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TONALITE COMPLEXES IN THE ABUKUMA AXIAL METAMORPHIC BELT, JAPAN*

by

Koji Uchiyama

(with 20 text-figures and 4 tables)

Abstract

In an effort to examine the natures and origin of tonalitic intrusive masses lying between Takanuki and Gozaisho metamorphic units in the Abukuma axial metamorphic belt a study has been made of the Usuki tonalite complex, which crops out in the Takanuki district, as the typical one of the intrusive masses.

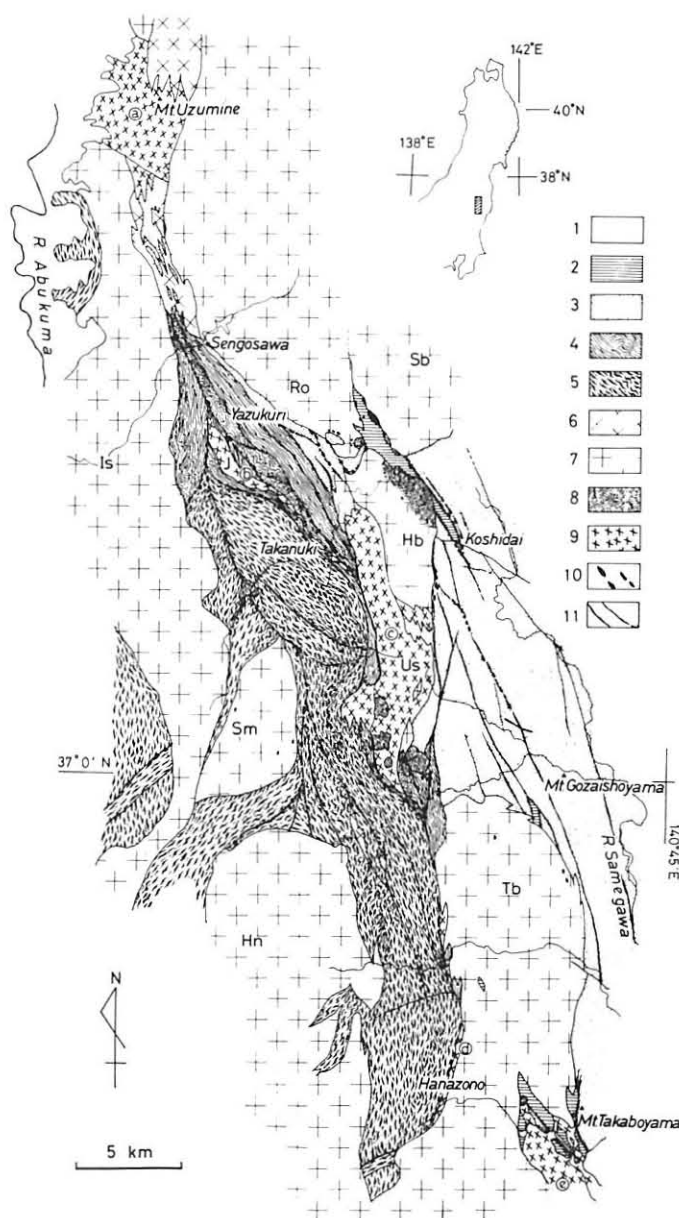
Two-thirds of the complex is represented by the lithofacies of tonalite proper, with which migmatitic and granodioritic lithofacies are intimately associated.

The host rocks of the migmatitic facies are biotite schist and amphibolite of both metamorphic units. The plagioclases formed in the neosomes of the migmatitic facies are fairly similar to those shown in tonalite proper; they are indicative of having been under overwhelming conditions of plagioclase formation taking place in the facies of tonalite proper, the conditions prevailing in the whole extent of the complex. Meanwhile, the granodioritic facies is of metasomatic replacement origin, which is considered to be a stable lithofacies according to the behaviour of its plagioclase. An examination of chemical characters of these lithofacies indicates that the lithofacies of granodiorite and tonalite proper are in a stable state of equilibrium. On the other hand, most of the neosomes seem to represent an unstable or transitional state of the lithofacies which deviated from the standard rock species.

Based on the geological and petrological evidence obtained through the detailed survey of the whole Takanuki district, the writer has arrived at the conclusion that the present tonalite which derives from crustal materials, did not come about from the partial melting of basic rocks. He does not agree to the currently accepted view concerning the origin of the early Precambrian voluminous trondhjemite-tonalite suite. Initially, it was formed beneath the central zone of the Takanuki metamorphic belt by the granitization of the Takanuki metamorphics at a deep level during the movement of the main stage of the Abean orogeny. Subsequently, the granitized materials at that level were rejuvenated and mobilized into the fracture zone formed between the Takanuki and the Gozaisho metamorphics during the subsequent stage of the orogeny. Measured data on lead isotope ratios of rocks of all types in the district also support the above conclusion.

Introduction

Tonalitic intrusives are disposed intermittently along the boundary zone lying between the Takanuki and the Gozaisho metamorphics, which are the major constituent units of the Abukuma axial metamorphic belt. Although those are revealed that this relationship of disposal holds for the whole extent of the axial metamorphic belt, it is somewhat distorted by the intrusion of quartz-diorite or granodiorite masses of younger ages, which are interweaved in the same boundary zone. The differences between those quartz-diorite or granodiorite masses and tonalitic intrusives are markedly evident in contrasted lithologic nature, tectonic relation and age of intrusion. These quartz-diorite or granodiorite masses seem to be comparable to those which developed prominently in the northern half of the Abukuma mountainland. Hence, they are



Text-fig. 1 Generalized geological map of the Uzumine, Takanuki and Hanazono districts, mid-part of the Abukuma axial metamorphic belt. (Compiled by the writer with reference to Inokuchi, 1976; Uchiyama, 1977; Machida, 1978; Takahata, 1979; Watanabe et al., 1978, 1979; Tsuchiya et al., 1980)

1: Quaternary and Tertiary. 2: Diaphthoritic rocks. 3: Gozaisho metamorphics. 4: Yazukuri schists. 5: Takanuki metamorphics. 6: Two mica granite. 7: "Older" and "younger" granites. 8: Gabbroic rocks. 9: Tonalitic intrusives along the Koshidai-Takaboyama-Daioh-in Structural Belt. 10: Ultrabasic rocks. 11: Sheared zones and faults.

Hb: Hanaboh quartz-diorite complex. Hn: Hanawa granitic mass. Is: Ishikawa granitic composite mass. J: Jyumonji tonalitic mass. Ro: Ronden granitic mass. Sb: Shibayama granitic mass. Sm: Samegawa granitic composite mass. Tb: Tabito granitic composite mass. Us: Usuki tonalite complex.

treated to be included in "older granite" (Text-fig. 1). The tonalitic intrusives mentioned above have long attracted much attention, and several pieces of information have been offered especially on the basis of observations carried out around the course of the Gozaisho highway, which is a representative section crossing the entire width of the northern part of the Abukuma axial metamorphic belt. In his classic paper entitled "The Archean Formation of the Abukuma Plateau", Koto (1893) referred to the tonalitic intrusive lying around the Gozaisho highway as a dome-shaped granitoid mass, and he suggested that it is referable to the lower Archean developing beneath the metamorphic members of the region, that is, the Takanuki and Gozaisho series, which are referred to the upper Archean.

After a lapse of five decades, Gorai (1944) studied the granitoid mass that Koto had defined, and established the "Miyamoto composite mass", which stretches in N-S trend and crosses the Gozaisho highway at its middle part. He observed that it contains quartz-diorite members, inclusive of the above-mentioned tonalitic members, and considered that it belongs to a single intrusive process which took place under the orogeny producing the metamorphics of the region. He then subdivided various lithologic facies, which, he suggested, was produced as a result of magmatic differentiation. He also mentioned that the existence of a small amount of metamorphic trondhjemite which suffered potash-feldspar blastesis in preexistent trondhjemitic rocks. Later, Ogura (1960) studied in detail the subdivision of facies made by Gorai (1944). Ogura (1956, 1958) also studied another separated tonalitic mass which developed in the western neighbourhood. He considered these tonalitic rocks the granitization products of basic rocks.

In the geological sheet map of "Takanuki" (1973) issued by Geological Survey of Japan, Kano et al. succeeded the Gorai's conception and set a new scheme of classifying distinctive lithologic facies into two main groups. They defined that every facies grades to each other, and made a detailed map of distribution of lithofacies as above. Recently Maruyama (1978, 1979) published his study, also following the views presented by Gorai and Kano et al.; he carried out the Rb-Sr dating of all rocks using the result of his study, whereby he suggested that 400 m.y. was an available age at least applicable to one of the main groups of rock facies, though there are many dispersed plots, to which he finds it difficult to give an interpretation.

Since 1973 the writer has made a geological and petrological study of the Takanuki district in the northwestern part of the Abukuma axial metamorphic belt as a member of a research group organized by Minato and Hunahashi. In close collaboration with the rest of members, he has mainly taken charge of examining the so-called "Miyamoto composite mass" as a rock mass constituting the major rock unit of this district. His finding turns out to conflict with the current view as follows:

Based on detailed field observations, the above-mentioned "composite mass" is subdivided into three main intrusive units. It is revealed that they are not in a gradual transitional relation but in a clear intrusive relation to each other. The first is a gabbroic intrusive mass occurring in a small dotted distribution; the second is a tonalitic intrusive complex accompanying such a large amount of migmatitic facies and the

complex occupies about two-thirds of the "Miyamoto composite mass"; and the third is a quartz-diorite complex developing mainly in the northern corner and also develops as intrusives in small dyke form in the southern part of the main mass. According to their lithological natures as well as intrusive relations observed in the field the writer comes to reach the conclusion that the "Miyamoto composite mass" should be separated chronologically and tectonically into the three independent intrusive units. They may be named "meta-gabbro mass", "Usuki tonalite complex" and "Hanaboh quartz-diorite complex". The first represents an earlier intrusion and the other two delayed intrusions.

The present paper concerns itself with the petrology of the Usuki tonalite complex. It refers to questions on the origin of tonalitic rocks on the basis of a detailed field survey and a petrographical study with the support of measured data of lead isotope ratios.

Geological Setting

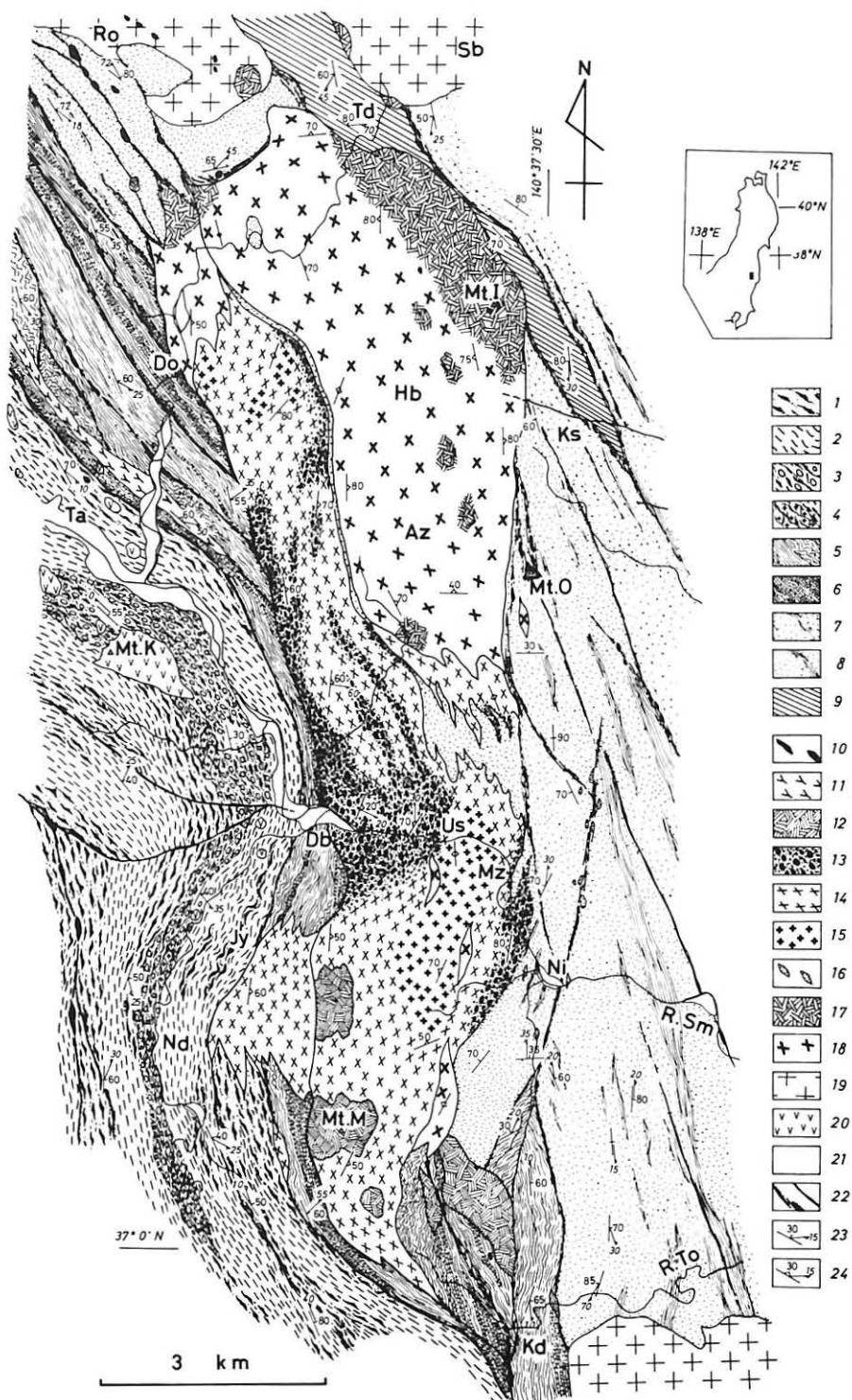
The Usuki tonalitic mass, on which the present study is focused, crops out as a sinuous mass, 15 km in length and 3 km in width, in the N-S trend. Its western neighbourhood is occupied by the Takanuki metamorphics and the eastern neighbourhood by the Gozaisho metamorphics (Text-fig. 2). For the understanding of the metamorphic and plutonic rocks of the region subjected to this study it may be useful to obtain the knowledge of the geological and petrographical features shown for the whole extent of the Abukuma axial metamorphic belt.

As to the present state of the knowledge of the Abukuma axial metamorphic belt, it is summarized in the recently published "Variscan Geohistory of Northern Japan: The Abean Orogeny", in which chapters on the metamorphic and plutonic rocks draw on the compilation based on the studies of the group of Minato et al. (1979). Its outline is introduced as follows:

There is a crystalline basement complex supposed to be of Precambrian age. It crops out at present mainly in the western half of the axial metamorphic belt. Overlying this basement and covering nearly the whole extent of the northern Japan, a sedimen-

Text-fig. 2 Geological map of the Usuki tonalite complex and near environs of the Takanuki and the Gozaisho unit.

1-4: Takanuki metamorphics (1: Biotite gneiss, 2: Quartzose gneiss, 3: Feldspars porphyroblastic gneiss, 4: Migmatite). 5-6: Yazukuri schist (5: Biotite schist, 6: Amphibolite). 7-8: Gozaisho metamorphics (7: Nematoblastic textured amphibole schist and biotite schist, 8: Granoblastic textured amphibolite and biotite schist). 9: Diaphthoritic rocks. 10: Ultrabasic rocks. 11: Jyumonji tonalitic mass. 12: Meta-gabbro mass. 13-15: Usuki tonalite complex (13: Migmatitic facies, 14: Tonalite proper, 15: Granodioritic facies). 16: Microdiorite dykes. 17-18: Hanaboh quartz-diorite complex (17: Gabbroic facies, 18: Quartz-dioritic facies). 19: "Older" and "younger" granites. 20: Andesite. 21: Alluvial deposits. 22: Sheared zone and fault. 23-24: Foliation and lineation (23: Metamorphics, 24: Plutonics). Az: Arizane. Db: Daibara. Do: Domeki. Hb: Hanaboh. Jy: Jyaguchi. Kd: Kaidomari. Ks: Koshidai. Mz: Mizunuma. Nd: Nyudoh. Ni: Nita. Ro: Ronden. Sb: Shibayama. Ta: Takanuki. Td: Takanukida. Us: Usuki. Mt. I: Inubotokeyama. Mt. K: Kamakuradake. Mt. M: Mikabuyama. Mt. O: Ohtsubeyama. R.Sm: Samegawa. R.To: Tokusagawa.



tary piling of geosynclinal natures, — the Abean geosyncline — formed during the early Devonian to the middle Carboniferous period is widely developed. At the end of the Carboniferous period the whole geosyncline transited into folding phases, which belong to the Japanese Variscan — Abean orogeny. The axial part of the Abean geosyncline may be referred to the Abukuma axial metamorphic belt at the present state. The products of metamorphism developed for the axial deep of the whole extent of the Abean orogenic zone are well revealed at present in the Abukuma plateau, though a greater part of the plateau is now occupied by younger granitic masses.

Metamorphism in the main stage

In the eastern margin of the plateau, metamorphism is represented by the formation of a quartz-albite-chlorite-sericite assemblage with a large number of relicts of original mineral grains and structure. Their nonmetamorphic correspondent is well traceable in the Japanese Palaeozoic stratigraphic sequence. The metamorphic grade increases step by step toward the west; in the Abukuma axial metamorphic belt, a zonal subdivision referable to the Barrovian type of regional metamorphism can be established. The zonal subdivision is summarized as in Table 1. Each zone is separated by a tectonic boundary, lacking in any kind of broad transitional zone. Specific lithology is also revealed within Ishizumi zone (4) and Takanuki-Hanazono zone (5). This lithology is characterized by the significant metasomatic reformation of regionally metamorphosed rocks. A greater part of zone (4) is composed mainly of amphibolite of coarse granoblastic texture, which is suggested to have been converted from hornblende schist of fine nematoblastic texture similar to those found in Saibachi zone (3). In zone (4), diopsidization of hornblende, formation of limesilicate assemblages, and biotitization of mafic minerals are extensively developed side by side. Meanwhile, some remnants of hornblende schist can be observed everywhere.

Table 1. Summary of the zonal subdivision of the Abukuma axial metamorphic belt (after Minato et al., 1979)

Zoning	Standard metamorphic zoning	Source rocks of the metamorphics
(1) Eastern marginal zone	Chlorite zone	Abean geosynclinal deposits and allied intrusive rocks
(2) Negishi zone	Biotite zone	
(3) Saibachi zone	Garnet zone	
(4) Ishizumi zone	Zone of metasomatic rock facies	
(5) Takanuki-Hanazono zone		Nishidohira metamorphic complexes
Nishidohira metamorphic complex (basement complexes)		

It is supposed from several pieces of evidence that source rocks of the metamorphics of zones (1)-(4) represent the Abean geosynclinal piling, about 70% of which consists of intermediate tuffs and basic sheets like intrusives, and about 30% of which consists of an argillaceous sedimentary. The newly proposed name of the Gozaisho metamorphics is applied to those metamorphic rocks which derived from the Abean geosynclinal pilings.

The metasomatic features which activated rocks contemporaneous with zone (4) are also developed prominently in zone (5), where argillaceous gneisses and schists belonging to the basement complex are converted into blastic gneiss and quartzose gneiss. The details of the lithology of these gneisses are given in the "Abean Orogeny". The source rocks of zone (5) are different from those composing zones (1)-(4). The major part of them is argillaceous rocks. The amount of basic rocks is no more than 5%. The Takanuki metamorphics are a newly designated nomenclature for these metasomatic gneisses reformed from the basement complex. The nonmetasomatized basement complex itself is treated as the Nishidohira metamorphics. A distinct difference exists between the Takanuki and the Gozaisho metamorphics, at least in age of source rocks.

Both zones (4) and (5) are characterized by duplicated events where metamorphosed rocks were regionally overprinted by a prominent metasomatic effect. Despite a wide difference in the facies of resultant metasomatic rocks between those of zones (4) and (5), they may commonly suffer the same metasomatic effect which ascended from the deep core of the Abean orogenic belt.

To make the grouping of the metamorphic rocks of the region into the Gozaisho and the Takanuki metamorphics corresponds approximately to the grouping of the metamorphic series by Koto (1893). The names, Gozaisho and Takanuki, of rock formation given by Koto are adopted by the newly proposed scheme as well, but their implication differs much from that of the original names.

Movement of the subsequent stage

The foregoing represents the results of metamorphic processes which took place in the main stage of Abean orogenic movement. Actually, they are further modified by the tectonism and plutonism in the subsequent stage, which is distinctive from those in the main stage. The main stage of the Abean orogenic movement ceased once before the Viséan stage; it was succeeded by the movements in the subsequent stage, which are characterized by fracturing tectonics. The formation of a boundary zone between the Takanuki and the Gozaisho metamorphics, which is named "Koshidai-Takaboyama-Daioh • in Structural Belt" (Watanabe et al., 1978), is one of the main products of the movements. Other sheared zones parallel to the axial trend and dividing the metamorphics into many tectonic units are prominently observed, which penetrate the whole succession including the Permian formations. The boundary zone has a width of 4 km in its maximum; and in this zone sheared and crushed rock facies are developed in a network form in association with prominent parallel slippages. In every place they contain small masses of serpentinite and sheared blocks of basement complexes. This

phenomenon has attracted such a great interest that has led to researches; and Watanabe et al. (1978, 1979) pointed the importance of the occurrences of diaphthoritic rocks. It is suggested that there are several kinds of sheared zones and tectonic nature and diaphthoritic rocks suffered alumino-silicates porphyroblastesis. Although the tectonic natures of the boundary zone will be presented in detail separately, the fundamental feature of the movement is the tectonic upheaval of the Takanuki unit relative to the Gozaisho unit.

The foregoing is a outline of "Variscan Geohistory of Northern Japan: the Abean Orogeny". Its broad historical course of metamorphic events may be referable to that of the European Variscan described for the Schwarzwald in detail by Mehnert and Büsch (Mehnert, 1953, 1957, 1962, 1963; Büsch, 1966).

In the environs of Takanuki town (Ta: in Text-fig. 2), several rock facies belonging to the Takanuki metamorphics are arranged zone by zone trending in NNW. Their central facies is represented by a zone of blastic gneiss, which attends quartzose gneiss zones in both flanks. The northern and eastern sides of the zone of quartzose gneiss transit to the zone of biotite gneiss. Many parallel sheared zones appear further in the northeastern outward direction. They belong to the above-mentioned boundary zone. The rock facies constituting this boundary zone is biotite schist, which is treated as the Yazukuri biotite schist. The metasomatism characterized by the Takanuki metamorphics is represented weakly in this biotite schist. The natures of the Nishidohira metamorphics are rather prominent there. The general trend of the Yazukuri biotite schist is truncated by the sheared zone bounded by the western side of the Usuki tonalite complex, but its southern continuation is narrowed to the width of 400 m, which adheres closely to the sheared zone in the western boundary of the Usuki tonalite complex. In the southern extreme part of the tonalite complex (Kd: in Text-fig. 2), where the Yazukuri biotite schist is developed, the member of amphibolite (Gozaisho metamorphics) lies separated from the Yazukuri schist by a prominent broad sheared zone. The zone of the Yazukuri biotite schist constitutes of itself a boundary zone between the Takanuki and the Gozaisho metamorphics, which is characterized by a large number of sheared zones running parallel.

Within the zone of blastic gneisses, small aureoles of granitized facies characterized by the formation of tonalitic rocks are known in everyplace, which increase in dimensions with increasing distance southward. Noteworthy is the occurrence of small tonalite dykes cutting the blastic gneiss with the initial association of migmatitic facies formation around them. A great similarity exists between the lithofacies of them and Usuki tonalite in macroscopic and microscopic natures.

The Gozaisho metamorphics lying in the eastern neighbourhood of the Usuki tonalite complex are constituted almost exclusively by the amphibolites of Ishizumi zone. Only 15% of argillaceous schist is intercalated with them. There is no prominent development of a sheared zone at the contact. Some contact metamorphic facies by the intrusion of tonalite are observed within the extent of 300 m from the tonalite contact. The general trend of the Gozaisho metamorphics is truncated obliquely by the tonalite intrusives and the Hanaboh quartz-diorite complex.

Usuki Tonalite Complex

The intrusive form of the complex is a long sinuous one. Although the main part of it takes the N-S trend, the northern continuation trends and tapers off to NNW, whereas the southern continuation trends and tapers off to SE. The western side of the complex is bounded by a prominent sheared zone 200-300 m in width filled with pulverizing sheared products. At the northern half of the sheared zone, the schistosity and structures of the Yazukuri schist are discordantly truncated, but the degree of concordance increases structurally, as the site approaches nearer to the south. Exceptional to this boundary relation, some concordant swarms of tonalite sheets are bulged to the west from the main mass beyond the sheared zone in the neighbourhood of Jyaguchi (Jy: in Text-fig. 2), where the distribution of sheets is not uniform but zones of gneisses and sheet-rich zones are roughly repeated. In the eastern side of the complex, 1 km northeast of Usuki village (Us: in Text-fig. 2), sheet-like intrusions are also known. They show the alternation of amphibolite and tonalite in association with contact metamorphic facies.

Although the western side of the complex is now bounded by a sheared zone, the primary boundary condition of the intrusive complex would be characterized by layered mixing of country rocks and tonalite in association with contact metamorphism on both side of the complex. These alternating zones are transited to the central homogeneous tonalite with a rapid decrease in amount of layers and blocks of country rocks. The main part of the complex is represented by this type of tonalite, which occupies about two-thirds of the complex.

In the southern half of the complex, small gabbroic masses are disposed dottedly, the intrusive activity of which is separable chronologically from the Usuki tonalite complex. However, the direct relationship of both units is not observable in the field because they are covered thickly with weathered soil. Mode of occurrence of the gabbroic unit suggests that the gabbro is the earliest intrusion. The primary gabbroic texture is well preserved in these gabbroic masses, but its pyroxene is entirely converted into brownish or greenish hornblende in which remain turbid pyroxene cleavages and a crystal habit that is considered to have been affected by the intrusion of tonalite.

On the other hand, the tonalite is intruded by the quartz-diorite unit, which is disposed along the eastern border of the tonalite complex. Parallel to the northern part of the tonalite complex, a large quartz-diorite complex which extends to the spreading of 3×8 km intruded. It is treated as an absolute intrusive unit which is named the Hanaboh quartz-diorite complex. Between the tonalite complex and the quartz-diorite complex, well continued septa made up of amphibolite belonging to the Gozaisho metamorphics is intercalated with the width of 200-300 m. But the direct contact of both complexes is also shown in the southern part. The southern end of the Hanaboh quartz-diorite complex is once pinched out, interfingering with tonalite part. Its southern continuation is represented by the small dykes intruding into the tonalite, which is disposed dottedly in the eastern border zone of the tonalite complex. Although the inner structure of the Hanaboh complex is strictly arranged parallel to its intrusive

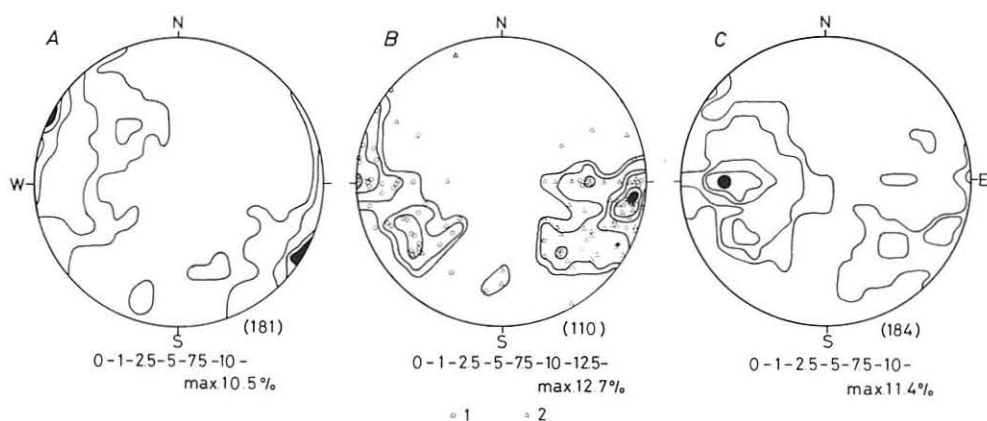
boundary, the foliation of the tonalite runs discordantly against the intrusive boundary of the quartz-diorite complex.

Three lithological facies are discriminated within the Usuki tonalite complex as follows: (i) migmatitic facies, (ii) tonalite proper, and (iii) granodioritic facies. Although they are transited to each other without any sharp boundaries, each of them constitutes a large domain with a single lithological facies, and the rough distribution of each can be mappable as shown in Text-fig. 2.

The domain of migmatitic facies crops out between Usuki village and Daibara village typically, which develops to the extent of 2×1.5 km. Its northern continuation is represented by several long continued narrow belts concordantly alternating with the tonalite facies. All the palaeosome of them are referable to the biotite schist of the Yazukuri schist complex belonging to the Takanuki metamorphics. Another type of migmatitic facies is known within a small extent around Mizunuma village situated in the eastern border of the complex, where the amphibolites belonging to the Gozaisho metamorphics are highly migmatized. At the border part of these migmatitic domains the amount of palaeosomes is rapidly reduced and lithofacies turns into tonalitic within a short distance.

The lithofacies of tonalite proper occupies the main part of the complex, and two-thirds of the complex is represented by this lithofacies. It is a medium-grained leucocratic rock with homogeneous texture and weak foliations. Although it appears similar in outlook in every place, its lithology is shown in the irregular fine mixing state of hornblende bearing facies (30%) and hornblende free biotite facies. Floating in this homogeneous tonalite, resorption remnants of the block of biotite schists, are observable in nearly every outcrop.

Granodioritic facies occupy rather smaller domains than the preceding ones, but



Text-fig. 3 π diagrams for foliations.

A: Projection from the northern part of the Usuki tonalite proper.

B: Projection from the southern part of the Usuki tonalite proper.

1: western half area 2: eastern half area

C: Projection from the Usuki migmatitic facies.

are exposed in every part of the complex forming small domains. They appear only within the domain of tonalite proper, with which replaceable relationships are closely traceable. The granodioritic facies is characterized by the dotted formation of potash-feldspar blasts, which is homogeneously formed in the central part of each domain. In the marginal part of the aureole the potash-feldspar blasts are formed sparsely among the tonalitic base, in which it is possible to trace a transitional course from tonalitic facies to homogeneous granodioritic facies.

The inner structure of the complex is characterized in general by the foliation shown with a westward dip at the eastern half and with an eastward dip at the western half of the main part of the complex (Text-fig. 3-B). Although the greater part of these foliations is roughly concordant to the outline of the complex, some discordant foliations trending in NNE against the outline trending in NNW of the complex are revealed in the northern part of the complex (Text-fig. 3-A). In this area the western side of the complex is truncated by the above-mentioned sheared zone, and by the intrusion of quartz-diorite at its eastern side. In any case, the funnel-shape structure revealed in the east-westerly vertical section may be the primary feature of the Usuki tonalite complex.

Another feature is displayed by a migmatitic domain which crops out in an area extending from Usuku village to Daibara Village. In this area the foliations of migmatite have a rather low angle than the surrounding steep-dipped foliation of tonalite proper, despite that the strikes of both parts are similarly developed. Hence, it is suggestive that the blockwise structure is included in the main tonalitic facies (Text-fig. 3-C). The northern continuation of the migmatitic facies divided into several narrow belts is, however, disposed entirely concordant to the surrounding tonalite.

The foregoing is concerned with the Usuki tonalite complex disposed in the northern part of the Abukuma axial metamorphic belt. Similar tonalitic complexes closely allied to it are known to exist in the following localities from the northern to the southern extremity of the axial metamorphic belt.

- (a)* The Uzumine tonalitic complex, which is composed of Uzumine migmatite and Kami-oyamada tonalite each in nearly equivalent abundance (Tsuchiya et al., 1980).
- (b) The Jyumonji plutonic mass lying in the northern part of the Takanuki district (Ogura, 1956, 1958; Kano et al., 1973). It is composed of homogeneous basic tonalite having the features of synkinematic intrusion.
- (c) The Usuki tonalite complex described in this paper.
- (d) The narrow migmatite zone, which continues in the boundary zone between the Takanuki metamorphics and the Tabito granitic mass in the district ranging from a point 4 km south of Kaidomari village to Hanazono village (Takahata, 1979).
- (e) A homogeneous tonalite mass lying around Mt. Takaboyama containing large diaphthorite masses. Its location is far separated from the Takanuki metamorphics by intrusion of the Tabito granitic mass of younger age (Watanabe et al., 1978).
- (f) A swarm of trondhjemitic dyke known in Hitachi district (Watanabe, 1975).

All of these tonalitic rocks are embraced in the boundary zone which was formed between the Takanuki and the Gozaisho metamorphics; and the boundary zone con-

* The localities of (a)-(e) are presented in Text-fig. 1.

stitutes the most significant structural belt in the Abukuma axial belt, which is named Koshidai-Takaboyama-Daioh • in Structural Belt (Watanabe et al., 1978).

Petrography

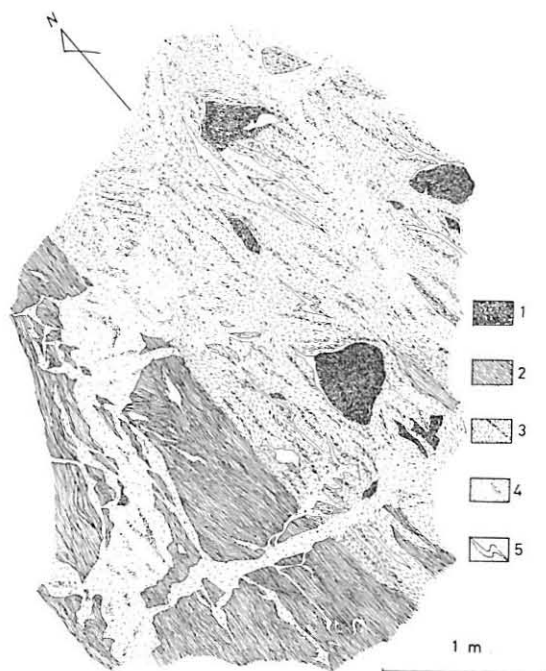
MIGMATITES

As already noted, there are two kinds of migmatitic facies in the tonalite complex. The one derives mainly from biotite schist and crops out in the western half of the complex (Western type), while the other is of amphibolite origin and occurs to a narrowly limited extent in a part of the eastern border (Eastern type). Different patterns of migmatization are revealed with both migmatitic facies. They are briefly given as follows:

Western type of migmatite

The formation of neosome, which is leucocratic and coarser-grained and has massive appearance, proceeds along the foliation of biotite schist to form layered structure. Several deformed features are predominant for the greater parts of the migmatite unit in the forms such as fine wavy crenulation and/or crushing into blocks of the remnant palaeosomes to form agmatitic or raft structure and the network impregnation of leucocratic veins.

With the formation of neosome and palaeosome, many varieties are displayed. (1) Close mixing of finely separated melanosomes and leucosomes accompanying minute



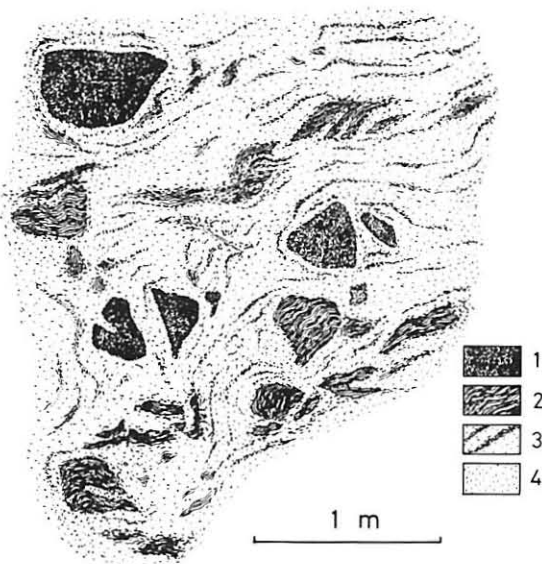
Text-fig. 4 An example of migmatitic fabrics in the Western type of migmatite. Loc. 500m north of Daibara village.

- 1: Palaeosome derived from amphibolite.
- 2: Palaeosome derived from biotite schist.
- 3: Neosome with finely separated melanosomes and leucosomes.
- 4: Leucocratic vein-formed neosome.
- 5: Quartzose layer.



Text-fig. 5 Migmatitic fabrics formed of coarse-grained neosome and crenulated palaeosome. Loc. 500m east of Daibara village.

- 1: Palaeosome derived from Amphibolite.
- 2: Palaeosome derived from biotite schist.
- 3: Coarse-grained massive neosome.
- 4: Neosome with blastic garnet.
- 5: Quartz pool.



Text-fig. 6 Raft structure in the Western type of migmatite. Loc. 100m west of Usuki village.

- 1: Palaeosome derived from amphibolite.
- 2: Palaeosome derived from biotite schist.
- 3: Nebulitic neosome with fluidal texture.
- 4: Coarse-grained massive neosome.

resorption remnants of palaeosome with random or fluidal texture to form nebulitic facies represents the one of predominant type (Text-fig. 4). (2) Another predominant type is the coarser-grained and nonfoliated neosome referable to the lithology of tonalite proper, which is finely alternated with the palaeosome of biotite schist origin, being characterized by the locally concentrated development of blastic garnet (Text-fig. 5). (3) Tonalitic neosome, which fills a broad interspace between agmatitic blocks with fluidal foliation to form raft structure, is often observed (Text-fig. 6). (4) A leucocratic part free from biotite is developed with the style of network impregnation cutting through the parts of palaeosome and neosome (Text-fig. 4). (5) Local minor occurrences of a coarse-grained and inhomogeneous leucocratic part are known. They have irregular fluidal foliation truncating the general banding of earlier formed

migmatite. (6) At the same time small lenses or thin layers of homogeneous tonalitic facies indiscriminable from the appearance of tonalite proper are inserted into these migmatites. (7) A greater part of palaeosomes are derivatives of biotite schist. However, a few blocks of basic rocks are known as palaeosome in an agmatitic part, which is now converted into an assemblage of diopside-garnet or brown hornblende-plagioclase. Partly altered blocks of amphibolite with the similar mode of occurrence are observed seldom. The tonalitic neosomes around these basic blocks contain minor hornblende. (8) Another kind of basic block of the similar occurrence is rarely known. The block shows microdioritic features nearly free from alteration.

All the rock facies with the above-mentioned features are closely mixed; and several styles of these migmatitic features lie side by side even within one outcrop. The development of a special type of migmatite with a specific spatial arrangement cannot be defined here.

It is suggested from the lithology and relative abundances of rock species that the original rock association of the Western type of migmatite is comparable to the Yazukuri schist complex, which crops out in the immediate western and the north-western neighbourhood. A greater part of the Yazukuri schist complex is constituted by biotite schist with intercalation of about 20% of thin seams of amphibolite and rare occurrence of small microdiorite dykes.

The initial lithological features of biotite schist remaining in the palaeosomes are the same as those of typical biotite schist, which has fine-grained homogeneous texture and is composed of biotite, plagioclase and quartz with seldom association of garnet and a very slight amount of magnetite. The relative abundance of the constituents averaged is

Qz: 40%, Pl: 30%, Bi: 28%, Musco: 2%.

The grains of quartz and plagioclase are 0.2 mm in average size and slightly elongated in form along the foliation. They are tightly assembled with xenomorphic granular texture. The prominent parallel arrangement of biotite flakes gives the rocks an appearance of typical schistose foliation, the flakes concentrating themselves, forming thin seams and alternating with parts in which quartz-plagioclase is enriched. As a result finely repeated banded texture is formed.

The first appearance of a migmatitic feature is represented by the formation of such thin layers of lenses from coarse-grained quartz and plagioclase that spread along the planes of foliation. Their grain sizes are enlarged to two to five times in these layers; and a coarser-grained layer has an outline showing either gradual transition from a fine base or sharp contrast. In this stage, quartz and plagioclase continue to preserve xenomorphic granular texture. It is a rule that the amount of coarser-grained layers increases rapidly to form neosome.

The representative form of neosome is characterized by the formation of idiomorphic stout prismatic plagioclase, which shows zonal structure. This plagioclase appears at first in pool-like pods formed dottedly in the above-noted granular textured part; and it is coarser-grained and somewhat deprived of a foliation arrangement. The typical neosome is also characterized by interfilling quartz and biotite of nearly the

same size. The appearance of muscovite in this mineral assemblage is also characteristic. Their relative abundance of the constituents averaged is

Qz: 35%, Pl: 45%, Bi: 18%, Musco: 2%.

Opaque minerals are totally absent.

Such equigranular texture is distinctive, and it has weak foliation because stout prismatic plagioclases and some of biotite plates have the subparallel arrangement. However, the neosome always contains a large number of fine-grained patches having the character of biotite schist arranged in parallel or random orientation. They are sharply contrasted to the main host part in grain size and texture.

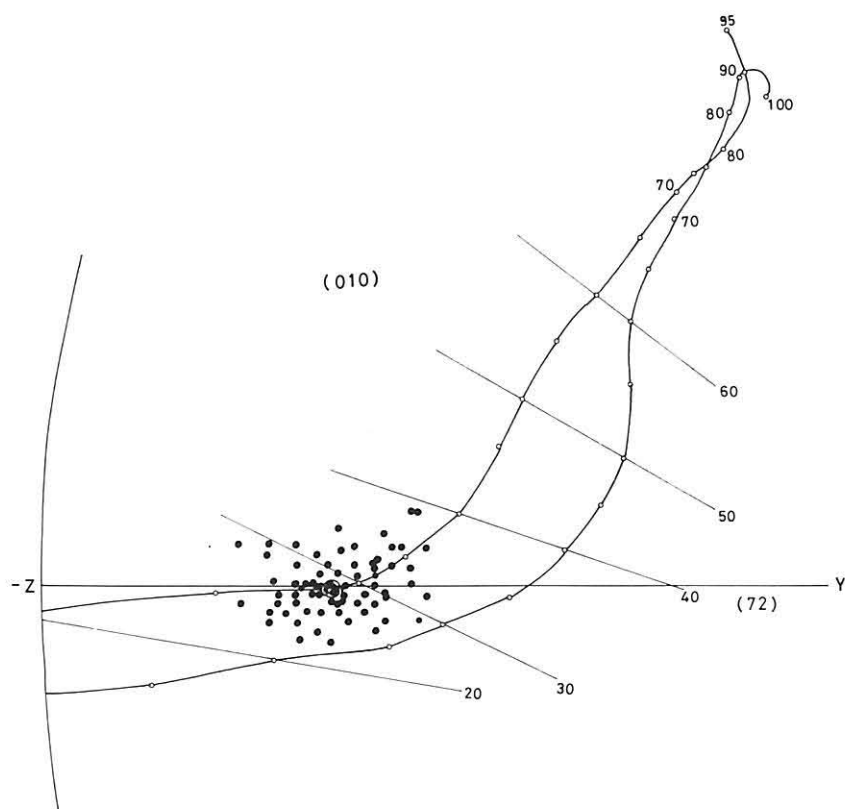
The representative form of melanosome is characterized by (a) the formation of aggregated layers of biotites, and (b) the formation of hornblende poikiloblast accompanying a large number of magnetite grains. The part which was formed by leucocratic veins developing in a network form is composed of quartz and plagioclase deprived of biotite. The texture of the leucocratic veins is not different from that of the typical neosome, but is somewhat coarser-grained.

Mineralogy: Plagioclases in every part of migmatite were optically studied in detail, with the following results:

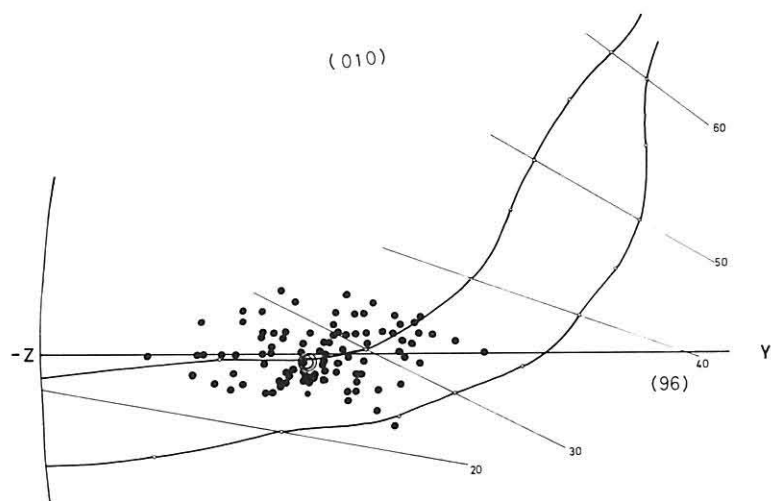
(1) The plagioclase of original biotite schist which survived in the palaeosome is in a nonzoned state in contrast with the zoned plagioclases grown in neosomes. The optical orientations of the plagioclases are usually dispersed around a statistic center, by which it is meant that the individual grain is in a different state of composition and ordering degree. In this case the optical orientations are concentrated around the position of An 28, which are plotted on the ordered line, and its variation ranges from An 23 to An 38 (Text-fig. 7). The prominent feature of palaeosome plagioclases is that their range of variation is more narrowly restricted than those shown by neosome plagioclases. Considerably similar natures are observed in those of Yazukuri biotite schist. Its variation ranges from An 24 to An 36, and statistic center of the plots is laid on An 27 (Text-fig. 8). It is nearly similar to those of migmatite palaeosome. However, a few exceptional cases in which a zonal structure is formed are known, the details of which are given in a later chapter.

(2) The plagioclase in neosome is characterized by a zonal structure constituted by a basic core, a transitional zone of oscillatory zoning and a more acidic mantle. However, the zonal structure observed is not only constituted by the superposition of zones of different compositions but by those in a different ordering state. Optical measurements were carried out only in both the core and mantle, because the measurements are difficult in the oscillatory zone. The actual states of them will be given in a later chapter. The ranges of variation in optical orientation are from An 25 to An 43 in the core and from An 21 to An 36 in the mantle (Text-fig. 9). These are diffused far wider than that of palaeosome plagioclases. The statistic center of the plots of a core is laid on An 35, and that of a mantle on An 28. Both of them are situated on the line of ordered state.

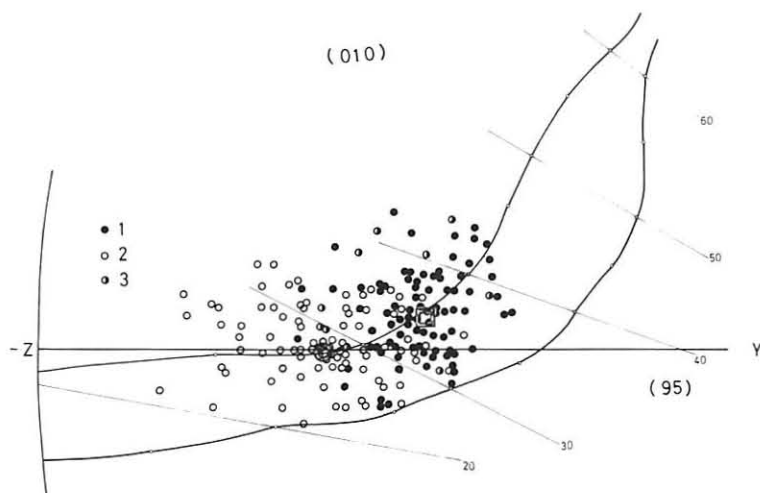
The composition of biotites of both palaeosome and neosome are analysed by EPMA. The results are shown in Table 2 as the composition of average values. There



Text-fig. 7 Variation in composition and ordering state of constituent plagioclases of palaeosome in the Western type of migmatite. Critical migration curve was depended on Burri et al. (1967). Double circle: statistic center.



Text-fig. 8 Constituent plagioclases of the Yazukuri biotite schist. Double circle: statistic center.



Text-fig. 9 Constituent plagioclases of neosome in the Western type of migmatite.
1: core, 2: mantle, 3: nonzoned plagioclase. Double square: statistic center of core, double circle: statistic center of mantle.

Table 2. Chemical data of biotites, garnets and hornblendes by EPMA.

Sample	Biotite		Garnet		Hornblende		amphibolite
	palaeosome	neosome	palaeosome	neosome	palaeosome	neosome	
Average of analyses	(5)	(3)	(6)	(4)	(5)	(5)	(6)
SiO ₂	38.08	36.15	38.21	38.40	43.73	42.92	48.88
TiO ₂	2.77	2.23	.01	.02	1.17	1.26	.40
Al ₂ O ₃	17.79	19.62	21.31	21.27	10.04	10.08	7.50
Cr ₂ O ₃	.03	.01	.00	.01	.01	.00	.20
FeO*	21.09	22.44	28.94	31.29	19.16	21.40	14.76
MnO	.29	.56	7.06	5.73	.32	.60	.24
NiO	.05	.06	.01	.00	.03	.02	.02
MgO	8.97	7.23	2.43	2.37	9.28	7.72	12.60
CaO	.00	.05	2.98	1.72	12.12	11.83	12.14
Na ₂ O	.09	.09	.01	.02	1.37	1.12	1.18
K ₂ O	8.40	8.22	.00	.00	.77	.89	.06
Total	97.56	96.66	100.96	100.83	98.00	97.84	97.98
Sample no. **	7(U-1)	10(U-2)	7(U-1)	10(U-2)	8(Mz-3)	13(Mz-7)	3(Go-1)

* Total iron as FeO. ** Sample no. is shown in Table 3.

(Analyst K. Uchiyama)

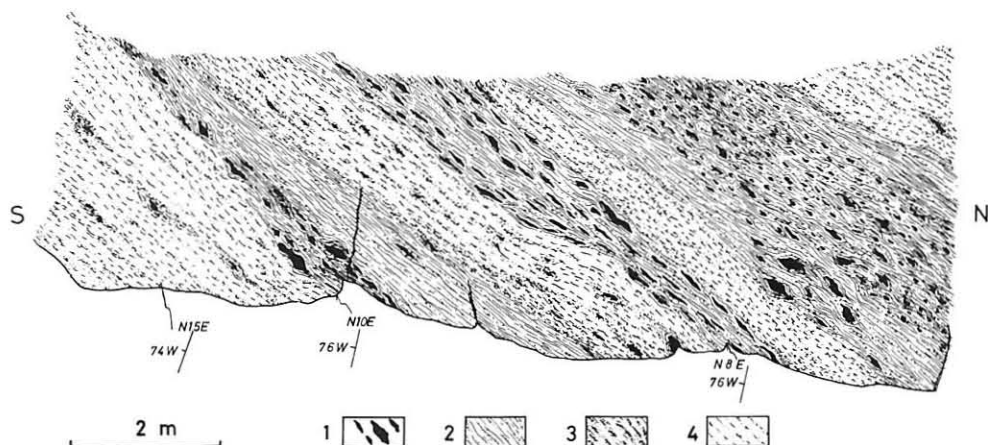
are slight differences in amounts of SiO_2 , Al_2O_3 , FeO^* and MgO , which are shown in neosome by decreases in silica and magnesia and increases in alumina and iron. The ratio of $\text{MgO}/(\text{FeO} + \text{MgO})$ of biotites is 0.431 in palaeosome and 0.365 in neosome.

As to the composition of garnet, there are distinct differences in amounts of FeO^* , MnO and CaO (Table 2). A comparison between the garnets of neosome and palaeosome shows that the former is marked by an increase in iron and decreases in lime and manganese. The component of the garnet in neosome is estimated as 65.4% of almandine, 16.2% of spessartine, 9.8% of pyrope and 8.6% of grossular; and of the garnet in palaeosome as 71.9% of almandine, 13.3% of spessartine, 9.7% of pyrope and 5.1% of grossular. The compositional transition toward the almandine type of garnet in neosome is distinctive.

Eastern type of migmatite

This type is characterized by the layered structure formed by the rough alternation of bands in different states of migmatization. However, a minor amount of agmatites is also associated with it in the layered migmatite. As is shown in Text-fig. 10, migmatization seems to proceed along the foliation of amphibolite, which derives from the Gozaisho metamorphics in accordance with the following steps:

(1) The basic part of layered migmatite contains a large number of small lenses, which are formed by palaeosomes, these being arranged along the foliation. The neosome, host base to the palaeosome, is constituted by its having gneissose texture; and it is somewhat coarser-grained and marked by fine wavy foliation. (2) The gneissose parts which are fairly free from palaeosomes also form a unit layer. (3) A more coarse-grained part formed with such fine irregular patches of leucosome and melanosome that have nebulitic appearances are developed, with which a slight discordancy aggressive to the surrounding foliation is rarely observed. (4) Layers of medium-grained



Text-fig. 10 Migmatitization fabrics in the Eastern type of migmatite, derived from amphibolite.

1: Palaeosomes derived from amphibolite. 2: Neosome with gneissose texture. 3: Nebulitic neosome with fine irregular patches of leucosomes and melanosomes. 4: Homogeneous neosome.

and homogeneous leucocratic facies containing streaks of resorption remnants of palaeosome interweave through other layers. (5) The agmatitic facies often shows raft structure with the base containing melanosomes formed by advanced disintegration of palaeosome.

From macroscopic appearances, the palaeosomes remaining in to basic layer seem to be formed by amphibolite similar to those known in the Gozaisho metamorphics of the immediate eastern neighbourhood. The original structure and constituent minerals of amphibolite remain in a nearly unchanged state in some of the palaeosomes. The main transformational features of the palaeosomes are only the macroscopic network of impregnation of quartz veins and a slight change from the greenish colour of hornblende of original amphibolite a brownish colour. Where neosome is formed along the foliation of amphibolite, it is characterized by the enlargement of the grain sizes of constituents, a decrease in amount of hornblende, an increase in amount of plagioclase, and a new appearance of biotite and quartz. The abundance of the constituents is

Qz: 2%, Pl: 73%, Bi: 5%, Hb: 20%.

As is noted on the migmatite of a biotite schist derivative, the plagioclase in this neosome is also grown to become stout, prismatic and zoned in a similar pattern. The rock texture of it gradually approaches to that of tonalite proper with the development of neosome. A gneissose part is constituted mainly by hornblende, biotite and plagioclase with a minor amount of quartz. The relative abundance of the constituents is

Qz: 5%, Pl: 65%, Bi: 10%, Hb: 20%.

A weak development takes place for neosome to separate into mafic and felsic part and form the gneissose texture. A coarser-grained gneissose part (3) is formed with hornblende, biotite, plagioclase and minor quartz. A contrast between melanosome and leucosome is shown more clearly; this contrast forms an irregular wavy gneissose banding. The total amount of mafic minerals is less than 25%, the main part being occupied by plagioclase. The relative abundance of the constituents is

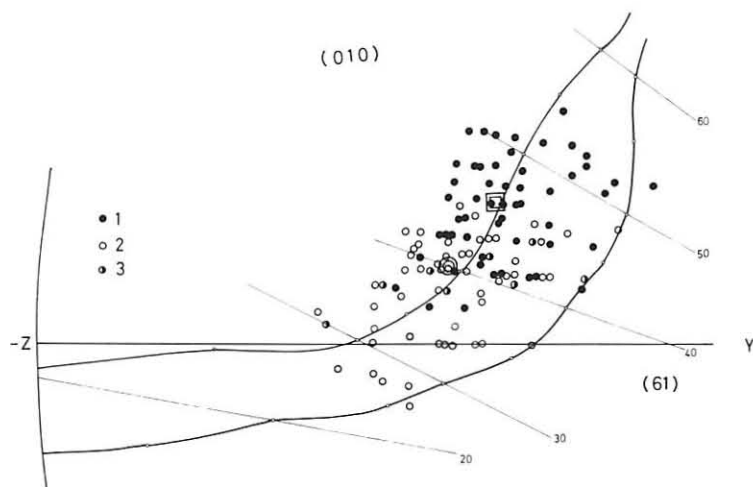
Qz: 10%, Pl: 65%, Bi: 10%, Hb: 15%.

The medium-grained and homogeneous leucocratic part (4) shows tonalitic features. It is fairly free from hornblende, the chief constituent being equigranular plagioclase, biotite and quartz. The averaged relative abundance of the constituents is

Qz: 25%, Pl: 50%, Bi: 25%.

The plagioclase is represented in a coarse-grained idiomorphic form. The rock foliation is due to the subparallel arrangement of biotite plates. The melanosomes accompanied in a minor amount are represented by the enrichment of biotite. The leucocratic pools (5) of minor occurrence is formed by the aggregation of quartz, plagioclase, microcline, and, in part, a large blast of hornblende.

Mineralogy: The optical orientation of plagioclase is measured in detail for every lithofacies. All the plagioclases of neosomes have the same zonal structure. The measured data of plagioclases in neoblastic facies are shown in Text-fig. 11. The core ranges from An 36 to An 54, and the mantle from An 26 to An 48. Each statistic center



Text-fig. 11 Constituent plagioclases of neosome in the Eastern type of migmatite. Symbols are the same as in Text-fig. 9.

value is laid on An 45 in the core and An 40 in the mantle. Their average compositions are more basic than that of argillaceous derivatives. The difference averages about An 10% between both cases. But the morphology and pattern of zoning of the plagioclases of neosome is fairly common to those of biotite schist derivatives. The results of further detailed measurements on zonal structure are given in a later chapter.

Three hornblendes separated from a representative facies were analysed by EPMA. The results are shown in Table 2 with a comparison with those of the Gozaisho metamorphics. There are slight differences in amounts of FeO^* and MgO . A comparison between the hornblendes of neosome and palaeosome shows that the former is marked by a decrease in magnesia and an increase in iron. The ratio of $\text{MgO}/(\text{FeO} + \text{MgO})$ is 0.460 in palaeosome, 0.391 in neosome and 0.603 in amphibolite.

TONALITE PROPER

Igneous habits are well displayed in this lithological unit; that is a homogeneous medium-grained appearance to the whole extent; the development of a rectangular joint system; and an intrusive relation against the country rocks. There are hornblende-bearing tonalite facies and hornblende-free tonalite facies closely mingled with each other. However, a distinctive difference in outlook between both rock facies are not easily detectable. Enclaves of biotite schists are sparsely distributed and are always converted into coarser-grained gneissic texture in a blurred state. However, amphibolitic enclaves are highly resistant, which show a sharp boundary between them and the tonalitic part with the formation of a leucocratic rim. The appearance of weakly developed foliation is due to the subparallel arrangement of stout prismatic plagioclases and biotite plates, interspaces of which are usually filled by fine cataclastic granules of quartz and biotite. When the foliation is visible more clearly, the cataclastic

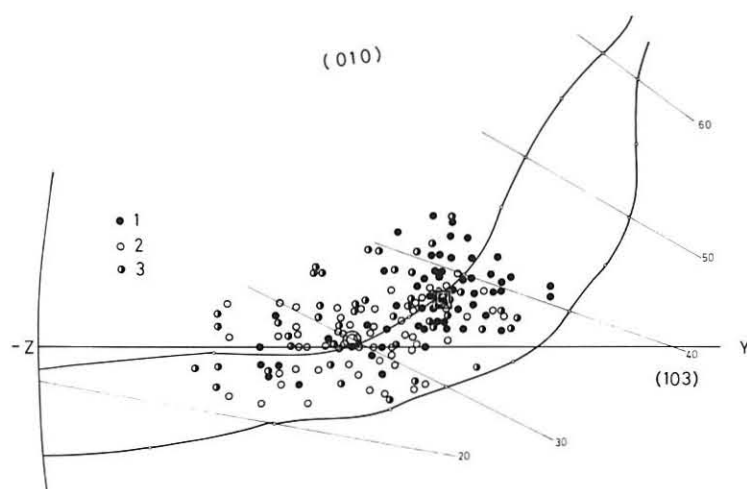
texture becomes prominent.

As for the mineralogy of constituent minerals, tonalite is referable to neosomes of migmatites. Both lithofacies have no difference in the style of zonal structure of plagioclase as well as the pattern of compositional transition. Biotite has a brownish colour with a weak greenish tint. Hornblende is also the same as those hornblendes described for the neosome of the Eastern type of migmatites. The plots of ratios of relative abundance of constituent minerals are concentrated to a limited area, the central value of which is represented by

Qz: 30%, Pl: 50%, Bi: 20%.

The amount of hornblende averages 4% in a mafic part.

The optical orientation of plagioclase was measured in detail. The core ranges from An 25 to An 43, and the mantle from An 22 to An 40. Each statistic center value is laid on An 38 in core and An 30 in mantle (Text-fig. 12).



Text-fig. 12 Constituent plagioclases of tonalite proper. Symbols are the same as in Text-fig. 9.

GRANODIORITE

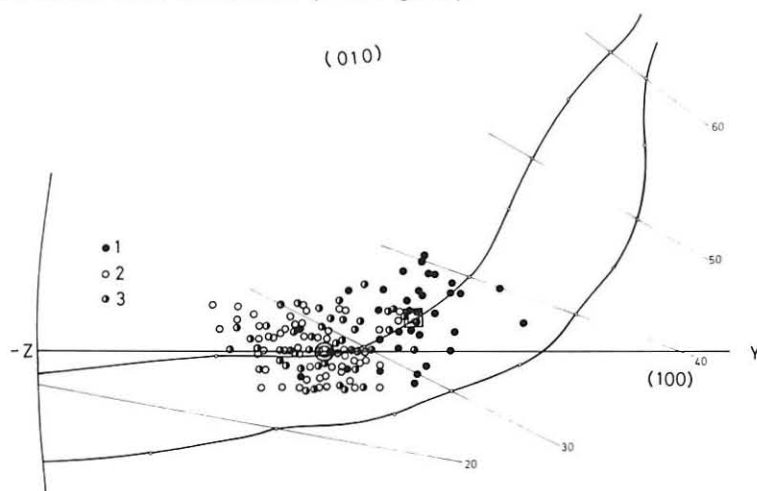
Granodiorite develops to with extent of 1×3 km in its maximum. It is divisible into parts of a inner and a outer facies. The outer facies is developed overlapping the neighboured tonalite by the formation of potash-feldspar porphyroblast. Meanwhile, the inner facies is granodiorite proper characterized by large pophyritic potash-feldspar. Between the inner and the outer facies, the boundary is not detectable, but a gradual transition is traceable.

The characteristic porphyritic potash-feldspar of the inner granodioritic facies attains to 10 mm in size, and has a somewhat idiomorphic habit. It abounds in fine grain-ed plagioclase, quartz and biotite, and is irregularly associated with the groundmass

minerals at its outer rim. Its groundmass has texture and constituents similarly to tonalite. However, it is characterized by the development of interstitial potash-feldspar to the amount of 15%.

The potash-feldspar blasts in the outer facies of granodiorite have nearly the same shape as those of the inner facies. Their porphyroblastic features suggestive of replaceable growth are more distinctly shown. The part of their groundmass is closely referable to that of tonalite proper in texture and mineral association, but there is no interstitial potash-feldspar. On the other hand, such potash-feldspar independently formed along the foliation of tonalite proper in the dimensions of small streaks or lenses is observable in every part of tonalite proper. Microscopically perthitic nature is prominent in the outer facies. In the inner facies, it is represented by the orthoclase type. The value of triclinicity in the inner facies is nearly zero.

The behaviour of plagioclases of the granodioritic facies is fairly distinct from the plagioclases of tonalite and neosome. Its range of compositional variation is concentrated into a narrower extent; the zonal structure contrasted by the difference in ordering states is more frequent; and the statistic compositional difference between the core and the mantle is similar to that of the tonaritic facies. The core ranges from An 26 to An 40, and the mantle from An 24 to An35. Each statistic center value is laid on An 35 in the core and An 28 in the mantle (Text-fig. 13).



Text-fig. 13 Constituent plagioclases of granodioritic facies. Symbols are the same as in Text-fig. 9.

CONTACT METAMORPHIC ROCKS

Contact metamorphic rocks are developed within a limited extent of less than 300 m from the intrusive boundary, and mixed with tonalite layer by layer. In the case of argillaceous biotite schist, most of them are represented by the formation of a large number of fine quartzose seams along the foliation of wall rocks in the form "lit-par-lit

injection'', in which fine wavy deformation is a rule. In the case of amphibolite, formation of irregular pools of skarn assemblages, e.g. diopside-garnet (andradite type)-epidote and/or biotitization of mafic minerals, are often observed, besides the development of quartzose seams. There are no migmatitic features analogous to the above-mentioned migmatites.

Details on Zoned Plagioclase

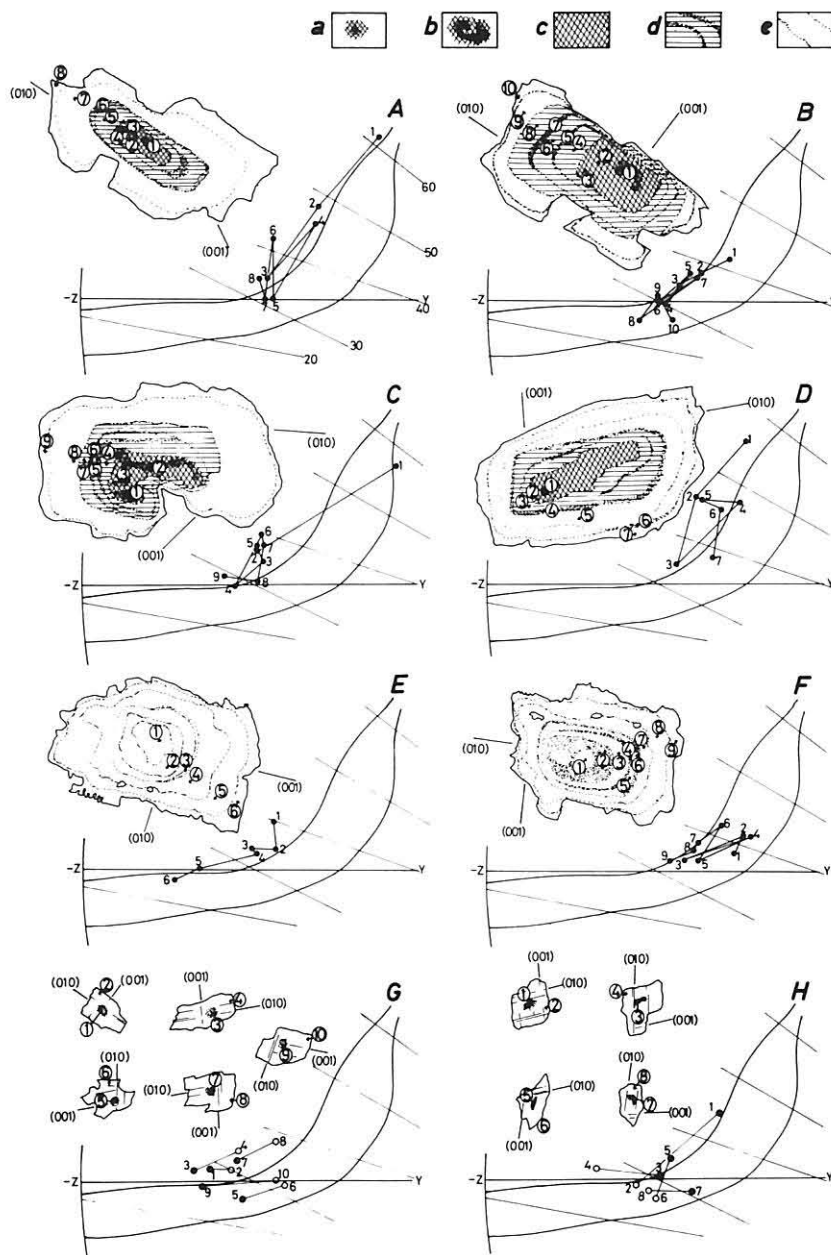
In the course of the foregoing statistic treatment of optics of plagioclase, measurements were made only of the average optic orientations of the core and the mantle part which occupy the main part of zoned plagioclase. Practically, the zonal structure of plagioclase is a more complicated one. The details of the zonal structure of plagioclase, which are observed in the tonalite proper, are as follows (Text-fig. 14-A, B):

The core always contains irregular shaped patches (b: in Text-fig. 14) which constitute a more basic part, suggesting that the patches represent either corrosive remnant or segregative aggregation. They are somewhat turbid and contain small peculiar spots (a: in Text-fig. 14), each having such a distinct optic orientation that suggests an extremely basic composition. Such a spot is not always detectable in a thin section, because its volume is so small that the possibility of being contained within a slice of the thin section is very rare, compared with that of a surrounding host, which is fairly large in volume. The main part of core (c: in Text-fig. 14) is in a clear and homogeneous state and has a large volume, the outline of which approaches an idiomorphic form.

A layer of thin oscillation zoning (d: in Text-fig. 14) is intercalated between the core and mantle. It is constituted by the repetition of thin filmy zones, which are either acidic or basic in composition. The first zone which envelops the core directly is always distinctly acidic. In some cases, features of discordant overgrowth are observable in this transitional boundary. And then, it is succeeded outward by a basic one having an approximate composition to that of the core. Further outward it transits to another acidic zone again. Such oscillations which take place two or three times are observable commonly, in which the acidic zone is more voluminous than the basic zone.

The mantle (e: in Text-fig. 14) is broadly developed. It can also be divided into two or three zones and accessory marginal filmy part. The compositions of the inner and outer zones of the mantle part are referable to those of the acidic parts in the oscillatory zone. The main difference in optic orientation between the inner and outer zones is represented by the difference between the ordering state of the inner zone and that of the outer zone, which have similar compositions. The outermost filmy zone is more acidic. Actual states of these zonal transitions in plagioclases of every lithofacies are represented in Text-fig. 14-A ~ H.

Although plagioclases with complex zones mentioned above are not observable within palaeosome biotite schist, those with simple zones are observed frequently. They have a small turbid core with an irregular form and a clear broader mantle. Their core



Text-fig. 14 Zonal details in plagioclases.

A,B: Plagioclases in the tonalite proper. C,D: Plagioclases in the migmatite neosome (C: Western type, D: Eastern type). E,F: Plagioclases in the granodioritic facies. G: Plagioclases in the palaeosome (Western type). H: Plagioclases in the Yazukuri biotite schist. a: small spot in a core part. b: irregular shaped patch in a core part. c: main core. d: part of oscillation zoning. e: mantle part. (a~e are corresponded to the description in text.)

part is so small that they were treated as nonzoned plagioclase in the foregoing statistic treatment. In the palaeosome which is biotite schist derivatives in the Western type of migmatite, the zoning is the reverse type having an acidic core of An 28 and a basic mantle of An 32 on the average (Text-fig. 14-G). Another type of plagioclase zoning is also known from the Yazukuri biotite schist, which is possible source rock of the Western type of migmatite. Plagioclases in the Yazukuri biotite schist show also a turbid core and a clean mantle; the zoning is the simple normal type having the core of An 32 and the mantle of An 28 on the average constitutes a common feature (Text-fig. 14-H).

As to plagioclases in a granodioritic facies, different styles of zoning are known. They are also formed by the accumulation of several zones. However, they are transited progressively in a normal order from the basic core to the acidic mantle along the line of an ordered state. There are none of reverse or oscillatory transitions and/or order-disorder transitions (Text-fig. 14-E). Another type is also known from granodiorite. It is represented in a more basic composition. The oscillatory zoning formed by a large number of different layers is significant in this type. The compositional difference between each layer is shown by an oscillatory relation. It seems to be a rule that the core is in a more disordered state and only a marginal part of it is in an ordered state (Text-fig. 14-F). In the outer facies of the granodiorite where spots of potash-feldspar are sparsely scattered, the zoned plagioclase in a normal ordered state assignable to plagioclases of the inner facies of the granodiorite is known. The only difference from them is the insertion of some order-disorder transitions during the formation. There may be several modified conditions for the growth of plagioclases in the granodioritic facies, but a great difference exists between them and conditions for the formation of plagioclases in the tonalite proper.

Anyhow, the former conditions for the whole tonalite complex vary with the lithofacies, as shown in the details mentioned of their plagioclase zonal structure.

As to the formation of tonalitic lithofacies, with the formation of plagioclase, which is idiomorphic, stout, and prismatic, in a granular-textured part of the neosome, the oscillatory zoning mentioned above appears instantly. In the neosome formed in amphibolite derivatives, similar idiomorphic, stout and prismatic plagioclase having the similar type of oscillatory zoning is formed. All of these plagioclases having the similar pattern of zoning may have been formed under the strictly same condition that prevailed in the formation of tonalite proper and also in the neosome impregnated as far as the extremity of the neosome which is finely diverged into the host rock.

The style of plagioclase zoning shown in the palaeosomes of biotite schist derivatives is greatly contrasted to the style shown in the neosome. But the formation of the reverse type zoning of plagioclase in palaeosome is not observable in the initial biotite schist, that is the Yazukuri biotite schist. Such formation may also be due to the effects which derive from the formation of neosomes.

The lithofacies of granodiorite shows another type of plagioclase formation. The plagioclases of granodiorite are shown statistically in a concentrated compositional range. Although some different patterns of zoning exist, as were noted, they seem to be

Table 3. Compositions of major elements of tonalite and related rocks.

Sample no.	1 Yz-1	2 Yz-2	3 Go-1	4* Go-2	5 Go-3	6* Go-4	7 U-1	8* Mz-3	9 Mz-5
SiO ₂	63.28	66.48	49.23	46.67	68.19	66.04	69.66	53.04	68.63
TiO ₂	.83	.91	1.10	1.63	.60	.60	.67	1.33	.46
Al ₂ O ₃	15.82	14.99	13.71	14.71	14.79	15.85	12.84	13.72	14.36
Fe ₂ O ₃	.87	1.26	2.60	6.73	1.21	1.04	1.92	2.97	1.41
FeO	5.18	4.24	8.99	5.95	3.23	4.00	4.71	8.33	3.06
MnO	.13	.06	.17	.21	.11	.10	.24	.18	.09
MgO	2.79	2.83	7.73	5.14	1.57	2.28	2.07	5.34	1.77
CaO	2.01	2.24	11.35	16.70	1.19	1.96	2.50	10.82	4.40
Na ₂ O	3.07	3.74	2.76	.85	4.56	3.80	2.40	2.21	3.21
K ₂ O	3.77	2.71	.15	.48	3.72	3.22	2.00	.69	1.33
P ₂ O ₅	.18	.22	.11	.19	.11	.14	.15	.17	.09
H ₂ O(+) / H ₂ O(-)	1.31	.52	1.45	.82	.69	1.18	.77 / .12	1.01	.74
Total	99.24	100.20	99.25	100.08	99.97	100.21	100.05	99.81	99.55

1,2: Yazukuri biotite schists (1: fine-grained schist. Loc. 2 km northwest of Daibara village. 2: coarse-grained schist. Loc. 2 km northeast of Takanuki town.)

3,4,5,6: Gozaisho metamorphics (3: amphibolite. Loc. 2 km northeast of Mizunuma village. 4: skarnized amphibolite. Loc. Nita village. 5: biotite schist. Loc. 500 m east of Nita village. 6: cordierite bearing biotite schist. Loc. Nita village.)

7,8,9: Palaeosomes in the Usuki migmatitic facies (7: biotite schist derivatives in the Western type of migmatitic facies. Loc. 500 m east of Daibara village. 8: amphibolite derivatives in the Eastern type of migmatitic facies. Loc. Mizunuma village. 9: biotite schist derivatives in the Eastern type of migmatitic facies. Loc. Mizunuma village.)

followed, in general, along the normal line of descent without any distinct breaks. According to the textural difference in plagioclase, it is suggested that a great difference exists between the condition for formation of granodiorite and that of tonalite or migmatite.

Chemistry

All chemical analyses of the representative rock samples collected individual lithofacies have been carried out by the wet method (for 13 samples) and by using the X-ray Emission Spectrometer (AFV-777, Toshiba) (for 6 samples). The analytical procedures and conditions using spectrometer followed those of Yamasaki (1979) and Yamasaki et al. (1980). The results are shown in Table 3. The rock species and geological positions of the samples are also shown in Table 3.

The occurrences of the samples are summarized as follows:

Table 3. (b)

10 U-2.	11 Mz-2	12 U-3	13* Mz-7	14 Mz-6	15 U-4	16 Mz-10	17* U-5	18* U-6	19 U-7
65.94	57.02	51.88	57.28	64.22	67.55	67.61	68.25	69.85	70.10
.52	1.10	1.95	.68	.60	.38	.56	.38	.34	.35
17.78	17.14	16.10	19.72	17.16	16.83	16.62	15.86	15.30	14.78
1.00	2.71	4.51	1.40	2.21	.43	1.17	.52	.44	1.69
2.86	5.61	7.13	4.05	3.03	2.80	2.26	2.38	2.18	1.62
.07	.14	.14	.11	.09	.11	.07	.06	.06	.07
1.19	3.15	2.52	1.81	1.35	.94	.86	.87	.78	.83
4.14	6.31	5.84	6.32	4.92	3.83	3.33	3.15	2.68	2.78
3.62	3.16	3.23	4.25	3.84	4.12	3.45	3.60	3.49	3.40
1.43	1.83	5.28	2.43	1.62	1.95	3.16	3.69	4.23	3.80
.17	.44	.56	.26	.30	.16	.37	.14	.13	.28
.64 .14	.80 .02	.80	.95	.64 .10	.79	.68 .08	.48	.60	.57 .02
99.50	99.43	99.94	99.26	100.08	99.89	100.22	99.38	100.08	100.29

(Analyst K. Uchiyama)

*Samples were analysed by X-ray Emission Spectrometer.

10: Neosome in the Western type of migmatitic facies. Loc. 500 m east of Daibara village.

11,12: Melanosomes in the Usuki migmatitic facies (11: Eastern type of migmatitic facies. Loc. Mizunuma village. 12: Western type of migmatitic facies. Loc. 300 m northeast of Usuki village.).

13: Neosome in the Eastern type of migmatitic facies. Loc. Mizunuma village.

14,15: Tonalite proper (14: Loc. Mizunuma village. 15: Loc. 300 m southwest of Usuki village.).

16,17: Marginal facies of granodioritic facies (16: Loc. Mizunuma village. 17: Loc. 200 m north of Usuki village.).

18,19: Granodioritic facies (18: Loc. 2 km east of Domeki. 19: Loc. Usuki village.).

(a) Possible source rocks of migmatite (nos. 1 ~ 6).

(b) Palaeosomes in migmatite (nos. 7 ~ 9).

(c) Nesomes in migmatite (nos. 10, 13).

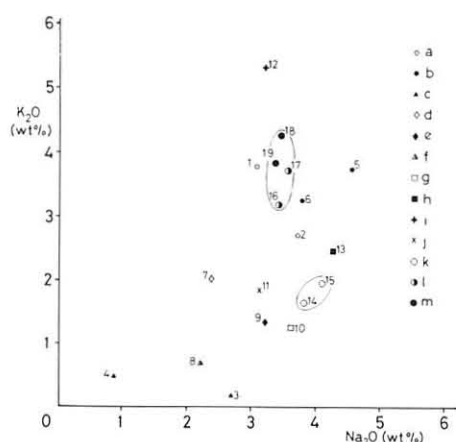
(d) Melanosomes in migmatite (nos. 11, 12).

(e) Tonalite proper (nos. 14, 15).

(f) Granodioritic facies (nos. 16 ~ 19).

For the discussion of chemical relationship and possible compositional change, an examination was made of correlations between $\text{Na}_2\text{O}-\text{K}_2\text{O}$: $\text{CaO}-(\text{Na}_2\text{O} + \text{K}_2\text{O})$; ACF diagram; and normative Q-Or-Ab system.

In the $\text{Na}_2\text{O}-\text{K}_2\text{O}$ relation (Text-fig. 15) several chemical changes which attend the transition of lithofacies were revealed. (1) Dealkalinization proceeds in palaeosomes of biotite schist derivatives by migmatization. The contents of alkalis in possible source rocks; that is, the biotite schists of Yazukuri (nos. 1, 2) and Gozaisho (nos. 5, 6)

Text-fig. 15 Na₂O-K₂O diagram.

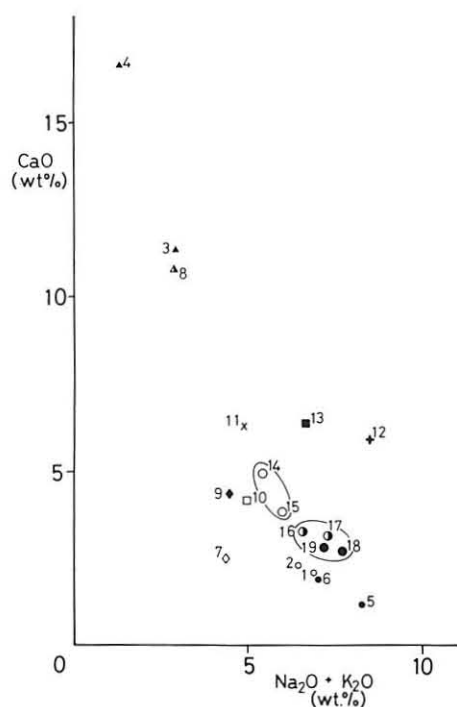
a: Yazukuri biotite schist, b: biotite schist belonging to the Gozaisho metamorphics, c: amphibolite belonging to the Gozaisho metamorphics, d: palaeosome in the Western type of migmatite (biotite schist derivatives), e: palaeosome in the Eastern type of migmatite (biotite schist derivatives), f: palaeosome in the Eastern type of migmatite (amphibolite derivatives), g: neosome in the Western type of migmatite, h: neosome in the Eastern type of migmatite, i: melanosome in the Western type of migmatite, j: melanosome in the Eastern type of migmatite, k: tonalite proper, l: outer facies of granodioritic facies, m: inner facies of granodioritic facies.

are found extremely lacking in the palaeosomes (nos. 7, 9) of migmatites of the Western and the Eastern type. (2) As to amphibolite, the content of alkalis is of course very low, which somewhat increases in the palaeosome (no. 8) of amphibolite derivatives and increases further in the neosome (no. 11) formed in close association with amphibolitic palaeosomes. (3) The plots of alkali content of tonalite proper are concentrated to a limited extent, to which the plots of neosomes of the Western and the Eastern type approach in a satellitic manner. (4) Granodiorite shows a peculiar domain distinctive from other lithofacies, which is properly characterized by enrichment of K₂O.

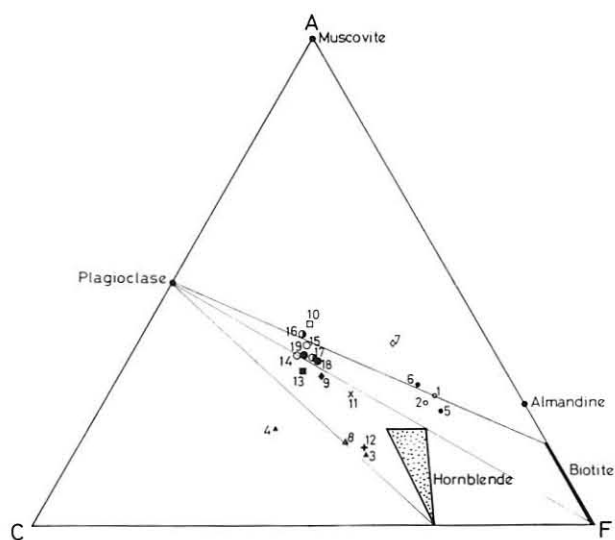
The diagram of CaO-(Na₂O+K₂O) (Text-fig. 16) is significant in the following aspects. (1) A distinction between amphibolitic and tonalitic rocks is represented by a difference in contents of lime and alkali. (2) The lime content of tonalite proper is slightly higher than that of granodiorite. (3) The neosomes in the Eastern type of migmatite are more basic in general, which is reflected in lime content.

Concerning the ACF diagram (Text-fig. 17) the following characters are noteworthy. (1) There is a distinctive domain on which the plots of tonalite proper, granodiorite and neosomes of migmatites are concentrated. (2) Another domain is formed by biotite schists and palaeosomes of their derivatives; also formed by amphibolite and their derivatives are also revealed. Every domain is separated far apart from one another. They correspond to the groups of tonalitic, amphibolitic and argillaceous lithofacies, respectively. The tonalitic and argillaceous domains are roughly referred to the field of a plagioclase-biotite assemblage. With these lithofacies cordierite is nearly absent in their mineral assemblage; instead, a minor amount of garnet and muscovite is often associated, especially with the migmatites of biotite schist derivatives. It seems to be probable that the cordierite component is represented by muscovite + garnet in the Usuki tonalite complex. The lithofacies which contain garnet and muscovite (nos. 7, 10) are plotted in a muscovite field beyond the plagioclase-biotite line.

On the other hand, the domain of tonalite is expanded beyond the line of



Text-fig. 16 CaO-(Na₂O + K₂O) diagram. Symbols are the same as in Text-fig. 15.

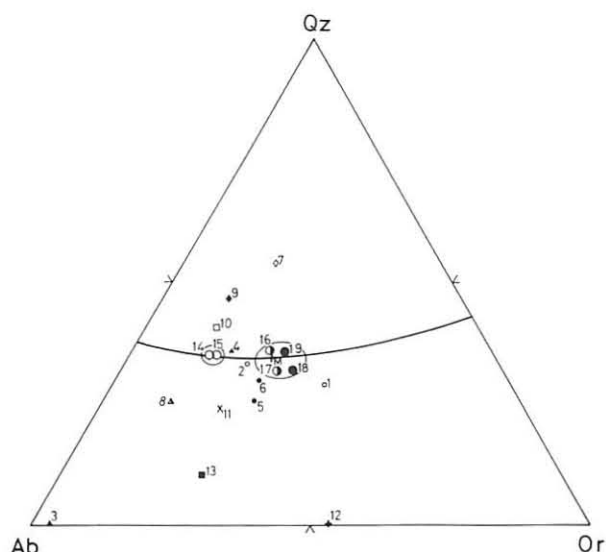


Text-fig. 17 ACF diagram. Symbols are the same as in Text-fig. 15.

plagioclase-biotite into the field of hornblende-plagioclase assemblage, plots of which are nos. 11 and 13. They are the derivatives from amphibolite. The amphibolite was metamorphosed from basic rocks belonging to the Abean geosynclinal sequence; at least the lithofacies (nos. 11, 13) contain some effects which results from it that such basic rocks are under the migmatitic condition. In this connection, White and Chappell

(1977) offered an interesting proposal recently. They established I- and S-types in granitic rocks, and considered that the I-type granite is a derivative from granitized basic igneous rocks. The observation that the plots (nos. 11, 13) are in the domain of the I-type granite conforms to the interpretation of White and Chappell. The fact that the plot of no. 4 deviates from an amphibolite field is due to its skarn assemblage produced by the contact effect of tonalitic intrusion.

Some prominent features can also be inferred from the normative Q-Or-Ab diagram (Text-fig. 18). (1) The plots of granodiorite are closely concentrated on definite area, which corresponds to the eutectic position of a granitic system at 2,000 bars (Tuttle and



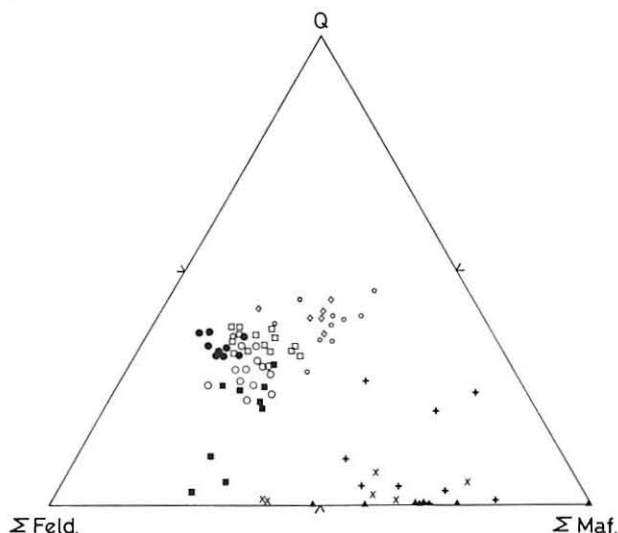
Text-fig. 18 Q-Ab-Or diagram. Solid line represents quartz-feldspar cotectics at 2,000 bars P_{H_2O} (Tuttle and Bowen, 1958). Symbols are the same as in Text-fig. 15.

Bowen, 1958). (2) On the other hand, the plots of the tonalites are concentrated on the experimentally defined cotectic lines of 2,000 bars that run through a tonalite field.

The features (1) and (2) may constitute the manifestation that their lithofacies represent stable rock facies under an equilibrium condition of a granitic system. Meanwhile, the plots of several lithofacies in migmatites are dispersed irregularly far from the sites of tonalite and granodiorite. It is not reasonable to represent the composition of biotite schists and their derivatives by an igneous normative scheme, and also that of basic rocks by a granitic system. However, because most of the lithofacies underwent the migmatitic condition and are closely associated with the tonalitic and granodioritic lithofacies, their behaviour may be referable to that in a condition of near granitic equilibrium. Viewed from this aspect, the deviated trends of migmatitic and basic lithofacies from the state of equilibrium may be defined as a temporal form in an unstable transitional state of disequilibrium. The plots of amphibolite derivatives are not adapted to this system. Some of deviated plots from normal domains in the AGF diagram are also plotted in places far deviated in the Q-Or-Ab system such as nos. 7, 9, 10, 11, 13.

Although some vague chemical natures are possible and interpretations are provisionally given above, the amount of analytical data is not so sufficient yet as to deduce the precise chemical nature of the complex.

As an effective control of the chemical composition, it is interesting to use the relative abundance of constituent minerals. Volumetric relations of all the lithofacies of the complex are given briefly by a triangle diagram of $Q-\Sigma\text{feld.}-\Sigma\text{maf.}$ as Text-fig. 19. In the diagram, (1) tonalites make a defined domain relatively rich in feldspar. (2) Another domain lies in the neighboured area toward the site of absence of feldspar, where a source rock, that is biotite schists, and derivative palaeosomes are gathered together. (3) The domain formed by neosomes in the Western type of migmatites lies between the above-mentioned domains of tonalite and biotite schist. (4) The granodiorite domain is situated at the site of absence of mafics than the tonalite domain. (5) The plots of amphibolitic rocks are concentrated around the line $\Sigma\text{feld.}-\Sigma\text{maf.}$ (6) The melanosomes occur in migmatites, in which the Western and the Eastern type are dispersed, by the concentration of biotite and/or the acceptance of quartz and/or feldspar in derivatives from biotite schists and amphibolites, respectively.



Text-fig. 19 Volumetric relations of $Q-\Sigma\text{feld.}-\Sigma\text{maf.}$ Symbols are the same as in Text-fig. 15.

Lead Isotopes

Measurements were made of the concentration of lead and ratio of lead isotopes for the purpose of obtaining a geochemical correlation between individual rock types arranged in the Takanuki district. As for the ratio of lead isotopes measurements were conducted under the instruction of Professor M. Murozumi at the Department of Applied Chemistry, Muroran Institute of Technology; the instrument used is a Surface Ionization Mass Spectrometer of the Hitachi RMU-6-Type. All the analytical pro-

cedures followed the method established by Murozumi et al. (1977, 1981), Yamasaki et al. (1978); and the analyses were made at Murozumi's ultraclean laboratory, using a single filament of rhenium as an ion source as well as phosphoric acid and silica gel as an ionization stabilizer. Lead was extracted by the dithizone-chloroform method. The concentrations of lead were determined by an isotope dilution analysis using a spike solution of ^{206}Pb . The effects of overall contamination were estimated to be less than 2 ng of Pb. The results of isotope ratios were normalized by NBS-SRM 981 standard sample.

The results are given in Table 4. The samples used for the analyses are also given in Table 4. The whole rock data from granitic rocks, and argillaceous gneisses and schists of the Takanuki and the Gozaisho metamorphics show a good concentration of lead isotopes to a limited extent: $^{206}\text{Pb}/^{204}\text{Pb} = 18.42\text{--}18.72$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.63\text{--}15.72$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.80\text{--}39.45$. However, amphibolites of the Gozaisho metamorphics show distinctively low values in $^{207}\text{Pb}/^{204}\text{Pb}$ (15.40, 15.47) and $^{208}\text{Pb}/^{204}\text{Pb}$ (38.24, 38.37). Concerning the granitic rocks of the district, lead isotope ratios were already measured and discussed by Shimizu (1970). His results are in a good agreement with the writer's results as far as the granitic rocks are concerned. The present paper contains new additional data, that is, the argillaceous metamorphics (the Takanuki and the Gozaisho metamorphics) of the region have also the same values as those of granitic rocks, and present clearly different values of lead isotope ratios of amphibolites of the Gozaisho metamorphics.

The measured data on biotite (T-b-1, T-b-2, U-2-b) show high ratios in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, which are considered to be due to the admixture of zircon including a large amount of initial uranium.

Lead concentrations vary greatly with the rock type and mineral. They are 5.81–16.00 ppm in granitic rocks; 10.44–22.97 ppm in argillaceous metamorphics; 0.573 ppm in amphibolite; and amount to 116.8 ppm in potash-feldspar.

Concerning the lead isotope ratios, several treatments are proposed. The questions as to age relations of host rocks can be discussed, though they are not sharply defined. An effective discussion is made, using lead isotope ratios, on the inquiry of whether a specific rock types derives from crustal or mantle materials. In this respect, the studies of Chow and Patterson (1962), Chow and Tatsumoto (1964), Tatsumoto (1966, 1978), Tatsumoto and Knight (1969) and Reynolds and Dasch (1971) are of interest. According to Tatsumoto (1966, 1978), the ratios of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ increase progressively in oceanic basalts, suggesting that the progressive evolution of mantle materials is reflected; that is, the mantle itself has progressively evolved ever since its birth. The above-mentioned oceanic basalts represent the total sum of the direct products from partial melting of the mantle materials in every stage of the course of evolution. All the rocks of mantle derivatives must be plotted on a "lead growth curve" of mantle evolution, because any differentiation cannot have an effect on the ratios of lead isotopes attained at every stage. In the diagram of $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$, the plots of the basalts which originate from mantle materials at individual stages of evolution shift progressively along the lead growth curve of mantle evolution.

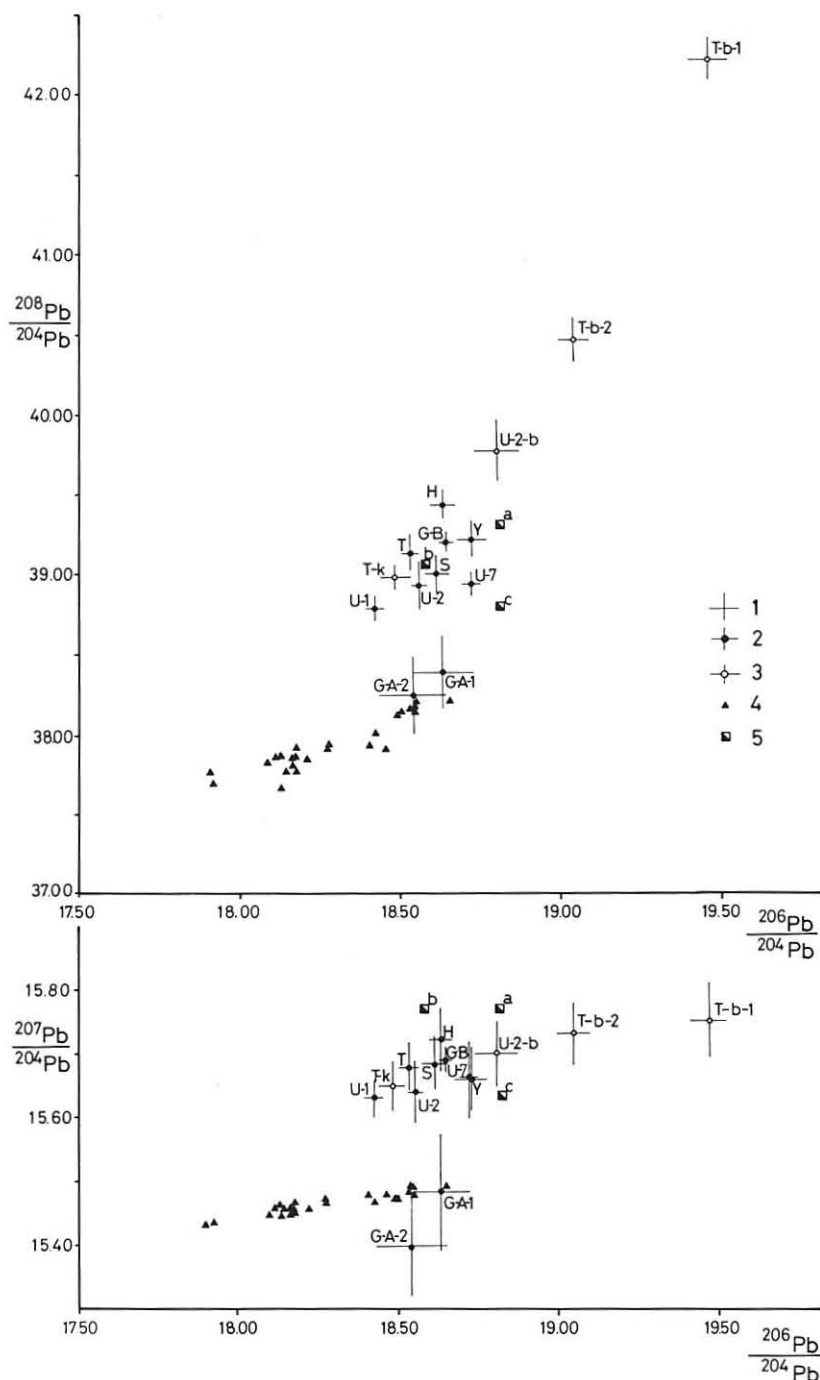
Table 4. Lead concentrations and isotope ratios.

Sample	Concentration (ppm)	$^{207}\text{Pb}/^{205}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
(1) T	22.97 $\pm$ 0.03*	0.8457 $\pm$ 0.0015*	2.112 $\pm$ 0.004*	18.53 $\pm$ 0.03*	15.68 $\pm$ 0.04*	39.15 $\pm$ 0.11*
(2) T-b-1	3.48 $\pm$ 0.03	0.8092 $\pm$ 0.0005	2.168 $\pm$ 0.001	19.46 $\pm$ 0.06	15.75 $\pm$ 0.06	42.22 $\pm$ 0.13
(3) T-b-2	nd.	0.8260 $\pm$ 0.0013	2.125 $\pm$ 0.004	19.04 $\pm$ 0.05	15.73 $\pm$ 0.05	40.47 $\pm$ 0.14
(4) T-k	116.8 $\pm$ 0.3	0.8472 $\pm$ 0.0017	2.111 $\pm$ 0.002	18.48 $\pm$ 0.05	15.65 $\pm$ 0.04	38.99 $\pm$ 0.08
(5) Y	14.01 $\pm$ 0.06	0.8363 $\pm$ 0.0012	2.096 $\pm$ 0.003	18.72 $\pm$ 0.05	15.66 $\pm$ 0.05	39.23 $\pm$ 0.11
(6) G-B	10.44 $\pm$ 0.03	0.8415 $\pm$ 0.0009	2.103 $\pm$ 0.002	18.64 $\pm$ 0.02	15.67 $\pm$ 0.02	39.21 $\pm$ 0.06
(7) G-A-1	0.573 $\pm$ 0.004	0.8300 $\pm$ 0.0020	2.059 $\pm$ 0.003	18.63 $\pm$ 0.09	15.47 $\pm$ 0.09	38.37 $\pm$ 0.23
(8) G-A-2	nd.	0.8306 $\pm$ 0.0025	2.062 $\pm$ 0.002	18.54 $\pm$ 0.11	15.40 $\pm$ 0.08	38.24 $\pm$ 0.23
(9) U-1	7.37 $\pm$ 0.03	0.8488 $\pm$ 0.0008	2.106 $\pm$ 0.002	18.42 $\pm$ 0.03	15.63 $\pm$ 0.03	38.80 $\pm$ 0.08
(10) U-2	11.65 $\pm$ 0.05	0.8424 $\pm$ 0.0012	2.098 $\pm$ 0.003	18.56 $\pm$ 0.02	15.64 $\pm$ 0.05	38.94 $\pm$ 0.15
(11) U-2-b	3.67 $\pm$ 0.02	0.8353 $\pm$ 0.0013	2.115 $\pm$ 0.006	18.80 $\pm$ 0.07	15.70 $\pm$ 0.05	39.78 $\pm$ 0.19
(12) U-7	16.00 $\pm$ 0.04	0.8367 $\pm$ 0.0007	2.081 $\pm$ 0.002	18.72 $\pm$ 0.03	15.66 $\pm$ 0.03	38.95 $\pm$ 0.07
(13) H	5.81 $\pm$ 0.02	0.8435 $\pm$ 0.0012	2.118 $\pm$ 0.003	18.63 $\pm$ 0.04	15.72 $\pm$ 0.05	39.45 $\pm$ 0.09
(14) S	9.58 $\pm$ 0.05	0.8427 $\pm$ 0.0008	2.096 $\pm$ 0.004	18.61 $\pm$ 0.04	15.68 $\pm$ 0.04	39.01 $\pm$ 0.12

*Standard deviation (2σ).

(Analyst K. Uchiyama)

(1) T: Feldspar porphyroblastic gneiss (abbrev. blastic gneiss) in the Takanuki metamorphics. Loc. 1 km southeast of Takanuki town. (2), (3) T-b-1, T-b-2: Biotites in the blastic gneiss (T). (4) T-k: Potash-feldspar in the blastic gneiss (T). (5) Y: Yazukuri biotite schist. Loc. Sengosawa. (6) G-B: Biotite schist in the Gozaisho metamorphics (cf. chemical analysis no. 5 Go-3 in Table 3). (7) G-A-1: Amphibolite in the Gozaisho metamorphics (cf. chemical analysis no. 3 Go-1 in Table 3). (8) G-A-2: Amphibolite in the Gozaisho metamorphics (Loc. 500 m northeast of Nita village). (9) U-1: Palaeosome in the Western type of migmatite (cf. chemical analysis no. 7 U-1). (10) U-2: Neosome in the Western type of migmatite (cf. chemical analysis no. 10 U-2). (11) U-2-b: Biotites in the neosome (U-2). (12) U-7: Granodiorite in the Usuki tonalite complex. Loc. Usuki village. (13) H: Quartz-diorite in the Hanaboh quartz-diorite complex. Loc. Hanaboh village. (14) S: Granodiorite in the Samegawa composite mass. Loc. 3 km west of Nyudoh village.



Text-fig. 20 Diagrams of $^{207}\text{Pb}/^{204}\text{Pb}$ (lower) and $^{208}\text{Pb}/^{204}\text{Pb}$ (upper) vs. $^{206}\text{Pb}/^{204}\text{Pb}$.

1: Uncertainty. 2: Whole rock sample (present study). 3: Biotite and potash-feldspar (present study). 4: Oceanic basalt (Tatsumoto, 1978). 5: Average value of pelagic sediments (a: North Pacific, Chow and Patterson, 1962; b: Near Japan Trench, Chow and Tatsumoto, 1964; c: manganese nodules, Reynolds and Dasch, 1971).

On the other hand, lead isotope ratios in pelagic sediments are characterized by fairly high values in the ratios of $^{207}\text{Pb}/^{204}\text{Pb}$ (Chow and Patterson, 1962; Chow and Tatsumoto, 1964; Reynolds and Dasch, 1971). Ratios of Japanese volcanics lie between the lead growth curve and the domain of pelagic sediments, which is considered by Tatsumoto (1966), and Tatsumoto and Knight (1969) to result from the mixing of mantle-derived materials and crustal materials at the crustal level of the Japanese islands.

It is suggested that the crustal materials produced through the repeated cycles of weathering, transportation and sedimentation tend to have higher values of the ratio of $^{207}\text{Pb}/^{204}\text{Pb}$.

The lead isotope ratios of granitic rocks and argillaceous metamorphics obtained by the present study are plotted on a narrowly limited area in the diagrams of $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ (Text-fig. 20), which show a great difference from the plots of the oceanic basalts that lie on the lead growth curve. They rather approach the domain of pelagic sediments. On the other hand, the plots of amphibolite of the Gozaisho metamorphics (G-A-1, G-A-2) show a close approach to the lead growth curve. It conforms to those of the mantle derivatives, because the amphibolite is a metamorphosed equivalent of basic effusive rocks or dykes prevalent in the Abean geosynclinal sequence.

Discussion

Highly voluminous leucocratic granitoid rocks, which constitute a trondhjemite-tonalite suite, are known in every early Precambrian terrain of the world. Concerning their origin and references to the crustal formation of the early history of the earth, much attention has been devoted, and several summarized reviews have been published (Barker and Arth, 1976; Barker, 1979; Glikson, 1979). As to the origin of such trondhjemite-tonalite suite, the current view held is that the suite was produced as a result of partial melting of basic or ultrabasic rocks at a mantle depth or at the basal part of the crust. This view is also supported by the geochemistry of trace elements and experimental petrology, on which papers have been published extensively (Geochemistry: Arth and Hanson, 1972, 1975; Barker et al., 1976; Arth et al., 1978, experimental petrology: Green and Ringwood, 1966, 1968; Holloway and Burnham, 1972; Lambert and Wyllie, 1972, 1974; Helz, 1973, 1976). As one of the studies on lead isotope ratios, the following study is of some interest. Arth and Hanson (1975) studied the geochemistry of rare elements of the early Precambrian greenstone-granite complex of the northeastern Minnesota, as well as carrying out the analyses of lead isotopes. The lead isotope ratios of a trondhjemite-tonalitic suite which they had obtained lie within the lead growth curve of mantle evolution. Based on this and other studies of rare elements, they concluded that all these leucocratic rocks are derivatives from partial melting of eclogite at a mantle depth, but not from the differentiation of basaltic magmas.

Meanwhile, trondhjemite and tonalitic rocks are widely observed within the area of

the orogenic core. In this area granitization proceeds and, as a result, a coarser-grained tonalitic lithofacies is formed through the migmatitic or metasomatic replacement of argillaceous gneisses; consequently, the tonalitic lithofacies prevails in the area. Actually, in an immediate western neighbourhood of the tonalitic complexes subjected to the present study, the granitized facies is associated with the blastic gneiss which constitutes the central zone of the Takanuki metamorphics.

Though the details of the granitized facies and blastic gneiss have not been published, the following are brief features: Blastic gneisses are formed from various assemblages of plagioclase, biotite, quartz, cordierite, sillimanite, and orthoclase, as a result of their conversion into massive lithofacies which are nonfoliated, coarser-grained and have a plagioclase-biotite-quartz assemblage and several features of in-situ replacement. The massive lithofacies contains basified palaeosomes of kinzigitic assemblage and small local domains of granitic lithofacies produced by the porphyroblastesis of feldspars. The plagioclases in these granitized lithofacies are not peculiarly zoned, as observed in the Usuki tonalite complex, but are in a nearly non-zoned state and aggregate to each other in granoblastic texture. Although a granitized lithofacies comes about in a small strip along the zone of blastic gneiss in the Takanuki district, the granitized part become larger as their location approaches to the south; the mobilization of granitized tonalitic rocks into surrounding blastic gneisses is a rule in the south. Another feature of the zone of blastic gneiss is the intrusion of tonalitic dykes of less than 3 m in width, around which migmatitic lithofacies are prominently developed. The nature of plagioclase observed in tonalite as well as in surrounding migmatite neosomes present a great similarity to those of tonalite proper described in the foregoing chapter.

All these features were formed through the events progressively developed in the main stage of the Abean orogeny. On the respect, following hypotheses may be acceptable.

The following is the first hypothesis: According to the current interpretation on the origin of trondhjemite-tonalite suite in the early Precambrian, the tonalite complexes are also considered to be the products from partial melting of materials of the mantle or basic materials of the lower crust existing under high pressure at the deep level of the region. Shimizu (1970) agree to this view, based on the ratios of lead isotopes he measured. However, the above-mentioned geological circumstances of the district to not conform to this view. The plots of lead isotope ratios in the Usuki tonalite complex do not lie on the lead growth curve of mantle evolution as shown in the above-mentioned case of the northeastern Minnesota (Arth and Hanson, 1975). In the case of the Usuki tonalite and related rocks, their plots rather fall in the domain formed by schists and gneisses of argillaceous origin, being separated far from the lead growth curve. It means that the tonalitic rocks derived from the crustal materials, or at least, contain many of crustal elements.

An alternative hypothesis suggested is as follow: It is related to the shearing processes prevalent in the boundary zone between the Takanuki and the Gozaisho metamorphics. Other than tonalitic intrusives, various kinds of sheared rocks as well as

blocks of highly developed diaphthorites are associated with each other in this boundary zone (Watanabe et al., 1978, 1979). Recently a paper was published on a felsite dyke swarm developing along the sheared zones in the eastern marginal region of the Abukuma axial metamorphic belt (Watanabe et al., 1983-a, 1983-b). The formation of these felsites was considered by the authors to be attributed to the shearing processes prevailing in the surrounding zones, where several features which mean that the shearing reaches pulverization-devitrification and brings about a molten state were confirmed. Whether such processes are attributable to the origin of the tonalitic complex subjected to the present study is of great interest. Within the boundary zone a large number of blocks of diaphthorites are contained as tectonic inclusions, which are considered to have been produced under a shearing process. However, evidence which connects such shearing products and tonalitic rocks is sought much; while the tonalite complex is too voluminously developed, it seems that cannot be conformed solely to the origin of shearing.

At present the writer prefers the following view as to the origin of the present tonalite complex: The products of regional granitization formed deep beneath the central zone in the main stage of the Abean orogeny were concealed. Then the rejuvenation of granitized materials which had taken place at a deep level resulted in the mobilization of them to cut into a boundary zone between the Takanuki and the Gozaisho metamorphics when the boundary fractured during the subsequent stage.

The present measurements of ratios of lead isotopes may well support such an interpretation. They surely mean that the original materials are of crustal origin. The materials which produce the tonalite complex subjected to the present study are attributable to the members of the Takanuki metamorphics which are buried far beneath the level of the present outcrop of granitized rock racies; and they cannot be considered to derive from the basic rocks at a mantle level or lower crustal level without observed evidence.

As to the migmatitic lithofacies developed widely within the tonalite complex, it is a striking feature that the formation of neosomes and palaeosomes in complicatedly mixed states is vastly different from the contact effects given to the wall rocks of the Takanuki and the Gozaisho metamorphics. The contact effects represent the formation of fine network of quartzose seams in the argillaceous schist, as well as representing biotitization and/or formation of pools of skarn assemblages for the amphibolite. In this respect, it may be considered possible that migmatization was carried out at a deeper level than the present level observed; that the domain of this migmatization activated was not only limited within the Takanuki metamorphics, but also broke into the members of the Gozaisho metamorphics, which might have lain at a somewhat higher level than the birth site of tonalite proper; and that those migmatized parts were also brought to the present level from their birth level by the intrusive movement of the tonalitic mobilisates.

Conclusion

The present study is concluded as follows:

- (1) The examined tonalitic complexes intruded along a boundary zone between the Takanuki and the Gozaisho metamorphics in the Abukuma axial metamorphic belt as one of the main event of the subsequent stage of the Abean orogeny. The Usuki tonalite complex is associated with a large number of migmatitic facies, the sources of which are the argillaceous metamorphics of the Takanuki metamorphics as well as amphibolite and biotite schist of the Gozaisho metamorphics.
- (2) Detailed optical measurement of constituent plagioclases have been carried out. Plagioclases in tonalite proper and neosome of migmatitic facies show a similar behaviour in a range of compositional variation and in ordering states. Characteristic zonal structure of plagioclase predominated for the whole extent of the complex, where a distinction between migmatite and tonalite is not shown. It is suggestive that the overwhelming condition for the growth of constituent plagioclase controls nearly the whole extent of the complex. However, granodiorite is fairly different from it in showing a more stable state.
- (3) All of the chemical analyses of representative samples of lithofacies have been carried out. As a result, several compositional relations are mentioned. A stable lithofacies, which is closely allied to the generally accepted normal rock type, and a deviated unstable lithofacies are distinguished from ACF diagram. The difference is revealed in the Q-Or-Ab diagram, in which the equilibrium lithofacies is only limited to tonalite proper and granodiorite, others seeming to represent transitional varieties.
- (4) For the correlation of rock types arranged in the Takanuki district, analyses have been made of lead concentrations and lead isotope ratios of representative types of granitic, argillaceous, and basic metamorphics of the region subjected to the study. The prominent result is that all of them, except the basic metamorphics, are not plotted on the lead growth curve of mantle evolution, but deviate far from the lead growth curve and forms a concentrated domain, which means a crustal inheritance.
- (5) On the origin of the present tonalite complex, the writer concluded that its initial formation is attributable to the granitization processes, which prevailed in the central zone of the Takanuki metamorphic unit during the main stage of the Abean orogeny. The highly granitized materials concealed beneath the granitized facies, which are presently observable at the surface, were rejuvenated and mobilized.

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