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ON MIGMATITES OF THE HIDAKA METAMORPHIC BELT

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(With 21 Plates and 13 Figures)
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CONTENTS

I. Introduction

1. Geological Position of the Hidaka Metamorphic Belt (Fig. 1)

The Japan Islands belong to one of the island festoons that skirt the

Pacific Ocean. The Honshū Arc of the Japan Islands includes the islands of Kyūshū, Shikoku, Honshū, and the southwestern part of Hokkaidō Island, which touches the Chishima (Kurile) Arc on the east and joins the Honshū Arc on the west respectively. The longitudinal direction of the axial part of the island of Hokkaidō coincides with that of the axis of Karafuto (Sakhalin).

In the Honshū Arc, the Ryōke-Sambagawa metamorphic belt (Hercynian) lies along the island festoon and encircles the Hida metamorphic terrane (Caledonian or PreCambrian?), the basement structure of the Japan Islands. The Alpine orogenic belt is believed to have formed concentric circles on the outside of the Ryōke-Sambagawa metamorphic belt, although it is now under the sea. It is said that the outer zone of the southwest Japan was laid down in the Alpine age and that the Hidaka belt along the axis of Hokkaidō is the northern extension the Alpine orogenic zone.

Although the orogenic belt of the Honshū Arc develops and moves from the continent toward the Pacific Ocean, the Hidaka belt moves rather from the Ocean westward to the Japan Sea. This fact indicates that the Hidaka belt is not the result of a concentric orogenic movement caused by the development of the Honshū Arc but a result of the movement of the Chishima Arc and the structural trend in the continent. It must have been affected by the movement of the Karafuto-Hokkaidō line, which coincides with the so-called Korean direction, one of the most important structural directions in the continent. The Hidaka orogenic movement is, therefore, an exception. The plutonism in the Hidaka orogenic zone is most typically represented by the Hidaka metamorphic belt surrounding the Hidaka Mountains.

The basement stratum of Hokkaidō is the Hidaka super-group, which consists of a monotonous nonfossiliferous sandstone and slate and is widely distributed in the central and northeastern regions of the island. It is deposited in the Hidaka geosyncline of pre-Cretaceous age. After the deposition schalstein was laid down in the Kamuikotan zone. Limestone and shale interbedded in the tuff contain ammonites and brachiopods, from which the formation is attributed to Jurassic, when an igneous activity, the forerunner of the Hidaka orogenic movement took place. That activity was followed by the metamorphism and plutonism of the Hidaka metamorphic belt; the plutonism went on also in the Okushibetsu and Otchube areas as a northern extension, but the most typical activity was found in the Hidaka metamorphic belt.

The Hidaka metamorphic belt, 140 km long and 10~20 km wide,

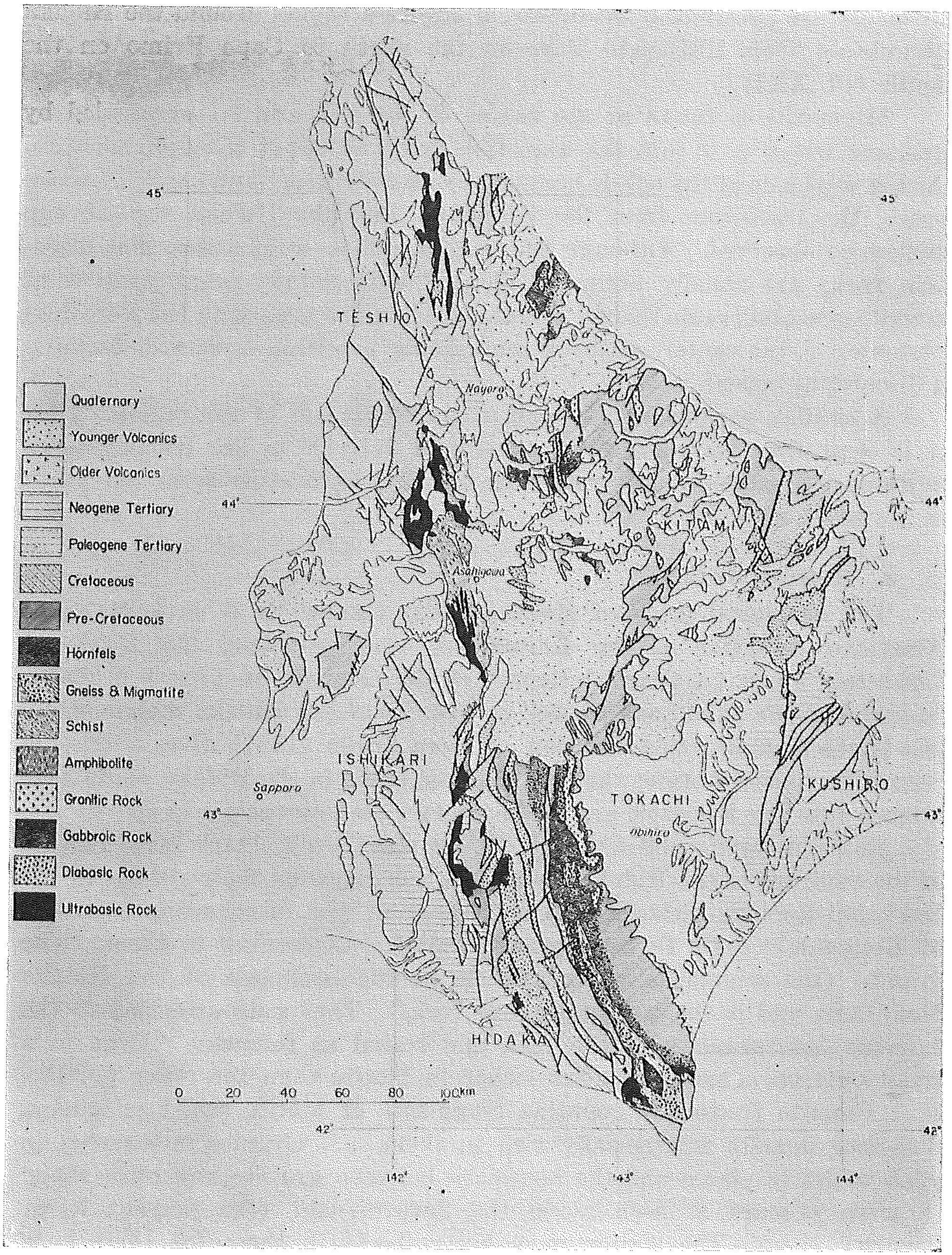

Fig. 1. Geological sketch map of the central part of Hokkaido

forms an arc protruding westward; it covers a region around the Hidaka Mountains from Karikachi Pass on the north to Cape Erimo on the south (Pl. XXI).

Migmatite is found at the center of the belt and is surrounded by gneisses which pass into the unmetamorphic sediment through hornfels. As the west side of the belt is bounded by an overthrust and basic intrusive rocks, the transition from the migmatite into the Hidaka super-group cannot be observed. Although the metamorphics, migmatites, and intrusive rocks are zonally arranged along the mountain range centers of activity are observable there. For example, in the area with the Poroshiri plutonics at the center, gabbros remarkably protrude eastward, forming a discordant massif.

A similar phenomenon is seen at the south end of the region. Thus it is clear that there are some centers of activity in the Hidaka metamorphic belt although the rocks are zonally distributed from the north to the south as a whole.

2. Historical Review

The geological study of Hokkaidō was started by B. S. LYMAN, an American geologist of the Kaitakushi, who published the Hokkaidō Chishitsu Sōron (A General Report of the Geology of Yesso) in 1877; he included the axial zone as well as granite of the Hidaka metamorphic belt in the Kamuikotan formation. Kotora JIMBO (1891) gives a detailed report, in which he states that the plutonic rocks in the Hidaka Mountains intrude into the Paleozoic and cause contact metamorphism in it.

Yōzō OKAMURA and Shinji YAMANE made preliminary investigation of the environs of the Hidaka Mountains and reported their studies in the Hokkaidō-Kōbutsu-Chōsa Hōkoku (Report of the Mineralogical Survey of Hokkaidō), early in the present century. According to them, "The granite (the migmatite of today) forms the backbone of the Hidaka Mountains and is the largest igneous rock." They paid attention to the extreme heterogeneity of the rock and stated as follows: "Even in a small outcrop, a portion is far richer in biotite than the other portion. .....Granite frequently contains fragments of biotite schist or gneiss. Schistose granite is especially rich in them......Granite is inserted in mica schist in places and the boundary between granite and mica schist is often obscure as seen along the Sarorun'ushi (the present River Saruru)....." The writer pays his respects to them for their keen observation.

Yasushi ODAIRA in the Engineering Faculty of Hokkaidō University published "Geological and Petrological Research in the Area of Horoizumi, Hidaka Province" in 1928. His research was based on the modern petrological method and contained detailed description, but his work did not develop further.

Jun SUZUKI (1934) studied the metamorphism of calcareous nodules in the southernmost part of the Hidaka metamorphic belt. His study marked the beginning of the petrological investigation of the southernmost area, which has continued to this day. In 1939 Masao ISHIBASHI examined the area of the upper streams of the Tottabetsu, Satsunai, and Hikata on the east side of the Hidaka Mountains and made clear that the most of the rock hitherto known as granite of the Hidaka Mountains was really a paragneiss and migmatite derived from sedimentary rocks. It was in 1940 that Mitsuo HUNAHASHI and Seiji HASHIMOTO began to investigate the Horoman and Oshirabetsu areas, where they found rock to describe which they used the word "migmatite" in the current sense. According to HUNAHASHI a certain diorite in the Horoman area "is not produced by a mere recrystallization, but some substance must be added from the outside. As the passage of the substance is never found, imbibition must work". (1941 graduation thesis.) His view is more advanced than that held by ISHIBASHI, who seemed to believe that the rock is formed by the contamination of granite.

The significance of the Hidaka metamorphic belt has gradually become clear through the study and discussion by many seminarists and research workers since the group for the investigating of the Hidaka was formed in 1949. The present study is one of the results of the research work.

3. Migmatite

M. ISHIBASHI in 1939 farsightedly attributed the granitic rock in the axial part of the Hidaka Mountains to migmatite.

What is migmatite? The import of migmatite, which is different in nature from the metamorphic or igneous rock and the origin and development of the term have been described by many students including J. J. SEDERHOLM. The writer enumerates the definitions.

J. J. SEDERHOLM proposed the term migmatite for the first time (Om Granit och Gneiss, 1907, p. 110). "For the gneisses here in question, characteristic of which are two elements of different genetic value, one, a schistose sediment or foliated eruptive, the other, either formed by the resolution of material like the first or by an injection from without, the author proposes the name of migmatites;.....The position of this rock group is intermediate between eruptive rocks, proper, and crystalline schists of sedimentary or of eruptive origin." The igneous component of migmatite consists of granites and it assimilates the older rock. The migmatite is therefore pertaining to granite.

In 1926 SEDERHOLM wrote in "On Migmatite and Associated Pre-Cambrian Rocks of Southwestern Finland" as follows: "It is necessary to use a designation for these hybrid rocks which really characterizes their appearance and origin. They look like mixed rocks, and they originate by the mixture of older rocks, and a latter erupted granitic magma, and therefore the name migmatite is most appropriate."

It is clear from the above that SEDERHOLM's migmatite is descriptive as well as genetic. Migmatite must have the appearance of a hybrid rock and is not homogeneous. Migmatization is the process whereby "magma injects to the older rock."

K. H. SCHEUMANN (1937) believed that knowledge of the provenance of magmatic substance was not necessary for the denomination. It is necessary that a magmatic substance which has no relation with granitic magma be produced. His concept is different from that of SEDERHOLM.

P. NIGGLI (1942, p. 36) defined migmatite as follows: "Migmatite is a rock which is very heterogeneous and magmatic and occurs in rocks or petrographic zones with a metamorphic structure. It grows in the transitional zone between magma and solid rock and is affected by a certain kind of metamorphism, during which it mostly liquefies or melts without a great voluminous change." This definition signifies a hetrogeneous mixture of old solid rock and new melt.

According to H. H. READ (1944, 1957, p. 116), "Any one who has worked in migmatite areas will admit that the products of inbibition soaking or permeation are usually medium-grained and homogeneous." Migmatite is not always a coarsely mixed rock. He further advanced the argument in 1951 (1957, p. 342) as follows: "The migmatites are mixed rocks, resulting from the mixture of any older rock with introduced material. This introduced material is often said to be magmatic, but that has to be proved in every case. Indeed, the nature, amount, and function of the introduced material provide the major problems of the migmatities. This material may vary, it seems to me, from magma to the most tenuous fluids capable of metasomatic action. The product may vary from a homogeneous rock produced by soaking to a coarsely mixed rock easily separable into relic and granitic or granitized portions......Later studies have forced most students to believe that the provenance of the *migma* portions of a migmatite is not an essential to the definition."

"This *magmatic* portion can arise in place and not be connected with granitic magma: migmatites may be special products of metamorphic differentiation." (T. F. BARTH, 1952, p. 364)

According to C. E. WEGMANN (1935), there are many types of classification of migmatite, e.g., venit, adergneiss, lit-par-lit injection, feldspar porphyroblasten schiefer od. gneiss, agmatit, etc. But these represent a few characteristics of various phenomena. The classification by the mineral composition is useless. The classification should be based on the structure and texture. "Die Migmatitforschung kann sich daher nicht nur auf das Studium von Handstücken oder einzelner Aufschlüsse beschränken; nur durch die Zusammenschau grosserer Bereiche und die Erfassung ihrer geometrischen Elemente kann sie zu befridigenden Ergebnissen gelangen." (C. E. WEGMANN, 1935, p. 310) Migmatite is, in a broad sense, a product of metamorphic differentiation. It should be classified on the basis of the structure and texture. The research can be accomplished only through analysis and understanding on a large scale.

4. Acknowledgment

The writer heartily thanks Emeritus Professor Jun SUZUKI and Professor Mitsuo HUNAHASHI who have afforded kind guidance during the course of the research. Obligation is acknowledged to members of the Hidaka Research Group, whose discussions and suggestions have promoted the work very much.

It is fitting that special mention should be made in this place of the help given by the Geological Survey of Hokkaidō and the assistance rendered by Mr. S. SUGIYAMA and Miss S. IKEDA in preparing the maps, plates and manuscript.

To comrades in the field, T. SAEKI, Y. KAWACHI, Y. OGUCHI, K. WADA, M. ISHIMURA, and T. KANAYAMA, more acknowledgment is due than can here be expressed.

II. Areas Divided on the Basis of the Tectonics[+]

1. General Geology (Fig. 2)

The Hidaka Mountains extend 140 km from north to south; they cover the Hidaka metamorphic belt where metamorphic rocks, migmatites, and intrusive rocks are zonally arranged.

The axis of the metamorphic belt or the backbone of the mountains consists chiefly of migmatite, which is surrounded by gneiss, schist, and

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[+] Migmatite tectonics of the Hidaka metamorphic belt is to be described in another paper.

hornfels east and west of the axis like beans covered by a peapod, although they do not form a perfect symmetry.

East of the backbone migmatite, banded gneiss, schistose hornfels, and unmetamorphosed sedimentary rocks lie zonally from west to east. West of the axis migmatite, plagioclase porphyroblast gneiss, and plagioclase porphyroblast schist are distributed from east to west. Thus the west side is characterized by the presence of schistose rock. The boundary between metamorphic and unmetamorphic sedimentary is marked by a great overthrust which limits the west margin of the Hidaka metamorphic belt. Therefore hornfels is locally found only in small areas on the west side of the axis.

The asymmetry is found in the distribution of plutonic rocks too. Many intrusive rocks, from basic to acidic ones, occur in the Hidaka metamorphic belt. The west and central parts of the metamorphic belt are characterized by harmonic sheets of basic rocks and the west margin is skirted by basic rocks such as peridotite, olivine gabbro and so on. But in the eastern part of the metamorphic belt, basic rocks at each massif discordantly cut across the structure of the country metamorphic rock, while granite predominates further eastward of the zone.

As a whole the zonal distribution of metamorphic rocks, migmatites and igneous rocks is remarkable. The zonal arrangement is broken by the centers of intrusions including the Poroshiri-dake massif, intrusions around Mt. Pirikanupuri, and the Horoman-Oshirabetsu massif.

The tectonics of migmatite is different from center to center. Poroshiri-dake massif is characterized by gneissose granite and an arch of biotite migmatite in the upper reaches of the R. Satsunai. The Horoman-Oshirabetsu massif is associated with groups of domes of cordierite migmatite. The intrusions around Mt. Pirikanupuri are emplaced on the boundary between biotite migmatite and cordierite migmatite, i.e., at the junction of the northern arch and southern domes. Therefore these areas have somewhat different lithologic character and structure respectively.

2. Upper Reaches of the R. Satsunai

The geologic formations of the upper reaches of the R. Satsunai consist of migmatites that occur widely south of the Poroshiri massif. Basic rocks predominate west of the axis of the Hidaka metamorphic belt.

The arrangement of rock species is given in the following table.

Geologic formations exposed in the upper
reaches of the R. Satsunai

West Unmetamorphic formation (Kamui Group)
—(Overthrust)—
Green schist
Gabbro-amphibolite (peridotite)
Brown hornblende amphibolite
Plagioclase porphyroblast biotite gneiss
Biotite hornblende gneiss
Migmatitic gneiss
Biotite migmatite
Granitic migmatite
Banded gneiss
Schistose hornfels
Hornfels
East Unmetamorphic formation (Nakanogawa Group)

The hornfels zone east of the axis is 6 km wide; it marks the outer limits of the metamorphic belt. It is composed of altered sandstone and slate and the metamorphism increases with the nearness to the metamorphic belt until it becomes a perfectly recrystallized hornfels. West of the hornfels zone through a sheared zone occurs schistose hornfels striking northwest, which is the over-all trend of the metamorphic zone. The gradual transition from hornfels to schistose hornfels can be observed only at limited places.

Leucocratic bands composed chiefly of quartz and plagioclase run parallel to the schistosity of schistose hornfels. They pass into banded gneiss when their grains become coarser. The area of banded gneiss is limited. A schistose hornfels is widely distributed again west of the banded gneiss. The hornfels is traversed by leucocratic nets at random. Palallel veins obliquely traverse the schistosity of schistose hornfels and banded gneiss in the area in question.

The axial part around the backbone of the Hidaka Mts. is composed of biotite migmatite, which is agmatitic migmatite including palaeosomes, that is, schistose hornfels, gneiss, migmatitic gneiss and amphibolite. It forms a slender arch structure. Obliquely cutting leucocratic veins of schistose hornfels and banded gneiss are the manifestation of a movement associated with the rise of the biotite migmatite to form an arch structure.

Granitic migmatite occurs like a narrow and long sheet along the outer (east) side of biotite migmatite. Small bodies of it are found in biotite migmatte.

The area is characterized tectonically by an arch of biotite migmatite and associated obliquely crossing leucocratic veins of schistose hornfels and banded gneiss.

3. Mt. Kamui Area

The distribution of rock species in the Mt. Kamui area is as follows:

Rocks exposed in the Mt. Kamui area
West Unmetamorphic formation (Kamui Group)
—(Overthrust)—
Green hornblende amphibolite
Brown hornblende amphibolite
Biotite hornblende gneiss
Biotite (or cordierite) migmatite
Banded gneiss
Granite
Schistose hornfels
Hornfels
East Unmetamorphic formation (Nakanogawa Group)

In this area a zone of honrfels, 4 km wide, is separated from schistose hornfels through a sheared zone. The schistose hornfels is likewise separated from banded gneiss through a sheared zone at some places or they merge into each other at some places. Schistose hornfels, I km wide and about 5 km long, occurs in banded gneiss zone. According to HASEGAWA (1958, p. 17) the hornfels protrudes westward in an arc, forming an anticline.

There are biotite migmatite (Hasegawa's agmatitic migmatite) north of the Mt. Kamui area and cordierite migmatite (HASEGAWA's biotite migmatite) south of it. They join in the area. The area is characterized by the presence of the Nupinai granite, which is the only one granite within the metamorphic zone, and it concordantly intrudes along the banded gneiss. The granite contains scanty potash feldspar and is of the character of tonalite. It gradually merges into granitic migmatite to the west (core).

4. Southernmost Area

The metamorphic belt along the Hidaka Mountains generally is about 20 km wide, but it swells to 30 km in width in the southernmost part to cover an area from Horoman, Hidaka province to Oshirabetsu, Tokachi province. The hornfels zone in the east side of the belt is 3 km wide and extends to the northward. The boundary between hornfels and schistose hornfels cannot be exactly made clear because of the intrusion of gabbros and of a sheared zone in the middle reaches of the R. Saruru. In the southwestern side the hornfels belt surrounds the Opira gabbro and attains considerable width along the extension of the gabbro. The schistose hornfels on the southwest side merges into plagioclase porphyroblast biotite schist or gneiss.

The area is characterized by domes of cordierite migmatite, of which the Oshirabetsu dome (KIZAKI, 1956), and Toyonidake dome (KASUGAI, 1957) are the most remarkable. There is an anticlinal dome about Mt. Rakko at the center north of the Oshirabetsu dome. Banded gneiss is distributed around these domes. There are granitic migmatite and gneissose migmatite along the boundary of these domes.

III. Petrography

1. Sedimentary Rocks

The Hidaka super-group which signifies the geosynclinal deposits in the Hidaka orogeny includes all the sedimentary rocks that surround the Hidaka metamorphic belt.

The Hidaka super-group is divided into the Sorachi, Kamui and Nakanogawa Groups. The Sorachi group (upper Hidaka super-group) consists mainly of schalstein and chert, which are accompanied by shale and sandstone. The Kamui group (middle Hidaka super-group) is composed of an alternation of shaly slate and sandstone with thin layers of schalstein. The Nakanogawa group (lower Hidaka super-group) is composed of an alternation of slate and indurate fine-grained sandstone (graywacke). It is monotonous although thin layers of conglomerate are interstratified in places.

The Kamui group and schalstein layers mostly occur west of the Hidaka metamorphic belt. Jurassic fossils have been discovered from the upper part of the Sorachi group. The relation between the Nakanogawa and the Kamui groups is not clear. They are assigned to pre-Cretaceous, including Jurassic and pre-Jurassic.

Nakanogawa Group

The Nakanogawa group is chiefly found east of the metamorphic belt; it consists of black fine-grained sandstone interbedded partially by black slate. The black slate, alternated thin layers in sandstone is generally massive and rarely possesses a well-developed fissility. The sandstone is hard, bluish dark gray, and graywacke-like. Lithologically it is monotonous without variation.

From the state of alternation of sandstone and slate the stratigraphic position can be known; it serves to make clear the structure of the Nakanogawa group. A dislocation that resulted from a minor fault is developed only on the slaty portion; it indicates a disturbance during the deposition in a geosyncline. A black small-grained sandstone is slightly arkosic; it abundantly contains fragments of quartz, chert, together with feldspar and pieces of sandstone and slate. As faults and shears caused by a later displacement are fewer in the Nakanogawa group than in the Kmui group, it is possible to verify the structure of the former by means of the gradational transition of alternating layers.

The general strike is N 10° W in the southern part, but it leans to the east in the northern part. The direction of folding axis is N 40° E in the neighbourhood of the upper reaches of the R. Satsunai. The dip is generally steep, about 50° at the lowest. Isoclinal foldings dipping southeastward or northwestward are repeatedly met with.

Kamui Group

The Kamui group is distributed west of the metamorphic belt; it is characterized chiefly by an alternation of sandstone and slate. Chert and limestone are interbedded in some places. Some portions include abundant schalstein. Slate is slightly shaly. Sandstone is composed of black fine-grained sandstone and graywacke. From lithological characteristics the Kamui group can be classified into some units, but their mutual relation is unknown as they are separated from each other by faults and do not possess any key bed. The structure of the Kamui group cannot be clarified without great difficulty because it is intensely crushed, sheared, and displaced. It generally strikes N 20°~40° W and dips steeply eastward.

In the west, shearing that resulted from the overthrusting of the metamorphic zone is extreme, runs parallel or oblique to the metamorphic belt, and forms cataclasite and phyllite.

The cataclasite is derived from the slate and/or fine-grained sandstone and is brownish dark gray or bluish gray in color. Under microscope it is seen to have a cataclastic texture with crushed plagioclase and quartz. The spaces around the crushed particles are partly filled with recrystallized fine-grained quartz. The rock is stained dark color as a whole. Some of the cataclasite which is composed of fine quartz grains less than 0.01 mm, is so finely grained that the original texture is nearly destroyed. The space between the quartz grains is filled with minute flackes of sericite, and chlorite accompanied by opaque minerals. The rock resembles quartz schist. Phyllite which shows a well-developed fissility, is siliceous.

The Hidaka super-group is monotonous sediment and forms the geologic foundation of Hokkaidō excepting the southwestern part. It is nothing but the sediment deposited in the Hidaka geosyncline, and the source of the Hidaka metamorphic rock. The structural discordance between the Hidaka super-group west of the metamorphic belt and that east of it, is important for locating the metamorphic belt.

2. Metamorphic Rocks

A. Hornfels

Hornfels is most widely distributed east of the metamorphic belt. In the west it is found in the vicinity of Karikachi Pass and covers small areas adhering to the overthrust.

East of the metamorphic belt the hornfels ranges 3 to 8 km in width except near the R. Tottabetsu where it is 1 to 1.5 km wide because of the eastward expansion of plutonic rock. It ranges from altered sandstone and slate to perfectly recrystallized hornfels. Based on the lithological characters it is classified as follows:

(i) Altered sandstone and slate
(ii) Biotite hornfels
(iii) Cordierite hornfels
(iv) Andalusite hornfels
(v) Garnet hornfels
(vi) Hypersthene hornfels

(i) Altered sandstone and slate

The zone of altered sandstone and slate, as wide as 5~6 km, extends from north to south between the unaltered rock and the hornfels along the east side of the hornfels zone. The process through which the unaltered Hidaka super-group transits to the metamorphic rocks can be observed only east of the metamorphic belt.

Altered sandstone and slate are generally massive, and the original stratification of alternation remains. A slaty part exists only in the neighbourhood of the metamorphic zone slips; it is disturbed.

Colorless or light brown anhedral biotite crystallizes out in the cementing substance composed of minute grains, 0.3 mm across, of plagioclase and quartz. The layered structures of sediment are preserved, though the growth of the anhedral biotite indicates the alteration. Biotite is more easily formed in sandstone than in slate.

(ii) Biotite hornfels

Biotite hornfels, several hundred meters to 1 km wide, is meridionally distributed west (in the inside) of the zone of altered sandstone and slate at the east of the metamorphic belt.

West of the metamorphic belt, biotite hornfels occurs in the neighbourhood of Karikachi Pass; in a few areas, it lies separately along the overthrust being several meters to some dozen meters wide ranging up to scores of meters.

The biotite honfels is massive, reddish-brown, and indurate; the original structure of the provenance is hardly clear. In specimens that are derived from the alternation of sandstone and slate, however, the arrangement of the carbonaceous substance in the argillaceous portion indicates a sedimentary structure even though the arenaceous portion is perfectly recrystallized.

Under the microscope the rock is seen to be equigranular (0.05~0.1 mm) with a typical hornfels texture. Quartz biotite plagioclase. Muscovite and hornblende are included in some places. Minute grains of iron ore are universally present. There are two varieties of quartz grains. One of them is less than 0.1 mm, recrystallizes as a matrix and becomes still smaller. The other variety is about 0.1 mm in size and rounded. Most biotite is about 0.05 mm and anhedral. Some biotites possesses a tabular structure and is subhedral. x=light brownish green light brown, y=brown, z=brown. γ=1.640±. Plagioclase is anhedral to subhedral, 0.05~0.1 mm, and mostly grows without twinning, An 30. Muscovite grains are generally few, but near a shear zone or a diabase dike they are abundantly found, leafy, and about 0.01 mm in diameter.

(iii) Cordierite hornfels

Cordierite occurs locally in biotite hornfels zone. It is found in the vicinity of Ochiai near Karikachi Pass and east of the metamorphic belt. Cordierite at Kanenosawa south of Ochiai is typical, where hornfels is exceedingly sheared and distinctly schistose with relict crystals showing layered structure of the original rock. Cordierite is associated with garnet and andalusite. Small cordierite "augen" are numerous in the part of biotite hornfels which is extremely schistose like phyllite along the eastern margin of the schistose hornfels zone. It is reported that there is a five meter thick schistose rock with many cordierites in the upper stream of the Kinen-zawa (HASHIMOTO, 1953).

Cordierite grains are 0.5~1.0 mm in size, as large as 5 mm, porphyroblastic, and anhedral. A few pseudohexagonal twinnings are found. Cordierite usually alters to pinite.

(iv) Andalusite hornfels, (v) Garnet hornfels

Andalusite hornfels and garnet hornfels are limited in locality. Most of them, garnet especially, are associated with cordierite. Andalusite hornfels is reported as cordierite-andalusite-garnet hornfels in the vicinity of Ochiai, Karikachi Pass (Madō, 1951). Garnet hornfels has been reported in the southernmost area (IGI, 1956).

(iv) Hypersthene hornfels (HASHIMOTO, 1953)

The hornfels occurs at a small area about the granite on the left of the middle stream of the R. Tottabetsu in the northern part of the metamorphic belt. Very coarse-grained hornfels is well developed like a pool near the contact with granite. The country rock is biotite hornfels derived from black slate. Plagioclase (An 35-30), 1~2 mm, is porphyroblastic and is associated with poikiloblastic quartz and potash feldspar. Porphyroblasts of plagioclase in which small hypersthene crystals are included, show a graphic texture resulting from the replacement of plagioclase by quartz along the cleavage and zonal structure.

B. Schistose Biotite Hornfels

Schistose hornfels is fundamentally different from massive biotite hornfels in texture. The latter has been subjected to thermal metamorphism, in which the original texture and the position in the Hidaka super-group, remain unchanged. Although the lithologic character of the former is nearly the same as that of the latter, it is characterized by schistosity, which is parallel to the general strike of the metamorphic zone and oblique to the over-all trend of the Hidaka super-group. Schistose biotite hornfels in this region is generally separated from biotite hornfels by a sheared zone. The former rather belongs to gneiss from the structural point of view.

Based on the presence of a biotite spot the rock is divided into two sorts: schistose biotite spotted hornfels and schistose biotite hornfels. The former is located east of the metamorphic zone, and the latter west.

Assemblages of the associated minerals are as follows:

Quartz-plagioclase-biotite
Quartz-plagioclase-biotite-muscovite-cordierite
Quartz-plagioclase-biotite-muscovite-cordierite-garnet
Quartz-plagioclase-biotite-muscovite-garnet
Quartz-plagioclase-biotite-muscovite-garnet-sillimanite
Quartz-plagioclase-biotite-(cordierite)-potash feldspar

The combination of quartz, plagioclase, and biotite is the most important. The schistose biotite hornfels is classified into three types as follows:

(i) Schistose biotite spotted hornfels
(ii) Schistose biotite hornfels
(iii) Other schistose hornfels

(i) Schistose biotite spotted hornfels

Schistose biotite spotted hornfels is intermediate between hornfels and banded gneiss and occurs east of the metamorphic belt. The body is narrow, long and scores of meters to one kilometer wide; it runs parallel to the metamorphic belt, striking northwest. The schistosity of the schistose biotite spotted hornfels is stronger westward generally. A leucocratic band is produced along the schistosity of the rock until it passes into a banded gneiss. In the migmatite zone, i.e., in the core zone of the metamorphic belt in the upper streams of the R. Satsunai, Nakano, and Saruru, schistose biotite spotted hornfels is fairly widely distributed; in it the schistosity is not very remarkable, and the leucocratic vein is not banded, but forms a network. The rock is directly agmatized as palaeosomes without passing through gneiss.

The rock is reddish brown and intensely schistose with spots of biotite arranged on foliation planes. Microfolds and lineation are distinct.

The microscope reveals the following facts. A flat biotite spot which is 1 mm in diameter and an aggregation of minute particles lies with a preferred orientation in a homogeneous matrix. The matrix is perfectly recrystallized. The grains, 0.1 mm, are equigranular without preferred orientation in part, but the matrix shows a parallel texture. Some quartz grains, 0.5~1 mm in diameter, are porphyroblastic and show slight undulate extinction. Plagioclase mostly is anhedral or subhedral without twinning, although some twins occur after the albite law. An 30-35. Biotite, 0.1 mm, is leafy and aggregates to a spot. x=light brownish green, y=brown, z=brown, $\gamma=1.635$. Iron ore, apatite, orthoclase, and muscovite are accessory constituents.

(ii) Schistose biotite hornfels

Schistose biotite hornfels is distributed from the west of the Horoman massif in the southernmost area to the west of the Toyonidake migmatite dome. It skirts the west (out) side of plagioclase porphyroblast biotite gneiss, and northward from the vicinity of Oizumi, it merges into plagioclase porphyroblast biotite schist in the direction of the strike. West of the Toyonidake dome it is the widest, attaining 2~4 km. Further west it is separated from the unmetamorphosed Hidaka super-group by the Asahi-Chipira fault.

Various basic rocks intrude into the schistose biotite hornfels, react on it, and form characteristic metamorphic rocks such as hornblende-cordierite-garnet schist (HUNAHASHI, 1948; HUNAHASHI and IGI, 1956).

The shistosity is variable, some rock being nearly massive while other is like biotite schist, but the hornfels texture is clear. The biotite spot is not present. The process that forms schistosity is as follows: After a rock is converted into hornfels, a fine slipping plane is formed in it to a definite direction. On the plane a pale band composed chiefly of quartz is produced. The rock generally is resinous, dark brown, and schistose. Lineations are remarkable.

Quartz and plagioclase are equigranular, grains being mostly less than 0.1 mm in size and possessing a mosaic texture. Plagioclase is anhedral or subhedral. Twins are not many. An 30±. Biotite is anhedral and leafy (0.3 mm) or cloudy and fills the spaces around plagioclase grains. x=greenish light brown, y=gellowish brown, z=reddish brown. r=1.637~1.643. Orthoclase, muscovite, minute scales (0.01~0.05 mm) of iron ore and apatite occur scatteringly. Iron ore takes the form of magnetite and pyrrhotite, which is disseminated not only in the hornfels zone but in the migmatite and gneiss areas.

(iii) Other schistose hornfels

Schistose hornfels containing cordierite, garnet, and/or sillimanite are locally distributed in the northern area and in the southernmost area of the Hidaka metamorphic belt.

Cordierite, 0.5 mm, is found as small porphyroblasts in spawn-shape. It mostly alters to pinite and usually associates with muscovite and garnet. Bits of garnet, about 5 mm in diameter, are granular, subhedral or euhedral, and probably belongs to almandine. Sillimanite is found as minute needles.

C. Plagioclase Porphyroblast Biotite Schist

Plagioclase porphyroblast biotite schist, in an area 1~2 km wide and 20 km long, is found only in the west side of the southernmost area. It lies between the overthrust and the gabbro amphibolite zone along the west side of the Horoman massif. Southward it gradually merges into schistose biotite hornfels along the strike. The plane of foliation generally strikes NNW and dips 60° E. Near the R. Onarushibe the dip is nearly horizontal, thrusting westward. The same phenomenon is met with in the southern part of the pyroxene peridotite near Horoman.

The rock is yellowish brown and very foliated and has a well-developed foliation plane spotted with many plagioclase porphyroblasts.

Under the microscope it can be seen that the rock has a schistosity with strong preferred orientation and that spindle-shaped plagioclase porphyroblasts are enclosed with quartz and biotite which appear to have been crushed. Important constituent minerals are plagioclase, quartz and biotite. Usual accessory minerals are zircon, apatite, and iron ore. Porphyroblastic plagioclase, 0.5~1 mm in length, is in the shape of spindles and An 30±. Quartz, less than 0.1 mm in diameter, mostly is irregularly granular and shows wavy extinction. Biotite, 0.05 mm in diameter, is leafy, partly shows undulatory extinction, and twinned. x=yellow, y≒z= reddish brown. It partly merges into chlorite. Cordierite, about 0.1 mm in diameter, takes the form of porphyroblasts, and includes minute grains of quartz. Usually it alters to pinite. Garnet, 0.1 mm in diameter, is granular and rarely euhedral.

D. Gneisses

Zones of gneisses are meridionally distributed on both sides of the migmatites. Banded biotite gneiss is on the east side and plagioclase porphyroblast biotite gneiss, biotite hornblende gneiss and most of migmatitic gneiss on the west side.

They do not uniformly occur from north to south. Their distribution and width are variable due to the structure and igneous activity. They are classified as follows:

(i) Banded biotite gneiss

(ii) Plagioclase porphyroblast biotite gneiss

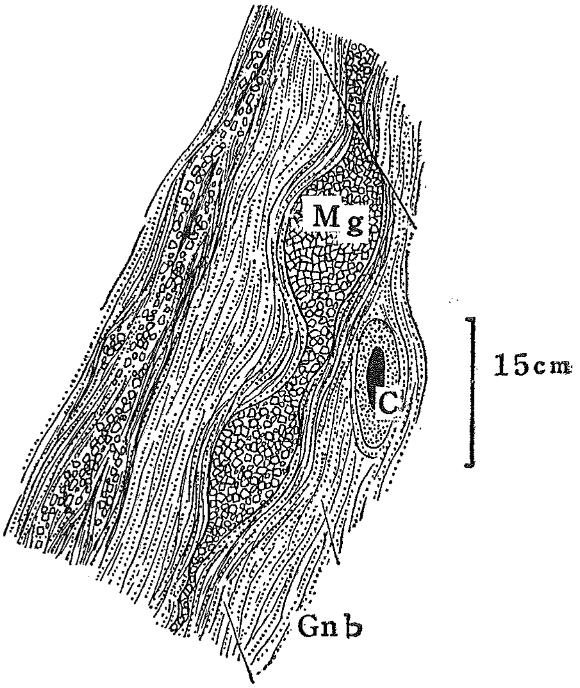


Fig. 2. Plagioclase porphyroblasts occurring in sheared part of banded biotite gneiss (Gnb) aggregate to make granitic migmatite (Mg), C: (calcareous nodule)

(iii) Biotite hornblende gneiss
(iv) Migmatitic gneiss

(i) Banded biotite gneiss

All those gneisses which occupy the eastern part of the metamorphic belt belong to the banded biotite gneiss type. They generally occur between the schistose hornfels and the migmatite zones. But a long narrow belt of banded biotite gneiss is west of gneissose granite in the upper reaches of the R. Pipairo. A narrow belt of the rock occurs locally west of schistose hornfels in the upper stream of the R. Satsunai. It is as wide as 3 km, and interbeds schistose hornfels in it in the upper reaches of the R. Nakano. Mostly it is only several meters wide at the margin of the Oshirabetsu dome, and it is interstratified between cordierite migmatite domes in the southernmost area.

It gradually merges into schistose biotite spotted hornfels and transits to migmatite abruptly. A leucocratic band grows along the plane of schistosity of schistose biotite hornfels. The quantity of the band increases and the rock becomes more coarse-grained until it passes into banded gneiss. Banded biotite gneiss is made up of white bands composed of leucocratic minerals and brown ones chiefly of biotite. The bands vary from 2 to 10 mm in width; they are usually marked with a microfold and a ptygmatic fold. Clear lineation is produced on the plane of foliation by the microfold and the arrangement of biotite.

The leucocratic portion is chiefly composed of quartz and plagioclase 0.5~1 mm in size; a small quantity of biotite is associated with it. Plagioclase partly is porphyroblastic (1 cm) in which inclusions of biotite and quartz are abundant. An 25-35. A basic portion consists essentially of biotite with a small amount of plagioclase and quartz. A remnant of schistose hornfels texture remains in a basic portion of low grade banded biotite gneiss. The rock generally is granoblastic. The parallel arrangement of biotite is remarkable. Biotite is 0.5~1.0 mm in size; x=light brown, $y \fallingdotseq z$=reddish brown; $r=1.634\sim1.642$. An of plagioclase attains 45 percent in basic brown band. Orthoclase, muscovite, apatite, and magnetite are usually met with. Orthoclase is anhedral and fills the space around other minerals, forming myrmekites. Cordierite, garnet, and fibrous sillimanite occur as accessory minerals.

(ii) Plagioclase porphyroblast biotite gneiss

Plagioclase porphyroblast biotite gneiss is typical representative of the gneisses west of the metamorphic belt. A zone of it, about 3 km wide, occurs east of plagioclase porphyroblast biotite schist and west of the Horoman plutonic massif in the southern area. It merges into schistose biotite hornfels along the strike in the southern area. From the middle to the northern area the rock branches into septa several to scores of meters wide and is intercalated in gabbro amphibolite or gabbro. The gneiss contaminated with amphibolite forms biotite hornblende gneiss.

Plagioclase porphyroblast biotite gneiss consist chiefly of biotite with many spots of plagioclase porphyroblasts. It is dark brown and has a strong schistose structure. Plagioclase porphyroblasts, 2~3 mm in size, concentrate along the plane of schistosity and form a band or a belt, several meters thick, developing a coarse-grained rock (migmatitic gneiss).

Under the microscope the rock is seen to have gneissose texture with conspicuously porphyroblastic plagioclases. Quartz and biotite among the porphyroblasts are crushed and compressed in a definite direction.

Principal minerals are plagioclase, biotite and quartz. Garnet, apatite, zircon, and iron ore are associated accessorily. Plagioclase grains are generally less than 1.5 mm in size, ellipsoidal, phenocrystal, slightly decomposed, and mostly sericitized inside. An 30-40. Biotite is about 0.2 mm in size, leafy, of preferred orientation, usually curved, strongly pleochroic, x=greenish light brown, y=brown, z=reddish, brown, γ=1.641. Quartz is less than 0.1 mm in size and irregular, form matrix, and shows wavy extinction. Garnet occurs usually in the rock from north to south, and is porphyroblastic, 0.2~0.5 mm in size. A few potash-feldspars form myrmekites. Andalusite porphyroblasts are found in the southernmost area.

(iii) Biotite hornblende gneiss

The gneisses described above are derived from sediments, but biotite hornblende gneiss is migmatized amphibolite.

It is distributed between the gabbro amphibolite and the migmatite zone in the area from the middle to the south of the metamorphic zone. It is not found near Mt. Kamui because migmatite protrudes westward there. The alternation of the plagioclase porphyroblast biotite gneiss and the sheet of amphibolite occurs at the southern extension of the biotite hornblende gneiss. In the northern area the blocks of amphibolite scatter or make a boudinage structure in the plagioclase porphyroblast biotite gneiss.

The biotite hornblende gneiss is very heterogeneous; a several meters thick layer of it alternates with coarse-grained migmatitic gneiss; the layers of five centimeters in thicknss that are composed chiefly of either hornblende or biotite make a banded structure. As a whole the rock is medium- or coarse-grained; it possesses strong schistosity and preferred orientaiton of minerals.

The microscope reveals that the rock is equigranular and granoblastic, has preferred orientation. It consists chiefly of plagioclase, hornblende and biotite, associated accessorily with quartz, apatite, zircon, and titanite. The plagioclase, 1~1.5 mm in size, is porphyroblastic which is anhedral to subhedral and partly shows ellipsoidal. An 35-45. Hornblende is 1 mm in size; $c \wedge z = 15^\circ \sim 22^\circ$; x=colorless, z=light brown~brownish light green. Biotite (1 mm) is leafy; x=light brown, $y \doteqdot z$=reddish brown.

(iv) Migmatitic gneiss

Migmatitic gneiss is scattered as small sheet-like bodies near the boundary between the plagioclase porphyroblast gneiss and biotite migmatite from the upper stream of the R. Satsunai of the northern area to the southernmost area. It corresponds to the portion of biotite hornblende gneiss that is free from hornblende. The color of biotite is darker than that of the other gneisses and migmatites.

Under the microscope it can be seen that the rock is granoblastic with plagioclase porphyroblasts. Principal minerals are plagioclase quartz biotite while accessory ones are garnet, muscovite, apatite, zircon, titanite, and iron ore. Plagioclase, 1~1.5 mm in size, usually is ellipsoidal, porphyroblastic. An 30-40. Quartz fills the space around particles of other minerals, and is irregular; it shows wavy extinction. A leaf of biotite surrounds plagioclase grains. x=brownish light green, y=brown, z= reddish brown. $\gamma=1.640$. Garnet is common, 1.5 mm in size, and porphyroblastic. Small grains of quartz, 0.1 mm in size, are included in a poikilitic condition of garnet.

Migmatitic gneiss in the upper reaches of the R. Soematsu of the middle area contains many porphyroblasts of garnet (HASEGAWA, 1958). The garnet possesses a cleavage perpendicular to the schistosity and includes grains of quartz and feldspar in a poikilitic state. The biotite in the migmatitic gneiss in question is pleochroic x=light yellow, $y \doteqdot z$ dark brown.

3. Migmatites

In the core of the Hidaka metamorphic belt, granitic rocks extend meridionally. The rocks occurring between two zones of the gneisses and being partly overlain with gabbro were formerly believed to be a kind of granite but now are assigned to migmatite on the basis of the following facts:

a) The granitic rock in question transits gradually from gneiss.
b) Remnants of the original gneissic structure remain in the so-called "granite" or "quartz dioritic rock."

c) Gneiss and/or hornfels exists as palaeosomes in migmatite.

d) A thin layer of amphibolite embedded in gneiss extends for a distance possessing original sheet-like structure even in the case where the country rock may be granitized.

e) Many calcareous nodules which have been metamorphosed are preserved as relics in gneisses and migmatites.

f) Microscope reveals that the granitic rock possesses a granoblastic texture, a product of metamorphism, in which plagioclase shows a round form.

g) Porphyroblasts of plagioclase are found in it.

Based on the occurrence and mineral composition the migmatite is classified as follows:

(i) Biotite migmatite
(ii) Cordierite migmatite
(iii) Gneissose migmatite
(iv) Granitic migmatite

(i) Biotite migmatite

Biotite migmatite, 1~5 km wide, is distributed along the main ridge of the Hidaka Mountains from the upper reaches of the R. Satsunai to the neighbourhood of Mt. Kamui forming a structural unit.

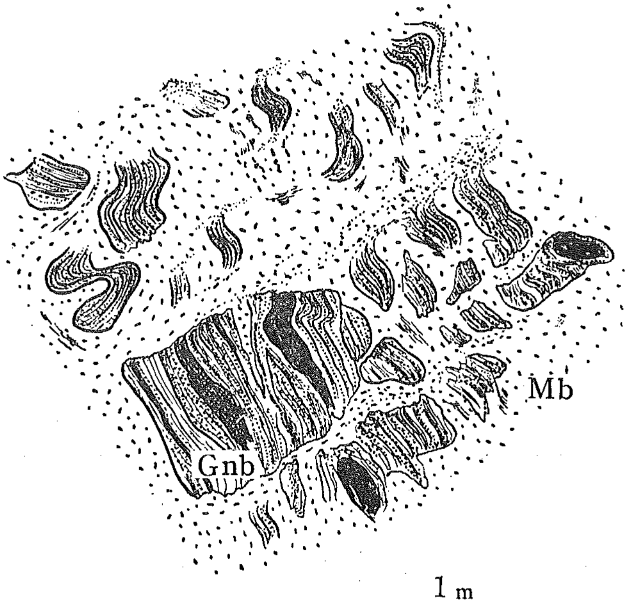


Fig. 3. Agmatitic part of biotite migmatite (Mb)

In the east side, migmatite is usually derived from banded gneiss and partly from polyvenite. The transformation generally is gradual, but unconformity is met with in places for blocks of schistose hornfels, gneiss, and migmatitic gneiss have been enclosed as palaeosomes (Figs. 3, 9).

The biotite migmatite shows an arch structure, which slopes northward and southward with its center in the vicinity of the upper stream of the R. Satsunai.

The rock is medium-grained and light gray and shows a slight preferred orientation. It is an agmatitic rock containing many palaeosomes such as gneisses, schistose hornfelses, amphibolites, and gabbros which are spindle-like from several to scores of centimeters in size, and schlieren composed of biotite.

Under the microscope the texture of the rock is seen to be granoblastic. The essential minerals are plagioclase>quartz>biotite whilst the accessory minerals are hornblende, potash feldspar, muscovite, apatite, chlorite, titanite, and iron ore. Plagioclase (1~2 mm) is rounded, anhedral or subhedral, partly saussuritized, and mostly fresh. Various twins are met with the albite twin being predominant. An 35±. Quartz grains, about 1 mm, are anhedral and fill the space around other minerals. Biotite (1~1.5 mm) shows a weak preferred orientation and a subhedral. x=brownish light green, y=brown, z=reddish brown; r=1.638. Hornblende, 1 mm in size, is light green and weakly pleochroic; it has a poikilitic texture with minute grains of quartz. Potash feldspar forms myrmekites and fills the space around other minerals.

Palaeosomes of gneiss:

The palaeosomes of gneiss in migmatite are slightly different from original gneiss mineralogically and more basic chemically. Plagioclase which is more calcic than that of true gneiss possesses a poikilitic or a sieve texture. An 35-45. Green hornblende grows in a poikilitic condition. Apatite and iron ore are relatively abundant.

(ii) Cordierite migmatite

Cordierite migmatite occurs from Mt. Pirika to the southern area. It can be roughly classified into three structural units. Each unit has a dome at the center and each dome is enclosed with gneiss. The northern unit along the ridge of the mountains is made up of an eastward inclining anticlinal dome of 6 km width and 20 km length. It is accompanied by the Oshirabetsu dome to the southeast and the Toyonidake dome to the southwest.

The Oshirabetsu dome, 2.5 km wide, is like a northward sinking fireball. The Toyonidake dome, 5 km wide, inclines northwest; it comes in contact on the east with schistose hornfels which has been brought there by a fault, and on the western front adjoins also schistose hornfels in which lie small lenses of cordierite migmatite. Banded biotite gneiss always occurs along the transitional zone (KASUGAI, 1957).

Palaeosomes, as large as 5~100 cm, occur in the cordierite migmatite which is agmatitic. Irregular pools of quartz are always present alongside of these palaeosomes. Palaeosomes are mostly elongated into ellipsoids without definite direction, showing S shape structure or rotation. The rock is light bluish gray, medium-grained, with slight preferred orientation. The migmatite which contains abundant cordierite shows peculiar light bluish gray.

Under the microscope the rock is seen to consist chiefly of plagioclase, biotite, quartz with subordinate amounts of cordierite, muscovite, potash feldspar, apatite, zircon, sphene, garnet, sillimanite and iron ore. Plagioclase, about 1 mm in size, is slightly subhedral ellipsoidal with many albite twins. An 30-35. Quartz, 0.5 mm, is anhedral. Usually quartz fills the space around components, and is porphyritic (1.0 mm) in part. Biotite pieces, 0.5~1.0 m, are flat; x=greenish light brown, y=brown, z=reddish brown; r=1.643~1.647. The amount of cordierite varies according to the locality, so that there is no cordierite at some localities. Generally cordierite is ellipsoidal in form, porphyroblastic, subhedral or anhedral and turns into pinite. $2V_X=45\pm$. $\beta=1.558$. A little muscovite is present, but in some places muscovite develops well, entirely replacing biotite. Hornblende is locally found, anhedral or subhedral, light green and very weak pleochroic. Garnet, 0.5 mm, is granular and sometimes decomposes into a fine plate of biotite.

(iii) Gneissose migmatite

A gneissose migmatite belt, 1~2 km wide and 15 km long, is distributed in cordierite migmatite in the middle reaches of the R. Saruru in the southernmost area.

The gneissose migmatite exhibiting alternations of cordierite migmatite with banded gneiss or schistose hornfels shows the structure of a lit-par-lit injection gneiss; it folds on a various scale. The main characteristic of this migmatite is that large porphyroblasts of cordierite and sillimanite are developed. Locally potash feldspar quartz are present. Their porphyroblasts exist together or one of them does predominate. They push away the plane of schistosity in order to grow. Quartz and potash feldspar are met with in the portion of a leucocratic band that is produced by segregation concentration.

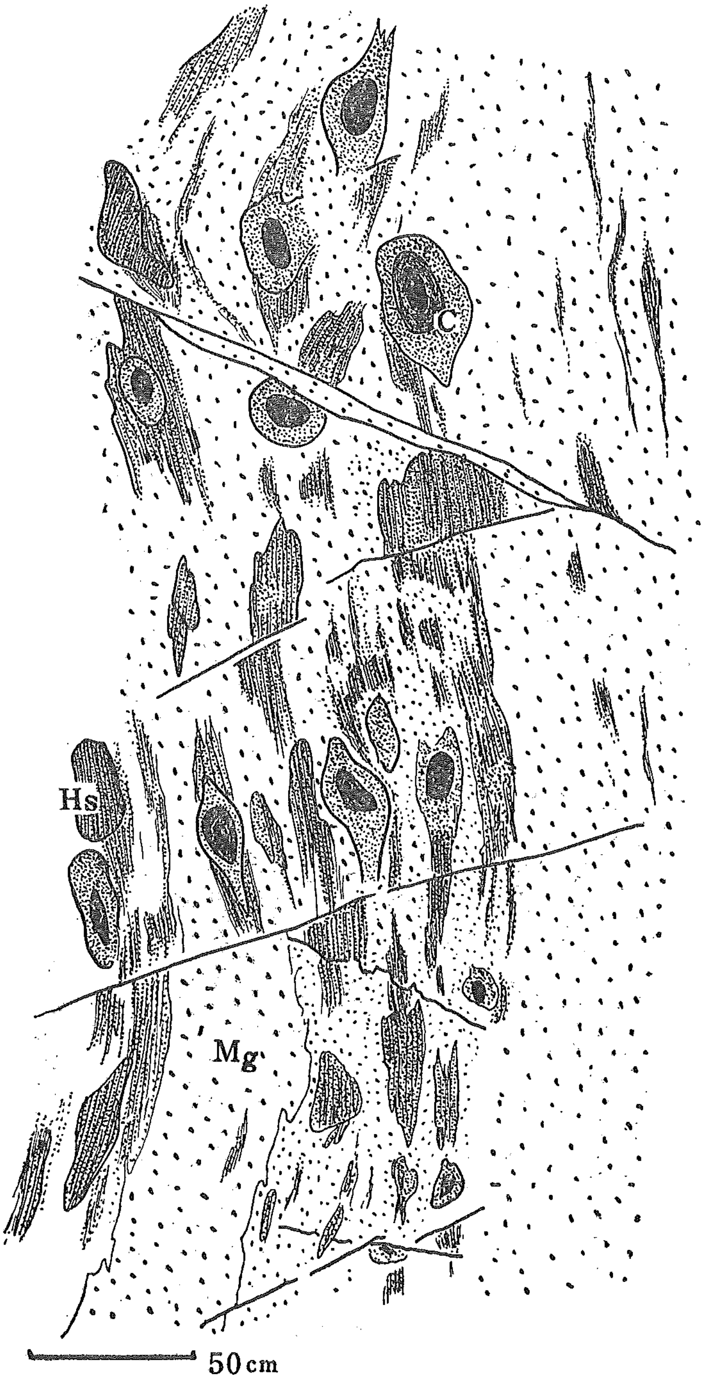


Fig. 4. Granitic migmatite (Mg) replacing schistose hornfels (Hs) in situ with calcareous nodules (C)

Sillimanite, 3.5×1 cm and as large as 5×3 cm, occurring in euhedral prismatic crystals, is bluish gray~light red. The cleavage is perfect and brilliant. $\alpha=1.664$, $\beta=1.671$, $\gamma=1.684$. $2V_z=31°$. Cordierite is 1.5×1 cm and as large as 7×5 cm, porphyritic, ellipsoidal, dark green, and euhedral, without twinning, $\gamma=1.563$. The matrix is equigranular, the crystals measuring about 0.5 mm. Essential minerals include plagioclase, quartz, biotite, and muscovite; accessory minerals are fibrous sillimanite, garnet, potash feldspare, apatite, zircon, and iron ore.

(iv) Granitic migmatite

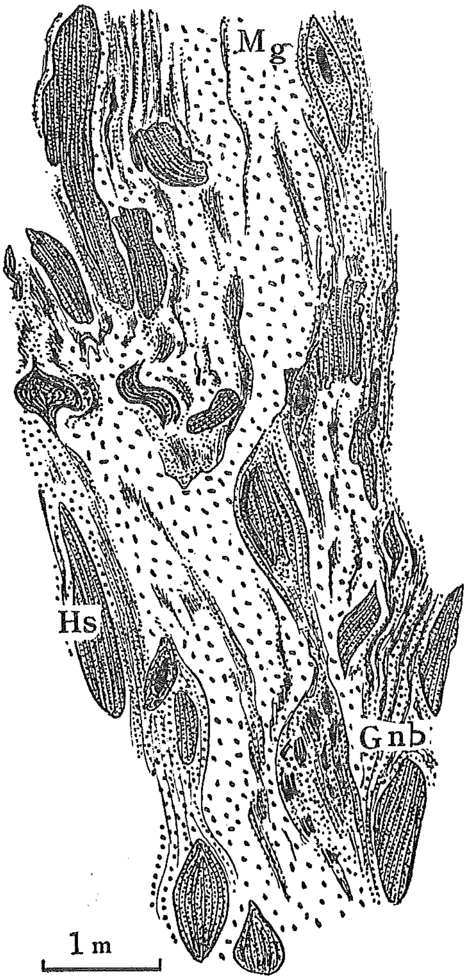


Fig. 5. Granitic migmatite (Mg) in which palaeosomes of schistose hornfels (Hs) are included, develops in banded biotite gneiss.

Generally small bodies of granitic migmatite are sporadically scattered in the biotite migmatite and cordierite migmatite areas. In the upper reaches of the R. Satsunai, this type of migmatite dozens to several hundred meters thick and 15 km long, occurs conformably in the banded biotite gneiss and schistose hornfels zones. Remnants of the gneiss lie in the migmatite parallel to the boundary. The migmatite is generally homogeneous although round or ellipsoidal aggregations of biotite are included. Lenticular bodies of granitic migmatite occur in cordierite migmatite. Irregular veins or networks of granitic migmatite grow in corderite migmatite, forming plagioclase porphyroblasts, the grains of component minerals turning coarser until small granitic bodies are produced.

The rock is coarse-grained, slightly massive, leucocratic and it shows a regular joint.

The microscope reveals that the texture of granitic migmatite is granoblastic and that of a comparatively coarser variety is pegmatitic. At the margin of the rock where transition takes place a plagioclase porphyroblastic texture develops well to produce a porphyritic structure. Essential minerals are muscovite, apatite, zircon, iron ore, and rarely light green hornblende. Plagioclase, 0.5~5 mm and mostly 2 mm in size, is subhedral or anhedral, An 35, includes biotite and quartz, and exhibits porphyroblastic character. Biotite, 1~2 mm is leafy or tabular. x= greenish light brown, y=yellowish brown, z=yellowish brown. The color of it is lighter than that of the biotite of gneiss. γ=1.649. Apatite is less than 0.5 mm in size, prismatic, and euhedral. Iron ore is in grains of less than 0.5 mm, mostly granular, and scattered. Fine grains of garnet are contained in places.

4. Aplite Dikes

Leucocratic aplite dikes, 0.5~2 m wide, traverse schistose hornfels, gneiss and migmatite in places. Some of them are dilation dikes or replacement dikes. The former are thought to have been caused by bulging of the country rock; the latter include palaeosomes of gneiss which are kept in original position. These dilation and replacement dikes are abundant in the zone of metamorphic rocks. Leucocratic dikes which occur at the outside of schistose biotite spotted hornfels along a shear zone are comprised of real aplites.

Under the microscope fine-grained aplite is seen to have a mosaic texture and medium or coarse grained aplite has constituents of remarkable plagioclase and quartz phenocrysts. Essential minerals are: plagioclase>quartz>biotite potash feldspar; and accessories, muscovite, titanite, zircon, zoisite, and chlorite. Plagioclase, 1~2 mm, is anhedral or subhedral, more or less saussuritized. Much plagioclase shows a distinct twin, and a sieve texture is present. Quartz, about 1 mm, is anhedral and shows wavy extinction. Minute pieces of biotite, about 0.3 mm are scattered; they are chloritized in part. x=light, greenish brown, y=brown, z=dark brown. Potash feldspar fills the spaces around other minerals and replaces plagioclase. Myrmekites are numerous.

5. Granitic Migmatite outside the Metamorphic Belt (Petroblastic Rock)

The granitic migmatite in question develops only on the eastern edge of the southern area, outside the metamorphic belt. It is typically formed in the upper streams of the R. Nozuka and R. Bihoro of the southernmost area; it is different in lithologic character and occurrence from the aplite that scatters along the sheared zone outside schistose biotite spotted hornfels.

In the upper reaches of the R. Bihoro a series of granitic migmatite occurrences are found in the biotite hornfels along a large sheared zone parallel to the metamorphic belt. The migmatite bodies are as wide as 200 m in maximum and range from several meters to 2 km long. The migmatite is characterized by plagioclase porphyroblasts and is very heterogeneous, comprising hornfels, biotite schist, biotite gneiss and fine grained gabbro. The portion of the hornfels where plagioclase porphyroblasts are scattered, abruptly passes into granitic migmatite as a result

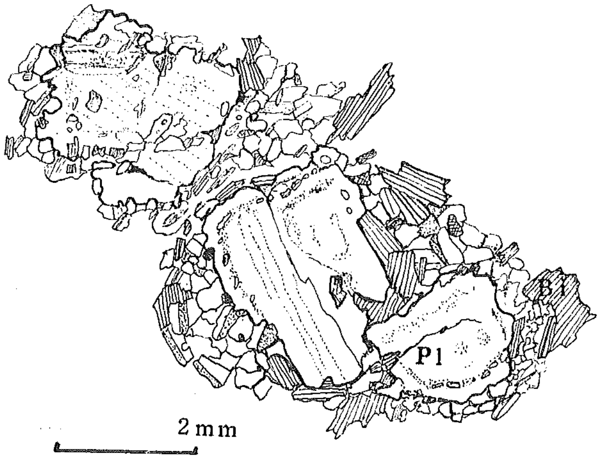


Fig. 6. Plagioclase porphyroblasts in hornfelsic part

of the concentration of the porphyroblasts. More precisely, quartz porphyroblasts, about 1.0 mm in size, grow in hornfels, then plagioclase phenocrysts, 1.5~2.0 mm in size, are made as porphyroblasts, but the size of biotite flakes don't increase very greatly and its hornfelsic character remains (Fig. 6). All the grains swell further inside of the body and the porphyroblasts are scattered or concentrated to make a pool several dozen millimeters across. Thus hornfels passes into granitic migmatite. Palaeosomes of gabbro, several to scores of centimeters in diameter, are scattered in the migmatite. In the palaeosomes, plagioclase porphyroblasts develop as mantleblast having a core of basic plagioclase of gabbro.

The granitic migmatite is coarse-grained, slightly porphyritic, and leucocratic. The essential minerals are plagioclase>quartz>potash feldspar>biotite; and accessory minerals, hornblende, muscovite, zircon, apatite, and iron ore. Plagioclase, about 2 mm in size, is porphyroblastic and possesses minute inclusions of biotite and quartz, which are arranged along zonal structure. Many small grains of plagioclase, 0.5~1.0 mm in size, aggregate into single crystal. The middle portion, An 40-45 and the outer mantle, An 20-25. Potash feldspar fills the space around other minerals and is anhedral. Some, in 2 mm grains, is porphyroblastic and includes plagioclase, quartz, and muscovite (Fig. 7). Quartz (1 mm) is anhedral. Under the microscope a quartz vein which extends from granitic rock to hornfels is seen to be composed of arranged anhedral porphyroblasts, 1 mm in size, including biotite, etc. of hornfels. Biotite, 1~1.5 mm long is leafy. x=light yellowish brown, y=z=natal brown.

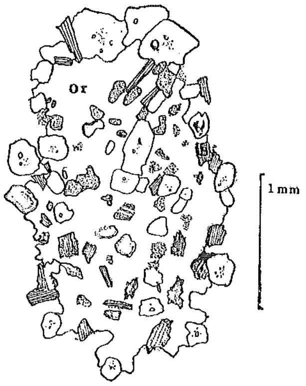


Fig. 7. Porphyroblast of orthoclase including quartz, plagioclase and biotite.

The granitic rock above described is judged from lithologic character, occurrence, and growth to correspond to the granitic migmatite in the metamorphic belt. The rock in question coincides with the so-called Kamishibetsu gneiss from Okushibetsu, northern Hokkaido (KIZAKI, 1959). The occurrence and lithologic character of them are very similar.

6. Granites

Granites occur only east of the metamorphic belt mostly in association with basic plutonic rocks. They are classified as follow:

(i) Gneissose granite
(ii) Granite

(i) Gneissose granite (HASHIMOTO, 1958)

Gneissose granite, in an area 4 km wide and 12 km long from NNW to SSE, occurs in the upper reaches of the R. Pipairo as a concordant intrusive. It is emplaced in the zone corresponding to the schistose hornfels and banded gneiss zones. The western part of the gneissose granite body is occupied by cordierite migmatite. The granite is a biotite granite that is coarse grained and has either schistosity or a linear structure.

The essential minerals are potash feldspar, plagioclase, quartz and biotite. The gneissose granite is generally crushed and recrystallized. Plagioclase, 2~0.5 mm, is subhedral and scarcely shows any zonal structure. An 30. Biotite plates, 0.5~1.0 mm, are parallel. x=light yellow, y≒z=reddish brown. Quartz and potash feldspar fill the spaces around plagioclase and biotite grains. Fine recrystallized grains of plagioclase are developed around the plagioclase phenocrysts. Potash feldspar spreads over the crushed or recrystallized portion replacing plagioclase.

(ii) Granite

Granite occurs usually at the east side of the metamorphic belt. Petrographically the granite belongs to biotite granite or granodiorite though the two are slightly different. The granite at Bitatanunke, Oshirabetsu contains a small amount of hornblende and potash feldspar while some portions are rich in biotite, keeping a gneissic structure. A portion of the granite cannot be different from cordierite migmatite as it shows the migmatitic character. The granite at Soematsu and Pirika is within the metamorphic belt and is gradually transformed from granitic migmatite west of the granite. At Tokachishimizu the granite is disseminated with pyrrhotite. Dissemination is a common character of migmatites.

Under the microscope the granite is seen to consist of long lath-shaped plagioclase, potash feldspar, quartz and biotite crystals. Although their combination and form is completely different from those in migmatite, the relation with migmatite is significant in connecton with the evolution of granitic rocks.

7. Calcareous Nodules

Calcareous nodules are universally found in fine-grained sandstone of the Nakanogawa group and also are distributed from hornfels to migmatite. Their forms become distinct when they undergo alteration the intensity of which corresponds to the grade of the metamorphism.

Nodules are spherical or lenticular, generally 10 cm across and as large as 1 m in the southern area. They are here and there interbedded parallel to the plane of sedimentation.

J. SUZUKI (1934) first described the calcareous nodules found in hornfels. They are hard and compact and have a concentric zonal structure. The surface is bluish or greenish light gray. The inner part consists of lime silicate minerals and has the composition of skarn.

The outer part is greenish, darker than the center, and composed of grains, about 0.1 mm across, of plagioclase, diopside, green hornblende, clinozoisite, quartz and amorphous dust particles. The plagioclase, less than 0.1 mm in size, is granular and An 70±. Diopside, 0.1 mm, is short-columnar. $2V_z=58^\circ$, $c \wedge z=40^\circ$. Nearly colorless hornblende, 0.3 mm in diameter, is long-columnar and subhedral. Clinozoisite, 0.1 mm, is long-columnar and subhedral. Clinozoisite, 0.1 mm, is anhedral and colorless. Biotite, less than 0.3 mm, is leafy, x=yellowish brown, y=brown, z=dark brown. In addition to it, iron ore occurs scatteringly. The central part is whitish with a tint of greenish or bluish-light gray: it is composed of plagioclase, which is specially abundant, diopside, quartz, clinozoisite light green hornblende and iron ore. Plagioclase, diopside and clinozoisite grains are similar to those in the peripheral part except that their size is generally larger ranging from 0.3 to 0.5 mm.

In gneiss some nodules are prolonged into lenticular form and are devoid of a zonal structure. Quartz in the nodule is increased and occurs as a minute grain, about 0.1 mm in size, forming the matrix and showing wavy extinction. Poikiloblastic diopside, 0.1 mm in size, is aggregated into porphyroblasts. In addition, there occur colorless or light green hornblende, clinozoisite and iron ore.

Garnet, besides the minerals above noted, occurs at the center of the nodules in the migmatite zone. When the garnet is yellowish brown and exhibits a poikiloblastic texture (1.0 mm in size), it entirely covers the central part. In this case the outer part is rich in biotite. Orbicular rock is met with in the transitional portion between banded gneiss and granitic migmatite in the upper reaches of the R. Satsunai. The periphery of the orbicular rock consists chiefly of biotite, plagioclase, and quartz and a fair amount of fine-grained titanite, chlorite and sericite. They show a mosaic texture, grains being less than 0.2 mm on an average. Biotite has a tendency to lie with its longer axis parallel to the concentric circle. The tendency is especially strong in the biotite that occurs in the periphery x=light brown, $y \fallingdotseq z$=brown. The plagioclase mostly measures less than 0.2 mm, is granular, and exhibits albite twins. The twinning plane chiefly is parallel to the concentric circle. An 35. Quartz, 0.1 mm, shows a mosaic texture. Nucleus part is separated from the periphery by three concentric zones of biotite aggregate, though the boundary between biotite rich zone and biotite poor zone is not distinct. The zones are marked by a gradual change in the amount of biotite. The nucleus which is generally dirty consists of hornblende, quartz, clinozoisite, chlorite, sericite, titanite and pyrrhotite. Light brown hornblende ranges from poikiloblast, 0.5 mm in size to very minute crystals of 0.1 mm and is anhedral with obscure cleavage; $2V_X=10^\circ$ and like ferrohastingsite. Quartz, 0.1 mm, has a mosaic texture and is similar to that in the pheriphery. Many minute pieces of titanite occur scatteredly. Minute, euhedral, hexagonal crystal, 0.05 mm, of pyrrhotite are abundantly found. The crystals as large as 0.1 mm are anhedral. As stated above the calcareous nodules in the Nakanogawa group are altered according to the grade of the metamorphism of the country rock.

In addition, a manganese nodule is found in banded biotite gneiss in the upper reaches of the R. Nakano in the middle part of the metamorphic belt (KIZAKI and KANAYAMA, 1958).

IV. Migmatization

The writer has employed terms based on rather the classic standard of classification. The idea of migmatite is formed chiefly from field observation. It is on a so large scale that microscopical investigation of specimens is not enough although such minute study is helpful.

As the definition of migmatite has already been clarified, the writer will describe the migmatization series based on field observations. The investigation is from the viewpoints of metamorphism, metasomatism and tectonics.

Migmatization starts at the stage of schistose hornfels. The schistosity of hornfels is intensified, and a leucocratic band, about 5 mm wide, is produced parallel to the schistosity. The grain of the band becomes coarser until the hornfels turns to banded gneiss. The veined schistose hornfels and banded gneiss are defined as venite. The band is, however, not always parallel to schistosity. The leucocratic band of schistose hornfels inside the gneiss zone is not invariably parallel to the schistosity, and the rock is marked with a network of veins which sometimes shows ptygmatic folding. The rock is to be considered as a kind of venite though the veins don't run parallel to the schistosity. In order to make distinction between them, the former is named α-venite which is characterized by parallel veins such as the veined schistose hornfels and banded gneiss, and the latter, γ-venite marked with networks. Polyvenite is another form, which is an α-venite traversed by oblique parallel veins that mark a high order structure associated with the upwarping of the biotite migmatite arch.

One of the most important factors in migmatization is the increase in the grain size as well as the development of leucocratic veins in schistose hornfels. The grain size abruptly increases according to the progress of

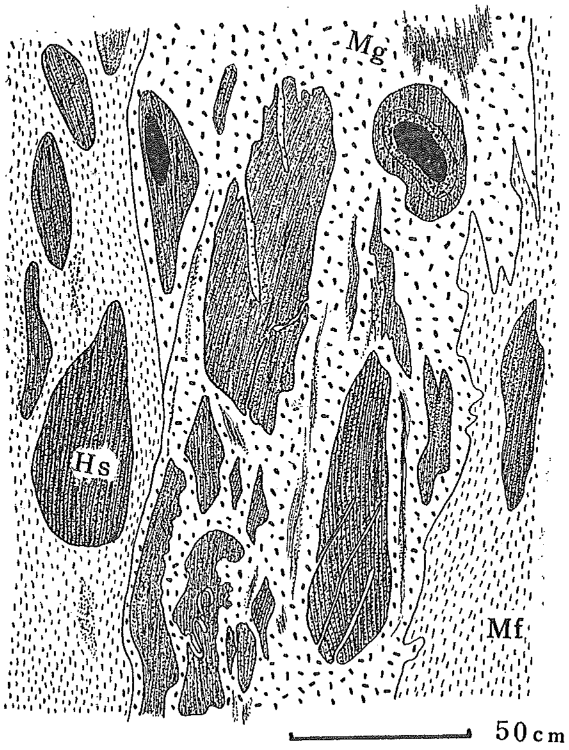


Fig. 8. Fine migmatite (coarse hornfels) (Mf) with palaeosomes of schistose hornfels (Hs) is replaced by granitic migmatite (Mg)

metamorphism successively from outside of the metamorphic zone accompanied by vein formation in schistose hornfels, α-venite or banded gneiss. The schistose hornfels without intense schistosity at the central part of the metamorphic belt as a roof pendant of the biotite migmatite arch, cannot show the enlargement in grain size like the schistose hornfels outside of the belt does. It is an interesting problem that the grain growth associated with the gneiss formation is not only abrupt, but also that the hornfels texture is completely altered to that of gneiss. The equigranular mosaic hornfels texture is retained even in the case of a slight growth of grain size in the latter. Furthermore, the grain growth in the static state cannot exceed a certain size (0.5 mm), and in this case the hornfels which is named coarse hornfels or fine migmatite, loses its schistosity and includes palaeosomes of schistose hornfels (Fig. 8).

On the other hand, in a part of the banded gneiss and the schistose hornfels, plagioclase porphyroblasts gather to form a coarse migmatitic gneiss with the result that the banded structure is obscure.

The biotite and cordierite migmatite are agmatitic and/or take the form of nebulitic migmatite including many palaeosomes of schistose hornfels, banded gneiss, migmatitic gneiss, amphibolite and gabbro (Fig. 9).

The granitic migmatite is the last product of the migmatization series. The granitic migmatite occurs everywhere, in banded gneiss zone, in cordierite migmatite zone and in biotite migmatite zone. The migmatite in the banded gneiss zone represents a harmonic sheet-like occurrence which forms plagioclase porphyroblast aggregate. The rock transits as a result of alternation with gneiss at the margin which signifies the emplacement in situ. In the cordierite migmatite and biotite migmatite, granitic migmatite is emplaced because of petroblastase as judged from field observations, though Y. SOTOZAKI (1956), and S. HIROTA (1952) stated that the granitic migmatite has melted and flowed rheomorphically according to the statistical analysis of plagioclase twins proposed by M. GORAI in 1950.

The migmatization series as follows represents a general scheme although the differentiation of tectonics results in more or less different series in different vicinities. The series at the east side of the metamorphic belt is schematized; it is a metatexis series (K. H. SCHEUMANN, 1937).

The series on the west side is characterized by the formation of plagioclase porphyroblasts and the assimilation of gneisses with basic intrusives. It may be a metablastesis series (K. H. SCHEUMANN, 1937).

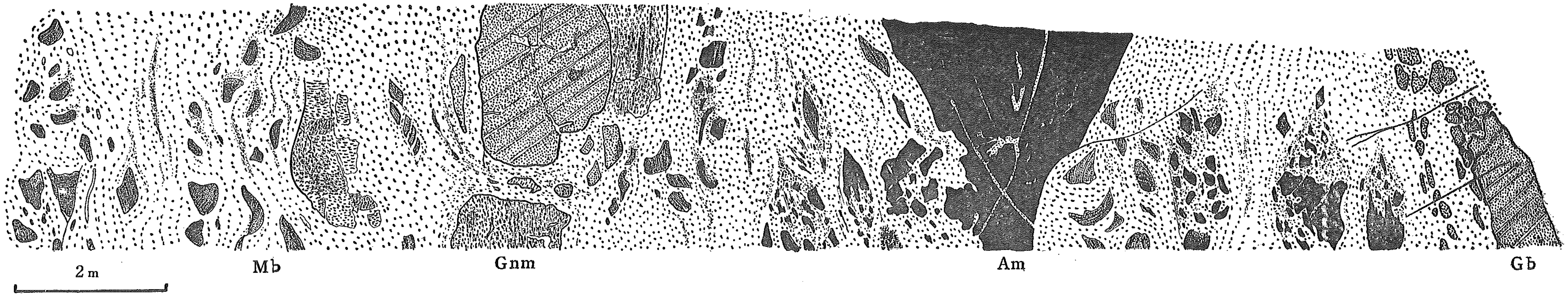
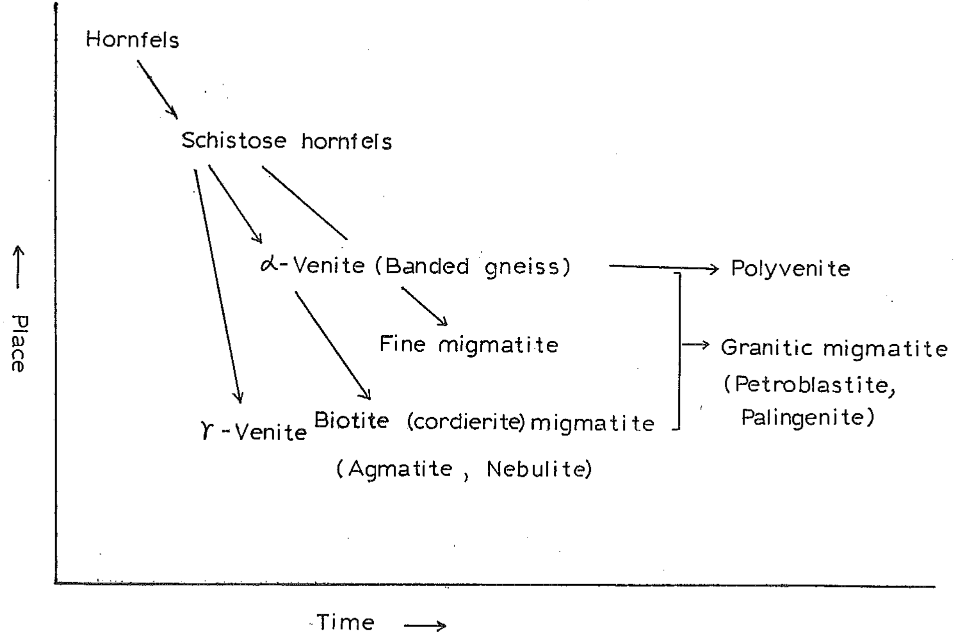
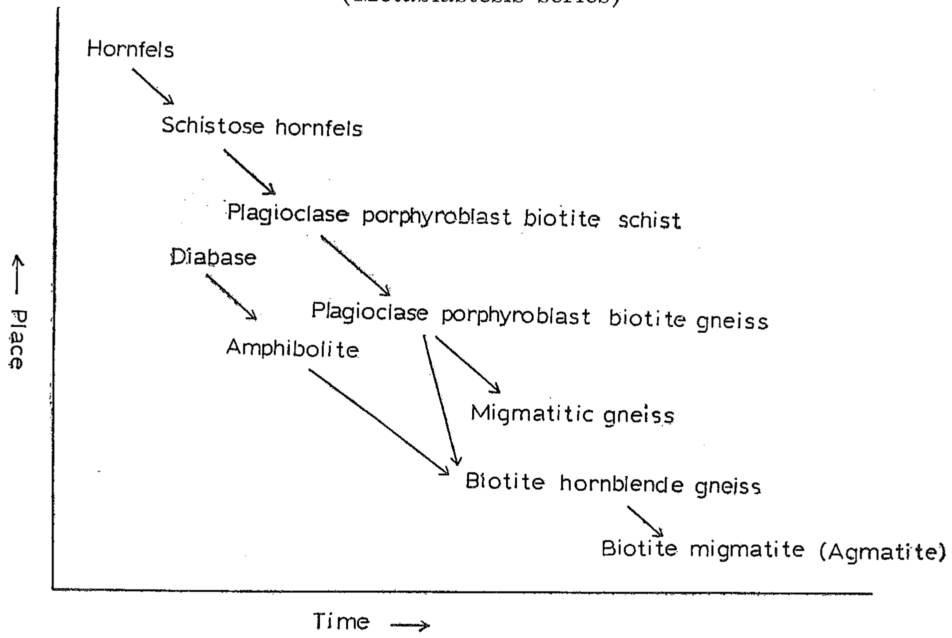


Fig. 9. Agmatitic part of biotite migmatite (Mb); Amphibolite blocks (Am) are scattered while gabbro (Gb) preserves a sheet like form. Gnm: migmatitic gneiss.

Migmatization series on the east side of the metamorphic belt.
(Metatexis series)



Migmatization series on the west side of the metamorphic belt.
(Metablastesis series)



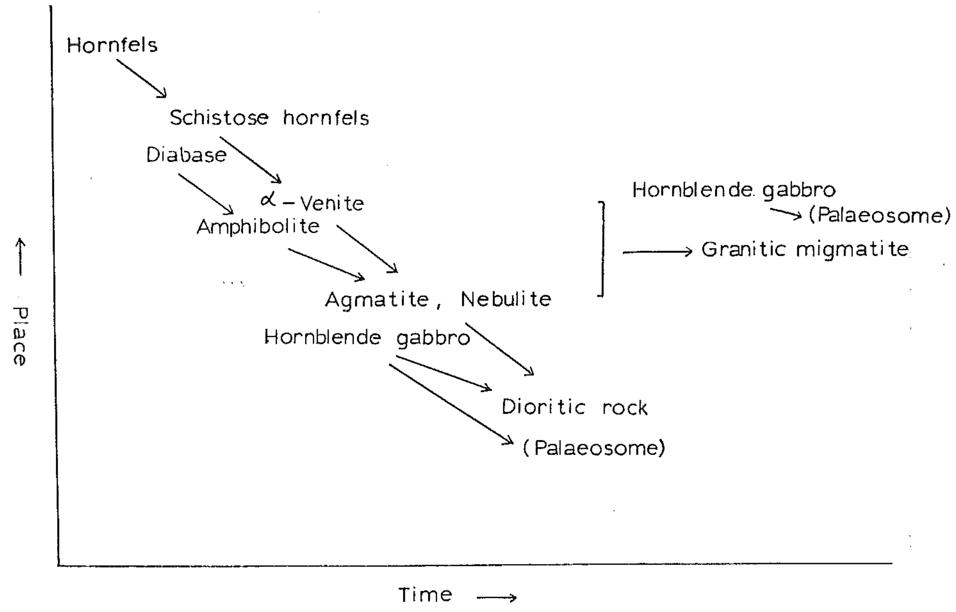
The metatexis and the metablastesis do not always develop separately but the two processes co-operate as in the migmatitic gneiss.

Migmatized sequence of basic rocks.

Amphibolite bands, scores of centimeters to several meters wide, extend incompletely a few meters to several tens of meters distant parallel to the foliation of the banded gneiss which does not occur in hornfels area. So, it seems that the amphibolite originated from diabasic rock intruded before the formation of gneiss in the zone. Amphibolite blocks as palaeosomes are included in the biotite migmatite and the cordierite migmatite; they are migmatized products of the gneisses.

The sheets of hornblende gabbro in the biotite migmatite and cordierite migmatite, are agmatized imperfectly at the margin though the sheet-like form is retained. The hornblende gabbro may be a forerunner of migmatization.

In the granitic migmatite, palaeosomes of amphibolite and also hornblende gabbro are included. The palaeosomes of the latter are interspersed only along the trend of the granitic migmatite which takes a sheet-like form. The schematic series with relation to the migmatization on the east side are as follows:



The diabasic amphibolites emplaced in the plagioclase porphyroblast biotite gneiss are biotitized only in the southernmost area; in the northern extension, they are migmatized to produce a rock species: the biotite hornblende gneiss.

$$\begin{tikzcd}
\text{Hornfels} \arrow[r] & \text{Schistose hornfels} \arrow[r, dashed] & \text{Plagioclase porphyroblast gneiss (schist)} \arrow[dd, dashed] \\
\text{Diabase} \arrow[r] & \text{Amphibolite} \arrow[dr] & \\
& & \text{Biotite hornblende gneiss}
\end{tikzcd}$$

The harmonic intrusion of diabases and small sheets of gabbro have an intimate relation with the migmatization. The basic activities as a whole play a part in every stage of migmatization. The large disharmonic plutonic massifs composed of gabbros also have some relations with migmatite tectonics: the Poroshiri-dake gabbro complex lies in a tectonic valley according to the lineation of migmatites between the gneissose granite and the biotite migmatite in the northern area; the Horoman gabbro complex occurs at the boundary or the discontinuous zone between the migmatite domes in the southern area. Migmatization and the physical and chemical activity of migmatite are intimately associated with the intrusion of the basic rocks.

V. Metamorphism

1. Introduction

A regional metamorphism such as this type should be considered from two different standpoints, one is the metamorphism from the view point of mineral facies principle and metasomatism, and the other is the migmatization and granitization which are characterized by the development of a leucocratic part and grain growth because the mineral composition of migmatities in every stage is common including quartz, plagioclase, biotite, cordierite, potash feldspar, garnet, sillimanite and so on. The migmatization and granitization thus signify the convergent tendency to the becoming a granitic rock from different original rock species though their facility for the operation may be different in each case.

The migmatization and granitization associated with the regional metamorphism represent an important problem related to the formation of migma and granitic magma in the core of the orogenic zone. The migmatization is different from a granitization at the boundary of an intrusive granitic body at a high level of the crust.

The migmatization of the Hidaka metamorphic belt accordingly is associated intimately with the regional metamorphism. Then, the migmatization series: venite→polyvenite→agmatite→nebulite→granitic rock may be deduced from the viewpoint of the formation of granitic part. The series: hornfels→schistose hornfels→gneisses may be defined as ex-

Table 1. Chemical compositions of metamorphic rocks, migmatites and granites.

Wt %	1	2	3	4	5	6	7	8	9
SiO_2	70.34	62.94	65.39	64.67	64.70	59.61	60.40	67.50	60.87
TiO_2	.69	.45	.50	.49	.60	.63	.56	.55	.47
Al_2O_3	16.12	15.76	12.78	13.51	16.03	16.03	15.57	16.48	19.06
Fe_2O_3	1.16	2.12	3.81	1.25	.07	4.91	1.89	2.61	.67
FeO	4.83	4.81	4.64	7.93	3.88	7.59	4.78	3.19	4.03
MnO									
MgO	2.85	3.60	3.75	2.11	3.40	2.85	3.54	1.58	2.76
CaO	.58	1.79	2.30	2.96	3.00	4.69	4.02	2.85	3.92
Na_2O	1.89	4.44	2.61	2.83	4.47	3.84	4.62	2.16	3.46
K_2O	.81	1.46	1.94	1.60	1.88	.52	2.13	1.38	3.40
H_2O (+)	1.11	2.61	2.53	1.07	1.59		.46	.56	1.06
(−)				1.53			2.03	.81	
Total	100.38	99.98	100.25	99.95	99.62		100.00	99.67	99.70

Cat %	1	2	3	4	5	6	7	8	9
Si	67.42	59.85	63.31	63.39	60.68	55.98	57.03	65.35	56.94
Ti	.52	.34	.49	.35	.45	.45	.40	.41	.34
Al	18.19	17.65	14.59	15.19	17.69	17.76	17.35	18.78	21.02
$Fe^{\cdot\cdot\cdot}$	.86	1.54	2.79	.49	.06	3.49	1.36	1.92	.45
$Fe^{\cdot\cdot}$	3.86	3.83	3.77	6.53	3.04	5.98	3.80	2.56	3.15
Mn									
Mg	4.09	5.08	5.41	3.12	4.73	4.00	4.99	2.27	3.82
Ca	.58	1.83	2.38	3.12	2.99	4.74	4.08	2.97	3.93
Na	3.51	8.17	4.88	5.36	8.11	6.99	8.45	4.07	6.30
k	.98	1.71	2.38	2.00	2.22	.62	2.55	1.69	4.05
Total	100.01	100.00	100.00	100.00	99.97	100.01	100.01	100.02	100.00

1 Metasandstone (S-14). Rokunosawa of R. Satsunai, (Kizaki, 1953)
2 Metaslate (202). R. Satsunai, (Kizaki, 1953)
3 Biotite hornfels (O-267). Noborisawa of R. Saruru, (Hunahashi et al. 1956)
4 Biotite hornfels (9). Ehaoi of Horoman, (Hunahashi et al. 1956)
5 Cordierite hornfels. Oshirabetsu (Suzuki, 1936)
6 Schistose biotite spotted hornfels (O-306). R. Biroo, (Hunahashi et al. 1956)
7 Schistose biotite spotted hornfels (O-262). Noborisawa of R. Saruru (Hunahashi et al. 1956)
8 Biotite schist (14). Ehaoi of Horoman, (Hunahashi et al. 1956)
9 Banded biotite gneiss (K-70). upper stream of R. Satsunai, (Kizaki, 1953)

Wt %	10	11	12	13	14	15	16	17
SiO_2	58.71	64.92	60.12	60.80	64.76	60.60	67.14	55.18
TiO_2	.70	.60	.60	.65	.48	.83	.42	.73
Al_2O_3	20.92	18.01	15.83	17.15	14.35	17.06	14.14	15.28
Fe_2O_3	1.02	.43	2.28	1.83	1.46	1.25	1.33	1.84
FeO	4.84	5.14	5.94	6.14	6.86		4.13	8.59
MnO								
MgO	2.42	2.43	3.02	3.51	2.57	5.87	1.88	5.25
CaO	2.96	3.64	3.42	2.01	3.10	2.50	4.07	4.56
Na_2O	2.97	2.84	4.34	4.07	2.64	3.29	3.64	1.67
K_2O	2.62	1.98	3.40	.80	1.61	3.21	1.13	2.69
H_2O (+)	1.15	.02	1.01	2.31	.30	2.01	1.42	3.31
(−)		.72			.77	2.77		
Total	98.31	100.73	99.96	99.27	99.90	99.39	99.30	99.10

Cat %	10	11	12	13	14	15	16	17
Si	56.14	60.80	56.24	58.33	62.78	58.66	64.44	54.67
Ti	.52	.45	.45	.46	.35	.58	.29	.54
Al	23.54	19.85	17.47	19.37	16.42	19.48	15.97	17.85
$Fe^{\cdot\cdot\cdot}$	.75	.28	1.63	1.33	1.05	.93	.98	1.37
$Fe^{\cdot\cdot}$	3.82	4.05	4.66	4.90	5.53	4.77	3.29	6.42
Mn								
Mg	3.44	3.37	4.21	5.01	3.73	3.60	2.71	7.73
Ca	3.04	3.66	3.43	2.07	3.20	3.43	4.21	4.82
Na	5.51	5.17	7.87	7.55	4.95	6.05	6.74	3.21
K	3.21	2.36	4.04	.98	1.98	2.50	1.38	3.39
Total	99.97	99.99	100.00	100.00	99.99	100.00	100.01	100.00

10 Banded biotite gneiss. upper stream of R. Satsunai, (Kizaki, 1953)
11 Banded biotite gneiss (O-220). upper stream of R. Saruru, (Hunahashi et al. 1956)
12 Banded biotite gneiss (O-573). R. Biroo, (Hunahashi et al. 1956)
13 Plagioclase porphyroblast biotite gneiss (K-138), R. Shibichari, (Kizaki, 1953)
14 Plagioclase porphyroblast biotite gneiss (5), Ehaoi of Horoman, (Hunahashi et al. 1956)
15 Migmatitic gneiss (K-144), Jyunosawa-cirque of R. Satsunai, (Kizaki, 1953)
16 Biotite migmatite (K-117), Kunosawa of R. Satsunai, (Kizaki, 1953)
17 Palaeosome of schistose hornfels in biotite migmatite. Kunosawa of R. Satsunai, (Kizaki, 1953)

Wt %	18	19	20	21	22	23	24	25
SiO_2	63.83	62.44	66.96	64.20	63.33	67.71	74.44	75.68
TiO_2	.65	.52	.38	.42	.71	.35	.18	.06
Al_2O_3	15.96	15.43	15.47	15.51	14.76	10.81	12.93	12.94
Fe_2O_3	2.25	2.56	2.57	1.25	.28	.64	.63	.56
FeO	6.13	5.27	3.68	4.20	7.14	8.47	.90	.86
MnO								.07
MgO	2.59	3.25	2.32	2.49	2.52	3.69	1.08	.62
CaO	2.60	4.18	2.41	3.25	3.52	3.97	1.48	1.05
Na_2O	3.62	2.93	3.72	3.06	3.55	3.99	3.75	3.91
K_2O	1.41	.87	1.92	3.94	2.78	.19	4.75	4.16
H_2O (+)		.20	2.92	1.41	1.69	1.51	.56	Ig. Loss
(−)		1.84					.12	.28
Total	99.04	99.49	102.35	99.73	100.28	101.33	100.82	100.19

Cat %	18	19	20	21	22	23	24	25
Si	60.60	60.32	63.03	60.91	60.02	63.85	69.18	70.63
Ti	.46	.41	.28	.28	.51	.23	.11	.06
Al	17.84	17.58	17.18	17.32	16.51	12.01	14.18	14.25
Fe'''	1.60	1.86	1.81	.91	.23	.45	.45	.39
Fe''	4.85	4.23	2.88	3.30	5.64	6.69	.73	.67
Mn								.06
Mg	3.65	4.70	3.28	3.53	3.59	5.21	1.51	.84
Ca	2.62	4.35	2.43	3.30	3.59	4.02	1.45	1.07
Na	6.67	5.51	6.78	5.64	6.55	7.31	6.76	7.07
K	1.71	1.04	2.32	4.79	3.36	.23	5.64	4.94
Total	100.00	100.00	99.99	99.98	100.00	100.00	100.01	100.02

18 Cordierite migmatite. R. Bihoro. Analyst. S. Hashimoto
19 Cordierite migmatite (O-205), upper stream of R. Saruru, (Hunahashi et al. 1956)
20 Cordierite migmatite (O-23), R. Oshirabetsu, (Hunahashi et al. 1956)
21 Granitic migmatite (S. B.-69), R. Saruru, (Hunahashi et al. 1956)
22 Granitic migmatite (2025), upper stream of R. Saruru, (Hunahashi et al. 1956)
23 Granitic migmatite. upper stream of R. Saruru, (Hunahashi et al. 1956)
24 Granite. Ishiyama, Shimizu, (Hashimoto, 1954)
25 Granite. Ishiyama, Shimizu, (Suzuki, Nemoto, 1935)

emplifying the regional progressive metamorphism from the viewpoint of the metamorphism.

The metamorphism and plutonism in the core of the orogenic zone cover the two important contents as stated above.

Since the classic controversy of the Heiderberg school against the French school, the relation of metamorphism, migmatization and granitization in a regional metamorphism has been discussed by many investigators until nowadays. It seems that for the settlement of the problem, some sort of synthesis of the two sides inconsistent with each other in the regional metamorphism may be necessary.

2. Metasomatism

The variation of chemical composition associated with metamorphism is one of the most important factors in a verification of metamorphism, especially the migration of matters in migmatization in the regional metamorphism as in this type. Next, the chemical and mineralogical variation with the progress of migmatization will be discussed.

On the east side of the metamorphic belt, the series is proposed: hornfels → schistose hornfels → banded gneiss → biotite (cordierite) migmatite → granitic migmatite.

Figs. 10, 11 show the variation diagrams which indicate the addition and reduction of cations on the basis of the composition of a hornfels.

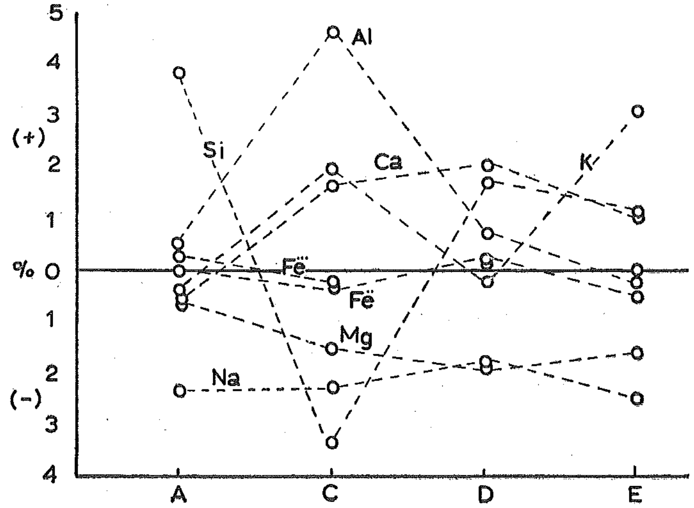


Fig. 10. Variation diagram of cations. A: biotite hornfels, B: schistose biotite spotted hornfels, C: banded biotite gneiss, D: biotite migmatite, E: granitic migmatite. (Upper reaches of the R. Satsunai)

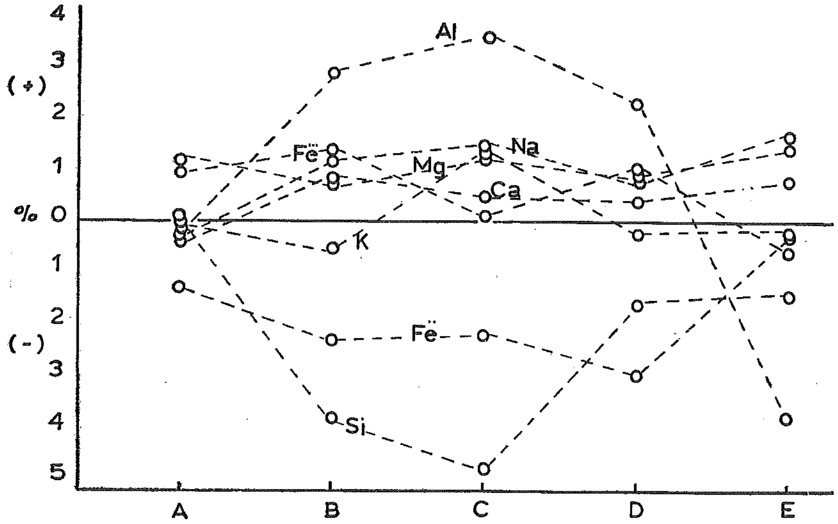


Fig. 11. Variation diagram of cations. (Southernmost area)

It is noted that the schistose hornfels and the banded gneiss, especially the latter, are rich in Al and K and are marked by poor Si content. K abounds in the granitic migmatite as well as in the banded gneiss. In granitic migmatite of Fig. 11, although the quantity of K is not very abundant because the value is averaged from two values one of which is abnormally poor in K, it is reasonable that K should be rich in the granitic migmatite from the standpoints of the inhomogeniety of distribution of potash feldspar and the tendency of enrichment of potash feldspar in migmatization.

The greater part of Al and K in the gneiss is included in biotite and the rest of them is held in basic plagioclase and potash feldspar respectively. It is doubtful in this case whether "the excessive K to constitute biotite is composed in potash feldspar in amphibolite facies" (BARTH, 1952, p. 342), because the potash feldspar is crystallized at the latest stage from the viewpoint of mineral paragenesis. The phenomenon that the quantity of Si is very small in spite of the increase of modal quartz, signifies nothing but the Si-Al substitution in biotite crystal as well as decrease of the modal plagioclase (Fig. 12).

The enrichment of K in granitic migmatite indicates the increase of the modal potash feldspar; the quantity of K is controlled by the inhomogeniety of the distribution of potash feldspar.

In the west side of the metamorphic zone, there is found the following series; hornfels→schistose hornfels→plagioclase porphyroblast biotite

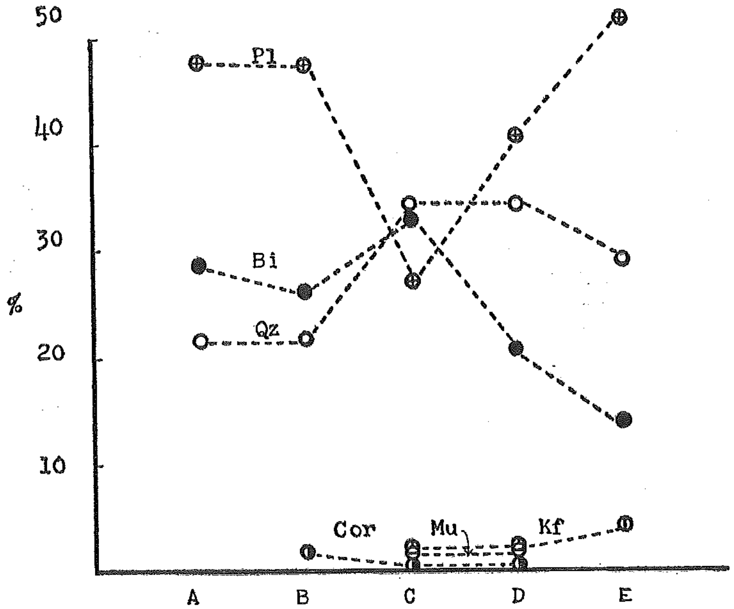


Fig. 12. Variation diagram of mode. A: biotite hornfels, B: schistose biotite spotted hornfels, C: banded biotite gneiss, D: biotite migmatite, E: granitic migmatite.

schist→plagioclase porphyroblast biotite gneiss→migmatitic gneiss.

In the series of the east side, the character of the structure and migmatization is different between the banded gneiss and biotite (cordierite) migmatite, but the continuous growth of plagioclase porphyroblast is recognized in the series of the west side which is a metablastesis series. It is observed in the latter series that the quantity of Al and Na increases while that of Si, decreases. The increase of Al is reflected by the increase of modal plagioclase and Si-Al substitution because the modal biotite decreases while the An content of plagioclase, An 35 is constant. Na increases with the increase of the modal plagioclase.

Chemical Composition of Palaeosomes: (Table 1-17)

In the hornfelsic palaeosomes of biotite migmatite which hold the plagioclase with An 35-45, that is higher than original hornfels and hornblende, Si and alkalis decrease while Fe and Mg increase compared to contents in the original rocks such as hornfels and schistose hornfels. Such a palaeosome shows a basification as the hornfels is migmatized to become a palaeosome. Palaeosomes are ordinarily digested to produce a homogeneous migmatite; then the geochemical culmination in a palaeosome is observed (REYNOLDS, 1946) as in the case of gneiss.

Variation of Mode: (Fig. 12)

In the migmatization series of the east side, plagioclase is the richest component of hornfels and schistose hornfels; it is poor in the banded gneiss, increases again in the migmatites. Quartz and biotite abound in the banded gneiss over the amounts in the others. The culmination in the variation of mode in gneiss is observed as in the chemical composition.

In the series of the west side, it is characteristic that the plagioclase increases continuously.

Biotite:

Biotite is a mineral generally found in every rock species from hornfels to migmatite; it has a wide stability range in metamorphism and in it cations can be exchanged easily. It seems that the mineralogy of biotite in the metamorphic series may be reflected by the metamorphism.

The refractive index is the lowest in banded gneiss which has the darkest biotite (Table 2). It is characteristic that Al of the biotite of banded gneiss is more abundant than that of others comparable in the bulk composition (Table 3).

Reduced formulae from the chemical compositions are as follows:

Biotite of banded gneiss $KAl_5Fe_2Mg_2Si_5(OH)_3O_{21}$

Table 2. Pleochroism and refractive indices of biotites in metamorphic series

	Pleochroism	Refractive Index
Hornfels	x: light brownish green y: brown z: brown	1.640±2
Schistose Hornfels	x: light brownish green y: reddish brown z: reddish brown	1.637–1.643 1.639±3
Banded Gneiss	x: light greenish brown y: reddish brown z: reddish brown	1.634–1.642 1.637±3
Biotite (Cordierite) Migmatite	x: brownish light green y: brown z: reddish brown	1.643–1.647 1.645±2
Granitic Migmatite	x: greenish light brown y: yellowish brown z: yellowish brown	1.643–1.649 1.646±2

Table 3. Chemical compositions of biotites.

Wt. %	a	b	c
SiO_2	34.58	37.69	35.96
TiO_2	2.69	1.53	1.96
Al_2O_3	22.64	18.19	18.37
Fe_2O_3	1.67	3.53	2.10
FeO	14.98	14.86	15.10
MgO	10.35	11.08	11.66
CaO	0.63	0.87	0.77
Na_2O	1.23	0.78	0.80
K_2O	6.50	6.21	8.08
H_2O (+)	3.20	4.91	4.28
(−)	0.88	0.15	0.16
Total	99.35	99.80	99.24

Atom Ratio (O=24)	a	b	c
Si	5.20	5.69	5.37
Ti	0.31	0.18	0.13
Al	4.44	3.24	3.23
$Fe^{\cdots}$	0.18	0.40	0.23
$Fe^{\cdot\cdot}$	1.89	1.88	1.88
Mg	2.32	2.49	2.59
Ca	0.10	0.14	0.13
Na	0.36	0.24	0.23
K	1.24	1.20	1.54
(OH)	3.21	4.93	4.27
O	20.79	19.07	19.73

a. Biotite of banded biotite gneiss, R. Satsunai, (Kizaki, 1953)
b. Biotite of biotite migmatite, R. Satsunai, (Kizaki, 1953)
c. Biotite of granite migmatite, R. Saruru, (Kizaki, 1953)

Biotite of biotite migmatite	$KAl_3Fe_2Mg_3Si_6(OH)_5O_{19}$
Biotite of granitic migmatite	$K_2Al_3Fe_3Mg_3Si_5(OH)_4O_{20}$

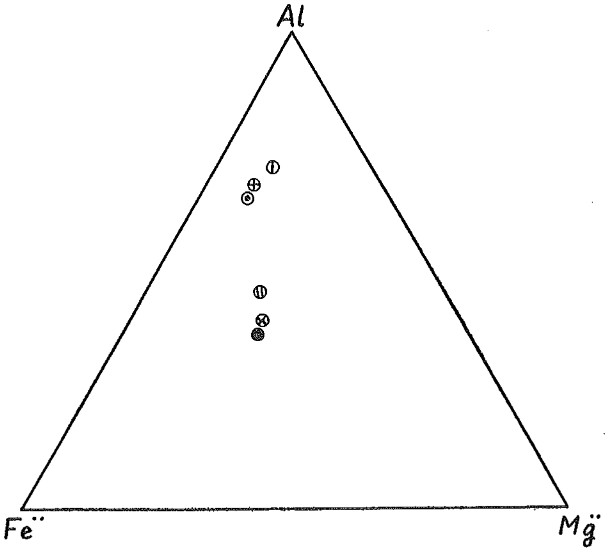


Fig. 13. Al-Fe-Mg diagram of biotites and of the bulk composition of the rocks containing them. ⦷: biotite of banded biotite gneiss (⦶), ●: biotite of biotite migmatite (⊙), ⊗: biotite of granitic migmatite (⊕)

The Al content of the biotite of banded gneiss is higher than that of others so that it is characterized by the substitution of four-coordinated aluminum as stated above in the paragraph on the chemical composition. It is apparent that there is a mutual relation between the chemical compositions of the biotites and that of the rocks containing them (Fig. 13).

The progressive metamorphism on both sides of the metamorphic belt, represents the desilication and the enrichment of Al and alkalies from the chemical point of view. The decrease of Si and alkalies and the enrichment of Fe and Mg are indicated in the palaeosomes. They are phenomena of geochemical culmination (Reynolds, 1946). Reynolds stated that the true granitization proceeds after once the country rock has been affected by desilication in granitization process.

"Desilication arises in three different ways (1) from increase in the total alkalis, in which case the rock is feldpathized (syenitized), (2) from increase in any or all of the cafemic constituents, the rock becoming basified and approaching or attaining the composition of a basic or ultrabasic igneous rock and (3) from a combination of (1) and (2). The products of this desilication change are characterized by having a higher percentage of alkalis and/or cafemic constituents than either the parent sediment or the adjoining granite" (Reynolds, 1946, p. 391).

The chemical change of palaeosome fits the case of (2). The metamorphic series of the two sides shows disilication of type (3) which is characterized by Al as cafemic constituent and by the special minerals: biotite on the east side and plagioclase on the west as alkali constituting minerals. The increase of alkalies is not only represented by felspathization as stated by Reynolds but also defined by biotitization in which each cation may become stable according to condition and place.

Cations migrate from the place with high chemical potential to the place with low chemical potential because the potential gradient and the mobility of cations is to be related to the radius of the ion (Lapadu Hargues, 1945). The mobility of cations according to the radius is as follows: (the radius of irons is after L. Pauling)

$$Al^{\cdot\cdot\cdot}(0.57) > Fe^{\cdot\cdot}(0.83),\ Mg^{\cdot\cdot}(0.78) > Na(0.98) > Ca^{\cdot\cdot}(1.06) > K(1.33) > Ba^{\cdot\cdot}(1.43)$$

Al, Fe and Mg show the highest mobility because of the radius. However, the mobility is not caused necessarily according to the radius of ions, but is controlled by electronegativity and other conditions. Bugge stated that alkali metals are easy to mobilize under the high pressure condition because they are compressed easily (Bugge, 1945).

It is reasonable therefore that alkalies concentrate in the zone where a strong stress has operated such as in the gneiss zone.

There is another explanation. The plagioclase and the biotite of gneisses may hold a plenty of four-coordinated aluminum. In general four-coordination of aluminum is promoted by increasing temperature. Minerals containing four-coordinated aluminum are characteristic of igneous rocks and of the products of thermal and high-grade regional metamorphism. When the amount of four-coordinated aluminum has replaced silicon, the coordination of oxygen cannot be satisfied. Then, eight-coordinated alkalies are necessary for neutralization and for resulting in the lowest potential energy, therefore the increase of four-coordinated aluminum i.e., the progress of metamorphic grade, is inevitably associated with the enrichment of Na or K.

What is the significance of the independence of Na on the west and K on the east which are represented by plagioclase and biotite respectively in the different geological positions? HUNAHASHI stated that it is owing to the difference of the tectonic movement of the metamorphic belt which is the compressional zone of the west and the extensional zone of the east caused by the metamorphic belt thrusting up to the west (1951, 1952, p. 406). However, the biotite has a higher density and is easy to be formed in the condition of strong shearing stress; further it has a wide stability range because of the facilitation of ionic substitution. On the contrary, the three-dimensional network of plagioclase is unstable under the condition of strong shearing stress through having wide stability range, so that the plagioclase cannot develop under an intense shearing stress. It appears rather that the banded gneiss on the east is formed due to more intense shearing stress than on the west from the field occurrences and from the mineralogy.

In the formation of plagioclase porphyroblast in the west, the crystallization phases may be analysed which will be separated as a nucleation stage under intense stress from the stage of crystal growth without stress.

3. Matamorphic Facies

The conception of mineral facies was defined by P. ESKOLA (1920) and has been a useful method for study and classification of metamorphic rocks. According to him, all the rocks, whether the associated minerals of which they are composed crystallized directly from a melt, or whether they are products of metamorphism, or of metasomatism of previously existing minerals of another kind, are classed in a particular mineral facies if they are formed under the conditions of temperature and pressure that result in the same mineral assemblage.

However today, the mineral assemblages of metamorphic rock have been mainly treated and the facies is defined by a particular stability condition which is characteristic.

According to TURNER's definition a metamorphic facies includes rocks of any chemical composition, and hence of widely varying mineralogical composition, which have reached chemical equilibrium during metamorphism under a particular set of physical conditions (TURNER, 1948, p. 54). He lays stress on the point of chemical equilibrium. Ramberg stated, "rocks formed or recrystallized within a certain P-T field, lmited by the stability of certain critical mineral of defined composition, belong to the same mineral facies" (RAMBERG, 1952, p. 136).

The facies classification of granitic rocks is very difficult because the associated minerals of which they are composed are stable in wide P-T field. Feldspars and quartz are difficult to define in a particular P-T field, but in some cases, it is possible to classify the metamorphic grade according to plagioclase and biotite.

Mineral assemblages of the metamorphic zone are as follows:

Hornfels: Biotite-cordierite-muscovite
Biotite-garnet
Biotite-andalusite

Schistose hornfels, Banded gneiss:
Biotite-(muscovite)-garnet
Biotite-(muscovite)-garnet-sillimanite (cordierite)
Biotite-muscovite-cordierite
Biotite-muscovite-(cordierite)-potash feldspar

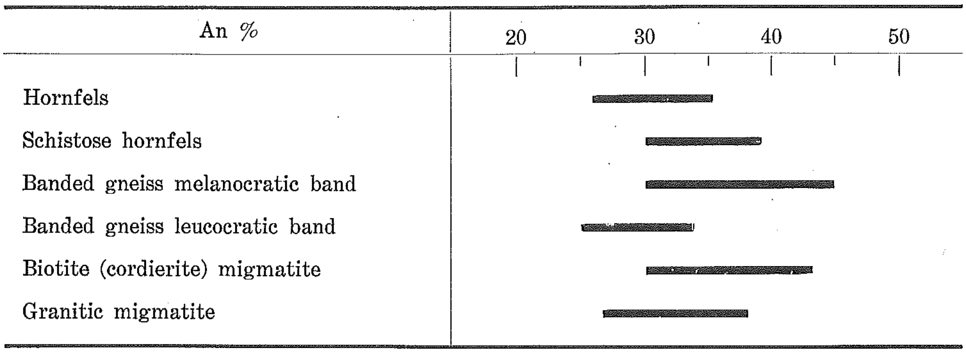
Biotite (cordierite) migmatite:
Biotite-muscovite-cordierite
Biotite-muscovite-cordierite-potash feldspar
Biotite-muscovite-garnet-potash feldspar

Granitic migmatite:
Biotite-potash feldspar
Biotite-potash feldspar-hornblende
Biotite-potash feldspar-muscovite-garnet
Biotite-potash feldspar-epidote

The assemblage of the associated minerals of all the rocks from hornfels to migmatite may be classed as an amphibolite facies, then, what is the metamorphism from hornfels to migmatite within the amphibolite facies? It is desired to know how the composition of particular minerals varies within their chemical stability range according to the process of metamorphism. The basic mineral assemblages of the series are those of quartz-plagioclase-biotite, in which the variation of plagioclase and biotite is considered as follows:

The An contents of plagioclases in every rock species is shown in Table 4.

Table 4. An contents of plagioclases.



The plagioclase with the highest An content, An 45, is met with in the melanocratic part of banded gneiss and then it acidifies to migmatite. The fact corresponds to the highest Al content of the bulk chemical composition of the gneiss. It seems clear that the metamorphic grade attains maximum in the banded gneiss.

Biotite has a wide stability range as well as plagioclase and is stable from the green schist facies to the lower part of the granulite facies, especially in epidote amphibolite and amphibolite facies. So, the changes of metamorphic condition may be traced by the variation in biotite.

It has been verfied that the quantity of Al of the biotite is enriched in proportion to the quantity of Al of the bulk composition in gneiss. The enrichment of Al in the biotite is associated with the highest An content of plagioclase, and an excess of Al over the theoretical quantity may replace Fe in part and Si in part with the advance of metamorphic grade.

Further, the variation of Ti, Mg/Fë and (OH) is treated as a criterion of the grade as follows: (RAMBERG, 1949, 1952)

Table 5. Ti, Mg/Fe$^{\cdot\cdot}$, (OH) in biotites

	Banded gneiss	Biotite (cordierite) migmatite	Granitic migmatite
Ti	0.31	0.18	0.13
Mg/Fe$^{\cdot\cdot}$	1.23	1.32	1.38
(OH)	2.21	4.93	4.27

The decrease of Ti and the increase of Mg/Fë represent the retrogression of metamorphism. It seems clear that the grade in the banded gneiss is at its highest because of the lowest index of biotite and the highest An content of plagioclase and according to the chemical data of biotite though the chemical data of biotite of hornfelses are not available.

The hydrosilicates of the metamorphic series in question are biotite and muscovite, especially the biotite is one of the main components commonly found through the series. Therefore, the composition of biotite may be influenced by water in the process of metamorphism and the migmatization. The quantity of water of biotite increases with migmatization. This phenomenon signifies the lowering of metamorphic grade associated with decrease of Ti, Al and the increase of Mg/Fë. However, the water content in the biotite of biotite (cordierite) migmatite is more than that of granitic migmatite as well as of the bulk composition. The phenomenon signifies that the biotite (cordierite) migmatite has formed an arch and domes, and moved rheomorphically, while the granitic migmatite in question has formed in situ.

As stated above, the series of hornfels-schistose hornfels-banded gneiss is assigned to progressive metamorphism, but the series of banded gneiss-biotite (cordierite) migmatite-granitic migmatite of migmatization in narrow sense, to retrogressive metamorphism in respect of the metamorphic grade. The regional thermal metamorphism exhibited by the series: hornfels-gneiss-migmatite, is common in the orogenic zone which is not represented by a simple progressive metamorphism but by the metamorphism combined with migmatization which is retrogressive from the metamorphic point of view.

The Si-Al series of schist-mica gneiss-granite, granulite was treated from the thermodynamic standpoint by LAPADU-HARGUES (1955). He concluded by his calculation applying FERSMANN's EK value that the internal energy could not vary through the process of the metamorphism. The free energy may be effected by strain energy and surface energy to attain equilibrium when the internal energy is constant. The strain energy as a function of preferred orientation; the deformation of minerals indicates the highest energy level in banded gneiss, and the lowering of the energy to biotite migmatite and granitic migmatite. At the same time, the grain size increases to make surface energy lower from gneiss to migmatites. The decrease of the strain energy is further accelerated by the grain growth. It seems clear that these phenomena represent the decrease of free energy i.e., the tendency toward stability. Migmatization and granitization are a particular convergent metamorphism toward a

Table 6. Average grain sizes (mm) of rock species

Hornfels	Schistose hornfels	Banded gneiss	Biotite migmatite	Granitic migmatite
0.1	0.1	0.36	0.46	1.1

thermodynamic equilibrium.

Paragenesis of cordierite and potash feldspar:

By ESKOLA (1939) and other investigators, it has been stated that cordierite and potash feldspar could not coexist in amphibolite facies except for its high temperature portion. HAYAMA (1956) stated that the coexistence of the two minerals may be possible under the influence of water vapour pressure. In the southernmost area of the Hidaka metamorphic belt, the coexistence of the minerals is general in cordierite migmatite. The paragenesis of the constituent minerals is divided into two phases according to the microstructure which is characterized by the microjoint related to the doming of cordierite migmatite. After the jointing microscopically, plagioclase alters to potash feldspar along the microjoint which disappears gradually owing to the neocrystallization of potash feldspar. At the same time, biotite alters to muscovite, quartz recrystallizes, garnet decomposes to minor flackes of biotite and cordierite turns into pinite. The transitional assemblages from the unstable older association to the newer association can be observed. These two associations are as follows:

(I) Biotite-cordierite-garnet

(II) Biotite-muscovite-potash feldspar-(pinite)

The assemblage of (I) represents the composition of banded gneiss. Then, the phase transition (I) → (II) indicates the retrogression of metamorphic grade; for the transition of garnet to biotite and cordierite to pinite, the addition of K and H_2O is necessary as well as in the case of the alteration from cordierite migmatite to granitic migmatite. Migmatization and granitization proceed even in cordierite migmatite as a beginning stage of granitic migmatite formation.

Potash feldspar in banded gneiss may exist due to the supply of K which extends over the gneiss zone at the later stage of migmatization because the potash feldspar bearing banded gneiss is ordinarily met with at the neighbourhood of granitic migmatite. At this stage, the metamorphic grade of the gneiss corresponds to that of the migmatite.

Now, it has been verified as stated above that the first half of the series: hornfels-schistose hornfels-gneiss, exhibits progressive metamorphism and the later series of gneiss-biotite (cordierite) migmatite-granitic migmatite represents retrogressive metamorphism. Even in the cordierite migmatite, a retrogressive phenomenon due to the addition of K and H_2O is indicated. However, the regional thermal metamorphism and the migmatization may be impossible of explanation according to the facies principle resulting from the phase equilibrium. The treatment involving in reaction kinetics is necessary in the case that metasomatism acts conspicuously because of migration of matters and porphyroblasts grow up rapidly. For instance, YODER (1952, p. 620) discussed the pelitic assemblages in the chlorite, biotite, and garnet zones of progressive metamorphism. He attributed the metamorphism to the kinetics of nucleation and growth rather than to attainment of thermodynamic equilibria. Contrariwise, TURNER stated "earlier, GOLDSCHMIDT's and ESKOLA's assumption of general approximation to equilibrium in the whole association of mineral assemblages in both the pyroxene-hornfels and the amphibolite facies seems well justified. The same assumption can be extended on similar ground to other facies......If in the light of future experimental work it becomes necessary to abandon these assumptions, it will also be necessary to include conditions pertaining to kinetics of reaction among the physical variables with which facies are correlated. To the present writer it seems unlikely that this situation will arise" (1958, p. 17).

It is well known, however, that the equilibria become unstable when the reaction culminates to promote the rapid growth of crystal. It is future problem to what degree the concepts of thermodynamic equilibria and reaction kinetics will be useful in explaining regional thermal metamorphism.

4. Porphyroblast and Stress

Migmatization is the ultrametamorphism which is represented by the formation of leucocratic veins at its early stage and of the porphyroblast of plagioclase and quartz with associated minerals. The growth of plagioclase porphyroblasts especially takes an important part in the migmatization as a metablastesis series.

HUNAHASHI stated in 1951 that granitic rock was formed by the increase of plagioclase porphyroblast and plagioclase porphyroblast biotite gneiss was defined by the growth of plagioclase porphyroblasts of which the free growth had been controlled by the stress in gneiss condition (1951, p. 11). He further stated that the plagioclase porphyroblasts of the gneiss begin to break due to the continued shearing stress (1956, p. 547). By means of these arguments, he stressed that the shearing stress was obstructive to the growth of the plagioclase. HUNAHASHI advanced this argument in 1956, "the intense foliation is used to develop about the band which contains plenty of large porphyroblasts turn small with weak foliation" (p. 548). He stressed this time that the influence of the shearing stress is helpful to the growth of plagioclase prophyroblasts. The present author reported in 1958 that the plagioclase porphyroblasts abound in the narrow zone where the shearing stress has acted intensely. It seems that the shearing stress has influence, effects both positive and negative, upon the growth of porphyroblasts: at first the stress promotes the nucleation and the crystallization but it turns to obstruction after the development of the porphyroblast.

Do plagioclase porphyroblasts usually grow up in association with shearing stress? They do not necessarily. Granitic migmatite is an aggregation of plagioclase porphyroblasts (petroblastic rock) and surrounding it plagioclase porphyroblasts are scattered without any structural connection. It is not uncommon that plagioclase porphyroblasts occur in a xenolith of granite and its contacts. What is the condition resulting in the plagioclase porphyroblast? There is some potential which leads to the formation of the porphyroblast. What is the origin of that potential? One of the causes of the potential is limited by the shearing stress in question.

Before the stress problem bearing on the metablastesis is discussed, the force of crystallization will be treated, which has been known since the idioblastic series of metamorphic minerals was arranged by F. BECKE (1903). According to his series, metamorphic minerals are divided into eight stages in which albite is categorized to the fourth stage and plagioclase to the seventh stage. Albite would seem to have a rather high position because the force of crystallization is seen to be inversely proportional to the fictive modal volume of the crystal (BARTH, 1952, p. 310) (TURNER & VERHOOGEN, 1951, p. 510). The force of crystallization may be ordered according to lattice structure: nesosilicates, inosilicates, phyllosilicates and tectosilicates. The tectosilicates with open framework show the weakest force of crystallization.

That force, however, cannot be identified directly with the power of minerals to grow in the form of idioblasts but the growth of a crystal depends on many factors. RAMBERG (1952) listed the following factors:

1. The force of crystallization.
2. The degree of supersaturation.
3. The concentration and mobility in the enclosing rock of the chemical constituents of the porphyroblast.

4. The energy of activation of a germ of the porphyroblast.
5. The effect of the surrounding minerals and of the size of the porphyroblast on its escaping tendencies (vapor tension, activity, etc.).
6. The plasticity of the surrounding minerals.

Crystalblastesis depends on the physico-chemical environment of the surroundings which are temperature, the degree of supersaturation, the nature of the pore fluid and the mechanical properties of the enclosing medium, as well as the power of minerals to grow up. The kinetics of crystal growth is probably just as important as surface energy relations in determining the habit and size of crystals. It is significant that the kinetics in a chemical circumstance is more important in crystal growth than the equilibrium of the crystal lattice. The stress promotes the rate of the diffusion of matters, the transport of pore solution, the degree of the supersaturation and reaction speed. Another important role of the stress is to energize nucleation. It is well known in metallurgy that nucleation and recrystallization are promoted by hard work and annealing. The annealing heat decreases (the recrystallization occurs at lower temperature) in inverse proportion to the intensity of strain because the strain energy is stored as the lattice strain. The absolute temperature of the recrystallization is from one-third to two-thirds of the absolute meling temperature. Nucleation is verified experimentally to take the following cause:

1. The nuclei are formed at an intensely deformed part.
2. The number of nuclei originated in a unit time increases abruptly with the increase of strain.
3. A particular relation of orientation is observed between the deformed sample and newly originated grains.

The grain boundary migrates to neighbour crystals to recrystallize owing to the gradient of strain energy because the new crystals grown up from the nuclei are stable. Grain growth continues to lower the grain boundary energy after the greater part of the strain energy is released. The stress causes the lowering of the temperature of recrystallization and also promotes recrystallization.

The speed of recrystallization may be related to impurity of material as well as to the intensity of strain. The influence of impurity is variable because even a small amount of impure material exhibits effects which both promote and obstruct recrystallization and grain growth.

Now, the occurrence of plagioclase porphyroblasts along intense foliation may be verified by the argument as stated above. Plagioclase with three-dimensional framework has a large capacity in its lattice not to be obstructed in its growth by impurity, so that it can grow up easily including impure material. The surface tension at the boundaries of crystals influences presumably the growth of plagioclase. Therefore, plagioclase has the possibility of growing larger porphyroblasts than other minerals.

The shearing due to stress plays an important part in the nucleation, the recrystallization and crystal growth and further in the transport of pore solution and the promotion of reaction speed.

VI. Concluding Remarks

Migmatites and the associated metamorphics in the Hidaka metamorphic belt, are treated geologically, petrographically and petrologically in this paper. The metamorphic series and migmatization series are systematized on the basis of field occurrence after the description and classification of the rock species. The metamorphic series is signified by the regional progressive metamorphism: hornfels-schistose hornfels-gneisses and the migmatization series is emphasized in respect to the development of leucocratic part included in the metamorphic series. It is the series of venite-polyvenite-agmatite-nebulite. The leucocratic part increases according to the succession of the series and then the comprized rock approaches to granitic character.

The metamorphism of the metamorphic series is attributed to the amphibolite facies but represents a progressive one from hornfels to gneisses. On the contrary, it seems clear that the migmatization of gneiss-biotite migmatite-granitic migmatite represents a retrogressive metamorphism which is characterized by metasomatism. It seems that the metamorphism of the metamorphic belt may be a combination of two different operations. BARTH stated (1936, p. 838) "other processes of material transfer, because less studied and less understood, have not yet been systematically classied but clearly they do not belong to the 'ordinary metamorphic processes', and a boundary between such processes and metamorphism proper must be drawn somewhere." And further "the study of both metamorphic rocks and syntectic rocks (migmatite in question) has been hampered in the past, because of an unfortunate method of classification." GOLDSCHMIDT (1921) in his studies of the Stavanger district stated that injection metamorphism operated successively over the regional metamorphism under the same physical condition. It is noteworthy that the difference between metamorphism and migmatism is recognized also in this case.

However, the migmatization in the Hidaka metamorphic belt starts at the stage of schistose hornfels in the metamorphic series which is defined by progressive metamorphism. It is represented by venite and polyvenite. The migmatization proceeds with progressive metamorphism in early stage as well as retrogressives in later stage, so that migmatism and metamorphism cooperate with the exception of the case of hornfels which is formed by static metamorphism. To express it in another way, migmatism and metamorphism operate at the same time in the zones where intense dynamic effect is active. MISCH (1949, p. 245) concluded as follows: "I wished to emphasize the general validity of the statement that high-grade regional metamorphism and synorogenic granitization were invariably and necessarily linked. They are expressions of one and the same process. There is not any region known to me either from study of the literature or from personal field-work, where katazonal or lower mesozonal crystalline schists occur without metamorphic migmatites or granitic rocks." READ (1957, p. 356) stated "if it is admitted that regional metamorphism is associated with the passage of energetic fluids through the rocks, then regroupment of the constituent materials is to be expected. This we see in the operations of metamorphic diffusion and differentiation—operations that become intensified in the juicier environments of migmatization." Further he said "it is as well to realize now that this separation (of orogenic metamorphism from granitization metamorphism) may be one largely of time—there is likely to be an ultimate genetic connexion between the two. Orogenic metamorphism is an early process in the history of the deformation of the geosynclinal pile, granitization metamorphism is a later process, initiated in the depth of the folded pile and taking time to extend its domain to the higher levels" (op. cit., p. 362).

It is reasonable roughly that regional metamorphism is considered an early process and migmatism, a later process, but under that explanation the occurrence of venites cannot be explained because they occur at an early stage so that the migmatization puts forth buds in schistose hornfels.

The present author wishes to stress the fact that the migmatization in the metamorphic series is caused by the dynamic metamorphism of regional metamorphism in an orogenic core. The zone of the regional metamorphism in the deep root of an orogenic zone usually exists under an intense stress which makes the rock deform plastically and then causes fracturings to occur. The cleavage of schist and gneiss is a characteristic intermediate phenomenon between plastic deformation and fracturing. When the gliding due to shearing stress to form, cleavage proceeds, leucocratic veins may be formed where the energy level descends because of the relaxion of stress, and transfer of matters occurs. The growth of minerals associated with stress proceeds as porphyroblastesis and the porphyroblasts aggregate to become granitic migmatite.

The metamorphic facies of granitic rock with wide stability range corresponds to all facies from green schist facies to the lower part of granulite facies. Almost all the rocks therefore show the tendency to become granitic rock under the chemical circumstance sufficient to produce it, whether it may be melt or solid. (1961, Dec.)

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Explanation of Plate I

Explanation of Plate I

Fig. 1. Nakanogawa group: Alternation of sandstone and slate.
Fig. 2. Polyvenite in schistose biotite hornfels.

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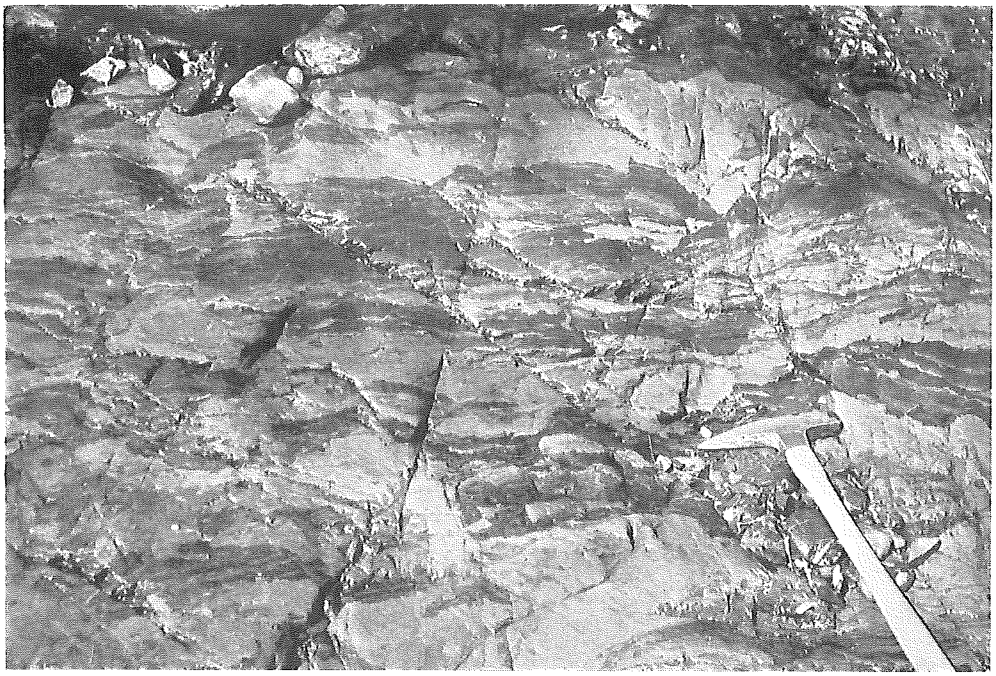

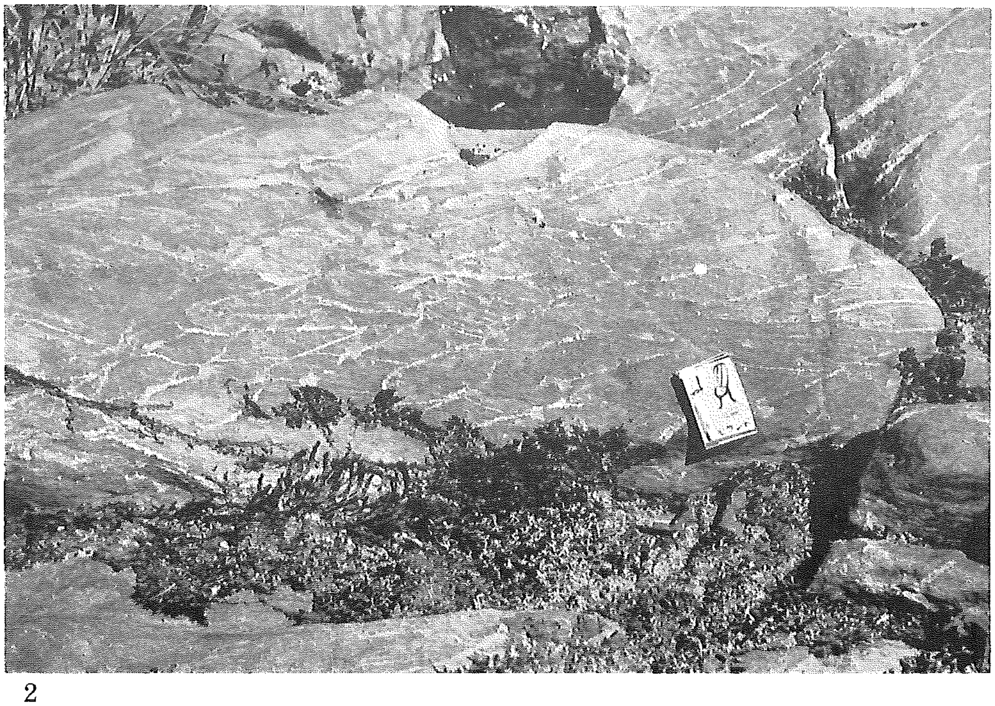

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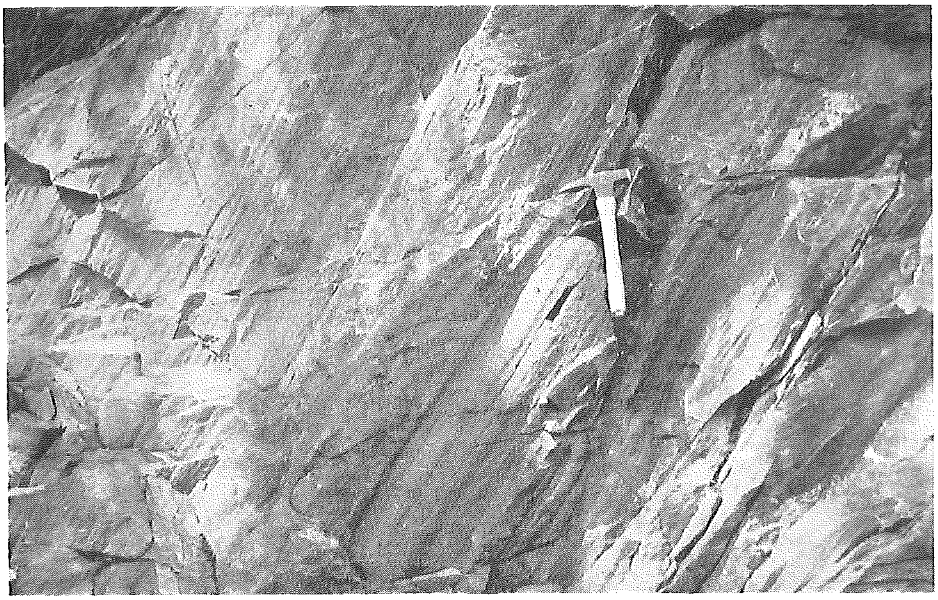
Explanation of Plate II

Explanation of Plate II

Fig. 1. Schistose hornfels.

Fig. 2. Quartz veins in hornfels: strike of veins parallel to that of banded biotite gneiss is oblique to the bedding of Nakanogawa group.

1



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Explanation of
Plate III

Explanation of Plate III

Fig. 1. Polyvenite.
Fig. 2. Polyvenite.
Fig. 3. Agmatitic part in banded biotite gneiss.

1

2

3

Photo K. KIZAKI

Explanation of
Plate IV

Explanation of Plate IV

Polyvenite.

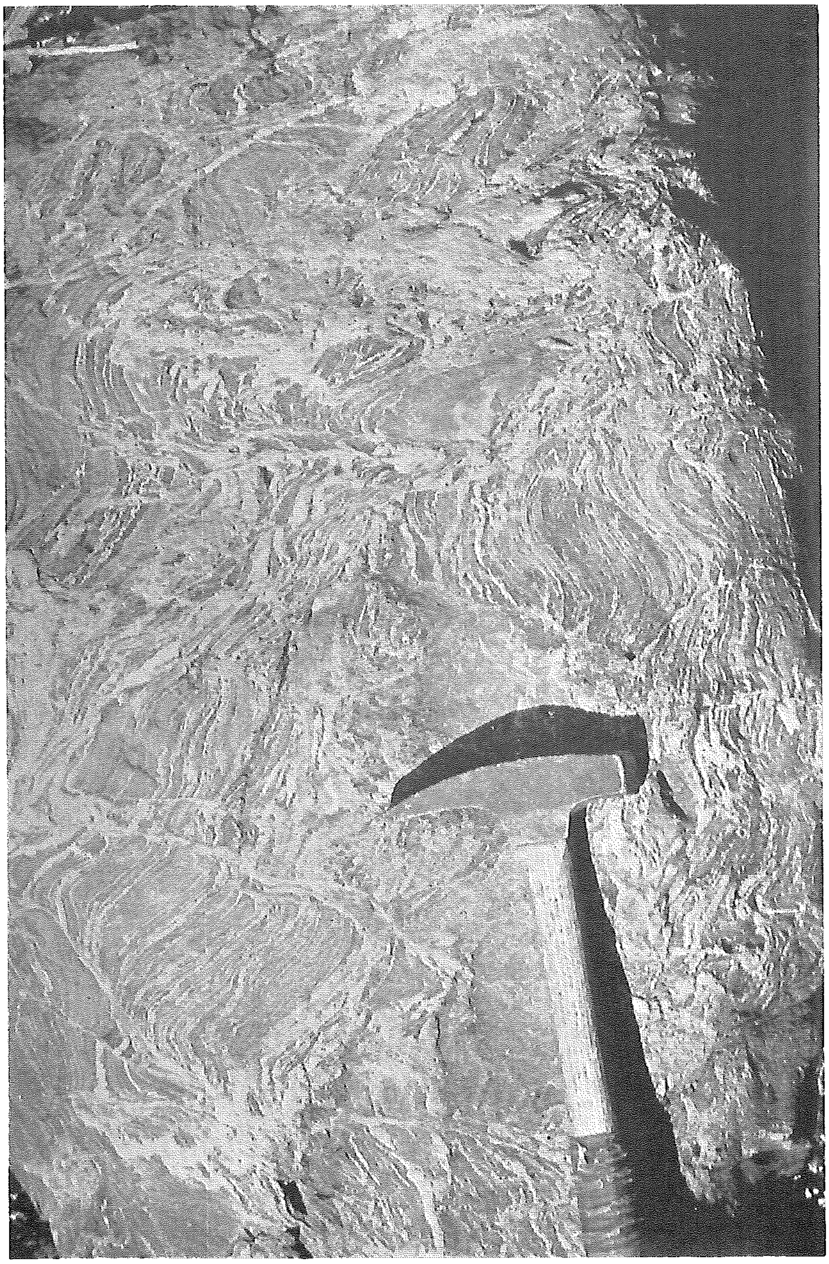
Plate IV

Photo K. KIZAKI

Explanation of Plate V

Explanation of Plate V

Polyvenite in the banded biotite gneiss which is traversed by oblique veins. Agmatitic part is shown at the upper part.



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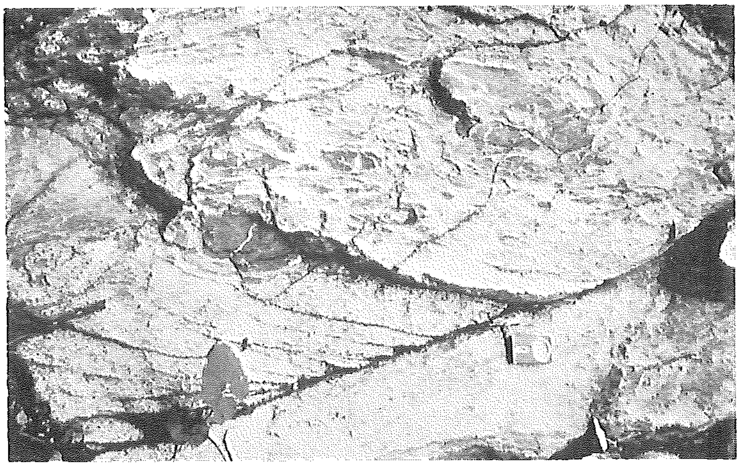
Explanation of Plate VI

Explanation of Plate VI

Fig. 1. Palaeosomes of schistose hornfels in biotite migmatite.
Fig. 2. Palaeosomes of gabbro in biotite migmatite.
Fig. 3. Agmatitic amphibolite in biotite migmatite.

1



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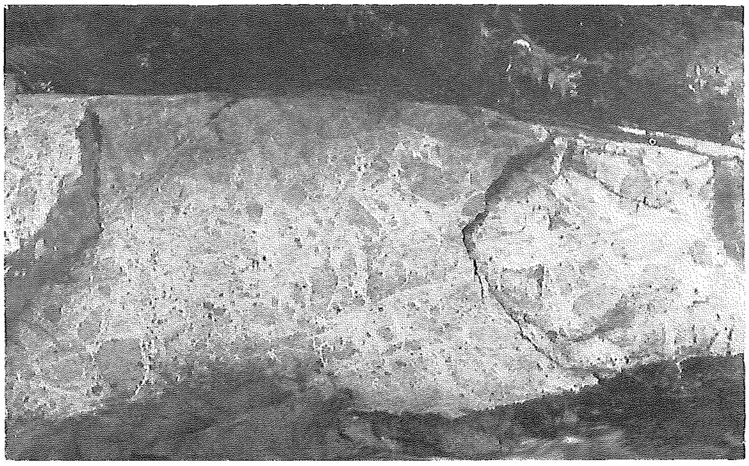

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Explanation of
Plate VII

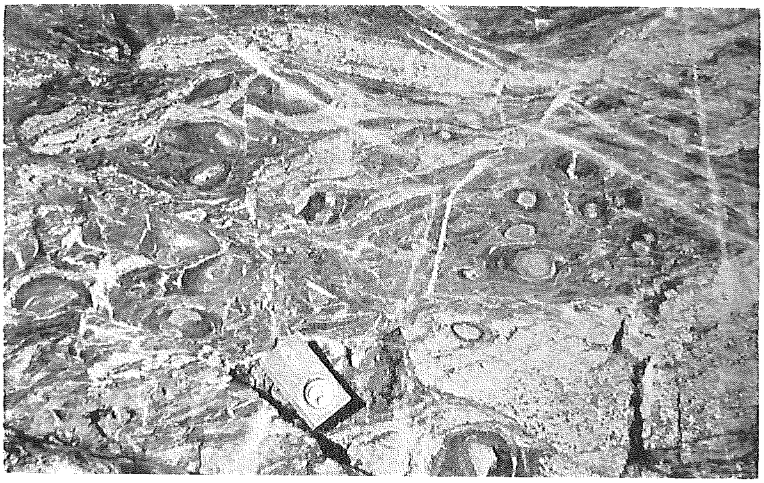
Explanation of Plate VII

Fig. 1. Contact of banded biotite gneiss with granitic migmatite, showing plagioclase porphyroblasts and metamorphosed calcareous nodules.

Fig. 2. Op. cit.

1

2



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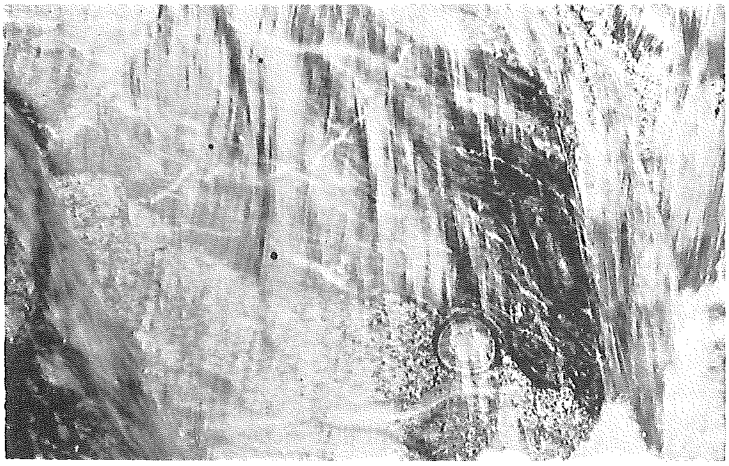
Explanation of Plate VIII

Explanation of Plate VIII

Fig. 1. Orbicular rock at the contact of granitic migmatite with banded biotite gneiss.
Fig. 2. Palaeosomes of banded biotite gneiss in biotite migmatite.

Plate VIII

1



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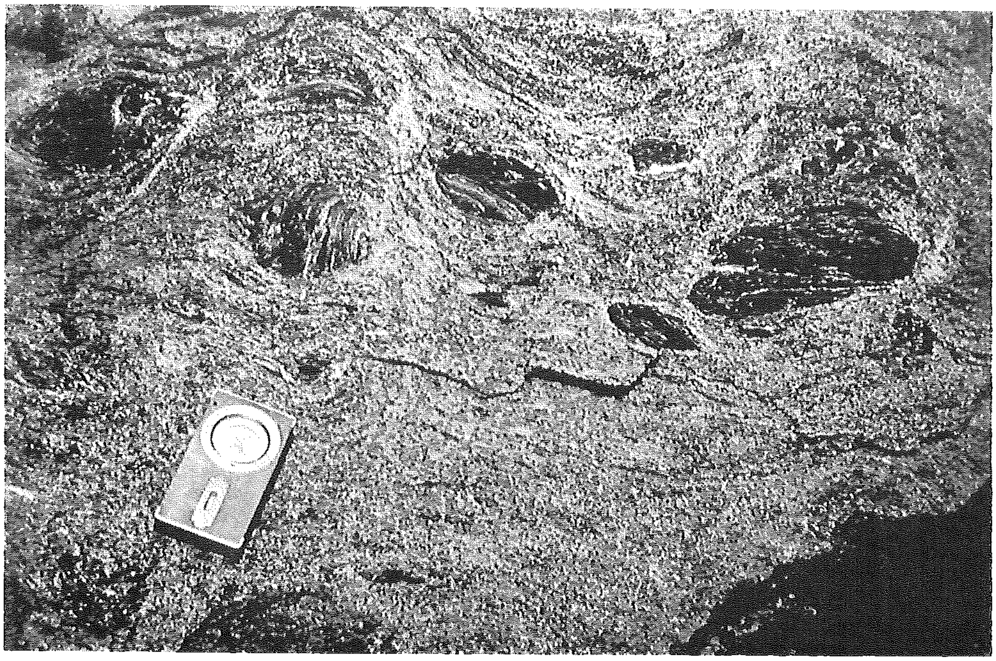

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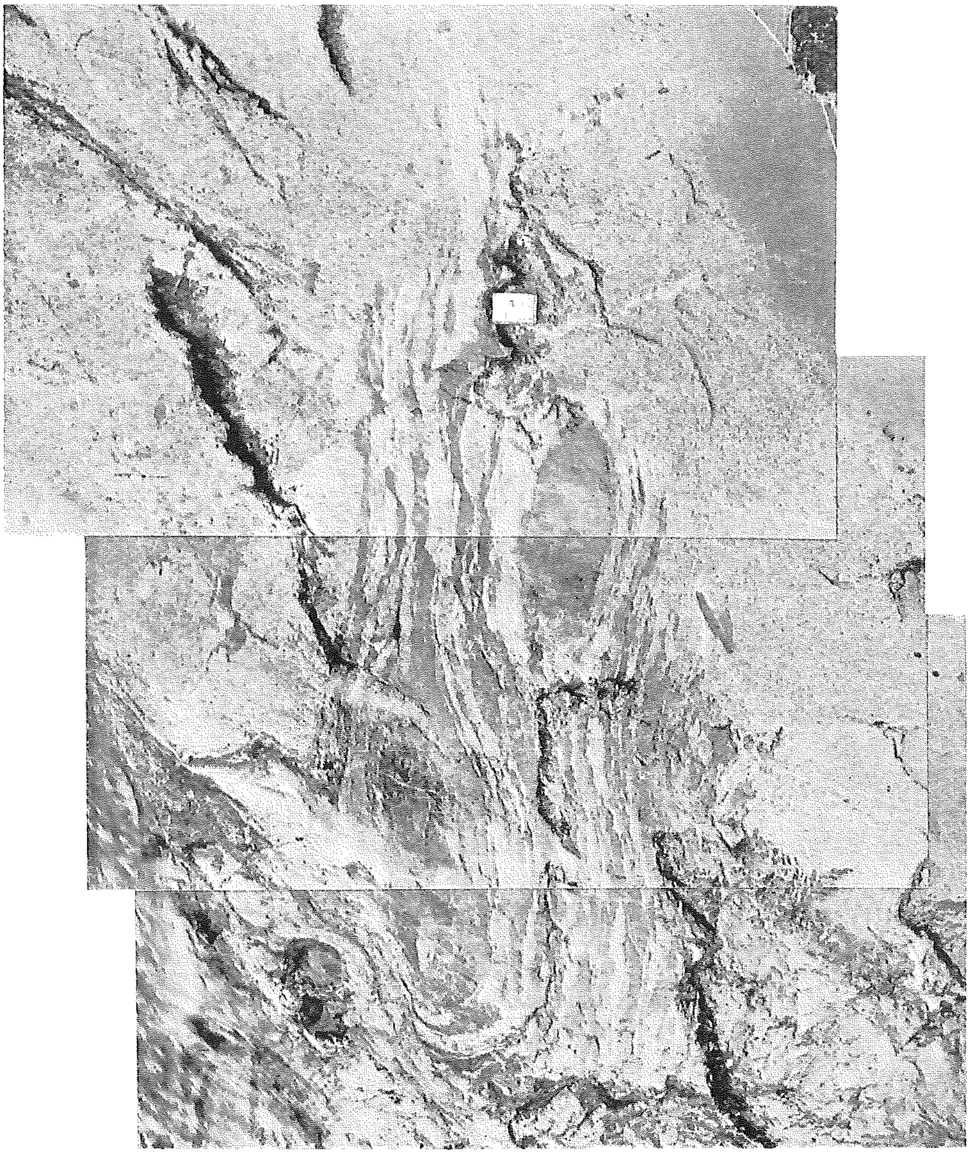
Explanation of
Plate IX

Explanation of Plate IX

Banded biotite gneiss is preserved in biotite migmatite.



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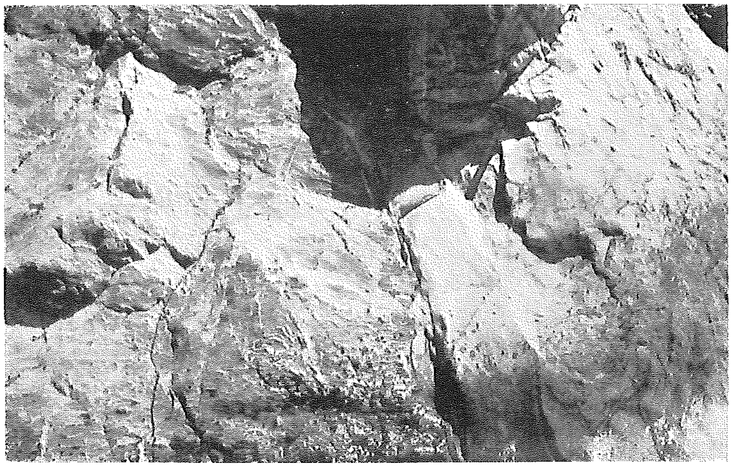
Explanation of
Plate X

Explanation of Plate X

Fig. 1. Aplite dike in venite.
Fig. 2. Nupinai granite and venite.

1



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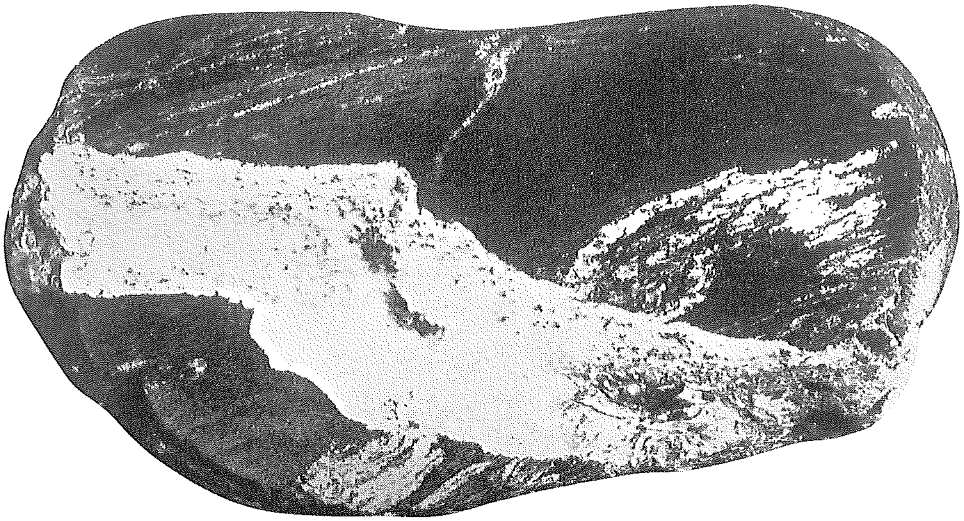
Explanation of Plate XI

Explanation of Plate XI

Fig. 1. Schistose hornfels and aplite vein. ×2/3

Fig. 2. Palaeosome of banded biotite gneiss in biotite migmatite. ×2/3

1



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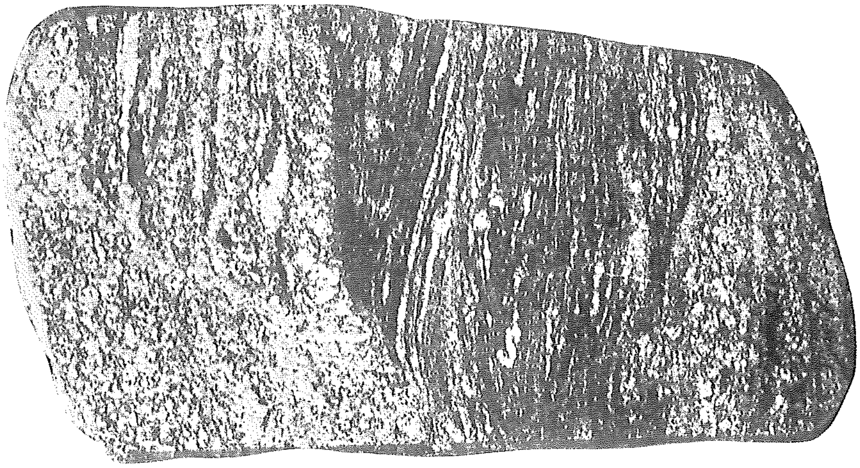

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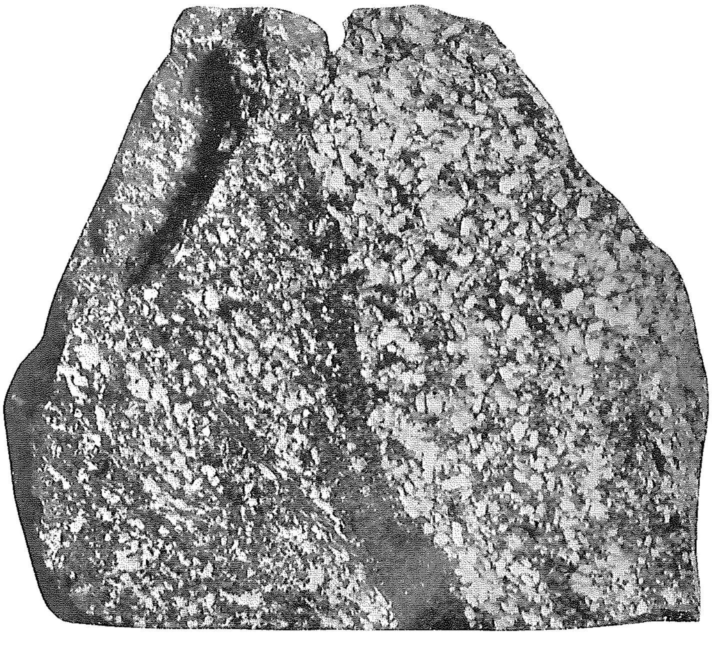
Explanation of Plate XII

Explanation of Plate XII

Fig. 1. Palaeosome with quartz pool in cordierite migmatite. ×2/3
Fig. 2. Granitic migmatite. ×2/3

1

2



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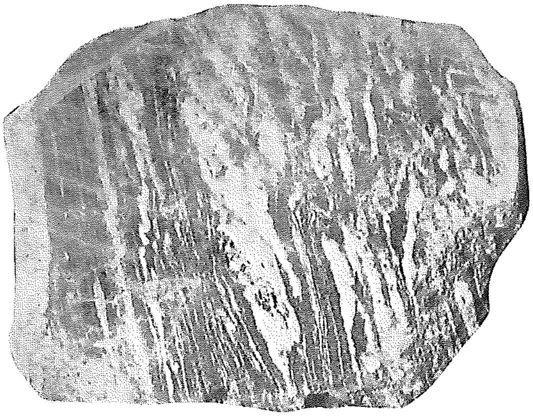
Explanation of
Plate XIII

Explanation of Plate XIII

Fig. 1. Banded biotite gneiss. ×1/2
Fig. 2. Op. cit. ×1/2
Fig. 3. Palaeosome of schistose hornfels in biotite migmatite. ×1/2

1



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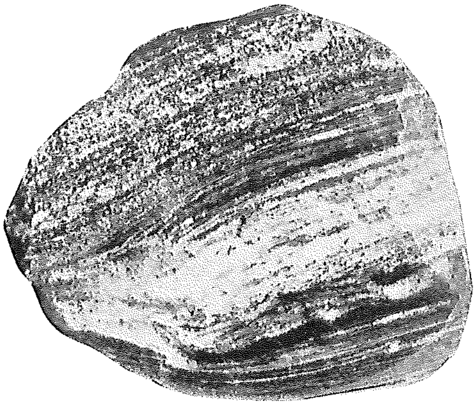

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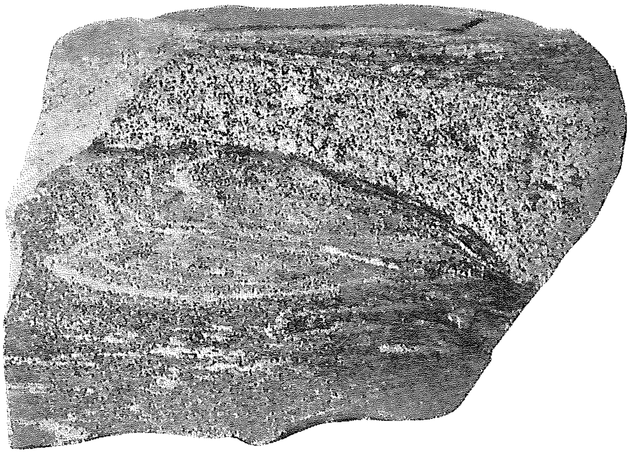

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Explanation of
Plate XIV

Explanation of Plate XIV

Fig. 1. Sandstone of Nakanogawa group. ×30
Fig. 2. Biotite hornfels. ×30
Fig. 3. Op. cit. ×30

Plate XIV

1

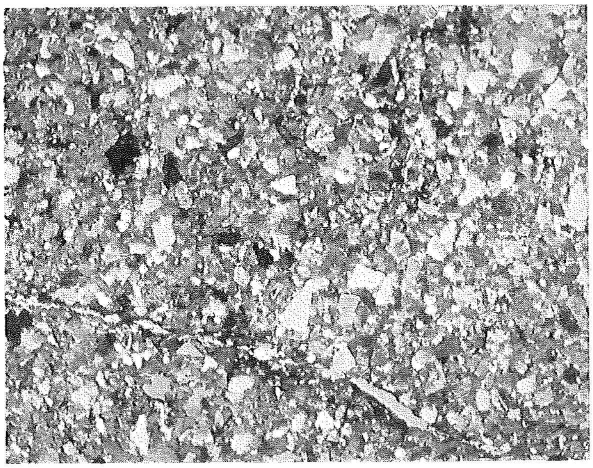

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Photo K. KIZAKI

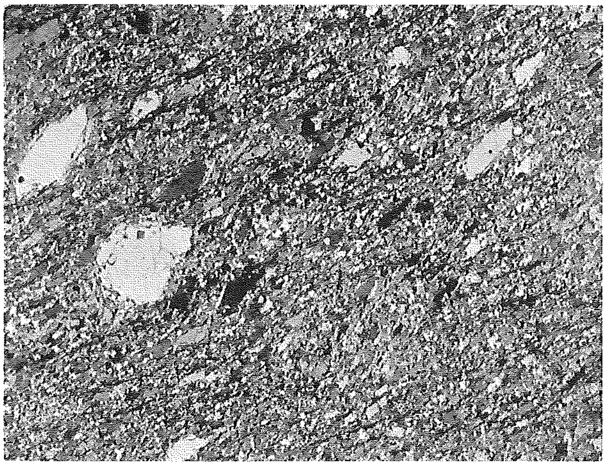
Explanation of
Plate XV

Explanation of Plate XV

Fig. 1. Schistose biotite hornfels. ×30
Fig. 2. Schistose biotite hornfels with vein. ×30
Fig. 3. Banded biotite gneiss. ×30

Plate XV

1



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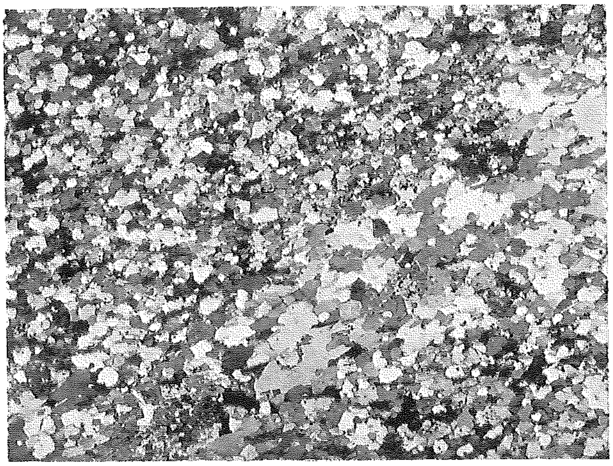

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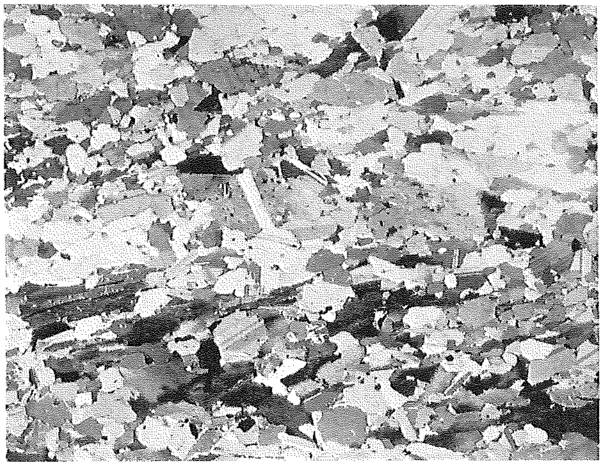


Photo K. KIZAKI

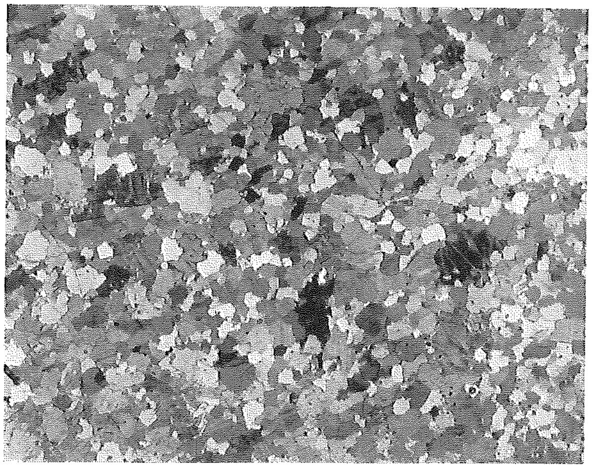
Explanation of Plate XVI

Explanation of Plate XVI

Fig. 1. Coarse biotite hornfels. ×30
Fig. 2. Banded biotite gneiss. ×30
Fig. 3. Op. cit. ×30

Plate XVI

1



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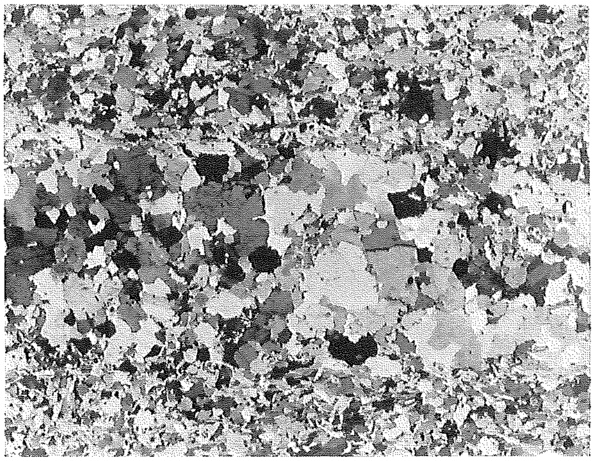

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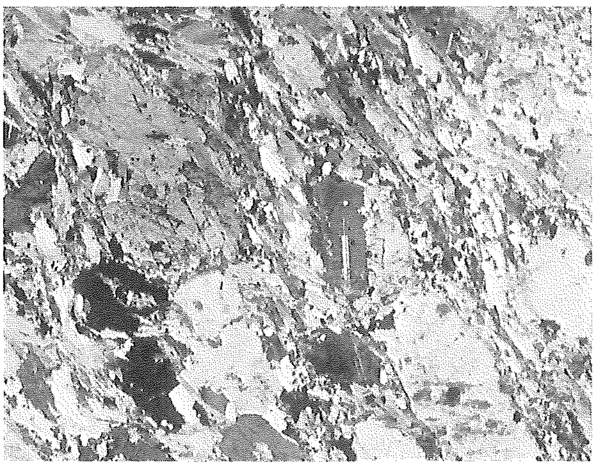
Explanation of
Plate XVII

Explanation of Plate XVII

Fig. 1. Plagioclase porphyroblast biotite gneiss. ×30
Fig. 2. Biotite migmatite. ×30
Fig. 3. Garnet in plagioclase porphyroblast gneiss. ×30

1



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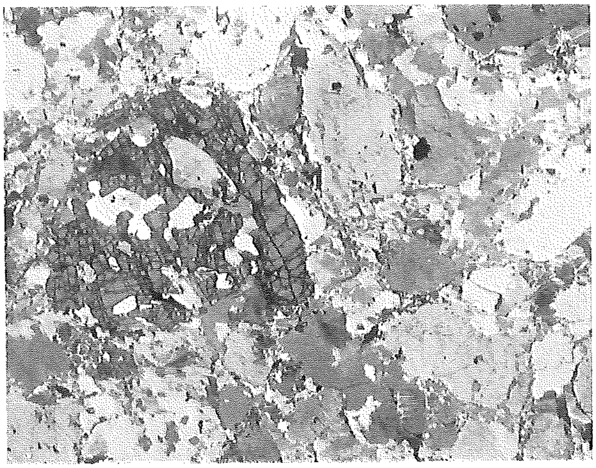

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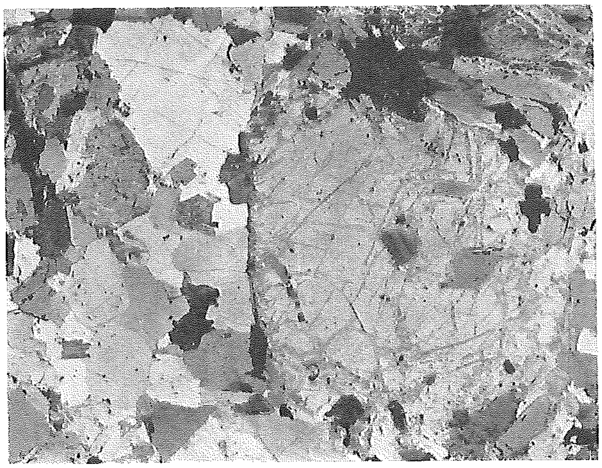
Explanation of
Plate XVIII

Explanation of Plate XVIII

Fig. 1. Cordierite in cordierite migmatite. ×30
Fig. 2. Potash feldspar porphyroblast in biotite migmatite. ×30
Fig. 3. Biotite migmatite. ×30

Plate XVIII

1



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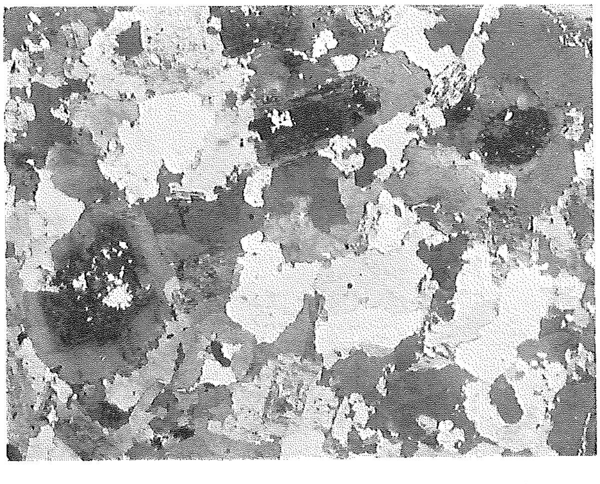


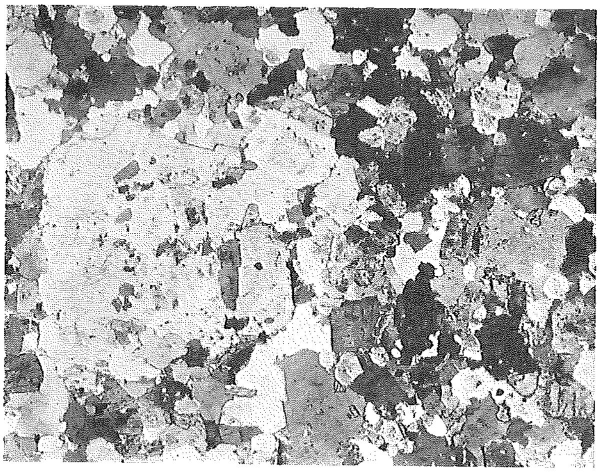
Photo K. KIZAKI

Explanation of Plate XIX

Explanation of Plate XIX

Fig. 1. Plagioclase porphyroblast in biotite migmatite. ×30
Fig. 2. Biotite migmatite. ×30
Fig. 3. Marginal portion of granitic migmatite. ×30

1



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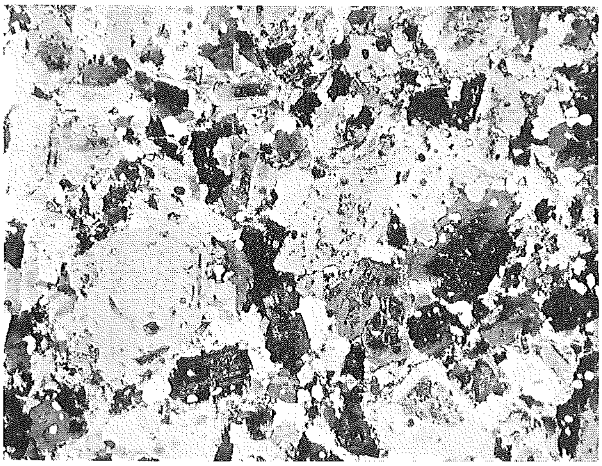


Photo K. KIZAKI

Explanation of
Plate XX

Explanation of Plate XX

Fig. 1. Granitic migmatite. ×30
Fig. 2. Granite. ×30

1

2

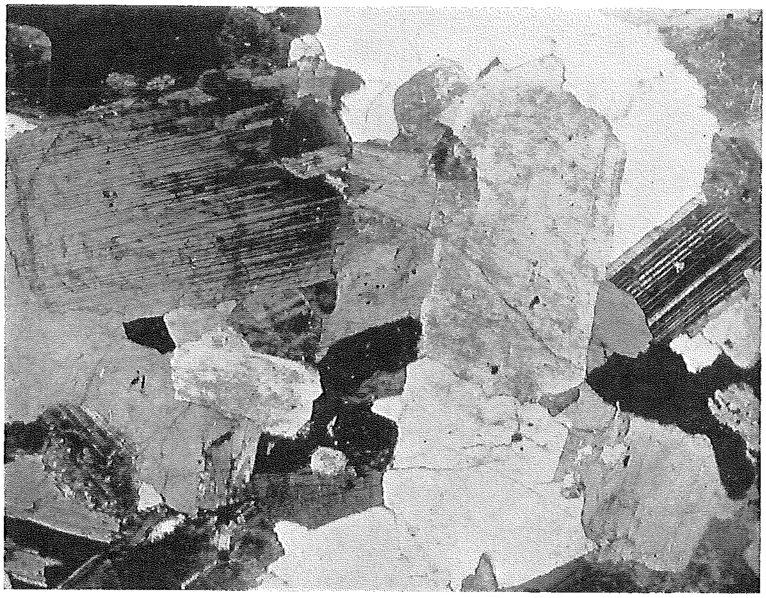
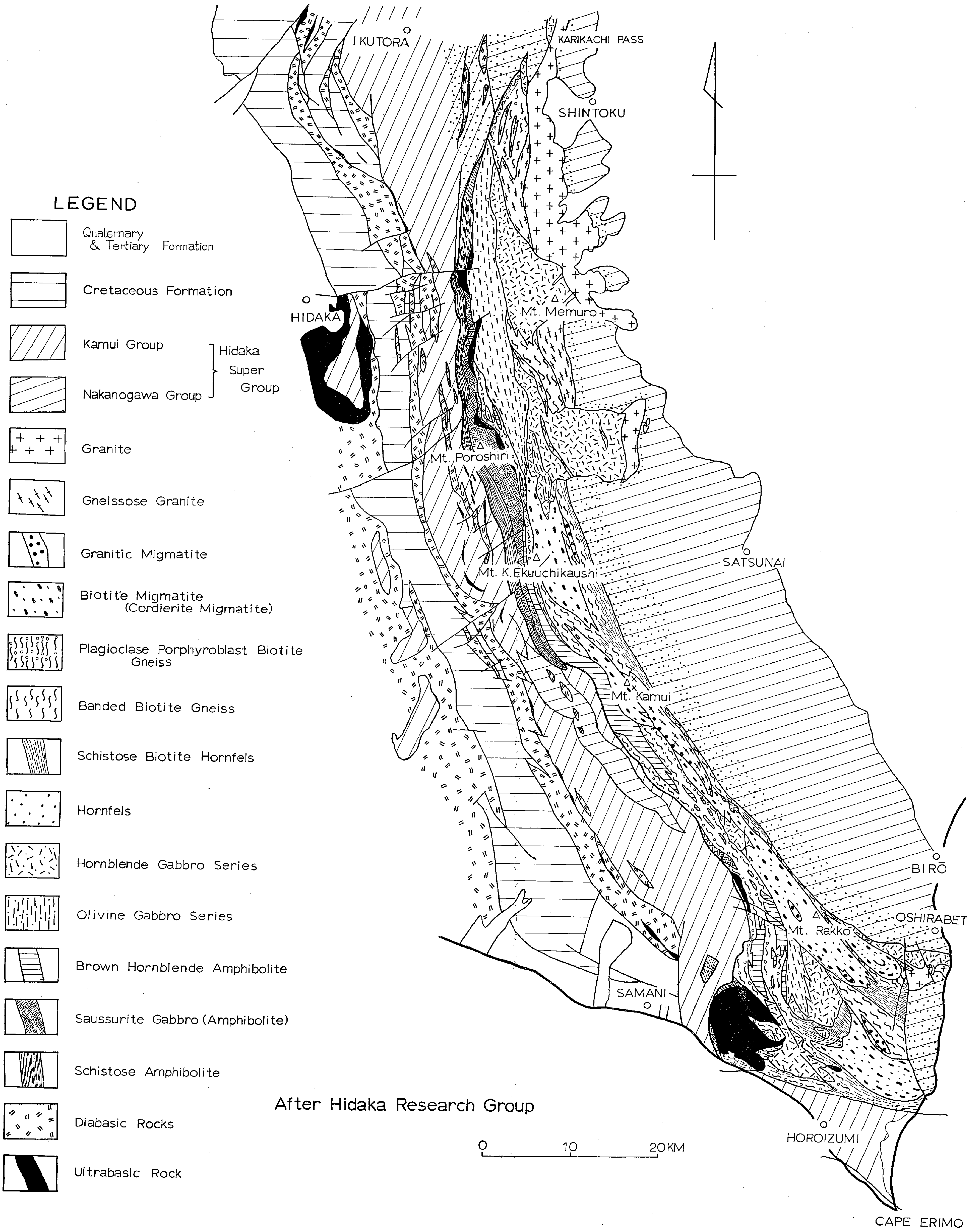


Photo K. KIZAKI

GEOLOGICAL MAP OF THE HIDAKA METAMORPHIC BELT

Plate XXI



After Hidaka Research Group