Petrology of the Tabashine plutonic complex, southern Kitakami Mountains, Japan

Hiroyuki OJI*, Nobutaka TSUCHIYA** and Satoshi KANISAWA***

*Department of Earth and Planetary Sciences, Graduate School of Science,
Hokkaido University, Kita 10 Nishi 8, Kitaku, Sapporo 060, Japan

**Department of Geology, Iwate University,
18-33 Ueda 3-chome, Morioka 020, Japan

***Institute of Mineralogy, Petrology, and Economic Geology,
Tohoku University, Kawauchi, Sendai 980-77, Japan

The Early Cretaceous Tabashine plutonic complex (TPC) in the southern Kitakami Mountains includes a range of intermediate to felsic rocks, and is divided into the North and South plutons on the basis of petrographical and petrochemical features. Rocks of the North pluton contain larger amounts of pyroxene and are slightly richer in K_2O but poorer in Al_2O_3 than those of the South pluton. On the other hand, rocks of the South pluton scarcely contain pyroxene and are characterized by euhedral crystals of hornblende. A possible petrogenetic interpretation is that they were derived from a common original magma, but underwent different evolutionary paths as a consequence of different water content in magma.

The North pluton shows normal continuous zoning, having more felsic composition with decreasing amounts of mafic enclaves inward. Such a kind of compositional zoning may be explained by a combined effect of differentiation occurring in a deeper chamber and mixing between mafic and felsic magmas rather than *in situ* crystal fractionation.

The TPC is accompanied by a gabbroic mass, quartz-dioritic and tonalitic intrusions, and the Bunatoge volcanics. The gabbroic mass and the TPC are characterized by high K_2O content and their emplacement occurred within a short time period. On the other hand, the Bunatoge volcanics and the quartz-dioritic and tonalitic intrusions are distinctly lower in K_2O contents. The Bunatoge volcanics erupted prior to the emplacement of the TPC, whereas the quartz-dioritic and tonalitic intrusions were emplaced later than the TPC. Thus, the Early Cretaceous magmatism in the study area is characterized by a complex variation in K_2O content with respect to time.

Keywords: Tabashine plutonic complex, Kitakami Mountains, K_2O variation, Magmatic water content, Zoned pluton, Cretaceous magmatism

I. Introduction

In the Kitakami Mountains, there are widespread exposures of calc-alkaline granitoid plutons whose radiometric ages range from 110 to 125 Ma (e.g., Kawano and Ueda, 1965; Shibata, 1968). These plutonic rocks are the I-type of Chappell and White (1974) and the magnetite series of Ishihara (1977). They

have been traditionally divided into zones I to VIb on the basis of their distribution, petrography, and petrochemistry (Katada *et al.*, 1974; Kanisawa and Katada, 1988; Fig. 1). Recently, Tsuchiya and Kanisawa (1994) has proposed an integrated model for the Early Cretaceous magmatism in the Kitakami Mountains, according to which the magmatism was related to the partial melting of the subducted oceanic

Fig. 1. Distribution of the Cretaceous igneous rocks and zonal arrangement of the plutonic rocks in the Kitakami Mountains (after Kanisawa and Katada, 1988).

crust and the mantle wedge due to subduction of the Farallon-Izanagi Ridge.

The Tabashine plutonic complex (hereafter abbreviated as TPC) belongs to zone VIb and its major-element chemistry is similar to that of the Orikabe pluton (Kato, 1974; Ishijima and Kato, 1971). Although a petrographical study by Shimazu (1955) revealed that the TPC is composed of a wide range of rock variety, relationships among these rocks still remain unknown. This paper elucidates the mode of occurrence and the petrographical and petrochemical features of the TPC, and finally describes the K_2O variation in this complex.

II. Geological setting

Fig. 2 shows a geological map of the TPC. The TPC intrudes the Toyoma Formation of Middle to Late Permian age, which is composed mainly of slate with a minor amount of conglomerate named the Usuginu Conglomerate. It also intrudes the Early Cretaceous Bunatoge volcanics (Shimazu, 1955; 1979), which is composed of andesite lava and pyroclastic rocks. The phenocrysts of the andesite lava are plagioclase, clinopyroxene, and hornblende. These country rocks are metamorphosed into hornfels for several hundred meters from the contact. The constituent minerals of pelitic hornfels are plagioclase, quartz, K-feldspar, muscovite, and biotite; and those of metamorphosed volcanics are plagioclase, quartz, K-feldspar, biotite, hornblende, clinopyroxene, and orthopyroxene. The hornfels of the country rocks also sporadically occurs as roof-pendant blocks within the pluton.

The TPC is intruded by a number of NE-SW-trending small dikes of felsite, dolerite, and porphyrite. The western part of the pluton is unconformably covered by the Neogene Ichinoseki Formation, which consists of sandstone and conglomerate.

III. Mode of occurrence

The TPC is composed of six intrusive units including a range of intermediate to felsic rocks, and is accompanied by a gabbroic mass and small intrusions of quartz diorite and tonalite. These plutonic rocks are massive and devoid of foliation and lineation. Aplite commonly occurs as small veins of several centimeters wide, but pegmatite is rare.

In this paper, nomenclature of plutonic rocks follows the classification scheme of Streckeisen (1976). The rocks are said to be fine-grained if the average grain size of their constituents is less than 1 mm; medium-

Fig. 2. Geological map of the TPC. 1, dike; 2, Ichinoseki Formation; 3, tonalitic intrusion; 4, quartz-dioritic intrusion; 5-10, Tabashine plutonic complex; 5-7, North pluton (5, N-3 type; 6, N-2 type; 7, N-1 type); 8-10, South pluton (8, S-3 type; 9, S-2 type; 10, S-1 type); 11, gabbroic mass; 12, Bunatoge volcanics; 13, Toyoma Formation.

grained if the average grain size is between 1 and 2 mm; coarse-grained if the average grain size is greater than 2 mm. The grain size is given in terms of maximum dimensions for individual grains.

1. Classification of rock types

The six intrusive units of the TPC are grouped into the North and South plutons on the basis of petrographical and petrochemical features. Rocks of the North pluton contain larger amounts of pyroxene and are slightly richer in K_2O but poorer in Al_2O_3 than those of the South pluton. On the other hand, rocks of the South pluton scarcely contain pyroxene and are characterized by euhedral crystals of horn-

blende. Each of the two plutons consists of three rock types, each of which represents a single intrusive unit.

The North pluton consists of the N-1, N-2, and N-3 types. The N-1 type is mainly composed of fine-grained quartz monzodiorite and is meridionally distributed in the eastern part of the pluton. It grades into the N-2 type around Mt. Ohira in the north. The boundary between the N-1 and N-2 types is defined by the C.I. (color index)=25. The N-2 type is zoned inward from quartz monzodiorite to granite, occupying the largest part of the pluton. The N-3 type is mainly distributed in the northwestern part of the pluton and is composed of fine-

grained granite.

The South pluton consists of the S-1, S-2, and S-3 types. The S-1 type is distributed in the southwestern part of the pluton and is composed mainly of fine-grained quartz monzodiorite. The S-2 type is the only rock type bounded by the North pluton, occupying the southeastern part of the pluton. It is composed mainly of medium-grained granite and granodiorite with a minor amount of granodiorite porphyry that occurs near the contact with the Toyoma Formation. The S-3 type is composed mainly of porphyritic granite, which grades into granophyre in the northern part.

2. Relationships among the rock types

Fig. 3 illustrates the relationship among the rock types based on our field observations. The granophyre of the S-3 type intrudes the granodiorite of the S-2 type. A large number of angular xenoliths (<1 m) incorporated into the granophyre suggests that the emplacement of the S-3 type was after solidification of the S-2 type magma. Rocks of the S-2 type commonly contain mafic and microgranular inclusions of which petrographical features are similar to the S-1 type in that they are characterized by euhedral hornblende crystals. These inclusions are generally several centimeters in diameter and invariably circular or elliptical in shape. The rounded shapes suggest that the mafic inclusions were incorporated before their solidification. Thus, they are interpreted as magmatic enclaves.

The N-3 type was found to have a chilled margin at its contact with the N-2 type, indicating that the N-3 type intruded after solidification of the N-2 type. The N-2 type commonly contain mafic and microgranular inclusions which petrographically resemble to the N-1 type in that they are characterized by anhedral hornblende and presence of pyroxene. These inclusions are generally several centimeters in diameter and invariably circular or

Fig. 3. Relationships among the rock types of the TPC and associated igneous rocks.

elliptical in shape. In addition, the N-2 and N-1 types were found to grade into each other around Mt. Ohira. These lines of evidence indicate that both rock types coexisted in magmatic states and the mafic inclusions are magmatic. It should be noted that the abundance of the mafic inclusions in the N-2 type is positively correlated with color index of the host rocks.

Although the S-2 type is bounded by the North pluton, no direct contact is observed due to lack of outcrops. However, a mafic and microgranular inclusion with petrographical features similar to the rocks of the N-1 type was observed in the rock of the S-2 type. The inclusion is approximately 20 cm in diameter and elliptical in shape. The marginal part of the inclusion is finer-grained and the crystals are juxtaposed along a boundary. Therefore, the mafic inclusion was not fully crystallized at the time of incorporation; i.e., the S-2 type and the N-1 type coexisted in magmatic states. Thus, the N-1, N-2, S-1, and S-2 types were emplaced penecontemporaneously. After their solidification, the N-3 and S-3 type rocks were

Fig. 4. Distribution of recrystallized rocks of the TPC. Cross represents locality of the rock samples *with* decussate aggregates of secondary biotite, and open circle represents the locality of the samples *without* decussate aggregates of biotite.

emplaced.

No direct contact between the gabbroic mass and the North pluton is observed, and their intrusive sequence is still poorly known. However, it is suggested that they were emplaced within a narrow geologic time span on account of the absence of contact metamorphic effect.

Rocks of the N-2 and N-3 types are recrystallized over a wide area around the quartz-dioritic intrusion (Fig. 4). Moreover, the grain size of the quartz-dioritic intrusion decreases near the contact, suggesting a chilled margin. These lines of evidence indicate that the quartz-dioritic intrusion was emplaced after solidification of the North pluton. No direct contact between the tonalitic intrusion and the North pluton is observed. It is interpreted that the tonalitic intrusion intrudes into the North pluton, because of no contact metamorphic effects by the North pluton and the petrochemical similarity to the quartz-dioritic intrusion.

IV. Petrography

1. North pluton

(1) N-1 type

The N-1 type ranges in composition from diorite to quartz monzodiorite. Rocks are fine-grained, and the textures vary from porphyritic to hypidiomorphic granular. The porphyritic appearance is due to euhedral large crystals of plagioclase set in a finer-grained matrix. It is more mafic and finer-grained around the hornfels blocks, and becomes more felsic and coarser-grained with increasing distance from the hornfels blocks. It also occurs as mafic enclaves in the rocks of the N-2 and S-2 types. The rocks are composed mainly of plagioclase, quartz, K-feldspar, biotite, hornblende, pyroxene, and magnetite. Ilmenite, apatite, sphene, allanite, and tourmaline occur as accessory minerals.

Small plagioclase crystals (0.1 to 1 mm) occur as weakly zoned, and well-shaped laths, of which aspect ratios significantly decrease with increasing distance from the hornfels blocks; it commonly exceeds 10:1 around the hornfels blocks, while it is usually less than 5:1 around Mt. Ohira. Phenocrystic crystals (1.5 to 3 mm) of plagioclase occur around Mt. Ohira and the abundance increases with decreasing color index. The plagioclase phenocrysts also occur in the mafic enclaves observed in the N-2 type. Quartz (0.1 to 0.3 mm) and K-feldspar (0.1 to 0.5 mm) typically occupy interstices, but can occur as poikilitic pools in which small crystals of plagioclase and pyroxene are set. K-feldspar has perthite texture.

Biotite (0.05 to 1.5 mm) is straw yellow in X-axial color and dark brown in Z-axial color. The anhedral biotite (Fig. 5A) frequently occurs as reaction rims surrounding pyroxene and opaque minerals, and sometimes occurs as poikilitic crystals enclosing small grains of plagioclase. Hornblende (0.05 to 1 mm) is

straw yellow in X-axial color and green in Z-axial color. The hornblende crystals are anhedral and generally occur as reaction rims surrounding pyroxenes (Fig. 5A) around the hornfels blocks, but discrete crystals commonly occur in this rock around Mt. Ohira. The hornblende sometimes occurs as poikilitic crystals enclosing small grains of plagioclase, and is often intimately associated with biotite. Pyroxenes occur as both discrete euhedral to subhedral grains and relict cores included in anhedral crystals of hornblende and biotite. Clinopyroxene (0.3 to 1.5 mm) is weakly zoned. Orthopyroxene (0.1 to 0.5 mm) is strongly pleochroic, pale pink in X-axial color and pale green in Z-axial color. Pyroxenes are sometimes replaced by actinolite or cummingtonite. Opaque minerals (<0.2 mm) occur as granular grains closely associated with mafic silicates.

(2) N-2 type

The N-2 type ranges in composition from quartz monzodiorite to granite. Rocks are fine- to medium-grained, and the textures are typically hypidiomorphic granular, but locally porphyritic due to euhedral large crystals of plagioclase (1 to 4 mm) set in a finer-grained matrix (<1 mm). Around Mt. Ohira, the rocks with porphyritic appearances are texturally indistinguishable from those of the N-1 type. As mentioned earlier, the rocks are recrystallized over a large area in the north and the west (Fig. 4). Those recrystallized rocks show a distinctive decussate texture of biotite (Fig. 5B). The rocks are composed mainly of plagioclase, K-feldspar, quartz, biotite, hornblende, pyroxene, and magnetite. Ilmenite, apatite, sphene, allanite, zircon and tourmaline occur as accessory minerals.

Euhedral to subhedral plagioclase (0.1 to 4 mm) shows normal and/or oscillatory zoning and mainly occurs as prismatic crystals. K-feldspar (0.2 to 6 mm) is mainly anhedral to subhedral, but small crystals (<0.3 mm) can

occur as remarkable euhedral prisms enclosed in larger anhedral crystals of hornblende (Fig. 5C). Quartz (0.1 to 1.5 mm) occurs as anhedral grains and often forms graphic intergrowth with K-feldspar (Fig. 5D).

Biotite (0.1 to 1 mm) is subhedral to anhedral in shape. It is straw yellow in X-axial color and dark brown in Z-axial color. The secondary biotite (0.002 to 0.1 mm) forms decussate aggregates closely associated with larger amphibole crystals (Fig. 5B). Hornblende (0.1 to 1.5 mm) is straw yellow in X-axial color and green in Z-axial color. It usually occurs as subhedral to anhedral crystals often poikilitically enclosing small grains of plagioclase. The hornblende crystals are often closely associated with biotite. Pyroxene (0.1 to 0.5 mm) is mainly clinopyroxene and orthopyroxene is less abundant. The pyroxene crystals mainly occur as relict core of hornblende. Strongly pleochroic orthopyroxene is pale pink in X-axial color and pale green in Z-axial color. The pyroxene crystals are frequently replaced by actinolite and cummingtonite. Opaque minerals (0.02 to 0.4 mm) occur as granular grains usually closely associated with mafic silicates. Tourmaline is abundant in the rocks distributed in the northern and western parts, and frequently occurs as veins of several centimeters wide.

(3) N-3 type

The N-3 type consists of granite with fine-grained hypidiomorphic granular texture. Some rocks are recrystallized and show decussate texture of biotite. The rocks are composed mainly of plagioclase, K-feldspar, quartz, biotite, and hornblende. Pyroxene, magnetite, ilmenite, apatite, allanite, sphene, zircon, and tourmaline occur as accessory minerals.

Plagioclase (0.3 to 4 mm) occurs as strongly zoned euhedral to subhedral prisms. Quartz (0.1 to 1 mm) occurs as subhedral to anhedral granular grains. K-feldspar (0.5 to 1.5 mm) is generally subhedral to anhedral, but euhedral

prisms also occur occasionally. The K-feldspar shows perthite texture. Quartz and K-feldspar commonly form remarkable graphic intergrowth.

Biotite (0.1 to 3 mm) is euhedral to subhedral and is dark brown to reddish brown in Z-axial color. The secondary biotite (0.002 to 0.1 mm) occurs as decussate aggregates closely associated with larger amphibole crystals. Hornblende (0.3 to 1 mm) is euhedral to subhedral and is straw yellow in X-axial color and green in Z-axial color. Pyroxene generally occurs as relict cores of larger hornblende crystals. It is often altered to actinolite or cummingtonite.

2. South pluton

(1) S-1 type

The S-1 type consists of quartz monzodiorite and quartz diorite with fine- to medium-grained hypidiomorphic granular to porphyritic texture. It also occurs as mafic enclaves in the S-2 type. Euhedral large crystals of plagioclase are responsible for the porphyritic appearance. The rocks are composed mainly of plagioclase, hornblende, biotite, quartz, and K-feldspar. Ilmenite, apatite, sphene, allanite, calcite, and pyroxene occur as accessory minerals. Secondary alteration involves chlorite, epidote, muscovite, and prehnite.

Most of the small crystals of plagioclase (0.2 to 1 mm) have conspicuous normal zoning and occur as euhedral to subhedral prisms. The plagioclase phenocrysts (2 to 6 mm) are also normally zoned and contain mottled cores. They commonly enclose small grains of hornblende and biotite. Quartz (0.1 to 1 mm) and K-feldspar (0.1 to 2.5 mm) are interstitial and sometimes occur as poikilitic pools in which the other crystals are set. They commonly form graphic intergrowth. K-feldspar has perthite texture.

Subhedral biotite (0.2 to 1 mm) is straw yellow in X-axial color and dark brown in Z-

axial color. Prehnite sometimes occurs in the cleavage of the biotite. The biotite is commonly altered to chlorite and epidote. Hornblende (0.5 to 3 mm) is generally greenish brown in Z-axial color and often brownish in core and greenish in rim. It occurs mainly as euhedral to subhedral crystals (Fig. 5E) and often encloses small grains of plagioclase. The hornblende crystals are often altered in part to chlorite. Pyroxene is rare, but a clinopyroxene crystal was found as a relict core of a larger euhedral crystal of hornblende. Ilmenite (0.1 to 0.2 mm) generally occurs as discrete granular grains.

The occurrence of some calcite crystals (0.2 to 0.7 mm) deserves special mention. They occur as interstitial grains and have a sharp linear contact with other minerals (Fig. 5F). This occurrence indicates that the calcite was not formed by secondary alteration, but crystallized at the latest stage of crystallization. Such calcite is also reported by several authors (e.g. Smith and Cohen, 1996; Tsuchiya, 1982; Grapes, 1974).

(2) S-2 type

The S-2 type consists of granite and granodiorite with a minor amount of granodiorite porphyry. The granite and granodiorite show medium- to coarse-grained hypidiomorphic granular texture. The rocks are composed mainly of plagioclase, quartz, K-feldspar, biotite, hornblende. Magnetite, ilmenite, apatite, allanite, sphene, zircon, and pyroxene occur as accessory minerals.

Plagioclase (0.5 to 4 mm) shows normal and/or oscillatory zoning. The euhedral to subhedral crystals of plagioclase often enclose small grains of hornblende and biotite. Quartz (0.1 to 2 mm) occurs as anhedral to subhedral granular grains. Anhedral grains of K-feldspar (0.2 to 2 mm) have conspicuous perthite texture.

Biotite (0.1 to 1.5 mm) is euhedral to sub-

hedral and frequently encloses small grains of plagioclase. The biotite is straw yellow in X-axial color and dark brown in Z-axial color. It is occasionally altered to chlorite. Hornblende (0.1 to 2.5 mm) is euhedral to subhedral (Fig. 5G) and often encloses small grains of plagioclase. The hornblende is straw yellow in X-axial color and green in Z-axial color. The hornblende crystals are frequently associated with biotite and sphene. Opaque minerals generally (0.1 to 1 mm) occur as granular grains closely associated with biotite and hornblende. Pyroxene is scarce and invariably occurs as relict core of hornblende. The pyroxene is frequently replaced by actinolite and only clinopyroxene was found as relicts.

The granodiorite porphyry differs from the medium-grained granodiorite only in the texture. The phenocrysts are plagioclase (1 to 5 mm), hornblende (0.5 to 2 mm), biotite (0.5 to 1.5 mm), and quartz (0.5 to 2 mm). The phenocrystic biotite and hornblende sometimes enclose small grains of plagioclase and opaque minerals. The groundmass is a fine-grained mosaic (0.1 to 0.2 mm) of plagioclase, quartz, K-feldspar, biotite, hornblende, and opaque minerals.

(3) S-3 type

The S-3 type consists of porphyritic gabbro and granophyre. The rocks commonly contain xenoliths (generally less than 1 cm) of pelitic hornfels. Phenocrysts include plagioclase (0.5 to 4.5 mm) with minor amounts of biotite (0.5 to 1 mm), hornblende (0.5 to 1 mm), and quartz, which are set in a fine-grained matrix (<0.2 mm) composed mainly of plagioclase, quartz, K-feldspar, biotite, and hornblende with a minor amount of magnetite, ilmenite, apatite, allanite, and sphene. Secondary alteration involves chlorite, epidote, muscovite, calcite, and prehnite.

Plagioclase is strongly zoned and often saussuritized. Biotite is straw yellow in X-axial

color and dark brown in Z-axial color. It is often altered to chlorite and epidote. Prehnite sometimes occurs* in the cleavage of biotite crystals. Hornblende is straw yellow in X-axial color and green in Z-axial color. Quartz and K-feldspar often occur as granular grains.

3. Gabbroic mass

The gabbroic mass shows distinct local variation in rock facies. However, due to lack of outcrops, relationships among these rock facies is still unresolved. We classified them into two groups on the basis of textural and mineralogical features; the monzogabbro and the gabbro.

(1) Monzogabbro

The monzogabbro shows fine-grained hypidiomorphic granular texture. The rocks are composed mainly of plagioclase, clinopyroxene, K-feldspar, biotite, olivine, magnetite. Apatite and ilmenite occur as accessory minerals.

Plagioclase (0.1 to 2 mm) occurs as weakly zoned, euhedral to subhedral laths. K-feldspar (0.1 to 0.4 mm) has perthite texture and occupies interstices among other minerals. Clinopyroxene (0.1 to 3.5 mm) occurs as weakly zoned euhedral granular grains, often enclosing small grains of plagioclase, olivine, and opaque minerals. Biotite is straw yellow in X-axial color and reddish brown in Z-axial color. The anhedral crystals of biotite usually occur as reaction rims around olivine, clinopyroxene, and opaque minerals. Olivine (0.2 to 1.5 mm) occurs as euhedral granular grains commonly associated with clinopyroxene crystals. Opaque minerals (0.02 to 0.5 mm) occur as granular grains generally enclosed in mafic silicates.

(2) Gabbro

The gabbro shows medium- to coarse-grained hypidiomorphic granular texture and is composed mainly of plagioclase, clinopyroxene, orthopyroxene, hornblende, biotite, and magnetite with a minor amount of quartz, K-feld-

Fig. 5. Photomicrographs of the rocks from the TPC. **A**: quartz monzodiorite of the N-1 type. Note the anhedronal biotite and amphibole. **B**: decussate aggregates of biotite closely associated with amphibole (N-2 type). **C**: euhedral K-feldspar enclosed in anhedronal amphibole (N-2 type). **D**: graphic intergrowth between quartz and K-feldspar (N-2 type). **E**: quartz monzodiorite of the S-1 type. Note the euhedral amphibole crystals. **F**: interstitial calcite from the S-1 type. **G**: Granodiorite of the S-2 type. Note the euhedral amphibole.

Abbreviations; Am, amphibole; Bi, biotite; Cpx, clinopyroxene; Opx, orthopyroxene; Opq, opaque minerals; Pl, plagioclase; Kfs, K-feldspar; Qtz, quartz; Cal, calcite; Sph, sphene.

spar, ilmenite, pyrite, chalcopyrite, apatite, and calcite. The rocks occasionally appear as cumulate (heteradcumulate to mesocumulate; Wager *et al.*, 1960), which consists of cumulus minerals of plagioclase, clinopyroxene, and orthopyroxene, and intercumulus minerals of hornblende, biotite, and magnetite. Secondary alteration involves minor muscovite over plagioclase and chloritization of biotite.

Plagioclase (0.1 to 3 mm) usually occurs as euhedral to subhedral crystals, but sometimes occurs interstitially among pyroxene crystals. It is frequently saussuritized. Quartz and K-feldspar occur interstitially among other minerals.

Clinopyroxene (0.5 to 6 mm) occurs either as euhedral to subhedral isolated grains or as relict core of anhedral hornblende. Orthopyroxene is less abundant and is pale pink in X-axial color and pale green in Z-axial color. The pyroxenes are frequently altered to actinolite or cummingtonite. Anhedral hornblende (0.4 to 6 mm) is often poikilitic and can form prominent oikocrysts containing cumulus crystals of plagioclase. The hornblende is straw yellow in X-axial color and brown to green in Z-axial color. Biotite (0.2 to 2 mm) is anhedral and occurs interstitially among the euhedral crystals of pyroxene and plagioclase. It frequently encloses smaller grains of pyroxene and plagioclase. The biotite is straw yellow in X-axial color and reddish brown in Z-axial color. Opaque minerals (0.05 to 0.7 mm) occur either as interstitial grains or as ragged acicular shaped crystals in the clinopyroxene crystals. The opaque minerals also occur as granular grains enclosed in mafic silicates.

Calcite (0.2 to 0.6 mm) occasionally occurs in interstices and sometimes encloses euhedral smaller grains of plagioclase. Such calcite crystals presumably crystallized at the latest stage of crystallization.

4. Quartz-dioritic and tonalitic intrusions

(1) Quartz-dioritic intrusion

The quartz diorite shows fine- to medium-grained hypidiomorphic granular texture. The rocks are mainly composed of plagioclase, biotite, hornblende, clinopyroxene, orthopyroxene, quartz, K-feldspar, and magnetite. Ilmenite, apatite, sphene, allanite, and tourmaline occur as accessory minerals.

Plagioclase (0.01 to 4 mm) is euhedral to subhedral and weakly zoned. It frequently occurs as rounded grains. Quartz and K-feldspar occur interstitially among other minerals. The K-feldspar has perthite texture.

Biotite (0.02 to 1 mm) is straw yellow in X-axial color and dark brown in Z-axial color. This occurs as anhedral grains poikilitically embracing small grains of plagioclase. Hornblende is anhedral and commonly encloses small grains of plagioclase. It is straw yellow in X-axial color and green in Z-axial color. Pyroxene occurs either as relict core of hornblende or anhedral to subhedral discrete grains. Clinopyroxene (0.1 to 1.5 mm) commonly encloses small grains of plagioclase. Orthopyroxene (0.05 to 1 mm) is pale pink in X-axial color and pale green in Z-axial color. Opaque minerals (0.02 to 1 mm) occur as granular grains closely associated with mafic silicates.

(2) Tonalitic intrusion

The tonalite shows medium-grained hypidiomorphic granular to fine-grained porphyritic texture. Euhedral large crystals of plagioclase (0.7 to 3 mm) give the rock a porphyritic appearance. The rocks are composed mainly of plagioclase, biotite, hornblende, clinopyroxene, quartz, and K-feldspar. Ilmenite, apatite, sphene, allanite and tourmaline occur as accessory minerals.

Plagioclase (0.1 to 3 mm) is euhedral to subhedral and weakly zoned. In the porphyritic rocks, the matrix plagioclase occurs as

small rounded grains (0.1 to 0.2 mm) set in poikilitic large crystals of hornblende, biotite and quartz. Quartz (0.2 to 2 mm) is anhedral and commonly encloses small grains of plagioclase. K-feldspar is interstitial, and has perthite texture.

Hornblende (0.1 to 2 mm) is straw yellow in X-axial color and brown to green in Z-axial color. It generally occurs as anhedral poikilitic crystals enclosing small grains of plagioclase. Biotite (0.1 to 1.5 mm) is straw yellow in X-axial color and reddish brown in Z-axial color. The biotite crystals are anhedral and frequently enclose small grains of plagioclase. Clinopyroxene (0.1 to 1 mm) occurs either as relict core of hornblende or as discrete anhedral to subhedral grains. Ilmenite (<0.1 mm) occurs as granular grains closely associated with biotite and sphene.

V. Modal variation of constituent minerals

Ninety-one modal analyses were determined for the rocks of the TPC and associated plutonic rocks. The analyses were made on the thin sections by counting between 1,500 to 2,000 points in each section. Modal compositions of representative samples are listed in Table 1.

Modal quartz-K-feldspar-plagioclase triangular diagram is shown in Fig. 6. In this figure, at least three trends are shown; those of the North pluton, the South pluton, and the quartz-dioritic and tonalitic intrusions. The quartz-dioritic and tonalitic intrusions are poorer in K-feldspar than the North and South plutons and show a trend approximately parallel to the quartz-plagioclase join. The North and South plutons show similar trends, but the North pluton is slightly richer in K-feldspar.

Fig. 7 shows modal pyroxene-hornblende-biotite triangular diagram. Rocks of the North pluton (except the N-3 type) commonly contain substantial amounts of pyroxene, while

Table 1. Modal compositions of representative rock samples from the TPC and associated plutonic rocks

Rock type	GB	GB	N-1	N-1	N-2	N-2	N-2	N-3	N-3
Sample no.	80206	80213	102505	80810	80809	102511	80874	80859	80851
Quartz	0.7	0.0	5.5	11.1	13.7	18.6	19.1	24.5	31.6
K-feldspar	0.4	9.6	4.8	11.7	8.1	15.5	29.4	39.2	42.5
Plagioclase	53.4	54.5	52.7	49.8	55.7	45.3	37.1	27.6	21.8
Biotite	17.9	6.8	17.1	9.1	10.1	4.7	8.2	3.9	2.6
Hornblende	13.4	0.0	3.5	14.9	8.6	13.2	0.3	3.7	1.0
Clinopyroxene	11.9	20.9	11.6	0.8	1.7	0.9	2.7	tr.	0.0
Orthopyroxene	0.0	0.0	2.2	0.2	0.0	0.0	0.7	0.0	0.0
Olivine	0.0	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Opacues	1.8	2.8	2.3	1.9	1.7	1.4	2.1	0.7	0.2
Others	0.5	0.2	0.3	0.5	0.4	0.4	0.4	0.4	0.3
Color Index	45.0	35.7	36.7	27.3	22.1	20.3	14.0	8.4	3.8
Rock type	S-1	S-1	S-2	S-2	S-2	S-3	QD	TN	
Sample no.	121001	80710	80705	80221	80104	80712	81734a	41801	
Quartz	10.8	10.7	21.0	21.6	26.2	25.4	8.9	15.7	
K-feldspar	8.5	8.5	18.6	20.7	22.3	28.7	2.3	4.4	
Plagioclase	46.3	53.2	42.7	40.7	39.5	35.0	54.4	51.8	
Biotite	0.7	6.2	8.0	9.8	5.1	7.6	17.9	8.7	
Hornblende	32.4	19.6	7.7	5.7	5.1	2.5	12.5	13.3	
Clinopyroxene	0.0	0.0	0.0	0.0	0.0	0.0	2.2	4.8	
Orthopyroxene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Olivine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Opacues	0.8	1.2	1.4	0.9	1.2	0.4	1.3	0.2	
Others	0.5	0.6	0.6	0.6	0.6	0.4	0.5	1.1	
Color Index	34.0	27.2	17.4	16.8	11.9	10.6	34.2	27.6	

Abbreviations, GB, gabbroic mass; QD, quartz-dioritic intrusion; TN, tonalitic intrusion.

Fig. 6. Modal quartz, K-feldspar, plagioclase diagram for the TPC and associated plutonic rocks (fields after Streckeisen, 1976). 1, granite; 2, granodiorite; 3, tonalite; 4, quartz monzonite; 5, quartz monzodiorite; 6, quartz diorite; 7, monzodiorite or monzogabbro; 8, diorite or gabbro. Abbreviations are the same as in Table 1.

rocks of the South pluton scarcely contain pyroxene.

In Fig. 8, modal variation of opaque minerals is plotted against modal quartz + K-feld-

Fig. 7. Modal pyroxene, biotite, hornblende diagram for the TPC. Symbols are the same as in Fig. 4.

Fig. 8. Modal opaque minerals vs. quartz + K-feldspar plot. Symbols are the same as in Fig. 4.

spar. This figure shows that the rocks of the South pluton are slightly poorer in opaque minerals than those of the North pluton when compared at similar modal quartz + K-feldspar.

The North pluton is zoned in modal composition with the exception of the N-3 type. Modal contents of quartz + K-feldspar and color index are presented as contour maps in Fig. 9. Rocks with the greatest abundance of quartz and K-feldspar and the lowest color index are distributed in the northwestern part of the N-2 type. Then the abundance of quartz and K-feldspar decreases continuously with a concomitant increase of color index

Fig. 9. Modal contour maps of the North pluton except for the N-3 type. Star represents the locality of analyzed rock samples. **A**: Contour map of color index variation. **B**: Contour map of quartz + K-feldspar variation.

outward. The rocks with the highest color index are distributed around the hornfels blocks in the east. The N-1 type has the highest color index, while the N-2 type has the lowest around the hornfels blocks. The compositional difference is such that there must be no continuity between the two rock types. Then, the color index of the N-1 type decreases with the increasing distance from the hornfels blocks, while that of the N-2 type increases contrarily to the N-1 type. The compositional gap between the two rock types gradually decreases as the distance from the hornfels blocks increases, and these rock types grade into each other in the vicinity of Mt. Ohira.

In contrast to the North pluton, the South pluton shows no systematic compositional zoning.

VI. Whole-rock chemistry

Fifty-two whole-rock chemical analyses of major oxides were determined for the rocks of the TPC and associated igneous rocks including the Bunatoge volcanics. The data were obtained from 1:5 dilution fusion discs analysed on a X-ray fluorescence (XRF) spectrometer fitted with Rh anode tube. Analytical method and accuracy are given by Tsuchiya and Hasenaka (1995). Chemical compositions of representative samples are listed in Table 2. The data are plotted on the Harker variation diagrams (Fig. 10).

The igneous rocks in the study area display wide range of compositions, ranging from 49 to 74% SiO₂. The North pluton shows a definite trend for any major oxides. The N-1 and N-2 types varies continuously from 52 to 64% SiO₂. On the other hand, the South pluton shows discontinuous variation; the S-1 type ranges from 54 to 57% SiO₂; the S-2 type ranges from 63 to 67% SiO₂; S-3 type contain approximately 66% SiO₂. The North pluton and the South pluton are indistinguishable in terms of total Fe₂O₃, MnO, Na₂O, and P₂O₅. The S-1 and S-3 types have lower TiO₂, MgO, and CaO than the North pluton, while the S-2 type is indistinguishable from the North pluton in terms of these three oxides. The common features of the three rock types of the South pluton are higher Al₂O₃ and slightly lower K₂O than the North pluton.

In the variation diagram of K₂O, the named fields of extrusive igneous rock series are given after Pecerillo and Taylor (1976). Although there is a slight difference in K₂O contents between the North and South plutons, rocks of the TPC and the gabbroic mass are characterized by high K₂O contents. In fact, most of

Table 2. Bulk-rock major element chemistry of representative rock samples from the TPC and associated igneous rocks

Rock type	GB	GB	N-1	N-1	N-2	N-2	N-2	N-3	N-3
Sample no.	80206	80213	102505	80810	80809	102511	80874	80859	80851
SiO ₂	49.13	49.84	52.84	56.50	58.92	60.73	63.74	66.43	73.97
TiO ₂	1.22	1.23	1.06	0.91	0.84	0.73	0.61	0.49	0.19
Al ₂ O ₃	16.92	16.34	16.59	16.30	16.09	15.52	15.00	14.78	12.86
Fe ₂ O ₃ *	11.32	12.10	10.26	8.07	7.18	6.11	5.29	3.97	1.63
MnO	0.18	0.18	0.17	0.14	0.13	0.10	0.10	0.07	0.02
MgO	5.41	5.24	4.86	3.55	3.14	2.66	2.11	1.55	0.45
CaO	9.57	9.54	8.46	6.77	5.53	4.90	4.19	2.86	1.29
Na ₂ O	3.02	2.97	3.17	3.29	3.31	3.41	3.15	3.29	3.04
K ₂ O	1.62	2.49	2.53	2.94	3.23	3.72	4.39	4.34	5.11
P ₂ O ₅	0.39	0.38	0.35	0.28	0.26	0.23	0.18	0.13	0.04
LOI	1.00	0.18	0.50	1.18	1.28	0.89	0.59	1.15	0.67
Total	99.78	100.49	100.79	99.93	99.91	99.00	99.35	99.06	99.27
Rock type	S-1	S-1	S-2	S-2	S-2	S-3	QD	TN	BN
Sample no.	121001	80710	80705	80221	80104	80712	81734a	41801	81721
SiO ₂	54.28	57.21	63.72	63.76	65.42	65.48	55.28	60.56	59.13
TiO ₂	0.90	0.73	0.57	0.57	0.49	0.37	1.00	0.70	0.75
Al ₂ O ₃	16.96	16.82	15.87	15.93	15.39	15.97	16.40	16.54	15.91
Fe ₂ O ₃ *	8.61	7.38	4.93	4.87	4.41	3.83	8.11	4.03	6.20
MnO	0.16	0.15	0.09	0.09	0.08	0.08	0.14	0.07	0.10
MgO	3.94	3.14	1.93	1.95	1.73	1.16	4.55	3.16	3.57
CaO	7.35	5.81	4.50	4.69	4.10	2.67	7.55	7.41	5.78
Na ₂ O	3.21	3.72	3.47	3.78	3.51	4.26	3.43	4.00	3.44
K ₂ O	2.31	2.58	3.27	2.96	3.80	3.50	1.78	1.63	2.23
P ₂ O ₅	0.31	0.28	0.17	0.19	0.16	0.13	0.24	0.23	0.19
LOI	1.68	1.62	0.75	0.56	0.51	1.47	0.74	0.78	2.03
Total	99.71	99.44	99.27	99.35	99.60	98.92	99.22	99.11	99.33

*LOI = ignition loss

Abbreviations, GB, gabbroic mass; QD, quartz-dioritic intrusion; TN, tonalitic intrusion; BN, Bunatoge volcanics.

them are plotted within the field of high-K calc-alkaline series, and some rocks of the North pluton and the gabbroic mass are plotted within the field of shoshonite series. On the other hand, the Bunatoge volcanics and the quartz-dioritic and tonalitic intrusions are distinctly lower in K₂O, and are plotted near the boundary between the fields of the calc-alkaline and high-K calc-alkaline series.

VII. Discussion

1. Depth of emplacement

Field observations and mineralogical investigations by several authors (Kanisawa, 1970; 1972a; 1972b; 1974; Kano *et al.*, 1978; Ujiie and Kanisawa, 1995) have suggested that the plutonic bodies in zone VI belong to the epizonal granites of Buddington (1959), and this is also true of the TPC as indicated by its mode of occurrence and mineralogical features: (1) intimate occurrence of volcanic rocks; (2) scarcity of foliation and lineation; (3) remark-

Fig. 10. Harker variation diagrams for the TPC and associated igneous rocks. Named fields of extrusive igneous rock series after Pecirillo and Taylor (1976) are shown in the K_2O variation diagram. Abbreviations are the same as in Table 2.

able variation in rock facies; (4) common occurrence of fine-grained and/or porphyritic rocks; (5) no regional metamorphism in the country rocks; (6) presence of roof-pendant blocks of the country rocks; (7) scattered ordering degree in plagioclase (Urano, 1958). In calc-alkaline granitoid plutons, crystallization pressures can be estimated by Al content of hornblende buffered by a nine-phase assemblage; hornblende + biotite + plagioclase + orthoclase + quartz + sphene + Fe-Ti-oxide + melt + vapor (Hammarstrom and Zen, 1986). There are seven hornblende analyses of the TPC by Kato (1974). One is of the S-2 type, and the others are of the N-2 type. Then, the calculated crystallization pressures after the equation of Schmidt (1992) are relatively low, ranging from 0.4 to 2.2 kb with the average of 1.3 kb and the standard deviation of 0.5 kb. This result together with the above field observations indicates that the eroded surface was a shallow level close to the earth's surface at the time of emplacement.

2. Compositional zoning in the North pluton

The North pluton is compositionally zoned with the exception of the N-3 type (Fig. 9). The N-2 type is concentrically zoned without discontinuity, having more felsic composition with decreasing amounts of mafic enclaves inward. A great deal has been written about the genesis of compositional zoning in granitoid plutons. The most favored one for normal continuous zoning is *in situ* crystal fractionation by progressive solidification from the margins of a magma chamber inward (e.g., Sawka *et al.*, 1990; Ragland and Butler, 1972). This process, however, hardly explains the systematic abundance of mafic enclaves. Zorpi *et al.*, (1989) proposed a model for the genesis of compositional zoning with systematic abundance of mafic enclaves. In this model, compositional zoning is a combined result of differentiation occurring in a deeper

chamber and mixing between felsic and mafic magmas. This process may account for the zoning observed in the N-2 type.

The N-1 and N-2 types are considered to have coexisted in magmatic states at the time of emplacement. The N-1 type is more mafic around the hornfels blocks and becomes more felsic with increasing distance from the hornfels blocks. On the other hand, the N-2 type is more felsic around the hornfels blocks and becomes more mafic as the distance from the hornfels blocks increases. The compositional gap between the two rock types is largest around the hornfels blocks, and then decreases with increasing distance from the hornfels blocks. Such compositional variations of both rock types can be explained by mixing between felsic and mafic magmas. Around the hornfels blocks, rocks of the N-1 type are most fine-grained and are characterized by highly elongated plagioclase crystals, suggesting that the N-1 type magma was chilled to solidify before it could mix effectively with the N-2 type magma. Then, with increasing distance from the hornfels blocks, the cooling rate of magma was reduced and mixing between mafic and felsic magmas was facilitated to produce such compositional variations. The cooling rate is reflected by the grain size and the aspect ratio of the plagioclase of the N-1 type rocks.

Thus, magma mixing together with differentiation occurring in a deeper chamber may have played an important part in producing the compositional variation in the North pluton.

3. Genetic consideration for the North and South plutons

In this section, we discuss how the petrographical and petrochemical difference between the North and South plutons may have been produced.

Rocks of the North pluton are characterized by larger amounts of pyroxene and an-

hedral crystals of hornblende, while those of the South pluton scarcely contain pyroxene and are characterized by euhedral crystals of hornblende. These distinct petrographical features can be attributed to the difference of water content in magma. It is well established that presence of dissolved water can significantly change the sequence in which different minerals crystallize from a silicate magma. The upper temperature stability limits of hornblende and biotite are virtually constant irrespectively of magmatic water content, whereas those of plagioclase, K-feldspar, and quartz are drastically depressed with increasing water content (Robertson and Wyllie, 1971; Maaløe and Wyllie, 1975; Wyllie, 1977; Naney, 1983). Accordingly, beginning of crystallization of hornblende in comparison with that of plagioclase strongly depends on water content in magma. The euhedral hornblende crystals characteristic of the South pluton therefore indicate the enhanced magmatic water content, while anhedral hornblende crystals of the North pluton suggest that they were crystallized under relatively anhydrous conditions.

The North and South plutons are also different in terms of K_2O content (Fig. 10). Rocks of the South pluton are slightly poorer in K_2O than those of the North pluton. Such two contrasting rock series differing in magmatic water content and K_2O within a single intrusive suite as exemplified by the TPC are well documented in Cretaceous plutons in northeast Japan, including the Matsumae pluton (Tsuchiya, 1985) in southwest Hokkaido, the Hiran-iwa pluton (Miki, 1985) and the Orikabe pluton (Ujiie, 1989; Ujiie and Kanisawa, 1995) in the Kitakami Mountains, and the Nishidohira cordilleritic body (Tanaka *et al.*, 1982) in the Abukuma Highland. Tsuchiya (1985) proposed a model for the genesis of such two contrasting rock series in a single intrusive suite. He suggested that elevated magmatic water con-

tent resulted in early-stage fractionation of amphibole rather than pyroxene, thereby produced the K_2O -poorer rock series in the Matsumae pluton. Petrochemical difference between the North and South plutons in the TPC can also be interpreted by a similar mechanism through which the difference in magmatic water content results in different compositional paths followed by residual liquids. It is suggested that elevated magmatic water content lead not only to early stage fractionation of amphibole but also to depressed fractionation of plagioclase, thereby produced K_2O -poorer and Al_2O_3 -richer trends of the South pluton.

Thus, a possible interpretation is that the six intrusive units of the TPC were derived from a common original magma, but underwent different evolutionary paths as a consequence of different water content in magma.

4. Diversity of K_2O content

The Early Cretaceous igneous rocks in the study area show remarkable variation in K_2O content. On the K_2O - SiO_2 variation diagram (Fig. 10), they can be roughly divided into two groups; one includes the TPC and the gabbroic mass, and the other includes the Bunatoge volcanics and the quartz-dioritic and tonalitic intrusions. The former is characterized by high K_2O contents, while the latter is distinctly lower in K_2O content.

As discussed above, the North and South plutons may be products of a single magmatic event and possibly derivatives from a common original magma, although they are obviously different in their K_2O contents. This possibility is also supported by the observation that the six intrusive units of the TPC were emplaced within a brief time span as indicated by the absence of contact metamorphic effects. By analogy, the gabbroic mass may have also been produced during the same magmatic event as indicated by its comparably high K_2O contents

Fig. 11. Schematic representation of the variation of K_2O content with respect to time. Abbreviations are the same as in Table 2.

and the absence of contact metamorphic effect. On the other hand, the latter group, including the Bunatoge volcanics and the quartz-dioritic and tonalitic intrusions, is unlikely to have been produced by the same magmatic event as that of the former group because of its distinctly lower K_2O contents. The Bunatoge volcanics erupted prior to the emplacement of the TPC, whereas the quartz-dioritic and tonalitic intrusions were emplaced later than the TPC. Thus, the magmatism in the study area is characterized by a complex variation in K_2O content with respect to time; i.e., the earliest manifestations are the Bunatoge volcanics with lower K_2O contents, followed by the gabbroic mass and the TPC with higher K_2O contents and finally by the tonalitic and quartz-dioritic intrusions with lower K_2O contents (Fig. 11).

VIII. Conclusions and summary

(1) The TPC was emplaced at the epizonal environment as indicated by its mode of occurrence and crystallization pressures estimated from Al in hornblende analyzed by Kato (1974).

(2) The North pluton shows normal continuous zoning, having more felsic composition with decreasing amounts of mafic enclaves inward. Such a compositional zoning may be explained by a combined effect of

differentiation occurring in a deeper chamber and mixing between felsic and mafic magmas.

(3) Rocks of the North pluton contain larger amounts of pyroxene and are slightly richer in K_2O but poorer in Al_2O_3 than those of the South pluton. On the other hand, rocks of the South pluton scarcely contain pyroxene and are characterized by euhedral crystals of hornblende. A possible petrogenetic interpretation is that they were derived from a common original magma, but underwent different evolutionary paths as a consequence of different water content in magmas.

(4) The Early Cretaceous magmatism in the study area is characterized by the complex variation in K_2O contents with respect to time. The earliest manifestations are the Bunatoge volcanics with lower K_2O contents, followed by the gabbroic mass and the TPC with higher K_2O contents and finally by the tonalitic and quartz-dioritic intrusions with lower K_2O contents.

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- (*in Japanese with English abstract)

南部北上山地東稲深成複合岩体の岩石学的研究

王子 裕幸・土谷 信高・蟹澤 聡史

東稲岩体は北部岩体と南部岩体からなり、さらに、はんれい岩類、ブナ峠火山岩類、石英閃緑岩及びトーナル岩岩体を伴う。東稲岩体とはんれい岩類はほぼ同時期の火成活動の産物であり、これらは高い K_2O 含有量で特徴づけられる。南部岩体と北部岩体を比較した場合、これらの間にわずかながら K_2O 含有量の差が認められるが、このような違いは同一の起源マグマから分別鉱物の量比の違いによって生じたとする説明が可能である。一方、ブナ峠火山岩類と石英閃緑岩及びトーナル岩岩体の K_2O 含有量は東稲岩体のそれよりもはるかに低く、また、活動時期も東稲岩体のそれとは異なる。ブナ峠火山岩類の活動は東稲岩体の活動よりも古く、反対に、石英閃緑岩とトーナル岩の活動は東稲岩体の活動よりも新しい。したがって、本地域の火成活動の特徴として、マグマの K_2O 含有量に時間的な変化があったことを指摘できる。

*Mt. Tabashine: 東稲山

Mt. Ohira: 大平山