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Tectono-metamorphic processes of the Ryoke belt in the Iwakuni-Yanai district, southwest Japan

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Abstract: The Ryoke belt in the Iwakuni-Yanai district is composed of low P／T type metamorphic rocks(Ryoke metamorphic rocks)and granitic rocks(Ryoke and Hiroshima granites). The Ryoke granites are divided into the older and younger granites. The older granites exhibit a sheet-like occurrence, whereas the younger granites occur as stocks. The Ryoke metamorphic rocks are divided into four metamorphic zones(the biotite, cordierite, garnet, and sillimanite zones)and these are as three nappes; the Tsuzu nappe of the biotite and cordierite zones, the Obatake nappe of the garnet zone, and the Yanai nappe of the sillimanite zone in descending order of structural level. The grade of metamorphism increases from the biotite zone, through the cordierite and sillimanite zones, to the garnet zone, indicating that the order of structural level does not agree with the order of metamorphic grade. There are the great gap(ca. 200℃-3kb)of metamorphic conditions between the cordierite zone and the garnet zone and inversion between the garnet zone and the sillimanite zone. The analyses of tectono-metamorphic processes clarify that the rocks of this district were metamorphosed through two phases(M0 and M1). In the cordierite zone there are two wide migmatite zones, the Tengatake and Nagano migmatites. The analysis of metamorphism of their restites indicates that the migmatites are composed of a mixture of granite and metamorphic rocks, which intruded along great fracture zones from the depth of ca. 6kb. The metamorphism(M0) of the earlier phase printed on the restites is nearly the medium P／T type. The peak metamorphism(M1)of the cordierite zone rocks occurred under ca. 3kb just after and／or during the intrusion of the migmatites and the Ryoke older granites, suggesting that the M1 metamorphism is a contact metamorphism by these intrusives. The formation of the nappes resulted in the ceasing of the M1 metamorphism. It was followed by intrusion of the Ryoke younger granites and the Hiroshima granites.

Key words: Ryoke belt, low P／T type metamorphism, tectono-metamorphic processes, sheet-like intrusion, migmatite, nappe structure

Introduction

The Ryoke metamorphic belt has been regarded as a typical one of low P／T type metamorphic belts associated with acidic magmatism, and forming a paired metamorphic belt with the Sambagawa metamorphic belt since Miyashiro(1961, 1972). It must be, therefore, very important for understanding the magma-arc processes in convergent margins to clarify

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the tectono-metamorphic processes of the Ryoke belt. Since Koide (1958), the granitic rocks of the Ryoke belt have been roughly divided into two types concerning their intrusion phase, older phase granites (Ryoke older granites) and younger phase granites (Ryoke younger granites), by many authors (e.g., Okamura, 1957, 1960; Nureki, 1960; Higashimoto *et al.*, 1983 in the Iwakuni-Yanai district). From geological data after Okamura (1957, 1960), Yoshizawa *et al.* (1965), Hara (1962), and Hara *et al.* (1980) pointed out that the older granites are of a sheet-like intrusion form and the younger granites are of a stock-like intrusion form. In the Ryoke belt and its northern outside (Kuga-Tamba-Mino Terrane) there is a developed series of sinistral *en echelon* upright folds (Hara *et al.*, 1980). Hara *et al.* (1980) have tried to classify the Ryoke granites concerning time-relationship between the upright folding and their intrusion. The granites of a sheet-like intrusion form predated the upright folding, while some granites of a stock-like intrusion form intruded during the folding and some others postdated the folding.

Sakakibara *et al.* (1989, 1990) and Ohtomo (1987, 1991) have clarified on the basis of microtextural analysis that the granites of a sheet-like intrusion form in the southern margin of the Ryoke belt are developed forming flat-lying ductile shear zones with a westward sense and that they were transported on the non-metamorphic and/or low-grade metamorphic rocks of the southern margin of the Ryoke belt. According to Sakakibara *et al.* (1989), the granites of a stock-like form intruded after the formation of the flat-lying shear zones.

The time-relationship between the metamorphism and deformation has been first analyzed by Seo and Hara (1980) and Seo *et al.* (1981) in the Ryoke belt of the Mikawa plateau, Central Japan. They have clarified that the biotite schists in the andalusite zone of the Ryoke belt in the Mikawa plateau suffered deformations in three phases and metamorphisms of two different types. One type of metamorphism was static, accompanying crystallization of andalusite, between the deformation of the first and second phase. The other type occurred with disappearance of staurolite during the third phase of deformation related to the formation of distinct schistosity. A similar relationship between metamorphism and deformation has been described by Ohtomo (1987, 1992) in the Ryoke belt of the Sakuma district, Central Japan. She suggested that the flat-lying ductile shear zones in the southern margin of the Ryoke belt formed just after the third phase of deformation. By these researches, the tectono-metamorphic processes of the Ryoke belt have been fairly well understood. In this paper there will be described and discussed the relationships among the metamorphism, deformation, and intrusion of granites in the Ryoke belt of the Iwakuni-Yanai district, Southwest Japan, for further understanding of the tectono-metamorphic processes in the Ryoke belt.

Outline of geology

The Ryoke belt in the Iwakuni-Yanai district consists mainly of metamorphic rocks, granites, and Tertiary volcanics (Fig. 1). The metamorphic rocks are mainly derived from pelites, psammites, and cherts with a subordinate amount of calcareous and basic rocks. These rocks developed on the north of Tsuzu, as a whole, form flat-lying geological structure, and they correspond to the southern extension of the Kuga Group (Kojima, 1953; Toyohara, 1974; Higashimoto *et al.*, 1983), which is the Jurassic accretionary complex (Toyohara, 1974; Hayasaka *et al.*, 1983; Takami *et al.*, 1990). The Kuga Group shows metamorphic grades of prehnite-pumpellyite facies and pumpellyite-actinolite facies (Toyohara, 1977; Hara *et al.*, 1979) with radiometric ages of 150-170 Ma (Takami *et al.*, 1990). The metamorphic grades related to the Ryoke regional metamorphism increase from the River Nishiki (nothern end of Fig. 1) toward the south, roughly speaking,

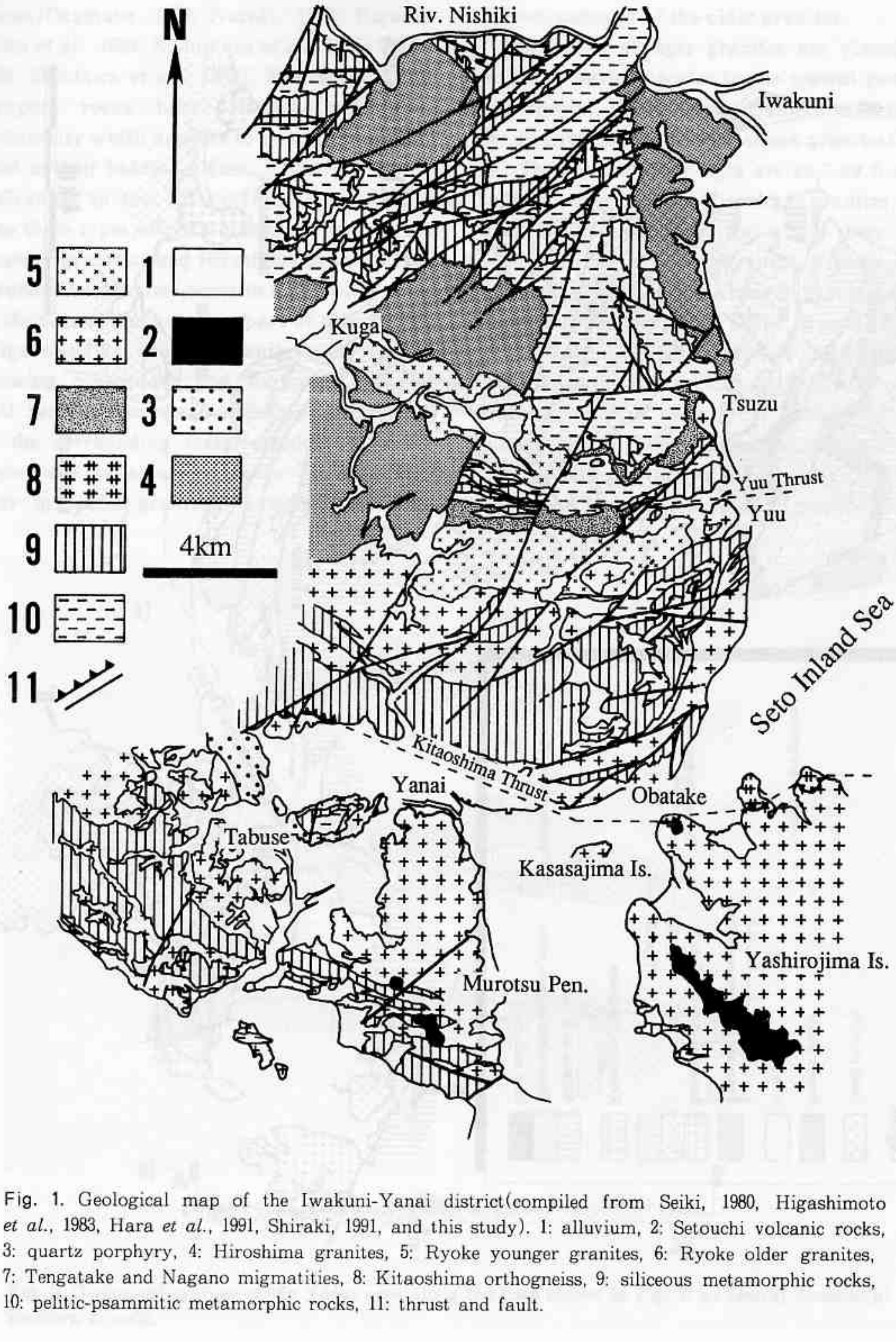

Fig. 1. Geological map of the Iwakuni-Yanai district(compiled from Seiki, 1980, Higashimoto *et al.*, 1983, Hara *et al.*, 1991, Shiraki, 1991, and this study). 1: alluvium, 2: Setouchi volcanic rocks, 3: quartz porphyry, 4: Hiroshima granites, 5: Ryoke younger granites, 6: Ryoke older granites, 7: Tengatake and Nagano migmatities, 8: Kitaoshima orthogneiss, 9: siliceous metamorphic rocks, 10: pelitic-psammitic metamorphic rocks, 11: thrust and fault.

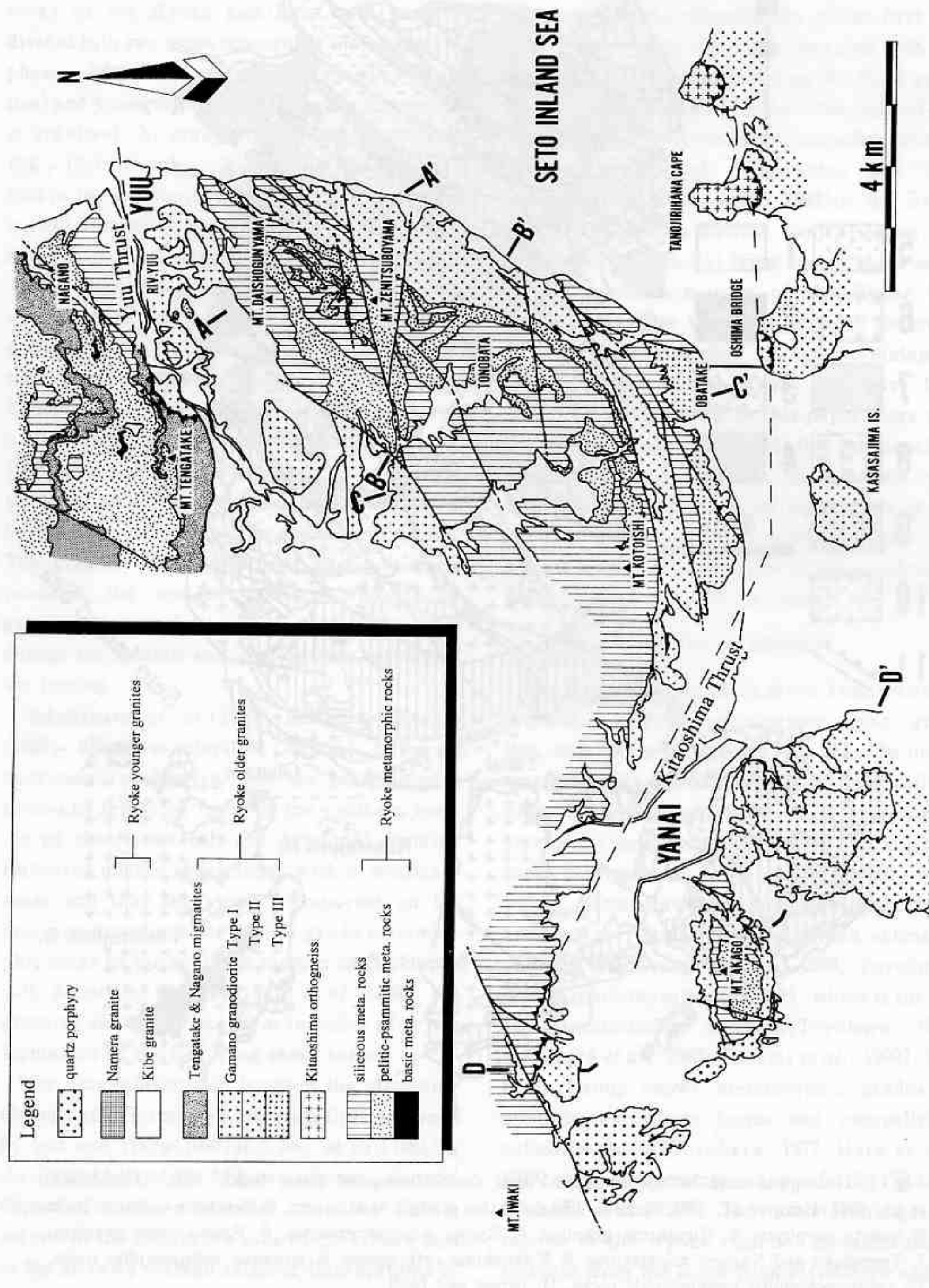

Fig. 2. Geological map of the Yanai area.

changing from the andalusite to the sillimanite facies (Okamura, 1960; Nureki, 1960; Higashimoto *et al.*, 1983; Nishimura *et al.*, 1985; Ikeda, 1991; Okudaira *et al.*, 1992). The Ryoke metamorphic rocks have distinct schistosity-gneissosity which appears to be commonly parallel to their bedding planes.

Granites in this district (Fig. 1) are divided into three types, Ryoke older granites, Ryoke younger granites, and Hiroshima granites. The Ryoke older granites occur in a sheet-like form in the central and southern part of this district (Figs. 1 and 2). The older ganites are gneissose showing concordant and harmonic relation with bedding planes and schistosity-gneissosity of the surrounding metamorphic rocks. The high-grade metamorphic rocks are restricted near the older granites. However, the high grade metamorphic rocks have no evidence of contact aureoles of the older granites.

The Ryoke younger granites are placed as stocks of various scales in the central part of this district, which is the southern margin of the distribution of the Hiroshima granites (Fig. 1). Their radiometric ages are 86.3-89.5 Ma, being younger than the Hiroshima granites, but with some exceptions, in which they are intruded by the Hiroshima granites (Higashimoto *et al.*, 1983). The Ryoke younger granites have gneissosity by preferred shape orientation of constituent minerals, parallel to the boundary to the metamorphic rocks and the Ryoke older granites. Such a orientation pattern of the gneissosity is different from that in the Ryoke older granites, which is independent from the boundary. The characteristics of major element

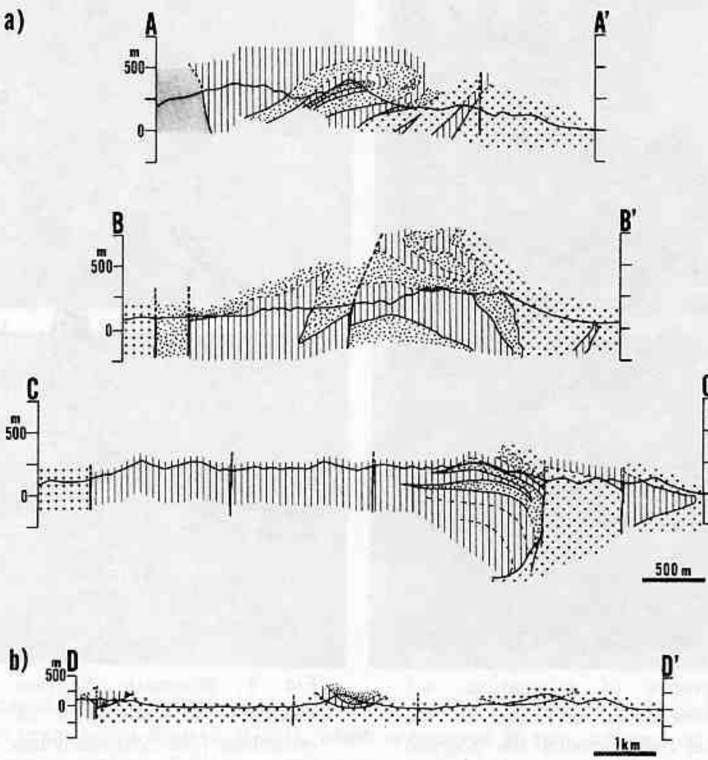

Fig. 3. Geological profiles of the Yanai area along the lines shown in Fig. 2. a) central domain. b) southern domain.

chemistry (Honma, 1974) and oxygen isotope (Honma & Sakai, 1975) of both Ryoke older and younger granites suggest their magmatic origin. The Hiroshima granites are, as a whole, massive and discordant to their surrounding metamorphic rocks, and give the contact effect to the latter. The Hiroshima granites have radiometric ages of 86-103 Ma (Higashimoto *et al.*, 1983).

The Ryoke belt in this district is divided into three domains by two shear zones (Yuu thrust and Kitaoshima thrust), northern domain, central domain, and southern domain (Figs. 1 and 2). The shear zones predate the Ryoke younger granites.

The metamorphic rocks in the southern part (Tsuzu-Yuu area) of the northern domain show gentle northward dipping of bedding planes, accompanying two large-scale zones of migmatite (Nagano migmatite and Tengatake migmatite) which run slightly oblique to the bedding planes (Fig. 2).

The metamorphic rocks in this district are characterized by single distinct schistosity-gneissosity. They are commonly folded in intrafolial fashion, frequently accompanying

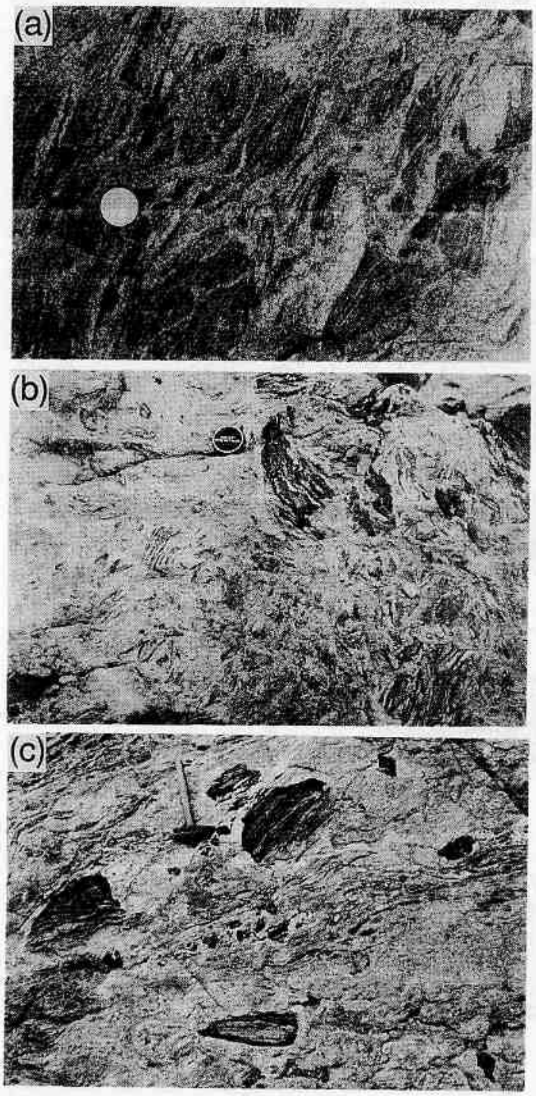

Fig. 4. Photographs of migmatites. a) granitizated fracture zones developed in the pelitic metamorphic rocks around the Nagano migmatite. b) agmatitic structure of the Tengatake migmatite. c) relict and surrounding metamorphic blocks in the Tengatake migmatite.

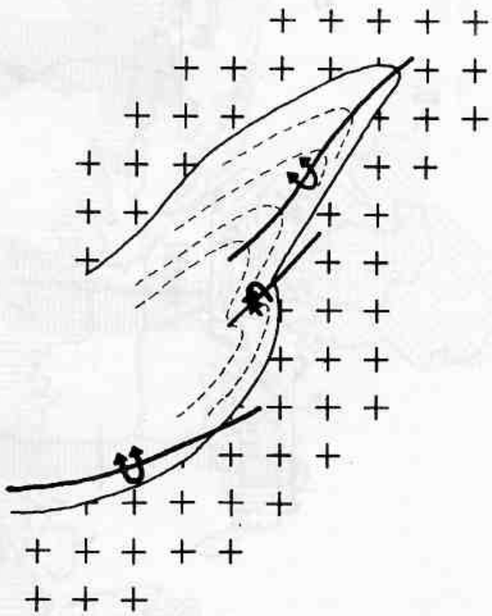

Fig. 5. Schematic diagram illustrating the structural characteristics of the large-scale recumbent fold (Zenitsuboyama recumbent fold) in the central domain in which the sheets of the older granites, together with the metamorphic rocks, are involved.

granitizated fracture zones with width of centimeter order(Fig. 4-a). These granitizated fracture zones are especially developed around the Nagano and Tengatake migmatites and older granites. These migmatite zones and the older granites appear to have been formed along large-scale fracture zones. However, the granitization degree and metamorphic conditions appear to show discontinuous change between the migmatite zones and their surroundings (Fig. 4-b). Fig. 4-c illustrates random orientation of metamorphic blocks in the migmatite zones.

The geological structure of the central domain is illustrated in Fig. 2. The older granites, together with metamorphic rocks, are characterized by NNE-NE plunging recumbent fold with SE-ward vergence, and the Kitaoshima thrust is located in the basal part of the fold. The recumbent fold is here called the Zenitsuboyama recumbent fold. The older granites are divided into three rock types, Gamano granodiorite Type Ⅰ, Ⅱ, and Ⅲ(Fig. 2). The former two have essentially the same petrological property, both showing lithofacies variation between hornblend biotite tonalite and hornblend-bearing biotite tonalite-granodiorite. They are assumed to be two parts of a single body, which are placed in the northern limb and the southern limb of the recumbent fold as shown in Fig. 5. The Gamano granodiorite Type Ⅲ is muscovite-bearing biotite tonalite-granodiorite containing a number of various scale lenses of metamorphic rocks, which are strongly granitizated. There are granite dykes which postdate the Zenitsubo-

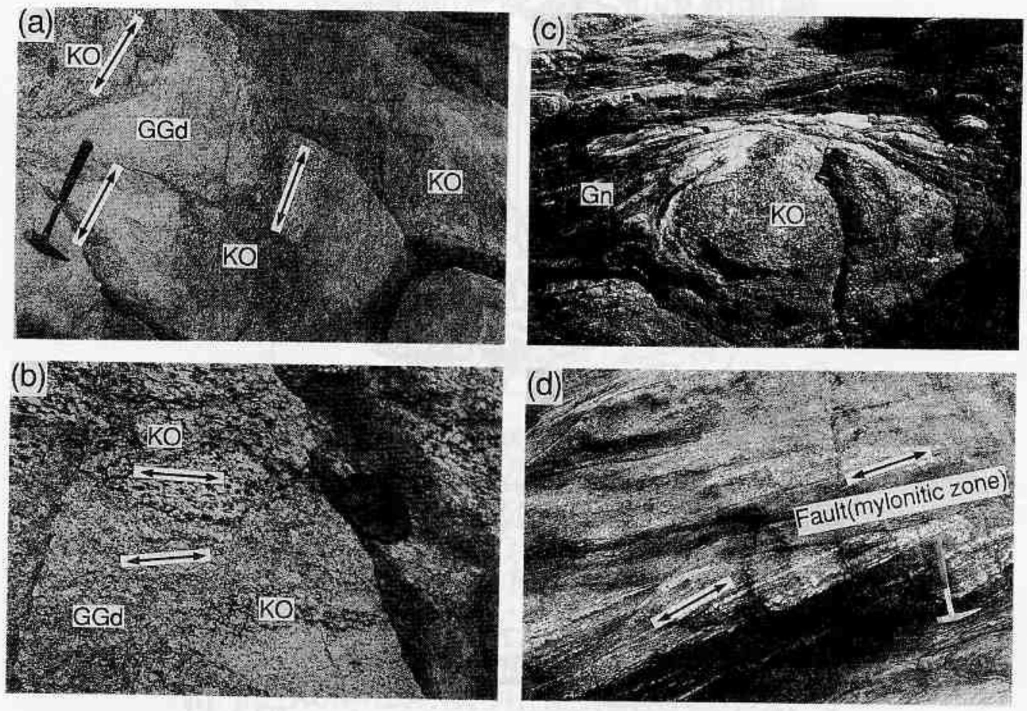

Fig. 6. Photographs of the Kitaoshima orthogneiss. a) and b) Kitaoshima orthogneiss(KO)intruded by the Gamano granodiorite Type Ⅱ (GGd), which is observed at two outcrops in the Kuroshima Island(arrows are orientation of the gneissosity). c) a tectonic block of the Kitaoshima orthogneiss (KO) in its adjacent metamorphic rocks(Gn)in the Tanojirihana Cape. d) mylonitic zone cutting across the gneissosity(arrows)of the Kitaoshima orthogneiss in the Tanojirihana Cape.

yama recumbent fold, being intruded by the Ryoke younger granites. The dykes are muscovite-bearing biotite granites with or without garnet and weakly gneissose.

In the southernmoust margin of the central domain there is a granite body with distinct gneissosity (Fig. 2), which has been called the Kitaoshima granite gneiss complex (Kitaoshima orthogneiss) by Kojima and Okamura (1968). The Kitaoshima orthogneiss is intruded by the Gamano granodiorite Type II (Fig. 6-a and-b), and is found as tectonic blocks of small scales in its adjacent gneisses (Fig. 6-c). Hara *et al.* (1991) assumed that the Kitaoshima orthogneiss was tectonically emplaced into the metamorphic rocks. In the Kitaoshima orthogniess

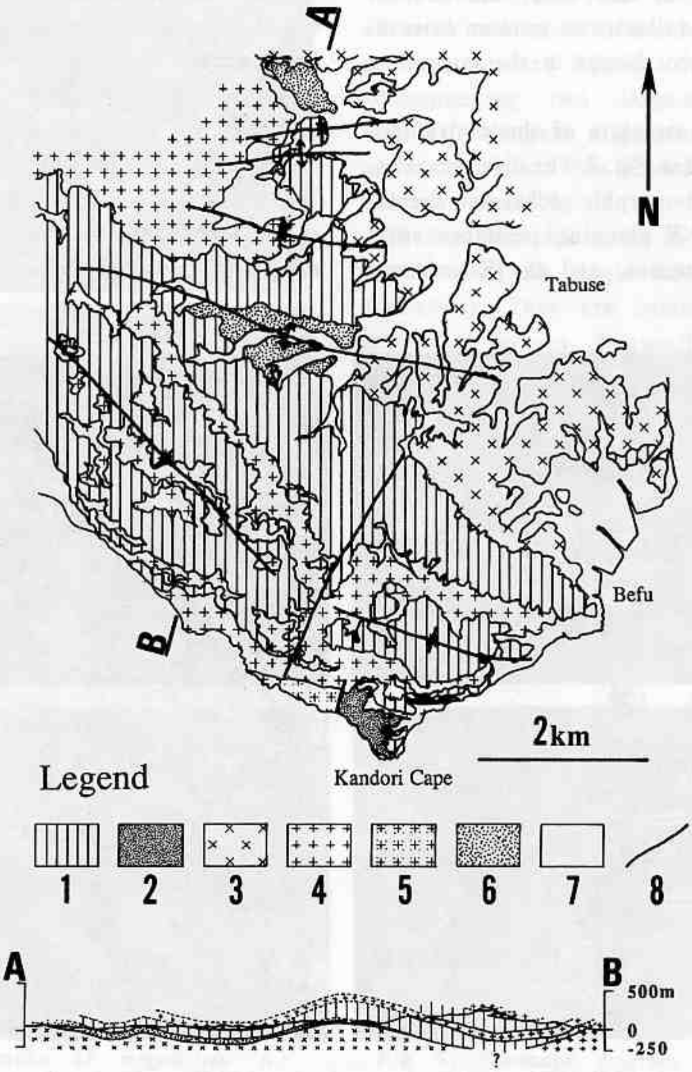

Fig. 7. Geological map and profiles of the Tabuse area (partly modified from Seiki, 1980). 1: siliceous metamorphic rocks, 2: Gokenya quartzdiorite, 3: Gamano granodiorite Type I, 4: Gamano granodiorite Type II, 5: Gamano granodiorite Type III, 6: Tabuse quartzdiorite, 7: alluvium, 8: fault.

mylonitic zones are found (Fig. 6-d). They are the simultaneous generation with the Kitaoshima thrust cutting across its gneissosity

The southern domain placed in the lowest structural level consists mainly of the older granites associated with a subordinate amount of metamorphic rocks (Figs. 1 and 2). The Gamano granodiorite Type I and II (Figs. 2 and 3) are developed as flat-lying sheets separated by sheets of metamorphic rocks (Fig. 7). The flat-lying sheets are gently folded in upright fashion of WNW-ESE to E-W trend.

The northern, central, and southern domains are nappes separated by the Yuu thrust and the Kitaoshima thrust, respectively, which are the Tsuzu nappe, Obatake nappe, and Yanai nappe in descending order of structural level (Okudarira *et al.*, 1992).

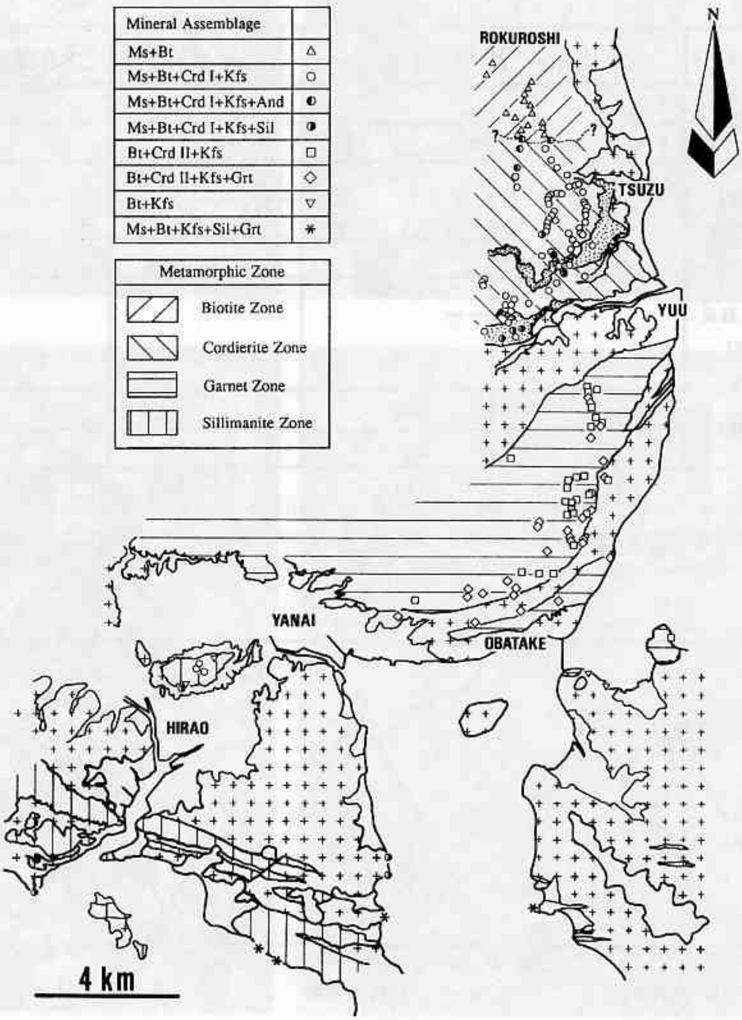

Fig. 8. Diagram illustrating the mineral zonation and distribution of critical mineral assemblages in pelitic-psammitic metamorphic rocks of the Rokuroshi-Hirao Town area. crosses: granitic rocks, stippled part: migmatites.

Metamorphism

1. Regional metamorphic zonation

The Ryoke metamorphic rocks in the central-southern part of the northern domain, central domain, and southern domain (Rokuroshi-Hirao Town area in Fig. 8), which appear to have scarcely been modified by contact metamorphism of the Ryoke younger and Hiroshima granites (Nureki, 1960, 1974; Higashimoto *et al.*, 1983; Nishimura *et al.*, 1985), show mineralogical zonation described in terms of biotite zone, cordierite zone, garnet zone, and sillimanite zone with reference to mineral assemblages of pelitic-psammitic rocks, which are crystallized during the highest-temperature phase (Okudaira *et al.*, 1992). Stability range of constituent matrix minerals of pelitic-psammitic rocks is shown in Fig. 9 [mineral abbreviations used in this paper are those of Kretz (1983)]. The critical mineral assemblage of each zone is illustrated in Fig. 8. The central

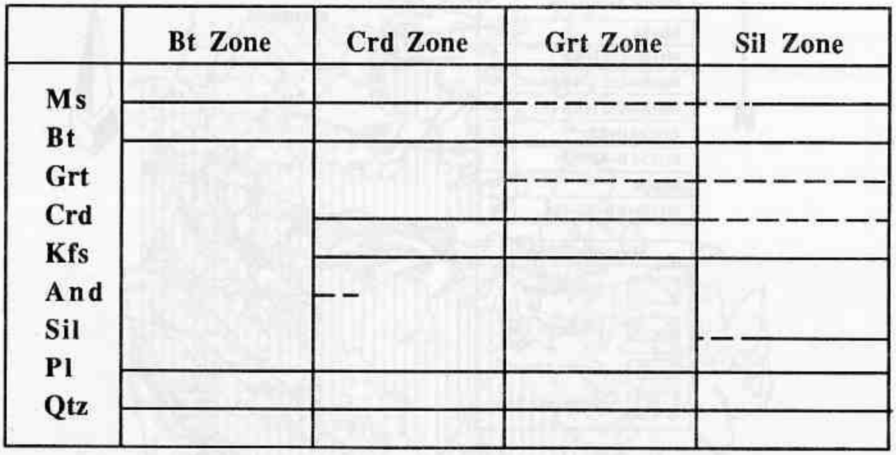

Fig. 9. Stability range of Se-forming minerals in pelitic-psammitic metamorphic rocks of four mineral zones. Accessory minerals, such as graphite, ilmenite, apatite, zircon, and tourmaline occur in the most of pelitic-psammitic metamorphic rocks.

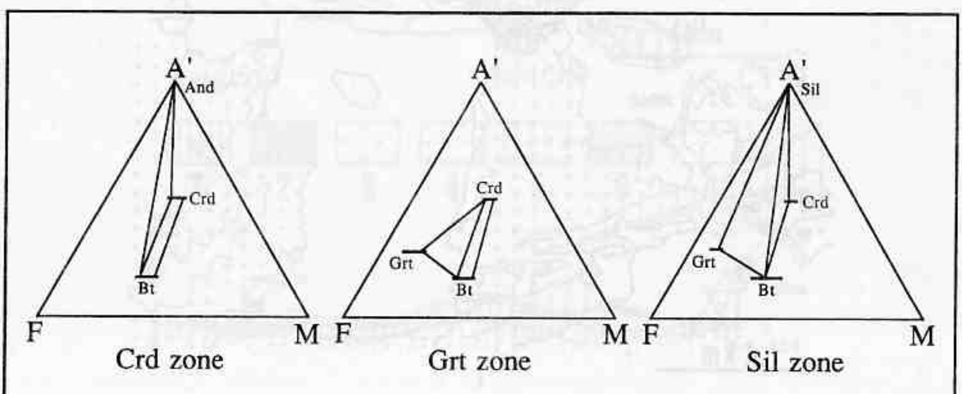

Fig. 10. A'FM diagrams projected from potash-feldspar in the Thompson's AKFM system for the cordierite, garnet, and sillimanite zones.

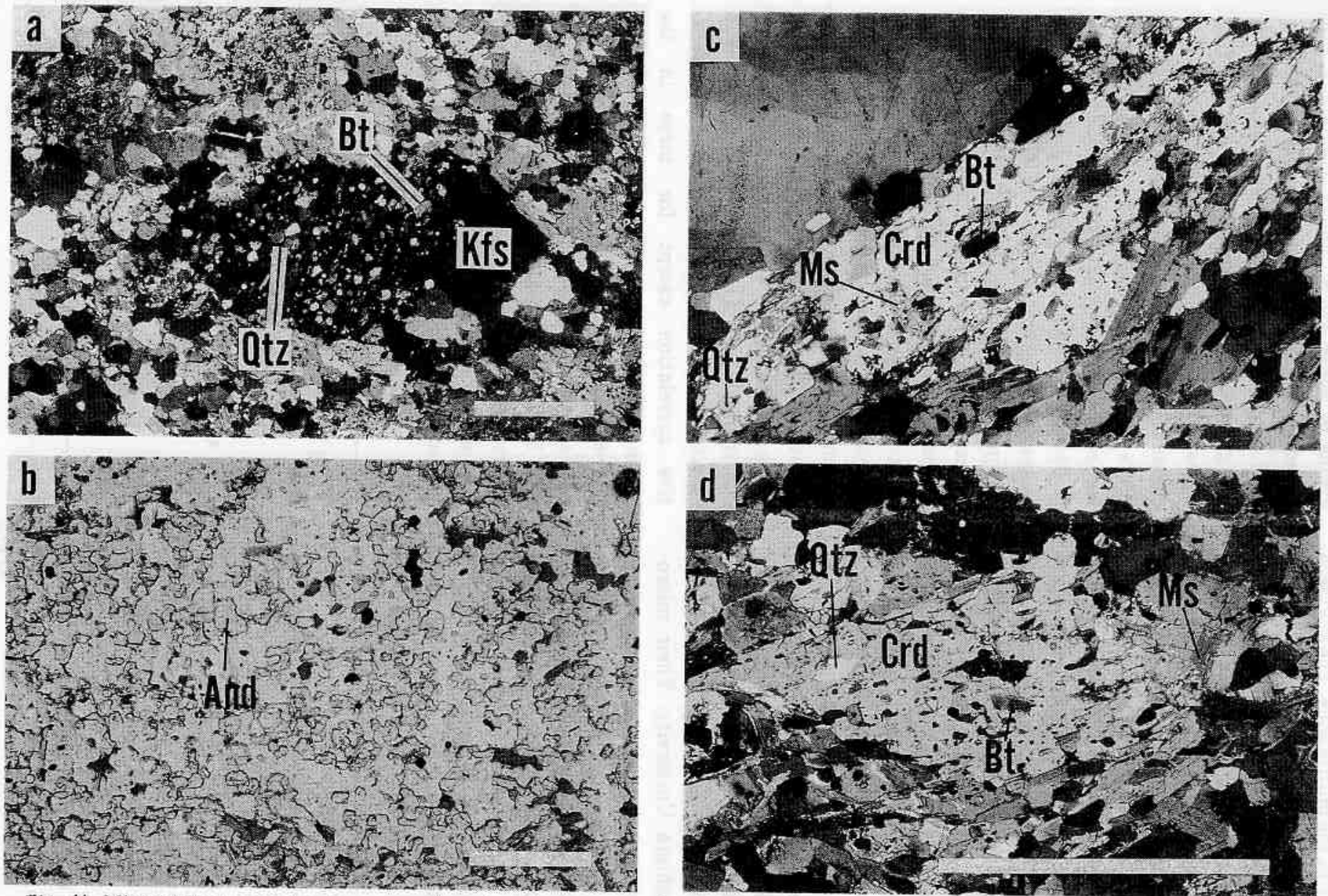

Fig. 11. Microphotographs showing some characteristic textures of pelitic-psammitic metamorphic rocks of the cordierite zone. a) potash-feldspar porphyroblast(Kfs)containing other kinds minerals such as quartz (Qtz) and biotite(Bt)as inclusions, which form Si-schistosity. Si is oblique at high angles to and discontinuous with Se-schistosity. Crossed polars. b) andalusite(And)showing a sieve structure. Plane-polarized light. c) cordierite porphyroblast(cordierite I, Crd)containing other kinds minerals such as biotite, quartz, and muscovite (Ms) as inclusions, which form Si. Si is nearly parallel to Se. Crossed polars. d) cordierite porphyroblast(cordierite I)with Si-forming minerals. Se is deflected around the porphyroblast, being oblique to and discontinuous with Si.

Scale bar : 0.5mm

part (Rokuroshi-Hiuchiiwa area) of the northern domain belongs to the biotite zone. The southern part (Hiuchiiwa-Yuu area) of the northern domain belongs to the cordierite zone except for the Tengatake and Nagano migmatities and their just contact aureoles, the central domain to the garnet zone, and the southern domain to the sillimanite zone. The biotite zone is considered to be the lowest metamorphic grade among these four zones. The changes of mineral bargainers in the cordierite, garnet, and sillimanite zones are described as shown in Fig. 10, using A'FM diagrams projected from potash-feldspar in Thompson's (1957) AKFM system.

2. Microtexture and chemistry of index minerals

Chemical compositions of representative metamorphic index minerals such as biotitie, cordierite, and garnet were measured by using an electron probe microanalyzer (JEOL, JCMA-733 II) of Hiroshima University. Their microtexture and chemistry are summarized as below.

Biotite Biotite occurs as one (Se-biotite) of schistosity-gneissosity forming minerals in all mineral zones and as one (Si-biotite) of inclusion minerals in potash-feldspar and cordierite in the cordierite, garnet, and sillimanite zones. Si-biotite, together with inclusion mineral grains of other kinds, shows commonly preferred shape orientation forming Si-schistosity (Fig. 11-a, -c and -d). Si-biotite is generally fine-grained than Se-biotite. Si-schistosity in potash-feldspar is commonly oblique and discontinuous with Se-schistosity (Fig. 11-a), while Si-schistosity in cordierite appeares to be frequently parallel, though sometimes oblique to Se-schistosity (Fig. 11-c and -d). Such a difference in Si-Se relation between potash-feldspar and cordierite would mean a difference in response to the deformation after their crystallization, owing to that in their shape. Potash-feldspar grains are commonly granular in shape, while cordierite grains appear to have commonly shapes fairly elongated along the schistosity-gneissosity.

Fig. 12 illustrates the relationship between Ti content and XFe [Fe/(Fe+Mg)] for Si- and Se-biotite in all mineral zones, showing positive correlation except for these in the sillimanite zone. According to Guidotti (1984), Ti content, as well as XFe, increases with rise of metamorphic grade. Ti content of both Si- and Se-biotite appear to increase from the biotite zone, through the sillimanite and cordierite zones, to the garnet zone, showing a harmonic relation with metamorphic grade.

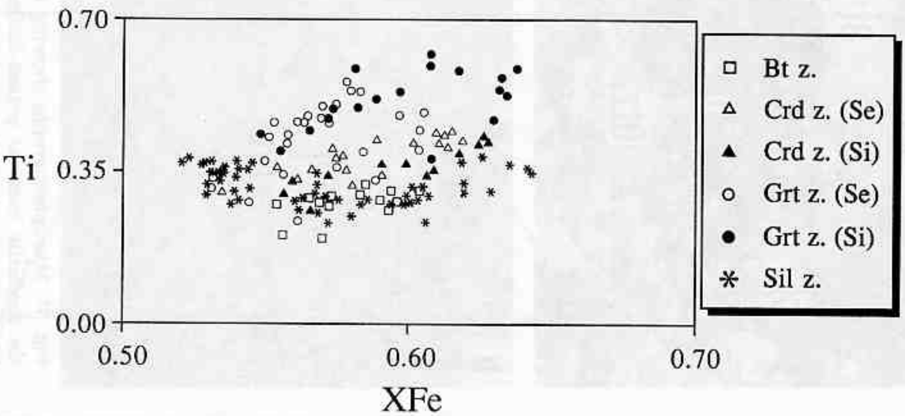

Fig. 12. Ti versus XFe(=Fe/(Fe+Mg)) for biotite in pelitic-psammitic metamorphic rocks from four zones. Numbers of ions on the basis of 22 oxygens.

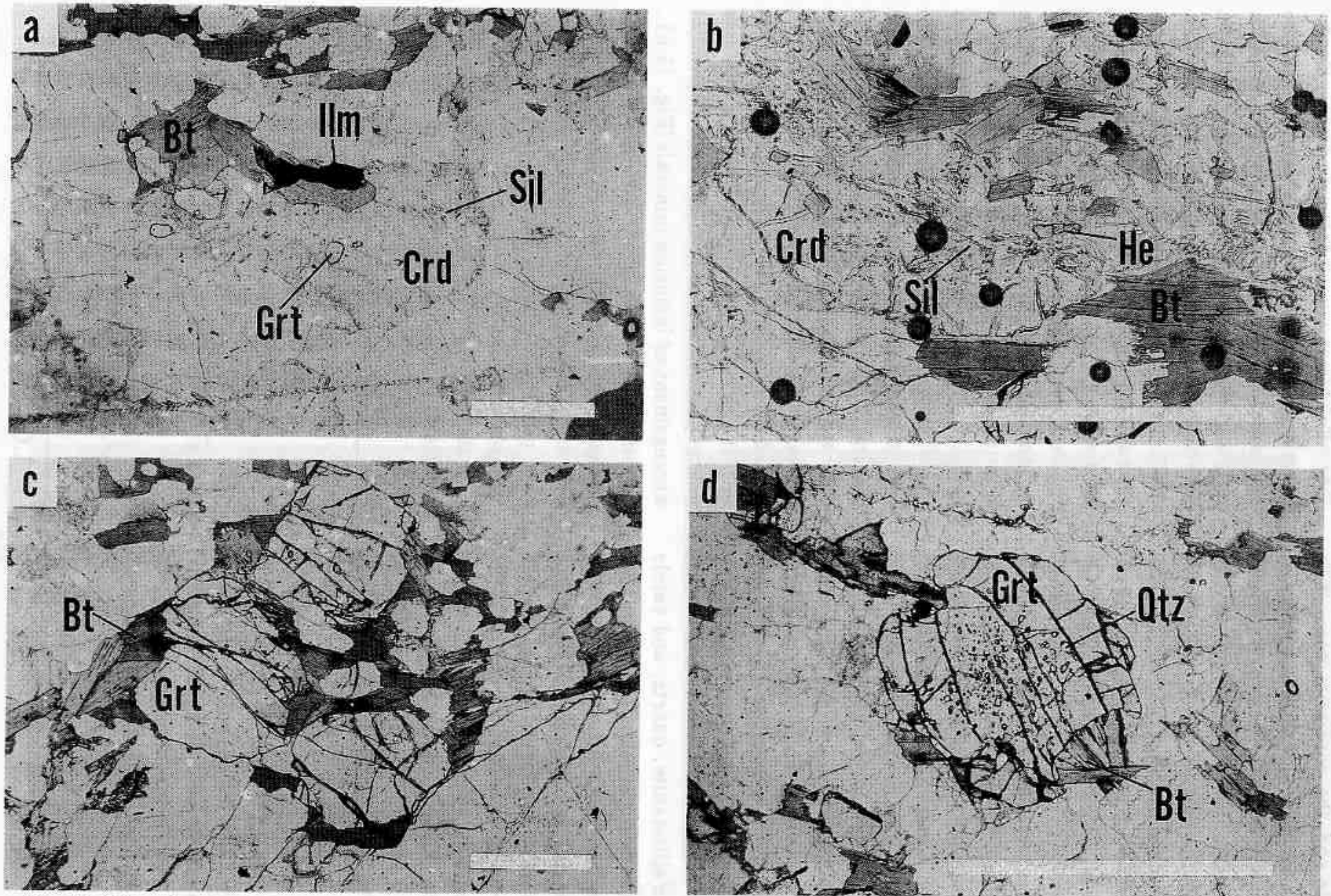

Fig. 13. Microphotographs showing some characteristic textures of pelitic-psammitic metamorphic rocks of the garnet zone. a) cordierite porphyroblast(cordierite II)containing sillimanite and garnet as inclusions. Plane-polarized light. b) cordierite porphyroblast(cordierite II)containing biotite, sillimanite, and Zn-rich hercynite(He). Plane-polarized light. c) inclusion-free garnet. Plane-polarized light. d) garnet with inclusion quartz. Se-forming biotite flakes are embayed in pressure shadows of garnet. Plane-polarized light.

Scale bar : 0.5mm

However, there is a reverse relation between the sillimanite zone and the cordierite zone. XFe varies within a small range between 0.52 and 0.65 for all mineral zones. As compared with each other in a fixed XFe value, Ti content in the cordierite zone is clearly larger in Se-biotite than in Si-biotite, probably showing that the former crystallized under the higher temperature. However, in the garnet zone, Ti content is not different between Si- and Se-biotite in XFe, in values of less than 0.58. Biotite with XFe larger than 0.61 is found only as Si-biotite.

Cordierite Cordierite occurs in pelitic-psammitic rocks of the cordierite, garnet, and sillimanite zones, though rarely in the sillimanite zone, as matrix grains and porphyroblasts containing inclusion of other minerals (Figs. 11-c,-d and 13-a,-d). Porphy-roblastic cordierite is divided into two types, cordierite I and II. Cordierite I includes biotite, muscovite, and quartz, and cordierite II includes biotite, fibrous sillimanite, quartz, and rarely Zn-rich hercynite and garnet. Cordienite I is found in the cordierite and sillimanite zones. Its texture and mineral assemblage of these zones suggest that it was a product of paragenetic reaction of Ms+Bt+Otz = Crd+Kfs+H_2O (cf., Masonne & Schreyer, 1987). Cordierite in the cordierite zone shows weak compositional zonation by the variation of mg value [Mg/(Mg+Fe)] from core(0.57) to rim(0.55). Cordierite II is found in the garnet zone. Its texture and mineral assemblage suggest that it was a product of prograde reactions of Bt+Sil+Otz =Crd+Kfs+Grt+H_2O and Bt+Sil+Otz= Crd +Kfs+H_2O(Holdaway & Lee, 1977). Fig. 14 illustrates mg values for cordierite in the cordierite, garnet, and sillmanite zones, showing that the values increase with increasing of metamorphic grade. However, there is a reverse relation between the sillimanite and cordierite zones. This circumstance having an exception in the sillimanite zone corresponds with the relationship between Ti content of biotite and the metamorphic grade.

Garnet Garnet occurs as porphyroblasts with inclusion minerals of other kinds(Figs. 13-c, -d and 15-b)and as matrix grains(Fig. 15-a)in the garnet and sillimanite zones. Si-fabric in some garnet porphyroblasts is characterized by radial arrangement of inclusion minerals (Fig. 15-b), like the case of Seo and Hara (1981). Garnet shows commonly equiaxial subhedral shapes but sometimes ellipsoidal shapes with longest axes parallel to the gneissosity, and its rims are commonly partly dissolved.

In the garnet zone garnet has homogeneous in chemistry, except for a narrow rim. Such the

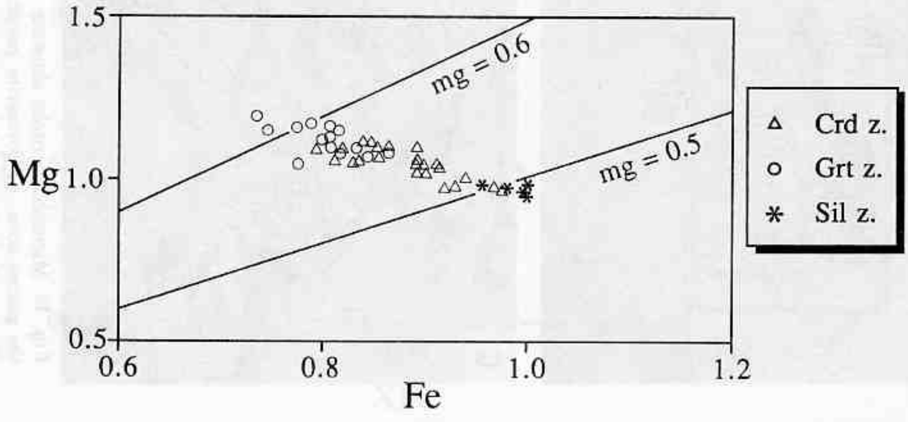

Fig. 14. Fe versus Mg for cordierite pelitic-psammitic metamorphic rocks from the cordierite, garnet, and sillimanite zones. Numbers of ions on the basis of 18 oxygens.

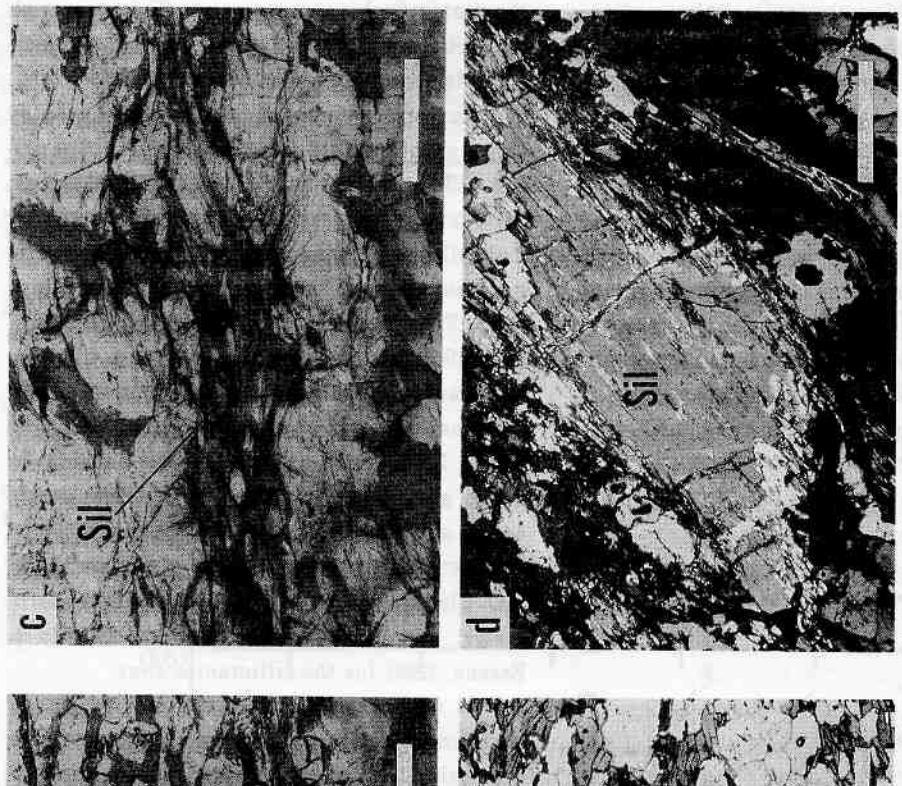

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Fig. 15. Microphotographs showing some characteristic textures of pelitic-psammitic metamorphic rocks of the sillimanite zone. a) fibrous sillimanite lamellae(Sil)and garnet. Plane-polarized light. b) garnet porphyroblast with inclusion minerals showing radial arrangement. Plane-polarized light. c) sillimanite and fibrolite. The former shows boudin. Plane-polarized light. d) sillimanite porphyroblast showing boudin whose separations are filled by quartz. Crossed polars.

homogeneous in chemistry of garnet would be interpreted as a result of post-growth volume diffusion obliterating any pre-existing compositional zoning that was probably printed during the prograde metamorphism. Namely, the diffusion is considered to have occurred during the cooling stage immediately after the peak metamorphism (cf., Tracy, 1982; Spear, 1991). In the sillimanite zone, however, some garnet shows complex zoning. The core shows a normal zoning and the rim is typical reverse zoning (Fig. 16). Such the compositional zoning must indicate that the core grew during the prograde metamorphism, while the rim was produced during the retrograde metamorphism. Preservation of the normal zoning in garnet core would mean that the temperature and period of the metamorphism were not sufficient enough to obliterate pre-existing compositional zoning.

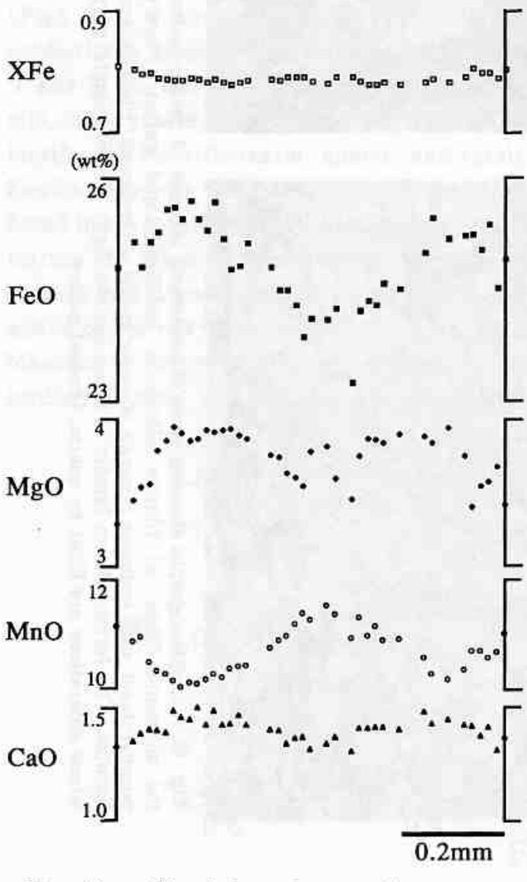


Fig. 16. Chemical zoning profiles across equatorial section of garnet from the sillimanite zone.

3. Metamorphic P-T conditions

Metamorphic temperature was estimated by using garnet-biotite geothermometers (Thompson, 1976; Holdaway & Lee, 1977; Perchuk, 1977; Indares & Martignole, 1985) for the garnet and sillimanite zones, by garnet-cordierite geothemometers (Thompson, 1976; Holdaway & Lee, 1977; Perchuk, 1977; Perchuk & Lavrent'eva, 1983) for the garnet zone, and by two-feldspar geothermometer (Haselton *et al.*, 1983) for the cordierite, garnet, and sillimanite zones. Metamorphic pressure was deduced by using garnet-cordierite geobarometers (Hutcheon *et al.*, 1974; Aranovich & podlesskii, 1983) for the garnet zone and garnet-aluminosilicate-SiO_2-plagioclase geobarometers (GASP geobarometer: Powell & Holland, 1988; Edwards & Essene, 1988) for the sillimanite zone.

It is one of very difficult works to clarify paragenetic relations between metamorphic minerals. The peak and retrograde metamorphism are difficult to distinguish each other. Ikeda (1991) has assumed that biotite with heterogeneous composition concerning Ti content was synchronously associated with reverse zoned garnet. He pointed out that Ti-poor biotite is produced by Fe-Mg partitioning between biotite and garnet, and concluded that the Ti-poor biotitie grew with the consumption of the garnet during the retrograde metamorphism. Thus, the temperature and pressure conditions for the peak metamorphism may be estimated by using chemical composition of the core of garnet and biotite, which are not in contact at present. The conditions for the retrograde metamorphism were estimated by using chemical composition of the rim of garnet and their associated biotite. On the other hand, cordierite, plagioclase and potash-feldspar are roughly homogenous and Ca content in garnet is also homogeneous. These may have preserved

Table 1. Temperature estimates (℃) from the various calibrations of the Grt-Bt, Grt-Grd, and two-feldspars geothermometers. Calibration abbreviations: T-Thompson (1976), H & L-Holdaway & Lee (1977), P-Perchuk (1977), I & M-Indares & Martignole (1985), P & L-Perchuk & Lavrent'eva (1983), H-Haselton *et al.* (1983).

	Grt - Bt				Grt - Crd				Two - Feldspar
	T	H&L	P	I&M	T	H&L	P	P&L	H
Cordierite zone									
F-8	—	—	—	—	—	—	—	—	501
F-11	—	—	—	—	—	—	—	—	590
Garnet zone									
900424-1	790	777	744	770	782	770	723	693	—
900510-4	752	745	718	731	827	808	755	726	784
Sillimanite zone									
911113-4	631	639	630	622	—	—	—	—	—
911005-4	717	701	700	682	—	—	—	—	—
911113-12	—	—	—	—	—	—	—	—	557
Corundum rock									
F-13 (peak)	699	698	680	696	—	—	—	—	676
F-13 (retrograde)	533	551	555	563	581	592	573	506	569

Table 2. Pressure estimates (kbar) from the various calibrations of the Grt-Crd and GASP geobarometers. Calibration abbreviations: H-Hutcheon *et al.* (1974), A & P-Aranovich & Podlesskii (1983), P & H-Powell & Holland (1988), E & E-Edwards & Essene (1988). F-13 (Corundum rock) indicates retrograde metamorphic pressure.

	Grt - Crd		GASP	
	H	A&P	P&H	E&E
Garnet zone				
900424-1	4.8	6.1	—	—
900510-4	5.2	6.4	—	—
Sillimanite zone				
911113-4	—	—	3.4	4.6
Corundum rock				
F-13	2.6	3.5	—	—

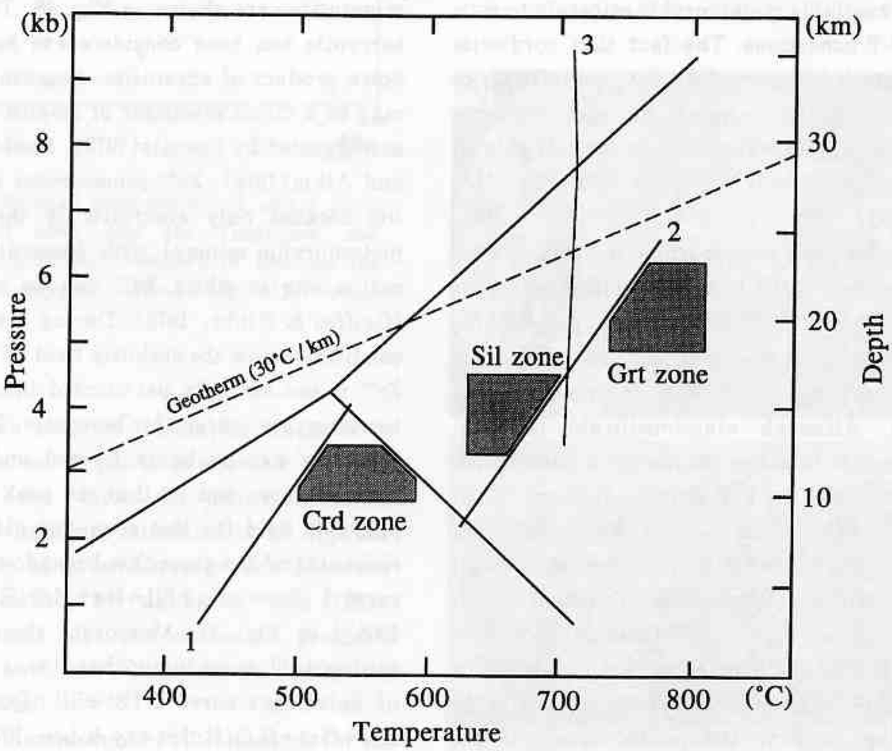


Fig. 17. P-T fields of the cordierite, garnet, and sillimanite zones. Reaction curves for aluminosilicate polymorphs (Salje, 1986). 1) Ms+Bt+Qtz=Crd+Kfs+H_2O (Masonne & Schreyer, 1987). 2) Bt+Sil+Qtz=Crd+Kfs+Grt+H_2O (Holdaway & Lee, 1977). 3) St=Grt+Sil+He+H_2O (Richardson, 1968).

their composition in the peak metamorphism during the retrograde metamorphism (cf., Jones & Brown, 1990). Therefore, the peak metamorphic conditions may be estimated by using garnet(core)-biotite(not in contact with garnet), garnet(core)-cordierite, two-feldspar, and GASP geothermobarometers. Whereas, the retrograde metamorphic conditions can be estimated by using garnet(rim)-biotite(in contact with garnet grain)geothermobarometers. The results of estimated metamorphic temperature and pressure are summarized in Tables 1 and 2, respectively. Estimated P-T field of each zone would be now assumed by correlation of observed change of the mineral assemblages with the experimentally determined curves of metamorphic reactions.

P-T field of each zone, except for the biotite zone, is illustrated in Fig. 17. P-T field of the biotite zone can not be determined because of lack of available metamorphic minerals to estimate P-T conditions. The fact that cordierite and potash-feldspar did not crystallize in pelitic-psammitic rocks of this zone indicates that its P-T field was placed in the left side of the reaction curve 1(Ms+Bt = Crd+Kfs+H_2O in Fig. 17).

While the peak metamorphic temperature for the cordierite zone has been estimated to be approximately 500-590℃ (Table 1), pressure for this zone has not been clarified, because of lack of index-mineral assemblage for pressure estimation. Although aluminosilicate is rare, andalusite is found in the northern part of this zone, and thus the P-T field was placed in the stability field of andalusite (Fig. 17). The occurrence of cordierite and potash-feldspar crystallized in pelitic-psammitic rocks of this zone indicates that its P-T field was placed in the right side of the reaction curve 1 (Ms+Bt = Crd+Kfs+H_2O in Fig. 17). As mentioned in the following section, the pelitic rocks of the Tengatake and Nagano migmatities had possibly experienced re-equilibrium under the peak metamorphic P-T conditions of the cordierite zone. The re-equilibrium P-T conditions of the pelitic rocks in the Tengatake migmatite is approximately 510-590℃ and 2.6-3.5kb (Tables 1 and 2).

The peak metamorphic temperature for the garnet zone was estimated to be 720-790℃ for the garnet-biotite pairs, and 690-830℃ for the garnet-cordierite paris (Table 1). However, Thompson's garnet-cordierite pair gives clearly higher temperature than the other methods, and Perchuk & Lavrent'eva's method gives lower value than the others. The peak metamorphic conditions given by other methods than Thompson's and Perchuk & Lavrent'eva's methods are approximately 720-810℃ and 4.8-6.4kb (Tables 1 and 2). The cordierite II often contains Zn-rich hercynite together with biotite, sillimanite, and quartz (Fig. 13-b). Chemical compositions of the Zn-rich hercynite in this zone and these in the Tengatake and Nagano migmatites are shown in Fig. 18. The Zn-rich hercynite has been considered to be a breakdown product of staurolite, because staurolite may be a direct precursor of Zn-rich hercynite, as suggested by Loomis (1972), Stoddard (1979) and Atkin (1978). Zn^{2+} concentrates on staurolite because only staurolite is the common metamorphic mineral with 4-coordinated Fe^{2+} cation site in which Zn^{2+} can be substituted (Griffen & Ribbe, 1973). During metamorphic condition below the stability field of staurolite, Zn^{2+} is not strongly partitioned into any particular phase, except for hercynite. The Zn-rich hercynite was probably formed under such a circumstance, and so that the peak metamorphic P-T field for this zone was placed in the right side of the staurolite-breakdown reaction curve 3 [St = Als+Sil+He+H_2O(Richardson, 1968)] in Fig. 17. Moreover, the texture of cordierite II must imply that it was of product of univariant curve 2 [Bt+Sil+Qtz = Crd+Kfs+Grt+H_2O(Holdaway & Lee, 1977)] in Fig. 17 and its P-T field was placed in the right side of this curve. Such a P-T field may cause partial melting *in situ* if P_{H_2O} was as high as P_{total}.

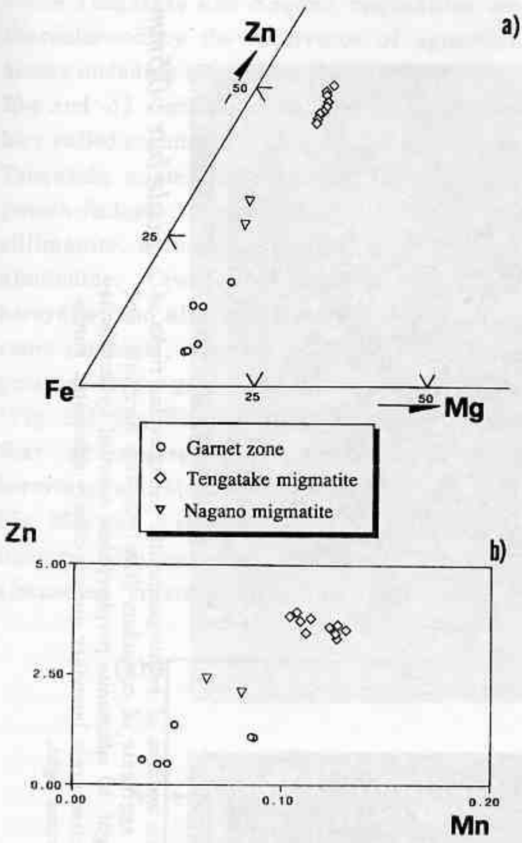


Fig. 18. Chemical composition of spinel from the garnet zone, and the Tengatake and Nagano migmatites. Numbers of ions on the basis of 32 oxygens. a) Zn-Fe-Mg. b) Zn versus Mn.

However, no evidence indicating anatexis *in situ* is observed in pelitic-psammitic rocks of this zone. X_{H_2O} values for pelitic-psammitic rocks in this zone are estimated to be approximately 0.2 by using cordierite-garnet-H_2O water fugacity indicator (Martignole & Sisi, 1981). Thus, anatexis was not evidenced probably because of such low X_{H_2O} values during the metamorphism.

The peak metamorphic P-T conditions for the sillimanite zone have been estimated to be approximately 620-720℃ and 3.4-4.6kb (Tables 1 and 2). Sillimanite is common. This would be assumed that the P-T field this zone was placed in the left side of univariant curve 2 in Fig. 17. Fig. 17 illustrates that the metamorphic grade increase from the cordierite zone, through the sillimanite zone, to the garnet zone.

4. Metamorphism related to the formation of the Tengatake and Nagano migmatites

The Tengatake and Nagano migmatites are developed as zones cutting at low angles across the gneissosity of their surrounding metamorphic rocks of the cordierite zone. In the migmatites there are many blocks of the metamorphic rocks with agmatitic stuctures. Fig. 19-a and -b illustrate granitization of siliceous metamorphic rocks. Some agmatitic blocks are distinctly different in the metamorphic P-T conditions from their surrounding metamorphic rocks of the cordierite zone, compared in the conditions of their peak metamorphism.

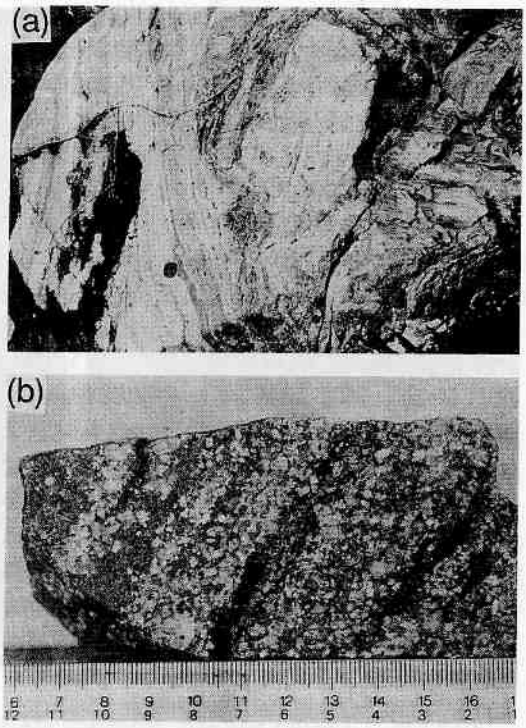
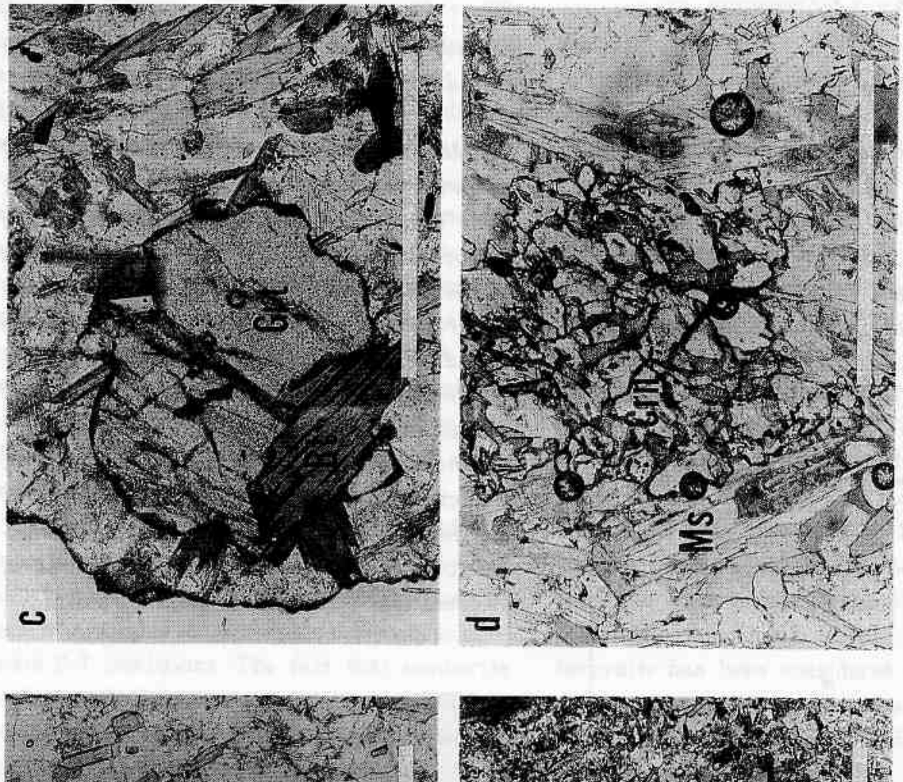


Fig. 19. Granitization of siliceous gneisses in the Tengatake migmatite.



Scale bar : 0.5mm

Fig. 20. Microphotographs showing some characteristic textures of pelitic-psammitic metamorphic rocks of the corundum rock in the Tengatake migmatite. a) aggregate of corundum (Crn), Zn-rich hercynite, and biotite. It is mantled by cordierite. Plane-polarized light. b) sillimanite porphyroblast mantled by cordierite and biotite. Plane-polarized light. c) garnet with resolved grain boundary and its closely associated biotite. Plane-polarized light. d) relict corundum. Plane-polarized light.

The Tengatake and Nagano migmatites are characterized by the occurrence of agmatitic blocks including corundum without quartz (Fig. 20-a and -d). Such the metamorphic blocks are here called corundum rocks. One of then in the Tengatake migmatite consists of plagioclase, potash-feldspar, biotite, muscovite, cordierite, sillimanite, corundum, Zn-rich hercynite, and almandine. Crundum, sillimanite, Zn-rich hercynite, and almandine are considered to be relict minerals, showing dissolved grain margins and larger grain size than other minerals (Fig. 20). Fig. 20-a shows such a microtexture that an aggregate of corundum, Zn-rich hercynite, and biotite is mantled by cordierite. Fig. 20-a and -c show that biotite was in equilibrium with early phase part of growing almandine crystal, suggesting that such a biotite grain may be relic. Fig. 20-b and -c illustrate microtexture of relict sillimanite and relict garnet, respectively. The mineral assemblage consisting of corundum, sillimanite, Zn-rich hercynite, and almandine may be assumed to be a product of anatexis, by which silica-deficient anhydrous restites was resulted (Harris, 1981). On the other hand, the matrix minerals such as plagioclase, potash-feldspar, biotite, muscovite, and cordierite correspond to a mineral assemblage produced in the later phase metamorphism. This mineral assemblage appears to be comparable with that of the cordierite zone mentioned in the preceding page, though the lack of quartz indicates that the later phase metamorphism under the same P-T conditions as the peak metamorphism of the cordierite zone.

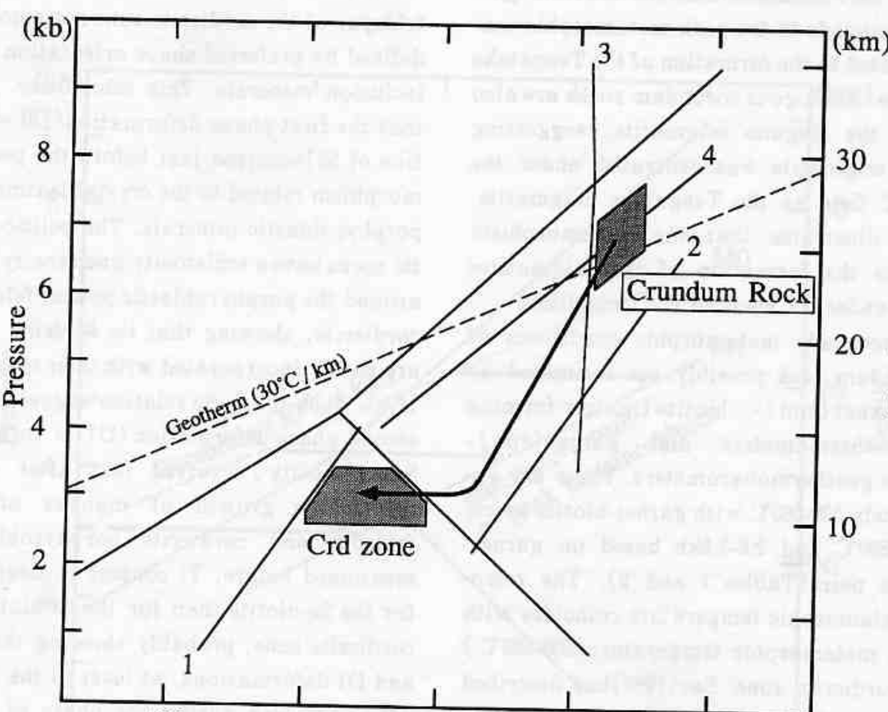


Fig. 21. P-T path of the corundum rock in the Tengatake migmatite. Reaction curves 1, 2, and 3 are the same as Fig. 17 and reaction curve 4 is for Alm+Crn=He+Sil (calculated *ln* K=1.2, Bohlen *et al.*, 1986).

The peak metamorphic conditions of the corundum rock are estimated by using garnet (core)-biotite (relict grain) geothermometers and corundum-almandine-sillimanite-spinel geobarometer (Bohlen *et al.*, 1986). The estimated temperature is approximately 680-700℃ (Table 1), and the pressure is around 6kb (calculated *ln* K is approximately 1.2). Bohlen *et al.* (1986) suggested that the method used here gives deviations of ±50℃ and ±1kb. The Zn-rich hercynite (Fig. 18) must have probably been formed by a staurolite-breakdown reaction, as the case of the garnet zone mentioned in preceding page, because the stability field of the corundum rocks was placed in the right side of the staurolite breakdown curve 3 in Fig. 21. Thus the peak metamorphic field of the corundum rock would be illustrated as shown in Fig. 21. It would be here assumed that the metamorphic field corresponds to the peak metamorphic condition related to the formation of the Tengatake migmatite. Analogous corundum rocks are also found in the Nagano migmatite, suggesting that the migmatite was generated under the same P-T field as the Tengatake migmatite. Fig. 21 illustrates that the metamorphism related to the formation of the migmatites occurred under the medium P/T condition.

The retrograde metamorphic conditions of the corundum rock possibly are estimated by using garnet (rim) - biotite (matrix-forming grain) geothermometers and garnet (rim) - cordierite geothermobarometers. These are approximately 530-560℃ with garnet-biotite pairs, and 510-590℃ and 2.6-3.5kb based on garnet-cordierite pairs (Tables 1 and 2). The retrograde metamorphic temperature coincides with the peak metamorphic temperature (500-590℃) for the cordierite zone. Seo (1987) has described such a mineralogical change of prograde path in pelitic rocks of the cordierite zone adjacent with the Nagano migmatite, that sillmanite and andalusite are mantled by cordierite grains. From this fact Seo (1987) suggested that the rocks just near the migmatite were thermally metamorphosed under ca. 620℃ and 3.3kb. Such the isobaric prograde metamorphism is ascribed to the contact metamorphism by the migmatites.

Thus it would be now concluded that the Tengatake and Nagano migmatites were produced under the metamorphic conditions of ca. 700℃ and 6kb, and then intruded into the cordierite zone of the metamorphic conditions of ca. 510-590℃ and 2.6-3.5kb. Intrusion of migmatites along the fracture zones causes contact metamorphism against their surrounding metamorphic rocks. Such the P-T path of the corundum rocks of the migmatities would be illustrated by Fig. 21.

Concluding remarks —tectono-metamorphic processes—

The Si-schistosity of cordierite and potash-feldspar of the cordierite zone metamorphics is defined by preferred shape orientation of some inclusion minerals. This schistosity indicates that the first phase deformation (D0 = formation of Si) occurred just before the peak metamorphism related to the crystallization of these porphyroblastic minerals. The pelitic-psammitic rocks have a schistosity-gneissosity deflected around the porphyroblastic potash-feldspar and cordierite, showing that its forming minerals are partly incorporated with their mantles (Fig. 11-a). Such the Si-Se relation suggests that the second phase deformation (D1 = formation of Se-schistosity) occurred just after and / or during the growth of mantles of potash-feldspar and cordierite porphyroblasts. As mentioned before, Ti content is clearly larger for the Se-biotite than for the Si-biotite of the cordierite zone, probably showing that the D0 and D1 deformations, at least in the cordierite zone, occurred during the phase of prograde metamorphism.

Mesoscpic ductile shear zones related D1 deformation are well recognized in the metamorphic rocks, cutting across the schistosity-gneissosity of the metamorphic rocks at low angles (Fig. 4-a). The shear zones appear to be Riedel Shear R1 or P (after Logan *et al.*, 1979; Rutter *et al.*, 1986) which was produced under bulk shear along the schistosity-gneissosity. The deformation related to the formation of the shear zones would be contemporaneous with the fracturing related to the intrusion of the Tengatake and Nagano migmatites. The transport direction of the D1 deformation may be top to the NE-ward sense (Okudaira *et al.*, 1992).

As clarified in the preceding page, the Tengatake and Nagano migmatites were metamorphosed under different P-T conditions between the earlier phase (M0) and the later phase (M1) of metamorphisms. The P-T conditions have been etimated to be ca. 680-700℃ and 6kb during the earlier phase and 510-590℃ and 2.6-3.5kb during the later phase. The M1 metamorphism occurred just after and/or during the intrusion of migmatites along fracture zones reached in contact with the cordierite zone rocks. The P-T field of the M1 metamorphism of the migmatites coincides with that of the peak metamorphism of the surrounding cordierite zone rocks. The P-T fields of the peak metamorphism of the garnet zone, the sillimanite zone, and the cordierite zone, together lie on a straight line (M1-line) as show n in Fig. 22. The geothermal gradient assumed from the M1-line is comparable with that of a low P/T type metamorphism (cf., Miyashiro, 1972). Whereas, the M0-line in Fig. 22 assumed from the P-T field of the M0 metamorphism suggests that the geothermal gradient comparable with the mean geothermal gradient (ca. 30 ℃/km) of a continent or an island-arc after Sugimura and Uyeda (1973).

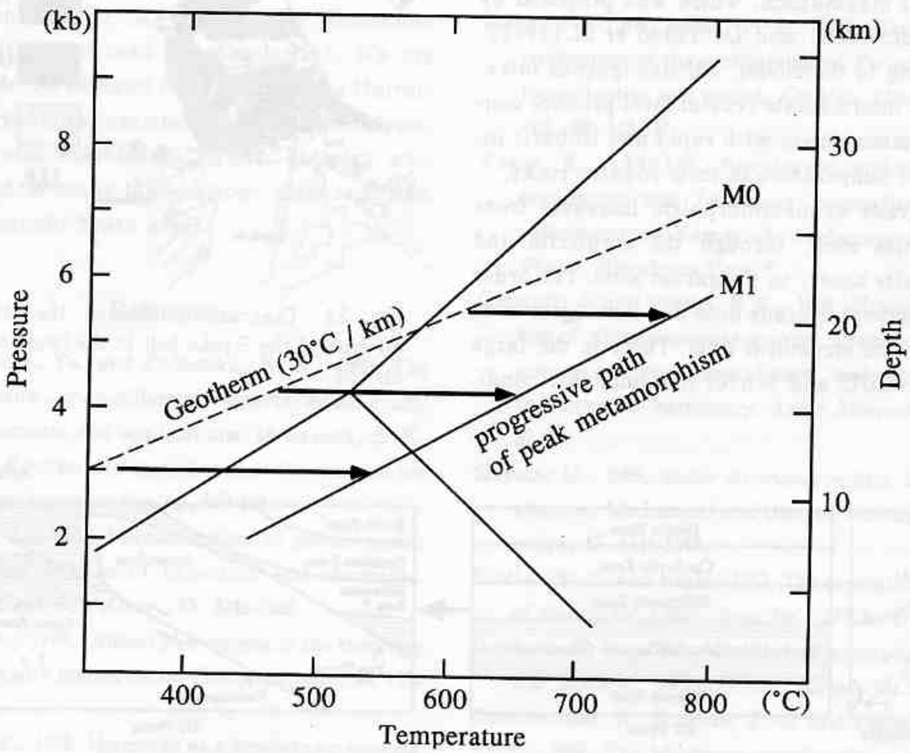


Fig. 22. Diagram illustrating the prograde path from the M0 metamorphism to the M1 metamorphism.

Fig. 22 illustrates the change in geothermal gradient from the M0 phase to the M1 phase. What is related to the M0 - M1 change of metamorphic conditions? The mineral assemblages of the peak metamorphic phase of the garnet and sillimanite zones are commonly recognized in the pelitic-psammitic rocks placed near and in the Ryoke older granites (Figs. 1 and 2). Any distinct contact aureole cannot be recognized. The gneissosity of the metamorphic rocks are commonly parallel to that of the surrounding older granites. The metamorphic rocks of the garnet and sillimanite zones had been clearly placed within their peak metamorphic conditions during and immediately after the intrusion of the older granites. The metamorphism of M1 phase may be ascribed to the contact metamorphism by the Ryoke older granites as sheets. This assumption is harmonic with the model of low P／T type metamorphism account by acidic magmatism, which was proposed by Lux *et al.* (1986) and De Yoreo *et al.* (1991). According to the model, sill-like igneous intrusions at intermediate crustal level produce contact metamorphism with rapid and isobaric increase of temperature in their country rocks.

The grade of metamorphism increases from the biotite zone, through the cordierite and sillimanite zones, to the garnet zone. The order of metamorphic grade dose not thus agree with the order of structural level. There is the large gap (ca. 200℃ and 3kb) of metamorphic conditions between the cordierite zone and the garnet zone. Furthermore, the garnet zone of higher pressure overlies the sillimanite zone of lower pressure. This discordant relationship was resulted from disordering of the primary P-T structure by the fromation of nappes. The cordierite zone possibly with the biotite zone, the garnet zone, and the sillimanite zone are respectively developed as the Tsuzu nappe, Obatake nappe, and Yanai nappe in descending order of structural level (Fig. 23). These nappes were produced just after the intrusion of the Ryoke older granites, forming mylonitic zones in their basal parts. The Zenitsuboyama recumbent fold is of the same generation as the Obatake nappe. The inverted metamorphic

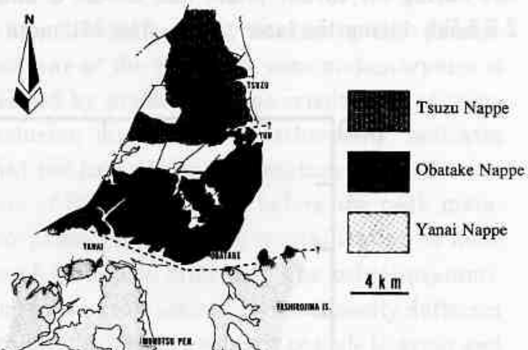


Fig. 23. Diagram illustrating the structural division of the Ryoke belt in the Iwakuni-Yanai district.

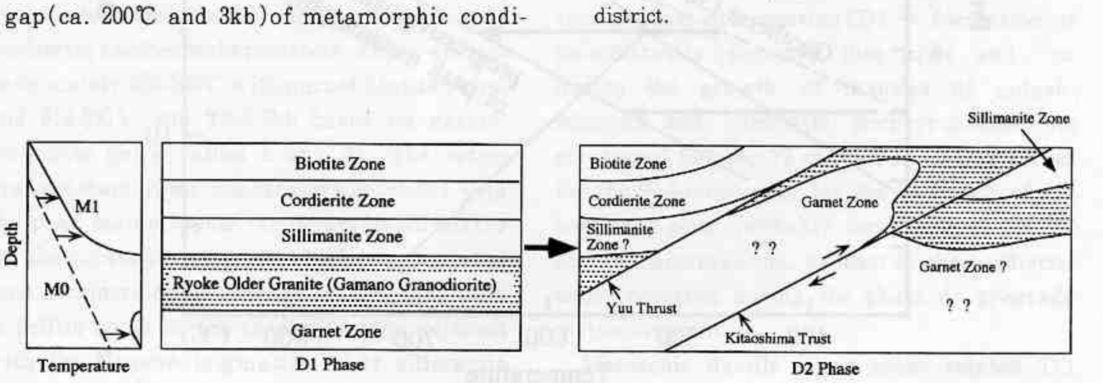


Fig. 24. Schematic diagram illustrating the tectono-metamorphic processes of the Ryoke belt in the Iwakuni-Yanai district.

zonation between the Obatake nappe(garnet zone)and the Yanai nappe(sillimanite zone)is ascribed to the formation of these nappes(D2 deformation). The coupling of the Obatake and Yanai nappes is related to the displacement along the Kitaoshima thrust, which produced mylonite zones developed at Kasasajima Island and Tanojirihana Cape. The transport direction of D2 deformation may be top to the WSW- or SW-ward sense(Okudaira *et al.*, 1992). Such the nappe formation processes will be schematically explained in Fig. 24.

The above described structural and metamorphic characteristics of the Ryoke metamorphic rocks in this district were locally modified by intrusion and related contact metamorphism of the Ryoke younger and Hiroshima granites (Nureki, 1960, 1974; Higashimoto *et al.*, 1983; Nishimura *et al.*, 1985). This contact metamorphism is here referred to M2 metamorphism.

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Okudaira, T., Hara, I., Sakurai, Y. and Hayasaka, Y. 1993, Tectono-metamorphic processes of the Ryoke belt in the Iwakuni-Yanai district, southwest Japan. 奥平敬元・原郁夫・桜井康博・早坂康隆：岩国－柳井地域領家帯の造構変成過程.)

岩国－柳井地域領家帯は主に低圧型変成岩(領家変成岩類)と花崗岩類(領家及び広島花崗岩類)から構成される．領家花崗岩類は古期花崗岩類と新期花崗岩類に大別され，前者はシート状であり後者はストック状である．領家変成岩類は四つの鉱物帯(黒雲母帯，菫青石帯，ザクロ石帯，珪線石帯)に分けられ，これらと領家古期花崗岩類は三つのナップ(構造的上位から通津ナップ，大畠ナップ，柳井ナップ)を形成している．通津ナップと大畠ナップとの間には，最高変成作用時の温度圧力条件において約3 kb，200℃のギャップがある．また，柳井ナップは大畠ナップの構造的下位に位置しているが，柳井ナップは大畠ナップよりも低温低圧の温度圧力条件を示す．このことは最高変成作用時の温度圧力構造が，後の造構作用によって改変されたものであることを示している．菫青石帯には二つのミグマタイト帯(天ケ岳及び長野ミグマタイト)が存在するが，これらはより深部(約6 kb)で形成され，破砕帯に沿って貫入上昇し，現在の位置に定置したものである．ミグマタイト中の含コランダムレスタイトの変成作用の解析結果から二つの変成時相(M 0，M 1)が識別され，M 0変成作用は中圧型に対応することが明かとなった．M 1変成作用はミグマタイトや領家古期花崗岩類の貫入直後に行なわれ，この変成作用はこれらの貫入岩の接触変成作用である可能性が高い．パイルナップ構造の形成はM 1変成作用後で，領家新期及び広島花崗岩類の貫入前である．

地名
Befu・・・別府
Daishogunyama・・・大将軍山
Hikari・・・光
Hirao・・・平生
Hiuchiiwa・・・火打岩
Iwaki・・・岩城
Iwakuni・・・岩国
Kandori・・・梶取
Kasasajima・・・笠佐島
Kitaoshima・・・北大島
Kotoishi・・・琴石
Kuga・・・玖珂
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