporated with former (Plate II-3). As seen in the lower type, the pools and veins cutting across dark inclusion are developed, but their petrographical characteristics seem to be more dioritic than that of the lower type dark inclusion. Furthermore these pools and veins tend to be smaller in size than those in the lower type and also the con stituent minerals of the former finer than in size than those of the latter (Plate II-4).

In the middle type there are occasionally leucocratic spheres whose size ranges from 5 millimeters to 3 centimeter in diameter (Plate II-5). They are composed mainly of quartz, K-feldspar and hornblende (Plate II-6), accompanied with plagioclase, biotite, epidote and sphene in accessory amounts. Their grain size ranges from 1 millimeter to 4 millimeters in length. Constituent minerals in the spheres do not enclave any mineral from host dark inclusion.

The upper type:

The upper type dark inclusion has square-like or angular shape. The boundaries between the dark inclusion and the host granodiorite are fairly distinct and sharp. Occasionally, quartzo-feldspathic veins are intruded into the dark inclusion. The upper type dark inclusion is finer and more melanoclatic than the middle type (Plates II-7 and II-8). It is compact and homogeneous. It is unique in containing clinopyroxene as main constituents. Clinopyroxene rims are replaced by green hornblende. Such dark inclusion can be sometimes found on the northwestern slope of Mt.Ichima.

It can be said that the dark inclusion is originally fine-grained dioritic rock. In order to compare the above-described types of dark inclusion with the host granodiorite, Qz+Kf−MM−Pl and Qz−Kf−Pl modal composition diagrams for them are shown in Fig. 10. Color index ranges from 10 to 35. Almost all specimens are plotted around the quadripartitive intersection point among the "tonalite", "granodiorite", "quartz-monzonite" and "quartz-diorite" regions.

Modal volumes of quartz and K-feldspar in dark inclusion vary, though they are generally poor, showing their regular decreasing from the lower to the upper type. The inclusions seem to preserve more their original feature and shape. As a result, it is supposed that granitic materials are supplied to the dark inclusion from the granodiorite. The amount of materials seems to decrease from the lower to upper types via the middle type.

The lithological change of dark inclusion is characterized by the formation of phenocryst-like plagioclase in the lower type, the disappearance of clinopyroxene in the lower−middle type and the decreasing of modal volume of quartz and K-feldspar from the lower type to upper type accompanying coarsening of constituent minerals. It would be regarded as the granitization process of dark inclusion the result of contamination with the host granodiorite body. The degree of contamination increased toward the lower level of the host body. As mentioned before, because the granodiorite is affected by the underlying medium-grained granite, the contamination effects for the dark inclusion may be partly ascribed to the medium-grained granite. The shapes of dark inclusion and associated quartzo-feldspathic veins and pools indicate that the granitization process occurred together with fracturing of dark inclusion rocks. Such a phenomenon suggest that the emplacement of the granodiorite has occurred accompanied with fracturing of its host rocks.

3. Porphyritic granite

The granite body in Dani area has generally been described as a member of the Hiroshima Granite in the Geological map of Hiroshima Pref. (1963). Detailed field and petrographical studies by the author reveal that this body is composed mainly of porphyritic granite, being associated by small amount of medium-grained granite, granodiorite and rhyolitic rocks.

Porphyritic granite is mainly composed of quartz, plagioclase, K-feldspar, biotite and hornblende. Allanite, zircon and Fe-Ti oxide occur in accessory amount. As phenocrystic minerals, quartz and plagioclase are predominant.

Plagioclase of phenocryst is euhedral or subhedral and has zonal structure. K-feldspar is almost anhedral and has perthite structure, rarely showing microcline grill. K-feldspar sometimes occurs in intergrowth with quartz. Quartz shows two modes of occurrence: One is subhedral grain as phenocryst, and another is anhedral grain in matrix, sometimes showing interstitial texture.

Porphyritic granite shows lithofacies variation based on the degree of development of porphyritic texture. It is classified broadly into the following two types: In the one (P-type) distinct porphyritic texture is observed by naked eyes (Plates III-1 and III-2), and in the other (E-type) it is observed only under microscope, though it seems equigranular by naked eyes (Plates III-3 and III-4). In porphyritic granite body is prevailed the E-type. Both types occasionally occur together in an outcrop. In the P-type, grain size of matrix forming minerals less than 0.01 millimeters, and that of phenocryst is from 0.5 millimeters to 4 millimeters. The P-type granite is found in some place of the upper part of Sakaidani gorge and in contact with the rhyolitic rocks. The boundary between them is difficult to determine exactly its position in outcrops as the matrix of the granite is as fine as the rhyolitic rocks.

In the E-type grain size of matrix-forming minerals is from 0.1 to 2 millimeters, and that of phenocryst is from 1 to 4 millimeters. Modal Qz+Kf−MM−Pl and modal Qz−Kf−Pl components are shown in Fig. 10. Almost all specimens are plotted in the "granodiorite" region.

Medium-grained granite are mainly found as small blocks-like bodies in the core part of the porphyritic granite body. The boundaries between the medium-grained granite and the host porphyritic granite are not always observed clearly and may be intergradational. It is not clear whether the medium-grained granite predated or postdated the porphyritic granite. Granodiorite is also found as small block-like bodies enclosed by the porphyritic granite, especially in its marginal part.

The porphyritic granite locally contains a small amount of dark inclusion, for instance, at the river bed of the River Ota in Dani. The mode of occurrence of dark inclusion is similar to that in the granodiorite mentioned above. The porphyritic granite contains no rock fragment except for the dark inclusion. The above-described occurrences and lithological features of the porphyritic granite may be ascribed to rapid cooling of magma.

4. Medium-grained granite

The medium-grained granite is characterized by bearing pink K-feldspar. This type has been considered to belong to main constituent of the "Hiroshima Granite batholith". Component minerals are mainly quartz, plagioclase, K-feldspar and biotite. Modal Qz+Kf−MM−Pl and modal Qz−Kf−Pl components are shown in Fig. 10. All examined specimens are plotted in the "adamellite" region. Hornblende occurs in accessory amount. Most of these minerals are generally anhedral.

The Medium-grained granite is almost massive and poor in lithological change. But, in the zone of roof contact in Mt.Ichima area, its lithofacies changes from medium-grained equigranular type to fine-grained type with phenocrysts. It contains dark inclusion in a small amount. The dark inclusion is scarcely granitized.

In the north of Tsubutani there is medium-grained granitic rock rich in mafic minerals. The rock can be regarded as a member of the granodiorite mentioned above. But it has not porphyritic texture, and is rich in pink K-feldspar.

5. Fine-grained granite and aplite

The fine-grained granite has equigranular texture. Its average grain size is from 0.02 to 2 millimeters and its mineral component is almost similar to that of the medium-grained granite mentioned above. Occasionally, it contains large quartzo-feldspathic phenocrysts whose size ranges from 2 millimeters to 5 millimeters. This type rock frequently changes to aplite which is rich in pink K-feldspar and contains little amount of mafic minerals. The aplite is often associated with pegmatite pools.

V. Mineralogy of Igneous Rocks in the Togouchi Area

A. Chemical characteristics of main constituent minerals

Granitic rocks and rhyolitic rocks in the studied area are composed of minerals such as quartz, K-feldspar, plagioclase, biotite and Fe-Ti oxides with or without amphiboles and pyroxenes (orthopyroxene and clinopyroxene). In this chapter, the chemical characteristics of these mineral will be described, in order to clarify genetical relationship among the granitic rocks as well as to discuss crystallization conditions of some of them.

Their chemical analysis has been performed by means of JEOL electron microprobe analyzer (JCMA−II) in the department of Earth and Planetary System Science, Faculty of Science, Hiroshima University. In this chapter, the medium-grained granite is called "granite".

All of chemical composition data analyzed in this study are deposited in Earth Science Laboratory, Faculty of School Education, Hiroshima University. Every person can refer to the author in the Laboratory for those data.

1. Pyroxenes

Pyroxenes are present in the tonalite and dark inclusion in the granodiorite. The tonalite contains both orthopyroxene and clinopyroxene. Commonly, they are partially or almost perfectly altered into the aggregate of actinolite or mica minerals. Othopyroxene is sometimes altered into cummintonite. In dark inclusion there is only clinopyroxene in very minor amount.

a. Orthopyroxene

The chemical compositions of orthopyroxene are plotted in En−Fs−Wo diagram (Fig. 11). They contain about 4% of Wo content and En content ranging from 55% to 74%. All of them are regarded as hypersthene. Al_2O_3 content ranges from 0.6 to 2.4 Wt%. Generally speaking, orthopyroxenes show a chemical zoning in which En and Al_2O_3 contents decrease from the core to the rim.

b. Clinopyroxene

The chemical compositions of clinopyroxenes are plotted also in En−Fs−Wo diagram (Fig. 11). They contain Fs content ranging from 55% to 74% and Wo content ranging from 32% to 45%. They are commonly augite and sometimes ferro-augite. Their chemical characteristics show no systematic change: e.g., in one grain, En content tends to increase from the core to the rim, but in the other grain, En content changes in reciprocal manner.

2. Amphiboles

Amphiboles analyzed here can be grouped into such two types as calcium-poor amphiboles (iron-magnesium-manganese amphiboles) and calcic amphiboles after the criteria by Leake (1978). The former type has rarely been found only in the granodiorite and its dark inclusion, but the latter type has been commonly found in all rock types except for aplite. Amphiboles of these two types are often partially replaced by actinolite.

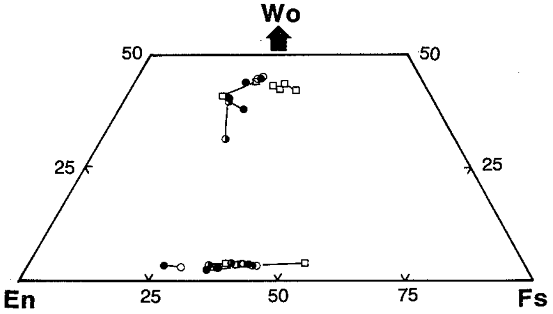

Fig. 11. En−Fs−Wo diagram for pyroxenes from the tonalite.
open circle: data for rim, solid circle: data for core, half solid circle: data for mantle, square: data for non-zoned grain.

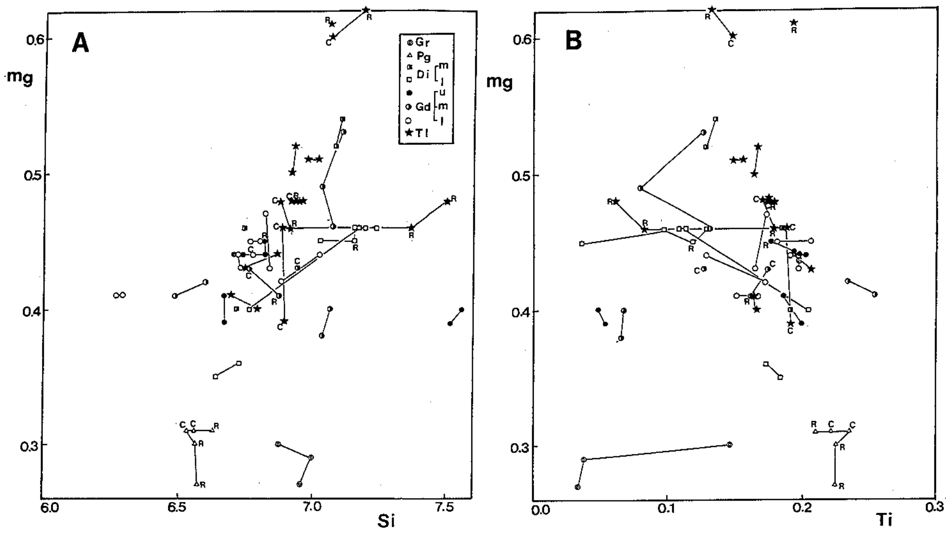

Fig. 12. mg−Si (A) and mg−Ti (B) diagrams for calcic amphiboles.
Gr: granite, Pg: porphyritic granite, Di: dark inclusion, Gd: granodiorite, Tl: tonalite. "u", "m" and "l" in the Gd and the Di show the upper, middle and lower litholofacies of the granodiorite respectively (See text).
C: core, R:rim.

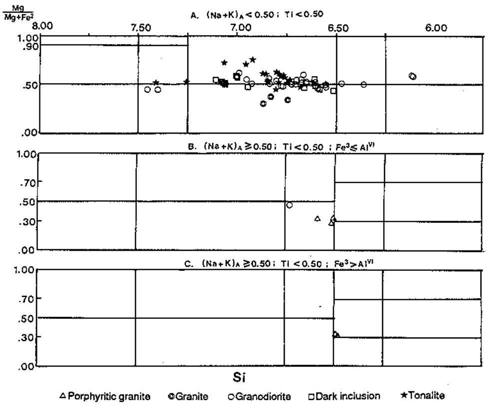

Fig. 13. Plots of calcic amphiboles on Leake's (1978) diagram.

a. Calcium poor amphiboles

This type amphiboles are "cummingtonite" after the criteria by Leake (op. cit.), whose Mg^{+2} content ranges from 0.3 to 0.4. They are plotted in Mg-poor part of cummingtonite region. Each cummingtonite grains appear as relic minerals enclosed by actinolite aggregate. They may be regarded as secondary minerals, probably derived from orthopyroxenes.

b. Calcic amphiboles

This type amphiboles show wide chemical variation in each rock type. The amphiboles the in tonalite tend to be richer in Mg than those in the other rock types. As shown in Fig. 12, the proportion of Mg/(Mg+Fe), called "mg value" hereafter, of them ranges from 0.40 to 0.62. In the dark inclusion, the amphiboles also tend to be relatively rich in Mg, and mg values range from 0.35 to 0.54. In the granodiorite, all amphiboles except for only one data are somewhat poor in Mg with mg value ranging from 0.32 to 0.49. The granite and porphyritic granite contain amphiboles with rather lower mg value ranging from 0.27 to 0.31. As seen in Fig. 12, both Ti and Si contents of amphiboles are not appreciably variable in each rock type. However, they show wider range in the granodiorite than in the other rock types, showing that Ti and Si values range from 0.03 to 0.25 and from 6.26 to 7.55

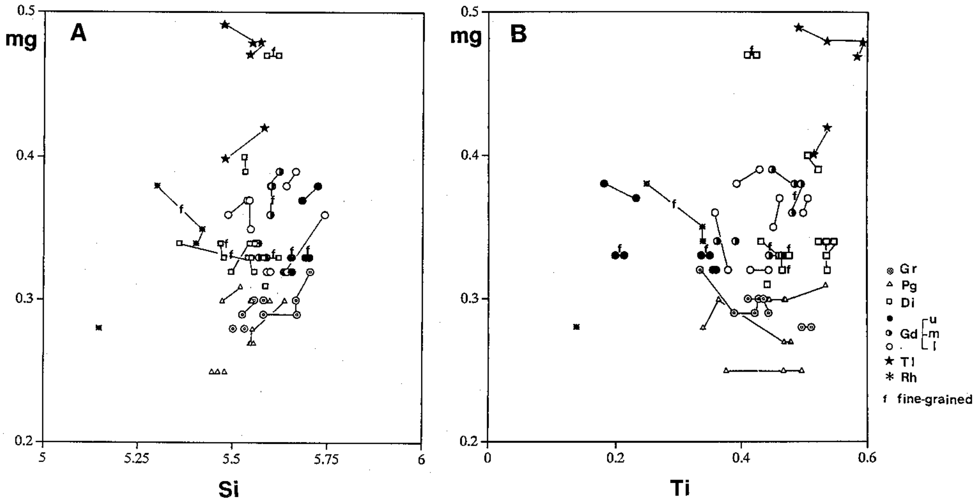

Fig. 14. mg—Si (A) and mg—Ti (B) diagrams for biotite.
Rh: rhyolitic rocks. Other abbreviations see Fig. 12.

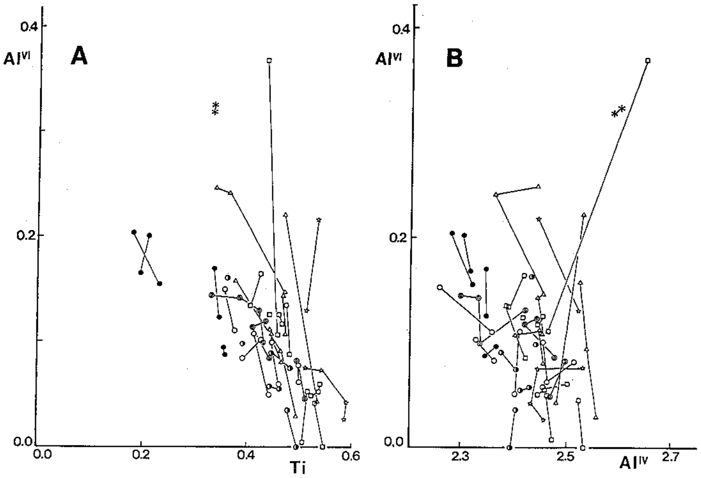

Fig. 15. Al^{VI}—Ti (A) and Ai^{VI}—Al^{IV} (B) diagrams for biotite.
For sumbols see Figs. 12 and 14.

respectively. Amphiboles in every rock types commonly show such a crystallization trend that Ti content increases and Si content decreases with decrease of Mg content. Almost all of analyzed amphibole grains show distinct chemical zoning (Figs. 12). All grains in the granite and one grain of the tonalite show wide variation in both Ti content and Si content. One amphibole grain in the dark inclusion shows also wide variation in Ti content. The growth history for some amphibole grains is opposite from the crystallization trend mentioned above.

As mentioned in the Chapters III and IV, the granodiorite shows three lithofacies with different types of dark inclusion, but the chemical composition of amphiboles is not severely different among the three types lithofacies of the granodiorite and dark inclusion.

All calcic amphiboles analyzed here are plotted in Leake's diagram (Fig. 13). Among them, magnesio-hornblende is most predominant and ferro-hornblende is subdominant throughout the whole rock types. Others are actinolitic hornblende, ferro-actinolitic hornblende, ferro-edenitic hornblende, magnesian hastingsitic hornblende, tschermakitic hornblende and tschermakite.

3. Biotites

Biotites are commonly present in all rock types in the studied area. The chemical characteristics of biotite are different among rock types. In the tonalite, biotites are rich in Mg with mg value ranging from 0.40 to 0.49 (Fig. 14). In dark inclusion, biotites are also fairly rich in Mg with mg value widely ranging from 0.31 to 0.47, the value being involved in the mg value range of the granodiorite and the tonalite. In the granodiorite, biotite is rather poor in Mg, and its mg value is in a narrower range of 0.32 to 0.39. In the granite, biotite is poorer in Mg with mg value ranging from 0.25 to 0.32.

Si content of biotite is not significantly different among all types of granitic rocks (Fig. 14-A), but Ti content of biotite seems to be different among them (Fig. 14-B). The latter is richer ranging from 0.43 to 0.58 than in the tonalite and dark inclusion than in the other rock types. For many biotite flakes of all types of granitic rocks, Ti content increases with increase of mg value, but for some biotite flakes it shows a reciprocal manner. Al^{VI} content in biotite decreases commonly with increase of Ti content (Fig. 15-A). Except for two biotite flakes of dark inclusion and the granite, Al^{VI} content of biotite tends to decrease with increase of Al^{IV} content (Fig. 15-B).

The chemical zonation of biotite is generally weak, but some biotite flakes in the porphyritic granite and the rhyolite show distinct chemical zoning in Ti content.

In the granodiorite and associated dark inclusion, biotite flakes from three lithofacies have not appreciably different chemical characteristics from each other (Figs. 14 and 15). Biotite flakes are microscopically grouped into two populations, coarse-grained type and fine-grained type. The latter was produced by recrystallization of the former, but the chemical composition is not different from each other.

4. Iron-titanium oxides

Fe-Ti oxides are present in almost all type of granitic rocks and rhyolitic rocks. They are classified into ilmenite and magnetite. The former is found in all rock types, but the latter has been found only in the granodiorite and its associated dark inclusion. Fe_2O_3 content in ilmenite is commonly less than 5 mol% but it sometimes reaches to 10 mol% in the tonalite. Magnetite commonly has ulvospinel content of less than 6 mol%. In the granodiorite, however, this content continuously varies from 4 mol% to 15 mol%. In the $FeTiO_3-MnTiO_3-Fe_2O_3$ system (Fig. 16), ilmenite in the tonalite contains $FeTiO_3$ of more than 95%. In ilmenite in the other rock types, $FeTiO_3$ content ranges from 83% to 94%. Ilmenite in the granitic rocks of the studied area commonly contains a little amount of Fe_2O_3. In the granodiorite and its associated dark inclusion there are Fe-Ti oxides rich in Fe_2O_3. Ilmenite in all types of granitic rocks of the studied area is plotted in the compositional range for that in igneous rocks of the San-yo zone which has been clarified by Imaoka (1985).

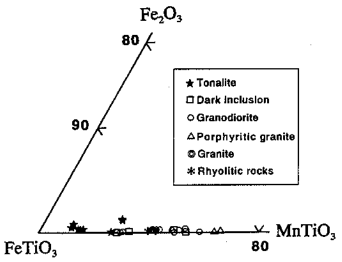

Fig. 16. $FeTiO_3-MnTiO_3-Fe_2O_3$ diagram for ilmenite.

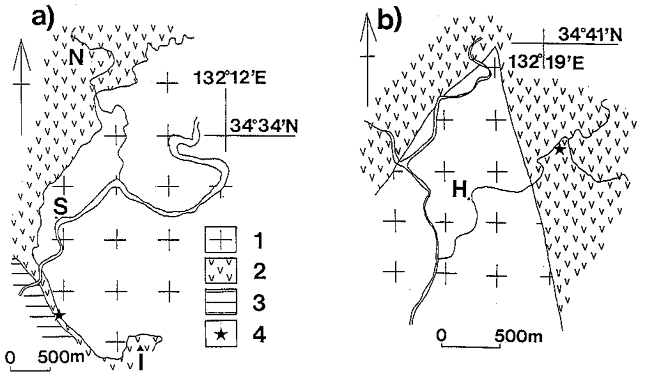

Fig. 17. Geological maps of the Sakane sub-area in the Togouchi area (a) and the Hinokidani area (b) and garnet localities.
1: granitic rocks, 2: rhyolitic rocks, 3: pre-Cretaceous formations, 4: garnet locality, H: Hinokidani, I: Mt.Ichima, N: Nasu, S: Sakane.

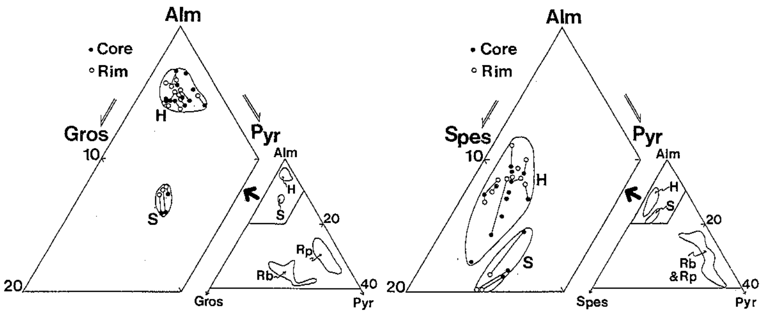

Fig. 18. Garnet from the Takada rhyolitic rocks and Pre-Ryoke or Paleo-Ryoke metamorphites.
(after Hayama, 1987, 1991)
Alm: almandine, Gros: grossular, Pyr: pyrope, H: Hinokidani area, S: Sakane sub-area, RP: metapelites from pre-Ryoke or Paleo-Ryoke land fragments, RB: metabasites from pre-Ryoke or Paleo-Ryoke land fragments.
open circle: rim, solid circle: core.

5. Garnet

Garnet has not yet been found in the Takada rhyolitic rocks. In this study, garnet has been newly found in rhyolitic rocks in the Sakane sub-area of the Togouchi area. On the other hand, garnet is also found in the rhyolitic rocks distributed in the Hinokidani area (Fig 17). The chemical compositions of garnets from the Sakane sub-area and Hinokidani area are plotted in Fig. 18. They are almandinous with the range of Xalm from 0.750 to 0.790. The mole fractions of pyrope and grossular are in the range of 0.042−0.053 and 0.059−0.072 respectively. Xspes ranges from 0.095 to 0.145. The core part tends to be more abundant in Mg and Ca, and poorer in Mn than the rims. Garnets from Sakane sub-area are regarded to formed by contact metamorphism of the granodiorite, while those from Hinokidani area are phenocrysts crystallized directly from felsic magma (Suzuki,M., Hayashi and Yoshimura, 1992).

6. Plagioclase

The chemical composition of plagioclase was analyzed on positions such as core, mantle and rim.

As mentioned in the Chapter IV, plagioclase in the tonalite, granodiorite, dark inclusion and porphyritic granite can be grouped into two populations with reference to grain size: The one is fine-grained forming ground mass, and the other is coarse-grained forming phenocrysts.

All grains of plagioclase show more or less chemical zoning. The characteristics of the chemical

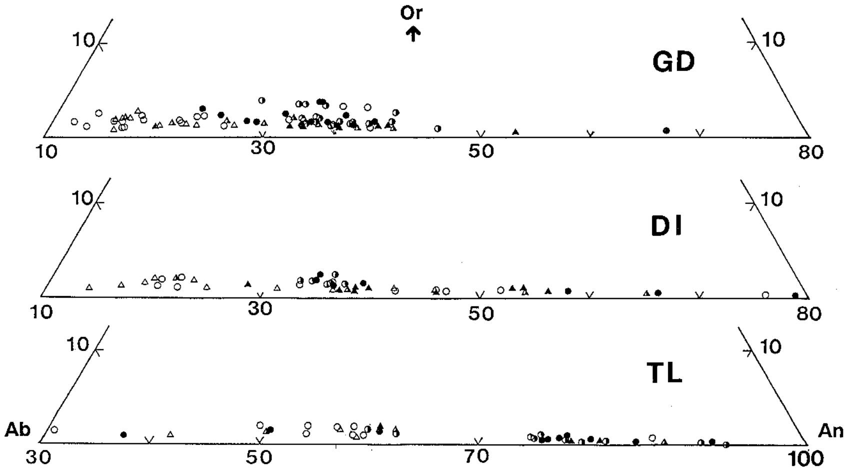

Fig. 19. Ab—An—Or diagram for plagioclase from the tonalite (TL), dark inclusion (DI) and granodiorite (GD). circle: coarse-grained, triangle: fine-grained, solid: core, half solid: mantle, open: rim.

zoning for plagioclase in all types of granitic rocks will be described in detail.

The chemical composition of plagioclase cores is especially different among the rock types. Coarse-grained plagioclase in the tonalite is richest in Ca with An content ranging from 37% to 91% in cores, ranging from 50% to 92% in mantles and ranging from 31% to 77% in rims (Fig. 19). An content for rims except for one data is less than 60%. That for cores is frequently more than 76%. Plagioclase in the tonalite shows that Or content increases continuously to 10% with decreasing of An content. With regard to chemical composition, fine-grained plagioclase is not appreciably different from coarse-grained one.

In the dark inclusion, plagioclase varies widely in chemical composition (Fig. 19). An content for cores ranges from 28% to 78%, showing bimodal concentration of 34% to 40% and higher than 50%. An content for rims ranges from 15% to 76% with a marked maximum between 15% and 25%. An content for mantles is plotted within the compositional range for the cores. Though plagioclase is not significantly different in chemical feature among three types lithofacies (Fig. 20), if forced to say, core composition is rather An-rich in the upper and middle lithofacies than in the lower lithofacies. Rims of the coarse-grained plagioclase are richer in An content than those of fine-grained plagioclase.

In the granodiorite, An content of plagioclase widely ranges from 12% to 88%, and contains Or content of less than 5% (Fig. 19). An content for cores ranges mainly from 25% to 61%. Range of An content for mantles is similar to that for the cores. Rims are poor in An content, ranging from 12% to 28%. Though plagioclase is not significantly different in chemical feature among three types lithofacies (Fig. 21), if forced to say, core composition of plagioclase from the middle lithofacies widely varies. The fine-grained plagioclase is not appreciably different in chemical feature from the coarse-grained plagioclase.

In the porphyritic granite, plagioclase is poor in An content, ranging from 17% to 48% (Fig. 22). It contains Or content of less than 5%. An content for rims ranges from 17% to 22%, and that for cores ranges from 23% to 48%. The range for mantles is similar to that for the cores. The fine-grained plagioclase is not appreciably different in chemical feature from the coarse-grained plagioclase.

Plagioclase in the granite is also poor in An content (Fig. 22). The chemical feature of plagioclase is similar to that in the porphyritic granite mentioned above. Plagioclase in the aplite is extremely

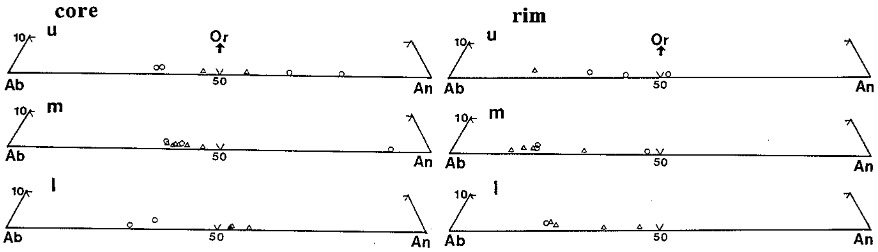

Fig. 20. Ab–An–Or diagram for cores and rims of plagioclase from various lithofacies in the dark inclusion.
"u", "m" and "l" show the upper, middle and lower lithofacies of the granodiorite in which the dark inclusion are included. circle: coarse-grained, triangle: fine-grained.

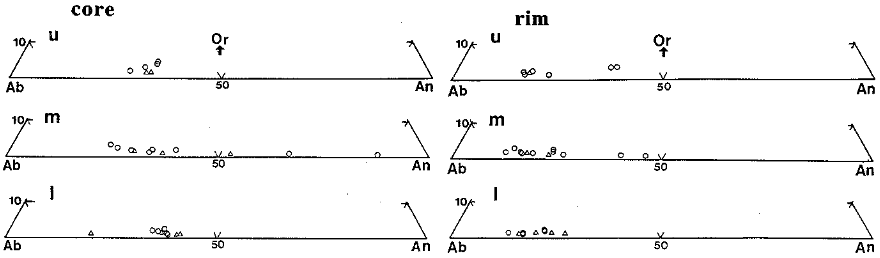

Fig. 21. Ab–An–Or diagram for cores and rims of plagioclase from various lithofacies in the granodiorite.
"u", "m" and "l" show the upper, middle and lower lithofacies of the granodiorite respectively.
circle: coarse-grained, triangle: fine-grained.

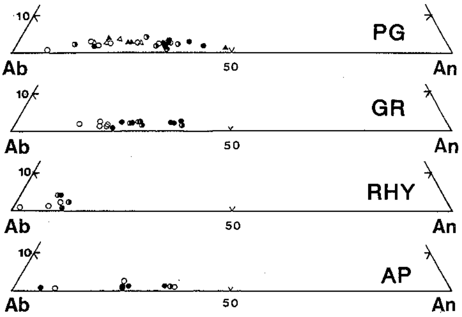

Fig. 22. Ab–An–Or diagrams for plagioclase from the porphyritic granite (PG), granite (GR), rhyolitic rocks (RHY) and aplite (AP).
For symbols see Fig. 19.

poor in An content, narrowly ranging from 2% to 14% (Fig. 22). In the rhyolite, it is also poor in An content (Fig. 22).

Plagioclase in all types of granitic rocks shows distinct chemical zoning whose features are grouped into two types: The one is of ordinary type characterized by decreasing of An content from cores to rims. The other is of extraordinary type in which An content increases from cores to mantles, and decreases from the mantles to rims. Such a chemical zoning is called here abnormal type.

In the tonalite, though An content for plagioclase cores varies from 38% to 74%, it for mantles shows high values ranging from 72% to 80%, and it for rims ranges from 52% to 60% (Fig. 23). The zoning feature of plagioclase in the dark inclusion is more complicated showing two types: In the first type, An content increases from cores to mantles, and decreases from the mantles to rims. In the

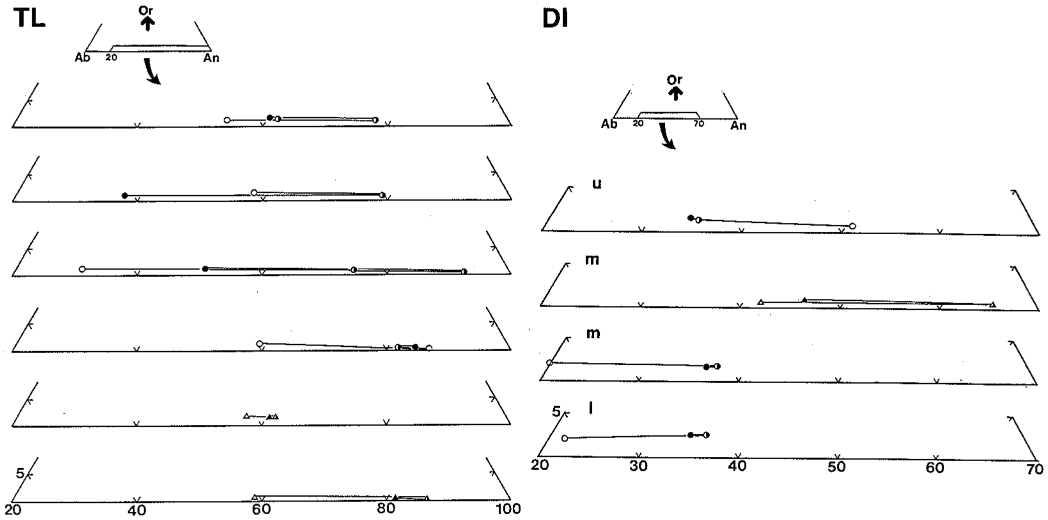

Fig. 23. Ab—An—Or diagrams for abnormal-zoning plagioclase from the tonalite (TL) and dark inclusion (DI). For symbols see Fig. 19.

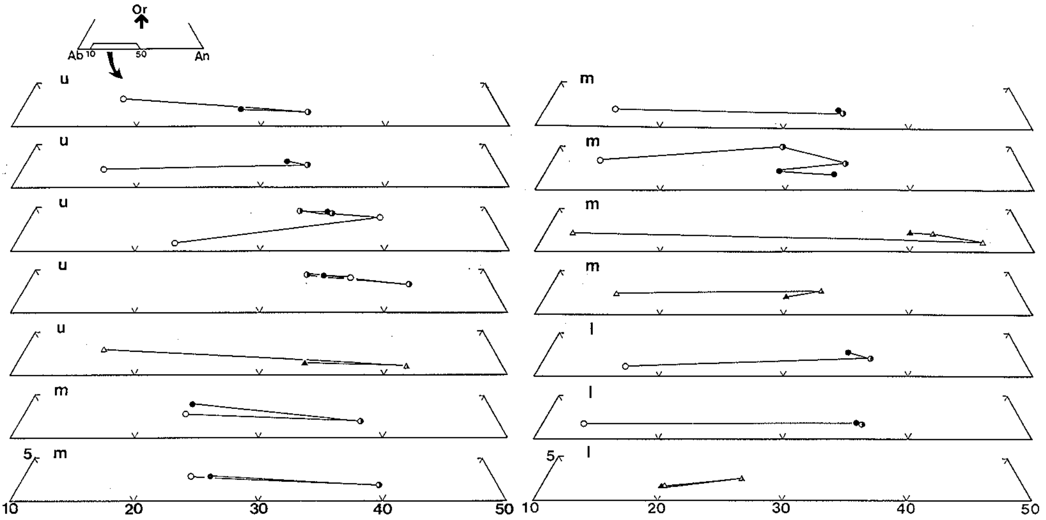

Fig. 24. Ab—An—Or diagram for abnormal-zoning plagioclase from the granodiorite. For symbols see Fig. 19.

second type, it increases only slightly by about 2% from cores to mantles and shows further increase from the mantles to rims. The former type appears in plagioclase from the middle and lower lithofacies which were highly granitized (Fig. 23).

In the granodiorite, An content of plagioclase cores varies from 21% to 41%. That for rims shows a wide range from 12% to 46%, while that for mantles ranges only from 34% to 43% (Fig. 24). The zoning feature of plagioclase in the granodiorite, except for that of one grain, is commonly similar to the first type zoning of plagioclase in the dark inclusion, but that for the exceptional grain is comparable with the second type zoning. In the other rock types such as medium-grained granite, porphyritic granite, aplite and rhyolitic rocks is generally found the abnormal zoning of plagioclase

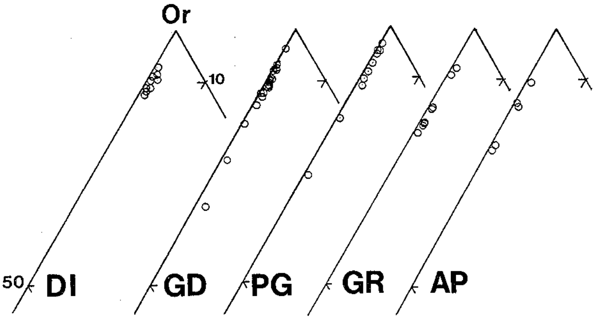

Fig. 25. Ab−An−Or diagrams for K−feldspar from spheres in the dark inclusion (DI), granodiorite (GD), porphyritic granite (PG), granite (GR) and aplite (AP).

which is comparable to the first type zoning for plagioclase of the dark inclusion. In all types of granitic rocks, coarse-grained plagioclase distinctly shows the abnormal zoning rather than fine-grained one.

7. K−feldspar

K-feldspar occurs in almost all types of granitic rocks, but its chemical analysis has not been performed for that in the tonalite and rhyolitic rocks due to the scarcity and intense alteration respectively. K-feldspar contains mostly Or content of larger than 80% and An content of all K-feldspar is less than 3%. Chemical composition of K-feldspar are plotted in Fig. 25.

K-feldspar in the dark inclusion, which occurs in small spheres mentioned in the chapter IV, has Or content ranging from 87% to 93%. In the granodiorite, many K-feldspar grains have Or content ranging from 85% to 96%, but Or content of some other grains shows a range lower than 82%. In the porphyritic granite, Or content of many K-feldspar grains ranges from 88% to 97%, except for two grains with Or content of 71% and 82%. K-feldspar in the granite has generally Or content ranging from 79% to 94%. In aplite, it shows a range of Or content from 76% to 90%.

B. Geothermobarometry

Several kinds of geothermometers and geobarometers may be available to estimate the P−T conditions during the crystallization and cooling processes of the granitic rocks in the Togouchi area.

1. Two pyroxene geothermometer

Wells (1977) proposed a method to obtain the temperature under which orthopyroxene and clinopyroxene are crystallized with an equilibrium relation. Using the method, the temperatures for the crystallization of two pyroxenes in the tonalite were estimated for three specimens. The detailed procedure for the calculation is not described here. The estimated temperatures vary depending upon data source such as cores and rims. The temperature based on the core data appears to be commonly higher than that based on the rim. Pyroxenes in the tonalite are considered to have crystallized under the temperature higher than 800°C.

2. Hornblende geobarometer

Quite recently, Vyhnal et al. (1991) proposed an empirical geobarometer which gives a pressure during the crystallization of hornblende based on the assumption that the activity of Al in calc-alkaline magmas clearly varies with pressure. The proposed formula is as follows;

$$P_{(\pm 0.5\mathrm{kbar})} = -3.46 + 4.23\mathrm{Al}^{\mathrm{total}}$$

They further have shown the empirical relation fact that there is such a strong correlation between pressure and temperature for the crystallization of hornblende from calc-alkaline magma as shown by the following formula;

$$T(°\mathrm{C}) = 25.3P + 654.9$$

After their methods, the pressure and temperature for the crystallization of hornblende in the

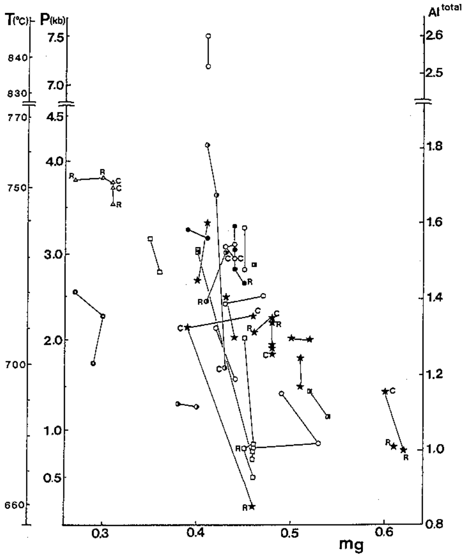

Fig. 26. Relationship between mg value and crystallization pressure and temperature for calcic amphiboles from the Togouchi area.
T: temperature, P: pressure, Al^{total}: total aluminum cation (O=23).
For symbols and abbreviations see Fig. 12 and for explanation see text.

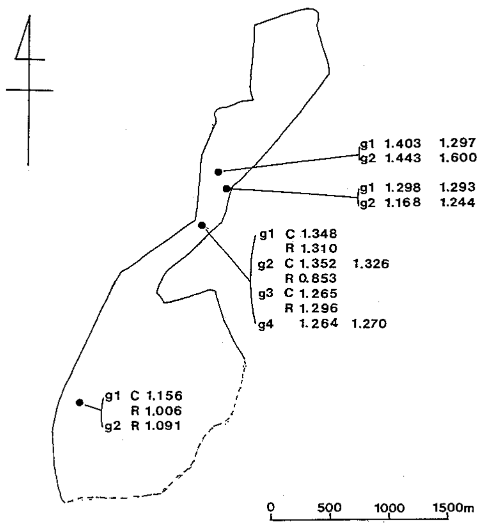

Fig. 27. Spatial variation of total Al (O=23) of calcic amphiboles in the tonalite.
g1 to g4: analyzed grain number, C: core, R: rim.

granitic rocks of the studied area are estimated. The obtained data are plotted in Fig. 26. Except for the data (pressure over 7kb and temperature above 830°C), for a specimen of from the granodiorite, the estimated pressure and temperature are less than about 4.5kb and 770°C respectively. The pressure and temperature are different between rock types but even between analyzed points in one hornblende grain. Although estimated pressures for the tonalite and granodiorite widely vary from 0.2 to 3.3 kbar, many of them for the granodiorite vary only in a short range from 2.2 to 3.3 kbar.

Amphiboles in the tonalite show a distinct tendency for Al content to decrease from cores to rims. Such the growth history would be ascribed to the cooling of magma in which amphiboles crystallized. Fig. 27 illustrates the spatial variation of Al content in amphibole, showing that it seems to decrease toward the south and so the crystallization temperature of amphiboles decreases toward the south.

3. Two feldspars geothermometer

Whitney & Stormer (1977) proposed a geothermometer based upon the partitioning of $NaAlSi_3O_8$ between microcline and plagioclase solid-solutions. In order to determine the crystallization temperature of the granitic rocks in the studied area using their method, 28 pairs of coexisting plagioclase and K-feldspar were selected from the granodiorite and its associated dark inclusion, granite, porphyritic granite and aplite. Fig. 28 is Whitney & Stormer's diagram for these 28 pairs. The equilibrium temperatures of many pairs range from 400°C to 500°C with an average value of 450°C, though some values are around and over 600°C.

C. Discussion

Crystallization environment of the granitic rocks in the studied area will be discussed on the basis of such chemical characteristics of minerals as mentioned above.

In general, the higher the crystallization temperature of calcic amphiboles are, the richer they are

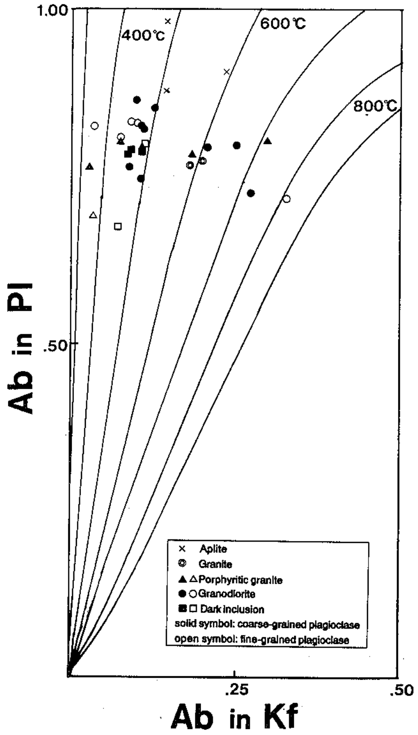

Fig. 28. Crystallization temperature deduced from two feldspars geothermometer.

in Al, Ti, Na and K (Leake, 1971 and so on). Kanisawa (1976), Tainosho et al. (1979) and Murakami (1981) indicated that, in amphiboles from plutonic rocks, the higher their mg value is, the richer their Si content is, and pointed that during the crystallization of amphiboles, the lower the oxygen partial pressure is, the poorer their Si content is. Some amphiboles from the tonalite, dark inclusion, granodiorite and porphyritic granite show a tendency for mg value and Si content to decrease from cores to rims. If the decrease of mg value is in accordance with decrease of the oxygen partial pressure, the fact that the mg value decreases toward rims with increasing of Si content may be related to the descent of the oxygen partial pressure during cooling of magma. On the other hand, Sakiyama (1986) pointed out that the chemical composition in amphiboles changes depending on mineral species crystallized in earlier magmatic stage. It seems to be difficult to estimate the genetical condition for the granitic rocks in question on the basis of the above-described amphibole data.

It is well known that biotites show a tendency to become poorer in Ti and richer in Si and Al^{VI} through the progress of crystallization. Analogous tendency is also equally obvious for those in the granitic rocks in question. Czamanske and Wones (1973), Guidotti et al., (1975) and Anderson (1980) pointed out that it depends on the falling down of magma temperature and compositional change of its residual liquid. Following their opinions, almost all of biotites in the granitic rocks of the studied area are regarded to have normally crystallized through magma cooling.

The abnormal zoning of plagioclase has been found in all types of granitic rocks, especially for coarse-grained plagioclase in the tonalite, dark inclusion, granodiorite and porphyritic granite. Such a zoning of plagioclase would be probably ascribed to the rising of vapor pressure during the progress of crystallization.

It is noteworthy that in the tonalite the cores of plagioclases with the abnormal zoning is commonly poorer in An content than those of plagioclases with ordinary zoning. Therefore, it would be said that the rising of vapor pressure occurred after some plagioclase had started to crystallize. Plagioclases in the granodiorite and its associated dark inclusion show essentially the same property of the chemical zoning as that in the tonalite mentioned above.

The rising of vapor pressure during the progress of crystallization is in harmonic with the change of physical environment suggested by the chemistry of mafic minerals mentioned before. Chemical reduction environment is yielded in magma by rising of hydrothermal vapor pressure. In such a magma, Fe may be consumed to form rather Fe-Ti oxides, especially ilmenite, than mafic minerals.

Then, the origin of the dark inclusion is discussed in terms of the composition of plagioclase in relation to the formation of the tonalite. In the dark inclusion, the cores of plagioclase widely vary in

An content. Plagioclase cores with high An content, which are mainly found in coarse-grained plagioclase of the upper lithofacies, are chemically similar to those of the tonalite. Such plagioclase cores can be regarded to be relict plagioclase survived from granitization which occurred when the dark inclusion rocks were coupled with the granodiorite magma. The cores of plagioclases from the middle lithofacies widely vary in An content, showing that some grains have similar composition to those of the dark inclusion. Such the grains in the granodiorite are possibly interpreted to be fragmental grains derived from the dark inclusion.

The chemical characteristics of amphiboles and biotite in the dark inclusion appear to be intermediate between those of the tonalite and those of the granodiorite. Furthermore, cummingtonite derived from orthopyroxene has been found, and clinopyroxene is rarely found as a relic mantled by amphiboles. It may then well be said that the chemical characteristics of the dark inclusion, except for its granitized part, is similar to those of tonalite, especially of the fine-grained tonalite as its marginal part.

Ayrton (1988) presented a hypothesis that the origin of mafic enclaves in zoned plutons is attributed to fragmentation of ring dike as an earlier phase product of their related magmatism. Following his opinion, it may be said that the tonalite and dark inclusion in the studied area were of the same generation in age and that the former shows the original characteristics and the latter is the part dismembered through the tectonics related to the emplacement of the granodiorite.

Orthopyroxene and clinopyroxene in the tonalite crystallized in the temperature of higher than 800°C. Amphiboles in the tonalite and dark inclusion appear to have crystallized under the condition of about 2kbar and 700°C, and those in granodiorite and granite around 3kbar and 730°C. These data do not immediately indicate the depth of emplacement but indicate the crystallization condition. Namely the crystallization of amphiboles appears to have begun at greater depth than the emplacement depth of the tonalite. While feldspars in all types of granitic rocks indicate that the later stage crystallization of their related magmas occurred under the temperature of ca. 450°C.

VI. Magnetic Susceptibility of Granitic Rocks in the Togouchi Area

Ishihara (1977) proposed that granitic rocks are classified into magnetite-series and ilmenite-series separated by 50×10^{-6}emu/g of magnetic susceptibility: granitic rocks with magnetic susceptibility of lower than the value belongs to ilmenite-series, and those with magnetic susceptibility of higher than the value to be magnetite-series. Granitic rocks in the Togouchi area are generally situated in the San-yo zone. Ishihara (1979) said that granitic rocks in the San-yo zone are commonly of ilmenite-series and those in San-in zone are of magnetite series. Strictly speaking, the studied area is situated in a transitional zone between the San-yo zone and the San-in zone. Therefore, the detailed study of magnetic susceptibility of granitic rocks in the area may give an information on tectonic condition of the boundary between the San-yo and the San-in zones.

Magnetic susceptibility for the granodiorite, porphyritic granite, medium-grained granite and fine-grained granite bodies was measured by the instrument of BISON－3101A type. The results are shown in Fig. 29.

Most of specimens from the granitic rocks, except for the fine-grained granite gave magnetic susceptibility of lower than 50×10^{-6}emu/g, showing that almost all of granitic rocks belong to the ilmenite-series. Suzuki,M (1987) pointed out that granodiorite has the high magnetic susceptibility referred to the magnetite-series. The discrepancy between both studies may be ascribed to the difference between the measurement method. Although many specimens from rhyolitic rocks show

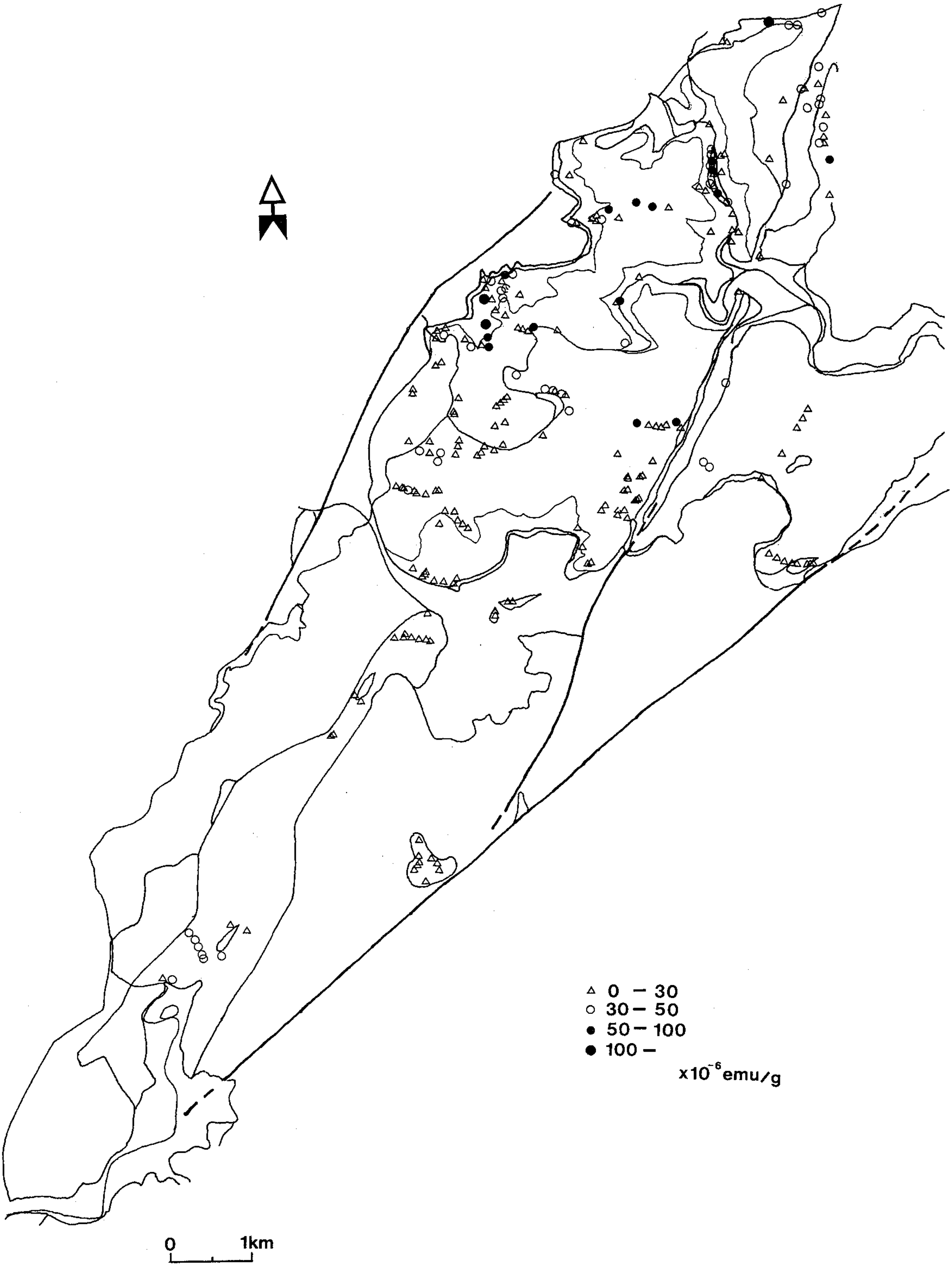

Fig. 29. Spatial variation of magnetic susceptibility of granitic rocks in the Togouchi area.

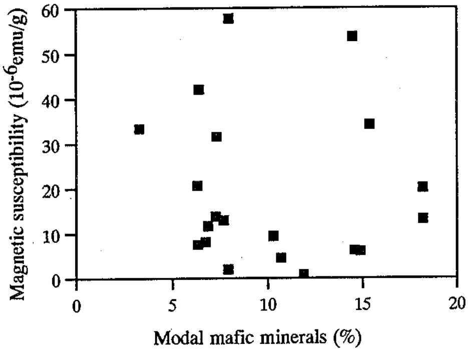

Fig. 30. Relationship between magnetic susceptibility and amounts of mafic minerals in the granodiorite.

magnetic susceptibility of lower than 50x10^{-6}emu/g, that of some others is much higher. The specimens with higher values have been collected from near Nasu where the rocks are in wall contact with the granodiorite. Near the contact, the fine-grained granite occurs as thin layered body.

Specimens from the lower lithofacies of the granodiorite, especially those from its bottom part, tend to show the magnetic susceptibility which is as high as that for the magnetite-series. Most of specimens from the fine-grained granite, even those from small dikes or veins observed in outcrops of the granitic rocks, tend to show the magnetic susceptibility of higher than 50x10^{-6}emu/g. Generally, magnetic susceptibility tends to increase with increase of mafic minerals. But, as shown in Fig. 30, its data from the granodiorite are not positively related to the amounts of mafic minerals. The magnetic susceptibility of the dark inclusion is rather lower than that of the host granodiorite. It may be supposed that original magnetite in the granodiorite changed to ilmenite during their cooling process affected by successive magmatism. Similar interpretation was given for the Takiyama-kyo granite in the Takiyama-kyo area to the north of Kake (Hayashi et al., 1992; Suzuki,M. et al., 1993). It is an important but unsolved problem why the fine-grained granite shows the higher value of magnetic susceptibility so that it is comparative with the magnetite series, while that of its host granitic rocks are as low as that for the ilmenite series.

VII. Microfabric of Quartz in Granitic Rocks in the Togouchi Area

A. Microfracture of quartz in the granodiorite and medium-grained granite

In quartz of the granodiorite and medium-grained granite are commonly found sealed microfractures defined by preferred orientation of fluid inclusions cutting across its grain boundaries. Such microfractures are rarely also developed in feldspars. Hereafter, the sealed microfracture will be called "FIPS". Orientation of FIPS in quartz has measured using universal stage, in order to clarify the tectonic environment during the cooling of the granodiorite and granite. FIPS would be probably referred to the "rift" or the "grain" after Dale (1923).

Wise(1964) described the characteristics of such microfracture system of the Precambrian basement of Montana and Wyoming including rift and grain, and discussed the relationship between the microfracture system and the tectonic environment. Plumb et al.(1984) discussed correlation between near surface in situ stress and microcrack fabric in the New Hampshire granites which had be studied by Dale (1923). No data for such a microfracture system has yet been reported from any granite in Japan.

In the Togouchi area, thirty five localities were selected to clarify the orientation of the healed microfracture throughout the granodiorite body (locality 1 to 34) and the medium-grained granite

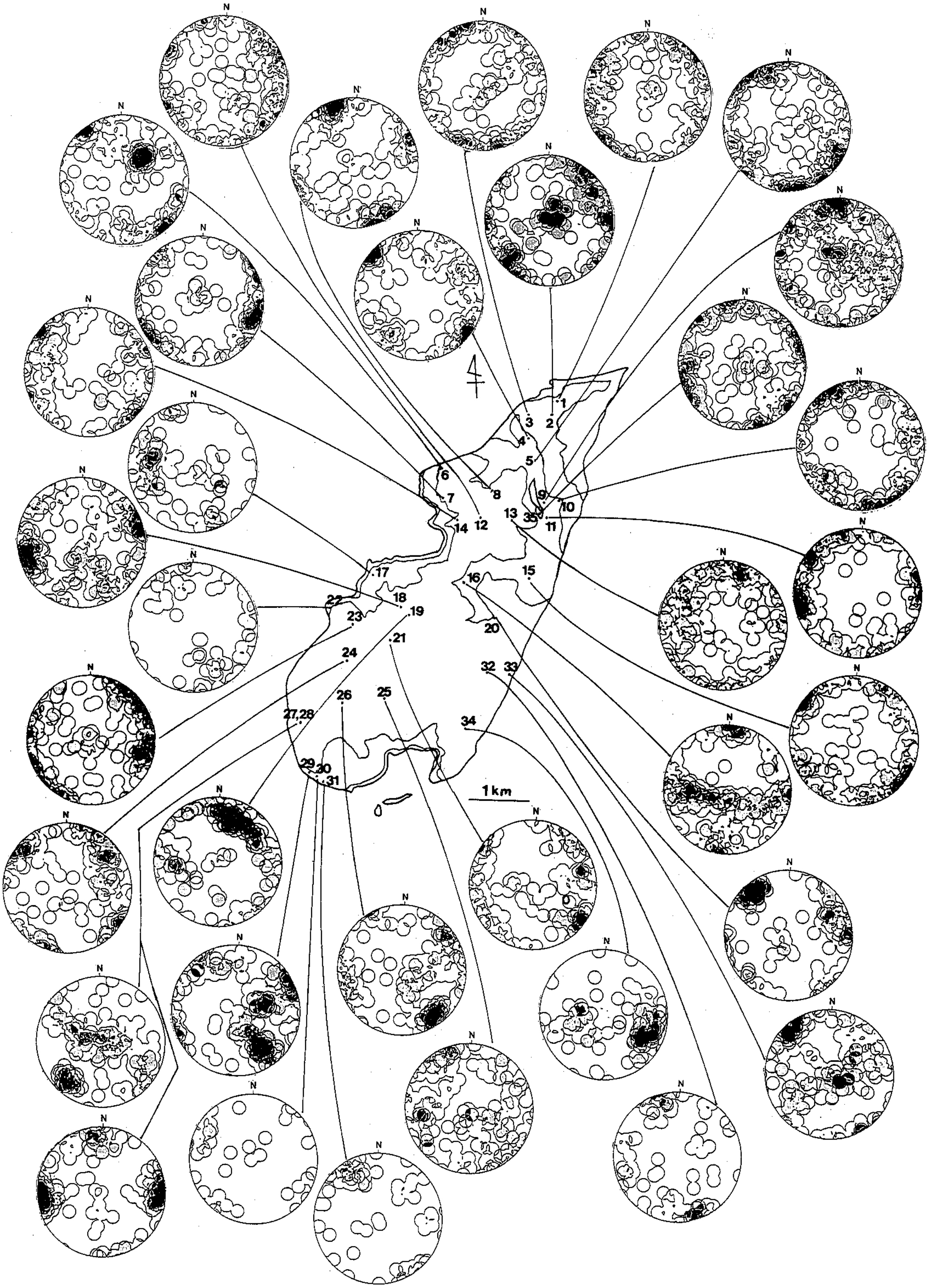

Fig. 31. Spatial variation of fabric (synoptic) of fluid inclusion planes in quartz of the granodiorite and medium-grained granite.
1 to 35: locality numbers.

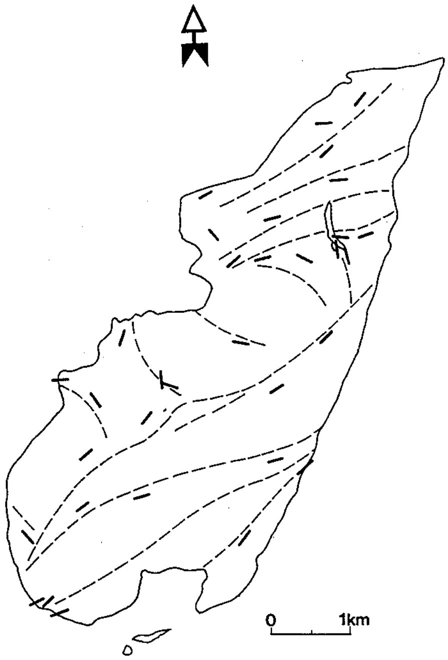

Fig. 32. Spatial variation of the orientation direction of the first order of fluid inclusion planes in quartz of the granodiorite and medium-grained granite.

body (locality 35) (Fig. 31) Three thin sections perpendicular to each other were prepared from an oriented specimen collected from each locality. The measurement has been done for all microfractures observed within a domain of about 1.5cm × 2.0cm on every thin section.

Two types of FIPS have been discriminated as shown in Plate III-5. The one is shown an as aggregate of short microfractures parallel to each other in quartz. Every FIPS of this type contains tiny inclusions. The other is long microfractures with straight or greatly curved shapes, sometimes extending into and throughout feldspar grains. Although two types of microfractures may have been produced under different age or stress fields, they appear to be commonly oriented parallel to each other. Therefore, the orientation data for the two types microfractures have been plotted indiscriminately on each diagram.

The data from three sections measured at each locality have been synthesized into a synoptic diagram. As is obvious in the figures, nearly vertical FIPS is predominant all over the localities, showing preferred orientation in selected directions. FIPS as flat or gently dipping planes is generally poor. In most of the localities, FIPS oriented nearly in NE−SW trend appears to be a prominent set and nearly NW−SE trending FIPS appears to be a subordinate set. Other concentration directions are nearly E−W and N−S, as shown in localities 9, 16, 18, 22, 28 and 35. FIPS from the locality No.16 and the locality No.27 shows a girdle-like pattern suggesting squeezing-type deformation. Many synoptic diagrams indicate that microfractures tend to develop with two or three prominent and subordinate sets in each locality (Fig. 31). They are called here the first set, the second and/or the third set depending on the order of point densities. The first set at each locality is also plotted on Fig. 32.

The orientation pattern of the first set of FIPS indicates that the granodiorite body is divided into three domains, N−domain, Central domain and S−domain (Fig. 32). The first set of FIPS is running in near NE−SW trend which is oblique at small angles to the elongation direction (NNE−SSW) of the granodiorite body, while in the central domains its orientation is complicated and it appears to be running in NW−SE to NNE−SSE trend. The trend of these domains is ENE−WSW, and appears to

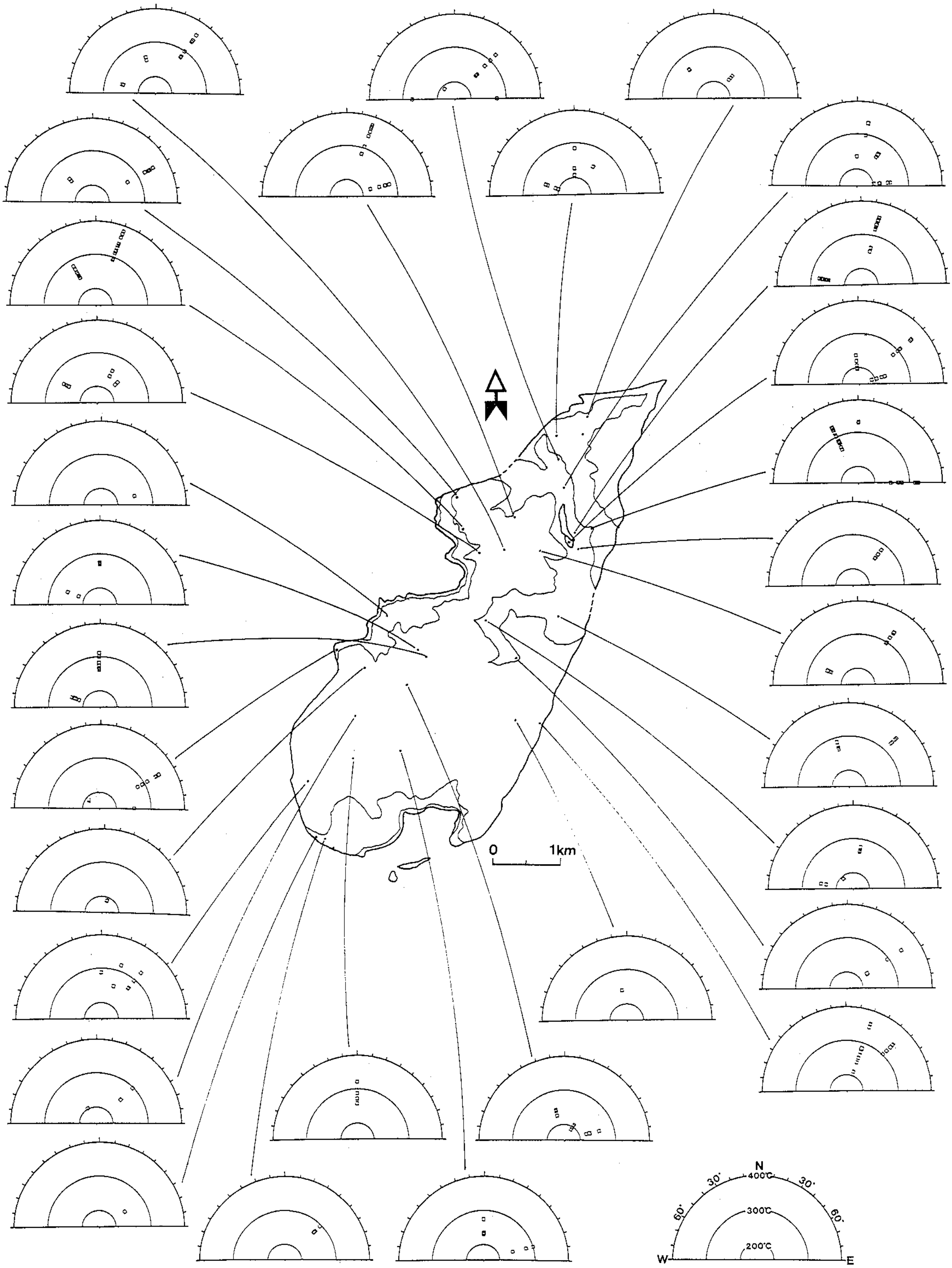

Fig. 33. Spatial variation of the orientation direction of fluid inclusion planes in quartz and their homogenization temperature in the granodiorite and medium-grained granite.

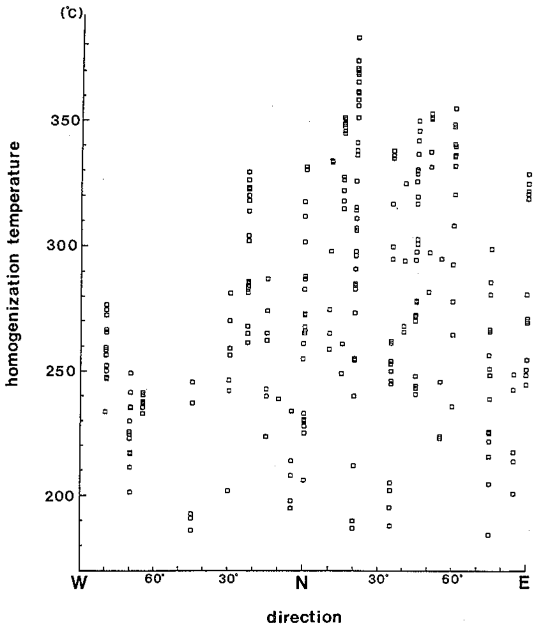

Fig. 34. Relationship between the orientation direction of fluid inclusion planes in the quartz and homogenization temperature in the granodiorite and medium-grained granite.

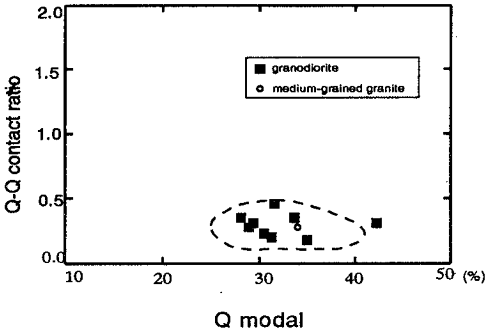

Fig. 35. Relationship between Q—Q contact ratio and modal Q.
Boken line shows the value range for the Ishizuchi granite by Sakurai and Hara (1979).

be slightly oblique to the orientation direction of the first set in the N—domain and S—domain. The first set of the Central domain is oriented oblique at high to moderate angles to the trend of the domains.

Lespinasse and Cathelineau (1990) proposed a method for relating fluid flow evolution to the bulk brittle network (microfracture system) which involves the use of fluid inclusions as a tool for the establishment of the physco-chemical conditions under which fluids were entrapped. In the St. Sylvestre batholith, central France, they classified three different types of quartz based on its formation stage and showed the ice melting and homogenization temperatures of each type of quartz. Furthermore, they showed that these temperatures of fluid inclusions trapped in healed microcracks of those three types of quartz, whose orientation is N—S, E—W and NW—SE respectively, are different from each other.

Then, the homogenization temperatures for fluid inclusions in quartz of the granodiorite of the Togouchi area have been measured. The results are shown in Fig. 33. Although the homogenization temperature widely varies ranging mainly from 200°C to 380°C in all localities, it appears to change depending on the orientation of FIPS. FIPS trending in near NE—SW tends to show relatively higher temperature, many of which are higher than 350°C in all localities. FIPS trending in near NW—SE shows around 340°C and those of trending in near E—W mainly show lower temperature than 300°C (Figs. 33 and 34).

Thus, it would be said that the healed microfracture in quartz was produced in near NE—SW trend under higher temperature than in near NW—SE trend and that those were produced in near E—W trend under lowest temperature among the three trends. Therefore, it is inferred that FIPS was initially produced in NE—SW to NNE—SSW trend, followed by near NW—SE trend and terminated by near E—W trend through cooling of the magma.

Vollbrecht et al. (1991) presented a hypothesis that the vertical FIPS of quartz is caused mainly by the internal thermal stress at the earlier stage during uplift of granitic magma and subhorizontal one mainly by external (unloading) stress at later stage. However, it is not clear whether or not the vertical FIPS of NE−SW to NNE−SSE trend and NW−SE to NNW−SSE trend in the Togouchi area is the Vollbrecht et al.'s case.

It may be said that FIPS trending nearly NE−SW dominated both in the N−domain and S−domain was reflected the fracturing formed by the compression with the axis of near NE−SW trend. While the Central domain may be a strain concentration zone, which was produced by sinistral movement trending near E−W in the later stage.

Based on studies of late Mesozoic dike swarms in the Inner Zone of Southwest Japan, Yokoyama (1984) clarified that the direction of the largest horizontally compressive stress had initially been E−W, followed by N−S, and then changed again to E−W in the period. Although at least some of these compressions may be related with formation of FIPS in the Togouchi area, a definite conclusion must be reserved.

Yoshimura and Hayashi (1989) reported on the orientation of joint system in the northern part of the granodiorite body. According to them, vertical joints trending in NE−SW are predominant, and vertical joints trending in NW−SE and N−S and flat-lying sheeting joint are rather subordinate. The formation of NE−SW trending joints would be related to the activity of the major faults trending in NE−SW in Chugoku Province which postdated the Cretaceous volcano-plutonism.

B. Grain contact ratio for constituent minerals in the granodiorite and medium-grained granite

Sakurai and Hara (1979) and Hara et al. (1980) indicated that, in general, the more intensely the granitic rocks are deformed, the higher the value of grain contact ratio of quartz versus quartz becomes. Arita (1988) reported that the Hiroshima Granite has higher value of contact ratio of K-feldspar versus K-feldspar than the Ryoke granites in Kojima Peninsula and Shiwaku Island, Okayama Pref..

In order to clarify the deformation style of the granitic rocks in the Togouchi area during their emplacement, the grain contact ratios of the constituent minerals have been measured with the method proposed by Rogers and Bogy (1957). It would be said that the contact ratios of quartz versus quartz are low, and those of quartz versus K-feldspar are high. The contact ratios of quartz versus quartz for the granodiorite ranges from 0.18 to 0.46, and those for the medium-grained granite is 0.38 (Fig. 35). These for the granodiorite in the Togouchi area are extremely low and comparable with those for the Ishizuchi granite (Sakurai and Hara, 1979), which was emplaced in a cauldron subsidence. Therefore, it would be said that the granodiorite was scarcely deformed in ductile fashion during cooling. High contact ratio of quartz versus K-feldspar in the granodiorite is well correlated with the development of micrographic texture for these minerals.

VIII. Shape and Structure of the Hiroshima Granite

The Hiroshima Granite distributed in the five areas, Saeki area (Fig. 36), Hiroshima-Kake area (Fig. 37), Yachiyo area (Fig. 38), Kumano area (Fig. 39), Takehara area (Fig. 40), Yasaka-kyo area (Yoshino and Hayashi, 1979), Takiyama-kyo area to the north of Kake (Hayashi et al., 1992) and Nomizima area (Hayashi, in prep.), in the T-Y-T district have been further investigated, focusing mainly upon its lithological features and geological structures. As a result, such lithological features and geological structures of granitic rocks as mentioned in the Togouchi area are commonly found throughout the T-Y-T district. Namely, it can be concluded that the Hiroshima Granite in the T-Y-T district shows, as a whole, a flat-lying layered structure consisting mainly of three types of lithofacies, which are fine-grained granite (fine-grained granite facies), medium-grained hornblende -biotite granodiorite (mafic-rich facies) and medium- to coarse-grained biotite granite (biotite granite facies). The fine-grained granite facies tends to commonly occupy the upper part of the mass, sometimes scattered among its constituent layers. The mafic-rich facies is mainly placed in the middle horizon of the mass, and the biotite granite facies tends to occupy mainly the lower horizon.

Fine-grained granite is well developed in the uppermost part of the large mass developed throughout the T-Y-T district, and in almost all of cases, it is in direct contact with pre-Cretaceous formations or Cretaceous volcanic rocks. In other words, this type rock lies between the wall rocks and the other type granitic rocks. Furthermore, this type rock frequently occurs as small layered bodies between layers of other type granitic rocks. Boundary surfaces between the fine-grained granite and the other type granitic rocks are commonly sharp.

In the western-central part of the district, especially in and around the Saeki and Hiroshima-Kake areas, there is hornblende-biotite granite occupying the upper part of the mass. Additionally, other types of rocks rich in mafic minerals are frequently found in the marginal part i.e. marginal part of the mass: These are the granodiorite and tonalite in the Togouchi area, the granodiorite near Kure and the granodiorite on the south of Iwakuni etc.. But boundaries between such mafic-rich facies and the biotite granite facies are frequently obscure, and both appear as rather intergradational relation. The biotite granite facies is widely distributed all over the district, occupying lower part of the mass. The granite is also sometimes in direct contact with the wall rocks. As shown especially in the Togouchi area, the mafic-rich facies is an earlier stage intrusive than the biotite granite facies. The mafic-rich facies or granitic rocks remaining more or less mafic-rich facies are also found in the uppermost part of the biotite granite facies.

Cretaceous volcanic rocks are predominantly distributed with NE−SW trend in the northern area of the district, being accumulated on pre-Cretaceous formations as a basement. As mentioned before, the volcanic rocks belong to the northern volcanic zone. In general, the northern limit of the distribution of the Hiroshima Granite appears to correspond to the southern limit of the northern volcanic zone. Along the northern coast of the Seto Inland Sea, especially in near Kure, there is an other zone of Cretaceous volcanic rocks, which has been called “Akitu-Sensui block” by Yoshida (1964). The volcanic rocks are composed mainly of dacite and its tuffaceous equivalents (Aki Research Group, 1983, Higashimoto et. al., 1985). It has been already said that those belong to the southern volcanic zone. The southern volcanic zone, as well as the northern one, is running in NE−SW trend. They are traced toward Okayama Pref.. These two volcanic zones are considered to have been two great fracture zones. The granodiorite is in direct contact with the rocks in the southern volcanic zone and underlain by the biotite granite facies (Figs. 3 and 4).

Hara et al. (1991) has presented the detailed geological map of the Oshima-Yanai-Kuga area, which is situated in the Ryoke zone and contains the southernmost of the T-Y-T district, and said that older Ryoke granites of this area occurs as layered bodies, being tectonically piled up each other. They also indicated that the younger Ryoke granites of this area appear in balloon-shaped bodies intruded into the older Ryoke granite and metamorphics.

The Hiroshima Granite in the south of Iwakuni is in direct contact with the older Ryoke granites. Although the boundary between them has not yet been exactly determined in the field, their boundary surface appears to dip gently to the south or southwest judging from their distribution features. Radiometric age data for granitic rocks of the Iwakuni-Yanai district indicate that the

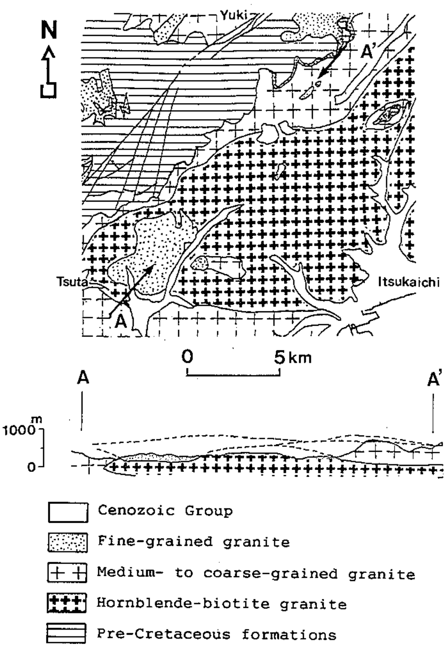

Fig. 36. Geological map of the Saeki area.
(compiled from Takahashi, Y. et al., 1989 and Takahashi, Y., 1991 and the present author's data)

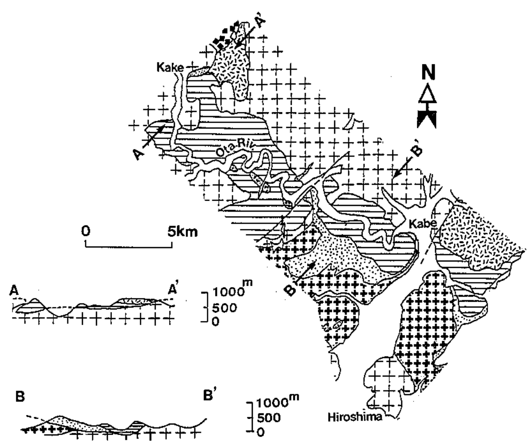

Fig. 37. Geological map of the Hiroshima-Kake area.
(compiled from Yamada et al., 1985 and the present author's data)
Symbles are the same as Fig. 36.

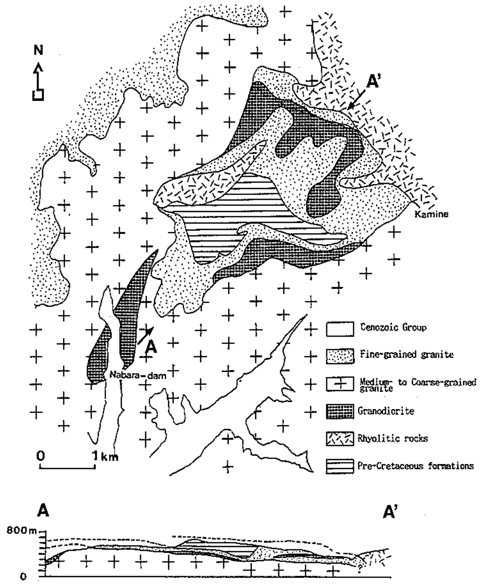

Fig. 38. Geological map of the Yachiyo area.
(compiled from Hara, 1955, Yamada et al., 1985 and the present author's data)

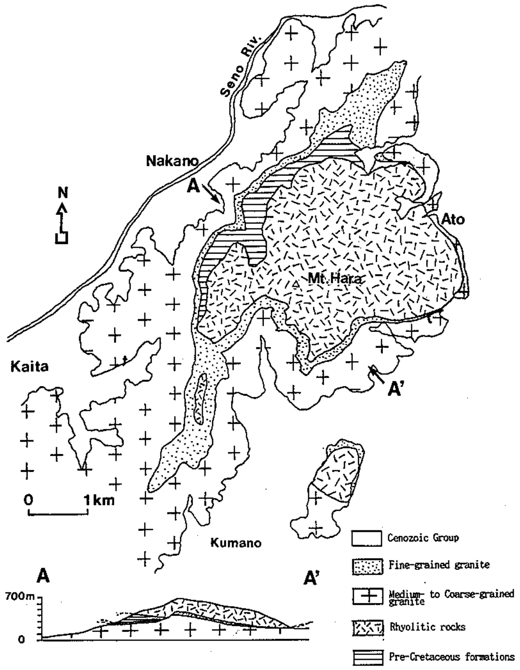

Fig. 39. Geological map of the Kumano area.

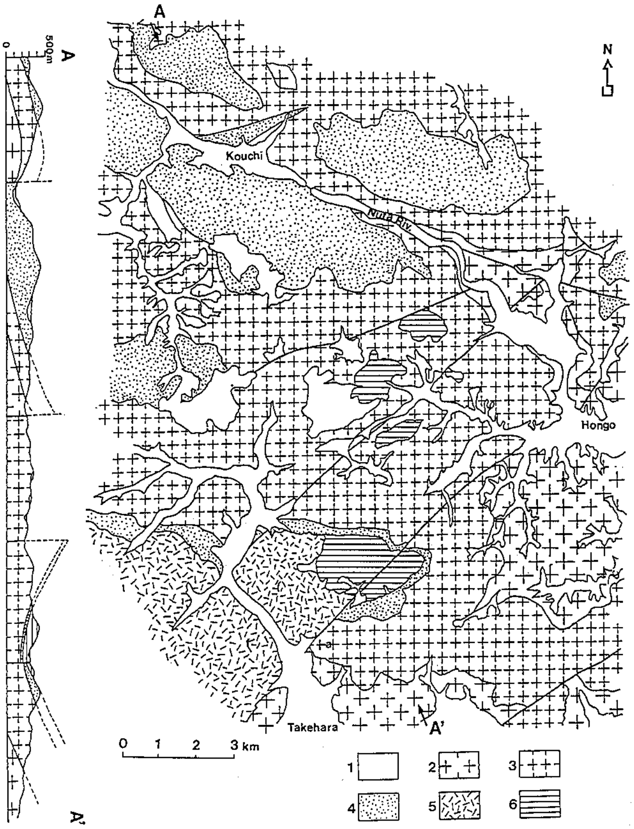

Fig. 40. Geological map of the Takehara area. (compiled from Yoshida et al., 1985 and the present author's data)
1: Cenozoic Group
2: Coarse-grained granite
3: Medium-grained granite
4: Fine-grained granite
5: Rhyolitic rocks
6: Pre-Cretaceous formation

younger Ryoke granites are younger in radiometric age than the older Ryoke granites and the Hiroshima Granite and that the latter two are of the same radiometric ages (cf. Hara et al., 1991). Therefore, the latter two would be probably of the same generation in age. The Ryoke metamorphic rocks placed near the southernmost margin of the Hiroshima Granite appear to have been produced at 2−3kb depth (cf. Okudaira et al., 1993).

The western margin of the Hiroshima Granite of the T-Y-T district is in contact with Cretaceous volcanic rocks as shallow depth intrusives and/or terrestrial sediments in the northernmost part, with the only weakly metamorphosed Kuga Group sediments in the central part and with the Ryoke metamorphic and older Ryoke granitic rocks in the southernmost, showing that the contact plane dips gently toward the south from near the ground surface in the northernmost part to 2−3kb depth in the southernmost part. The internal layered structure of the Hiroshima Granite mentioned in the preced ing pages is generally oriented parallel to such a southward dipping contact.

The northern volcanic zone is placed in and around the northern margin of the Hiroshima Granite. The eastern part of the Hiroshima Granite is in contact with the northern volcanic zone and also with the southern volcanic zone along the northern coast of Seto Inland Sea, The granite in contact with the southern volcanic zone can be regarded to be a small derivative intrusive from the major mass of the Hiroshima Granite.

On the basis of the above-described evidence and consideration, it is supposed that the Hiroshima granite occurs, as a whole, as a large sheet-like mass gently inclined toward the south or southwest (Hayashi et al., 1992).

Fig. 41 schematically summarizes the above-mentioned geological setting as well as the tectonic framework of the Hiroshima Granite. The symbols E and W in this figure indicate east and west as

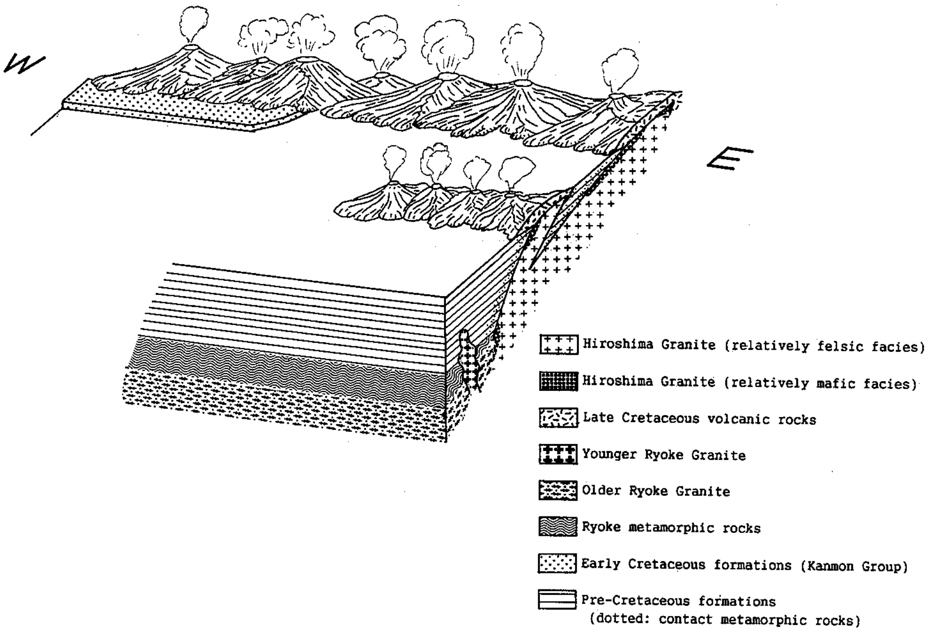

Fig. 41. Schematic diagram illustrating geologic events occurring in the central–western Chugoku Province during late Cretaceous period.

the present geographic directions respectively.

IX. Intrusion Tectonics of the Hiroshima Granite

A. Recent history of studies on the intrusion mechanism of granitic rocks

The most momentous problem on the intrusion mechanism of granite is so called the "space problem". It has been emphasized on how to produce space for accommodation of granite magma forming apparently so large rock mass, as well as on how granite magma ascend from the deeper crust. It would be important to discuss such problems not only based upon local geological evidences, but also taking account of global tectonic environments.

Several models for explaining the intrusion mechanism have been so far proposed, based mainly on the geological and rock structures of granitic rocks. The famous and classical models are "diapirism", "cauldron subsidence" and, needless to say, mechanisms comprising these two in various degrees. Some studies concerning to these models are summarized in the following.

The diapirism model has well been developed, frequently being applied to explain intrusion mechanisms of various granites. Theoretical hypotheses and experimental studies for the diapirism within the crust have been performed by Biot and Odé (1965), Hamilton et al.(1967), Ramberg (1967, 1970), Berner et al.(1972), Hara and Shimamoto (1979) and others, clarifying the relationship between the shapes of diapirs and the physical properties of related rocks such as density and viscosity and the deformation style of host rocks related to the diapirism.

Sweeny (1975) pointed out that, judging from gravity data, both of Mt.Waldo and Lucerne granite batholiths in south-central Maine are relatively thin and tabular in shape and their emplacements would be explained in terms of buoyant diapirs that reach shallow depth within the crust, though their emplacements were possibly aided by pre-existing faults or fracture system in the host rocks.

Sylvester et al.(1978) also reported that the Mesozoic Papoose Flat pluton as a satellite of Sierra

Nevada batholiths is a typical epizonal pluton forcibly emplaced into the present structural level as a viscous, almost completely crystalline mass. Their opinion base is the structural relationship between the pluton and its envelope, and deformation fabrics of both. As to creating "room" for the pluton in the country rocks, they placed great emphasis not only on its forcible emplacement mechanism but also on the contrasting response of anhydrous and hydrous parts of the host strata to the elevation of temperature and to the radial pressure related to the invading pluton.

Bateman (1984) pointed out that the mode of magma ascending changes depending upon the ratios between melt and crystals: Many magmas begin their ascent through the crust as mushes with at least 50% melt, and when a magma becomes too crystalline (melt<25%) to continue its ascent, it is immobilized and then forms a pluton growing as a ballooning diapir by accretion of magmas. He also pointed out that, emphasizing the distinction between processes that operate during ascent and those that determine the mode of final emplacement, diapiric deformation is not directly a function of depth of emplacement, but of ductility contrast between intrusive magma and envelope. Moreover, he suggests that magmas, which are able to ascend to shallow depths largely by virtue of lower water content and higher initial temperature, tend to be finally accommodated by such brittle processes as stoping and cauldron subsidence, and that shallow level intrusions tend to become tabular, being fed through dikes or conduit. Further, Bateman (1985) considered the evolution of Cannibal Creek Granite in northeastern Australia with reference to close connection between structural development and petrological development, concluding that a change from slow fractional crystallization to much more rapid equilibrium and cotectonic crystallization can be directly related to a change from ascent to final emplacement.

Woodcock and Underhill (1987) reported the other complexities of ballooning at shallow levels in a heterogeneous crust than the deep-level, emphasizing heterogeneous stretching and uplift strongly controlled by a nonuniform stratigraphy and by reactivation of older faults. In addition to vertical diapirism above mentioned, Courrioux (1987) presented a hypothesis of oblique diapirism for the emplacement of Criffel granodiorite/granite zoned pluton in SW Scotland, clarifying uneven distribution pattern of strain within the pluton.

The mode of "cauldron subsidence" has also been frequently applied to explain emplacement of granite batholiths with reference to connection between the formation of the batholiths and their contemporaneously associated or closely related volcanism. Cobbing and Pitcher (1972) mapped the Coastal Batholith in Peru and clarified the variety of intrusives composing batholith and structural interrelationships among them, suggesting that cauldron subsidence and associated stoping played an important role on the emplacement of the batholith, i.e. fracturing and stoping might have been the dominant process in the rigid plate of overlying volcanics. Myers (1975) also showed that the Coastal Batholith is constituted by piles of thin tabular shaped plutons with flat roofs and steep walls which pass downward into ring dikes and upward into ring dikes and calderas, and that it was formed through the process of repeated cauldron subsidence. He also showed how those intrusives rose through their last few kilometers by a process of magmatic stoping. In his opinion, each subsidence was preceded by the formation of small shear zone. Pitcher and Bussell (1977) regarded for magmas of the Coastal Batholith to have been emplaced along major fault lines in ancient crystalline basements and for the emplacement of individual plutons to have been closely controlled by transcurrent faults and smaller scale joint patterns. Pitcher (1978) showed schematically that the Coastal Batholith was intruded and emplaced along the vertical shear zones which possibly reach the asthenosphere. Furthermore, Pitcher (1979) stated that only in Andinotype batholiths there is a clear space/time relationship between plutonism and volcanism and that, in emplacement of Andinotype batholiths, cauldron subsidence is a dominant process accompanied by stoping of brittle basements of calderas or volcanic ejecta, while, in that of Hercynotype batholith, diapir ascending and in situ ballooning in the ductile crust is dominant. He emphasized that the batholith emplacements may be controlled by major deep shear zone in the crust.

In Chugoku Province, Imaoka (1986) reported several examples for the igneous complex bodies consisting of volcanic rocks and contemporaneous plutonic rocks in the San-in zone, which appear to have formed through such a process of cauldron subsidence. In Kyushu Province, Takahashi, M. (1985) reported that the Okueyama zoned pluton was emplaced through stoping like the case of the Coastal Batholith shown by Myers (1975).

Although such two models may be relevant to the interpretation of the intrusion mechanism of the Hiroshima Granite, some authors have recently presented a new interpretation for the intrusion mechanism of Cretaceous granite in the Inner Zone of Southwest Japan to which belongs the Hiroshima Granite (for example, Kanaori, 1990; Kanaori et al., 1990). They said that the space for the granites were produced by the movement of the major strike-slip faults such as the Median Tectonic Line, Atera Fault, Yanagase Fault and many others. Their interpretation is based only on such evidence that these strike-slip faults occurred during Cretaceous age. They do not take any account for the internal structure of granitic rocks and the structural relationship between the granitic rocks and the host rocks.

Ramsey (1981) and Holder (1981) calculated the increasing of pluton diameter during the emplacement process. Brun and Pons (1981) presented simple simulation for the orientation pattern of the foliation produced by interference between the ballooning of magma and the regional deformation events.

Hutton (1982) proposed a tectonic model for the emplacement of the Main Donegal Granite in NW Ireland. The model is that the shear zone locally created high strain rate and instability which caused the zone to bend, split lengthwise and progressively create an internal low pressure zone into which the magma for the Main Granite was emplaced.

Meneilly (1982) also discussed the relationship between the formation of the regional structure and the granite intrusion in the Dalradian of the Gweebara Bay area, southwesterly adjacent to the Main Donegal Granite. Davis (1982) reported plutons are associated with the Njad fault system characterized by wrench fault, shear zone of which had a role of conduit for their magmas.

Castro (1985, 1986) presented a hypothesis for the intrusion mechanism of the Central Extremadura "Batholith" in Hercynian belt, Spain: Several plutons, which are considered to be a batholith in genetic viewpoint, were emplaced and deformed in an E—W, dextral, deep, intracontinental shear zone characterized by extensional fracture after the first Hercynian deformation phase.

Bruno et al., (1987) proposed that the Variscan Mortagne granite in France was emplaced in a pull-apart void formed by the early movement of the South Armorican Shear Zone characterized by a sinistral shear.

Hutton (1988) proposed that the Caledonian Storontian granite in Scotland was emplaced essentially passively in the extensional termination of a dextral transcurrent shear zone, which is a splay controlled by a slight releasing bend in the major Great Glen fault and by a large, pre-existing, asymmetrical synform in Proterozoic metasedimentary country rocks.

B. Intrusion mechanism of the Hiroshima Granite (discussion and conclusion)

The intrusion mechanism of the Hiroshima Granite will be discussed in the light of above

-mentioned previous works.

The late Cretaceous to Palaeogene igneous rocks in the Inner Zone of Southwest Japan, which contains the Hiroshima Granite, have been thought to be a series of volcano-plutonisms. Judging from their distribution features, the volcanic rocks appear to be arranged in at least two different volcanic rows with vigorous acidic volcanic rocks on the pre-Cretaceous formations as the basement. As shown before, the one of the rows is referred to the northern volcanic zone, and the other to the southern volcanic zone. In the beginning of the volcanism, in general, it is characterized by relatively mafic ones as Kisa andesite and dacite of lower Takada rhyolites (Iizumi et al., 1985). The northern volcanic zone is the main zone of volcanism and is associated with the development of andesite and early Cretaceous sedimentary rocks (Kanmon Group) (Fig. 41). The southern volcanic zone is only the subordinate one.

Murakami (1974) has proposed that the NE−SW trending in central-western Chugoku Province was probably active fissures since the Mesozoic period and the Cretaceous volcanic activities took place along the fissures. It is said that the intrusion of the Hiroshima Granite followed the volcanism. However, the Hiroshima Granite is mainly developed just on the south of the northern volcanic zone, showing that the boundary between its main body and host rocks is gently inclined toward the south, intruding the volcanic rocks in the northern margin and the Ryoke metamorphic rocks of 2−3kb depth in the southern margin.

The geological structures related to cauldron subsidence such as collapse topography for caldera, ring dikes and circularly distributed plutons as well as evidences for stoping, have not yet been found in any area of the Hiroshima Granite, even in near the rhyolitic rocks. On the other hand, the layered structure of the Hiroshima Granite and the step structure of the granite contact characterized by combination of roof contact and wall contact described in the preceding pages may interpreted in terms of the vertical subsidence of the crustal rocks during the emplacement which is a fundamental factor of cauldron subsidence, like the case of the Coastal batholith (Myers, 1975).

As many authors pointed out, generally, diapirism, as well as ballooning, is not characterized only by the ductile deformation of country rocks, but also by that of the pluton itself. The ductile deformation of the Hiroshima Granite and country rocks is scarcely found. The apparent diameter of the Hiroshima Granite mass of the T-Y-T district is greater than 50km. The diapiric intrusive and/or ballooning of such great mass must induce the great deformation of the host rocks throughout great extent. However, such a great deformation of the host rocks is not found in any fashion but commonly shown only by the formation of granite veins (and dikes) in narrow zone adjacent to the granite. Therefore, it can be said that the emplacement of the Hiroshima Granite was accompanied by fracturing of the host rocks just near its contact. The development of the step structure in the Hiroshima Granite may be closely related to the fracturing. The Hiroshima Granite had not brought also the stoping of the country rocks in great extent.

It may be notable that a diapiric granite intruded into shallow crust can be thin and tabular (Sweeny, 1975). Besides, batholith formed by cauldron subsidence can be constructed by layered granite masses with different lithofacies (Myers, 1975; Pitcher & Bussell, 1977; Pitcher, 1978). These also indicate that the "tabular mass" is a common specific phenomenon of granites intruded into higher level in the crust. The Hiroshima Granite seems to be also tubular mass with layered structure consisting of different types of lithofacies. However, it is notable that the layered tabular mass was not of flat-lying type but gently inclined toward the south or southwest.

It is important that so large mass of the Hiroshima Granite had not printed significant deformation

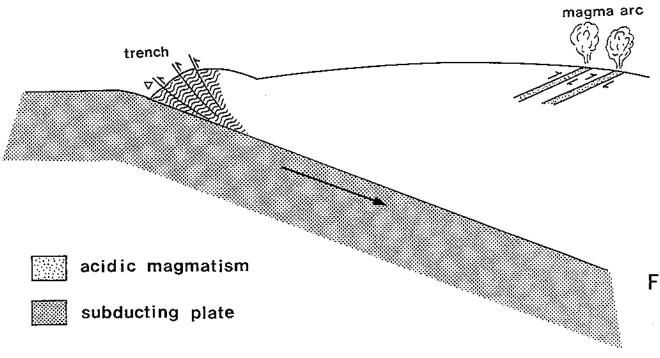

Fig. 42. Schematic diagram illustrating tectonic framework related with late Cretaceous igneous activities.

effects on the country rocks and within the mass itself through its intrusion process. Judging from such field evidences, the granite seems to have come in contact with the country rocks in rather static condition. The granite undoubtedly formed through "passive intrusion".

On the basis of the above-described evidence and consideration, it may be said that the shape of the Hiroshima Granites is a fossil of a path of magma ascend which was placed along great fracture zone. The layering within the granite mass, which consist of different type lithofacies, may indicate continuous but intermittent intrusion by magma pulse, which was controlled by intermittent activity of shear zone. The shear zone was oriented with southward inclination (Fig. 41). The northern volcanic zone must have been placed at the top of the shear zone. As mentioned before, the granodiorite in the Togouchi area is an earlier stage constituent of the Hiroshima Granite, which postdated the original rocks for the dark inclusion. The Kisa andesite and dacite may be volcanic equivalent of these rocks. The southern volcanic zone may be a branch from the shear zone for the main body of Hiroshima Granite. The Hiroshima Granite appears to be different from both the Hercynotype batholith and the Andinotype batholith (Pitcher, 1979). Anyway these two types of batholith are essentially characterized by process of vertical magma movement. While the Hiroshima Granite appears to be related to "lateral magma movement" along gently dipping shear zone. Consequently, the author wishes to propose flat-dike type mass for the emplacement mechanism of a large granite mass. Fig. 42 illustrates the general model for the granite intrusions of flat-dike type in magma arc.

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J: in Japanese, J＋E: in Japanese with English abstract.

Explanation of Plates

Plate I

1. Photomicrograph of the tonalite, near Dani, Yoshiwa.
2. Texture of the lower lithofacies of the granodiorite, near Togouchi Hongo, Togouchi.
3. Photomicrograph of the lower lithofacies of the granodiorite, near Togouchi Hongou, Togouchi.
4. Photomicrograph of K-feldspar (KF) in plagioclase (PL) from the lower lithofacies of the granodiorite, near Togouchi Hongou, Togouchi.
5. Texture of the middle lithofacies of the granodiorite, on the northwestern slope of Mt. Ichima, Togouchi.
6. Photomicrograph of the middle lithofacies of the granodiorite, on the northwestern slope of Mt. Ichima, Togouchi.
7. Texture of the upper lithofacies of the granodiorite, on the northwestern slope of Mt. Ichima, Togouchi.
8. Photomicrograph of the upper lithofacies of the granodiorite on the northwestern slope of Mt. Ichima, Togouchi.

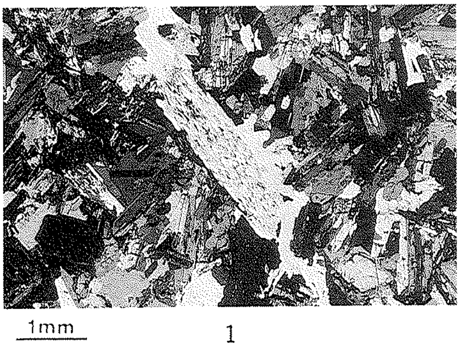
Plate II

1. Texture of the dark inclusion in the lower lithofacies of the granodiorite, near Togouchi Hongou, Togouchi Town.
2. Photomicrograph of the dark inclusion in the lower lithofacies of the granodiorite, near Togouchi Hongou, Togouchi.
3. Texture of the dark inclusion in the middle lithofacies of the granodiorite in the northwestern slope of Mt.Ichima, Togouchi.
4. Photomicrograph of the dark inclusion in the middle lithofacies of the granodiorite in the northwestern slope of Mt.Ichima, Togouchi.
5. Field occurrence of leucocratic spheres in the dark inclusion in the northwestern slope of Mt. Ichima, Togouchi.
6. Photomicrograph of leucocratic spheres in the dark inclusion in the northwestern slope of Mt. Ichima, Togouchi.
7. Texture of the dark inclusion in the upper lithofacies of the granodiorite, near Nasu, Togouchi.
8. Photomicrograph of the dark inclusion in the upper lithofacies of the granodiorite in he northwestern slope of Mt.Ichima, Togouchi.

Plate III

1. Texture of the porphyritic granite, more distinctive porphyritic type (P-type).
2. Photomicrograph of the porphyritic granite, more distinctive porphyritic type (P-type).
3. Texture of the porphyritic granite, less distinctive porphyritic type (E-type).
4. Photomicrograph of the porphyritic granite, less distinctive porphyritic type (E-type).
5. Photomicrograph of fluid inclusion in quartz in the granodiorite.

PLATE I



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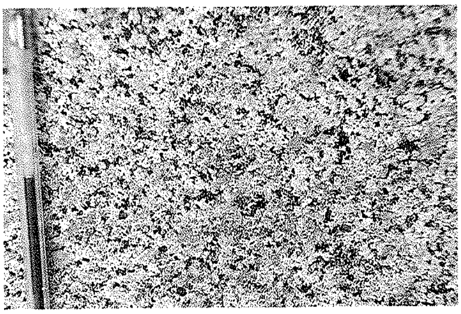

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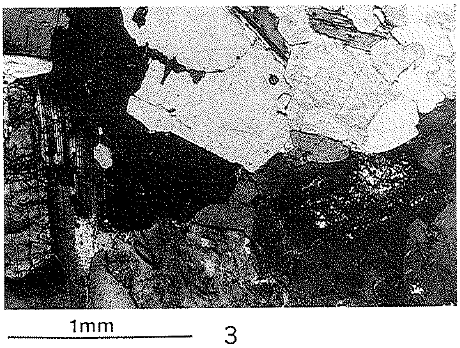

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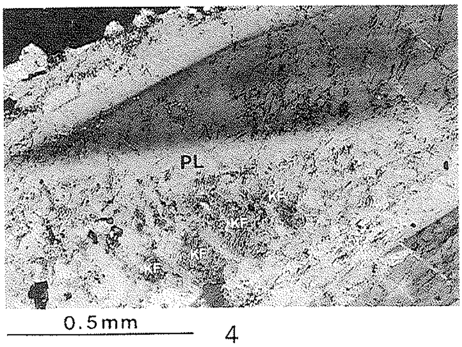

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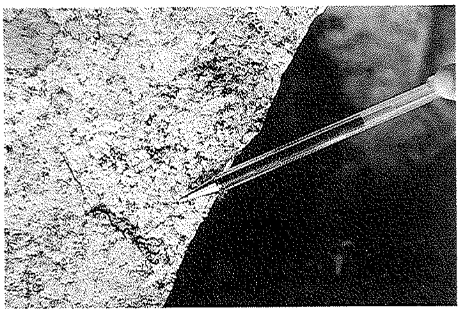

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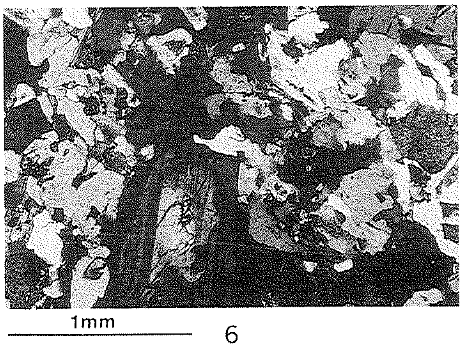

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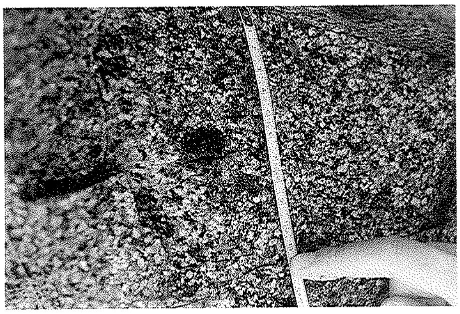

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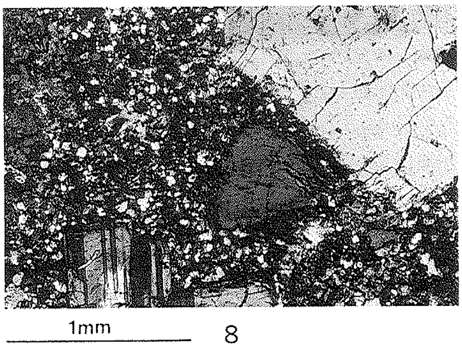

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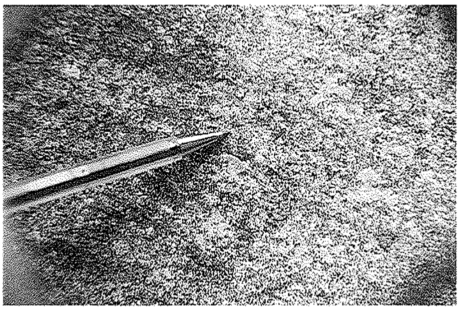

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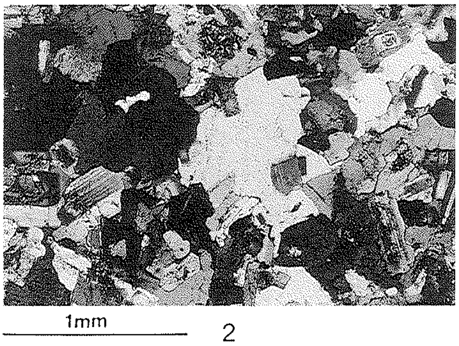

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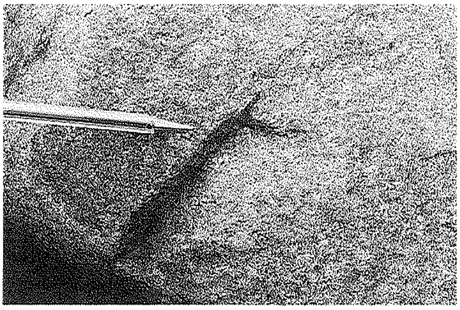

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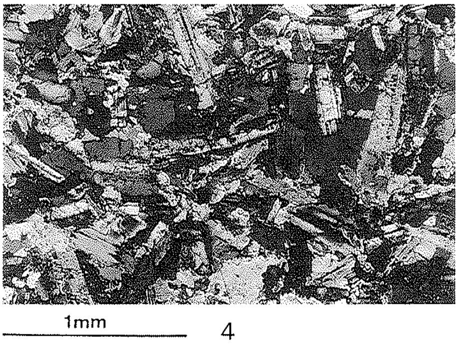

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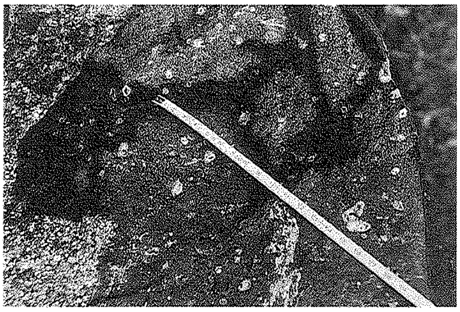

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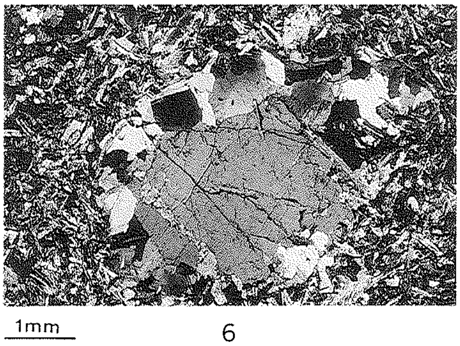

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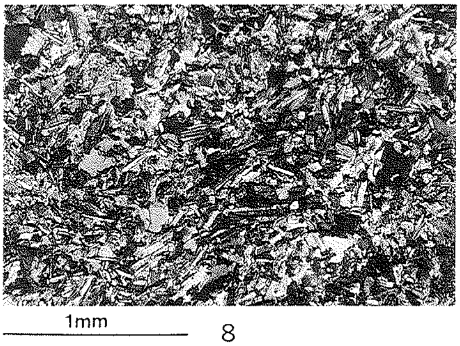

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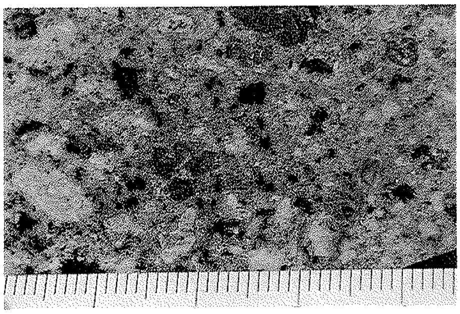

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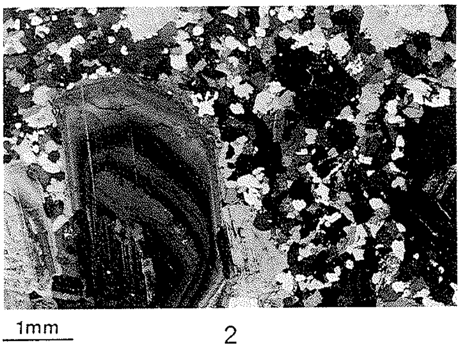

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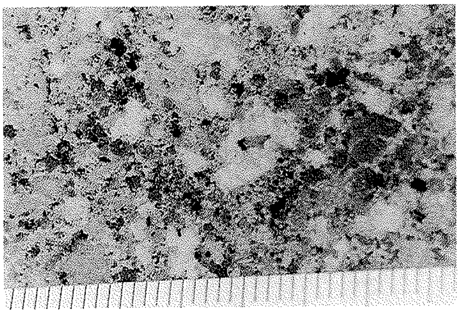

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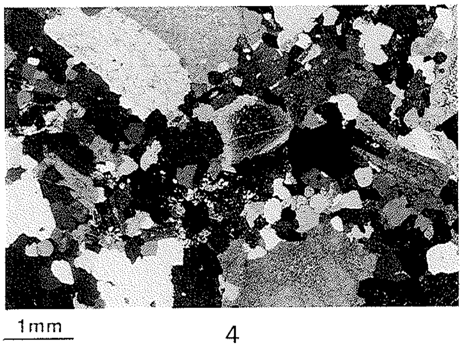

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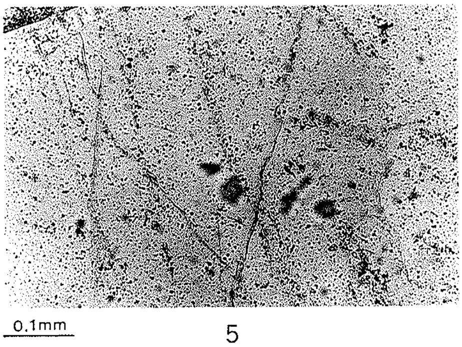

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