Hutton Symposium V, Field Guidebook
Geological Survey of Japan, Interim-Report no.28, p.23 − 40, 2003

Trip A2

Mid-Cretaceous plutono-metamorphic complex of the Ryoke and San-yo zones in the Iwakuni-Yanai district, SW Japan

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Abstract: The trip will illustrate the cross-section of the Ryoke plutono-metamorphic belt from the non-metamorphic to high-grade (lower granulite facies) rocks. The Ryoke metamorphic belt is a typical low-pressure/high-temperature metamorphic belt formed at a convergent plate margin, and the emplacement mechanisms and geochemical characteristics of the granites of the San-yo and Ryoke zones changed systematically with metamorphic grade. The Older Ryoke granite sheets occur only in the high-grade zones, and they have been considered to be the heat source of the regional Ryoke metamorphism, whereas the San-yo and Younger Ryoke batholiths, with narrow contact aureoles, have huge volume but their thermal effect was local. To understand the mutual relation between regional low *P/T* metamorphism and plutonism at a convergent plate margin, we will examine successively both the metamorphic and granitic rocks at the same crustal depth from shallow to deep crustal levels.

Key words: Cretaceous, field excursion, Hutton symposium, Iwakuni-Yanai district, Plutono-metamorphic complex, Ryoke metamorphic belt, Ryoke and San-yo zones, SW Japan

1. Introduction

Active convergent plate margins are one of the most important granite-forming sites. Before the opening of the Japan Sea during the Miocene, the Japanese Islands were a part of the Eurasian continental margin. The Cretaceous-Paleogene granitoids are exposed all over SW Japan from Kyushu to central Japan, extending for nearly 800 km and is similar in size to that of the Sierra Nevada and Peninsular Ranges batholiths in western North America. As shown in Fig. 1, the Inner Zone defined as a zone on the continental side of the Median Tectonic Line of SW Japan is generally divided, based on granitoids and related mineralizations, into the following three granitoid zones from south to north:

- Ryoke zone with no associated mineral deposits, located along the Seto Inland Sea;
- San-yo zone, with tungsten (copper, etc.) deposits;
- San-in zone, with molybdenum deposits, located along the Japan Sea.

This classification originated from the Kinosaki's (1952) ore provinces and it was refined from the viewpoint of granite mineralogy by Ishihara (1977) with his new categorization of ilmenite-series and magnetite-series. Most granitoids in the San-in zone are of magnetite-series and those from the San-yo and the Ryoke zones are of ilmenite-series. These three zones are not tectonically juxtaposed suspect terranes, but a geologically continuous single unit, because the granitoids of different zones are in intrusive contact. Across-arc variation of the granitoids from San-in, San-yo and Ryoke zones has been studied well, such as magnetic susceptibility (Kanaya and Ishihara, 1973), oxygen isotopes (Honma and Sakai, 1976) and Sr-Nd isotopes (Kagami *et al.*, 1992). Kagami *et al.*(1992) noted the low Sr*I* (= initial $^{87}Sr/^{86}Sr$ isotopic ratio) and high εNd in the San-in zone, middle Sr*I* and εNd in the San-yo zone, and high Sr*I* and low εNd in the Ryoke zone in the Chugoku district. However, this isotopic zonal distribution is likely to be unclear in the other districts of SW Japan (Nakajima, 1996).

Granitoids of the first two zones show similar ages of emplacement (mid-Cretaceous), whereas the San-in granitoids are younger (early Paleogene). It means that the San-yo and Ryoke granitoids constitute a part of the Cretaceous Circum-Pacific granite belt, on the other hand the San-in granitoids may reflect the different tectonic setting of post-Cretaceous rift-drift history of microplates in northwestern Pacific rim. Actually, the age of the youngest San-in granitoid overlaps even the reconnaissance stage of the opening of the Japan Sea. Therefore, it seems better to concentrate our target to the San-yo and the Ryoke granitoids for discussing the Cretaceous granitic magmatism of SW Japan without the noise of post-Cretaceous activity.

Characteristics of the first two granitoid types are summarized in Table 1. Based on their geochemical characteristics, the San-yo and Ryoke granitoids are cogenetic, and they can be called as the Ryoke - San-yo series (Moutte and Iiyama, 1984). Although not well constrained, based on the Al-in-hornblende barometer, the depth of emplacement of granitoids was >400 MPa in the Ryoke zone and <400 MPa in the San-yo zone (Takahashi, 1993). Pressure estimation of associated metamorphic rocks gave similar results as that of the granitoids

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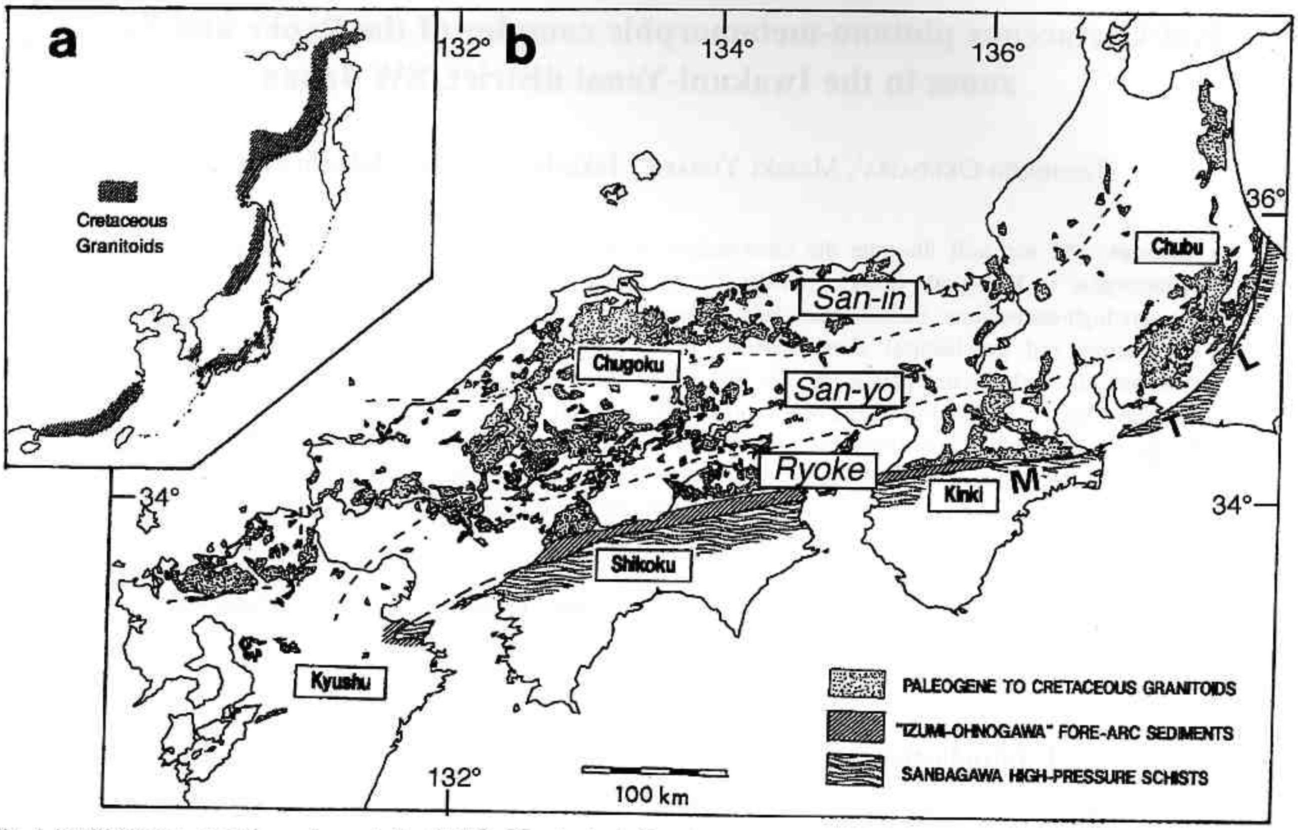

Fig. 1 (a) Cretaceous granitic provinces in the NW Pacific rim including the Japanese Islands. (b) Three granitic provinces in SW Japan (Nakajima, 1996). MTL denotes the Median Tectonic Line, a large strike-slip fault which runs through the center of SW Japan along the arc trend.

Table 1 Characteristics of the granitoids of the San-yo and Ryoke zones, based on Moutte and Iiyama (1984) and Kagami *et al.* (1992).

	San-yo zone	Ryoke zone	
		Younger granitoids	Older granitoids
level of emplacement	shallow (< 0.4 GPa)	intermediate (~ 0.4 GPa)	deep (> 0.4 GPa)
volume	batholith	stock	sill
lithology	massive to porphyritic	gneissose to massive	gneissose
relation with host rock	discordant	discordant	concordant
enclaves	very rare	some	many
major rock type	adamellite + aplite	granodiorite + granite + diorite	granodiorite + tonalite + diorite
mean SiO_2 (wt%)	65 - 75	65 - 75	60 - 70
I/S type	I type	I type	I type
opaque mineral	Ilm > Mt	Ilm >> Mt	Ilm >> Mt
ore deposit	W	none	none
$\delta^{18}O$ quartz	9 - 10‰	12 - 14‰	13 - 15‰
$^{87}Sr/^{86}Sr$ initial ratio	0.706-0.708	0.707-0.709	
Sr (ppm)	12-538 (mean: 176)	13-410 (mean: 203)	

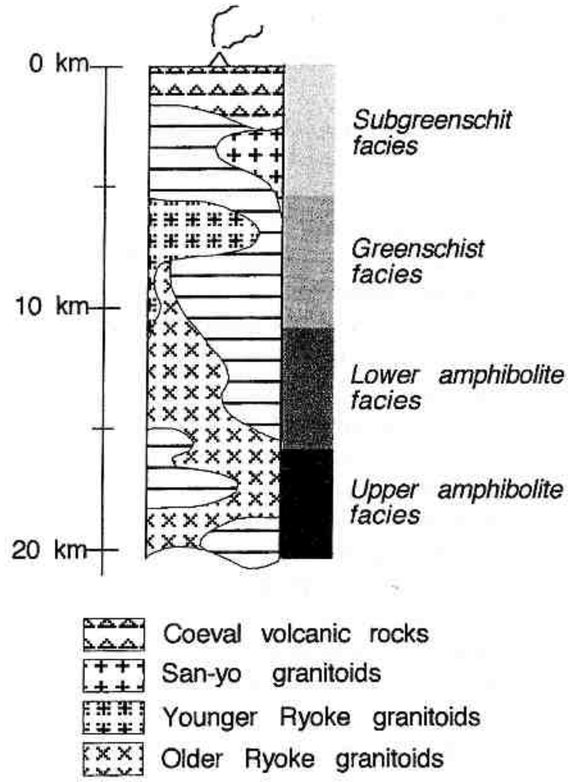

Fig. 2 Schematic cross-section from the San-yo to Ryoke zones exhibiting a crustal cross section down to middle crustal level.

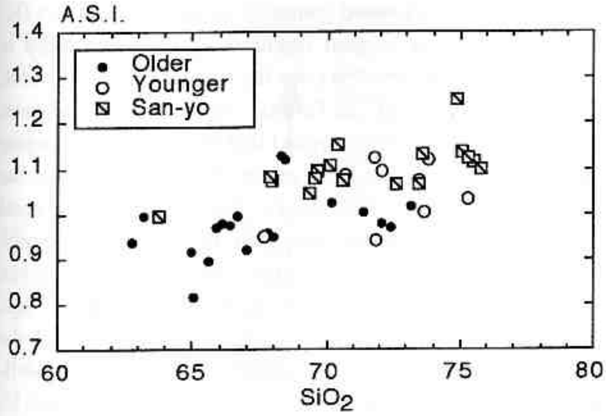

Fig. 3 Positive correlation between ASI and SiO_2 content of the granitoids of the San-yo and Ryoke zones in the Iwakuni-Yanai district. Data source: Honma (1974), Moutte (1990) and Owada *et al.* (1995).

(Ikeda, 2003).

Since early days, Ryoke granitoids have been divided into two groups: Younger Ryoke granitoids and Older Ryoke granitoids. The Younger Ryoke granitoids are nearly unfoliated and intruded as relatively small stock-like bodies crosscutting the general structure of the weakly-metamorphosed host rocks, whereas the Older Ryoke granitoids are foliated and occur as sheet-like bodies intruding high-grade gneisses concordantly to their gneissose structure. Similar to the Younger Ryoke granitoids, the San-yo granitoids are unfoliated and occur as batholithic large bodies emplaced in the unmetamorphosed sedimentary rocks. This geological succession from the San-yo to Ryoke zones exhibits a crustal cross section down to middle crustal level (Nakajima, 1994, 1996; Fig. 2). This is a part of the Circum-Pacific Cordilleran-type orogenic belt formed at an ancient arc-trench system or active continental margin (*e.g.* Miyashiro, 1994; Nakajima, 1994; Brown, 1998; Okudaira *et al.*, 2000).

For the San-yo and Ryoke granitoids, the aluminium saturation index (ASI) and SiO_2 show a positive correlation (Fig. 3) with other I-type granitoids in the world (Nakajima, 1996), implying that the major source of these granitoids are mafic magmatic rock or its metamorphosed equivalent, as also suggested by Kagami *et al.* (1992). Kutsukake (2002) showed REE pattern of the I-type granitoids (Fig. 4) and discussed that they were generated by the dehydration melting of amphibolite or hydrous melting of tholeiite at 1 GPa or higher pressure. Furthermore, these granitoids are designated as arc-type granitoids in terms of minor element chemistry (Kagami *et al.*, 1992; Kutsukake, 1993, 2002; Nakajima, 1996; Fig. 5). On the initial εSr vs. εNd diagram, the Ryoke granitoids are plotted in high Sr*I* and low εNd region (Yuhara *et al.*, 2000; Fig. 6), and the contribution of upper crustal recycled materials seems to be small (Kagami *et al.*, 1992).

The Ryoke granitoid zone is equivalent to the low-*P*/high-*T* Ryoke metamorphic belt which has been considered to be a typical example of Miyashiro's (1961) low-*P* facies series or andalusite-sillimanite type. The Ryoke metamorphic belt and the high-*P* Sambagawa metamorphic belt are typical example of paired metamorphic belt, (*e.g.* Miyashiro, 1961, 1994). They are considered to have formed at different *P-T* conditions and geological settings. The former formed beneath volcanic arc or fore arc at a depth of 15-20 km, whereas the latter formed near trench zone at *ca.* 30 km deep (*e.g.* Miyashiro, 1994; Iwamori, 2000; Okudaira *et al.*, 2000). The process of

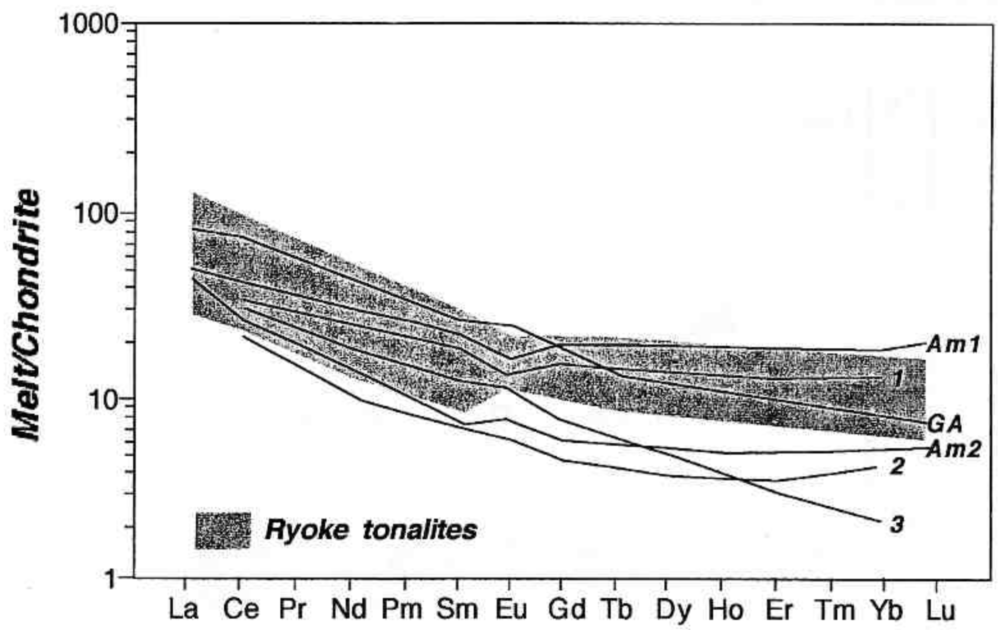

Fig. 4 Chondrite-normalized REE patterns for the Ryoke tonalites and the tonalitic modeled melts (Kutsukake, 2002). 1-3: Tholeiitic sources (1 gabbroic residue, 2 amphibolitic residue, 3 eclogitic residue; Gromet and Silver, 1987), Am1 and Am2: Amphibolitic source (Leake, 1990), GA: Garnet amphibolite source (Anderson and Cullers, 1990).

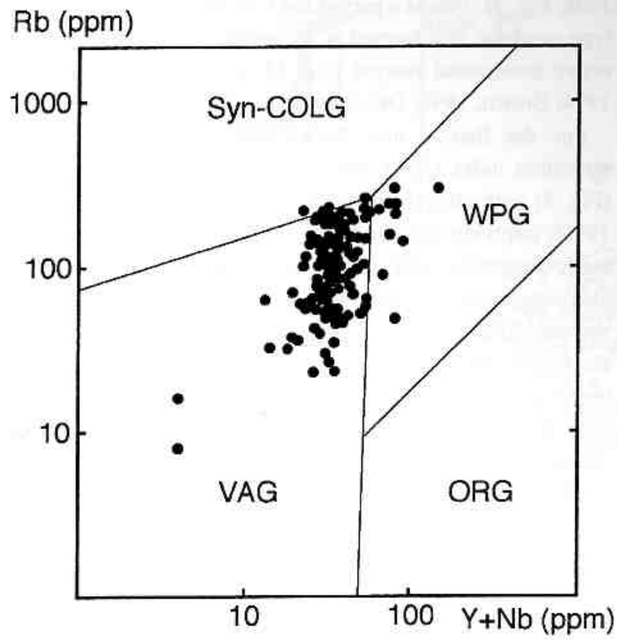

Fig. 5 Rb versus Y + Nb diagram (simplified from Nakajima, 1996). syn-COLG: syn-collision granites, WPG: within plate granites, ORG: ocean ridge granites, VAG: volcanic arc granites (discrimination lines from Pearce *et al.*, 1984).

exhumation and juxtaposition of different types of metamorphic belts are important to clarify continental margin processes and geological evolution of the Japanese Islands.

The Cretaceous granitic magmatism in SW Japan has been ascribed to the interaction of mid-oceanic ridge to the trench of the Eurasian continental margin (Uyeda and Miyashiro, 1974; Kinoshita and Ito, 1986; Nakajima *et al.*, 1990; Nakajima, 1994; Kinoshita, 1995; Brown, 1998; Iwamori, 2000). Along-arc, eastward younging variation of the ages (K-Ar ages and Rb-Sr mineral isochron ages) of granitoids is considered to be the evidence for the ridge subduction model. Based on the CHIME U-Th-total Pb monazite age data, Suzuki and Adachi (1998) argued that the eastward younging ages of the Ryoke granitoids so far documented reflect the differential uplift of the Ryoke belt rather than lateral migration of magmatism. Based on the Rb-Sr whole-rock isochron ages, Yuhara *et al.* (2000) considered the outbreak of magmatism all over SW Japan to be around 120 Ma. However, it should be noted that the magmatic ages of the San-yo granitoids given by SHRIMP U-Pb zircon ages, well-defined Rb-Sr whole rock isochron ages, Th-Pb thorite and U-Pb uraninite ages show the eastward younging trend approximately from 100 Ma at western Chugoku to 70 Ma at central Japan. It seems that this problem has not yet been settled with a convincing conclusion for all.

To discuss the shallow to mid-crustal process during the mid-Cretaceous, this field trip focuses on the shallow- to deep-seated granitic rocks, such as San-yo and Ryoke granitoids and related low-*P*/high-*T* metamorphic rocks in the Iwakuni-Yanai district, Yamaguchi Prefecture. Route map and locations of stop points in the Yanai-Iwakuni district is available in Appendix.

2. Geology of the Iwakuni-Yanai district

As the Iwakuni-Yanai area includes the San-yo and Ryoke zones (Fig. 7a), we can enjoy a variety of the San-yo and Ryoke granitoids with host metamorphic rocks of various metamorphic grades from virtually unmetamorphosed to lower granulite grade. Roughly, the San-yo zone represents the shallow level of the orogen and it goes to deep in the crust as we traverse this area to the south in the Ryoke zone.

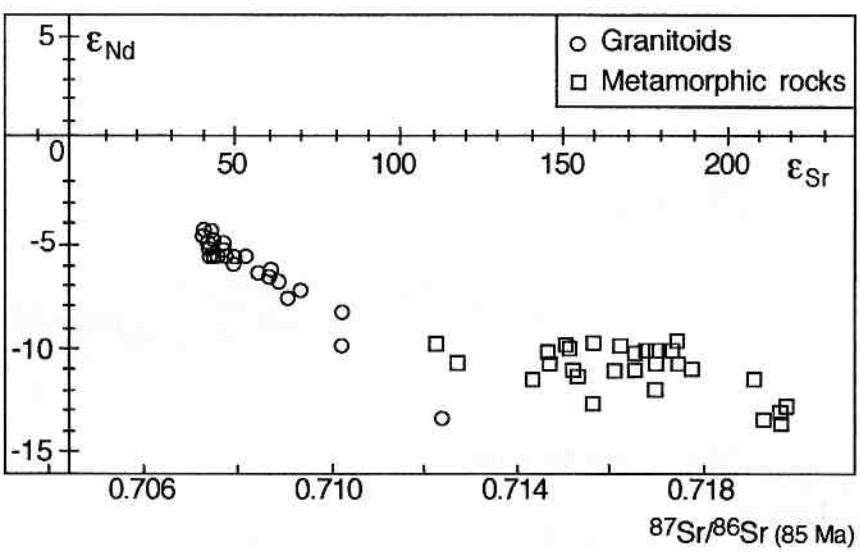

Fig. 6 Initial εSr versus εNd diagram for Ryoke granitic and metamorphic rocks (partly modified from Yuhara *et al.*, 2000). Chondritic uniform reservoir (CHUR) parameters for calculation of initial εSr versus εNd are: $^{87}Sr/^{86}Sr$ (present) = 0.7045, $^{87}Rb/^{86}Sr$ (present) = 0.0827, $^{143}Nd/^{144}Nd$ (present) = 0.512638, $^{147}Sm/^{144}Nd$ (present) = 0.1966.

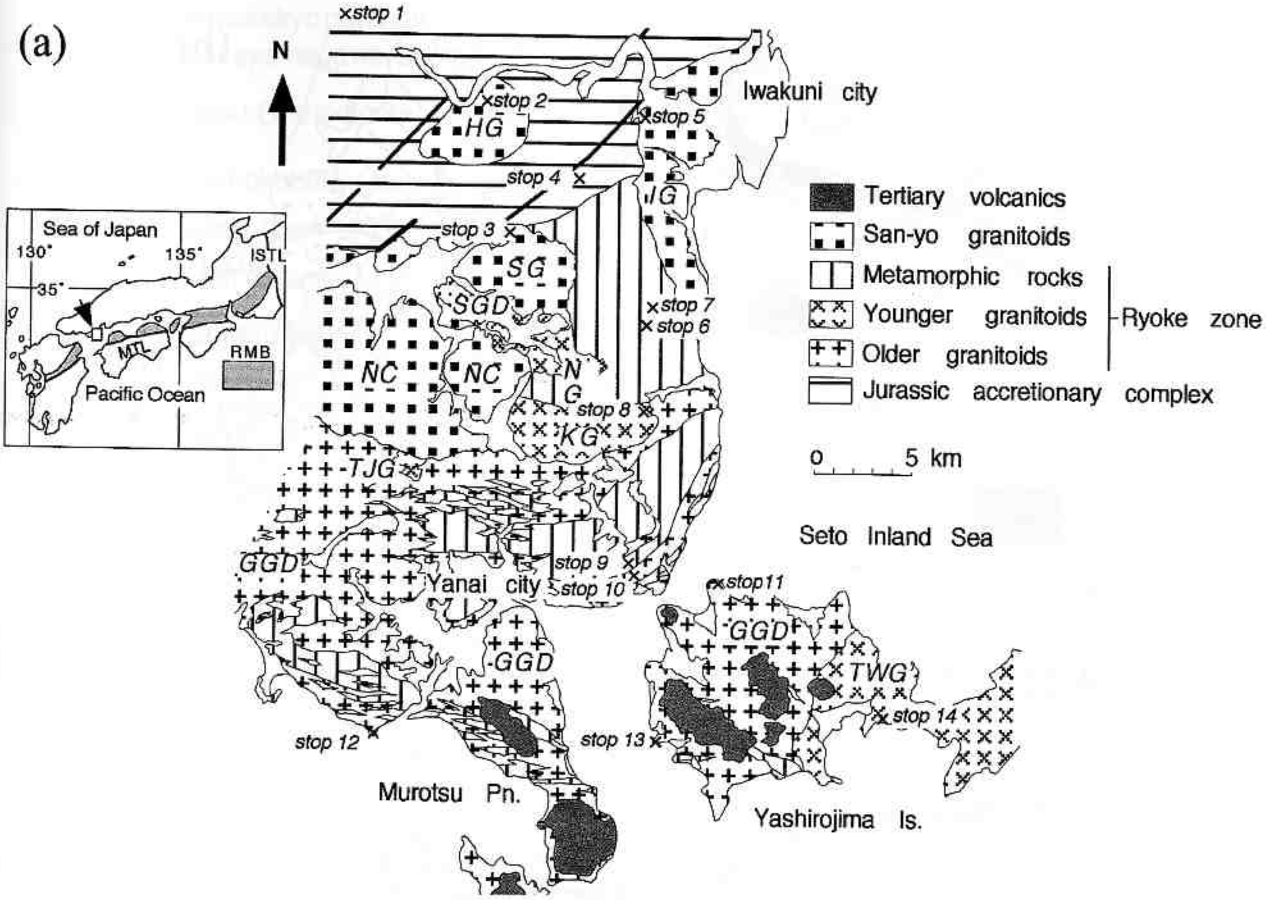

Fig. 7 (a) Geological map of the Iwakuni-Yanai district (modified from Higashimoto *et al.*, 1983). Individual granite bodies are identified as HG (Habu granodiorite), IG (Iwakuni granite), SG (Shimokubara granite), NC (Nakayamagawa complex), SGD (So-o granodiorite), NG (Namera granite), KG (Kibe granite), TJG (Tajiri granite), TWG (Towa granite), and GGD (Gamano granodiorite). RMB (Ryoke Metamorphic Belt) in Index map.

The host rocks in this area are Jurassic accretionary complex of the Mino-Tamba belt. Radiolarian fossils in the complex suggest a pre-Early Cretaceous stratigraphic age for the protolith of the metamorphic belt (*e.g.* Takami *et al.*, 1990; Takami and Itaya, 1996). These protoliths were regionally metamorphosed under low-*P*/high-*T* conditions during mid-Cretaceous. They show a distinct tectonic foliation which appears to be commonly parallel to their bedding planes. The metamorphic grade increases southward, except in the southernmost area where it decreases, whereas the highest-grade zone is located in the central region of the district. Therefore, the order of increasing metamorphic grade does not agree with the order of increasing structural level. There is, however, still controversy regarding their pressure estimation (Ikeda, 2003). In the southern part of the Iwakuni-Yanai district, Miocene high-Mg andesite covers the Ryoke granitic and metamorphic rocks sporadically.

2.1 Granitic rocks

In the Iwakuni-Yanai district, the San-yo granitoids are exposed in the northern part, the Older Ryoke granitoids occur in the southern part of the area, and the Younger Ryoke granitoids mostly constitute the middle part but some are also exposed in the San-yo granitoid area (Fig. 7b). The San-yo granitoids intrude the Younger Ryoke granitoids, and the Younger Ryoke granitoids intrude the Older Ryoke granitoids where the intrusive contact is observed. The CHIME ages of the granitoids (Suzuki and Adachi, 1998) seem to be concordant with the intrusive relationships (Fig. 8).

The granitoids of the San-yo zone include Iwakuni granite, Habu granodiorite, Shimokubara granite and Nakayamagawa complex (Fig. 7a). They are mostly unfoliated coarse-grained biotite adamellite to granodiorite associated with hornblende-bearing varieties. Some adamellites have pink or pale brown K-feldspars. Most of the San-yo granitoids are equigranular and homogeneous, but some of them are porphyritic with K-feldspar megacrysts of 2 to 5 cm in size. The San-yo granitoids are mostly felsic with 70-75 wt% SiO_2. The San-yo granitoids often have contact aureole of max. *ca.* 500 m. Hornfels with cordierite porphyroblasts occur near the contact boundary of the Iwakuni granite.

The Ryoke granitoids are mostly of I-type, but have been known to include S-type-like granitoids, such as garnet-and/or muscovite-bearing granitoids (without magmatic cordierite nor sillimanite). This S-type-like character was often too much emphasized and the Ryoke granitoids are categorized as I'-type in some papers (*e.g.* Pitcher, 1983). However, the amount of these S-type-like granitoids is small

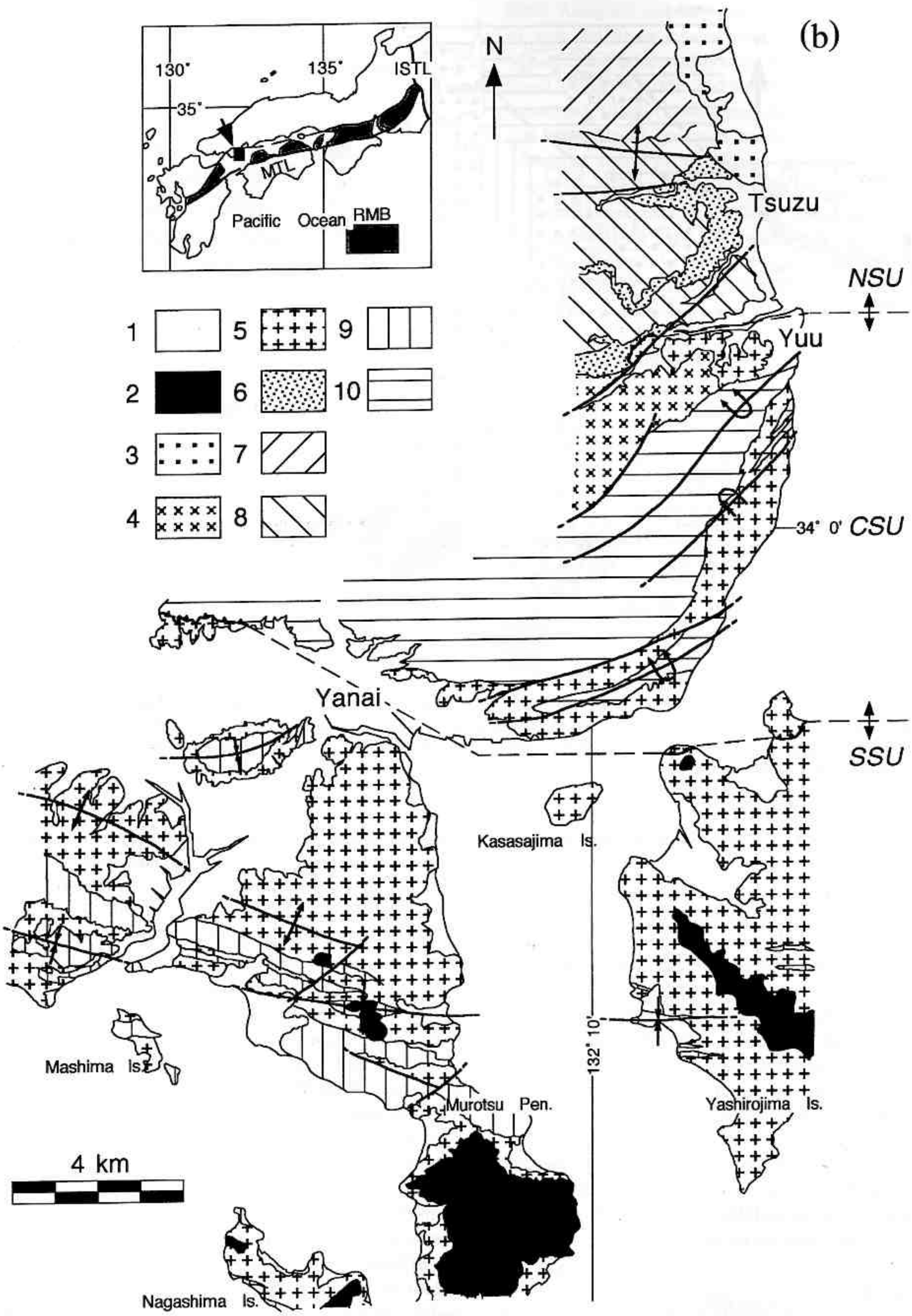

Fig. 7 (b) Geological map of the Yanai district (Okudaira *et al.*, 2001). 1: alluvium. 2: Tertiary volcanics. 3: Iwakuni granite. 4: Younger Ryoke granitoid (Kibe granite). 5 and 6: Older Ryoke granitoids (5 Gamano granodiorite, 6 Tengatake-Nagano migmatite). 7-10 : Ryoke metamorphic rocks (7 biotite zone, 8 cordierite zone, 9 sillimanite zone, 10 garnet-cordierite zone). NSU: Northern structural unit, CSU: Central structural unit, SSU: Southern structural unit.

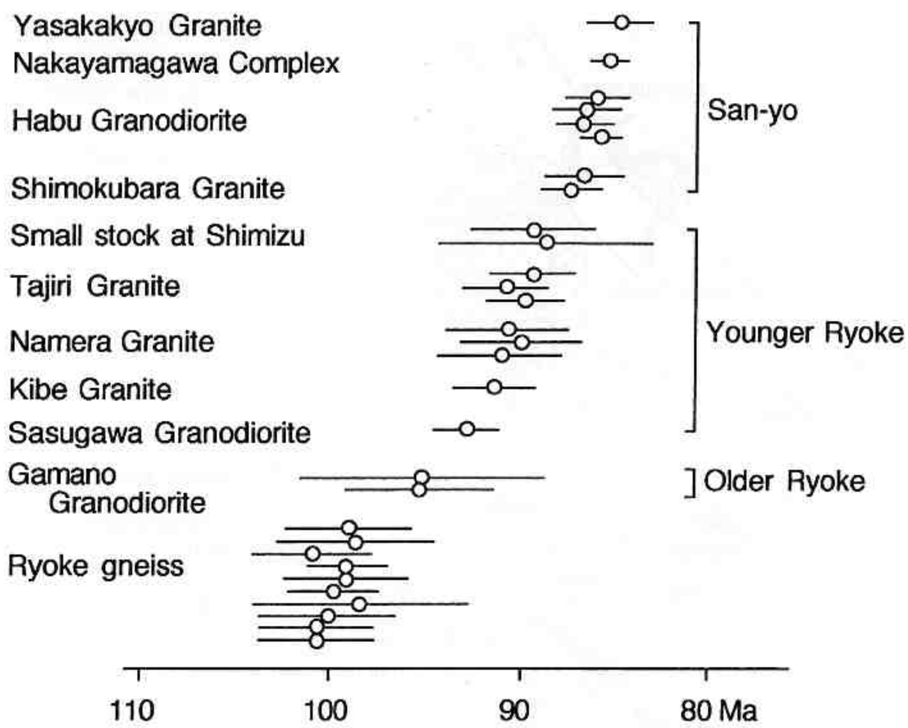

Fig. 8 Summary of CHIME monazite ages for gneisses and granitoids (partly modified from Suzuki and Adachi, 1998).

and their total surface exposure area is nearly 5% of the whole area of the Ryoke granitoids in SW Japan. All these S-type-like granitoids belong to the Younger Ryoke granitoids, whereas the Older Ryoke granitoids do not have such peraluminous minerals.

The Younger Ryoke granitoids in this area include Namera granite, Tajiri granite, Kibe granodiorite, So-o granodiorite and Towa granite. Tajiri granite, a fine-grained leucocratic granite of a few kilometers in size, is the only two-mica granite in this area. Namera granite is a coarse-grained biotite granite stock and partly contains garnet. Other bodies are all free from garnet and muscovite. Cordierite has been reported in some old literatures but not confirmed. Contact metamorphism around the Younger Ryoke granitoids is not observed well, presumably because, most of them intrude the regional metamorphic rocks of higher metamorphic grade than the biotite zone.

The widespread foliated Older Ryoke granitoids in this area is called Gamano granodiorite. It has a lithological variation from foliated coarse-grained hornblende-biotite tonalite to hornblende-bearing biotite granodiorite. The Gamano granitoids are exposed in an area elongated concordantly to the general structure of the wall rocks and the foliation is parallel to them. Gamano granodiorite is less silicic (SiO_2 = 65-70 wt%) than the Younger Ryoke and the San-yo granitoids.

2.2 Metamorphic rocks

2.2.1 Mineral zonation and *P-T* conditions

Using pelitic mineral assemblages, the progressive metamorphism can be described as a sequence of seven zones from north to south, *i.e.* chlorite, chlorite-biotite, biotite, muscovite-cordierite, K-feldspar-cordierite, garnet-cordierite and sillimanite-K-feldspar zones (Ikeda, 1993, 1998a,b; Fig. 9). However, the metamorphic zones different from Ikeda's zones have been proposed by Okudaira *et al.* (1993, 2001) and Nakajima (1994). In order to avoid confusion about these different zones, correlation among them are illustrated as below:

Ikeda (1993, 1998a,b)	**Okudaira *et al.* (1993, 2001)**	**Nakajima (1994, 1996)**
chlorite	—	chlorite
chlorite-biotite	—	chlorite
biotite	biotite	biotite
muscovite-cordierite	biotite	cordierite
K-feldspar-cordierite	cordierite	sillimanite-I
garnet-cordierite	garnet-cordierite	sillimanite-II
sillimanite-K-feldspar	sillimanite	sillimanite-I

The locations of the zone boundaries also differ slightly. The difference in the metamorphic zonation may be due to the difference in the identification of the stable mineral parageneses in each zone during peak regional metamorphism. For avoiding confusion, the metamorphic rocks in this paper are described based on Ikeda's classification.

The areas in the chlorite-biotite, biotite and the muscovite-cordierite zones locally overlap with contact aureoles of the San-yo granitoids. Even though the extent of the contact aureoles is difficult to discern, cordierite with trilling and randomly oriented muscovite are taken as evidence for

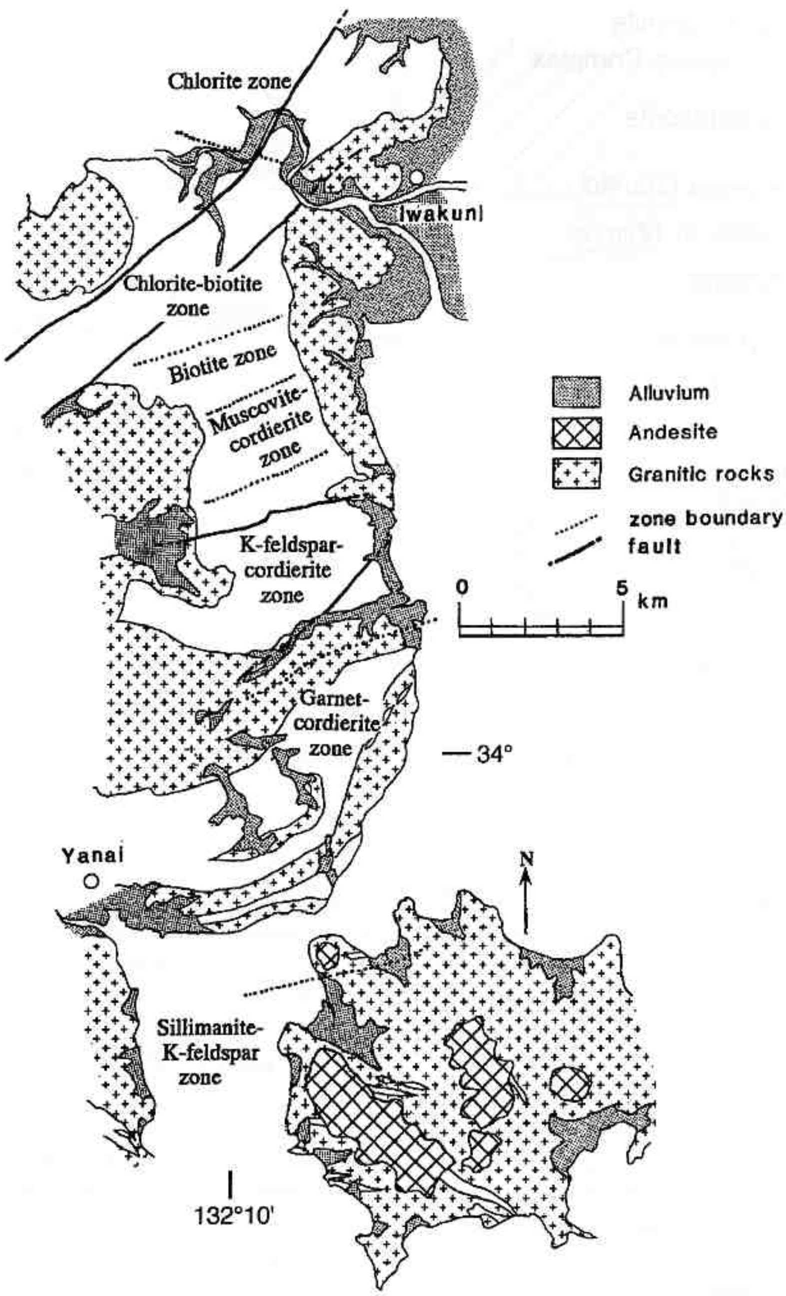

Fig. 9 Metamorphic zonation map of the Iwakuni-Yanai district (Ikeda, 1993, 1998a).

contact metamorphism. The arrangement of the metamorphic zones does not represent progressive changes in metamorphic grade, i.e. the highest-grade garnet-cordierite zone occurs between the K-feldspar-cordierite and sillimanite-K-feldspar zones (Ikeda, 1993, 1998a.b; Okudaira *et al*., 1993; Nakajima, 1994; Okudaira, 1996b).

According to Okudaira (1996b), estimated *P-T* conditions for the mineral zones are 460-590°C at ca 300 MPa (K-feldspar-cordierite zone), 630-690°C at 300-500 MPa (sillimanite-K-feldspar zone), and 730-770°C at 550-650 MPa (garnet-cordierite zone). However, the pressure estimates for the sillimanite-K-feldspar zone and garnet-cordierite zone were calculated based on different geobarometry, still uncertainty persists in the fact that the pressure condition of the garnet-cordierite zone is higher than that of the sillimanite-K-feldspar zone. Recently, based on internally consistent *P-T* estimation, Ikeda (2003) indicated the *P-T* conditions of each zone to be *ca.* 470°C at 20-50 MPa (chlorite-biotite zone), 450°C at 90-120 MPa (biotite zone), 520-550°C at 40-100 MPa (muscovite-cordierite zone), 600-680°C at 120-370 MPa (K-feldspar-cordierite zone), 700-760 °C at 500-640 MPa (sillimanite-K-feldspar zone), and 790-860 °C at 460-760 MPa (garnet-cordierite zone). Inferred metamorphic field gradient of the metamorphic belt is of 40-50°C/km. It has been suggested that the 'regional' low-*P* metamorphism resulted from the thermal effect of intrusion of the Gamano granodiorite (Okudaira *et al*., 1993; Okudaira, 1996a,b; Ikeda, 1998a,b).

The following description for each mineral zone is essentially after Ikeda (1998a,b).

Chlorite zone This zone is defined by absence of biotite in pelitic rocks. Dominant pelitic assemblage is chlorite + muscovite + albite together with quartz. K-feldspar locally occurs in siliceous rocks.

Chlorite-biotite zone This zone is characterized by the occurrence of biotite coexisting with chlorite and muscovite. Near the biotite isograd, biotite is fine-grained (< 50 mm long) and occurs only sporadically as a constituent of the schistosity. In the higher-grade part, biotite occurs not only as single grains parallel to schistosity but also as ovoidal aggregates with long axes of 0.1-0.2 mm. Such aggregates are composed of biotite grains that are coarser (0.1 mm in maximum) than those forming the schistosity, and are locally associated with quartz grains in their centers. Such aggregates persist into the biotite zone. The dominant assemblage in pelitic rocks is Chl + Bt + Ms + Pl. K-feldspar occurs only rarely in pelitic rocks but is common in siliceous rocks.

Biotite zone The disappearance of chlorite from most pelitic rocks defines the start of the biotite zone. Both biotite and muscovite are coarse-grained (0.1 mm long) compared with those in the chlorite-biotite zone. In this zone, the dominant mineral assemblage is Bt + Ms + Pl.

Muscovite-cordierite zone The coexistence of cordierite and muscovite defines the zone. Cordierite is minor, < 5% in modal amount, and now occurs as fine-grained pinite in the assemblage of Crd + Bt + Ms + Pl. However, this assemblage is uncommon and the most frequent assemblage in the pelitic rocks are same as that of the biotite zone. The grain sizes of muscovite and biotite are similar to those in the biotite zone and increase up to 0.3 mm.

However, according to Okudaira *et al.* (1993), the muscovite-cordierite zone cannot be distinguished from the biotite zone, since the mineral characteristics of both the zones are essentially the same.

K-feldspar-cordierite zone The first appearance of cordierite that coexists with K-feldspar defines the start of this zone. There is a marked reduction in the preferred orientation of muscovite and biotite, and the development of compositional banding composed of quartzo-feldspathic and micaceous layers occurs in this zone. The first appearance of andalusite, which is poikiloblastic including biotite and carbonaceous materials, coincides approximately with this isograd. In the southern part of this zone, andalusite with its armor of cordierite is partly or completely transformed to sillimanite. Most pelitic and siliceous rocks contain muscovite which occurs either as coarse (0.3 mm long) tabular grains in the matrix, or as aggregates replacing the cordierite rimming andalusite and sillimanite. The muscovite in this zone and at higher metamorphic grades is thought to be of retrograde origin. However, there is a possibility that some of the muscovite was stable at the peak metamorphism. The representative mineral assemblages in pelitic rocks are:

- andalusite and/or sillimanite + cordierite + biotite + K-feldspar + plagioclase
- cordierite + biotite + K-feldspar + plagioclase
- garnet + biotite + K-feldspar + plagioclase.

A tourmaline-out isograd that is defined by the disappearance of tourmaline is delineated within this zone (Kawakami and Ikeda, 2003).

Sillimanite-K-feldspar zone The sillimanite-K-feldspar zone is defined by the occurrence of sillimanite and K-feldspar in the matrix assemblage. Sillimanite occurs as fibrous or columnar grains and is commonly associated with biotite. The assemblages of Sil + Bt + Kfs + Pl and Sil + Grt + Bt + Kfs + Pl are dominant in pelitic and siliceous rocks. Cordierite is less common in this zone compared to the K-feldspar-cordierite zone, coexisting with sillimanite, biotite and K-feldspar while no coexisting garnet is found.

Garnet-cordierite zone The coexistence of garnet and cordierite is characteristic in this zone. The dominant mineral assemblages in pelitic rocks are:

- cordierite + biotite + K-feldspar + plagioclase
- garnet + biotite + K-feldspar + plagioclase
- garnet + cordierite + biotite + K-feldspar + plagioclase

The garnet + biotite + K-feldspar + plagioclase assemblage is dominant in both pelitic and siliceous rocks. Cordierite locally includes fibrous or rounded sillimanite in the center of a single grain. Spinel is observed only in this zone. The spinel is rare and occurs along grain boundaries within cordierite clusters and coexists with biotite and K-feldspar. Orthopyroxene occurs only in basic rocks of this zone and coexists with hydrous minerals such as biotite, hornblende (Ikeda, 2002).

2.2.2 Metamorphic *P-T* path

Metamorphic *P-T* paths for the rocks in the Iwakuni-Yanai district have been estimated petrologically (Ikeda, 1998a,b; Brown, 1998). As shown in Fig. 10, the prograde *P-T* paths for the K-feldspar-cordierite zone and garnet-cordierite zone are nearly isobaric, suggesting the possibility that the heat source for the low-*P*/high-*T* Ryoke metamorphism was caused by the intrusion of the Older granitoids (*e.g.* Okudaira *et al.*, 1993).

2.3 Deformation

2.3.1 Large-scale structures

The Older granitoids and metamorphic rocks occurring in the Yanai district were folded together, and they are divided into three structural units: the northern, central and southern units (Okudaira *et al.*, 1993, 2001; Fig. 7b). The geological structure of the northern unit is characterized by gentle upright folds with fold axis gently plunging toward ESE. The geological structure of the southern unit is also characterized by gentle folds of upright fashion and of WNW-ESE to E-W trend. In contrast to the structures of the northern and southern units, the geological structure of the central unit is characterized by overturned folds facing toward the southeast direction with NNE-NE plunging fold axes. Although the boundaries among the structural units can be recognized in the limited areas, they have a east-west strike and a northward dip.

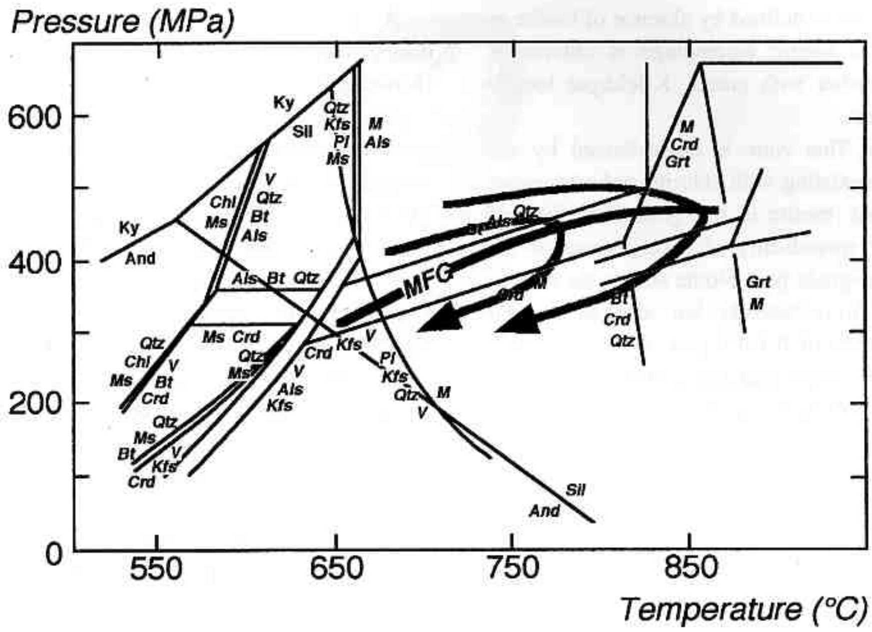

Fig. 10 *P-T* paths of the highest grade rocks of the Ryoke metamorphic belt (partly modified from Brown, 1998).

2.3.2 Deformation events

In the Older granitoids and metamorphic rocks, deformation structures caused by three different phases (D1, D2 and D3) of high-*T* ductile deformation have been recognized (Okudaira *et al.*, 1993, 1995a,b). Deformation structures resulting from D1 and D3 are penetratively observed, while the occurrence of D2 structure is limited. In all the rocks, D1 structure is characterized by a distinct foliation (S1-foliation) parallel to lithologic boundaries. In some metapelites, there are many kinds of asymmetric deformation structures. Judging from the asymmetric structures, the overall movement picture of D1 is top to the north. The emplacement of the Older granitoids partly occurred during D1. D2 is related to the formation of large-scale overturned folds and their parasitic folds (F2-folds), which are facing toward SE with NNE-NE plunging fold axes in the central unit, and of distinct shear zones (D2-shear zones) truncating S1-foliation. D2-shear zones are well observed near the boundary between the central and southern units, while it is not clear near the boundary between the northern and central units. In the northern part of Yashirojima Island, where the boundary between the central and southern units is located, many fine-grained layers with distinct foliation (S2-foliation) are recognized as D2-shear zones truncating S1-foliation in the coarse-grained granodiorite. The fine-grained layers consist of fine grains produced by dynamic recrystallization of constituent minerals of the coarse-grained granodiorite. The asymmetric structures in the D2-shear zones near the boundary between the central and southern units indicate the shear sense of top to the WSW-SW. D3 is responsible for the formation of gentle upright folds (F3-folds) with E-W trending axes. D1 and D2 structures are folded by F3-folds.

2.3.3 Tectonic perspective

Tectono-metamorphic processes of the Ryoke metamorphic belt in the Iwakuni-Yanai district have been summarized as follows (Okudaira *et al.*, 2001; Fig. 11).

- The accretion of the sedimentary rocks of the Mino-Tamba belt at the eastern margin of the Eurasian continent, from Early to Late Jurassic.
- The northward dipping large-scale extensional fracture zones which appear to have top to the NNE-NE sense of shear occurred at intermediate to shallow crustal levels. The Older Ryoke granitoids ascended along the northward dipping large-scale extensional fracture zones from the lower to middle crust (*ca.* 95 Ma). The emplacement of the Gamano granodiorite resulted in the low-*P* metamorphism in the upper and middle crust (Fig. 11a).
- Immediately after the emplacement of the granodiorite, the metamorphic sequence was modified by D2 low-angle faults and large-scale recumbent folds (Fig. 11b,c). The mylonite zones developed along the MTL also represent this tectonic event (*e.g.* Hara *et al.*, 1991; Ohtomo, 1993; Okudaira *et al.*, 1993). The D3 upright folds with E-W trending axes were formed. After D3, a large amount of granite (Younger Ryoke and San-yo granitoids) intruded as stocks. The intrusion of the granite stocks resulted in a narrow contact metamorphism of the wall rocks.

3. Description of field stops

Day 1 (August 30)

Stop 1 : Weakly metamorphosed protolith of the Ryoke metamorphic rocks (Gonomoto, Mikawa Town)

This outcrop is dominated by low-grade metamorphic rocks, belonging to a Jurassic accretionary complex of the Mino-Tamba belt. Early Jurassic radiolarian fossils included

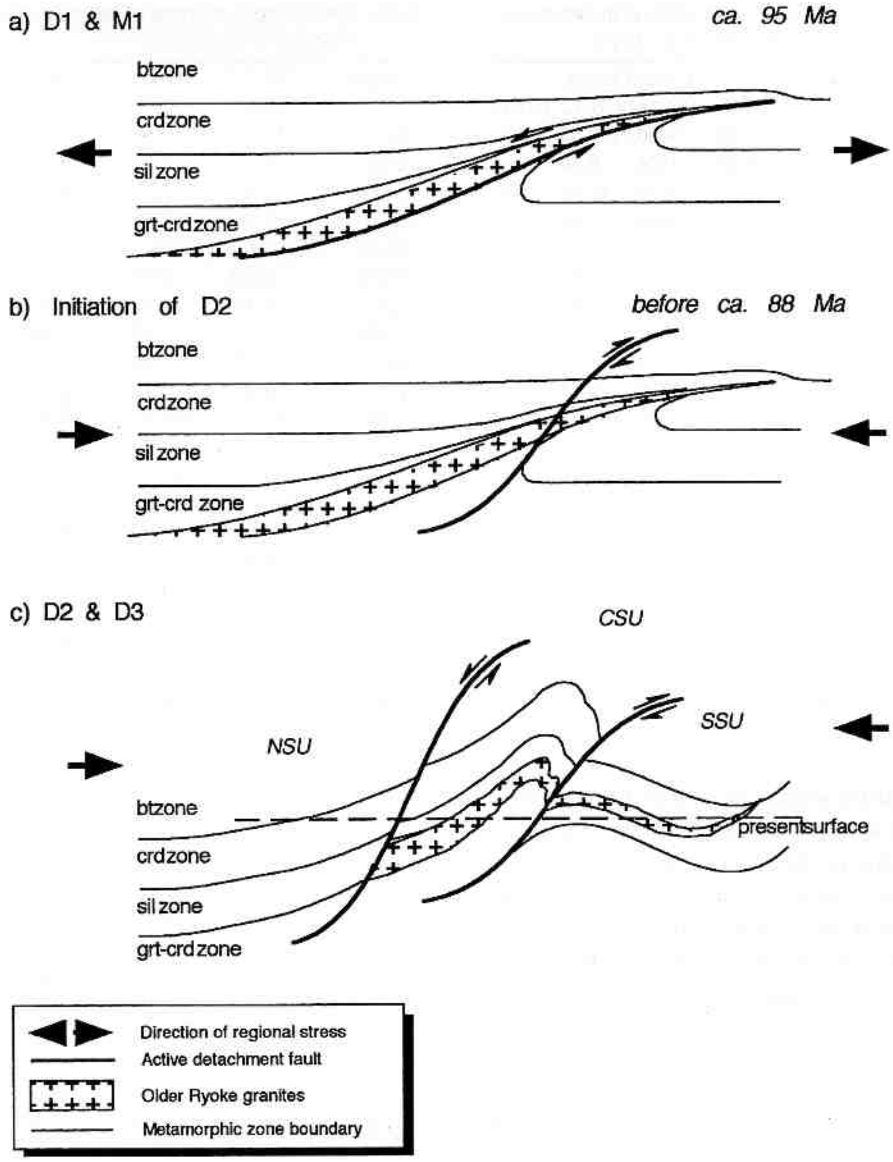

Fig. 11 A possible tectonic model for the Ryoke metamorphic belt in the Yanai district during Cretaceous time (Okudaira *et al.*, 2001).

in the pelitic rocks represent its accretion at a trench around 200 Ma (Takami and Itaya, 1996).

There is a schistosity defined by the preferred orientation of fine-grained muscovite and chlorite. Crenulation cleavages also develop. The fine-grained muscovite and chlorite are not of detritus grains, but recrystallized grains. The muscovite K-Ar ages of 176-165 Ma suggest that the rocks of this outcrop were metamorphosed at a subduction zone before the Ryoke metamorphism (Takami and Itaya, 1996). The basic rocks involve the mineral assemblages of chlorite + pumpellyite + epidote + stilpnomelane, chlorite + pumpellyite + actinolite or chlorite + epidote + muscovite, suggesting the high-*P*/low-*T* metamorphism (upper prehnite-pumpellyite to pumpellyite-actinolite facies: Takami and Itaya, 1996).

Stop 2 : Habu granodiorite (Habu, Iwakuni City)

At this stop we observe an example of the San-yo granitoid. The Habu granite is composed of two lithological unit; medium-grained biotite granite of main facies and medium-grained hornblende-biotite tonalite to granodiorite of marginal facies. These two units have distinctly different Sr*I* confirmed by apatite work, indicating to be derived from two different magmas (Tsuboi and Suzuki, 2003). They obtained Rb-Sr mineral isochron ages of 90 Ma (marginal granodiorite) and 91 Ma (central granite). The CHIME ages of 87-86Ma (Suzuki and Adachi, 1998) and SHRIMP zircon age of 90 Ma (Tsuboi *et al.*, 2001) on the Habu granodiorite are concordant with them. There is, however, still controversy regarding the age of the granodiorite, such as a whole-rock isochron age of 124 Ma (Owada *et al.*, 1995), hornblende K-Ar age of 104 Ma (Yuhara *et al.*, 1999) and biotite K-Ar ages of 103 Ma and 99 Ma (Higashimoto *et al.*, ages 1983). This stop stands in the main biotite granite facies of this body. Representative whole-rock chemistries of the

Table 2 Whole-rock analyses of the Habu granodiorite (Owada *et al.*, 1995; Yuhara *et al.*, 1999).

	Marginal facies			Central facies			
	HB-04	HB-07	HB-08	HB-05	HB-11	HB-12	HB-101
SiO_2	67.84	63.77	63.77	69.59	70.60	69.57	—
TiO_2	0.41	0.56	0.58	0.29	0.24	0.30	—
Al_2O_3	16.36	16.82	16.97	15.77	15.59	15.95	—
Fe_2O_3	4.16	5.66	5.38	3.23	3.08	3.36	—
MnO	0.09	0.10	0.11	0.08	0.07	0.07	—
MgO	1.40	2.08	2.12	0.96	0.79	0.95	—
CaO	3.56	4.72	4.72	2.69	2.44	2.69	—
Na_2O	3.23	3.34	3.36	3.51	3.77	3.58	—
K_2O	3.07	2.65	2.71	3.48	3.59	3.73	—
P_2O_5	0.14	0.16	0.15	0.11	0.09	0.11	—
Total	100.26	99.86	99.87	99.71	100.26	100.31	—
Rb	111	94	90	140	146	139	115
Sr	270	306	305	208	191	222	257
SrI*	—	—	—	—	—	—	0.70607
ASI	1.08	0.99	1.00	1.09	1.07	1.08	—

* Estimated by whole-rock-mineral isochron

Habu granodiorite by Owada *et al.* (1995) and Yuhara *et al.* (1999) are shown in Table 2.

Stop 3 : Shimokubara granite (Kinmeiji, Kuga Town)

Coarse-grained porphyritic biotite granite is predominant. Existence of porphyritic K-feldspar up to 5 cm is a characteristic feature. This granite consists of quartz, plagioclase, K-feldspar and biotite, with small amounts of apatite, zircon, monazite, allanite and ilmenite. K-Ar biotite age and CHIME monazite ages of this granite have been estimated to be 88 Ma (Kawano and Ueda, 1966), and 86.6±2.1 and 87.3±1.6 Ma (Suzuki *et al.*, 1996), respectively. Bulk-rock chemistry of the granite is homogeneous (Table 3). The homogeneity may be considered as indicating the emplacement of the granite as a largely molten mass and a differentiation before emplacement and not in situ (Moutte, 1990).

Table 3 Whole-rock analyses of the Shimokubara granite (Moutte, 1990).

sample	817 Aplite	1101	1135	1114	1126
SiO_2	74.90	69.30	70.40	70.10	67.90
TiO_2	0.018	0.202	0.230	0.226	0.197
Al_2O_3	13.4	15.2	14.5	15.5	16.6
Fe_2O_3	0.74	2.25	2.29	2.41	2.11
MnO	0.133	0.072	0.068	0.077	0.066
MgO	0.046	0.456	0.325	0.54	0.44
CaO	0.44	2.15	2.09	2.52	2.33
Na_2O	3.50	3.89	3.05	3.46	3.77
K_2O	3.85	3.90	3.50	3.43	4.65
P_2O_5	0.08	0.02	0.07	0.09	0.07
Total	97.1	97.4	96.5	98.4	98.1
Li	20	51	63	98	74
Rb	310	157	155	181	173
Cs	33.6	12	14	16	14
Be	6.5	3.1	4.6	4.5	4.0
Sr	14	170	130	141	162
Ba	34	430	280	215	300
Zr	33	98	79	81	81
Hf	—	2.7	3.0	2.8	3.4
Nb	12.5	14.2	13	16.6	14
Ga	18.1	17.6	17.2	17.4	19.2
Pb	16.3	23	19	24	29
Sn	18.2	9.2	12	13	12
Sc	3.0	3.8	3.6	3.4	2.8
V		9.4	7.6	10.5	9.1
Co	0.20	—	—	2.8	2.9
Cu	30	—	244	—	—
Zn	12.5	53	41	58	54
Ce	23	57	51	48	48
Eu	—	0.68	0.55	0.59	0.67
Y	9.7	23.3	23.0	26.0	32.0
Th	1.0	6.1	5.1	7.0	6.5
ASI	1.25	1.05	1.15	1.11	1.07
Sr/Y	1.44	7.30	5.65	5.42	5.06

Stop 4 : Metamorphic rocks of the Bt zone (Hashirano, Iwakuni City)

A large quarry of weakly metamorphosed rocks mainly derived from pebbly shale. This outcrop is located near the cordierite isograd which defines the upper limit of biotite zone marked by the absence of both chlorite and cordierite. The common mineral assemblage is muscovite + biotite. Pressure-temperature conditions of the zone was calculated to be *ca.* 90-120 MPa and 450°C (Ikeda, 2003).

Stop 5 : (This stop will be visited, if possible) : Iwakuni granite (Kawanishi, Iwakuni City)

This stop presents another example of the San-yo granitoid. The Iwakuni granite is exposed in a wide area along the seashore extending from Iwakuni to Tsuzu. It consists of hornblende-bearing and hornblende-free coarse-grained biotite adamellite. The hornblende-bearing adamellite occurs at the central part and the hornblende-free adamellite at the northern and southern part of the N-S trending body. This stop is an area of hornblende-free biotite adamellite. K-feldspar looks slightly pinkish.

Day 2 (August 31)

Stop 6 : Metamorphic rocks of the Kfs-Crd zone (Tsuzu, Iwakuni City)

The K-feldspar-cordierite zone is defined by the assemblage of cordierite + K-feldspar. Occasionally, andalusite coexists with K-feldspar and cordierite. Temperature condition of this zone was calculated to be *ca.* 460-590°C, based on two feldspar thermometry (Okudaira *et al.*, 1995a; Okudaira, 1996b), whereas Ikeda (2003) estimated the *P-T* conditions of this zone using Gibbs' method to be *ca.* 120-370 MPa and 600-680°C.

Stop 7 : Tengatake-Nagano migmatite (Tsuzu, Iwakuni City)

Tengatake-Nagano migmatite is a strange small body

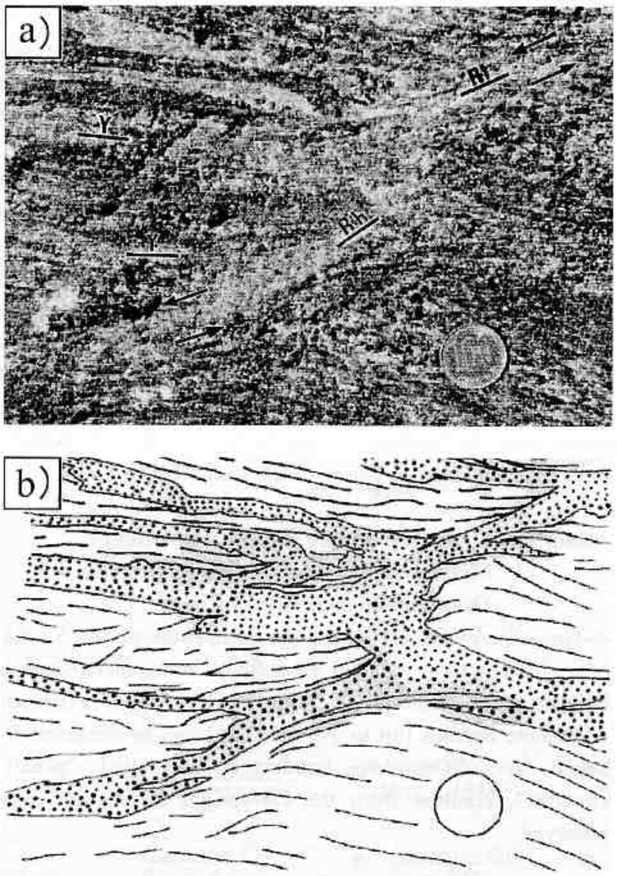

Fig. 12 (a) Photograph showing structure of the melt (fluid ?)-filled fractures around the Nagano migmatite. (b) Sketched profile of photograph (dot: granitic part, strip: metapelite).

designated so far as the Older Ryoke granitoids. The zone of the agmatitic migmatite occurs in the K-feldspar-cordierite zone of the metamorphic sequence where partial melting did not take place extensively. As shown in Figure 12, it is composed mainly of agmatitic metamorphic blocks with matrix of leucocratic rocks which intruded along non-coaxial shear fractures.

Stop 8 : Kibe granite (Nagata, Yuu Town)

This granite is predominantly coarse-grained biotite granite and characterized by preferential alignment of porphyritic K-feldspar. Marginal facies of this granite is medium- to fine-grained without porphyritic K-feldspar. Modal compositions of this granite is: 28.6 % plagioclase, 36.3 % K-feldspar, 26.9 % quartz, 8.2 % biotite (Okamura, 1960). They have weak foliation striking EW, defined by preferential alignment of biotite and porphyritic K-feldspar. K-Ar biotite age and CHIME monazite age of this granite have been estimated to be 86.3±4.3 Ma (Higashimoto *et al.*, 1983) and 87 Ma (Kawano and Ueda, 1966), and 91.3±2.1 Ma (Suzuki and Adachi, 1998), respectively. Representative chemical compositions of the Kibe granite are shown in Table 4.

Table 4 Whole-rock analyses of the Kibe granite (Moutte, 1990).

sample	1292	1295	828	914	1000
SiO_2	73.8	75.3	73.7	70.7	73.5
TiO_2	0.017	0.073	0.042	0.356	0.290
Al_2O_3	12.7	12.7	14.0	14.3	13.8
Fe_2O_3	0.801	0.405	0.37	2.54	2.14
MnO	0.10	0.018	0.006	0.044	0.040
MgO	0.055	0.154	0.107	0.74	0.62
CaO	1.26	0.91	1.14	1.75	1.38
Na_2O	2.06	3.25	2.72	2.6	3.05
K_2O	5.25	4.9	6.85	5.3	4.95
P_2O_5	—	—	0.03	0.13	0.11
Total	96.0	97.7	99.0	98.5	99.9
Li	16	62	18	61	86
Rb	142	136	270	275	300
Cs	19	13	—	—	12.3
Be	—	5.2	1.8	2.2	3.5
Sr	84	72	120	130	95
Ba	210	270	270	480	350
Zr	94	66	44.7	166	135
Hf	3.4	3.0	—	4.5	5.6
Nb	2.0	4.6	3.1	17.8	19.7
Ga	12.5	12.6	14.2	15.8	16.0
Pb	30	32	36.6	31.7	35.8
Sn	—	3.2	—	—	3.4
Sc	3.2	1.05	0.90	6.8	5.5
V	3.5	3.0	1.4	25.6	18.3
Co	0.60	0.90	1.1	3.05	2.45
Cu	—	—	—	—	—
Zn	10	11.2	7.9	59	59
Ce	29	13	15	111	80.4
Eu	0.50	0.40	0.60	0.78	0.63
Y	45	5.3	22.1	24.1	18.0
Th	4.5	3.1	4.6	32	20.5
ASI	1.12	1.03	1.00	1.08	1.07
Sr/Y	1.87	13.58	5.43	5.39	5.28

Stop 9 : Metamorphic rocks of the Grt-Crd zone (Obatake, Obatake Town)

The garnet-cordierite zone is defined by the assemblage of garnet + cordierite + K-feldspar in the pelitic rocks. *P-T* conditions have been estimated to be 730-770°C, 550-650 MPa (Okudaira, 1996b), whereas according to Ikeda (1998a,b, 2003), *P-T* conditions of this zone were calculated to be 790-860°C at 460-760 MPa.

Stop 10 : Gamano granodiorite (Obatake, Obatake Town)

The Gamano granodiorite concordantly intruded into the high-grade metamorphic rocks at *ca.* 100-95 Ma (SHRIMP zircon: Nakajima *et al.*, 1993; CHIME monazite: Suzuki *et al.*, 1994; Suzuki and Adachi, 1998), and its foliation, defined by the preferred shape orientation of plagioclase, biotite and hornblende is harmonic in trend with that of the surrounding metamorphic rocks. Representative chemical compositions of the Gamano granodiorite are shown in Table 5.

Table 5 Whole-rock analyses of the Gamano granodiorite (Moutte, 1990; Nakajima, unpub. data).

sample	1176	1413	92072405	92072301
SiO_2	66.1	68.0	67.90	69.38
TiO_2	0.605	0.461	0.73	0.42
Al_2O_3	15.4	14.0	15.52	16.85
Fe_2O_3	4.91	4.08	5.42	2.94
MnO	0.057	0.076	0.10	0.04
MgO	1.01	0.874	1.27	0.91
CaO	3.94	3.22	3.92	4.76
Na_2O	4.0	3.3	3.11	3.31
K_2O	1.88	3.21	2.69	1.63
P_2O_5	0.34	0.27	0.19	0.06
Total	98.2	97.5	100.84	100.29
Li	78	36	—	—
Rb	117	115	138	60
Cs	12	10	6.9	2.7
Be	2.1	2.6	—	—
Sr	250	240	266	306
Ba	180	590	1142	370
Zr	122	132	196	146
Hf	3.9	3.5	5.8	4.6
Nb	22	14.7	21	12
Ga	21.3	19.7	—	—
Pb	16	19	—	—
Sn	8.0	6.0	—	—
Sc	6.8	8.6	12	6.3
V	33	31	33	31
Co	5.9	6.0	11	6.0
Cu	5.0	15.1	15	2.4
Zn	98	81	96	52
Ce	42	71	105	37
Eu	1.3	1.25	1.1	1.4
Y	15	22.0	14	12
Th	2.7	8.1	17.0	5.7
Ni	—	—	7.6	4.8
Cr	—	—	16	18
ASI	0.98	0.95	1.02	1.06
Sr/Y	16.7	10.9	19.6	24.9

Stop 11 : Gamano (Kita-Oshima) granodiorite (Hirarehana cape, Oshima Town)

A kilometer-sized granodiorite block exposed at the northernmost part of Yashirojima Island is very coarse-grained and strongly foliated compared to the Gamano granodiorites around it. In old days it was considered to be a fragment of the ancient "geosynclinal basement" of SW Japan (Kojima and Okamura, 1968). Since isotopic and U-Th-Pb ages of the Kita-Oshima granodiorite are not old but similar to the Gamano granodiorite (Honma and Sakai, 1975; Shigeno and Yamaguchi, 1976; Suzuki *et al.*, 1994; Herzig *et al.*, 1998), they have now been regarded as a part of the Gamano granodiorite. However, the name of Kia-Oshima granodiorite is often used for this characteristic block.

The Rb-Sr whole rock-mineral (biotite, plagioclase and K-feldspar) ages of the granodiorite fall in a range of ca 89-87 Ma. The fission-track zircon and apatite ages are 68.9±2.6 Ma and 57.4±2.5 Ma, respectively (Okudaira *et al.*, 2001). As shown in Figure 13, two distinctive cooling stages have been revealed; 1) a rapid cooling (> 40°C/Myr) for a period (~10 Myrs) soon after the thermal peak of the Cretaceous Ryoke metamorphism (~98 Ma) and 2) the subsequent slow cooling stage (~10°C/Myr) after *ca.* 85 Ma.

Around this outcrop, where the boundary between the central and southern units is located, many fine-grained layers with distinct foliation (S2-foliation) are recognized as D2-shear zones truncating S1-foliation in the coarse-grained granodiorite. The fine-grained layers consist of fine grains (*e.g.* quartz and feldspar) produced by dynamic recrystallization of constituent minerals of the coarse-grained granodiorite. The asymmetric structures in the D2-shear zones near the boundary between the central and southern units indicate the shear sense of top to the WSW-SW.

Stop 12 : (This stop will be visited, if possible) : Metamorphic rocks of the Sil-Kfs zone (Kandori-misaki, Hikari City)

This outcrop is dominated by metapelites of the Sil-Kfs zone. Metamorphic mineral assemblage in the metapelites is sillimanite + cordierite + biotite + K-feldspar. Prismatic sillimanite needles (up to 2-3 cm long) can be observed by naked eyes. Complete boudinages, so-called "pencil structure", resulted from the D3-upright folding are also observed.

Day 3 (September 1)

Stop 13 : Migmatite of the Sil-Kfs zone (Himisaki cape, Oshima Town)

Spectacular migmatite outcrop on the seashore. We can enjoy various lithologies of hybrid "migma" flowing and folded (Fig. 14). Metamorphic mineral assemblages in metapelite blocks and melanosome of the migmatite are sillimanite + cordierite or sillimanite + garnet with K-feldspar. *P-T* conditions have been estimated to be 630-690°C at 300-500 MPa (Okudaira, 1996b) and to be 700-760°C at 500-640 MPa (Ikeda, 2003). We can observe tourmaline boudinages in naked eyes.

On the approach to the Himisaki cape, beautiful outcrops of metamorphosed bedded chert are exposed along the seashore promenade. In the sillimanite zone, metamorphic rocks are less abundant than the cordierite-garnet zone and the percentage of metachert in the metamorphic rocks is larger than in the other zones.

Stop 14: (This stop will be visited, if possible): Towa granite (Tateiwa, Tachibana Town)

Towa granite which is one of the Younger Ryoke granitoids varies petrographically ranging from granodiorite (Pl 40.8%, Qtz 37.2%, Kfs 14.1%, Bt 7.5%, Hbl 0.4%) to adamellite (Pl 34.8%, Kfs 34.6%, Qtz 23.8%, Bt 6.2%, Hbl 0.1%). Its modal composition becomes gradually adamellitic toward the east. The granodiorite is most widespread in the metamorphic belt on the scale of batholithic dimension. This granodiorite is weakly foliated, coarse-grained hornblende-

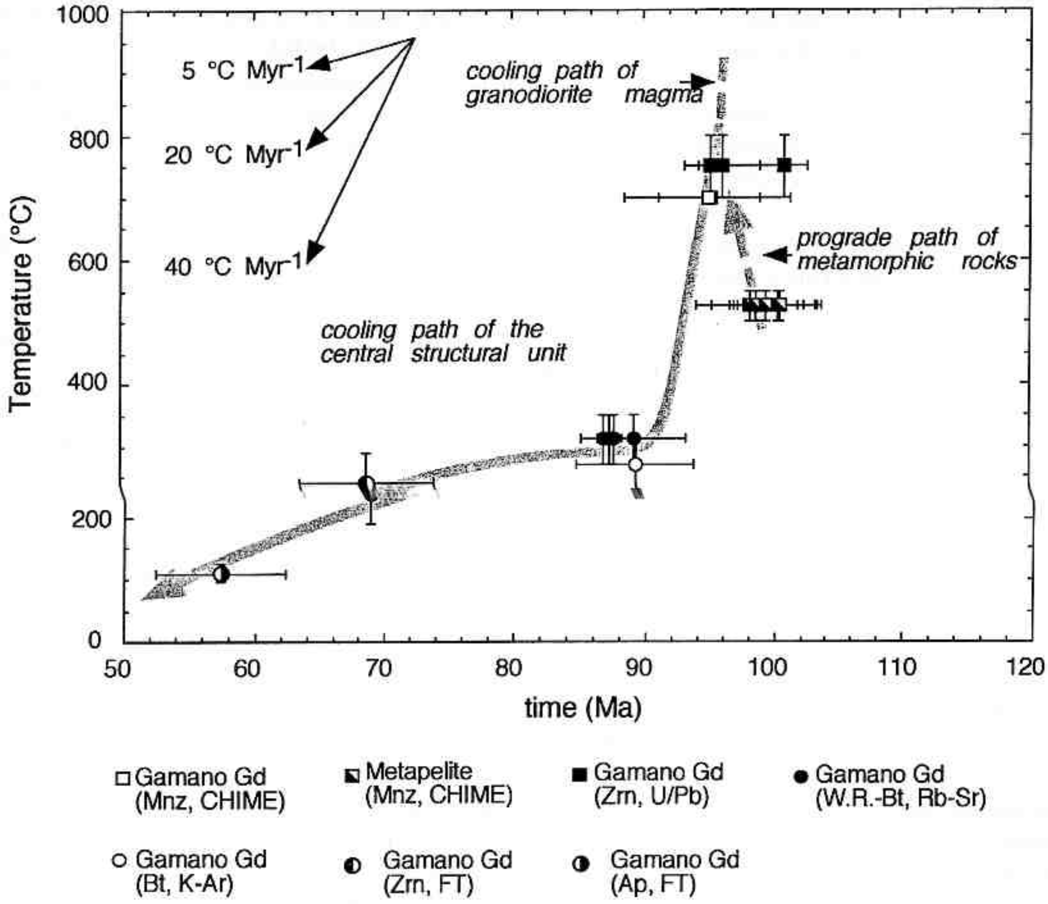

Fig. 13 Cooling history of the central unit of the Ryoke metamorphic belt in the Yanai district (Okudaira *et al.*, 2001 and references therein). In this figure, the range of age represented by the length of the bar reflects the two sigma error. Arrows indicate a possible temperature-time path (cooling history) of the rocks of the central structural unit. Two distinctive cooling stages can be recognized as; 1) a rapid cooling (>40 °C/Myr) for a period (~10 Myrs) soon after the thermal peak (~98 Ma) and 2) subsequently the slow cooling stage (~10°C/Myr) after ca 85 Ma.

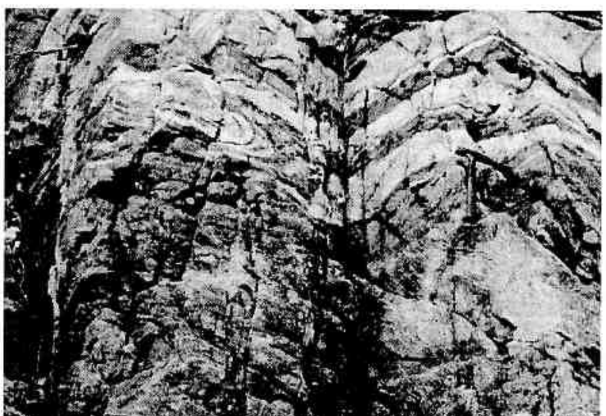

Fig. 14 Photograph of layered migmatite (sillimanite-K-feldspar zone) at Himisaki Cape.

biotite granodiorite. Quartz grains occasionally show undulatory extinction under microscope. Plagioclase composition ranges from An_{28} to An_{34}.

Acknowledgments: We thank M. Tsuboi for providing his paper in press. M. Owada and T. Shimura are thanked for his careful review and his editorial handling, respectively.

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*: in Japanese with English abstract.

**: in Japanese.

Received May 20, 2003
Accepted July 3, 2003

Appendix. Route map and locations of stop points in the Iwakuni-Yanai district.